Final Project Report

Project Title: PREMIUM FUEL PRODUCTION FROM MINING AND TIMBER WASTE USING ADVANCED SEPARATION AND PELLETIZING TECHNOLOGIES

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Recipient: Mr. John Davies, Commonwealth of Kentucky/Kentucky Division of Energy 663 Teton Trail, Frankfort, Kentucky 40601 6th Congressional District

Subcontractors: University of Kentucky Research Foundation 201 Kinkead Hall Lexington, Kentucky 40506-0057 Jason Hardin (859-257-4526; e-mail: jason.hardin@uky.edu

Principal Investigator: Rick Honaker

Department of Mining Engineering, University of Kentucky Lexington, Kentucky 40506-0107 Phone: 859-257-1108; Fax: 859-323-1962; e-mail: rhonaker@engr.uky.edu

Co-Principal Investigators: B.K. Parekh, Center for Applied Energy Research (UK); Darrell Taulbee, Center for Applied Energy Research (UK); Daniel Tao, Mining Engineering (UK)

Other Partners: Pine Mountain Lumber, LLC, Lexington, Kentucky 40544; James River Coal Services Co., London, Kentucky 40741-3123; H & S Lumber, Clay City, Kentucky 40312; Global Energy, Louisville, Kentucky.

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EXECUTIVE SUMMARY

The Commonwealth of Kentucky is one of the leading states in the production of both coal and timber. Kentucky ranks third in coal production with about 150 million tons annually while also being the leading timber producer east of the Mississippi river. Both industries produce a vast amount of waste material that contains a significant amount of energy value. In the coal industry, the recovery of fine coal is usually not attempted due to issues related to high moisture, handling, and transportation of this material. It is estimated that about 3 million tons of fine coal, having a high heating value greater than 12,500 Btu/lb, are disposed in waste-slurry impoundments annually with an additional 500 million tons stored at a number of disposal sites around the state due to past practices. Likewise, the timber industry discards nearly 35,000 tons of sawdust on the production site due to unfavorable economics of transporting to industrial boilers where wood waste could be used as fuel. With an average heating value of 6,700 Btu/lb, the monetary value of the energy disposed in the form of sawdust is approximately \$490,000 annually.

Since the two industries are typically in close proximity in the eastern and western regions of Kentucky, one promising avenue is to selectively recover and dewater the fine-coal particles and then briquette them with sawdust to produce a high-value fuel. The benefits are i) a premium fuel product that is low in moisture and can be handled, transported, and utilized in existing infrastructure, thereby avoiding significant additional capital investment and ii) a reduction in the amount of fine-waste material produced by the two industries that must now be disposed at a significant financial and environmental price. As such, the goal of this project was to evaluate the feasibility of producing a premium fuel with a heating value greater than 10,000 Btu/lb from waste materials generated by the coal and timber industries. Laboratory and pilot-scale testing of the briquetting process indicated that the goal was successfully achieved. Low-ash briquettes containing 5% to 10% sawdust were produced with energy values that were well in excess of 12,000 Btu/lb.

Characterization of the fine coal waste streams in two eastern Kentucky coal preparation plants revealed these streams contained significant amount of coal. In one plant, 22% of the waste stream reporting to the thickener for disposal had a particle size greater than 37 microns and a

dry heating value exceeding 13,900 Btu/lb. This equates to about 51 tons/hr of this high-heating-value coal that is being sent to the waste impoundment. Likewise, the fine waste of a second eastern Kentucky plant contained 38% of + 37 micron coal with a heating value of about 9,000 Btu/lb. For both sources, froth flotation was found to provide efficient coal recovery and thus could serve as the primary separation process on a commercial scale. For coals that do not respond well to flotation, a centrifugal teeter bed technology was evaluated and the separation performance was shown to be improved by the injection of air bubbles into the feed stream. Dependent on the product-ash content, coal recovery improvements of 10 to 20 absolute percentage points were achieved.

A major economic hurdle associated with commercially briquetting coal is binder cost. In an effort to reduce this cost, tests were performed to determine if the binder reagents could serve multiple purposes, i.e., as a collector in froth flotation or as a dewatering agent. However, the evaluation revealed that those reagents that were the more effective binders were of little benefit to either process. Further, it was initially believed that combining saw dust with the clean-coal slurry prior to filtration could be an inexpensive means to improve coal dewatering performance. A detailed experimental program to evaluate the effectiveness of sawdust as a dewatering aid found that the presence of sawdust negatively impacted filtration performance.

Approximately fifty formulations, both with and without lime, were subjected to an extensive laboratory evaluation to assess their relative effectiveness as binding agents for the briquetting of 90% coal and 10% sawdust blends. Guar gum, wheat starch, and a multi-component formulation were identified as most cost-effective for the production of briquettes targeted for the pulverized-coal market. REAX/lime and a second multi-component formulation were identified as the most cost-effective for the production of briquettes targeted for the stoker-coal market.

Various sources of sawdust generated from different wood types were also investigated to determine their chemical properties and to evaluate their relative performance when briquetted with clean coal to form a premium fuel. The highest heating values, approaching 7,000 Btu/lb, were obtained from oak. Sawdusts from higher-density, red oak, white oak, hickory, and beech trees provided higher quality briquettes relative to their lower-density counterparts. In addition

to sawdust type, a number of other parameters were evaluated to characterize their impact on briquette properties. The parameters that exhibited the greatest impact on briquette performance were binder concentration; sawdust concentration and particle size; cure temperature; and ash content. Parameters that had the least impact on briquette properties, at least over the ranges studied, were moisture content, briquetting force, and briquetting dwell time.

Samples of clean coal from flotation and spiral cleaning circuits were blended in an effort to determine if packing efficiencies could be improved while simultaneously reducing binder concentration requirements. These tests demonstrated that the highest packing efficiencies were obtained with blends containing about 4 parts spiral to one part flotation product. When a binder was added to the spiral/flotation blends, some improvements were noted in both packing density and briquette strengths for blends containing 20%-50% by weight of the spiral product, a finding that could have economic implications depending on the relative availability of clean coal products and the product market.

The continuous production of briquettes from a blend of coal and sawdust was evaluated using a 200 lbs/hr Komarek Model B-100 briquetter. The heating values of briquettes produced by the unit exceeded the goal of the project by a large margin. A significant observation was the role of feed moisture on the stability of the mass flow rate through the briquetter and on briquette strength. Excessive feed moisture levels caused inconsistent or stoppage of material flow through the feed hopper and resulted in the production of variable-quality briquettes. Obviously, the limit on feed moisture content has a significant impact on the economics of coal-sawdust briquetting since it will ultimately dictate dewatering costs. Interestingly, the maximum feed moisture was found to be dependent to some extent on the binder type with molasses-containing blends being difficult to feed when the moisture content approached 12% while guar gum blends flowed consistently at moisture levels as high as 15% by weight.

An economic analysis was conducted on the basis of the coal recovery and briquetting operations being integral components in one of the eastern Kentucky coal preparation plants. Due to the low ash and moisture contents of the coal-sawdust briquettes, a production increase of about 50 tons/hr would potentially be realized at the 1,400 ton/hr preparation plant. The overall capital

cost of a 50 ton/hr flotation and briquetting addition was estimated to be around \$8 million. Based on a conservative briquetting operating cost of \$12/ton, the annual profit before taxes was approximated to be \$4 million thereby indicating a return on investment in about 2 years. The internal rate of return based on a 10 year life was an attractive 43%.

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1. INTRODUCTION

1.1 Background

The state of Kentucky has a significant concentration of industries that rank near the top in energy consumption. This fact is likely due to the low electricity cost in the state, which is currently 4.2 cents/kwh. Two of the industries, i.e., the Mining and Timber industries, rank near the top in production when compared to all other states. Kentucky ranks third in coal production with about 150 million tons annually while also producing the largest amount of timber products east of the Mississippi River. A majority of the timber production occurred within or near the coalfields within Kentucky.

Before 1980, the ability to efficiently treat the -28 mesh material in coal processing plants, which typically represents 10% - 20% of the run-of-mine feed, was limited due to the lack of effective technologies and the inability to dewater the final product to acceptable levels. Thus, vast quantities of fine, high quality carbon material were disposed into fine coal refuse ponds for several decades, thereby representing not only a loss of valuable energy resources but also an environmental hazard. Estimates indicate that over 500 million tons of fine coal refuse are currently stored in refuse ponds in the state of Kentucky. After 1980, the development of light weight materials led to the popular use of spiral concentrators for cleaning the 28 x 100 mesh fraction, which greatly improved energy recovery and reduced overall waste generation. In addition, froth flotation processes have become more popular in the industry for the recovery of coal in the -100 mesh fraction. However, according to a recent survey (Coal Age, October 2000), only about 20% of the total plant capacity in Kentucky currently employs froth flotation for this purpose. This fact is likely due to concerns related to a potential increase in overall product moisture, lack of understanding the technical aspects of the process and operating costs. Based on a typical plant feed weight of 5% reporting as -100 mesh material and an estimated mass yield of 50%, the amount of lost, high quality coal that is disposed annually in Kentucky is approximately 3 million tons, which currently has a revenue value of around \$150 million annually.

In 1997, the production of all timber products in the state of Kentucky totaled 293 million cubic feet (Stratton and Lowe, U. S. Department of Agriculture Report, 1999). However, the timber processed by the saw mills generated a substantial amount of residues with 33% of the residues being in the form of sawdust. Sawdust has little value as a material-based product and is normally disposed as waste. The amount of sawdust generated during 1997 was 35 million cubic feet or about 12% of the total production. Nearly 47% of the sawdust was used as an industrial fuel while the remaining was disposed in landfills. It is a goal of the current Timber Industry to utilize 100% of the sawdust for autonomous energy production. The approach described in this proposal will significantly enhance the possibility of reaching this goal.

The U. S. Department of Energy has recognized the carbon currently existing in refuse ponds as a valuable energy source. Through a solicitation in 1998 (DE-RA26-98FT97098), a total of 9 projects were awarded to investigate methods to recapture the valuable energy source from abandoned and active slurry ponds. The problem identified from the conclusion of these projects was dewatering of the final product to required levels and the cost of agglomerating the fine coal particles, which is necessary for handleability issues. The cost of the binder agent was found to be the most critical factor with total costs being in the range of \$5 to \$8/clean ton (Clark et al., 1999; Black, 1999; Coal Preparation Conference). The application of the sawdust waste may enhance the dewatering of the fine coal product and provide strength enhancements and binder cost reductions in the production of coal/sawdust briquettes that could be used as a premium fuel by utilities.

1.1.1 Fine Coal Upgrading

Recent reports indicate that the cleaning of coal extracted from coal seams within the state of Kentucky will become increasingly difficult due to the presence of greater amounts of middling (mixed-phase) particles (Weisenfluh et al., Kentucky Geological Survey, IC 59, 1998). This fact will result in greater amounts of waste material being generated from the coal preparation plant. Current technologies such as dense medium cyclones have the ability to efficiently treat the intermediate and coarse middling particles. However, conventional fine coal (i.e., -1 mm) cleaning units, such as spiral concentrators and associated circuitry arrangements, fail to adequately provide efficient ($< 0.05 E_p$), low density (< 1.6 relative density) separations. As

shown in previous studies, achieving efficient fine coal cleaning is a substantial economical benefit for the entire mining operation (Brake and Eldridge, 1996; Honaker et al., 1999).

One of the most significant developments in coal preparation during the past decade has been the development and commercialization of column flotation technologies. Column flotation generally allows a more efficient recovery of fine coal particles (i.e., -150 µm) than conventional flotation while providing improved selectivity through the use of wash water and relatively deep froth depths. As a result, the installation of flotation columns in operating preparation plants have resulted in significant economic gains due to an improved product quality produced from the fine coal fraction and improved mass yield values (Brake and Eldridge, 1996). In some cases, this benefit allows greater mass recoveries from the coarse and intermediate particle size fractions (Yoon et al., 1998; Honaker et al., 1999) which helps to alleviate the concerns pertaining to increased overall product moisture due to dewatering restraints that are also addressed in this proposal.

Despite the success of column flotation, a significant disadvantage of any froth flotation process is the inherent inefficiency in the selectivity achieved on fine coals containing significant amounts of middling and/or coal pyrite particles. For this reason, gravity-based separations provide superior or equal separation performances compared to froth flotation processes depending upon sufficient gravitation forces, retention time and coal characteristics (Adel et al., 1989; Wang et al., 1992; Mohanty et al. 1998). Based on this fact, maximizing the use of gravity-based processes for the treatment of fine coal would be advantageous for optimizing the rejection of impurities and the undesirable trace elements from coal while achieving the ultimate mass recovery values.

In terms of gravity-based separations for fine coal cleaning, spiral concentrators have received the most attention during recent years. Their popularity with coal operators for treating the nominally 1 mm x 150 μ m coal is derived from low capital and operating costs and operational simplicity. In addition, spiral concentrators inherently do not bypass light coal to the tailings stream. However, a deficiency of spiral units is a limit on the ability to achieve separations at low relative density (d_{50}) values. The lowest d_{50} reported for spiral concentrators used for

primary cleaning only has been around 1.75 while achieving moderate separation efficiencies as indicated by probable error (E_p) values of around 0.15 to 0.18. Recent research has found that spiral concentrators can be used in a circuitry arrangement to achieve lower d_{50} values of around 1.60, which has led to significant economic gains for an operating coal preparation plant (Luttrell et al., 1999). However, the circuit E_p values remained in the same range as a primary spiral and a significant number of secondary spirals were needed in the overall circuit.

1.1.2 Dewatering

One of the biggest hurdles in utilization of fine coal cleaning technology by the coal industry is the economic dewatering of the fine clean coal product. Until an economical and practical solution to dewatering of fine clean coal is achieved, the efforts put in developing fine clean coal technology will be wasted. The proposed program offers an economic potential solution to dewatering which is very much relevant to immediate needs of recovering clean coal from refuse pond and utilizing the wood waste which are abundant in Commonwealth of Kentucky.

The degree of difficulty associated with dewatering increases as the particle size decreases or the surface area of particles to be dewatered increases. The high surface moisture retained by the fines offsets many of the benefits of coal cleaning and can seriously undercut utilization of advanced coal cleaning technologies, which can provide an ultra-clean coal. Even a one-percent increase in clean coal moisture can result in significant increase in transportation costs. A power plant using 3.0 million tons/year of coal from a plant located 250 miles away might spend about \$350,000 per year to transport the additional one percent moisture. From an utility perspective, it is believed that a one-percent increase in moisture can offset up to 4.5 percent reduction in ash. This situation clearly identifies the need for advanced dewatering technology and such technology could result in significant cost savings for the coal-using industry.

Dewatering of fine coal, thus, becomes a very important step for the application of advanced coal cleaning processes. Industry has shown reluctance in adopting the advanced coal cleaning technologies due to unavailability of an efficient and economical dewatering process.

A wide variety of equipment such as solid bowl centrifuge, screen bowl centrifuge and vacuum disk are used for fine particles dewatering. However, the moisture content in the final product is unacceptable. Figure 1 shows coal-dewatering cost as a function of particle size. Note that the dewatering cost increases sharply for coal particles finer than 0.5 mm (28-mesh).

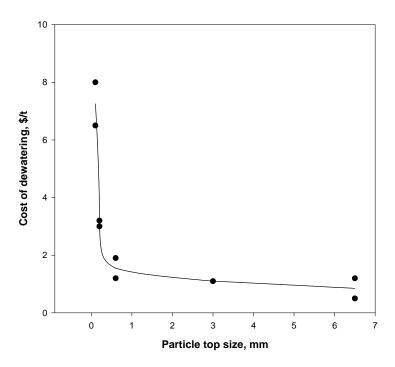


Figure 1.1. Coal dewatering costs (after Hucko 1990).

Currently, most coal preparation plants utilize vacuum filtration technology for dewatering fine clean coal, providing a dewatered product containing about 25% to 30% moisture. The filtration of fine size coal slurries generally requires use of chemical reagents (surfactants or polymers) in lowering moisture of the filter cake. The cost of chemicals constitutes a significant portion of the total cost of dewatering. In hyperbaric (high pressure) filtration, in addition to reagents, high air consumption adds to the high dewatering cost.

The coal industry will be very much interested in utilizing an economical dewatering technique that allows them to avoid the use of the more expensive option of thermal drying. Also, if the dewatered product is obtained with sufficient strength, it could be handled easily during

transportation. a novel dewatering approach of combining all the various benefits listed above in a single stage operation was evaluated in the project.

Although the term "dewatering" refers to the removal of water, researchers have used different terms and descriptions to define water associated with particles. Brown et al. (1) classified five types of water associated with coal including interior adsorption, surface adsorption, capillary, interparticle and adhesion water. The last three types of water are termed as "free" water and are potentially removable by mechanical techniques. However, the first two types of water, known as "inherent" moisture, can only be removed by energy-intensive techniques such as thermal drying.

A variety of techniques are now used in contemporary practice for dewatering coal. The type and efficiency of various dewatering equipment varies as a function of particle size. The degree of difficulty associated with mechanical dewatering increases as the surface area of the particle increases. Particles finer than 0.5 mm (28 mesh) present the greatest dewatering difficulty.

1.1.3 Briquette Processing

The low-ash, high-Btu fine coal recovered from cleaning and dewatering processes are generally still too wet and unhandleable to be sold as a stand-alone marketable product. In rare instances, the recovered coal fines could be blended with the output from an adjacent coal preparation plant without adversely impacting the overall product quality. Briquetting is often a necessary step in utilizing fine coal waste, particularly for synthetic fuel operations established under Section 29 tax credits (Harrison, 2000).

High quality premium fuel can be produced from fine coal and sawdust wastes through an agglomeration process to convert fine wastes into lumps of acceptable size to improve their handling and processing characteristics. Briquetting is one of the most effective agglomeration process and is widely used in agglomerating a variety of fine particles, including coal fines (Lyne and Johnston, 1981; Anon, 2000). The process of briquetting often consists in applying pressure to a mass of particles with or without the addition of a binder to form an agglomerate. The most

common briquetter is the ring-die-type extruder in which rotation of the die in contact with the roller compresses material between the roller and the die and the resulting pressure forces the material through the die holes, producing cylindrical pellets with diameters ranging preferably from 3/8" to ½" (Leaver, 1979). An understanding of briquetting process involves a knowledge of the cohesive and repulsive forces between solids, the adhesion of binders, heat transfer characteristics, heat effects on surface properties, and the rheological behavior of particulate masses inside the briquetter. The physical and surface characteristics of particles are very important for the effectiveness of briquetting. Factors that affect the strength of pellets include coal rank, size distribution, moisture, mineral components, particle surface charge (zeta potential), compression force, induration temperature, binder type and dosage, etc.

Binders are often used in pelletization of fine particles to enhance particle cohesion and the pellet strength (Young and Kalb., 1994; Olson et al., 1995; Mehta and Parekh, 1996; Baykal and Doven, 2000; Yaman et al., 2000). The most common binders include soluble salts, bentonite, inorganic chemicals, and organic materials. Soluble salts do not improve the strength of wet pellets. Upon the evaporation of the host moisture, salts recrystallize and form solid bridging to impart dry strength. Bentonite is the most common additive binder for mineral industry. The amount used varies from 0.5 to 1.0% by weight. It improves the pellet strength by increasing the viscosity and surface tension of the water and by aiding in the compaction of the pellets. However, it increases the ash content of coal and is rarely used in coal pelletization. The use of lime as an inorganic binder for coal fines helps capture sulfur during combustion and adds fluxing properties to the pellet. Organic binders usually rely on adhesion and cohesion within themselves and adhesion to the particles, forming bridges between coal particles. Starch is the typical example of organic binders. It significantly increases the strength of wet and dry pellets. Bitumen is rapidly becoming the most popular coal binders because of its unique characteristics. It is inexpensive, contributes little to the ash of pellets, produces mush less smoke than tar pitch and distributes readily on the coal surface. Fibrous wastes such as sawdust are also very promising coal binder (Gunter, 1993). Their combined use with bitumen may be able to reduce binder cost significantly while producing strong and water resistant pellets with improved combustion characteristics.

Binders can be classified into matrix- and film-type binders according to their functional behavior (Young and Kalb, 1994). Bitumen is probably the most widely used fine coal binder. It is a matrix-type binder that provides an essentially continuous medium in which the particles to be pelletized are incorporated. The binder may occupy about 10% of the pellet volume and acts to fill the void space between particles. The pellet strength is dependent on the degree of void saturation with the binder. Starch, another popular coal binder, is a film-type binder which acts like an adhesive to stick the particles together. The high cost of binders (usually more than \$5/t of coal) is the major hurdle to the commercialization of pelletization processes. Identifying most cost effective coal binders is critical for commercial success of the proposed process.

Since the binder cost is the principal operating cost of briquetting and it consumes whatever profit might be generated from the value added process (Tucker et al., 1996), efforts have been made to eliminate the use of binders during briquetting. Earlier studies have shown that binderless briquetting of fine coal is possible under high pressure at elevated temperature (Messman, 1977; Miller et al., 1979; Davidson and Kalb, 1991; Tucker et al., 1996). Several types of bonds are involved in coal particle interactions. They include ionic bond, atomic bond, van der Waals bond and hydrogen bridge, resulting from the large number of functional groups, e.g., hydroxyl, carboxyl and carbonyl groups of the aliphatic and aromatic components of the coal macromolecules. The pellet strength progressively increases with an elevated intensity of compression as different bond forces become linked to each other in sufficient proximity. To minimize the repulsive forces caused by the contained moisture making the phase change into steam, moisture in coal is reduced to a certain level.

It has been observed that pellets often lose strength when they are cured or dried. This can be attributed to the loss of moisture, which results in the decrease of capillaries that hold green pellets together. To increase the strength of dry pellets, more attention should be devoted to induration and sintering. Induration refers to the high temperature phase of agglomeration and implies bonding together particles by solid state mechanisms, which is in contrast to sintering where substantial formation of the liquid phase is in the bonding network. The major mechanism of solid state bonding occurs by intergranular bridging of particles. With sufficient temperature

and time, particles become enlarged and recrystallization may occur. Conventional binders are unable to considerably increase the strength of dry pellets since they are *water activated*. When water vaporizes, its activity decreases and so does adhesion. A fundamentally innovative binder, referred herein as the *heat activated binder* (HAB), will have to be developed to significantly enhance the strength of dry coal pellets. An effective HAB will have low softening point, low solubility, opposite surface charge to coal, good surface hydrophobicity, etc. to facilitate induration and/or sintering. The distribution of pore size after induration and sintering is very important for the strength of pellets. In general, a reduction in the overall porosity will lead to an increase in the pellet strength. Pore size distribution may also affect combustion characteristics of coal pellets. Coal particle size and sawdust particle size play an important role in determining the porosity of pellets and a better understanding of their effects will lead to improvement in the pellet strength.

One of the advantages of briquetting fine coal in the presence of sawdust is that the heat produced during high pressure extrusion at elevated temperature may be sufficient to cause sawdust sintering, which may enhance binding between fine coal particles. It is known that the presence of even minute amounts of a liquid phase formed as a result of sintering strongly enhances the rate of the pelletizing process (Wynnyckyj and Batterhamt, 1985). The thermodynamic driving force for sintering is also the capillary pressure.

There are many factors that affect the strength of coal pellets. They include coal rank, size distribution, moisture, mixing, mineral components, particle surface charge (zeta potential), compression force, induration temperature, binder type and dosage, other chemical additives such as solid lubricant, etc. A systematic study of effects of these parameters is essential to maximize the pellet strength and/or minimize pelletizing cost.

1.2 Project Approach

The overall goal of the project was to produce a premium fuel from the waste material generated from two large producing industries in the state of Kentucky using advanced particle processing technologies. Currently, no substantial industrial use exists for the sawdust generated in Eastern Kentucky, which represent tons of wasted energy. In addition, approximately 150 million tons

of coal are mined in Kentucky annually with approximately 5% of this production being rejected to fine refuse ponds due to the lack of efficiency cleaning and dewatering technologies. Transporting the fine material if recovered is difficult without briquetting or pelletizing, which is typically cost prohibitive (e.g., \$5-8/ton). Thus, the project investigated methods to combine the waste to form an economical fuel for utility use.

Figure 3 illustrates the concepts of the project. The fine coal refuse was subjected to upgrading using advanced technologies and innovative process circuitry. One of the proposed concepts was to replace the typical chemicals used in the froth flotation process with the binders that were applied in the briquetting process. Enhanced gravity separators (EGS) are a novelty that have been developed and commercialized during the 1990's and fully-continuous units remain under development. Past studies have shown that EGS units have the potential to provide effective cleaning for the 65 x 325 mesh particle size fraction (Honaker, 1996). However, air injection into the feed slurry may provide improvement in the separation efficiency and expand the effective particle size range.

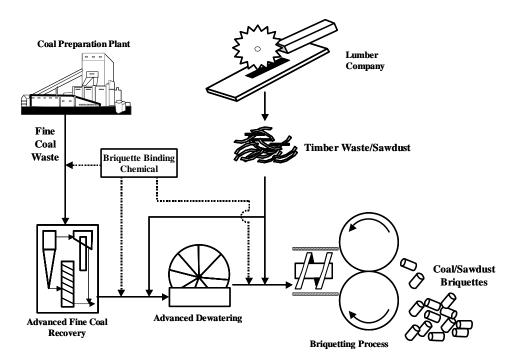


Figure 1.2. Schematic of the proposed concept of coal/sawdust premium fuel production.

It was hypothesized that dewatering of fine coal can be accelerated and a significantly low moisture filter cake could be obtained if the diameter of the capillary formed in filter cake could be increased and the porosity of the cake be improved. The addition of fibers in the filter cake provides channeling effect in the filter, as well as, higher porosity to the filter cake. The high filter cake porosity significantly improves the filtration rate, which in turn increases solids throughput in the dewatering machine. Preliminary studies conducted at the University of Kentucky Center for Applied Energy (UKCAER) confirmed the high dewatering rates and lower moisture filter cake through addition of paper pulp and wood waste. Because of the random distribution of fibers, the wet fitter cake had significant strength. In this research, it was also strongly hypothesized that a small amount of asphalt emulsion or an oil-water emulsion addition will provide assistance in dewatering as well as reconstitution of the filter cake. In this program, a novel dewatering technique was evaluated which involved the utilization of vacuum and pressure combination developed by the UKCAER. A previous study conducted using the novel technique provided about 25% reduction of moisture in the filter cake compared to the conventional one technique approach.

Previously, the U.S. Department of Energy funded a project that pelletized coal with sawdust material and subsequently tested the product in a grinding process to observe handleability problems (Akers et al., 2000). However, the project used a heavy oil that inherently creates handleability problems and reportedly emits undesirable environmental pollutants during combustion. The project that is the subject of this report investigated 1) the minimization of binder requirements due to multiple addition points in the cleaning and dewatering steps and the general addition of sawdust and 2) the selection of a binder that has minimal effects on handleability during grinding and on combustion. The overall process was demonstrated in a pilot-plant operation.

To summarize, the innovations and uniqueness of the project included:

i. Premium fuel production from two industrial wastes that are located within the same region in Kentucky;

- ii. Utilization of binder agents that can replace chemicals generally used in coal cleaning and dewatering stages;
- iii. Development and evaluation of novel cleaning concepts employing methods for improved selectivity and enhanced gravity concentrators with air bubble injection;
- iv. Evaluation of dewatering benefits gained from the addition of sawdust and/or other fibrous wood wastes in the feed stream;
- v. Fundamental evaluation of the coal and sawdust pelletization process;
- vi. Optimized reagent consumption for the production of coal/sawdust briquettes;
- vii. Pilot-scale testing of the optimum process units and chemical amounts;
- viii. Grindability and combustion testing of the ultimate products;
 - ix. Detailed economic evaluation of the overall process.

1.3 Project Goals and Objectives

The goal of the project was to develop an economical premium fuel from the waste materials created from the production of coal and lumber. A specific target was to produce a fuel having an energy value around 9,000 to 10,000 btu/lb from the processed waste material. Specific objectives included:

- i. Cleaning fine waste coal using advanced separation technologies;
- ii. Dewatering clean coal to lower moisture levels than currently realized by adding wood fibers utilizing an enhanced dewatering technique;
- iii. Combining and reconstituting clean, dewatered coal and sawdust through briquetting to form a utility fuel that can be easily handled through the transportation process;
- iv. Evaluating burn characteristics and assess emission impacts by performing combustion tests on the final premium fuel product;
- v. Performing a detailed economic evaluation of the total process.

1.4 Report Organization

To successfully achieve the project goals and objectives, the work plan was divided into six separate and distinctly different tasks. The experimental approach and findings associated with each task are discussed in individual chapters within this report. The tasks and the corresponding chapter containing the results and discussions are as follows:

Task 1: Sample Collection and Characterization	Chapter 2
Task 2: Development of Advanced Separation Technologies	Chapter 3
Task 3: Evaluation of Advanced Dewatering Technologies	Chapter 4
Task 4: Briquetting	Chapter 5
Task 5: Pilot-Scale Testing	Chapter 6
Task 6: Economic Analysis	Chapter 7
Summary and Conclusions	Chapter 8.

2. SAMPLE CHARACTERIZATION

2.1 Coal Sample

Fine coal slurry discharged to an impoundment at an operating coal preparation plant was collected over a period of one operating shift. The plant was processing coal from the Hazard No. 4 coal seam, which is a high-volatile bituminous coal with a dry-based heating value of around 14,200 Btu/lb. As shown in Table 2.1, the coal slurry sample contained mostly ultrafine coal with 77% by weight having a size below 37 microns. The particles coarser than 37 microns were very clean with an ash content of less than 6% and a heating value of 14,439 Btu/lb on a dry basis. As such, efficient classification of the material could provide a high-quality product representing 23% of the total mass of the waste coal.

Froth flotation of the entire fine coal sample reduced the ash content from 48.53% to 6.03% while recovering 57.4% of the total mass as shown in Figure 2.1. The flotation results were produced from a release analysis, which approximates the optimum separation performance achievable by any flotation process. Fuel oil was used as a collector and a polyglycol as a frother. The heating value of the 6.03% ash product exceeded 14,000 Btu/lb on a dry basis.

Table 2.1. Particle size-by-size analysis results of the fine coal waste slurry sample at James River Coal Company's Leatherwood preparation plant; dry basis.

Particle Size	Weight	Ash	Total	Heating
Fraction			Sulfur	Value
(microns)	(%)	(%)	(%)	(Btu/lb)
+210	0.17	2.99	0.77	14520
210 x 150	0.62	3.00	0.77	14515
150 x 75	8.00	3.03	0.77	14431
75 x 44	9.26	6.39	0.74	13878
44 x 37	4.33	11.05	0.70	13101
-37	77.62	60.80	0.35	4850
Total	100.00	48.53	0.44	6886

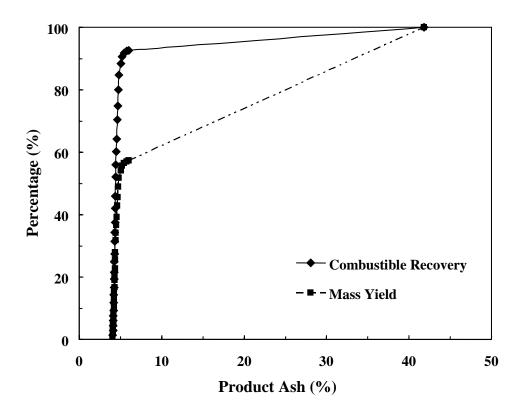


Figure 2.1. Flotation release analysis conducted on the James River coal waste slurry sample.

A second fine coal waste sample was utilized, which was collected from the thickener feed stream of a Cooke & Sons plant treating Elkhorn No. 3 seam coal in Letcher County, Kentucky. The coal is ranked as high volatile bituminous. As shown in Table 2.2, this sample contained mostly high ash -37 micron material representing 61% of the total weight. However, the remaining 39% of the coal (+37 micron material) had a relatively high heating value of 8915 btu/lb which could be upgraded through cleaning. The total sulfur content in the +37 micron fraction was 1.56% which could be potentially reduced by a cleaning process due to a total-to-pyritic sulfur ratio of about 3:2.

Table 2.2. Particle size-by-size analyses of the Cooke & Sons fine coal reject; moisture free.

Size	Cumulative				
Fraction (microns)	Weight (%)	Ash (%)	BTU/Lb	Sulfur (%)	Pyritic Sulfur (%)
+600	2.62	50.94	5751	1.78	1.12
600 x 300	8.54	50.20	6013	1.70	1.02
300 x 212	11.87	44.87	6627	1.65	0.97
212 x 150	16.25	39.19	7967	1.63	0.90
150 x 75	26.53	32.59	8984	1.63	0.91
75 x 44	35.64	32.32	8837	1.58	0.96
44 x 37	38.79	33.41	8915	1.56	0.95
-37	100.00	60.02		0.90	0.63

Flotation release data indicates the ability to reduce the ash content to 6% at 30% weight recovery, which corresponds to a combustible recovery of around 85%. The clean coal had an air-dried heating value of 13,623 Btu/lb. However, the total sulfur percentage remained unchanged due to the concentration of pyrite in the flotation product. Based on the washability data, density-based separations could reduce the ash and total sulfur contents to less than 4% and 1.4%, respectively.

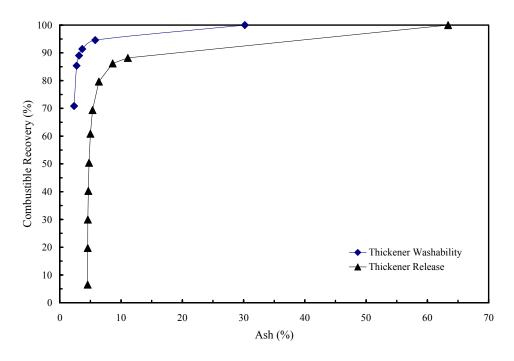


Figure 2.2. Flotation release and +37 micron washability data on the Cooke & Sons fine coal waste sample.

2.2 Wood Sample

A 200-liter drum full of sawdust was collected from a timber mill in eastern Kentucky, which uses a circular saw. The sample consisted of a typical mixture of the tree species being harvested in eastern Kentucky, primarily white oak, red oak, and poplar. The entire sample was screened through a 9.5 mm (3/8 inch) sieve, manually mixed to ensure homogeneity, split, and then stored in sealed containers. These splits were frozen to minimize aging. Several other samples were collected from different sources and treated in the same manner.

Characterization of saw dust samples from five different sources, which varied by location and tree type (i.e., popular and oak) revealed that the wood waste has a significant heating value. As shown in Table 2.3, the average energy value was 6696 Btu/lb on an as-received basis with a minimum of 6390 Btu/lb and a maximum of 7014 Btu/lb. The average moisture content was 18.8% by weight. Oak sawdust has the highest heating value and also the greatest amount of lignon, which is a substance that enhances the binding strength of the briquette.

Table 2.3. As-received heating values of several saw dust types.

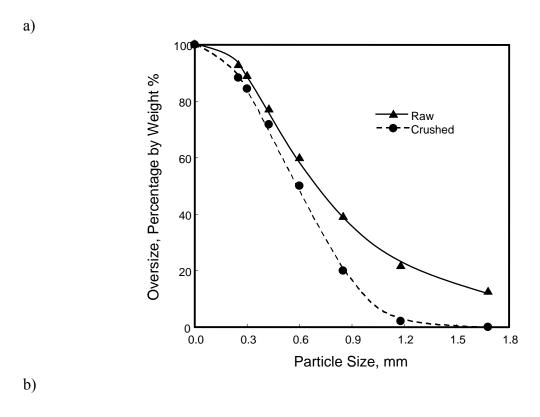
Sawdust	Moisture	Heating Value
Sample	(%)	(Btu/lb as rec.)
Poplar	21.43	6390
White Oak	15.83	6835
Oak	16.27	7014
Mixture	17.85	6751
Hickory	22.65	6493

Particle size analyses conducted by dry screening on the as-received sample revealed an average particle size of around 1 mm based on a wet screen analysis and 0.86 mm using dry screening (Table 2.4). The increased particle size when wet screening is believed to be due to water absorption and swelling. The swelling causes some cracking and reduced strength during briquetting Less than 10% of each saw dust sample had a particle size less than 0.21 mm (60 mesh) while the amount of +1.68 mm (12 mesh) material was highly dependent on the lumber production technique.

Table 2.4 Particle size distribution of the sawdust sample as determined from dry screening.

Size Fraction (mm)	Weight (%)	Oversize (%)
+ 1.68	10.00	10.00
1.68 x 1.18	11.31	21.30
1.18 x 0.85	19.02	40.32
0.85 x 0.60	20.79	61.11
0.60 x 0.425	16.21	77.32
0.425 x 0.30	10.89	88.21
0.30 x 0.25	3.82	92.03
-0.25	7.97	100.00

Since most sawdust consists of particles coarser than the optimum size for the briquetting process, size reduction may be necessary. Two sawdust samples were tested using a Wiley mill; oak sawdust produced by a circle saw and poplar sawdust produced by a band saw. A significant size reduction was obtained as shown in Figures 2.3 (a) and (b). It is clear that size reduction is more easily achieved on the poplar sawdust, which is due to the fact that the oak has a fibrous structure of higher strength than the poplar.



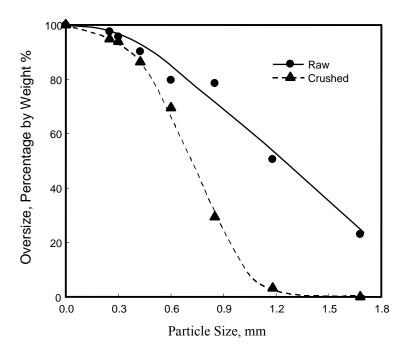


Figure 2.3. Size reduction for a) oak (7-3-3) and b) poplar sawdust (7-3-5) using a Wiley mill: crushing time = 10 minutes.

2.3 Coal and Sawdust Surface Charge Characterization

Surface properties of the sawdust and coal particles are very important parameters for understanding and utilizing the attractive interaction between the sawdust and coal particles to enhance briquette strength and reduce surfactant dosage requirements. Zeta (ζ) potential is an estimate of particle surface charge, which is the electrokinetic charge occurring at the solid-liquid interface. It can be either positive or negative and is expressed in millivolts (mv). The zeta (ζ) potential of a poplar sawdust sample is shown in Figure 2.4. The measurement of zeta (ζ) potential for the sawdust was conducted in distilled water with sawdust of 4% by weight using a zeta (ζ) potential meter manufactured by Zeta Meter, Inc. in Long Island, NY. Tests were conducted at the cell voltage of 100 ± 1 V and temperature of $20\pm2^{\circ}$ C. The influence of pH on the zeta (ζ) potential is very significant. With an increase in the pH value, the zeta (ζ) potential decreased from +80 mv at pH 2.5 to -68 mv at pH 11.2, suggesting that the briquetting process should be conducted under a controlled pH value to optimize the process. For this particular sawdust sample, the optimum pH may be at pH 4.9 at which the zeta potential of the sawdust is near zero to minimize the repulsion between sawdust particles and the other materials utilized in the process.

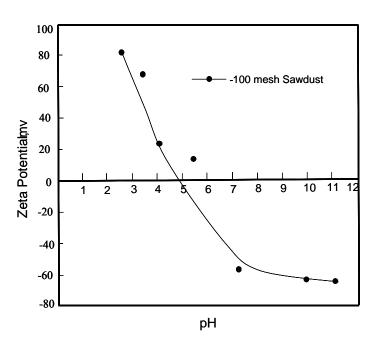


Figure 2.4. Zeta (ζ) potential of the poplar sawdust under different pH conditions.

Since binders may reduce the energy barrier required to be overcome by coal and sawdust particles prior to agglomeration, their effects on zeta potentials on coal and sawdust particles were investigated under various pH conditions and binder dosages. Eight binders, including high glutin wheat flour, black molasses, high starch wheat flour, paper sludge, colona, fishmer, reax, and guar gum, were tested.

Of the eight tested binders, the guar gum was the most effective in reducing the zeta potential for both coal particles and sawdust particles. Figure 2.5 shows the typical zeta potential change as a function of guar gum dosage at pH 4.6. An addition of 2.5×10^{-5} M of guar gum reduced the zeta potential of coal particles from 23.7 mV to 2.9 mV and that of poplar sawdust particles from 22.1 mV to 9.7 mV. An increase of guar gum dosage to 5.0×10^{-5} M reversed the zeta potential of the coal particles from a negative value to a positive value suggesting that guar gum has a natural positive charge at pH 4.6. No zeta potential reversal was observed with the sawdust particles by guar gum although higher dosages of guar gum further reduced the zeta potential of sawdust particles to some extent.

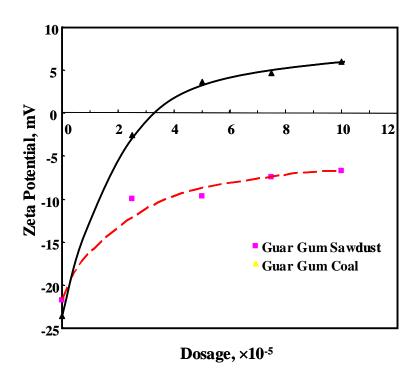


Figure 2.5. Zeta potential of coal and sawdust particles as a function of guar gum dosage.

Ideally, the surface charge of coal particles should be opposite to that of sawdust particles so that the strength of the coal/sawdust briquette is enhanced by electrostatic attraction between coal particle and sawdust particle. Figure 2.5 indicates that the ideal condition may be achieved in the presence of 5.0×10^{-5} M or more guar gum at pH 4.6.

Figures 2.6 – 2.12 show the effect of solution pH on zeta potentials of coal and poplar particles with and without the binders including high glutin wheat flour, guar gum, black strap molasses, high starch wheat flour, paper sludge, colona, and Fishmer, respectively. Guar gum, high starch wheat flour, and high glutin wheat flour lowered the zeta potential of the coal particles while the surface charge of poplar sawdust was significantly reduced by paper sludge, molasses, and guar gum. It should be noted that colona had no effect on the zeta potential of coal particles but increased the zeta potential of sawdust particles, which may result in reducing the coal-sawdust binding strength. The binder Fishmer had no affect on the surface charge of coal and sawdust particles. To create an electrostatic attraction between the coal and sawdust particles, binders such as high glue wheat flour, guar gum, and high starch wheat flour, and acidic pH values below 5 should be used for making coal-sawdust briquettes.

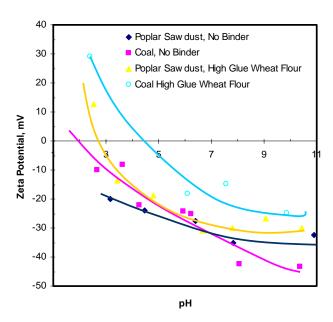


Figure 2.6. Effect of high glue wheat flour on zeta potential of coal and sawdust particles at different pH values.

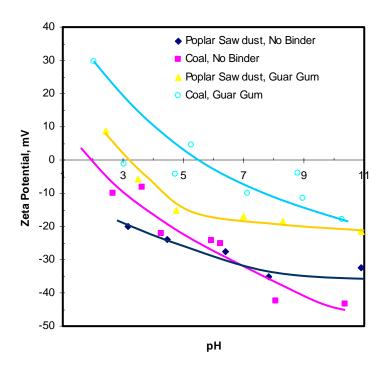


Figure 2.7. Effect of guar gum on zeta potential of coal and sawdust particles at different pH values.

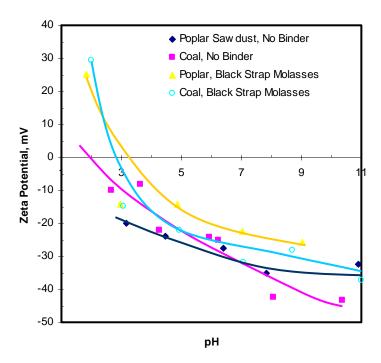


Figure 2.8. Effect of molasses on zeta potential of coal and sawdust particles at different pH values.

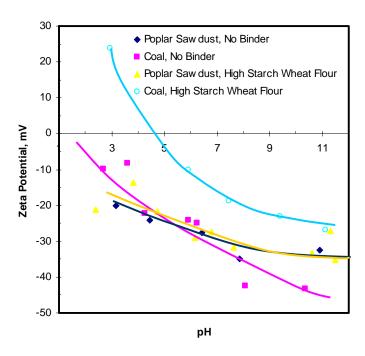


Figure 2.9. Effect of high starch wheat flour on zeta potential of coal and sawdust particles at different pH values.

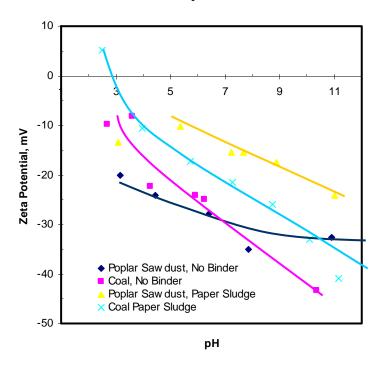


Figure 2.10. Effect of paper sludge on zeta potential of coal and sawdust particles at different pH values.

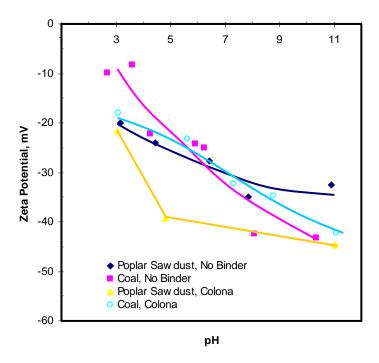


Figure 2.11. Effect of colona on zeta potential of coal and sawdust particles at different pH values.

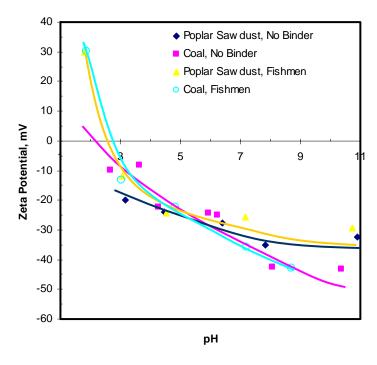


Figure 2.12. Effect of Fishmer on zeta potential of coal and sawdust particles at different pH values.

2.4 Briquette Characterization

2.4.1 Briquette Quality

Randomly chosen briquettes produced during the binder screening study were evaluated for their energy value. As shown in Table 2.4, the ash contents of the briquettes are below 5%, which is reflective of the efficiency achieved during the cleaning process. More importantly, the moisture contents are also about 5% or lower. These values are about 20 absolute units lower than the ultrafine clean coal produced in commercial plants. The majority of the moisture reduction occurs during the briquetting process. Intense compression of the wet solids significantly increases packing density, which reduces the amount of void volume existing between the particles. As a result, water is forced outward and through the surfaces of the briquette. However, the greatest amount of moisture reduction occurs during the curing process, especially when a hydrophobic binder is employed. As such a result of the coal cleaning and briquetting processes, the combined low ash and total moisture contents (i.e., total inerts) can be utilized to significantly impact the overall coal preparation plant performance by allowing for greater total inert and thus mass recoveries from the coarse cleaning circuits as previously discussed (Yoon et al., 1998).

The average energy value for the briquettes was 13,605 Btu/lb on an as-received basis with the high value being 14027 Btu/lb and a low of 13199 Btu/lb. This high energy product was generated using coal that is currently being discarded due to concerns related to product moisture and handleability.

Table 2.5. Briquettes qualities including heating value produced from Elkhorn No. 3 coal and mixed wood waste.

Binder Type	Ash (%)	Moisture (%)	As- Received Btu/lb	Dry Btu/lb
1	4.78	2.71	13807	14192
13	4.94	5.37	13199	13948
8	4.61	2.30	14027	14357
21	4.82	3.12	13457	13890
23	4.62	4.62	13537	14193

3. ADVANCED COAL CLEANING

3.1 Introduction

Froth flotation is the most commonly used process to recover ultrafine (-150 micrometer) coal in operating preparation plants. According to the results of a survey reported by Kempnich [1], 7% of the processed coal worldwide is treated by flotation, which equates to approximately 142 million tons annually. However, the floatability of coal pyrite and high-ash mixed-phase particles often limits separation performance (Olson and Aplan, 1984; Laskowski et al. 1985; Olson and Aplan, 1987; Hirt and Aplan, 1991; Yoon et al., 1991). In addition, a significant amount of fine coal that is weakly to moderately floatable exist worldwide, which is currently being discarded as fine refuse in most cases. A novel approach to improve the selectivity achievable by froth flotation processes involves the addition of highly hydrophobic material into the froth phase of the process, which will result in selective detachment of the coal pyrite and mixed-phase particles from the bubble surface.

Ata et al. (2002) reported that the addition of hydrophobized silica into the froth phase of a flotation unit treating hematite resulted in the selective detachment of the hematite particles. Based on this finding, it was hypothesized that the addition of material into the froth phase that has a greater degree of surface hydrophobicity than the feed coal could enhance selectivity by replacing the lower quality particles during bubble surface area reduction events. The material injected into the froth could be obtained from low density material of the coal being treated. The lowest density material in coal typically has the highest degree of hydrophobicity and thus floatability. Alternatively, fine coal from another seam or source having a high degree of hydrophobicity could be used.

To avoid the problems associated with flotation selectivity, a potential alternative is the use of enhanced gravity separators. Enhanced gravity separators (EGS) utilize conventional density-based separation techniques in the presence of a centrifugal field that is applied through mechanical action. The various commercial units differ fundamentally by the type of density-based separation mechanism, i.e., jigging (Kelsey jig, Altair jig), flowing film (Falcon Concentrator), tabling (Multi-Gravity Separator) and fluidized-bed (Knelson Concentrator).

Initial development of EGS technologies in the 1980's was directed at fine gold recovery where the yield to the high density stream was typically below 1% for which semi-batch units are commonly employed. However, identification of applications where the yield to the high density stream is significantly greater led to the development of fully-continuous EGS units.

The initial studies evaluating the potential of EGS technologies for ultrafine coal cleaning were directed at reducing the pyritic sulfur content present in flotation concentrates (Riley and Firth, 1993; Venkatraman et al., 1995; Honaker et al., 1995). During these studies, it was observed that significant ash reductions were also achieved in the 150 x 25 micrometer size fraction. Relative separation densities as low as 1.5 were achieved by several of the EGS units while realizing effective separation efficiencies. Detailed reviews of the EGS units and their application in coal cleaning have been provided elsewhere (Luttrell et al., 1995; Honaker et al., 1998).

Static fluidized-bed (or teeter-bed) separators have been recently evaluated and found to achieve very efficient, low-density separations when treating 1 x 0.15 mm coal (Nichols and Drummond, 1997). As a result of the performances, several commercial units have been installed in coal preparation plants (Drummond et al., 1998). The application of a centrifugal field to a fluidized-bed system as provided by the Knelson Concentrator may provide similar separation performances for particles with a size below 150 micrometer. A significant modification to the continuous Knelson Concentrator was implemented in the late 1990's, which involved a redesign of the bowl and the fluidized water injection system as well as the provision to vary the applied centrifugal field. A recent study evaluated the parametric effects of the newly designed concentrator for the treatment of a sulfide ore (McLeavy et al., 2001).

A problem with teeter-bed units is the limited particle size range in which an acceptable separation performance is achieved. Specifically, oversized coal particles entering the unit report to the tailings stream due to its overall mass while undersized heavy particles report to the product stream due to the lack of overall mass. In addressing this problem, Kohmuench and Luttrell [2000] injected air-bubble into the fluidization water. The air bubbles attach to the coarse hydrophobic particles due to natural its hydrophobicity. Since the particle-bubble aggregate will have a density that approaches or is lower than the density of water, the recovery of the coarse

particles to the overflow stream is enhanced. The enhanced teeter-bed unit has been successful in expanding the top size from 1 mm to 2 mm.

Using the same principles, air bubble injection into a centrifugal teeter-bed was evaluated in the investigation. The effect on separation performance was investigated on relatively strong and moderately hydrophobic fine coal materials and optimized using results from a statistically-designed test program. Improvements in process efficiencies were quantified and described herein on a particle size-by-size basis.

3.2 Froth Flotation

The clean coal samples used for the laboratory briquette studies were obtained by treating a split stream of the thickener feed at the Leatherwood coal preparation plant operated by James River Coal Company (Figure 3.1). All thickener reagents added prior to entry into the thickener was turned off during the collection of the flotation concentrate. A pilot scale Jameson cell was used which uses a venturi tube concept to achieve bubble generation within the feed slurry. The cell diameter and length was 15 cm and 1.5 m, respectively (Figure 3.2).

The feed solids concentration varied during the tests from 3% to 5% by weight while the feed rate was held constant at 12 liters/min. Fuel Oil No. 2 was added as a collector at a concentration of 1.0 lb/ton and 15 ppm of polyglycol was used as a frother. Wash water was added internally into the froth phase while adjusting the pulp level to ensure that 60% of the wash water reported to the tailings stream. The ash and total moisture contents of the dewatered flotation concentrate were 4.85% and 26.8%, respectively. The heating value of the clean coal exceeded 13000 btu/lb on a dry basis. Approximately 8 fifty-five gallon drums of flotation concentrate were collected for use in the dewatering and briquetting studies.

For the Cooke & Sons coal, several drums of the waste stream at the Sapphire preparation plant was collected and transported to the UK Center for Applied Energy Research. The samples were treated using the Jameson cell and the concentrate collected for the dewatering and briquetting investigation.



Figure 3.1. Photograph of the clean coal production using the Jameson Cell flotation unit.

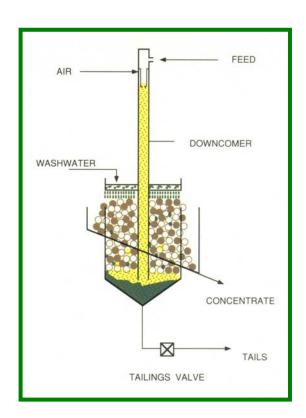


Figure 3.2. Schematic of the Jameson flotation cell operation.

3.2 Binder Benefits in Froth Flotation

A few of the potential binders evaluated for briquetting the coal and wood waste have potential to serve as a collector in the froth flotation process. An objective of the project was to reduce the overall cost of coal cleaning, dewatering and briquetting by using the same reagents in each process so that the overall amounts of surfactants would be reduced. In this subtask, binders with hydrophobic properties were evaluated as potential collectors for the flotation of fine waste coal.

3.2.1 Experimental

The evaluation was performed using flotation kinetic rate tests which provided the ability to assess the change in the rates as a result of using the binders. The binders evaluated include REAX and tall oil. Tests were also conducted using the standard collector, i.e., Fuel Oil No. 2, to quantify the effect of the binders on flotation rate. Fuel oil was not used in the tests involving the binder reagents. Methyl-isobutyl-carbinol (MIBC) was used a frother in all tests at concentrations ranging from 10 to 30 ppm. The collector-to-frother ratio was maintained constant throughout the test program. The collector was added and conditioned for five minutes followed by the addition of the frother.

The tests were performed using a batch laboratory Denver flotation machine with a one liter cell. A rotational speed of 1000 rpm was used throughout with the air valve opened fully. The James River coal sample was floated in the tests at a solids concentration of 5% by weight. Froth concentrate samples were collected for flotation times of 0.5, 1.0, 2.0, 3.0 and 4.0 minutes. The samples were dried, weighed and analyzed for ash content. The weight percentage floated was plotted as a function of time to obtain the flotation rates.

3.2.2 Binder Flotation Results and Discussion

The flotation rate results shown in Figure 3.3 clearly indicate that increasing concentrations of REAX has a negative impact on the flotation rate of coal. By increasing the concentration from 0.5 to 1.5 lbs/ton, mass yield was reduced by about 13 absolute percentage points after 2 minutes of flotation time.

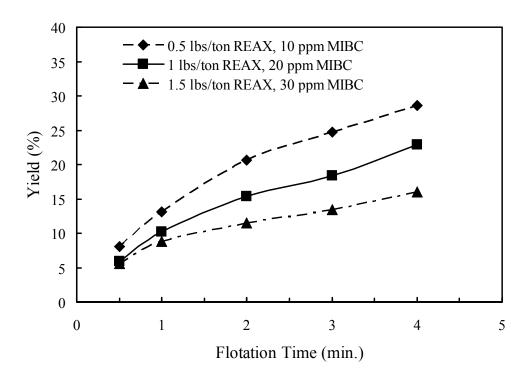


Figure 3.3. Effect of REAX binder as a flotation collector for coal.

On the other hand, increasing dosages of tall oil improved flotation yield as shown in Figure 3.4. Increasing the concentration from 0.5 to 1.0 lbs/ton enhanced yield by about 10 absolute percentage points after 1 minute of flotation time. The ability of pine oil to serve as a collector was expected since it is used in the flotation of various oxide minerals. However, the flotation rate provided in the coal application is significantly inferior to that achieved by the use of fuel oil which is evident by comparing the flotation results of Figure 3.4 with those in Figure 3.5.

A summary of the flotation data is provided in Table 3.1. The flotation rate of coal using fuel oil was more than twice the value obtained when using tall oil. At the lowest concentration of 0.5 lbs/ton, the flotation rate with fuel oil was nearly five times greater and the selectivity was better as indicated by the lower ash contents in the flotation concentrate. As supported by the results in Figure 3.3, an increase in the REAX dosage from 0.5 to 1.5 lbs/ton reduced the flotation rate from 0.13 to 0.08 min⁻¹. Based on these results, the use of the binding agents in the recovery of coal using flotation would not be beneficial.

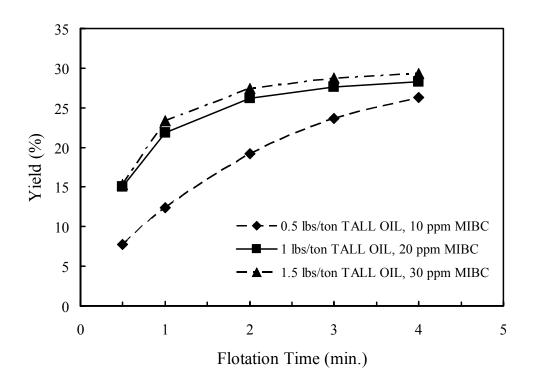


Figure 3.4. Effect of Pine Oil binder as a flotation collector for coal.

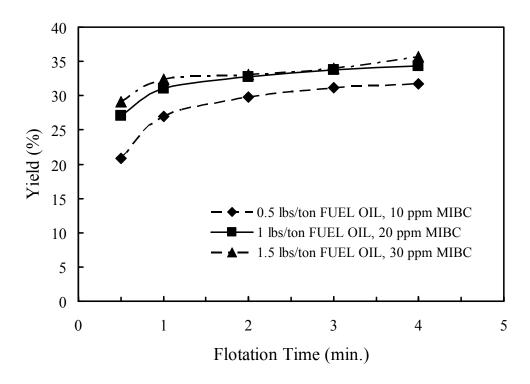


Figure 3.5. Baseline coal flotation rate coal data using fuel oil as collector.

Table 3.1. Summary of flotation tests using binders as a collector.

Collector	Collector Collector			Flotation			
Type (lbs/ton)	(MIBC)	0.5 min	1 min	2 min	3 min	Rate (min ⁻¹)	
	0.5	10 ppm	18.88	19.71	22.94	24.87	0.13
REAX	1	20 ppm	24.60	25.44	28.69	30.15	0.11
	2	30 ppm	7.16	11.52	14.07	15.31	0.08
	0.5	10 ppm	11.36	11.37	12.55	13.60	0.15
Tall Oil	1	20 ppm	12.43	13.01	15.26	17.24	0.33
	2	30 ppm	14.34	15.29	17.22	18.76	0.35
	0.5	10 ppm	8.47	9.22	11.85	13.83	0.72
Fuel Oil	1	20 ppm	15.70	16.21	17.90	19.67	0.81
	2	30 ppm	17.89	18.85	19.79	21.45	0.84

3.3 Improved Froth Flotation Selectivity

The objective of this subtask was to improve the selective of the froth flotation process with specific focus on improving the rejection of mixed-phase particles and coal pyrite. To meet this object, the novel approach of injecting highly hydrophobic coal into the froth zone of a flotation column was investigated. The material was injected through the wash water system. Because the James River and Cooke & Sons coals contained very little mixed-phase material, fine coal from a different fine coal waste source was used in this study.

3.3.1 Experimental

<u>Coal Sample:</u> To allow the measurement of selectivity improvement, coal from two different sources and ranks were used in this study. Anthracite coal typically has relative solid densities greater than 1.5 whereas the majority of the bituminous coal has a density within the range of 1.1 and 1.6 RD. As such, the bituminous coal collected at the James River preparation plant was subjected to a float-sink test using a 1.30 RD medium density. The 1.3 RD material was used as the highly hydrophobic material in the tests which could be removed from the flotation product

and tailing streams by a simple float-sink procedure at a 1.3 RD. The fine anthracite coal was the focus of the column flotation cleaning effort in this subtask.

The anthracite coal sample was obtained from a waste storage area in Pennsylvania (USA) that is currently being considered as feedstock to a coal gasifier. A particle size fraction of 212 x 75 μ m was used in all the flotation tests since coal flotation is optimum and entrainment is minimal in this size range. The flotation of coal particles greater than 212 μ m generally results in a substantial decrease in flotation rate and thus recovery due to an elevated probability of detachment.

Both the anthracite and the 1.3 RD float fraction of the bituminous coal were screened using a 75 micron sieve in a laboratory scale Sweco unit. The ash contents of the 212 x 75 μ m anthracite and 1.3 RD float bituminous coal were 50.72% and 3.56%, respectively.

Sample Floatability Characterization: Using an electronic induction timer (MCT-100), the time intervals required for particles in five density fractions of the anthracite coal and in the 1.3 RD float bituminous coal to attach to a bubble after collision were measured (Yoon and Yordan, 1991; Ye et al., 1989). Measurements of induction time were accomplished by moving a captive bubble toward a bed of particles for successfully longer periods of time until the particles become attached to the bubble. The induction-time measurement technique monitors attachment percentage with a given number of tests at a controlled contact time to obtain a distribution of percent attachment versus contact time. The induction time then is chosen to be the value of a particular contact time at which 50% of the tests resulted in bubble/particle attachment. This procedure allows the actual contact time between the bubble and particle bed to be measured. The results were used as an indicator of floatability. Induction times were measured with and without collector (i.e., fuel oil No. 2) at pH values of 3, 5 and 7.

As shown in Table 3.2, induction time values for the anthracite density fractions decreased substantially when the pH was adjusted to values below 7, thereby indicating that optimum flotation performance would be achieved using medium pH values in the acidic range. Also, the

addition of fuel oil significantly reduced the induction time, which is in agreement with the floatability findings of Olson and Aplan (1984). An unexpected finding was the relatively good floatability of the 2.2 RD sink material, which was comprised of mostly hydrophilic mineral matter that results in an ash content of 91.81%. Microscopic petrographic analysis of the 2.2 RD sink material revealed the presence of 'bone' particles, which are a complex mix of coal and mineral matter.

As previously stated, the purpose of the 1.3 RD float bituminous coal was to evaluate the effect of enriching the froth phase with a more hydrophobic material with nearly the same density as the coal being added in the collection zone. The induction times in Table 3.2 confirms that the 1.3 RD float material is more floatable than the anthracite coal, which is likely due to a greater degree of hydrophobicity.

Table 3.2. Induction time values obtained for each density fraction in the anthracite coal and the 1.3 RD float material in bituminous coal over a range of medium pH conditions.

D. L.	Induction Time (milliseconds) - 212 x 75 micron anthracite coal								
Relative Density	рН	t = 3	pН	= 5	pl	H = 7			
Fractions	Collector	(Fuel Oil)	Collector	(Fuel Oil)	Collecto	r (Fuel Oil)			
	none	1 lbs/ton	none	1 lbs/ton	none	1 lbs/ton			
1.6 float	2.70	<2	2.70	<2	6.60	1.85			
1.6 x 1.7	3.00	<2	3.90	<2	7.00	1.95			
1.7 x 1.9	4.15	2.35	7.44	2.86	10.07	3.54			
1.9 x 2.2	6.44	4.99	9.27	6.20	12.72	6.93			
2.2 Sink	10.30	9.40	12.10	8.50	15.60	7.80			
	Inducti	Induction Time (milliseconds) - 212 x 75 micron bituminous coal							
1.3 float	<2	<1	<2	<1	<2	<1			

<u>Column Flotation Tests:</u> A flotation column was constructed of Plexiglas tubing having an inside diameter of 5 cm. The total height of the cell was 1.27 m, which resulted in a length-to-diameter ratio of about 25:1. As a result, the hydrodynamic conditions in the collection zone were nearly plug-flow, which is an ideal bubble-particle collision environment. A MicrocelTM bubble generator employing a static mixer and pump configuration was used with the column.

Feed slurry was injected into the column at a distance of 70 cm below the product overflow lip using a variable speed pump. Pulp level was maintained by utilizing a control valve, which was connected to the tailings stream of the column.

The tests were conducted over a range of volumetric feed rates and feed solid concentrations. As a result of the varying feed mass rates, flotation data was obtained under kinetic-limiting and carrying-capacity limiting conditions. All other parameters were maintained at constant values, which are provided in Table 3.3. A polyglycol reagent was used as a frother while fuel oil No. 2 was employed as the collector. The 1.3 RD float bituminous coal with a 212 x 75 µm particle size was added in the wash water distributor at concentrations that are expressed as a percentage of the total anthracite feed added in the collection zone. The distribution ring was located at a distance from the top of the column that was 1/3 the total froth depth.

Table 3.3. Flotation column operating conditions.

Feed Rate	912 cc/min to 1451 cc/min
Feed Solids Concentration by weight	10% to 15%
External Feed Concentration by weight	5% - 10% - 15%
Frother Concentration (Poly- 630)	30 ppm
Collector Concentration (Fuel Oil No.2)	0.45 kg/ton
Froth Depth	45 cm
Superficial Gas Velocity	2 cm/s
Volumetric Wash Water Rate	400 cc/min

The flotation column tests were conducted for a period equivalent to three particle residence times to ensure steady-state operating conditions. Once this condition was achieved, timed samples were collected from the feed, product and tailing streams. The process stream samples were filtered, dried, weighed, and subjected to density fractionation to separate the bituminous coal from the anthracite material. Ash analyses were also performed on all samples.

3.3.2 Improved Froth Selectivity Results and Discussion

The initial evaluation was to determine if the 1.3 RD float bituminous coal was attached and recovered in the froth zone or collection zone or lost to the tailings stream. Under rate limiting conditions (i.e., feed volumetric flow rates < 1451 cc/min), 100% of the 1.3 RD bituminous coal reported to the column product stream. A slight loss of bituminous coal to the tailings stream occurred when the volumetric feed rate was increased to 1451 cc/min, which provided carrying capacity conditions (i.e., completely loaded bubbles exiting the column into the product launder). Table 3.4 outlines the distribution path of the externally added bituminous coal in the flotation column. Less than 2% of the bituminous coal added in the froth phase was lost to the tailings stream while operating under carrying-capacity limiting conditions. This finding indicates that the bituminous coal particles are replacing the weaker hydrophobic anthracite particles on the surface of the bubbles.

Table 3.4. Bituminous coal distribution during the external froth enrichment tests; feed volumetric flow rate = 1451 cc/min and feed solids concentration = 15% by weight.

	Percent Bituminous Coal Addition					
Process Stream	5% of Anthracite	10% of Anthracite	15% of Anthracite			
	Feed	Feed	Feed			
Product	98.26	99.08	98.84			
Tailings	1.74	0.92	1.16			
Feed	100.00	100.00	100.00			

The addition of the 1.3 RD float fraction of a highly floatable bituminous coal into the froth phase provided significant improvements in the selectivity achieved from the treatment of the anthracite coal as shown in Figure 3.6. The bituminous coal was removed from the product and tailing samples by performing a density fractionation at a 1.40 RD. As such, the data in Figure 3.6 represents the improved performance on the anthracite coal only. At a given recovery value, the product ash content was reduced from 19% to nearly 14% by the addition of 1.30 bituminous coal at a concentration equal to 15% of the feed mass flow rate.

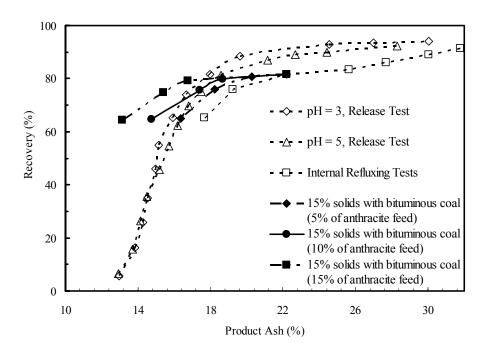


Figure 3.6. Improvement in the separation performance achieved on the anthracite coal as a result of the addition of the 1.30 RD bituminous coal into the froth phase.

As shown in Figure 3.7, the impact on selectivity occurred as a result of a decrease in the overall recovery of particles having a collection zone rate smaller 0.941 min⁻¹. This finding correlates well with the induction time measurements in Table 3.2. The 1.30 RD float material only replaced particles that possessed a significantly lower degree of floatability. Similar to the findings of the carrying-capacity limited tests, the most significant reduction in recovery was realized by particles which had a collection zone rate of 0.51 min⁻¹ and an induction time of 4.9 ms as compared to less than 1.0 ms for the bituminous coal.

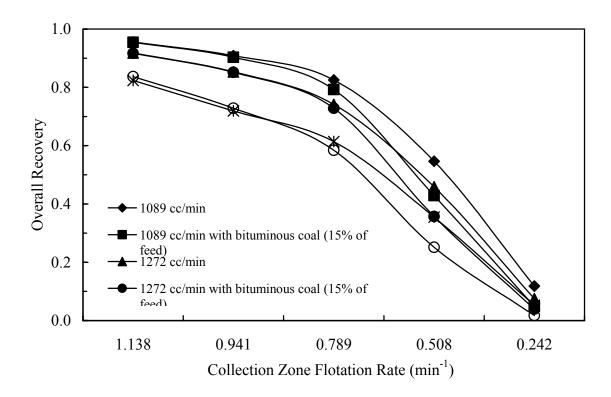


Figure 3.7. Effect of froth zone enrichment on the overall recovery of each density component in the anthracite coal.

3.4 Centrifugal Teeter Bed

The objective of this subtask was to evaluate the separation performance of a centrifugal teeter bed separator for the treatment of fine coal. The proposal was to conduct the investigation using a semi-batch laboratory unit. However, a concern developed pertaining to the ability to correlate the laboratory performance with those from a fully continuous unit. As a result, the test program was performed on a 5 ton/hr pilot scale unit of a commercial centrifugal teeter bed commercially known as the Knelson Concentrator. An additional industrial partner was obtained to locate the pilot scale unit in an operating coal preparation to treat a split stream containing a nominal 150 x 37 micron coal.

3.4.1 Experimental

<u>Centrifugal Teeter-Bed Concentrator:</u> The Knelson Concentrator is essentially a fluidized bed system operating in a mechanically-applied, enhanced gravity field. As shown in Figure 3.8, the unit consists of a rotating cone into which water is introduced through a series of fluidization holes located in the concentrate ring. The feed enters through the central inlet. When the slurry reaches the bottom of the cone, it is forced outward and driven up the cone wall toward the concentrate ring. The slurry fills the concentrate ring against the inward movement of elutriation water, which creates a fluidized particle bed. Pinch valves are actuated allowing heavier material to be drawn from the concentrate ring at a controlled rate. The high-density particles report to a dedicated launder. The lighter particles flow out the top of the cone into an overflow launder.

<u>Ultrafine Coal Source:</u> A pilot-scale, continuous discharge model of Knelson Concentrator was installed in an eastern U.S. coal preparation plant, which treats separately coal from both the Coalberg and Powelton seams. The unit was fed a split stream from the underflow of a secondary classifying cyclone bank, which is nominally 150 x 44 μm and treated in two parallel conventional cyclone banks. The solids concentration averaged around 22% by weight in the classifying cyclone underflow stream for both coals.

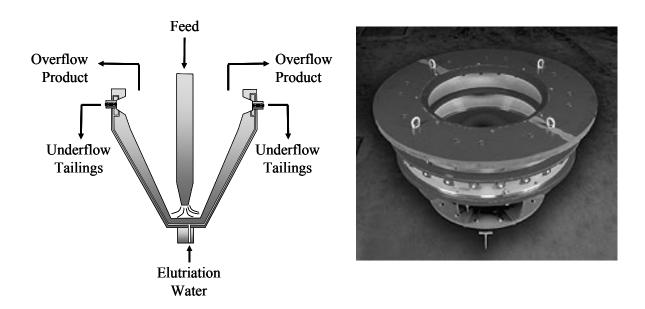


Figure 3.8. A schematic diagram of a continuous Knelson concentrator.

The cleanability of the two $150 \times 44 \mu m$ coal sources differ significantly as indicated by the density-based washability data in Table 3.5 and the flotation release data in Table 3.6. The Coalberg coal contains a greater amount of mass in the middle density fractions, which indicates a more difficult cleaning task. Also, the flotation rate of the Coalberg coal was relatively slow, which provided higher product ash values as compared to the Powelton coal.

<u>Experimental Procedure:</u> A test program was conducted to evaluate and optimize the operating parameter values with the goal of maximizing the mass product yield over a range of desired product ash content values. The in-plant installation of the 30-cm diameter Knelson unit required that a constant volumetric feed rate of about 37 liters/min be used throughout the test program, which equates to a mass feed rate of about 0.5 tph. At a given feed rate, the critical operating variables that control performance include the rotational speed of the bowl, the elutriation water flow rate and the pinch valve opening and closing times. An experimental program based on a 3-level Box-Behnken statistical test design was performed which involved approximately 30 total experiments. The value range for each operating parameter evaluated in the test program is shown in Table 3.7.

Empirical models describing the mass yield, recovery and product ash as a function of the operating parameter values were developed from the test data. The models were used in conjunction with a non-linear optimization technique to determine the parameters values providing maximum mass yield and recovery. Subsequent tests were conducted to validate the optimum conditions and collect samples to be subjected to washability analysis in an effort to develop partition curves that provide an understanding of the performance characteristics and overall efficiency.

Table 3.5. Cleanability characteristics of the two ultrafine coal sources as determined by density-based washability analysis data.

Powelton Coal			Coalberg Coal				
Density Fraction	Weight (%)	Ash (%)	Density Fraction	Weight (%)	Ash (%)		
1.3 Float	70.53	3.12	1.3 Float	54.05	2.50		
1.3 x 1.4	7.99	6.98	1.3 x 1.4	14.45	6.94		
1.4 x 1.6	4.99	18.56	1.4 x 1.6	7.69	22.49		
1.6 x 1.9	2.08	40.43	1.6 x 1.8	3.92	37.72		
1.9 Sink	14.42	87.21	1.8 x 2.0	3.31	54.52		
			2.0 Sink	16.58	81.75		

Table 3.6. Cleanability characteristics of the two ultrafine coal sources as determined by flotation release data.

	Powelton Coa	1	Coalberg Coal			
Sample ID	Cumulative	Cumulative	Sample	Cumulative	Cumulative	
	Weight (%)	Ash (%)	ID	Weight (%)	Ash (%)	
C1	11.35	4.70	C1	10.63	9.42	
C2	24.09	4.74	C2	27.88	10.08	
C3	35.83	4.83	C3	46.63	10.18	
C4	46.35	5.17	C4	62.96	10.18	
C5	59.71	5.67	C5	75.38	10.36	
C6	74.55	6.07	C6	83.38	10.60	
C7	84.34	6.72	C7	86.27	10.86	
C8	91.55	9.95	C8	93.06	12.99	
C9	100.00	16.93	C9	100.00	17.14	

Table 3.7. Operating parameters and their respective value range evaluated.

Operating Parameter	Parameter Value Range
Bowl Speed (rpm)	400-1100
Teeter Water (lpm)	5-10
Valve Open Time (sec)	0.14-0.16
Valve Close Time (Sec)	2-7

3.4.2 Centrifugal Teeter-Bed Results and Discussion

<u>Separation Performance</u>: As expected from the characteristic feed data in Tables 3.5 and 3.6, the separation performance achieved on the Powelton Coal on the basis of the recovery-product ash relationship was superior to that realized from the treatment of the Coalberg coal. As shown in Figure 3.9, a reduction in ash content from 17.0% to nearly 7% was achieved by the Knelson unit while recovering greater than 70% of the energy-producing components of the Powelton feed coal. However, due to the excellent floatability characteristics of the coal, the flotation release performances were significantly better.

On the other hand, the Knelson Concentrator produced significantly lower product ash values as compared to froth flotation for the treatment of the Coalberg coal as shown in Figure 3.10. It is obvious from observations of both Figures 3.9 and 3.10 that the Knelson Concentrator performances deviate substantially from the ultimate density-based performance predicted by washability analysis. This fact indicates the presence of inefficiencies in the separation process. According to the particles size-by-size data presented in Table 3.8, the inefficiencies may be explained by the variable performances being achieved on each size fraction. For the +150 µm fraction in the Powelton coal, a relatively low separation density is apparently being achieved as indicated by an ash reduction from 7.04% to 2.79% and a comparison with the feed washability data (Table 3.5), which results in a significant loss in recovery. For the 150 x 75 µm fraction, a greater ash reduction is observed, which produces a clean coal ash content of 4.96% at a relatively high combustible recovery of 93.2%. One should note, however, that the separation achieved on both size fractions is nearly ideal based on a comparison with the washability data in

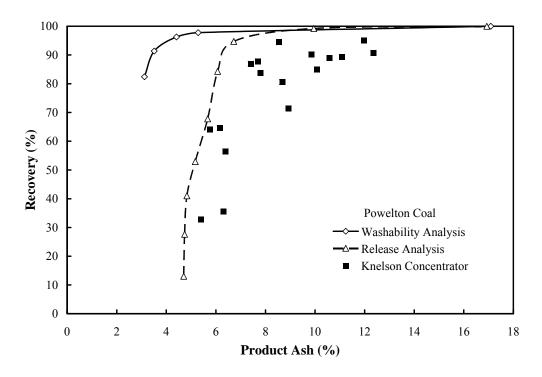


Figure 3.9. A comparison of the separation performance achieved by the Knelson Concentration on the Powelton coal with those obtained by washability and flotation release analysis.

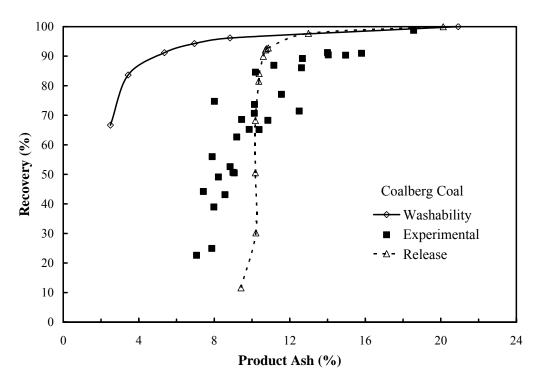


Figure 3.10. A comparison of the separation performance achieved by the Knelson Concentration with those obtained by washability and flotation release analysis.

Table 3.8. Particle size-by-size performance achieved on the ultrafine Powelton coal.

Particle	Feed		Product		Taili	ngs	Energy
Size Fraction	Weight	Ash	Weight	Ash	Weight	Ash	Recovery
(µm)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
+150	32.73	7.04	30.52	2.79	44.07	16.90	73.08
150 x 75	46.09	17.85	48.94	4.96	31.40	71.26	93.20
75 x 44	21.18	43.06	20.54	22.40	24.52	89.09	94.06
Total	100.00	19.65	100.00	7.88	100.00	51.68	83.83

Table 3.5. The performance substantially deteriorates for the 75 x 44 μ m fraction for which the product ash content is relatively high. The high product ash content is likely a result of a high density separation and significant by-pass of a large amount of ash-forming minerals to the clean coal (overflow) concentrate stream.

Process Efficiency Evaluation: The partition curves generated from data obtained by operating the Knelson unit under conditions that provided the maximum mass recovery over a range of product ash contents are shown in Figure 3.11. It is obvious from the curves that a significant amount of low-density particle bypass to the tailing stream occurs when operating the Knelson unit under conditions that provides low relative separation densities approaching 1.4. Likewise, as the relative separation density is increased, the amount of high-density particle bypass to the product stream increases. The overall shapes of the partition curves indicate relatively low separation efficiency compared to the values typically achieved by conventional cleaning technologies on coarse coal and reflective of the performance comparisons between the washability and Knelson results shown in Figures 3.9 and 3.10. However, the density-based separations provided by the Knelson are effective considering that the cleaning was achieved on nominal 150 x 44 μm particles. Furthermore, it should be noted that a majority of the inefficiency can be linked to the finest size fraction (i.e., 75 x 44 μm) as discussed previously in relation to Table 3.8.

As concluded from the parametric analysis, the most critical parameter that requires manipulation to achieve the optimum separation performances is bowl speed. Decreasing the bowl speed reduces the particle velocity toward the underflow discharge points due to a decreased centrifugal force. As a result, particles of increasing density and ash content report to the product stream, which elevates the relative separation density and clean coal ash content as shown in Table 3.9. A wide range of relative separation densities was achieved including a low value of 1.46. As a result, the product ash content was varied from 6.85% to 15.82%. The probable error (E_P) values achieved over the range of relative separation densities are typical of single-stage water-only cyclone (WOC) units when treating 10 x 1 mm coal. Contributing to the relatively high E_P values in Table 3.9 is the bypass of low-density coal to the underflow tailings stream, which is also an inherent problem of WOC units. For this reason, a two-stage, rougher-scavenger circuit is normally employed in a manner shown in Figure 3.12.

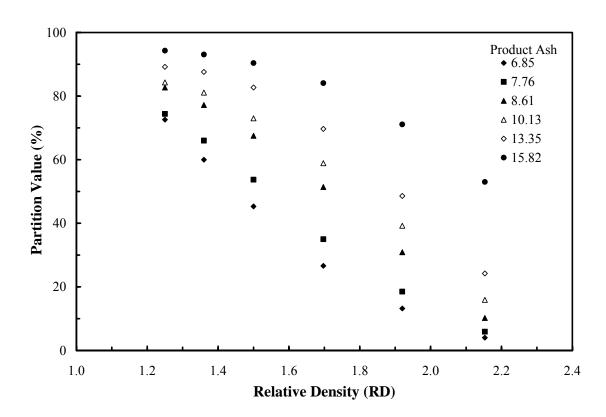


Figure 3.11. Partition curves obtained for the optimum performances achieved when treating the ultrafine Coalberg coal.

Table 3.9. Process performance summary at various optimum operating conditions when treating the ultrafine Coalberg coal.

PARAMETER			TEST N	UMBER		
TARANVIL I EK	1	2	3	4	5	6
Bowl Speed (rpm)	1100	1100	700	700	400	400
Elutriation Rate (lpm)	7.5	7.5	5.0	5.0	7.5	5.0
Valve Opening Time (sec)	0.15	0.14	0.14	0.14	0.14	0.15
Valve Closing Time (sec)	7.0	7.0	4.5	7.0	2.0	4.5
Feed Ash (%)	20.92	20.96	20.95	20.78	20.73	21.33
Product Ash (%)	6.85	7.76	8.61	10.13	13.35	15.82
Reject Ash (%)	37.13	38.30	44.75	44.76	43.68	53.79
Yield (%)	53.53	56.79	65.87	69.25	75.67	85.49
Recovery (%)	63.06	66.28	76.15	78.56	82.71	91.48
Ash Rejection (%)	67.26	62.98	58.90	51.25	35.60	25.83
SG50	1.46	1.54	1.71	1.80	1.90	2.18
Ep	0.245	0.290	0.295	0.300	0.265	0.270
Low-Density Bypass (%)	28	25	17	16	11	6
Organic Efficiency (%)	67.1	69.8	79.3	81.4	84.8	92.9

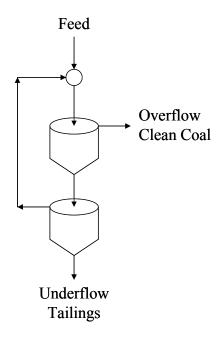


Figure 3.12. Rougher-scavenger cleaning circuit.

Simulations conducted to estimate the separation performances achievable by a rougher-scavenger Knelson found that the overall efficiencies significantly improve as shown by the sharpness of the partition curves in Figure 3.13. The goal of the rougher unit is to produce an acceptable clean coal product and, as such, the partition curve in Figure 3.11 providing the lowest relative separation density was used. The circuit performance was varied by using each of the partition curves in Figure 3.11 to simulate the scavenger unit performance. The simulated partition curves in Figure 3.13 indicate that the circuit substantially reduces the amount of high-density and low-density by-pass that is realized from single-stage Knelson cleaning (Figure 3.11 and Table 3.9). As shown in Table 3.10, the predicted product ash contents vary from 6.49% to 8.35%. Organic efficiency (=actual recovery/theoretical recovery) values significantly improve by greater than 20 absolute percentage points over the same product ash value range with a high value of 95% at a product ash content of 8.35%. In addition, E_P values are typical of those achieved by spiral concentrators when treating the coarser 1 x 0.15 mm coal fraction (Osborne, 1988).

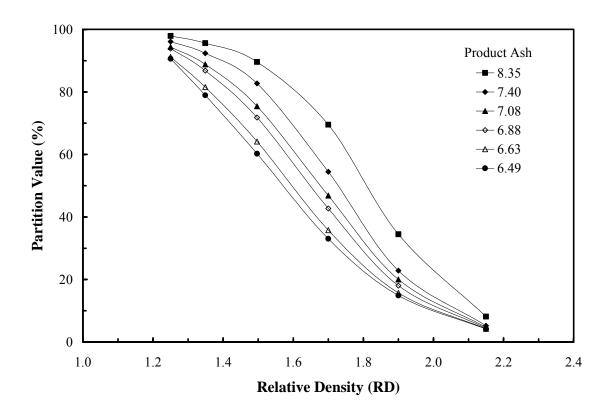


Figure 3.13. Predicted partition curves for the rougher-scavenger Knelson Concentrator circuit.

Table 3.10. Simulated separation performance summary for the rougher-scavenger Knelson circuit; feed ash = 20.92%.

Parameter	Single	Rougher-Scavenger Circuit					
1 arameter	Stage	1	2	3	4	5	6
Product Ash (%)	6.85	6.49	6.63	6.88	7.08	7.40	8.35
Yield (%)	53.53	67.50	68.63	71.81	72.94	75.40	78.83
Recovery (%)	63.06	79.82	81.03	84.56	85.71	88.29	91.36
SG50	1.46	1.57	1.60	1.65	1.68	1.73	1.81
Ep	0.245	0.205	0.205	0.188	0.180	0.170	0.175
Organic Efficiency (%)	67.10	85.33	86.48	89.77	90.70	92.94	95.17

3.5 Air-Assisted Enhanced Gravity Separation

The problem with enhanced gravity separators is the upper particle size limitation and the inefficiency of the classification systems used to remove oversize material from the feed stream. A novel concept was evaluated which utilized the injection of air bubbles in the feed stream in an attempt to reduce the effective density of the coarse coal by bubble-particle aggregation. The objective was to increase recovery and possibly the upper particle size limit.

3.5.1 Experimental

<u>Coal Samples:</u> The coal source and characteristics were the same as those described in section 3.4.1.

<u>Air-Injection System</u>: For the tests involving the injection of air bubbles, the feed stream was mixed with air by pumping through a static mixer as shown in Figure 3.14. Frother (methylisobutylcarbinol, MIBC), which reduces the liquid surface tension, was added into the feed stream before the air injection point at a rate that provided a concentration of 40 ppm. As a result of the intense mixing, air bubbles were generated in the presence of the coal suspension, which provided an efficient environment for bubble-particle collision and attachment. A collector was not employed for enhancing surface hydrophobicity.

Optimization of the process parameter values was achieved on the basis of maximizing mass recovery to the product stream while achieving a given clean coal ash value. To optimize the operating parameter values, test programs were conducted with and without air injection using a Box-Behnken statistical experiment design. The experimental data was used to develop empirical models that describe the response variables (i.e., recovery and product ash) as a function of the parameter values. The model predictions were applied to identify the optimum values needed to achieve the maximum recovery over a range of five product ash values.

A total of four operating parameters that were determined to be critical to the separation performance were selected for the evaluation. The parameter value ranges for the test programs conducted with and without air are shown in Table 3.11. Since the tests were conducted in an

operating preparation plant, feed solids concentration was not adjustable and thus maintained at the approximate 20% by weight level provided in the feed stream. Also, the volumetric feed rate was kept constant at 37 L/min (10 gpm) since this represents a minimum capacity for the enhanced gravity unit being tested and greater flow rates were not available. It should be noted that both these parameters have a significant impact on performance.

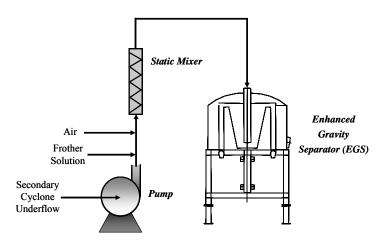


Figure 3.14. Flowsheet showing a) the placement of the Knelson concentrator in the fine circuit of an operating plant and b) the method employed for air bubble injection.

Table 3.11. Range of operating parameters tested in the experimental program.

Parameters	Witho	out Air Inje	ection	With Air Injection			
1 arameters	Low	Middle	High	Low	Middle	High	
Bowl Speed* (rpm)	400	700	1000	500	700	900	
Fluidization rate (L/min)	18.5	27.8	37	18.5	27.8	37	
Valve close time (sec)	2	4.5	7	2	4.5	7	
Valve open time (sec)	0.14	0.15	0.16	0.15	0.15	0.15	
Aeration rate (L/min)	0	0	0	0	100	200	

^{*400} rpm = 13 g's; 1000 rpm = 88 g's

3.5.2 Air-Injection Centrifugal Teeter Bed Results and Discussion

The separation performance data obtained from the treatment of the Powelton coal by the Knelson Concentrator with and without air injection are compared with washability data for the feed coal in Figure 3.15. The optimized parameter values were identified using the empirical models and tests subsequently conducted to achieve the optimized results shown in Figure 3.15. It is clear that the injection of air bubbles into the feed stream of the unit provides a superior recovery-grade curve. Air injection allows the production of clean coal containing less than 5% ash, which is 2 percentage points less than the values achieved when no air was added. Combustible recovery was significantly improved by 10 percentage points or more.

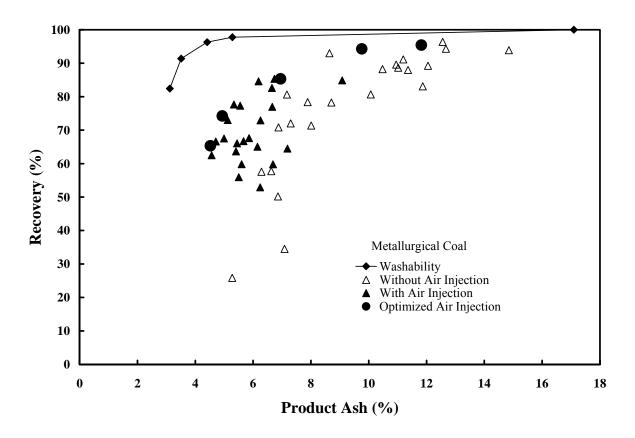


Figure 3.15. Comparison of the feed washability data and the separation performances achieved from the treatment of the Powelton (metallurgical) coal with and without air injection.

A direct comparison of the optimum separation performances achieved with and without air injection reveals that the air bubbles may indeed provide the desired effect of improved coal recovery as a result of producing a low-density, bubble-particle aggregate. As shown in Table 3.12, the ash contents of the tailings corresponding to nearly equal product ash values are significantly higher when air bubbles are injected into the feed stream. As a result, substantially greater combustible recovery values were achieved. This data supports the hypothesis that the injection of air bubbles preferentially enhances the recovery of coal particles to the product stream. Furthermore, based on the parametric study, the rejection of ash-bearing minerals is improved by increased settling rates resulting from the effect of lowering the medium density.

Table 3.12. The comparison of the optimum separation performance results achieved on the Powelton coal with and without air injection.

Test	Ash (%)			Recovery
Number	Feed	Product	Tailings	(%)
No Air				
1	16.90	5.28	20.31	25.86
2	17.65	6.88	35.70	70.81
3	17.84	10.07	39.64	80.68
4	17.07	12.05	43.72	89.25
Air Injection				
1	20.59	4.93	46.14	74.24
2	20.84	6.95	57.64	85.33
3	21.11	9.76	74.30	94.27
4	20.47	11.82	73.82	95.40

A high level of recovery was achieved over the entire particle size range using air injection as indicated by particle size-by-size results shown in Table 3.13. Without air injection, coal recovery for the coarsest size fractions decreases substantially. In addition, significant ash reductions were achieved on each size fraction although the finest size fraction in the clean product contains a relatively large amount of ash-bearing material. This indicates a shift to higher separation densities with a decrease in particle size.

Table 3.13. Particle size-by-size performance achieved on the ultrafine Powelton coal using air injection.

Particle	Fe	ed	Pro	duct	Taili	ngs	Recovery
Size Fraction	Weight	Ash	Weight	Ash	Weight	Ash	(%)
(microns)	(%)	(%)	(%)	(%)	(%)	(%)	
+ 150	38.10	6.16	38.29	3.60	40.19	24.26	90.02
150 x 75	51.22	24.57	44.91	7.63	42.67	76.61	92.39
75 x 44	10.69	41.77	16.80	21.81	17.14	85.18	91.99
Total	100.00	19.39	100.00	8.47	100.00	57.04	88.01

Further support for the proposed mechanisms associated with the air injection effects was obtained from the treatment of the Coalberg coal, which has very poor flotation characteristics as indicated by the release analysis performance results shown in Figure 3.16. Release analysis provides the ultimate separation performance for froth flotation processes, which is the most commonly employed method for cleaning -150 micron coal. As shown in Figure 3.16, the ultimate performance for gravity-based separations as predicted by washability analysis is far superior to that provided by froth flotation for the Coalberg coal. The separation performances achieved by the Knelson concentrator indicate the ability to produce lower clean coal ash contents. However, the results do not appear to improve when air bubbles are injected into the unit. This finding is likely due to the inability of the air bubbles to attach to the poorly hydrophobic coal particles, thereby minimizing the positive impact realized from the treatment of the Powelton coal (Figure 3.15 and Table 3.12).

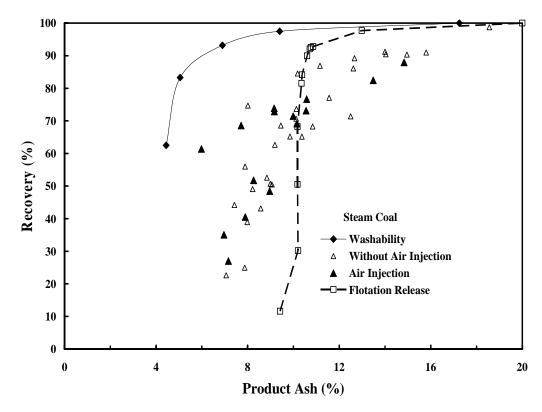


Figure 3.16. A comparison of the separation performances achieved on the Coalberg (steam) coal with and without air injection with those obtained from washability and release analyses.

The sets of operating parameter values that provided the optimum separation results in Figure 3.15 are provided in Table 3.14. Movement down the recovery-grade curve toward lower product ash values requires decreases in both the bowl speed and aeration rate while manipulating the underflow valve closing time. Fluidization water rate is maintained at a relative constant value until the aeration rate is nearly zero at high recovery values.

Partition curves generated from the optimized tests indicate that the relative separation density can be varied from a relatively low value of around 1.3 to a high of about 1.8 when treating + 44 micron coal (Figure 3.17). Without the addition of air, the range was from 1.5 to 2.2. The probable error (Ep) values, which are a measurement of the slope and thus efficiency of the process, generally range between 0.20 and 0.25. A perfect separation corresponds to an Ep value of zero (0). It is apparent that the Knelson unit bypasses a significant amount of high density particles to the product stream, which is mostly associated with material in the finest particle size fractions.

Table 3.14. Optimized parametric values used for the treatment of the Powelton coal; frother concentration = 40 ppm, valve open time = 0.15 sec.

Performance		Optimized Parameter Values				
Test No.	Product Ash (%)	Recovery (%)	Bowl Speed (rpm)	Water Rate (gpm)	Valve Close Time (sec)	Aeration Rate (L/min)
1 2 3 4 5	4.52 4.93 6.95 9.76 11.82	54.45 74.24 85.33 94.27 95.40	880 875 900 563 579	8.5 8.5 8.2 8.4 9.8	4.30 5.85 6.89 7.00 5.63	115 137 73 41 2

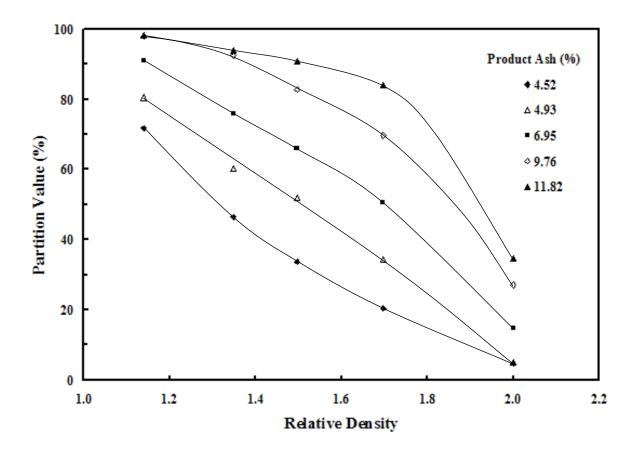


Figure 3.17. Partition curves generated from the optimized tests utilizing air injection for the treatment of the +44 micron Powelton coal.

3.6 Summary and Conclusions

The primary objectives of advanced cleaning project task were to 1) recover clean coal from waste streams and/or impoundments for subsequent dewatering and briquetting studies, 2) evaluate the potential of using briquette binder reagents as a flotation collector and 3) improve the selectivity in fine coal recovery and cleaning.

A pilot-scale advanced flotation unit commercially known as the Jameson Cell was used to recover coal from active fine coal waste streams in two eastern Kentucky coal preparation plants (i.e., James River's Leatherwood facility and Cooke & Sons' Sapphire facility). Product ash values less than 5% were achieved which resulted in enhanced heating values of around 14000 Btu/lb on an air-dried basis. The clean coal samples were used in the majority of the laboratory dewatering and briquetting tests.

For the continuous briquette tests performed on a pilot-scale unit, the flotation concentrate samples were collected from the product stream of a flotation column at TECO's Clintwood-Elkhorn No. 3 coal preparation plant. The coal was originally from the Elkhorn No. 3 coal seam. The flotation concentrate contained about 14% ash and had a heating value of around 14000 Btu/lb on an air-dried basis.

Two briquetting binders that were identified as potentially usable as a flotation collector were tested by quantifying their effects on coal flotation rates. The REAX binder a negative impact on flotation rates with the rates decreasing with a continuous rise in reagent concentration. Selectivity also deteriorated with the use of REAX as compared to the performance provided by fuel oil No. 2. On the other hand, tall oil provided good collector performance however the overall flotation rate was three-to-five times less than that realized by fuel oil. Based on these findings, the binder reagents did not provide attractive benefits for use as a collector in coal flotation.

Improvement in the selectivity achieved by froth flotation processes was achieved by the addition of coal having a higher degree of hydrophobicity into the froth zone of a flotation

column. The more hydrophobic material attaches to the bubbles and, as bubbles coalesce and decrease surface area availability, the more weakly hydrophobic mixed-phase material and coal pyrite are selectively detached due to lower binding energies with the bubble surface. The detached particles report to the collection zone where they are more likely to move into the tailings stream. The result was a 5 absolute percentage point decrease in the product ash content at equal recovery values.

Teeter-bed technologies have reportedly achieved exceptional separation performance when treating 1 x 0.15 mm coal. In this study, a centrifugal teeter-bed technology known as the Knelson Concentrator was evaluated for its potential to improve the selectivity of cleaning -150 micron coal. Fundamentally, gravity-based separations should always be superior to those obtained by froth flotation. Tests conducted on a relatively 'easy-to-clean' coal and a 'difficult-to-clean' coals showed that the fluidized bed unit has the ability to provide significant reductions in ash content. The ash content for the 'difficult-to-clean' coal was reduced from nearly 22% to values approaching 8% while recovering approximately 70% of the combustibles, which equates to a performance that was superior to that achieved by froth flotation.

Evaluation of the process separation efficiencies revealed that the Knelson unit has the ability to provide a wide range of relative separation densities from a low value of 1.46 RD to a high value of 2.18 RD. However, achieving low density separations resulted in a significant amount of coal being bypassed to the underflow tailings stream while high density separations provided a substantial amount of ash bearing material being bypassed to the overflow product stream. The probable error values (E_P), which defines the overall separation efficiency, varied within the range of 0.245 to 0.300. Based on a particle size-by-size performance analysis, inefficiencies may be associated with the cleaning performance achieved on the finest size fraction (i.e., 75 x 44 μ m).

To improve the performance achieved by the Knelson Concentrator, air-bubbles were generated in the feed coal stream and injected into the unit. The hypothesis was that the air bubbles would collide and attach with the coal particles and create low-density aggregates which are more likely to report to the clean coal product stream. For the 'easy-to-clean' Powelton coal which had a

high degree of floatability, air bubble injection was found to have a significant effect on the operating characteristics of the Knelson Concentrator and the separation performances. A 10 – 20 percentage point improvement in recovery was obtained by injecting air bubbles into the feed stream while also providing the ability to lower the product ash by 2 percentage points. The improvement in recovery was largely due to a decrease in coarse coal losses to the tailings stream. Lower product ash values are attributed to enhanced particle settling rates caused by a reduced medium density, which is a result of the high population of micron size bubbles. By manipulation of the operating parameters, the relative separation densities were varied from 1.3 to 1.8 with corresponding probable error values around 0.20.

The injection of air bubbles into the feed stream of Coalberg coal having weak flotation characteristics did not provide an improvement in the separation performance. However, the Knelson Concentrator reduced the ash content from about 18% to 8% while recovering almost 80% of the energy value. In addition, the separation performance was superior to that achieved by froth flotation, which was the process used to clean the fine coal at the test site. In conclusion, the exploitation of both density and surface-based property differences provided improvements in the separation performances achieved by an enhanced gravity concentrator when treating ultrafine hydrophobic coal.

4. ADVANCED DEWATERING

4.1. Introduction and Problem Statement

A typical coal preparation plant produces about 20% of the mined coal as minus 0.5 mm (28 mesh). Generally, this fine fraction is discarded due to its high cost of processing. However, with the development of advanced coal cleaning technology, such as column flotation, cleaning of fine size coal to low ash and low pyritic sulfur is feasible at high recovery. One of the biggest hurdles in utilization of fine coal cleaning technology by the coal industry is the economic dewatering of the fine clean coal product.

In the U.S.A., about 60 percent of mined coal is cleaned in preparation plant by mostly water-based processes. Typically, coal cleaning in preparation plants is achieved by separating coal into three different particle size fractions to ensure optimum separation performance by the cleaning units typically employed. For the coarse and intermediate fractions which typically account for 80% of the feed mass to the preparation plant, cleaning efficiency is generally greater than 95% and the water added during processing is easily removed. However, ash reduction in the -1 mm coal is also fairly efficient, however the water is difficult to remove due to the high particle surface area and the small capillaries that are formed when a packed-particle bed is formed. In numerous cases, the inability to reduce the moisture content of the fine coal has resulted in a decision to send a portion or all of the fine coal into the plant fine coal waste stream.

Since most coal in the U. S. is used as fuel for electric utilities, the addition of water that can not be removed has the same negative impact as mineral material in regards to the heating value of the clean coal product. The additional moisture also adds to transportation cost. For example, a power plant using 3.0 million tons/year of coal from a plant located 250 miles away might spend about \$350,000 per year to transport the additional one percent moisture (1985). The development of an advanced dewatering technology has the potential to provide a significant cost savings for the coal industry.

As discussed above, the degree of difficulty associated with dewatering increases as the particle size decreases or the surface area of the particles to be dewatered increases. A wide variety of equipment such as solid- bowl centrifuges, screen-bowl centrifuges and vacuum disks are used for fine particles dewatering, however, moisture content of the final product is high (~30%). Moisture content of the fine coal could be lowered using thermal driers, however, high operating cost as well as air pollution and fire hazard associated with fine coal makes thermal drying unattractive.

This section of the report describes the results obtained using a novel dewatering approach. The goal was to produce a filter cake having 20-25% moisture which is suitable reconstitution using a briquetting process.

4.2. Goals and Specific Objectives

The goal of this task was to develop a technique for effective and efficient dewatering of ultrafine clean coal slurries generated by cleaning in column flotation. Specifically, the objectives were to test the effect of chemical addition (surfactants and flocculants) and saw dust on the dewatering of fine coal suspension. It was also the objective of the project to study the applicability of a novel two stage dewatering approach i.e., either vacuum-pressure or low pressure-high pressure combinations, for dewatering.

4.3 Literature Review

Although the term "dewatering" refers to removal of water, researchers have used different terms and descriptions to define water associated with particles. Tschamler and Ruiten (1963) classified five types of water associated with coal, including interior adsorption, surface adsorption, capillary, interparticle and adhesion water. The last three types of water are termed as "free" water and are potentially removable by mechanical techniques. However, the first two types of water, known as "inherent" moisture, can only be removed by energy-intensive techniques such as thermal drying.

A variety of techniques are now used in contemporary practice for dewatering coal. The type and efficiency of various dewatering equipment varies as a function of particle size. The degree of difficulty associated with mechanical dewatering increases as the surface area of the particles increases. Particles finer than 0.5 mm (28 mesh) present the greatest difficulty to dewater. Table 4.1 lists the theoretical amount of water present on various size coal particles. Note that 5 to 10 µm particles carry a significant amount of surface moisture.

Table 4.1. Effect of Particle Size on Amount of Surface Moisture Present on Coal Particles.

Particle Size	External Surface Area(m ² /g)	Surface Moisture* (Wt. %)	
2"	0.9	0.009	
3/4"	2.4	0.024	
28 mesh	90.2	0.90	
200 mesh	601	6.18	
10 microns	4511	54.7	
5 microns	9023	131	

^{*}Assuming a 1 micron thick film of water

There has been a rapid increase in research and technology involving developments to improve fine-coal dewatering. Parekh et al. (1989) have published a review on fine coal and refuse dewatering which also included new dewatering technologies being developed in dewatering of fine coal. Methods for improving filtration of fine coal can be divided into two groups: those involving equipment modification and those involving process modifications.

Among the technologies available, Ama pressure filters are capable of achieving a low clean coal moisture level (Dosoudil, 1987). High gravity centrifuges capable of creating forces up to 2,000 times gravity have been reported to be successful in dewatering a froth flotation product to less than 12-percent moisture. Coal Technology Corp. developed a super 'g' centrifuge capable of achieving forces up to 4,000 times the force of gravity (Smith and Durney, 1991). Other new

equipment includes The Shoe Rotary Press (Barbulesclu, 1986), membrane pressure filter (Vickers, 1982), and electro-acoustic dewatering (Muralidhara, 1986) techniques.

Perhaps a more promising avenue to improved dewatering of fine coal lies in the category of process modifications. Viscosity reduction, flocculation and surfactant additions have proven to be effective at improving fine coal dewatering performance.

4.3.1 Enhanced Dewatering

Two important aspects of dewatering fine coal are the dewatering rate and the final moisture content of the product produced; the most desirable conditions would be to have a fast dewatering or filtration rate and low product moisture. Filtrate clarity is not of primary importance in coal applications because filtrate water and the suspended solids are generally recirculated within the dewatering circuit. Theoretical treatment of the dewatering process has concluded that product moisture is reduced while the dewatering rate is increased with:

Increasing

- driving force (gravity, vacuum or pressure),
- permeability of the medium (filter cloth and filter cake),
- contact angle or hydrophobicity,
- filter area, and

Decreasing

- viscosity of the filtrate,
- cake thickness, and
- filtrate surface tension.

When considering these factors, the driving force, medium permeability and filter area is determined by the dewatering device. The other parameters are properties of the slurry, which can be controlled by the use of chemical additives.

<u>Capillary Rise Effect:</u> The driving force required to achieve a given product moisture is a function of the void space size formed when the particles are concentrated during dewatering into a cake structure. The interconnected voids or pores in filter cakes form irregular capillary tubes. This analogy is frequently used in soil mechanics to describe the pore structure of soils. If one considers the cake structure to simplistically be a bundle of capillary tubes, residual saturation can be related to capillary rise or the level of water within a capillary tube (Wakeman, 1997). The capillary rise formula is:

$$h = \frac{2\gamma \cos \theta}{g\rho R} \tag{4.1}$$

where h is the capillary rise, γ the liquid/air surface tension, θ the liquid/solid contact angle, R the capillary radius, g the acceleration due to gravity, vacuum or pressure and ρ the liquid density. The primary mechanisms responsible for the improved dewatering achieved in laboratory studies with the surface modification treatment can be related to reducing the capillary rise.

<u>Capillary Radius Effect:</u> Maximizing the radii of the capillaries within the filter cake structure can be accomplished in several ways. The most obvious is to blend coarser material to effectively increase the average particle size and reduce the surface area of the solids to be dewatered. While this would decrease the filter cake moisture, the coarser material could be more effectively dewatered with equipment other than filters and the net moisture reduction would be minimal.

Flocculants can be used to increase the effective particle size by agglomerating fines which increases permeability and results in a faster filtration rate. However, during floc formation, water can be entrained within the floc structure which ultimately limits the amount of water that can be removed and results in higher cake moisture. To reduce the floc size, surface chemical

modification can be used to induce agglomeration if filtration is conducted at or near the point of zero charge (pzc).

<u>Effect of Contact Angle:</u> The contact angle is a measurement of the hydrophobicity of the solid particles to be filtered. The adsorption of surfactants onto solids can increase the contact angle and make the surface more hydrophobic (Keller at al., 1979; Gala et al., 1983). Increasing the contact angle can significantly lower the capillary rise as shown in the capillary rise equation.

<u>Effect of Surface Tension:</u> Numerous studies have shown that surfactants can indeed lower the moisture content of coal filter cake during dewatering. The general mechanism is that surfactants reduce the interfacial tension at the liquid/air interface which reduces capillary retention forces. Reduction of interfacial surface tension at the liquid/air interface will lower the capillary rise, hence reducing the moisture contained in the capillaries.

Literature evidence challenges the importance of surface tension in dewatering. Silverblatt and Dahlstrom (1954) reported that the moisture content obtained at surface tensions of 72 and 32 dynes per centimeter were essentially equal, however, moisture content was significantly decreased between 32 and 36 ergs/cm². The conclusion was that the improvement was due to surface reactions between the coal and the surfactants rather than a change in the liquid/air interfacial tension. Others have also shown that dewatering is more closely related to surfactant adsorption than to surface tension reduction (Keller at al., 1979; Gala et al., 1983; Pearse and Allen, 1983). Dewatering aids have been developed claiming increased adsorption on solids, and measurements of the filtrate have shown very little decrease in surface tension but significant decrease in cake moisture (Wang, S.S. and Lewellyn, 1979, 1978; Quinn et al., 1978).

Gray (1958) used flocculants, oil and surfactants and reported that each improved dewatering. The benefit of the oils may have been due to impurities of surface active components in the oils, while evidence of surfactant adsorption onto the coal was reported even though his work assumed that surfactants only lowered the liquid/air interfacial tension. Dolina and Kominski (1971) used several surfactants during vacuum filtration and found that the residual moisture content of the filter cake decreased or increased depending on which surfactant was used. This is

not surprising because solution pH and electrolyte content have a significant influence on surfactant adsorption (Rosen, 1975). Nicol (1976) reported improvements in dewatering of coal using anionic surfactants, while Brooks and Bethell (1976) found that a cationic surfactant also improved dewatering. Keller et al. (1979) showed that surfactants added during the washing period of the filtration cycle improved dewatering by i) changing the pressure differential required for dewatering and ii) lowering the residual water content of the filter cake. The pressure differential required was correlated with a decrease in surface tension while the residual moisture content was related to surfactant adsorption at the solid/air interface. Cationic, anionic and nonionic surfactants showed similar effectiveness at different dosages.

The use of surfactants as filtration aids shows potential benefits for lowering cake moisture, particularly in longer filtration cycles. There is contradictory evidence in literature pertaining to the mechanism responsible for this improvement. Some evidence exists for surfactant adsorption increasing the hydrophobicity of the substrate. Additional research suggests that lowering the surface tension at the solid/liquid interface is the primary mechanism. Regardless of the mechanism responsible, removal of "free" or "surface" water is the primary objective and the addition of agglomerating as well as surface tension modifying reagents can indeed reduce the moisture content of fine coal.

<u>Effect of Gravity, g:</u> In the capillary rise formula (Eq. 4.1), elevated gravitational forces minimize the capillary rise. For fluid to flow through the medium (filter cake and filter medium), it is necessary that a pressure drop be applied across the medium. The driving force to achieve the pressure drop can be gravity, vacuum or pressure. Elevating the driving force will increase moisture removal from the capillary network in the filter cake. Gravity filters are not used in the mineral industry, rather a similar principle is employed by high speed centrifuges where forces are several hundred times greater than gravity are generated. Pressure, and much more frequently, vacuum are commonly used as driving forces in the mineral industry. The basic principle remains essentially the same.

4.3.2 Industrial Practice

Vacuum filtration is by far the most commonly practiced for dewatering of fine coal slurries. Vacuum disc filters are generally chosen over rotary drum filters because of the higher capacity. The production rate is approximately 60 to 70 lb/hr/ft² for clean coal and 20 to 30 lb/hr/ft² for coal refuse.

Centrifuges are also used for dewatering minus ³/₄-inch coal slurries. The centrifuges are mounted horizontally and high rotation speed used to exert high centrifugal forces on the particle bed which forces the water through the capillaries. For a screen bowl centrifuge, the solids are then conveyed to a chamber where the walls are perforated and further dewatering takes place through the walls. For a solid bowl centrifuge, the solids are advanced to the discharge point by a scroll-conveyor and additional water drains back into the decantation zone.

Hyperbaric (high pressure) filtration is widely used in Europe and China, however, it has not been adopted by the U.S. coal industry. The Andritz-Ruthner Hyperbaric Filter (HBF) consists of a high specification vacuum disc filter installed in a pressure vessel and applies dewatering pressures up to 90 psi (6.2 bar). Commercial units vary in size from 260 to 1300 ft² (24 to 120 m²) of filter area and under plant operating conditions with fine coal has produced 17.9% moisture versus 25.7% on a vacuum filter at Ruhrkohr mines in Germany (Ehlert, 1991). Parekh et al. (1996) also evaluated the applicability of hyperbaric filtration for fine coal dewatering and reported obtaining about 13% moisture in the filter cakes. While hyperbaric filters produce a very low moisture filter cake, their capital and operating costs are often prohibitively high.

Several other dewatering devices such as the belt filter press or vacuum belt filter press are also used, but their primary application is for refuse dewatering. Despite relatively high capacities, high chemical consumption and high product moisture limit their use.

Dewatering of ultrafine clean coal ($d_{50}\sim25~\mu m$) produced in advanced flotation technology is difficult to dewater to a low (less than 20 percent) moisture due to large surface area. Table 2 lists dewatering test data obtained on a column flotation product using various types of

equipment (Parekh and Bland, 1989). Note that only pressure filters were able to provide a low moisture product.

4.3.3 In-Situ Dewatering/Hardening

Wen et al. (1993) investigated an in-situ cake hardening process for fine coal slurry. They reported that addition of 2% to 8% by weight of asphalt emulsion lowered the filter cake moisture, as well as reduced the dust formation. Wilson et al. (1994) reported success in a single stage dewatering and briquetting process in which Orimulsion was used as dewatering and binding agent.

In summary, there is an immediate need for an economical and efficient process that will reduce the moisture content of fine coal filter cakes to about or below 20% level. Treatment of coal slurry prior to filtration by flocculant and surfactant can provide some benefits but may not be cost effective. Similarly, use of steam can be effective in dewatering but may not be economical. For the hyperbaric filter, capital and operating costs may be prohibitively high.

Table 4.2. Dewatering Test Data on Clean Coal Slurry Using Various Types of Equipment.

Equipment	Filtration Rate (lb/hr/ft ²)	Moisture (%)
Vacuum Disc Filter	4.9	25
Horizontal Belt Vacuum Filter	15	25
Belt Press Filter	2.8	40
Belt Press Filter*	10	30
Belt Press Filter*	20	38
Plate and Frame Pressure Filter		22.7
Ama Filter (Continuous Pressure Filter)	21	21

^{*}Organic polymeric flocculant used

4.3.4 Oil Assisted Dewatering

Capes et al. (1983) reported that oil-assisted dewatering caused agglomeration of solids and improvements in drainage rates, solids recovery and equilibrium moisture. Reductions in cake moisture from 27 percent to 10 percent have been reported by adding 3% kerosene to the slurry prior to filtration (Loo and Slechta, 1987). Meenan and Wasson (1987) used fuel oil prior to filtration and reported that increased cake thickness reduced the applied vacuum and, even though the cake was more permeable, short circuiting of air through the cake was more probable. These results showed that the oil dosage had no effect on cake moisture in the dosage range of 0.6 to 11.4 lbs/ton.

Phillips and Thomas (1955) observed that by changing the hydrophobicity of glass spheres with chlorosilane, the water retained in the pendular state to be 11% for a 0° contact angle and 1.2 % for a 90° contact angle. However, the study conducted by Harris and Smith (1957) showed no decrease in the final moisture content. By increasing the contact angle of the glass spheres, the pendular state in a bed of glass spheres was reached more rapidly. They also observed that the pendular state occurred when a sufficient amount of water had been removed from the bed so that no continuous net work of water existed except discrete rings of water at the points of contact of the particles.

Several processes utilize oil for the beneficiation as well as dewatering of fine coal. The moisture content in the clean coal has been reported to be 5% to 25% depending on the amount of oil used (Capes et al., 1983). One example is the Otisca-T process, which utilizes pentane for agglomerating and cleaning ultra-fine coal. Pentane is a low temperature volatile liquid that evaporates thereby providing a dry, clean coal product. The evaporated pentane is captured, condensed and recycled in the process (Meenan and Wasson, 1987). Loo and Slechta (1987) conducted oil-assisted filtration experiments on -500 µm coal in a pilot plant. About 1.5% diesel oil addition caused a cake throughput increase by about 40%. Their investigation also showed that the cake moisture content also slightly increased when the throughput was raised with oil addition.

Dewatering improvement by oil agglomeration has been studied in detail by Capes et al. (1983).

They concluded that the enhanced dewatering capability is due to the displacement of water by the attached oil; and the oil concentration is found to be the most significant parameter in coal dewatering by agglomeration.

Although surface tension may play a role in moisture reduction, increasing the solid/liquid contact angle seems to be the most important factor in the filter cake moisture content reduction by surfactants. In addition, with respect to the effect of coal particle size, flocculants reduce the cake moisture of coarse particles more effectively than fine particles.

Much less research has been conducted on the use of oils in coal dewatering perhaps because oil addition tests revealed the ineffectiveness in promoting coal dewatering: the high cost resulted from the high oil consumption.

4.4 Experimental

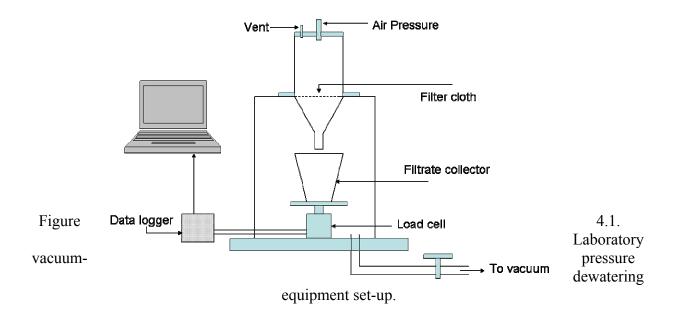
4.4.1 Experimental Setup and Procedure

A schematic diagram of the laboratory dewatering unit is shown in Figure 4.1. A commercially available filter cloth was used in the filter unit, which was supported by a wire mesh at the bottom. The filtrate was collected in a beaker and the weight of the filtrate was continuously recorded using a load cell connected to a computer.

A measured volume of reagent conditioned coal slurry was transferred immediately to the filtration cell and a cake was formed by applying the vacuum. The vacuum was applied continuously for a required period of time. The volume of water removed during both cake formation and drying times were recorded as a function of time. For each test, the cake formation time was monitored as the measure of the dewatering kinetics.

The filter cake moisture was determined by weighing the wet cake and then drying it overnight in the oven at $60 \, \text{C}^{\text{O}}$ and weighing it, using the following formula:

% moisture =
$$\frac{Loss\ of\ weight\ of\ filter\ cake}{weight\ of\ wet\ filter\ cake} \times 100$$
 (4.2)



4.4.2 Reagents

The surfactants used for the studies were a NAS 08 (anionic), Triton X-114 (Non-ionic) and Cetyl Pyridinium Chloride (Cationic). The flocculants used were Nalco 83949 (Anionic) and Nalco 9580 (cationic). All the reagents used were of technical grade. Tables 4.3 and 4.4 list various characteristics of the surfactants and flocculants used for the study, respectively.

Table 4.3. Surfactants Characteristics

	Sodium 2-	Octyl Phonoxy	1-Hexadecyl
	Ethylhexyl sulfate	Polyethoxy Ethanol	Pyridinium Chloride
Type	Anionic	Non-ionic	Cationic
Commercial Name	NAS 08	TRITON X-114	Cetyl Pyridinium
			Chloride
Molecular Weight	232	536	340
Manufacturer	Niacet Co.	Rohm & Hass	Sigma Chemical

Table 4.4. Flocculant Characteristics (Nalco).

Name	Туре	Molecular weight (million)
Nalco 83949	Anionic	15
Nalco 9850	Cationic	1

Three practical approaches for enhancing fine coal dewatering were investigated in this project. The effect of surfactant and flocculant addition, novel approaches of oil-water emulsions and hybrid vacuum/pressure systems were tested. The effect of adding chemicals with the hybrid vacuum/pressure system was also investigated. A series of experiments were conducted by adding saw dust or binders used in the briquetting to investigate their effect on fine coal dewatering.

Five different series of tests were performed to examine effects of vacuum and pressure on cake formation and cake drying, as summarized in Table 4.5.

Table 4.5. Series of fine coal dewatering tests conducted with hybrid vacuum/pressure system.

Series Number	Cake Formation	Cake Drying
1	Vacuum	Vacuum
2	Pressure	Pressure
3	Vacuum	Pressure
4	low Pressure	High Pressure

4.5 Results and Discussions

4.5.1 Sample Characterization

For the dewatering studies, the clean coal slurries produced from the thickener feed of the Cook and Sons and the James River Coal using the Jameson cell were used. Representative samples of the clean coal slurries were characterized for pH, particle size distribution, solids concentration and ash content. The solids content of the Cook and Sons Jameson cell product was 15.63% by

weight with a slurry pH of 6.71 and that of the James River Jameson cell product was 17.84% with pH of 8.54.

Figure 4.2 shows the particle size distribution of the two Jameson cell products. Note that the median (50^{th} percentile) size of the Cook & Sons and James River samples are 44.30 μ m and 36.89 μ m, respectively.

Table 4.6 lists the analysis of the two clean coal samples. The ash contents of Cook & Sons and James River Jameson products are 8.32% and 5.91%, respectively. The volatile matter and fixed carbon contents are similar for the two products.

Table 4.6. Proximate Analysis of the Coal Samples; moisture free basis.

Coal Sample	Ash %	Volatile Matter %	Fixed Carbon %
Cook and Son	8.32	32.69	58.99
James River	5.91	33.84	60.24

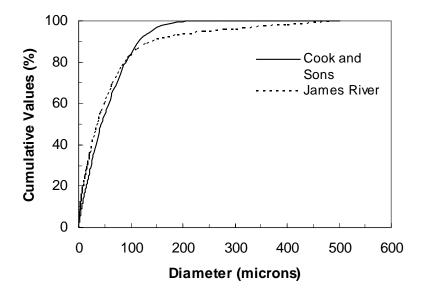


Figure 4.2. Size distribution of the 'as received' column flotation concentrate samples.

4.5.2 Vacuum Filtration Tests

Baseline Dewatering Tests: The effect of cake drying time on the filter cake moisture using the vacuum filtration for a constant 8 mm thickness cake for the Cooke and Sons and the James River sample is shown in Figure 4.3. As expected, the filter cake moisture decreases as the cake drying time increases. The filter cake moisture content reaches a stable value in 80 seconds, further increase in filtration time did not provide any significant reduction in the filter cake moisture. The cake moisture contents of 25.36% and 33.67% were obtained for the Cooke & Sons and the James River coal samples, respectively, using 80 seconds cake drying time.

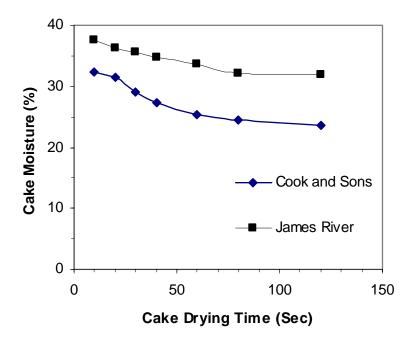


Figure 4.3. Effect of cake drying time on the filter cake moisture using the vacuum filtration for the Cook and Sons and James River slurries; cake thickness ~ 8mm.

The effect of cake thickness on the filter cake moisture using vacuum filtration for a constant cake drying time of 60 sec is shown in Figure 4.4. The cake moisture rises with an increase in cake thickness. Using a cake thickness of 8 mm, the moisture contents for the Cooke & Sons and James River coal samples were 25.35% and 25.36%, respectively. The total dewatering time and cake thickness were maintained at 90 sec and 8mm, respectively.

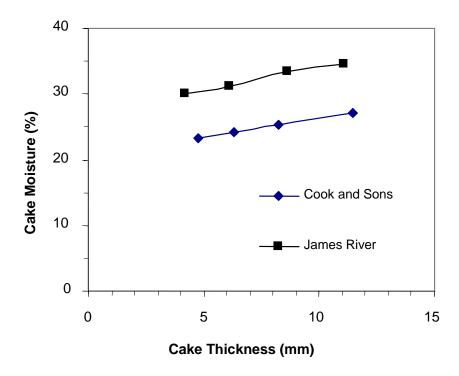


Figure 4.4. Effect of cake thickness on the filter cake moisture using vacuum filtration for the Cook & Sons and James River clean coal slurries; 60 sec cake drying time, cake thickness ~ 8mm.

<u>Enhanced Dewatering Using Additives:</u> The results of addition of flocculants, surfactants, emulsions, saw dust and binders on the dewatering performance the Cook and Sons and the James River Jameson cell products are reported in this section. All the dewatering experiments were conducted using the vacuum technique. The volume of slurry used for the dewatering test was 200 ml; the solids percentage of the sample was 15%; total filtration time was kept constant at 90 seconds.

The effect of surfactant and flocculant additions on dewatering performance of the two fine coal slurries was studied using the chemicals listed earlier in Tables 4.3 and 4.4. For each test, surfactant or flocculant was added to the coal slurry and conditioned for 30 seconds prior to dewatering.

Figures 4.5 shows the cake moisture content and the cake formation time for the Cook and Sons coal as a function of the surfactant dosages. With the nonionic surfactant, both the cake moisture content and the cake formation time slightly decreased with increasing surfactant dosage. The lowest 21% cake moisture was obtained using 0.5 kg/ton of X-114, which is 2 absolute percent lower than the baseline dewatering data achieved using no reagent. The cake formation time reduced to about 21 sec compared to 24 sec obtained in the baseline data. Further increases in surfactant dosage elevated both cake moisture and cake formation time.

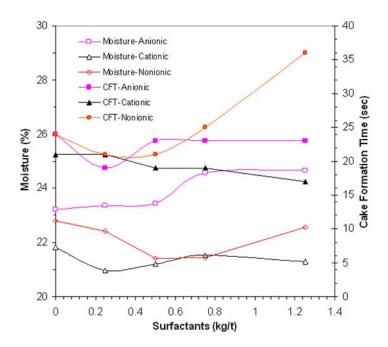


Figure 4.5. Effect of surfactant dosages on the cake moisture content and the cake formation time for the Cook & Sons Jameson Cell clean coal product using vacuum. (15% solids, total filtration time: 90 sec.)

For the cationic surfactant (CPCl), the addition of 0.25 kg/ton slightly decreased the cake moisture content from 21.83% to 20.95% without a change in the cake formation time. Increasing the surfactant dosage to 1.25 kg/ton increased the moisture content to 21.30% with a reduction in cake formation time from 21 sec to 17 sec.

For the anionic surfactant (S2ES), the cake formation time decreased from 24 sec to 19 sec at 0.25 kg/ton addition. Cake moisture remained relatively unchanged at 23.20%. Increasing the

surfactant dosage to 1.25 kg/ton increases both the cake formation time and the cake moisture content to 23 sec and 24.65%, respectively.

These results indicate that the nonionic and cationic surfactants were not effective in decreasing the filter cake moisture for the Cook & Sons coal sample.

Figures 4.6 show the effect of surfactants dosages on cake moisture and the cake formation time for the James River coal. Addition 0.25 kg/ton of nonionic surfactant lowered the cake formation time from 61sec to 42 sec with no appreciable change in the cake moisture content of 33%. Further increase in the surfactant dosage to 1.25 kg/t decreased the cake moisture content to 29%, with increase in the cake formation time 42 sec to 55 sec. At a surfactant dosage of 1.25 kg/t the absolute reduction in cake moisture content was 4%.

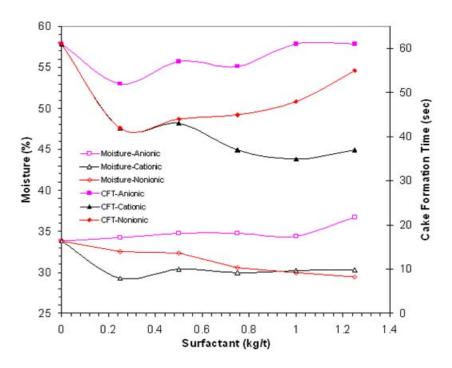


Figure 4.6. Effect of nonionic surfactant dosage on the cake moisture content and the cake formation time of the James River clean coal product using vacuum; 15% solids, total filtration time: 90 sec.

Similar dewatering results were obtained using the cationic surfactant (CPCl). With the addition of 0.25 kg/ton of CPCl, the cake moisture decreased from 33.82% to 29.32%, and then increased to 30.38% with a further increase in dosage to 0.5 kg/t and remained constant afterwards. The cake formation time was reduced from 61 sec to 42 sec upon addition of 0.25 kg/ton of CPCl and continued to decrease with increasing dosage to 37 sec at 0.75 kg/t, with no change in further addition of surfactant.

For the anionic surfactant (S2ES), the cake formation time initially decreased from 61 sec to 52 sec with the increasing of the dosage from 0 to 0.25 kg/ton, and then increased back to 61 sec at 1.25 kg/ton. The cake moisture content increased with the addition of surfactant and increased from 33.82% to 36.76% at S2ES concentration of 1.25 kg/t.

Figures 4.7 and 4.8 show the cake moisture content and the cake formation time for the Cooke & Sons coal as a function of the anionic and cationic flocculant dosage, respectively. When adding either the anionic flocculant (Figure 4.7) or the cationic flocculant (Figure 4.8), the cake formation time decreased with increasing flocculant dosage. Using 10 to 20 g/t flocculant, the cake formation time decreased from 25 sec (baseline) to values in the range of 15 to 17 sec. Using 20 g/t of the anionic flocculant, the cake moisture content decreased from 24% to about 20%. Similarly, using 20 g/t of cationic flocculant the cka moisture decreased from 24% to 22%. Further increase in anionic flocculant increased both cake formation time and moisture content. However, with the cationic flocculant, a further increase in concentration beyond 20 g/t did not appreciably change the cake moisture content, even though there was a slight continued decrease in cake formation time.

The effect of anionic and cationic flocculant addition on dewatering of the James River coal slurry is shown in Figures 4.9 and 4.10, respectively. The filter cake moisture reduction with the addition of the anionic flocculant was minimal (34.19% to 31.48% at 15 g/t), however, cake formation time reduced from 57 sec to 22 sec using 10 g/t of the flocculant (Figure 4.9). A further increase in the anionic flocculant dosage beyond 15 g/t increased the cake moisture content while with no change in the cake formation time.

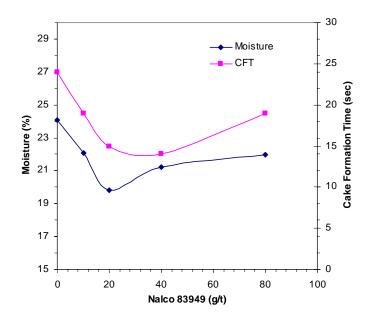


Figure 4.7. Effect of anionic flocculant dosage on the cake formation time and the cake moisture content of the Cooke & Sons clean coal product using vacuum; 15% solids, total filtration time: 90 sec.

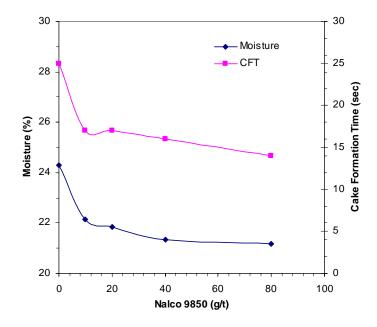


Figure 4.8. Effect of cationic flocculant dosage on the cake formation time and the cake moisture content of the Cooke & Sons clean coal product using vacuum. (15% solids, total filtration time: 90 sec.)

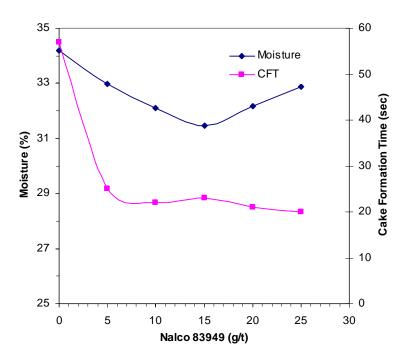


Figure 4.9. Effect of anionic flocculant dosage on the cake formation time and the cake moisture content of the James River clean coal product using vacuum; 15% solids, total filtration time: 90 sec.

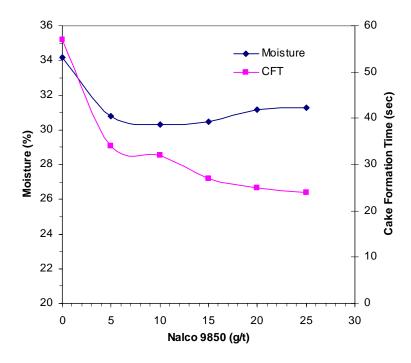


Figure 4.10. Effect of cationic flocculant dosage on the cake formation time and the cake moisture content of the James River clean coal product using vacuum; 15% solids, total filtration time: 90 sec.

The addition of 10 g/t of the cationic flocculant lowered the filter cake moisture from 34.19% to 30.31% and cake formation time from 57 sec to 32 sec (Figure 4.10). A further increase in cationic flocculant addition did not improve the cake moisture content, however some decrease in the cake formation time was observed.

<u>Effect of Oil-Water Emulsion Addition:</u> The effect of oil-water emulsions on the dewatering performance on Jameson Cell fine coal slurries was studied using fuel oil and CPCl as an emulsifier. For each test, the required amount of emulsion was added to the coal slurry and conditioned for 30 sec prior to dewatering.

Figures 4.11 and 4.12 show the cake moisture content and the cake formation time for the Cook and Sons coal as a function of the emulsion dosage at two different emulsifier (CPCI) concentrations. For comparison, data obtained with tests conducted with fuel oil emulsion prepared without emulsifier are also shown in the figures. Addition of 15 ml emulsion prepared with no emulsifier decreased the cake moisture content from 25.22% to 19.09% with change in cake formation time from 26 sec to 16 sec. Tests conducted with emulsion made with 0.01% emulsifier slightly increased the moisture content without much change in the cake formation time. Using 15 ml of the emulsion prepared using the emulsifier concentration to 0.1% reduced the cake moisture from 25.73% to 18.23% with a reduction in cake formation time from 26 to 10 sec. The decrease in emulsion dosage with increase in surfactant concentration clearly indicates the possibility of improved emulsification of oil droplets, which improves the hydrophobicity of the particles and their agglomeration. The agglomeration of the particles is evident from the clear filtrate obtained with the emulsions as compared to the filtrate obtained with surfactants.

To test the hypothesis that the increased CPCl dosage is responsible for the reduction in the emulsion dosage required in dewatering, tests were conducted emulsion prepared with 1% CPCL. Figure 4.13 shows that a cake containing 19.22% moisture can be obtained using only 5 ml of emulsion. A reduction of 50% in emulsion dosage compared to the emulsion prepared with 0.1% CPCL. The cake formation time reduced from 26 sec to 16 sec. However, further increase

in emulsion dosage to 15 ml increased both the cake moisture and the cake formation time to 21.21% and 40 sec respectively. At this dosage the coal slurry dispersed probably due to steric stabilization.

Figures 4.14 shows the cake moisture content and the cake formation time for the James River coal as a function of the emulsion dosage prepared with 1% CPCl. It can be seen from the figure that as the emulsion dosage increases up to 7.5 ml, the cake moisture decreases from 35.65% to 24.98%, with a reduction in cake formation time from 59 sec to 25 sec. However, further increase in emulsion concentration beyond 7.5 ml increases both cake moisture and cake formation time. It is clearly evident from the visual inspection is that the coal slurry is dispersed at higher concentration of emulsion.

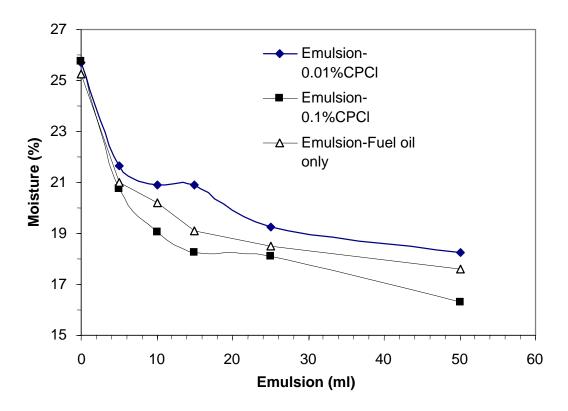


Figure 4.11. Effect of oil-water emulsion dosage on the cake moisture content of the Cook & Sons clean coal product; 15% solids, total filtration time: 90 sec.

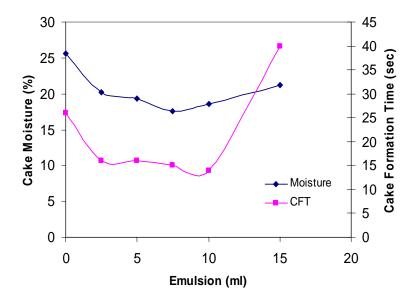


Figure 4.12. Effect of oil-water emulsion dosage on the cake formation time of the Cook and Sons clean coal product; 15% solids, total filtration time: 90 sec.

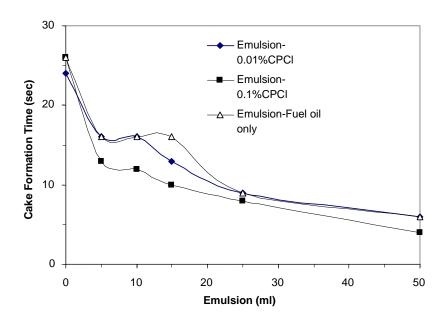


Figure 4.13. Effect of oil-water emulsion dosage prepared with 1% CPCL on the cake formation time and the cake moisture content of the Cooke & Sons clean coal product; 15% solids, total filtration time = 90 sec.

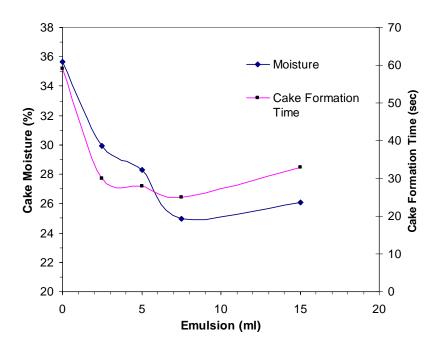


Figure 4.14. Effect of oil-water emulsion dosage prepared with 1% CPCL on the cake formation time and the cake moisture content of the James River clean coal product; 15% solids, total filtration time = 90 sec.

Effect of Saw Dust Addition: Another factor that affects the dewatering performance is the cake porosity, which is directly related to the microstructure of the cake. The addition of coarse particles to the slurry will change the size distribution and will improve the cake porosity. A main component of the project was the blending of saw dust with fine clean coal to form a premium fuel in briquette form. If the saw dust is added while dewatering the Jameson cell products, the coarser saw dust particles may facilitate the dewatering process thereby improving the cake moisture content and reducing the dewatering costs. To tests this hypothesis, dewatering tests were carried out with the saw dust 'as received', saw dust treated with surfactant and fuel oil and with three different saw dust size fractions. The three size fractions were + 16 mesh, 16×30 mesh and - 30 mesh. The saw dust was added to the fine coal slurry at concentrations of 2%, 4%, 6%, 8% and 12% by weight of the coal present in the slurry. Prior to the dewatering tests, the saw dust was added to the coal slurry and mixed for 60 seconds.

Figures 4.15 and 4.16 show the effect of saw dust on the cake moisture and cake formation time for Cooke & Sons and James River Jameson Cell clean coal products, respectively. By using 2% by weight of saw dust with the Cooke & Sons coal (Figure 4.15), the cake moisture and the cake formation time increased from 24.34% to 26.62% and from 24 sec to 37 sec, respectively. A further increase in saw dust addition to 12 wt% raised both cake moisture and cake formation time to 33.30% and 131 sec, respectively. Similar results were obtained with the James River clean coal product (Figure 4.16). At a saw dust dosage of 12% by weight, the cake moisture and cake formation time increased from 34.82% to 39.30% and 61 sec to 84 sec, respectively.

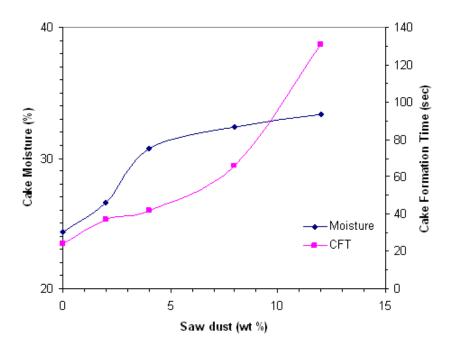


Figure 4.15. Effect of 'as received' sawdust dosage on the cake moisture and cake formation time of the Cooke & Sons clean coal product.

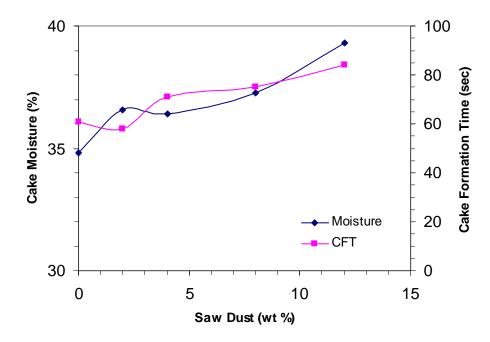


Figure 4.16. Effect of 'as received' saw dust dosage on the cake moisture and cake formation time of the James River clean coal product.

The results indicate that the addition of saw dust does not improve filtration rate and cake moisture content. Based on visual observation, it is envisaged that the increase in cake moisture content is due to the water entrapped in the saw dust. Therefore, tests were conducted with Cooke & Sons clean coal product using saw dust coated with asphalt emulsion or fuel oil rendering it hydrophobic.

Figures 4.17 and 4.18 show the effect of saw dust treated with asphalt emulsion or fuel oil on the cake moisture and cake formation time for Cooke & Sons clean coal product. With the addition of 2 wt% of saw dust treated with asphalt emulsion, the cake moisture and the cake formation time increased from 25.54% to 28.13% and from 26 sec to 36 sec, respectively. Whereas, with the addition of 2 wt% of saw dust treated with fuel oil, the cake moisture and the cake formation time increased from 24.79% to 27.48% and from 24 sec to 41 sec respectively. A further increase in treated saw dust addition showed a detrimental effect on both cake moisture and cake formation time for the both slurries.

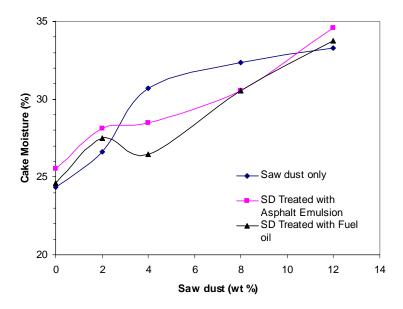


Figure 4.17. Effect of saw dust dosage treated with asphalt emulsion or fuel oil on the cake moisture of the Cooke & Sons clean coal product.

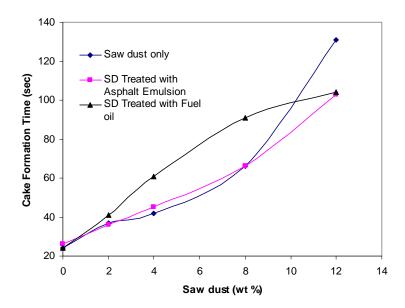


Figure 4.18. Effect of saw dust dosage treated with asphalt emulsion or fuel oil on the cake formation time of the Cooke & Sons clean coal product.

The tests conducted with saw dust rendering it hydrophobic did not improve the cake moisture content or filtration rates compared to the tests conducted without treating saw dust sample. Hence, tests were conducted with different fractions of saw dust without any treatment. The three size fractions tested were +16 mesh, 16 x 30 mesh, and -30 mesh.

Figures 4.19, 4.20, and 4.21 show the effect of addition of the saw dust of different fractions on the cake moisture and cake formation time for Cooke & Sons Jameson cell product. It can be seen from Figure 19 that addition of 2 wt% + 16 mesh fraction saw dust increased the cake moisture and cake formation time from 24.12% to 27.12% and 28 sec to 32 sec, respectively. Further increase in saw dust concentration up to 12 wt% did not increase the cake formation time, but the cake moisture increased to 36.94%. This result indicates that the addition of +16 mesh fraction saw dust did not significantly affect the filtration kinetics and moisture content compared to the addition of 'as received' sample.

The addition of 16×30 mesh fraction saw dust (Figure 4.20) provided similar results. However, a 2×6 mesh saw dust concentration significantly changed both cake moisture content and cake formation time (Figure 4.21). The addition of 2×6 saw dust increased the cake moisture content from 24.03% to 36.23% and cake formation time from 29×6 sec. Further increase in saw dust dosage up to 8×6 did not significantly affect the cake moisture and cake formation time. However, the addition of 12×6 saw dust increased the cake moisture to 41.28% and cake formation time to 46×6 sec. These results indicate that the addition of coarse saw dust ($-16 + 30 \times 6$) mesh) did not severely affect the dewatering performance compared to the addition of -30×6 mesh saw dust. In general, the addition of saw dust prior to filtration does not improve the dewatering performance.

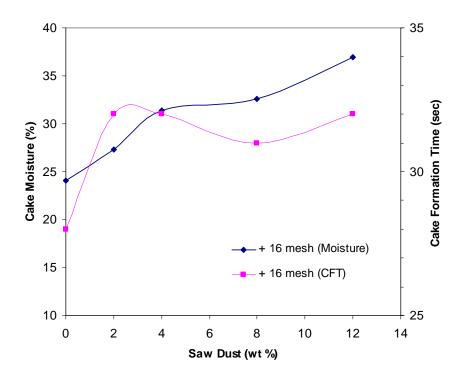


Figure 4.19. Effect of addition of +16 mesh fraction saw dust on the cake moisture and cake formation time of the Cooke & Sons clean coal product.

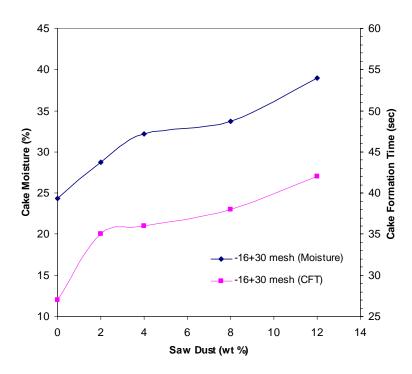


Figure 4.20. Effect of addition of 16 x 30 mesh fraction saw dust on the cake moisture and cake formation time of the Cooke & Sons clean coal product.

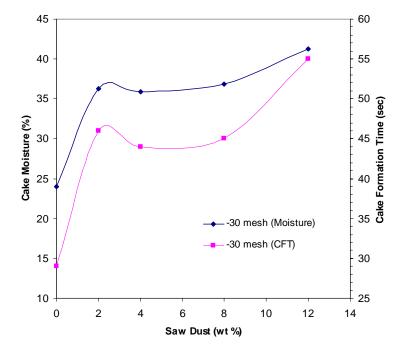


Figure 4.21. Effect of addition of -30 mesh fraction saw dust on the cake moisture and cake formation time of the Cooke & Sons clean coal product.

<u>Binder Addition Effects:</u> In general, the addition of chemicals improves filtration kinetics and cake moisture content. During briquetting of coal, binders are used to bind the coal and saw dust particles. It was speculated that the addition of the binders may be helpful in dewatering of the fine coal slurry. The objective of this task was two fold, i.e., i) to replace dewatering chemicals with binders thus providing saving in the cost of chemicals and ii) to reduce the amount of binder needed during the briquetting process since the coal will be already treated with binding agents.

Figure 4.22 shows the effect of REAX-SN addition on the cake moisture and cake formation time using the vacuum filtration technique. The addition of only 0.05 kg/t of REAX-SN increased cake moisture and cake formation time from 33.59% to 35.09% and 60 sec to 66 sec, respectively. Further increases in REAX-SN concentration rapidly increased cake moisture and cake formation time, reaching 39.55% and 95 sec, respectively, at a REAX-SN concentration of 0.25 kg/t.

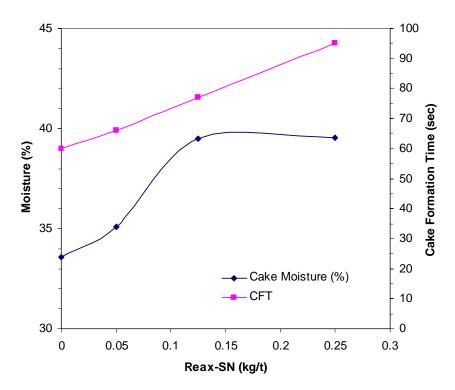


Figure 4.22. Effect of addition of REAX-SN on the cake moisture and cake formation time of the James River clean coal product; 15% solids, total filtration time = 90 sec.

The effect of Genvis-600 addition is shown in the Figure 4.23. At a low concentration of 0.5 kg/t, Genvis-600 increased the cake moisture and cake formation time from 33.08% to 35.20% and 60 sec to 72 sec respectively. However, at a concentration of 1 kg/t, both cake moisture content and cake formation time returned to the base line values. Further increases in the Genvis-600 concentration up to 5 kg/t did not affect the cake moisture and cake formation time.

The effect of Kalona addition is shown in the Figure 4.24. As the concentration of Kalona increases, both cake moisture and cake formation time sharply decrease. At a Kalona concentration of 2 kg/t, the cake moisture reduced from 34.95% to 27.71% and the cake formation time reduced from 60 sec to 30 sec. An absolute 7 percentage point reduction in the cake moisture was achieved with a 50% reduction in the cake formation time. These data indicate that the Kalona binder addition was effective in dewatering of coal slurry.

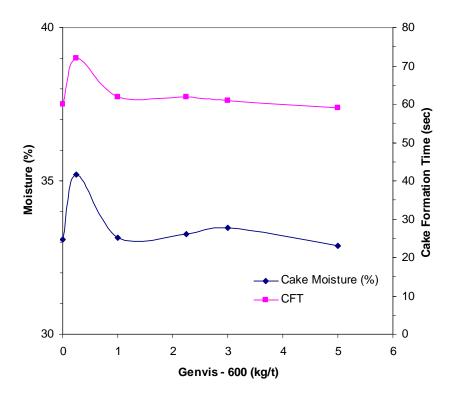


Figure 4.23. Effect of Genvis-600 addition on cake moisture and cake formation time achieved on the James River clean coal product; 15% solids, total filtration time = 90 sec.

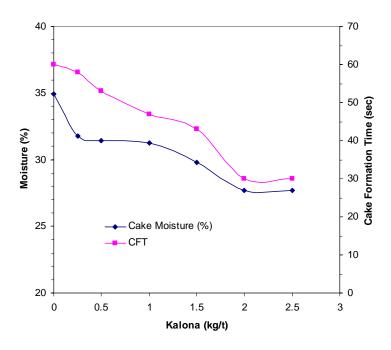


Figure 4.24. Effect of Kalona addition on cake moisture and cake formation time achieved on the James River clean coal product; 15% solids, total filtration time = 90 sec.

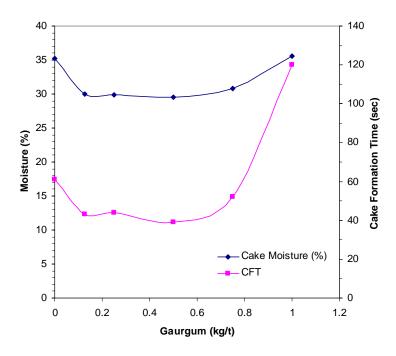


Figure 4.25. Effect of Gaur gum addition on cake moisture and cake formation time achieved on the James River clean coal product; 15% solids, total filtration time= 90 sec.

As shown in Figure 4.25, the addition of 0.125 kg/t of Gaur gum reduced the moisture and cake formation time from 35.27% to 29.94% and 61 sec to 43 sec, respectively. A 5% reduction in moisture content and about 1/3 reduction in cake formation time indicates that the Gaur gum acts as a flocculant at low concentrations. However, further increasing the Gaur gum dosage to 0.75 kg/t did not improve the results. Any further increase in Gaur gum dosage beyond 0.75 kg/t was detrimental to the filtration process.

4.5.3 Pressure Filtration Tests

As summarized previously, dewatering research and plant operating data suggest that pressure filtration provides the lowest product moisture results. The tests involving pressure filtration in this study were performed on the Cooke & Sons clean coal slurry. The dewatering tests involved varying the amount of pressure applied (driving force) and the reagent type and concentration. The slurry volume and filtration time were kept constant at 600 ml and 90 sec, respectively.

As expected, the filter cake moisture reduced from 25.51% to 17.57% as the pressure was increased from 30 psi (~2 bar) to 50 psi (~4 bar) as shown in Figure 4.26. These moisture levels are notably lower than those achieved by vacuum filtration. Using 10 g/t of a Nalco anionic flocculant at 50 psi (~4 bar), the cake moisture was 19.30%, which was slightly higher than the base line moisture. However, it can be seen that at a lower pressure of 20 psi (~1.3 bar), usage of the anionic polymer provides lower cake moisture compared the data using pressure alone. These results indicate that with the usage of flocculants the water entrapped within the floc structure, is not readily removable with pressure. Using 0.25 kg/t of the cationic surfactant (CPCL), the lowest filter cake moisture of about 15 percent was obtained at 50 psi (~4 bar).

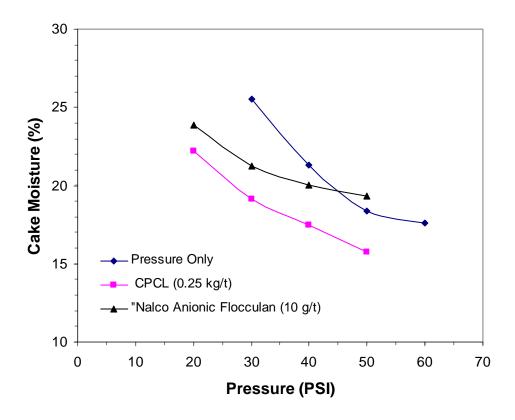


Figure 4.26. Effect of reagents and pressure on the cake moisture for Cooke & Sons clean coal product.

4.5.4 Novel Two-Stage Filtration Tests

Research at the University of Kentucky has found that filtration performance is improved by a novel two-stage filtration approach. The first phase involves controlled conditions for bulk water removal and cake formation while the second phase efforts are to remove capillary water. The optimum conditions for the two phases are different. In this investigation, two dewatering schemes incorporating the two-phase approach were evaluated, which included:

Test Condition No. 1: Phase 1: Applied vacuum for cake formation; Phase 2: Applied pressure for cake drying.

Test Condition No. 2. Phase 1: Low pressure (20 psi) for cake formation; Phase 2: high pressure for cake drying.

Figure 4.27 shows the effect of pressure variations on the filter cake moisture for a 10 mm thick filter cake using Test Condition No. 2 at a given reagent concentration. The two-stage filtration process provides lower filter cake moisture compared to the one-stage vacuum alone technique. At 30 psi (~2 bar) pressure, the tests without reagents, with CPCL and cationic flocculant provide cake moisture values of 30.5%, 27.2% and 23.5%, respectively.

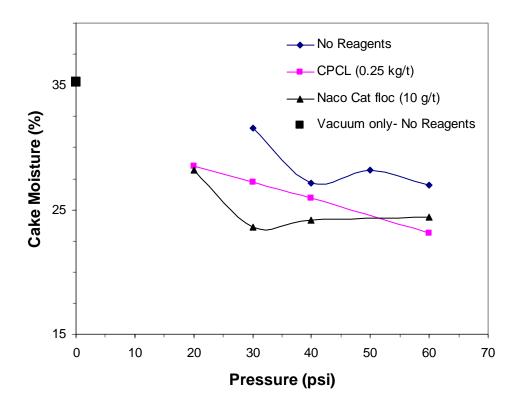


Figure 4.27. Effect of reagents and pressure on the cake moisture for Cooke & Sons clean coal product; vacuum for cake formation and pressure for cake drying.

Figure 4.28 shows the effect of pressure variations on the filter cake moisture for a 10 mm thick filter cake using a low pressure 20 psi (~1.4 bar) for cake formation in Phase 1 at a given reagent concentration. At an applied pressure of 30 psi (~ 2 bar) in the second phase, the filter cake moisture obtained without the addition of reagent was 23.8%. At the same pressure, the addition of 0.25 kg/t of cationic surfactant (CPCL) reduced the moisture by 1.6 absolute percentage points

whereas 10 g/t of a cationic flocculant provided a decrease of 3.3 percentage points. The lowest cake moisture value of 18.5% was obtained using 0.25 kg/t of CPCL at 60 psi (~4 bar) pressure.

The two stage results indicate that using a two phase approach incorporating high and low pressure stages provided lower cake moisture values compared to those achieved by a combination of vacuum and pressure.

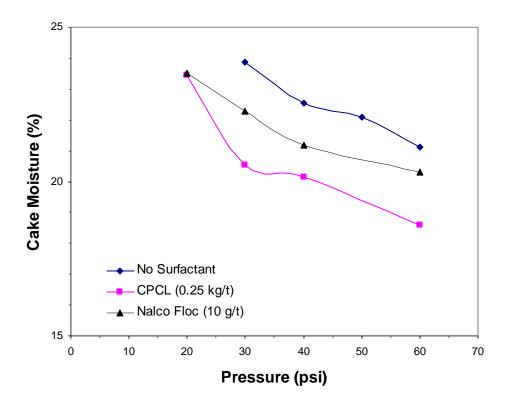


Figure 4.28. Effect of reagents and second stage pressure on the cake moisture for Cooke & Sons clean coal product; low pressure (20 psi) for cake formation.

4.6 Conclusions

4.6.1 Dewatering without Additives

The baseline vacuum dewatering tests conducted on the Cooke & Sons and James River Jameson cell products using 60 seconds cake drying time provided a filter cake with about 24% and 33% moisture, respectively.

The baseline pressure filter dewatering data indicated that, using 60 psi (~4 bar) pressure and 90 seconds filtration time, a filter cake with about 17% moisture can be obtained for the Cooke & Sons Jameson cell product, which was about 7 absolute percentage points lower that that obtained with vacuum filtration.

Using a two phase filtration process incorporating vacuum for cake formation and 60 psi (~4 bar) pressure for cake drying, a filter cake moisture of 26% was obtained for the James River Jameson cell product, which was about 7 absolute percentage points lower than that obtained with vacuum alone.

Using a combination of a low pressure for cake formation and a high pressure for a total 90 sec filtration time provided a filter cake with about 21.5% moisture, which was $\sim 11.5\%$ absolute lower than that obtained with vacuum alone.

4.6.2 Dewatering with Additives

Cationic (CPCL) and nonionic (Triton X114) were marginally effective in lowering the cake moisture formed from the Cooke & Sons slurry from 23% to 21%. For the James River product, the moisture reduction was from 34% to 29%. The anionic surfactant (NAS 08) was not effective in reducing the filter cake moisture.

• For the Cooke & Sons slurry, the addition of 20 g/t of anionic flocculant lowered filter cake moisture from 24% to 20% using vacuum filtration and lowered the cake formation time from 25 sec to 17 sec. Similarly, 20 g/t of the cationic flocculant decreased the filter cake moisture from 24% to 20% and decreased the cake formation time from 25 to 17

sec. For the James River Coal slurry, the addition of 15 g/t of either the anionic and cationic flocculant lowered the filter cake moisture from 34% to about 31% and cake formation time from 57 sec to 22 sec.

• The addition of 5 ml of oil-water emulsion, prepared by using 2% fuel oil and 1% CPCL, reduced the moisture content of the Cooke & Sons coal slurry from 24% to 19%. Similarly, the moisture content of the James River coal slurry was reduced from 36% to 25% with the addition of 7.5 ml oil-water emulsion. These results indicated that the presence of a greater amount of emulsifier improves the emulsification and the adsorption of the emulsion on the particles.

Using 50 psi (~ 3.4 bar) pressure and 0.25 kg/t of CPCL provided filter cake with about 15% moisture.

• A two-stage filtration system (vacuum for cake formation and pressure for cake drying), provided lower filter cake moisture compared to the one-stage vacuum alone. Using 30 psi (~2 bar) pressure during the drying cycle the filter cake moisture obtained without reagents, with the CPCL, and the cationic flocculant were 30.5%, 27.2% and 23.5%, respectively

A two stage pressure filtration system, a low pressure (20 psi or 1.4 bar) for cake formation and high (30 psi or~2 bar) pressure for cake drying showed that the filter cake moisture obtained without reagents, with the CPCL and the cationic flocculant were 23.8 %, 22.2% and 20.5%, respectively. A lowest cake moisture of 18.5% was obtained using 60 psi (~4 bar) pressure in presence of 0.25 kg/t of the CPCL.

4.6.3 Addition of Saw Dust

• The addition of 'as received' saw dust to the fine coal slurry did not improve the filtration rate and cake moisture content, however, it increased the moisture content of the cake.

The saw dust coated with fuel oil and asphalt also increased the cake moisture content and cake formation time.

4.6.4 Addition of Binders

• The addition of binders REAX-SN and Genvis-600 sharply increased the moisture content of the cake. However, the addition of binders Kalona (2 kg/) and Gaur gum (0.125 kg/t) reduced the cake moisture content achieved by vacuum filtration from 35% to 28% and 30%, respectively. An absolute 5% to 7% reduction in the cake moisture.

5. LABORATORY BRIQUETTING STUDIES

5.1 Goal and Objectives

The goal of the project was to produce a premium fuel from two waste materials. The method employed was to reconstitute clean coal recovered from a fine waste stream with saw dust using a briquetting process. It was hypothesized that the lignin in the wood may allow briquetting without the use of a binder. As such the objectives in this task were i) to evaluate the potential of binderless briquetting with saw dust, ii) to identify a binder(s) that may provide economical briquetting if the binderless option proves unfeasible, iii) to optimize the binder concentration based on briquette characteristics such as compressive strength and weathering and iv) to determine the allowable amount of sawdust that can be used in the briquette.

5.2. Procedures

5.2.1. Briquettes Formation and Curing

A common difficulty when comparing binders or briquetting parameters is an inability to maintain a constant or repeatable set of conditions during the study, particularly if test results are being collected over a period of months or years. Variations in any of a number of parameters can lead to significant scatter which in turn, lessens the reliability of and the confidence one can place in the results. Among the parameters with which to be concerned during a comparative briquetting study are the surface oxidation and/or moisture loss from the feedstock materials; variability in the briquetting pressure or dwell time, variation in briquette weights; fluctuations in temperature and humidity during curing; inhomogeneities in the master samples of coal or sawdust; the speed at which briquettes are crushed for compressive-strength determinations; and inconsistent mixing of the fine coal, sawdust, and binder blends. The impact on test results from uncontrolled variations of these parameters can be of such a magnitude as to easily mask differences in binder performance. Accordingly, a number of precautions were taken throughout the study to minimize the impact of such variations.

Each large-scale sample of coal or sawdust that was used during the study was first manually mixed on a plastic-lined concrete pad, coned and quartered, passed through a mechanical splitter,

sealed in one-liter containers, and then frozen. Each blend of sawdust, coal, and binder was prepared by weighing each component into a 2-liter stainless-steel mixing bowl and then blending for the same amount of time at the same blender speed. An automated hydraulic press (Carver presses) with selectable dwell times and briquetting pressures (100 lbs) was used to press briquettes from 17.0 g of each feedstock blend in a 1.125-inch diameter cylindrical die. With a 1.125-inch diameter die (~one square inch surface area), pounds of force essentially equates to psi. A photograph of the Carver Press is shown in Figure 5.1.

While this method of making briquettes is slow and labor intensive, it provides for tighter control of the briquetting parameters than can be obtained with a continuous briquetter. Disadvantages are that the dynamics of briquette formation and the briquette shape differ from those of a continuous, roller-type briquetter. For the purposes of comparing binder performances, it was assumed that the relative binder performance would follow the same order for briquettes that are formed one-by-one in a cylindrical die as they would for briquettes formed in a continuous roller and that the ability to maintain a more stringent control of briquetting conditions more than offset any disadvantages. However, it should be noted that this only an assumption and may not hold for binders that are activated by the heat of compression imparted by a continuous briquetter.

A standard set of briquetting conditions was used throughout the laboratory-scale binder evaluations unless otherwise noted. These include a sawdust addition rate of 10 weight per cent (10% of the dry coal weight), a binder-addition rate of \$8/ton of briquetted product, 17.0 ± 0.05 g of coal/sawdust blend per briquette, a 4,000 lbs briquetting force, and a three-second dwell time.

To ensure that the conditions under which the briquettes were cured were tightly controlled, each set of briquettes was placed into a Caron Model 6010 environmental chamber at a constant temperature and relative humidity until tested (Figure 5.2). For the majority of the project, briquettes were cured at a temperature of 22.2°C (72°F) and relative humidity of 80%. However, the relative humidity was increased to 90% in the latter portions of the study in which the briquettes were subjected to a more extensive set of physical tests as it was felt this would more realistically simulate stockpile conditions.



Figure 5.1. Automated hydraulic press used to form briquettes.



Figure 5.2. Environmental chamber for controlling temperature and humidity during briquette curing.

5.2.2. Briquette Testing

Compressive strengths were determined with a Mark 10 Model EG-200 compressive-strength meter, equipped with a one-inch diameter disk and mounted to an automated Chatillon TCM 201 test stand (Figure 5.3). Compressive-strength measurements were made at a constant compression speed of one-inch/minute along the same axis as used to apply force during briquette formation (flat side). The reported values represent the average of five determinations and were normally conducted at 30 minutes, 24 hours, and seven days after the briquettes were formed. In a set of preliminary screening studies, briquette compressive strengths were used to identify the more promising binders for more extensive evaluations. These additional physical tests included measurement of water resistance, shatter resistance and attrition and were conducted on briquettes that had been cured in the environmental chamber for seven days.

Water resistance testing entailed recording the weight of four briquettes and then submerging the briquettes in water for 8 hours. Following submersion, the physical condition of the briquettes was classified as intact, partially disintegrated, or fully disintegrated. If still intact, the briquettes were removed from the water, reweighed to determine water uptake, cured overnight in the environmental chamber, and crushed the following morning to determine the post-submersion compressive strengths. Briquettes for which compressive-strength values are shown in this report are those which survived the water submersion step and are thus considered to be water resistant

Attrition indices were determined by first recording the weight of 7-8 briquettes (~100 g), placing the briquettes into a 12-inch diameter Plexiglas cylinder that was equipped with three, two-inch lifters, tumbling the briquettes for five minutes at 40 rpm, and then screening the sample through a 50 mesh screen. The attrition index was reported as the per cent of the briquette weight retained by the 50-mesh screen.

Shatter resistance was reported as the average number of drops to failure for four briquettes dropped from a height of 18 inches onto a steel plate. Higher test values equated to better performance for all four of the physical tests described above.



Figure 5.3. Compressive meter and test stand used to determine compressive strengths.

5.3. Preliminary Studies

5.3.1. Binderless Briquetting

The first in a series of *scoping* studies was an attempt to produce acceptable briquettes from preparation-plant fines without the use of a binder as has been reported for lower-rank coal fines.¹ Briquettes were prepared from blends of JR1 coal and Gaye Brothers sawdust (10%) at briquetting forces of 4,000, 10,000 and 20,000 lb_f. This approach generated briquettes with 7-day compressive strengths of 8, 31, and 43 lb_f for the three briquetting forces, respectively. While the strengths obtained at 10,000 and 20,000 lb_f were a significant improvement over that obtained at 4,000 lb_f, the strengths obtained at the higher pressures were still inadequate, the briquettes formed were highly friable, and the use of such high pressures during briquetting would increase both capital and energy costs while slowing plant throughput. This line of research was not pursued further.

5.3.2. Sawdust Particle Size

A sawdust particle-size study was initiated early in the project after it was observed that many of the briquettes containing the circular-saw sawdust (larger particle size) tended to form horizontal cracks as they cured, resulting in lower cured strengths. The larger-sized sawdust particles were suspected as being responsible for these defects. To test this hypothesis, a sample of the Gaye Brothers sawdust was screened into four particle-size fractions; +16, 16 x 20, 20 x 30, and -30 mesh. Using an asphaltic emulsion as binder (5%), these size fractions were blended with the JR1 fine coal and pressed into briquettes. This study revealed an inverse relation between compressive strength and the sawdust particle size. For example, the seven-day strengths were determined to be 23, 28, 39, and 82 lb_f for briquettes prepared with the +16, 16 x 20, 20 x 30, and -30 mesh saw dust samples, respectively. Green strength and one-day strength values exhibited similar trends. Visual inspections of the briquettes showed a clear decrease in the extent of the horizontal cracks in briquettes formed with smaller size sawdust particles (Figure 5.4) prompting a switch to smaller-sized, band-saw saw dust samples for most subsequent studies (H&S oak and H&S poplar).



Figure 5.4. Briquettes formed with different particle-size sawdust showing increased cracking with larger sawdust particles (l-r, +16, 16 x 20, 20 x 30, and -30 mesh).

5.3.3 Binder Screening Studies

5.3.3.1 Binder Addition (5% Concentration by Weight)

The initial binder comparisons were conducted to refine our procedures and to reduce the large quantity of potential binders identified at the beginning of the study to a more manageable number. For this evaluation, briquettes were prepared from each of the approximately 50 potential binders by blending with the JRI coal and the Gaye Brothers sawdust. All briquettes were prepared under the same conditions and using the same proportions of coal, sawdust (10%), binder (5%), and water (5%, note-water was added to facilitate binder dispersion). A Kitchen-Aide blender was used to mix the components and sixteen briquettes were prepared from each blend by weighing 17 ± 0.05 g to a 1.125-inch cylindrical die and applying 4,000 lbs pressure for three seconds. Average green and cured compressive strengths were then determined on briquettes that were crushed at 30 minutes, at 24 hours, and at seven-days following preparation. The 24-hour and seven-day briquettes were stored at 22.2 °C (72 °F) and 80% relative humidity until crushed.

The results from the initial binder investigation are shown in Table 5.1. These data represent the average strength of five briquettes and reveal a wide range in performance. In some instances, the compressive strengths were no better (and sometimes worse) than measured for the control briquettes in which no binder was added (10% sawdust, 5% water only). In two instances (Guar gum and WS700), the seven-day briquette strengths exceeded 200 lb_f. The better-performing binders are shown in bold in Table 5.1 and include softwood pulp, spring wheat, wheat flour, wheat starch, corn starch, and an asphalt emulsion with two per cent lime. Those formulations that did not provide improvement in compressive strength relative to the control briquettes (~30 psi green strength, 40 psi one-day strength, or 50 psi seven-day) were eliminated from further consideration. This screening approach eliminated approximately 20 of the potential binder formulations.

Table 5.1. Compressive strengths of briquettes made with 5 wt% binder blended with JR1 coal and 10 wt% Gaye Bros. sawdust.

Binder	Lb_{f}						
Туре	Green Strength	1-day Strength	7-day Strength				
Control-5% water	27	15	9				
Polybond 300G	22	19	26				
Polybond	20	20	17				
CLC-3	25	15	11				
Sodium Silicate	27	46	44				
Reax SA	27	28	38				
Coal Tar	27	15	34				
So. Bentonite	19	13	10				
Western Bentonite	20	30	32				
Reax SN	24	19	88				
DK 19	16	16	25				
Phenolic Resin	24	14	11				
CORN OIL	10	9	9				
Mineral Oil	10	7	8				
Cola Syrup	15	17	13				
HFMS Asphalt	24	11	12				
Black-strap molasses	23	19	20				
Brewex	22	14	21				
Hardwood pulp	50	21	30				
• • •							
Tall Oil Pitch	34 24	17 22	24				
Lavabond			38				
Gilsonite	20	12	13				
Guar gum	38	68	200				
Softwood pulp	91	88	101				
Paper Sludge	32	22	14				
Boric Acid	23	14	9				
Peridur 300	19	12	118				
Peridur 330	20	15	29				
CaFormate	32	23	11				
Quicklime	24	18	22				
Lime kiln dust	23	14	19				
Slackwax	24	13	12				
Petroleum waste	25	10	12				
Cob flour	8	5	4				
Control-repeat	20	7	7				
PVA	6	3	5				
Wheat flour	24	34	59				
Wheat flour-polymer	30	48	141				
SS-1H asphalt	32	18	31				
RS-asphalt	25	19	17				
Spring wheat	39	55	173				
SS-1H Asphalt/ Lime	47	37	73				
SS-1H Asphalt/ Lime	48	43	57				
Promo1	18	15	16				
Promo2	19	12	17				
Wheat starch 6	45	50	144				
Wheat starch 7	23 56	38 93	200+				

5.3.3.2 Addition of Binders on an Equivalent-Cost Basis

An effort to identify the more cost/performance-effective binders was conducted for the approximately 30 materials that remained following the preliminary screening study. Compressive strengths were again used as a screening tool as time did not permit for an extensive study of each formulation. The objective here was to eliminate a number of binders that did not significantly improve briquette strength so that the more remaining materials could be subjected to a more rigorous evaluation. Further since in a commercial operation, binder selection will ultimately be based on cost versus performance, the binders were compared by adding each to the coal fines/sawdust blends on an equivalent-cost basis of \$8/ton of briquetted product. To calculate the equivalent-cost application rate, a market price for each binder was obtained to which was added \$25/ton for estimated delivery costs. While this simple approach is crude at best as it does not consider a number of potentially significant variables, e.g., market-price fluctuations, differences in the delivery costs between binders, or differences in the cost of the application equipment for different binders, it nonetheless provides a reasonable starting-point approximation.

The \$8/ton binder application rate that was selected was somewhat arbitrary but thought to be near a break-even point for a commercial operation and yet high enough as to make differences in briquette performance more easily discerned. Briquetting conditions of 2-tons pressure, 3-sec dwell time, and 5% moisture again were used to make briquettes from blends of the JR1 coal fines and Gaye Brothers sawdust (10 wt%) for this round of testing. Results are shown in Table 5.2 and reveal that while no single binder provided both the highest green- and seven-day strengths, some of the materials tested did perform well at all three time intervals at which the briquettes were crushed. These materials were selected for more extensive testing.

5.3.4 Lime-Addition Studies

A second round of binder comparisons was conducted, only this time with a focus on determining the impact of adding slaked lime (calcium hydroxide) to the coal/sawdust blends. Lime is a commonly used additive for agglomeration in a number of industries, including the agglomeration of coal fines, as it is relatively inexpensive and generally improves the

Table 5.2. Compressive strengths of briquettes prepared with an \$8/ton binder-application rate. Briquettes prepared at 4000psi, 3-s dwell time with JR1 coal and Gaye Bros. sawdust (10 wt%).

Binder	Binder Wt %	Green Strength (lb _f)	1-day Strength (lb _f)	7-day Strength (lb _f)
Peridur 300	0.4	34.3	35.7	180.4
Western Bentonite	6.7	34.5	35.1	70.9
Wheat Flour, Wal-Mart	3.4	39.2	37.8	126.1
Spring Wheat Flour	7.2	42.6	42.5	161.3
Lavabond	6.7	30.5	40.0	71.0
Corn Starch	2.9	39.0	51.0	121.2
Black Strap Molasses	6.4	33.1	37.0	49.9
Coal Loading Tar	5.0	43.4	39.9	73.6
Paper Sludge	17.8	41.0	29.2	33.8
Lime	8.0	45.6	32.6	67.1
RS-2	4.8	32.8	22.6	23.2
Sodium Silicate	8.0	31.3	68.9	73.6
Polybond 300G	6.2	30.2	33.7	55.4
Polybond	9.4	25.7	34.1	45.9
Guar Gum	1.0	43.7	70.4	142.9
Bleached Softwood pulp	1.5	54.6	35.8	34.4
Brewex	17.8	41.4	40.7	73.9
Wheat starch 7	1.0	35.6	37.6	93.2
Wheat starch 6	2.9	45.2	53.6	141.3
Reax	4.8	31.5	34.5	61.1
Cola Syrup	12.3	33.0	28.5	
Asphalt-SS	4.8	39.2	31.1	
Asphalt-MS	4.8	29.6	26.9	
No binder (Control)	0.0	30.9	19.3	

agglomerate properties, particularly green strength. However, lime alone, even when added at relatively high concentrations, does not produce coal briquettes that can withstand the rigors of shipping and handling. Further, depending on the ash composition of the coal and the design and operation of the combustion boiler, lime may enhance slagging and fouling in some pulverized coal boilers when present at higher concentrations due to the lowering of the ash-fusion temperature for some coals. On the other hand, lime can significantly enhance the performance of some binders resulting in better briquettes at a lower cost. Lime addition can also be attractive in certain applications such as in slagging boilers, where a lower ash fusion temperature is desirable, for SO₂ capture in fluidized-bed boilers, or in some stoker boilers where the briquette integrity is more critical than the ash content of the fuel.

The evaluation of lime addition was conducted with blends of binder (\$8/ton briquettes), H&S oak sawdust (10 wt%), and Cooke & Sons coal. Two tons briquetting pressure and a 3-sec dwell time were again employed. In an effort to more clearly determine the impact of lime addition, each blend was first split into two portions with one split briquetted without lime and the second being briquetted after the addition of two weight per cent lime. A comparison of briquettes prepared with and without lime thus permitted for a direct measure of the impact of lime addition on briquette strength.

Results for selected binders, with and without added lime, are shown in Table 5.3. The better-performing formulations are shown highlighted. As can be seen, briquettes containing lime generally exhibited higher green strengths than briquettes prepared without lime from otherwise identical blends. Further, while results with the Cooke & Sons coal did not precisely track those obtained earlier with the JR1 coal (Table 5.1), the best results without lime for both coals were obtained for guar gum and the starch-based binders. For those briquettes prepared with lime, the performance of guar gum and starch generally declined while the performance for molasses, paper sludge, and the three REAX binders exhibited notable improvements in strength.

5.4 Selection and Evaluation of the Most Cost-Effective Binder Formulations

Based on the compressive-strength data as shown in the previous sections, the potential binder list was narrowed to a more manageable number of approximately 10 materials. Briquettes were prepared with these formulations for more extensive testing with the aim of identifying 1) the most effective lime-containing formulation for stoker or fluidized-bed applications and 2) the most effective combustible binder, targeted for pulverized-coal boilers.

Briquettes were again prepared at 4,000 lbs force, 3-sec dwell time, 10% sawdust, and \$8/ton binder application rate using the cleaned JR2 coal and H&S oak. In addition to repeating the

Table 5.3. Comparison of compressive strengths (Lb_f) for briquettes prepared with and without 2wt% lime. (\$8/ton binder application rate, Cooke & Sons coal, and 10% H&S oak sawdust.)

Binder	Binder		No Lime			2% Lime	
Туре	Weight (%)	Green Strength	1-day Strength	7-day Strength	Green Strength	1-day Strength	7-day Strength
Wheat starch 7	1.01	21.0	25.0	81.6	29.8	30.8	68.1
Wheat starch 6	2.90	31.3	43.8	203.5	43.8	44.3	129.8
Polybond	9.40	15.2	20.6	29.5	37.0	46.4	48.2
Paper Sludge	17.89	27.6	33.0	42.0	49.0	55.4	99.7
REAX-N-EF	4.32	22.1	25.4	105.3	36.0	49.4	200.0
REAX-N-DK	4.28	20.8	27.5	43.3	32.6	41.6	111.3
REAX-A	4.95	23.0	27.9	49.4	39.6	48.0	118.1
Peridur300	0.42	23.1	23.8	88.6	27.8	20.4	43.4
Peridur330	0.51	21.0	22.2	129.0	26.4	18.2	46.6
Black Strap Molasses	6.64	20.9	23.6	28.2	44.7	51.6	90.0
Black Strap Molrepeat w/lime	6.38				47.0	60.8	108.9
Peridur300-repeat	0.41	22.5	18.2	61.7	29.1	18.2	46.7
Brewex	17.75	26.2	27.6	49.5	29.6	33.6	106.3
Ashalt-MS	4.83	27.5	20.6	23.8	37.9	38.9	61.2
Hardwood Pulp	1.94	26.1	19.3	19.1	36.9	34.4	62.7
Softwood Pulp	1.52	34.6	22.5	27.8	47.4	56.4	80.0
Guar gum	1.00	26.8	23.8	172.2	30.6	21.1	55.6
Coal Tar	5.11	23.0	17.2	36.7	27.9	26.0	77.2
SS-1 asphalt emulsion	4.78	28.7	21.5	25.9	37.6	35.5	68.4
RS-2 asphalt emulsion	4.84	25.2	16.5	19.4	30.0	31.7	46.6
Corn starch-polymerized	2.90	36.8	43.8	105.7	50.5	50.2	98.1
Corn starch-unpolymerized	2.90	29.9	24.7	28.2	38.0	32.0	78.3
Slack wax (212)	2.10	32.6	27.2	25.0	45.9	47.1	60.3
Phenolic resin-unheated	0.80	21.8	13.2	17.3	31.1	33.1	61.1
Cola syrup	10.8	21.0	21.5	29.2	34.0	33.4	62.5
Polybond 300G	6.20	20.8	23.9	12.2	39.3	43.6	53.9
Promo-1	5.00	19.7	16.2	19.9	23.5	37.6	51.3
Wheat flour-Walmart	3.12	32.2	38.8	153.1	40.4	43.1	100.2
Wheat flour-High gluten	2.89	38.0	49.8	201.0	39.5	41.8	126.6
Wheat flour-High starch	2.89	33.2	38.8	167.4	37.3	32.8	119.9
Tall Oil	2.50	25.4	18.4	19.1	41.2	42.6	70.6
No binder (control)	0.00	24.3	12.0	15.3	31.3	28.0	56.2

compressive strength measurements, tests of shatter resistance, water resistance, and attrition indices were conducted for briquettes formed with the selected formulations following a sevenday cure in an environmental chamber (22.2°C and 80% relative humidity). For all physical tests, higher test values equated to better performance.

The results for these tests are shown in Table 5.4 and indicate that guar gum and the wheat starch binders (Hi-gluten and wheat starch 6) binders provided the best overall performance for the combustible-binder formulations. Likewise, the Reax (sodium lignosulfonate) was identified as the most effective of the lime-containing formulations.

Table 5.4. Physical properties of briquettes prepared with various binders, with and without added lime. All briquettes prepared with JR 2 coal; 10% H&S sawdust, 4000 lbs force, and a 3-sec dwell time.

Binder Type	Binder Wt %	Green Strength	1-day Strength	7-day Strength	Drop Test #drops	H20 resist (lb _f CS)	Attrition Index
Black Strap Molasses*	6.70	91.7	102.4	174.9	17.8	Disintegrated	55.5
Hi-Gluten Wheat Flour	2.90	64.7	78.4	>200	46.8	24.1	67.5
Guar Gum	1.00	63.6	86.1	>200	51.3	41.7	81.1
Hi-Starch Wheat Flour	2.89	51.3	61.7	>200	27.3	17.8	56.8
Corn Starch	2.9	50.4	66.2	169.8	24.8	36.8	46.0
Paper Sludge*	17.90	78.4	83.7	135.8	4.3	85.0	36.0
Wheat starch 6	2.90	58.1	N/A	>200			71.7
Control w/ lime only	2.00	57.6	N/A	45.5	1.0	35.9	31.1
Tall Oil Emulsion*	5.3	45.9	38.0	64.4	2.8	42.5	34.1
Molasses*	5.7	55.9	71.4	151.5	9.0	disengrated	55.2
Reax*	4.3	43.7	89.0	>220	>100	disengrated	91.1
Reax & ASPHALT*	2.5&1.2	59.6	87.5	195.2	28.0	58.2	50.4

^{*}contains 2% slaked lime

5.5 Evaluation of Selected Briquetting Parameters

Using the three formulations that were identified as the most effective binders for the briquetting of fine-coal/sawdust blends (REAX, guar gum, and starch), a series of experiments was carried out to evaluate the impact of a number of briquetting parameters. The parameters investigated included binder concentration, sawdust concentration, sawdust particle size, briquetting pressure and dwell time, moisture content, cure temperature, and wood species. A full matrix evaluation

for this number of variables would have required a prohibitive number of tests. Instead, tests were conducted using a standard set of conditions with only one of the parameters varied for a given set of experiments. The JR2 coal and H&S oak were used for all tests using the standard conditions of an \$8/ton binder application rate, 10% sawdust, a -3/8-inch sawdust particle size, 5% added water, 4,000 lbs briquetting force, 3-sec dwell time, and 22.2 °C cure temperature. Two weight% lime was added to those briquettes in which Reax (lignosulfonate) was used as a binder but not to those briquettes prepared with guar gum or wheat starch (Genvis).

5.5.1 Binder Concentration

Table 5.5 shows the briquette performance when binders were applied at concentrations equating to \$2, \$4, \$6, or \$8 per ton of product. As expected, briquette performance improved at higher application rates for all three binders.

Table 5.5. Variation of binder addition rate (\$2, \$4, \$6, and \$8/ton application rates). All briquettes were prepared with JR 2 coal; 4000 lbs force; 3-s dwell, 10% sawdust, and 22.2 °C cure temperature.

Binder	Binder Wt %	Green Strength	1-day Strength	7-day Strength	Drop Test #drops	H20 resist (lbf CS)	Attrition Index
Guar Gum	0.25	47.7		98.8	2.8	23.1	32.1
Guar Gum	0.50	60.8		190.0	7.5	31.8	47.7
Guar Gum	0.75	58.8		>200	20.0	45.9	55.7
Guar Gum	1.00	63.6	86.1	>200	51.3	41.7	81.1
Wheat starch 6	0.75	42.3	41.9	55.8	2.0	disengrated	24.3
Wheat starch 6	1.50	42.8	44.3	95.0	4.0	disengrated	36.2
Wheat starch 6	2.20	50.2	67.0	157.0	11.0	disengrated	51.1
Wheat starch 6	2.90	64.8		>200	40.0		73.9
Reax w/2% lime	1.10	48.2	66.5	127.8	7.3	29.2	37.0
Reax w/2% lime	2.10	55.0	71.1	164.3	14.8	39.5	45.3
Reax w/2% lime	3.25	57.7	95.9	>200	27.5	Partial disint	54.4
Reax w/2% lime	4.30	43.7	89.0	>200	>100	disengrated	91.1

This was particularly notable for the shatter resistance, attrition indices, and the 7-day compressive strengths which exhibited steady and substantial improvements as a function of binder concentration. On the other hand, little or no differences were noted in the green strength or water resistance as binder concentration was varied. In fact, the briquettes formed with REAX, which also contained a constant two weight-per-cent lime, showed better water resistance at the lower REAX-application rates. This latter is attributed to the water solubility of REAX with the favorable property of water resistance apparently conveyed by the constant amount of lime being added as the Reax concentration was varied.

5.5.2 Sawdust Concentration

The impact of sawdust concentration was evaluated by adding sawdust to the fine coal at 0, 5, 10, or 25 per cent by weight (Table 5.6). Both green and one-day strengths, water and shatter resistance, and attrition indices declined significantly with increasing sawdust concentration for both guar gum and wheat starch. On the other hand, sawdust concentration had little impact on the compressive strengths of the briquettes containing the REAX/lime binder. The briquettes formed with Reax also exhibited excellent shatter resistance, attrition indices, and, to some extent, water resistance up to approximately 10% sawdust addition but declined substantially at the higher 25% addition level. These results suggest that guar gum and starch may provide better briquettes when little of no sawdust is blended with the coal fines but that REAX may be preferable at higher rates of sawdust addition.

5.5.3 Sawdust Particle Size

The impact of the sawdust particle size was evaluated in briquettes formed from fine coal and 10-weight % sawdust in which the sawdust was added as a minus 3/8-inch, a -20 mesh, a -30 mesh, or a 20 x 30 mesh size fraction (Table 5.7). Some improvement was noted in the green and one-day compressive strength tests for guar gum and REAX in briquettes prepared with the 20 x 30 mesh sawdust. Otherwise, there were little or no clear trends in briquette performance as a function of the sawdust particle size over the range evaluated. It should be noted that the H&S oak sawdust used in this study was generated in a band-saw mill as opposed to the circular-saw sawdust described in the sawdust particle-size study earlier in this report. The larger-particle-

size sawdust used in the earlier study likely explains the discrepancies between results from that study and the results that are shown here for the smaller particle-size H&S sawdust.

Table 5.6. Variation of sawdust concentration (0, 5, 10, & 25 wt% addition rates).

Binder ID	Green Strength	1-day Strength	7-day Strength	Drop Test #drops	H20 resist (lb _f CS)	Attrition Index	Sawdust (%)
Guar Gum	110.1	192.3	>200	88.0	120	83.2	0%
Guar Gum	72.6	147.5	>200	40.3	41	64.7	5%
Guar Gum	63.6	86.1	>200	51.3	42	81.1	10%
Guar Gum	60.0	68.7	>200	23.3	20	65.8	25%
Wheat starch 6	117.3	169.3	>220	>100	85	93.2	0%
Wheat starch 6	84.6	122.8	>220	83.8	56	92.2	5%
Wheat starch 6	64.8	N/A	>200	40.0	n/a	73.9	10%
Wheat starch 6	60.7	77.8	>220	17.5	disntgrted	68.1	25%
Reax w/2% lime	53.9	88.1	>220	>100	115	93.9	0%
Reax w/2% lime	54.2	91.2	>220	>100	120	92.1	5%
Reax w/2% lime	43.7	89.0	>220	>100	disntgrted	91.1	10%
Reax w/2% lime	59.2	95.5	>183.5	10.5	disntgrted	48.5	25%

Table 5.7. Variation of sawdust particle size (10% addition rate).

Binder	Binder Wt %	Green Strength	1-day Strength	7-day Strength	Drop Test #drops	H20 resist (lbf CS)	Attrition Index	Sawdust Part Size
Guar Gum	1.0	63.6	86.1	>200	51.3	41.7	81.1	As rec'd*
Guar gum	1.0	55.8	96.6	>220	35.5	28.8	62.5	-20 mesh
Guar Gum	1.0	59.3	93.7	>220	52.0	38.9	78.2	-30 mesh
Guar Gum	1.0	75.2	104.8	>220				20x30 mesh
Wheat starch 6	2.9	64.8	N/A	>200	40.0	n/a	73.9	As rec'd
Wheat starch 6	2.9	53.9	69.0	>220	20.3	Partial disint	61.4	-20 mesh
Wheat starch 6	2.9	49.0	63.7	216	22.5	Partial disint	59.9	-30 mesh
Wheat starch 6	2.9	35.6	58.4	>220				20x30 mesh
Reax w/2% lime	4.3	43.7	89.0	>200	>100	disengrated	91.1	As rec'd
Reax w/2% lime	4.3	49.2	83.2	>220	>100	84.5	88.3	-20 mesh
Reax w/2% lime	4.3	47.0	78.2	>220	>100	70.8	87.9	-30 mesh
Reax w/2% lime	4.3	66.0	92.7	>220				20x30 mesh

*As rec'd equates to -6 mesh

5.5.4 Briquetting Force and Dwell Time

The impacts of the force applied during briquetting (2,000, 4,000, and 10,000 lbs) and the time over which the applied force was maintained (dwell time; 1, 3, and 8 sec) are shown in Tables 5.8 and 5.9, respectively. Relatively minor improvements in green and cured compressive strengths were noted for the briquettes as a function of higher briquetting pressures. Otherwise, the impact of this parameter on the briquette properties was minimal. Likewise, little or no

Table 5.8. Variation of briquetting force (2,000, 4,000, and 10,000 psi).

Binder	Green Strength	1-day Strength	7-day Strength	Drop Test #drops	H20 resist (lb _f CS)	Attrition Index	Briquetting force (x 1000 psi)
Guar Gum	45.5	71.6	>200	57.25	32.70	79.43	2
Guar Gum	63.6	86.1	>200	51.25	41.70	81.06	4
Guar Gum	58.9	69.1	>200	62.00	38.80	78.88	10
Wheat starch 6	44.5	63.1	>220	43.75		68.90	2
Wheat starch 6	58.1	N/A	>200			71.71	4
Wheat starch 6	64.8	N/A	>200	40.00	n/a	73.92	4
Wheat starch 6	84.2	110.3	>220	40.50		75.88	10
Reax w/2% lime	40.3	77.2	>220				2
Reax w/2% lime	43.7	89.0	>220	>100	disengrated	91.10	4
Reax w/2% lime	47.0	92.7	>220				10

Table 5.9. Variation of briquetting dwell time (1, 3, and 8 sec).

Binder	Binder	Green	1-day	7-day	Drop Test	H20 resist	Attrition	Dwell
	Wt %	Strength	Strength	Strength	#drops	(lbf CS)	Index	Time
Guar Gum	1.0	60.1	93.6	>220	54.8	49.2	72.71	1 sec
Guar Gum	1.0	63.6	86.1	>200	51.3	41.7	81.06	3 sec
Guar Gum	1.0	60.4	94.2	>220	54.3	51.3	79.36	8 sec
Wheat starch 6	2.9	50.6	59.2	>220	36.3	33.9	64.38	1 sec
Wheat starch 6	2.9	58.1	N/A	>200			71.71	3 sec
Wheat starch 6	2.9	64.8	N/A	>200	40.0	n/a	73.92	3 sec
Wheat starch 6	2.9	52.2	59.3	>220	14.3	29.1	60.88	8 sec
Reax w/2% lime	4.3	40.0	82.4	>220				1 sec
Reax w/2% lime	4.3	43.7	89.0	>220	>100	disengrated	91.10	3 sec
Reax w/2% lime	4.3	43.3	88.1	>220				8 sec

correlation was observed between dwell time and briquette performance. Both of these findings are favorable with respect to commercial operation as they suggest that it should be possible to use a lower energy input and faster roller speeds without a significant sacrifice in briquette quality.

5.5.5 Moisture Content

To evaluate the impact of moisture content, briquettes were prepared from coal/sawdust/binder blends to which either 0, 5, or 10% water was added. The master sample of JR2 coal used for this study had an initial moisture content of 20.7%, meaning that the study was conducted roughly over the range of 20-30% moisture. The dry weight of coal, sawdust, and binder used to form each briquette was held constant by adjusting for the differences in water content between blends. The results for these experiments are shown in Table 5.10.

Table 5.10. Variation of moisture content (0, 5, and 10% added water).

Binder Type	Binder Wt (%)	Green Strength	1-day Strength	7-day Strength	Water Addition (%)
Guar Gum	1.0	53.6	83.3	>220	0%
Guar Gum	1.0	54.4	94.0	>220	5%
Guar Gum	1.0	31.4	47.9	>220	10%
Wheat starch 6	2.9	40.0	53.3	173.8	0%
Wheat starch 6	2.9	53.3	73.6	>220	5%
Wheat starch 6	2.9	60.1	85.4	>220	10%
Reax w/2% lime	4.3	63.6	101.5	153.7	0%
Reax w/2% lime	4.3	43.7	89.0	>220	5%
Reax w/2% lime	4.3	59.4	98.7	166.8	10%

As with variation of dwell time, no clear trends between briquette performance and the initial water content were apparent. The highest compressive strengths were obtained with either 0 or 5% water addition for both guar gum and starch. In contrast, for the REAX binder, five per cent water addition gave the lowest green and one-day compressive strengths but the highest sevenday strengths. While not quantified, we noted throughout the project that some water addition appeared to improve briquette qualities. It was believed that this improvement stemmed from a

more uniform coating of the coal and sawdust particles. Without some water addition, many of the binders, particularly the powdered or viscous-liquid binders, were difficult to disperse leading to an inhomogeneous blend and a non-uniform coating of the coal/sawdust particles. However, when the water content was too high, the excess water was squeezed from the blend during compression. This likely carried away a portion of the binder, particularly the more water soluble binders, leaving behind less binder in the briquette. It should also be noted that briquettes in this study were manually loaded to and formed individually in a cylindrical die. By loading in this manner, excessive water is not a problem. However, excess water is a problem in a continuous briquetter as it leads to bridging and an unsteady feed rate. In the continuous briquetting experiments described later in this report, briquette strengths were found to improve slightly with increasing water content to the point at which the blends began to stick in the hopper and could no longer be fed in a uniform manner. Our conclusion from these as yet to be described continuous-briquetting experiments was that the optimum water content is the maximum at which the blend can be fed at a constant rate and that low moisture content (<10 wt%) is not a prerequisite for producing good briquette properties.

Further, the amount of water content that can be tolerated appears to be a function of the binder as some of the binders evaluated in this study appear to be more tolerant of high moisture levels than others. This is in contrast to the requirement that the coal fines be dried before briquetting, as is the case with asphalt or coal-tar binders, which were the most prevalent binders used for coal briquetting in the early and middle portions of the 20th century.

5.5.6 Cure Temperature

The impact of cure temperature was evaluated by curing briquettes for 30, 60, and 120 minutes at either 50 or at 80° C before crushing (Table 5.11). For comparison, a set of control briquettes prepared at the same time were crushed following a two-hour cure at ambient temperature. The extent of hardening for 30 minutes at 50 °C was not much different than obtained after two hours at ambient temperature. Even the 2-hour cure at 50 °C appears to have had a minimal effect. At 80 °C, some improvement was noted after 30 minutes compared to the control sample. However, the briquettes were fully hardened after two hours at 80 °C and exhibited compressive strengths

comparable to or greater than those of briquettes cured for one week at ambient temperature.

Table 5.11. Compressive strength as a function of cure temperature and time.

Binder Type	Binder Wt %	Cure Temp (deg C)	30-min Strength	1-hour Strength	2-hour Strength	Control (2hr ambient temp Strength)
Guar Gum	1	50	55.9	67.4	86.0	52.8
Wheat starch 6	2.9	50	61.6	65.8	87.6	65.7
Reax w/2% lime	4.3	50	58.8	78.9	102.2	54.0
Guar Gum	1	80	50.3	89.2	>200	52.8
Wheat starch 6	2.9	80	73.8	119.0	>200	65.7
Reax w/2% lime	4.3	80	61.2	87.2	>200	53.5

5.5.7 Sawdust Types

The relation between briquette strength and the species of tree from which the sawdust was derived was examined using eight saw dusts from trees common to East Kentucky. The *pure* saw dusts were produced with a chain saw and screened to -4 mesh. Six of the sawdust samples were collected from a log yard in Breathitt County (Eastern) Kentucky and represented the more commonly harvested tree species in that area (red oak, white oak, poplar, ash, maple, and hickory). The remaining two saw dusts were also collected in Breathitt County from live trees and represented common species that are seldom or never marketed (beech and willow). Each sawdust was screened to -4 mesh prior to use. Briquettes were prepared using 1% guar gum binder with the standard briquetting conditions as before. Compressive strengths were measured at 0.5, 24, 48, and 72 hours after preparation with the results of the strength data and bulk densities shown in Table 12a.

It was not surprising that forming coal/sawdust briquettes with different sawdust types would result in measurable differences in compressive strengths. However, the magnitude of these differences was unexpected. The highest compressive strengths, particularly day two and day three strengths, were obtained with the higher-density red oak, beech, white oak, and hickory saw dusts, relative to the softer and less-dense wood types (poplar, willow, ash, and maple). One

Table 5.12a. The relation between sawdust type and briquette strength.

Wood	SD Bulk	Compressive Strength						
Type	Densities	30 min	1-day	2-day	3-day			
		(Lb_f)	(Lb_f)	(Lb_f)	(Lb_f)			
Beech	0.797	140	182	>220	>220			
Ash	0.694	69	82	147	>220			
Maple	0.694	83	108	167	>220			
Hickory	0.900	108	157	200	>220			
Poplar	0.579	81	127	176	>200			
White Oak	0.878	78	134	>220	>220			
Red Oak	0.893	141	205	>220	>220			
Willow	0.485	53	50	100	169			

Table 5.12b. Briquette strength as a function of sawdust type using saw dusts with equivalent particle-size distributions.

Wood Type	Briquette Height (mm)	Compressive Strength		
		30 min (Lb _f)	1-day (Lb _f)	2-day (Lb _f)
Beech	24.5	161	183	>220
Poplar	24.9	92	115	144
Red Oak	23.0	143	196	>220
Willow	25.1	40	59	100

concern in attributing the observed differences in strength solely to differences in the sawdust type was that the different tree species likely produced saw dusts with different particle size distributions due to inherent differences in hardness between species. In an effort to determine if the observed differences were due to differences in sawdust type instead of sawdust particle size, samples of the two better performing saw dusts (red oak and beech) along with two of the lesser performers (poplar and willow) were screened to the same six particle size ranges. Each size range was then recombined at the same ratios to ensure a more uniform particle-size distribution. The four recombined sawdust samples were then used to form briquettes that were tested for

compressive strength as before (Table 5.12b). The red oak and beech saw dusts again significantly outperformed the willow and poplar saw dusts indicating that the differences in performance for the different sawdust types was related to something other than differences in their particle size distributions.

A reasonable explanation for the observed differences in performance, other than dissimilarities in surface or bulk chemistries, is simply the aforementioned differences in the sawdust densities. It was shown earlier in this report that higher sawdust concentrations were generally detrimental to briquette performance. This correlation was based on a weight relationship for the sawdust but is believed to be more a reflection of the volume of the briquette occupied by the sawdust. Assuming this to be the case and considering that, for a given weight, higher-density saw dusts occupy a lesser volume of the briquette than do the less-dense saw dusts, then the higher density red oak and beech woods would be expected to outperform the lower-density saw dusts as observed. A plot of the one-day strengths as a function of the sawdust bulk density, shown in Figure 5.5, suggests that the briquette strength correlates directly with sawdust density. While it cannot be stated with certainty that the observed differences in strength can be attributed to differences in the sawdust density (instead of the sawdust chemistry), the correlation between sawdust density and briquette strength in Figure 5.5 indicates that the wood density can at least be used as a predictor of briquette strength.

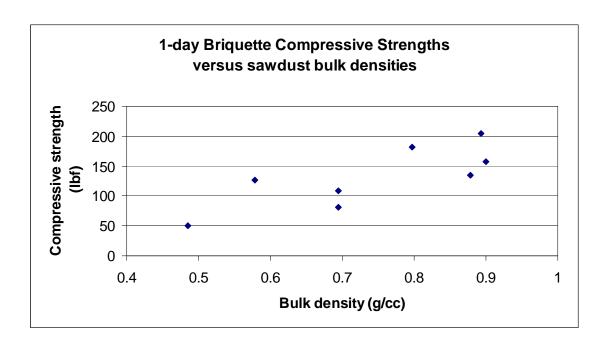


Figure 5.5. The relation between saw dust density and briquette strength in fine coal/sawdust briquettes.

5.5.8 Fine-Coal Ash Content

The pilot-plant phase of the project called for collecting and cleaning a large-scale sample of fines (~3 tons) to be used as the feed to a continuous briquetter. Collecting a large sample from a thickener underflow as originally planned would require a substantial effort in both the field and the laboratory. However, a quicker means to collect a larger fine-coal sample was simply to collect the semi-concentrated froth stream from a commercial flotation unit such as the one at TECO Coal's Clintwood #3 plant. This approach would save considerable time and effort with the only downside being that a relatively high-ash (~14%) fine coal was generated in this unit and might require additional cleaning in the laboratory before use.

Before proceeding with the pilot-plant production runs, an investigation of the impact of using a high-ash fine coal on briquette properties was conducted. A sample of relatively high-ash fine coal was collected from TECO Coal's flotation facility, then split and cleaned to varying ash contents (2.78, 4.66, and 10.4%). Together with the original sample that contained 14.2% ash, this provided four samples with differing ash contents for briquetting. Briquettes were produced

from these samples using one per cent guar gum as binder and the same standard briquetting conditions as before. Briquettes were then subjected to compressive strength, water resistance, and attrition measurements. Briquettes produced with the higher ash samples exhibited better green and one day strengths as well as a higher resistance to attrition. Compressive strengths as a function of ash content are shown in Figure 5.6. While a higher-ash fuel product is not desired, this plot suggests that the recovery and briquetting of a higher-ash fine coal might result in reductions in binder cost and higher fine-coal-recovery rates, thereby potentially improving the overall plant economics.

On the other hand, the higher strengths obtained with the higher-ash fine coals may simply be a reflection of the smaller-volume of the briquettes that were formed with these higher density feedstocks. That is, since a fixed weight of coal/sawdust blend was used to form briquettes in the cylindrical die, a higher density feed blend (higher ash) would result in a smaller briquette, which all else being equal, would be expected to have a higher strength due to its shorter height. If this is the case, then a similar improvement in strength with higher-ash fine coals may not be obtained in a continuous briquetter in which the briquette volume is fixed.

5.6 Compaction of Flotation and Spiral-Product Blends

One of the more significant parameters governing packing efficiency of fine particles is the size distribution of those particles. Improving the packing efficiency of coal and wood waste blends could be of significance during briquetting as it would result in a reduction in void space, potentially producing a stronger briquette with less binder. Further, adjusting the particle size distribution could be easily controlled in a commercial scenario by simply adjusting the proportions of fine flotation coal and coarser spiral product used as the briquetter feedstock.

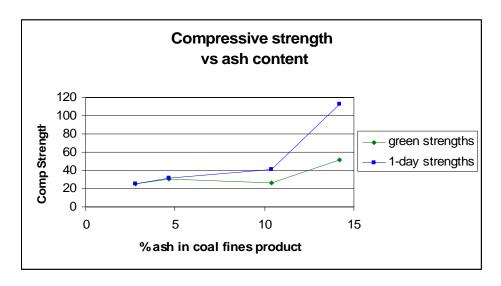


Figure 5.6. Green and one-day compressive strengths as a function of the fine-coal ash content. (Briquettes prepared using standard briquetting conditions and one per cent guar gum).

5.6.1 Methods

Samples of a fine-sized flotation coal and a coarser spiral coal, both from the James River Leatherwood plant, were blended in varying proportions in order to study the impact of the particle-size distribution on packing density, and ultimately on briquette strength. The study was carried out using blends of 1) fine and coarse coal, 2) fine and coarse coal mixtures with sawdust, and 3) fine and coarse coal mixtures with sawdust and binder.

Modified Proctor-density values were obtained by compacting each blend into an approximate one-liter volume with an impact hammer and then recording the weight of compacted material. The modified Proctor densities are referred to as *packing densities* in the following sections. Briquettes were formed from each of the test blends in essentially the same manner as before using the *standard* conditions of 4,000 lbs briquetting force, 3-s dwell time, and 22.2 °C cure temperature. Briquette porosities were determined from measurements of the briquette volume and weight.

The sample of spiral concentrate from the James River Coal Plant was mildly dried in room air to facilitate handling and then screened to -8 mesh. Blends of the fine flotation coal and coarser spiral concentrate were then prepared by varying the proportion of spiral concentrate from zero to 100% in 10% increments. These initial blends are referred to as the *wet* blends. After subjecting the wet blends to modified Proctor-(packing) density tests and briquetting studies, each of the blends was then moisture-equilibrated in an environmental chamber for seven days at 80% RH and 22 °C. The resulting reduced-moisture blends are referred to in this report as the *dry* blends. These blends were also subjected to modified Proctor-density tests and briquetted. Finally, these same blends were used to examine the impact of moisture addition, sawdust addition, and/or binder addition on packing density and briquette strength. For the moisture addition tests, the weight of material used to form individual briquettes was adjusted to compensate for the differences in moisture content between the different blends, i.e., to maintain a constant weight of dry material in each briquette.

5.6.2 Compaction Study Results

5.6.2.1 Coal-only blends

Error! Reference source not found. shows the packing densities of the coal-only blends (no sawdust or binder) as a function of the per cent of spiral product in the blend. Packing density was found to maximize at a higher than expected 70-80% spiral-product content. This high value may be in part explained by the high ash content (~20%) of the spiral product used in this study.

Figure 5.8 shows the compressive strength and porosity of briquettes formed from the wet, coalonly blends without binder. Briquette green strengths (day 0) were highest for briquettes prepared from 100% flotation coal (0% spiral). Green strengths generally declined with increasing spiral content but did exhibit an inflection at about 50% spiral-product, beyond which compressive strengths declined sharply.

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¹The particle-size distribution of the spiral concentrate obtained from the James River plant was unusually large as will be discussed later in the chapter.

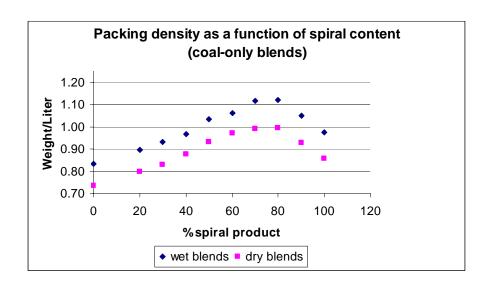


Figure 5.7. Packing densities for blends of spiral and flotation products.

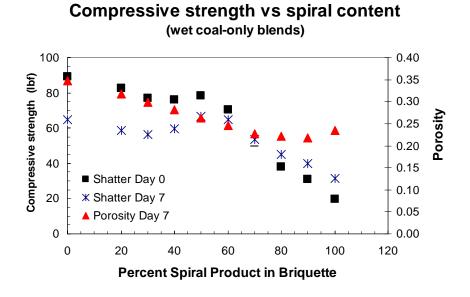


Figure 5.8. Compressive strength and porosity of briquettes formed from the coal-only blends.

In contrast, compressive strengths maximized in the 50:50 blend for the cured briquettes (day 7). Also, note the crossing green (day 0) and day-seven compressive-strength curves in Figure 5.8. These curves reveal that compressive strengths decreased as the briquettes cured for the blends containing higher proportions of fine flotation coal but increased over the same period for those blends containing more of the spiral product. As there is a significant amount of water evaporation from day zero to day seven, these data suggest a more beneficial role for moisture in

terms of enhanced green strengths for the smaller particles (polar attractions/surface tension) but a detrimental role for the larger particles (acts more as a lubricant). This advantage disappeared as the moisture evaporated.

The height of the fixed-diameter briquettes coupled with the skeletal densities of the coal fines were used to calculate briquette porosities. Briquette porosity was found to minimize at approximately 90% spiral product. This minimum in porosity is at a higher spiral content than that at which the maximum seven-day compressive strength (50% spiral) was observed. This lack of an inverse correspondence between porosity and briquette strength is somewhat puzzling as such a relation had been anticipated when the study was initiated. The reason for this lack of correlation is not clear but may relate, at least in part, to the high mineral-matter content of the spiral product as well as the fact that the larger spiral particles have less surface area per unit weight than do the smaller, flotation particles.

The compressive strength and the porosity of briquettes that were formed from the dry, coal-only blends² are shown in Figure 5.9. Just as the results for the wet blends shown in Figure 5.8, porosity minimized in the 70-90% spiral-product range, the highest green strengths were obtained with the 100% flotation product, and the maximum seven-day strengths were obtained with the 50:50 spiral:flotation blend. However, unlike results for the wet blends, the slope of the compressive strength curves for the dry blends was both flatter and lower in magnitude relative to the wet blends, particularly at lower spiral-product concentrations. In fact, the day-zero compressive-strength curve for the dry blends in Figure 5.9 is nearly identical to the analogous day-seven curve for the wet blends in Figure 5.8, or in other words, after the wet blends have dried. This again confirms the significant role of water in determining briquette green strength in the absence of a binder though such a role appears to be transient.

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²Water was added at 5wt% to the dry blends in order to form briquettes that would hold together, i.e., >5 lb_f strength.

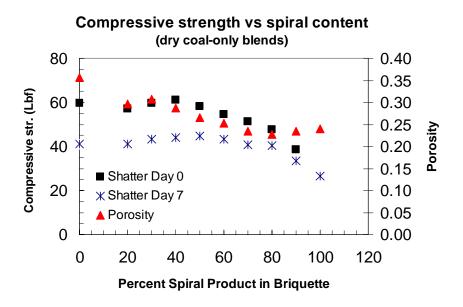


Figure 5.9. Compressive strengths and porosities of briquettes formed from blends of spiral- and flotation-coal products.

5.6.2.2. Coal-Sawdust Blends

After completing the tests of the coal-only blends, 10% sawdust was added to each blend along with zero, five, or fifteen per cent water. Figure 5.10 shows plots of the packing density for the coal/sawdust blends at three moisture concentrations. The curve shapes are similar to those observed for the coal-only blends only the maxima are shifted to a slightly lower spiral-product concentration (60-70% vs 70-80% for the coal only blends). The curves are also offset to lower densities since, as expected, packing densities decline with the addition of the lower-density sawdust.

Next, each of the coal/sawdust blends were formed into briquettes using either 5% or 20% water addition and tested for compressive strength (Figure 5.11). The addition of sawdust resulted in a substantial reduction in the briquette strengths, both green and cured, relative to the briquettes prepared without sawdust (Figure 5.9). For the briquettes prepared with five per cent addedwater, both green and cured strength were highest when 100% fine flotation coal was used. In contrast, with 20% water addition, the seven-day compressive strength was slightly better when some spiral product was blended in (20% spiral). Even so, briquette strength exhibited an

Packing weight as a function of product stream (Coal/sawdust blends) 1.20 1.10 Weight/Liter 1.00 0.90 0.80 0.70 0 20 40 60 80 100 120 % Spiral product ◆ Dry blend + 5% w ater ■ dry blends ▲ Dry Blend + 15 % w ater

Figure 5.10. The impact of water addition on packing density of coal/sawdust blends.

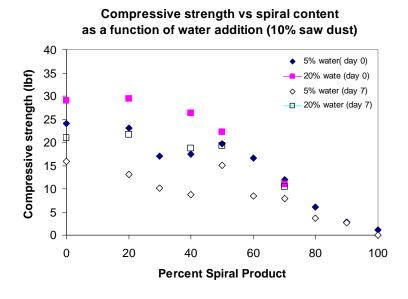


Figure 5.11. The effect of water addition on compressive strengths as a function of spiral content for coal/sawdust blends.

inverse relation with spiral content and tended to converge as the spiral content increased regardless of the cure time or the level of water addition. It is also notable that both the green and cured strengths of briquettes prepared with 20% added water were greater than those prepared with 5% added water, even though each briquette contained the same weight of dry blend.

The packing densities for the cured briquettes that were prepared from both coal-only and coal/sawdust blends are compared in Figure 5.12. This plot shows more clearly that the density of briquettes formed from coal-only blends maximized at a higher spiral content (~80%) than those containing 10% sawdust (60%-70% spiral content). Also note that the densities of briquettes formed with 20% added water were higher than briquettes formed with only 5% added water despite the fact that the briquettes were allowed to equilibrate under identical conditions for seven days and the initial weights were adjusted to compensate for differences in the initial moisture. These observations are favorable as they suggest that it may not be necessary to radically reduce the moisture content prior to briquetting as the presence of excess water appears to improve packing efficiency.

5.6.2.3. Packing Densities

The results of the blending/compaction experiments confirmed that a more efficient packing (higher density) could be obtained by blending coarser spiral particles with smaller-sized flotation particles. However, the higher packing efficiencies did not equate to higher-briquette strengths, at least not in the absence of a binder. It was possible that the lack of a correlation between density and strength was a result of the high ash content (~20 weight %) and/or an unusually high proportion of coarse particles in the spiral sample that was used. To explore this possibility, the blending/compaction experiments were repeated, only with a spiral product that contained less ash and fewer coarse particles. The ash content was first reduced from ~20 wt% to ~9.5 wt% via a gravity separation in an aqueous solution of lithium meta-tungstate at a medium density of 1.50 g/cm³. The proportion of coarse particles was then reduced by screening the spiral product into +16 and -16 mesh fractions and then recombining these fractions at one

Density of 7-day Cured Briquettes vs Spiral content 1.2 Dried coal + 5% Water A Dried coal + 10% SD + 5% Water O Dried coal + 10% SD + 20% Water 1.1 1.0 0.9 0.9

Figure 5.12. Effect of spiral-product content in coal only and in coal + sawdust (10%) blends on the briquette density.

Percent Spiral Product in Briquette

60

80

100

40

0

20

part +16 mesh to nine parts -16 mesh to simulate a more typical spiral product. In the repeat experiments, only wet flotation/spiral blends were tested and these were tested both with and without sawdust and both with and without a binder (guar gum).

For the coal-only blends (Figure 5.13), packing density maximized at about 60% spiral product versus the \sim 70-80% spiral product observed before with the higher-ash sample (Figure 5.12). Similarly, the maximum packing density of the coal/sawdust blends shifted from 60%-70% spiral product to around 40%-50% spiral (Figure 5.14) with the lower-ash sample. Also note that the addition of sawdust resulted in a shift in the maximum packing-density to a lower proportion of spiral product relative to the coal-only blends, suggesting that the smaller flotation particles may have packed more efficiently when blended with the larger sawdust particles.

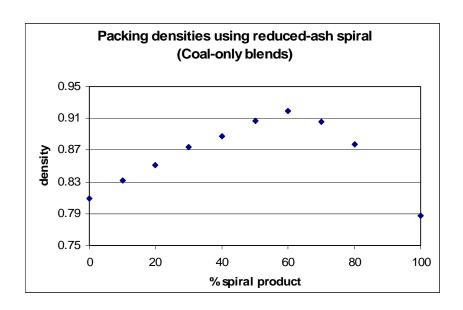


Figure 5.13. Packing densities for spiral/flotation blends using a reduced ash content spiral product (coal-only blends).

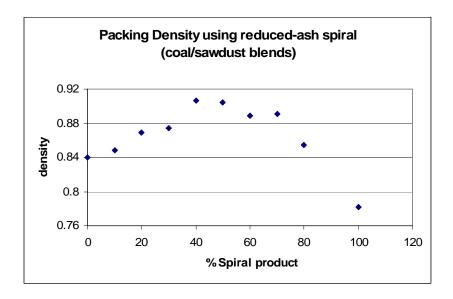


Figure 5.14. Packing densities for spiral/flotation blends using a reduced ash content spiral product (coal/sawdust blends).

5.6.2.4 Briquette Properties for Coarse and Fine Coal Blends with Binder

Briquettes were again formed from the coal-only blends without an added binder and tested for compressive strength. These repeat tests confirmed that the highest compressive strengths were obtained for the briquettes containing 100% flotation product with relatively minor reductions in strength up to the addition of approximately 50% spiral product. Compressive strengths were next determined for briquettes made from coal/sawdust blends that were formed both with and without an added binder (1% guar gum). As before, when no binder was used, the higher strengths were obtained in the 100% flotation product with a steady decline in both the initial and 7-day strengths as a function of spiral content. However, with the addition of a binder, the highest green strengths were no longer clearly obtained with 100% flotation product but instead were essentially the same for blends containing between 0 and 50% spiral product (Figure 5.15). The maximum in compressive strengths became more pronounced for the blends containing between 20% and 50% spiral product on day one and more defined at 50% spiral product on day seven. The briquettes formed with mixtures of flotation and spiral product that were prepared with a binder were also found to be more durable than analogous briquettes formed with 100% flotation product. Shatter resistance (drop tests) was found to maximize in those briquettes that contained 50%-60% spiral product (Figure 5.16). Thus, unlike the results that were obtained without a binder, it would appear that when a binder is present, stronger briquettes are formed when the fine-coal flotation product is blended with a larger particle-size spiral product than when the briquettes are formed with the flotation product alone.

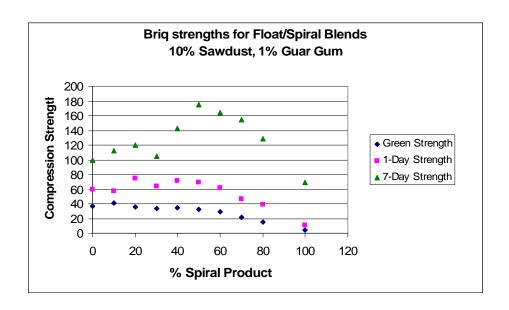


Figure 5.15. Briquette strengths for coal/sawdust blends as a function of spiral product content when using a binder.

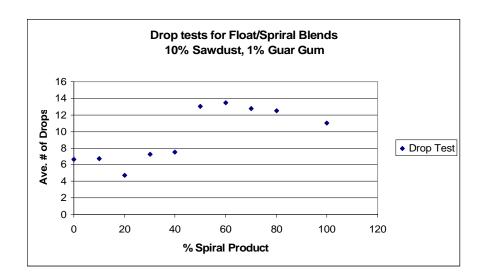


Figure 5.16. Shatter resistance for briquettes formed from coal/sawdust/binder blends.

5.7. SUMMARY

Guar gum, wheat starch, and REAX/lime were identified as the best performing binders for briquetting coal and sawdust when applied on an equivalent-cost basis. The parameters that exhibited the greatest impact on briquette performance were binder concentration; sawdust concentration, particle size, and type; cure temperature; and ash content. Parameters that had the least impact on briquette properties, at least over the ranges studied, were moisture content, briquetting force, and briquetting dwell time. More efficient compaction and higher briquette densities and cured strengths could be obtained by blending coarser coal fines with fine flotation fines, both with and without added sawdust. These effects were more pronounced when a binder was added.

6. PILOT-SCALE TESTING

6.1 Goals and Objectives

The ultimate goal of this task was to demonstrate the production of a premium fuel from fine coal and wood waste in a continuous briquetter and to demonstrate that such fuels had acceptable combustion and emission characteristics. Objectives included i) evaluation of the process parameters associated with a 200 lb/hr continuous briquetter, ii) testing and confirmation of binders that were identified as the most cost effective in the laboratory study (Chapter 5) and iii) evaluation of the combustion characteristics including flue gas emissions.

It is noted that the pilot-scale briquette equipment and the combustion testing capacity were significantly greater in scale than proposed in the original work plan. Initially, use of a 15 lb/hr capacity briquetter was proposed instead of the 200 ton/hr unit that was used. Also, the combustion testing was to be performed in the Conversion and Environmental Process Simulator (CEPS) at the Energy & Environmental Research Center, University of North Dakota. However, to gain more confidence in the combustion data, a significantly larger combustion simulator (i.e., 31,000 btu/hr, 80 lbs/grate-ft) at Penn State University was used to evaluate the combustion characteristics of pilot-scale briquette samples.

6.2. Pilot-Scale Briquetting

6.2.1. Materials and Methods

Due to the need for a relatively large amount of fine clean coal for the continuous-briquetting studies, seven 55-gallon drums of froth were collected directly from the product stream of a commercial column flotation cell at TECO Coal's Clintwood-Elkhorn No.3 plant. This entire sample was dewatered by vacuum filtration, thoroughly blended, and then resealed in 55-gallon drums until needed. The initial dewatered product contained about 21% moisture.

The continuous roll-type briquetter used in the study was a Komarek model B-100 with a nominal throughput up to 200 lbs/hr (Figure 6.1). The unit produces briquettes that are

approximately 4-cm in length as in Figure 6.2. Dwell time and, to a large extent, total throughput is governed by the roller speed. The pressure applied during briquetting was indeterminate but believed to be in the range of 10 tons according to the manufacturer's specifications. Some additional briquetting pressure can be applied with a manual fixed-pressure hydraulic system.

The briquetting procedure entailed loading a sample or blend of particulate matter to the feed hopper from where it is fed to the roller with a variable-speed screw feeder (Figure 6.3). The screw-feed rate must be adjusted for a given roller speed to deliver the optimum amount of material to the roller cavities. An insufficient feed rate results in poor quality briquettes while too much feed requires more power than the unit can deliver leading to run stoppages. For each run, about 1.5 kg of the TECO fine coal was blended with a -4 mesh sample of chestnut-oak sawdust (H&S oak) and binder (\$8/ton application rate). The blend was then transferred to the feed hopper and briquetting initiated by starting in succession, the feed-hopper mixer, briquetting rollers, and feed screw. The briquetter throughput was governed primarily by the roller speed and feed rate with these two settings being adjusted to keep the roller cavities filled. Because it could not be accurately controlled and was subject to variation during a given run, the briquetting rate was not routinely measured during a run. However, a limited number of measurements indicated that the briquetting rate was typically in the range of 20-25 kg/hr (~50 pounds/hr). Tests were generally conducted in duplicate with the average results/properties being reported.

The physical properties of the briquettes were determined in essentially the same manner as the batch experiments described in Chapter 5. Tests included compressive strength, attrition, and shatter and water resistance. A modification from the earlier work is that the compressive strength values represent the average for ten briquettes instead of five. As before, the attrition index, water resistance, shatter resistance, and seven-day compressive strengths were determined on briquettes that had been stored for seven days at 22.3 °C and 90% relative humidity in an environmental chamber.

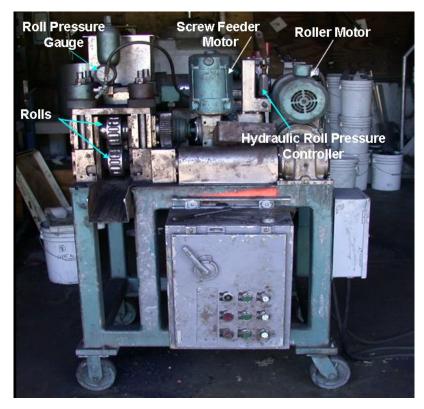


Figure 6.1. Komarek Model B-100 continuous briquette unit.



Figure 6.2. Briquettes produced from fine coal/sawdust blends.

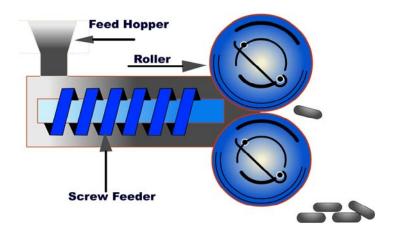


Figure 6.3. Schematic diagram of the continuous briquetter.

Statistically designed experiments were carried out according to a Box-Behnken design to provide data for developing models to maximize briquette strength via the optimization of selected briquetting-parameter values. The parameters selected for evaluation included sawdust concentration, binder addition rate, and moisture content. In the laboratory batch tests, it was observed that a higher moisture content (20% to 25%) was necessary to obtain a the higher briquette strength. However, it was not possible to process blends in the continuous briquetter with moisture levels in this range due to problems with bridging and erratic briquetter-feed rates. Thus, moisture levels had to be reduced to a range that could be fed more consistently (~15% maximum). The rate of binder addition was on a binder-cost basis and was added at either \$4, \$8, or \$12/ton of briquetted product. A total of 17 experiments were performed using the Box-Behnken design with briquettes tested for compressive strength at 30 min, one day and seven days following formation. The parameter ranges evaluated in the three-level test design are listed in Table 6.1.

Table 6.1. Parameter values explored in the 3-level test program conducted on the continuous briquetting unit.

Parameter	Parameter Value Level				
Value	-1	1			
Sawdust Content (%)	2	6	10		
Binder Cost (\$/ton)	4	8	12		
Moisture Content (%)	5.6	9.3	13.0		

6.2.2. Preliminary Testing

Initial briquetting trials with the dewatered flotation coal were unsuccessful as the high-moisture content of this sample (21%) caused sample bridging and frequent feed stoppages. In an attempt to avoid this problem, a split of the flotation coal was further dried to 17% moisture. While this reduced-moisture sample behaved much better, its feed rate was still erratic resulting in highly variable briquette properties. An inability to maintain a steady feed rate with the dewatered fine coal made it clear that the moisture content would have to be further reduced before proceeding with the pilot-scale briquetting tests. The question was, 'What moisture range would make for an acceptable feedstock?' To address this question, the moisture content for another split of the TECO flotation sample was air dried to 6.5% by weight. The relationship between fine-coal moisture content and the ability to consistently feed that material to the briquetter was then evaluated by briquetting a series of blends of the low-moisture coal, 5% sawdust, and 1% guar gum in which the moisture content of successive blends was increased in 2 percent increments.

Figure 6.4 and 6.5 shows the compressive strength, shatter resistance, and attrition indices of briquettes made with the TECO flotation coal as a function of moisture content. Green and one-day compressive strength were relatively unchanged over this range as was the attrition index. However, both the day-seven compressive strengths and the shatter resistance showed notable improvements as the moisture content was increased. These data suggest that forming briquettes with higher-moisture content fine coal is certainly not detrimental and perhaps even improves briquette quality, at least with a guar gum binder. However, it should be restated for emphasis

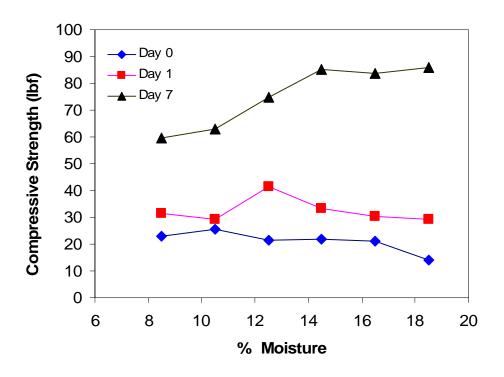


Figure 6.4. Effect of moisture content on compressive strength.

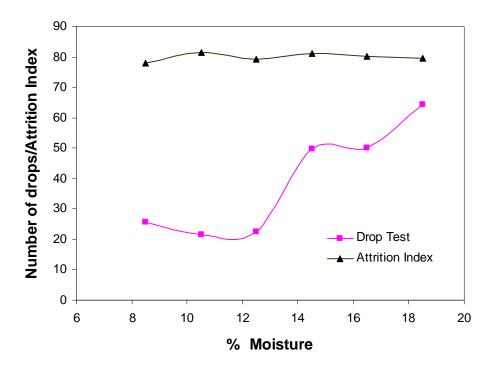


Figure 6.5. Effect of moisture content on shatter and attrition resistance.

that producing good quality briquettes with the higher moisture fine coal was not the problem; being able to feed the higher-moisture samples to the briquetter rollers in a consistent manner was the problem. During these tests, it was observed that the samples containing up to 14-15% moisture could be fed in a reasonably consistent manner. However, while the highest two moisture levels blends as shown in Figures 6.4 and 6.5 (16.5% and 18.5%) could still be fed with some effort, maintaining a consistent feed rate over the course of a run was difficult, resulting in more variation in the briquette properties and more frequent run stoppages.

After completing the moisture-addition tests using guar gum, subsequent testing revealed the practical working range of moisture content was also a function of the binder type. Some of the binders (e.g., guar gum, starch, lime) tended to absorb a portion of the available moisture and were thus suitable for use at higher ranges whereas others (e.g., molasses) tended to exacerbate the feeding problems and could only be fed consistently when less moisture was present in the blend. This relation between moisture content, flowability, and the binder being used can be seen in Table 6.2. This table shows briquette properties for selected binders that were blended with splits of the TECO flotation coal containing 6.5%, 9% and 12% moisture. These results reveal that briquette properties generally improve as a function of moisture content for the BF1, guar gum, and starch binders, particularly the properties of shatter resistance, attrition index, and surprisingly, water resistance. In contrast, briquette properties were generally better for the BF2 and molasses/lime binders when they were added to a lower moisture fine-coal. Thus, while this study indicates that it is possible to produce high-quality briquettes with relatively high-moisture coals, the optimum moisture range must be chosen with consideration given to the binder being used. This finding is significant in that it has implications for binder selection in a commercial facility.

Table 6.2. Effect of binder formulation and moisture content on briquette properties.

Moisture	Binder	Compre	ssive Stren	igth (lb _f)	Drop	Water	Attrition
%	ID	Day 0	Day 1	Day 7	Tests	Resistance	Index
6	BF1	23.1	43.6	147.9	61	No	89.7
9	BF1	25.9	55.8	115.6	71	4.6	93.0
12	BF1	22.6	57.1	110.9	74	14.6	95.3
6	BF2	30.9	54.1	121.8	56	33.0	87.0
9	BF2	26.1	51.9	116.4	47	15.2	92.3
12	BF2	20.9	46.0	50.4	25	15.8	92.0
6	Guar gum	21.1	45.6	68.8	10	No	89.0
9	Gaur gum	26.7	55.3	70.6	20	0.2	91.3
12	Guar gum	21.0	38.4	55.8	22	No	91.6
6	Molasses/Lime	28.6	40.9	113.8	46	No	91.2
9	Molasses/Lime	16.9	37.4	105.9	25	No	91.7
12	Molasses/Lime	10.0	29.5	14.3	3	No	84.9
6	Starch	33.1	55.4	121.9	47	No	87.9
9	Starch	29.6	54.9	138.9	71	12.2	95.3
12	Starch	25.8	43.8	123.7	67	29.9	96.2

In the earlier laboratory-scale batch studies (Chapter 5), it was found that higher fine-coal moisture contents (20% to 25%) were necessary for producing briquettes with acceptable properties. However, higher moisture content in the continuous briquetting process creates handling problems requiring that the moisture content be reduced prior to briquetting. It is believed that it might be possible to design a briquetter feed system that would permit the consistent introduction of high-moisture feed blends without undue handling and feed problems. However, due to time and budget constraints, a decision was made not to pursue this avenue but rather to proceed with the continuous briquetting studies using a reduced moisture coal (10%).

6.2.3 Parametric Evaluation

The results of the pilot-scale briquette tests using a statistical-design test program are provided in Table 6.3. The response data were used to develop empirical models that describe the response variables as a function of the parameter and parameter interactions.

The quadratic models defining the briquette compressive strength (lbs) for 30 minutes, one and 7 days curing are:

30 min Compressive Strength =
$$23.56 - 4.03 * A + 10.18 * B + 7.17 * A^2$$
 (6.1)

Day One Compressive Strength =
$$27.21 - 5.09 * A + 11.98 * B + 9.36 * A^2 + 7.69 * A * B$$
 (6.2)

Day Seven Compressive Strength =
$$47.79 - 7.97 * A + 19.59 * B + 10.40 * A^2$$
 (6.3)

Where A is sawdust concentration and B is binder concentration. Analyses of the parameter and parameter interactions using the empirical models revealed that moisture content had an insignificant effect on briquette strength over the range of moisture contents studied and thus this parameter is not included in the final models above. The empirical models represented by Eqs. (6.1) - (6.3) satisfactorily passed ANOVA analyses and have coefficients of determination (R^2) values greater than 0.8.

As opposed to moisture content, binder and saw dust concentrations were found to each have significant and opposing impacts on briquette strength. As shown by a plot of the model results (Figure 6.6), an increase in sawdust concentration results in a significant decrease in briquette strength. However, this strength reduction can be countered by an increase in binder concentration. In other words, a substantial increase in binder cost will be associated with higher addition rates of sawdust.

Table 6.3. The design matrix and responses for the Box–Behnken test program conducted with a continuous briquetter unit.

Run No.	Sawdust (%) A	Binder Cost (\$/ton) B	Moisture (%) C	Green Compressive Strength (lbs)	One day Compressive Strength (lbs)	7 day Compressive Strength(lbs)
1	10	8	5.6	25.80	26.10	49.56
2	10	8	13.0	15.90	25.18	39.62
3	2	12	9.3	43.18	47.70	75.46
4	6	4	13.0	14.86	15.86	16.04
5	6	12	13.0	30.62	37.44	60.92
6	10	4	9.3	12.68	15.18	22.98
7	6	8	9.3	21.10	25.26	57.86
8	10	12	9.3	52.38	59.44	88.74
9	2	8	5.6	35.38	42.38	73.60
10	2	4	9.3	27.34	34.20	48.74
11	6	8	9.3	26.30	37.18	57.74
12	6	4	5.7	21.06	18.48	34.35
13	6	8	9.3	21.56	22.76	57.86
14	6	8	9.3	21.16	26.78	43.14
15	6	8	9.3	24.18	26.18	48.52
16	6	12	5.6	31.16	34.98	53.69
17	2	8	13.0	33.14	42.38	66.86

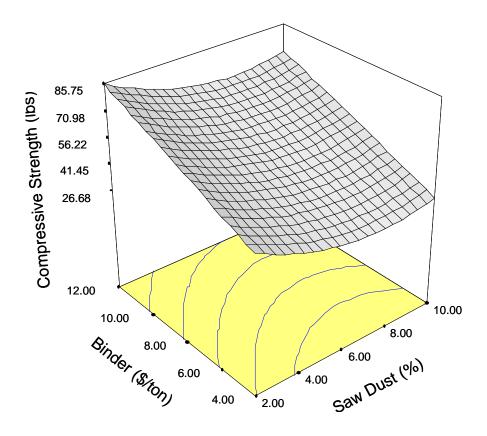


Figure 6.6. The effect of binder and saw dust concentrations on one-day briquette strengths.

6.2.4 Binder Comparisons

A comparison of the more promising binder formulations that were identified in the laboratory-scale briquetting study was undertaken in the continuous briquetting unit. These included guar gum, starch, molasses/lime, Reax/lime, and two binder formulations referred to simply as BF1 and BF2. The BF1 and BF2 binders were multi-component binder formulations that were developed with the steam and the FBC/stoker markets in mind, respectively. That is, BF1 was comprised solely of combustible components (PC market) whereas BF2 contained lime (stoker). Each binder was added to blends of the TECO flotation coal (10% moisture) and H&S oak sawdust (5%) at a rate of \$8/ton of briquetted product. Each continuous-briquetting run was conducted in duplicate with the average briquette properties from the duplicate runs reported.

Table 6.4 shows the properties of the briquettes produced from the group of combustible binders. As one would expect, the control briquettes that were prepared without a binder exhibited the poorest briquette properties across the board. Of the three samples prepared with a binder, those produced with starch and the BF1 formulation exhibited the best physical properties. These two binders were quite similar in performance with a slight edge given to BF1 as this binder produced briquettes with a modestly higher seven-day compressive strength and attrition index relative to starch. Accordingly, the BF1 formulation was identified as the best of the organic binders and selected to be used in subsequent combustion studies.

Table 6.4. Comparison of briquette properties for combustible binder formulations (10 wt% feed coal moisture, 5% H&S sawdust).

Binder	Compressive Strengths			Drop	Water	Attrition
ID	Day 0	Day 1	Day 7	Tests	Resistance	Index
Control	12.1	12.2	13.0	3.4		41.4
Starch	35.8	35.3	44.4	25.5	10.1	90.9
Gaur gum	21.9	21.7	26.4	7.7	No	66.1
BF1	31.8	31.8	51.0	24.3	13.6	93.5

In an analogous manner, Table 6.5 shows the properties of briquettes made with a binder formulation containing lime as one of the components. Each of the samples in Table 6.5 was prepared with two weight per cent lime in addition to the base binder materials which were applied at a rate of \$8/ton of product. The control briquettes were prepared with two weight per cent lime only, and again exhibited the poorest briquette properties. On average, the compressive strengths of the lime-containing binders were not as high as those of the combustible binders shown in Table 6.4. However, these binders generally exhibited equivalent or higher shatter resistance and attrition indices than did their combustible-binder counterparts. Fo the three lime-containing formulations, the REAX/lime and BF2 formulations generally performed better than did the molasses/lime formulation. These two formulations were essentially equivalent in terms of their compressive strength and attrition indices with the BF2 formulation having an advantage in shatter resistance as it exhibited the highest shatter-resistance

value of the binders evaluated (Tables 6.4 and 6.5). For this reason, the BF2 formulation was selected over the REAX/lime formulation to be used for subsequent combustion tests.

Table 6.5. Comparison of briquette properties for the lime-containing binder formulations. (2 wt% lime, 10 wt% feed coal moisture, 5% H&S sawdust).

Binder	Compressive Strengths			Drop	Water	Attrition
Type	Day 0	Day 1	Day 7	Tests	Resistance	Index
Lime	10.6	14.4	18.5	3.7	8.8	72.1
Reax/Lime	21.3	26.0	30.8	19.0	10.0	93.4
Mol/Lime	19.3	22.8	23.8	20.0	10.2	89.7
BF2	23.7	30.5	28.8	30.6	13.4	93.0

6.3. Combustion Testing

6.3.1. Combustion Samples and Procedures

6.3.1.1 Briquette Samples: For the reasons discussed, the BF1 and BF2 binder mixtures were used to produce two 8 kilogram briquette samples for combustion/emissions testing. The BF1 and BF2 binders were each added at a rate of \$8/ton to blends of the dewatered TECO flotation coal and 5% H&S oak sawdust and formed into briquettes. In a similar manner, an additional batch of briquettes was prepared without an added binder to serve as a control.

The physical properties of these samples are shown in Table 6.5. These samples were briquetted in the continuous unit in a free-run mode in which the feed rate and roller speeds were not as carefully monitored and controlled as they were in the earlier binder-comparison studies. As a result, briquette qualities of strengths and attrition were often not as good as attained with the same formulations when more care was taken to optimize the briquetter throughput.

Table 6.6. Properties of the briquette samples prepared for combustion studies. (10 wt% feed coal moisture, 5% H&S oak sawdust).

Binder	Compre	Attrition		
ID	Day 0	Index		
Control	17.8	17.7	19	46.0
BF1	26.0	27.4	63.8	84.9
BF2	19.7	20.5	22.9	80.9

Laboratory analysis results of the three samples prepared for combustion studies are shown in Table 6.6. The differences in the analytical results for the control and the BF1/BF2 briquettes are believed mainly due to the addition and nature of the BF1 and BF2 binders. Scrutiny of these data reveals that the as-received heating values of the BF1 and BF2 samples were approximately 12,700 Btu/lb (Table 6.6). This is a significant point as this value greatly exceeds one of the stated project objectives of a producing a premium fuel from waste products with a heating value of 9,000-10,000 Btu/lb. Interestingly, the total moisture contents were remarkably low and agree

Table 6.7. Analysis of the three briquetted fuel sample.

Characteristic	Fuel Type				
Characteristic	Control Sample	BF1	BF2		
Moisture (%, as received)	1.4	0.7	0.9		
Proximate Analysis (%, dry basis)					
Volatile Matter	27.2	29.3	31.4		
Ash	10.8	11.0	14.3		
Fixed Carbon	62.0	59.7	54.3		
Ultimate Analysis (%, dry basis)					
Carbon	76.1	72.7	71.6		
Hydrogen	4.5	4.4	4.5		
Nitrogen	1.4	1.3	1.3		
Sulfur	1.0	0.9	1.0		
Oxygen	6.2	9.7	7.3		
Ash	10.8	11.0	14.3		
Heating Value (btu/lb)		_			
As-fired	13,468	12,647	12,737		
Dry	13,655	13,165	13,289		

with the values obtained from the laboratory briquettes. If the low moisture contents can be realized on a commercial scale, significant economical benefit can be realized. This is also a potentially significant point and as such will be discussed in greater detail in Chapter 7.

6.3.1.2 Combustion Apparatus: A series of combustions tests firing of three different briquettes in a stoker simulator were conducted at the Pennsylvania State University's Energy Institute. The objectives of the tests were to evaluate combustion stability and quantify emissions for the two briquetted fuels (BF1 and BF2) and control. The flue gas from the stoker simulator was sampled and analyzed, per EPA test protocol, for CO₂, CO, SO₂, and NO_x emissions.

A schematic diagram of a section of the fuel bed on a traveling grate stoker is shown in Figure 6.7. Combustion of coal on a traveling grate can be divided into three zones:

- 1. Ignition zone -- where ignition occurs initially at the top of the bed and the bed height remains constant. The fuel devolatilizes and the volatiles burn above the ignition plane. The plane of ignition travels slowly downwards to the grate;
- 2. Combustion zone -- where the semi-coke formed after ignition and devolatilization is burned. The semi-coke may swell and resist the flow of air, resulting in an increase in the pressure drop across the fuel bed. The development of plasticity increases the pressure drop, which measures the resistance to the flow of air. Various properties such as the rank of coal, particle size, operating pressure and petrographic characteristics determine thermoplastic behavior. As the ignition proceeds to the grate (with most of the bed being in the burning stage) the air requirement for combustion increases; and
- 3. Burn-off zone -- where the surface of the semi-coke or coke bed recedes as burning continues, leaving residual ash and clinkers containing some combustibles. The combustion air requirement in this zone is minimal.

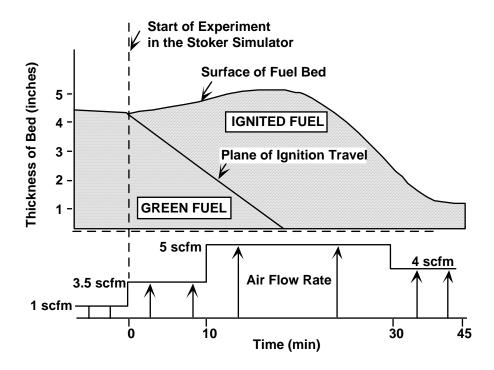


Figure 6.7. Combustion of fuel in a traveling grate stoker -- section of a fuel bed with time; Scfm is standard cubic feet per minute.

6.3.1.3 Combustion Test Procedure: A schematic diagram of the stoker combustor apparatus is shown in Figure 6.8. Combustion air to the stoker simulator was supplied from the bottom of the chamber through a distributor plate. The air flow rate was varied during a test to simulate the variable air flow rate in an operating stoker boiler. During the 45-minute test, the air flow rate for the first 10 minutes was set at 3.5 standard cubic feet per minute (scfm), then changed to 5 scfm for the next 20 minutes and then lowered to 4 scfm for the last 15 minutes. The bed was purged with nitrogen after the 45-minute test period to ensure that further combustion of the bed does not occur after the test was completed; assist in cooling the bed quickly in order for it to be removed; and mimic the bed dropping into an ash pit where, theoretically, no further combustion occurs. The variation of air with time is shown in Figure 6.7. During the peak combustion period at an air flow rate of 5 scfm, the cold air velocity through the grate is approximately 1 ft/s. Although this velocity is lower than the conventional velocity of 1.2 to 1.5 ft/s, it is consistent

with the trend of reducing the combustion air flow rate through the grate and increasing the overfire air flow rate to minimize pollutant emissions.

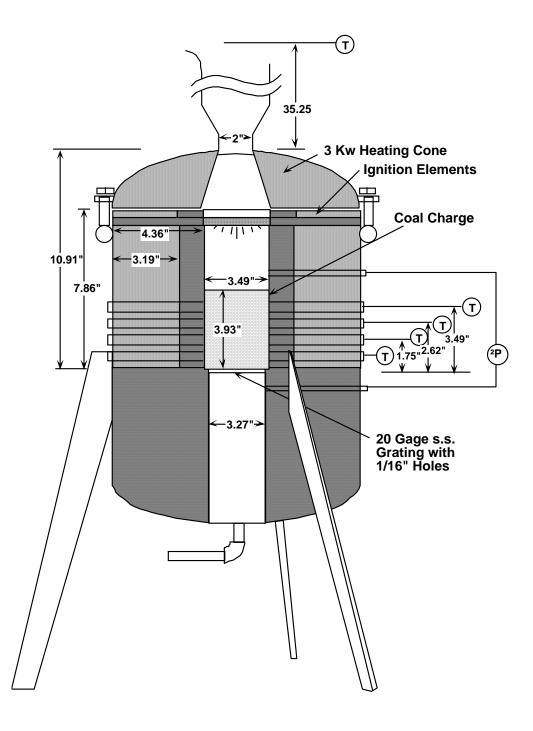


Figure 6.8. Schematic diagram of the modified stoker simulator.

A gas sampling port was installed at the simulator outlet to extract flue gas for collection and measurement. A computer data acquisition system was used to collect the temperatures, the gas concentrations, and the pressure drop across the bed

The ash samples were analyzed for moisture and ash to calculate the combustion efficiency using the ash tracer technique as follows:

$$Burnout(\%) = \left[1 - \frac{A_c(100 - A_r)}{A_r(100 - A_r)}\right] \times 100$$
(6.4)

where A_c is the weight percent ash in the coal (dry) and A_r the weight percent ash in the residue (dry).

6.3.2 Combustion Results and Discussion

A summary of the combustion tests is provided in Table 6.7, which contains the average level of O_2 in flue gas during the 20 minute period of maximum air flow, and average emissions normalized to 3% O_2 .

6.3.2.1 Control Briquettes: Two tests were performed using the control briquettes and are labeled A and B (Tests are labeled alphabetically for ease of discussion.) in Table 6.7. The results from the tests are similar in that the bed burnout (*i.e.*, combustion efficiency calculated from Equation 3) was approximately 87% for both tests, although the average level of O₂ in the flue gas was higher for Test B than Test A, *i.e.*, 6.9% as compared to 4.0%, respectively. It appears from the stack emissions profiles, shown in Figures 6.9 and 6.10, that combustion was more rapid in Test A (as depicted by the dip in the O₂ profile in the middle of the test) than in Test B. This is further illustrated in the temperature profiles (Figures 6.11 and 6.12) where the slopes of the lines are greater in Test A than in Test B and the maximum temperatures achieved were higher in Test A than in Test B.

Table 6.8. Summary of the Stoker Combustion Tests.

Test	Coal	Bed	Test O ₂	Average Emissions @ 3% O ₂			
Code	Type	Burnout	Level	CO	CO_2	SO_2	NO_x
		(%)	(%)	(ppm)	(%)	(ppm)	(ppm)
A	Control	87.3	4.0	242	15.5	671	168
В	Control	87.3	6.9	241	15.4	739	203
C	BF1	85.5	4.7	261	16.1	444	145
D	BF1	83.4	4.6	294	15.8	685	141
Е	BF1	86.5	4.9	254	15.5	632	201
F	BF2	98.3	1.2	>6,000°	15.5	671	168
G	BF2	97.6	1.0	N.R. ^b	15.4	885	75
Н	BF2	96.0°	5.4	233	15.6	682	126

Stack Emissions for Brig. - Feed Tested on 12/15/04

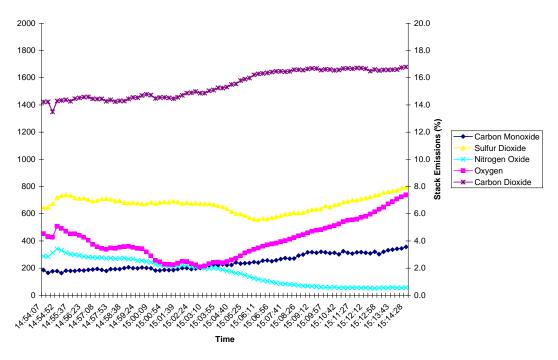


Figure 6.9. Stack Emissions for Test A.

^a CO emissions were off-scale, which is greater than 6,000 ppm.

^b Not reported. As can be observed from Figure 10, CO emissions were off-scale (*i.e.*, >6,000 ppm) for a portion of the test period.

^c Test J was performed with a fuel charge of 600 g (1.32 lb) as compared to the standard 800 g (1.76 lb).

Stack Emissions for Briq. - Feed Tested on 12/17/04

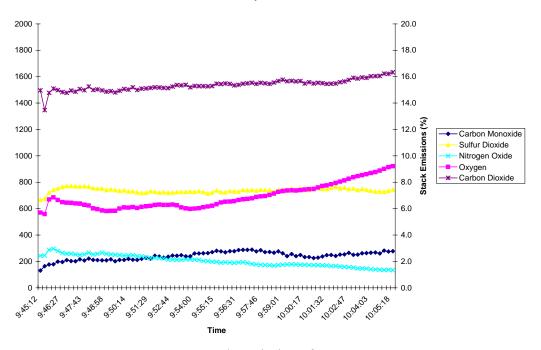
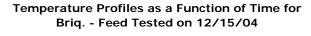


Figure 6.10. Stack Emissions for Test B.



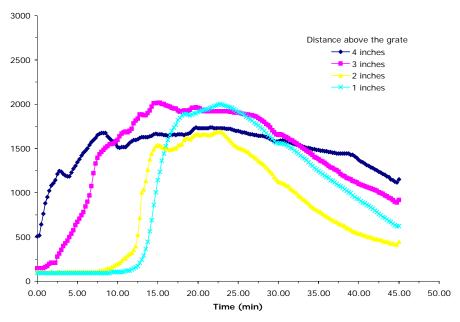


Figure 6.11. Temperature profile as a function of time for feed coal briquettes (Test A).

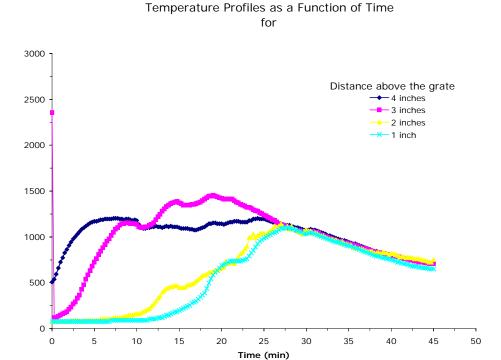


Figure 6.12. Temperature profile as a function of time for feed coal briquettes (Test B).

6.3.2.2 BF1 Briquettes: Three tests were performed using the BF1 briquettes and are labeled C, D and E in Table 6.7. The third test (Test E) was performed because of the large discrepancy in SO₂ emissions between Tests C and D, which averaged 444 and 685 ppm (@ 3% O₂), respectively.

In Tests C and D, the bed burnouts were similar (\approx 86 and 84%, respectively) as were the gaseous emissions other than SO₂. The sulfur in the bed ash was higher in Test C (0.70%) than in Test D (0.59%), which would indicate increased sulfur capture in the bed and less sulfur in the flue gas.

In Test E, the average SO₂ emissions were 632 ppm (corrected to 3% O₂), which are slightly less than the emissions observed in Test D. The sulfur content in the bed ash for Test E was 0.64%. A trend of decreasing SO₂ emissions with increased sulfur retained in the bed ash was observed with this fuel series.

The NO_x emissions in Test E were slightly higher than those observed in Tests C/D, *i.e.*, 201 ppm as compared to 145/141 ppm, respectively. Interestingly, the temperature profile plot for Test E differs from the plots for Tests C and D, which were similar. The temperature profile plot for Test E (*i.e.*, slower rate of temperature increase resulting in a longer residence time at peak or near-peak temperatures and a lower peak temperature) exhibits trends similar to Test B where the NO_x in test B (for the Feed briquette) was higher than that noted in Test A.

6.3.2.3 BF2 Briquettes: The BF2 briquettes burned with such intensity that the system was starved of oxygen and CO emissions were excessive. Burnout ranged from 96 to 98% (see Table 6.7). Increasing air flow was helpful for the first twenty minutes, however, it became too excessive and the bed of coal/ash was blown off of the grate. As a final test, Test H, the coal charge was reduced from 800 g (1.76 lb or a firing density of 26.7 lb/ft²) to 600 g (1.32 lb or a firing density of 20.0 lb/ft²) while maintaining the same air flow/time periods. This test was successfully performed and the emissions results are summarized in Table 6.7 with the emissions profile shown in Figure 6.13.

Sulfur contents in the bed ash were also analyzed. They were 0.35, 0.34, 0.33, and 0.61%, respectively, for Tests F, G, H, and J.

Temperature Profiles as a Function of Time for

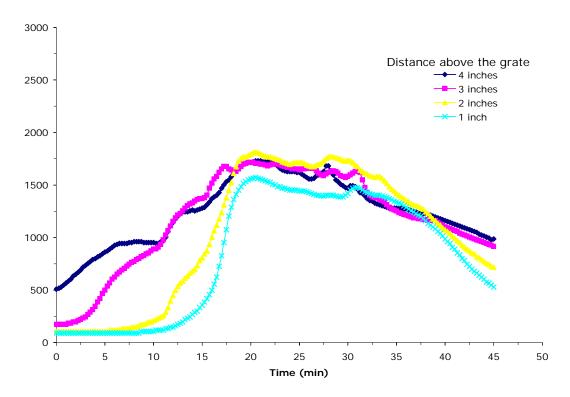


Figure 6.13. Temperature profile as a function of time for the BF2 Briquettes (Test H).

6.4 Summary and Conclusions

6.4.1 Pilot-Scale Briquetting

To determine the potential of producing a premium fuel from cleaned fine coal and wood waste, a continuous briquetter was used to conduct a parametric study of three of the more significant briquetting parameters (moisture, binder, and sawdust concentrations); binders that were identified as cost effective in the prior laboratory briquetting study were re-evaluated; and the most effective binders were identified and used to produce briquettes for combustion studies. The conclusions from this phase of the investigation were:

- i. The main goal of the project was successfully achieved or exceeded, i.e., the production of a premium fuel from fine coal and wood waste having a heating value between 9,000 and 10,000 btu/lb. Briquettes containing 5% sawdust and with a heating value of approximately 12,700 Btu/lb (as received) were produced in a continuous, 200 lb/hr briquetter.
- ii. The detrimental effects of higher sawdust concentrations on briquette properties that were observed in the laboratory batch-briquetting studies were confirmed in the continuous briquetter. The highest compressive strength values were obtained without sawdust addition.
- iii. To maintain briquette strength when adding sawdust, binder concentration must be increased.
- iv. Controlling the feed flow rate to the continuous briquetter is critical to forming good briquettes. A less than optimum flow rate results in a lower compressive force being applied during briquetting and in turn, poor briquette characteristics. Feed rates exceeding the optimum results in roller binder and briquetter run stoppages. An erratic feed flow, which appears related mostly to high feed moisture, produces briquettes of variable quality.
- v. While both laboratory and continuous briquetting studies indicated that strong briquettes could be made even with relatively high levels of moisture present in the feed blend, due to bridging in the feed hopper, a consistent feed rate could not be attained in the continuous briquetter when the feed moisture exceeded about 12-15%. This feed problem precluded the production of good quality briquettes.
- vi. The maximum level of feed moisture that could be tolerated by the continuous unit was related to the nature of the binder used. For example, guar gum was found to provide consistent feed flow at moisture levels as high as 15% whereas molasses/lime and the BF2 binders could only be used with feed blends containing about 12% or less moisture.

6.4.2 Combustion Tests

Combustion tests were conducted in a Stoker simulator unit at The Energy Institute of The Pennsylvania State University on three briquetted samples. Two of the samples were formed from 95% clean coal and 5% sawdust using two binder formulations identified as the most cost effective in a series of continuous briquetting tests. The third sample was prepared in a similar manner only without an added binder and served as a control. The conclusions from the combustion study were:

- For the control sample made with coal/sawdust only, the bed burnout was about 87.3%;
 CO and CO₂ emissions were 240 ppm and 15.5%, respectively; and average SO₂ and NO_x were 705 ppm and 186 ppm, respectively.
- ii. For the BF1 briquettes, the bed burn out was about 85%; the CO emissions were 257 ppm SO₂ emissions averaged 658 ppm; NO_x emissions averaged 185 ppm. There were no statistically significant reductions observed in SO₂ and NO_x emissions relative to the control sample.
- iii. The BF2 briquettes burned with high intensity and starved the system of oxygen resulting in excessively-high CO emission and difficulty in obtaining reliable emissions data. The bed burnout was about 97%. While there did not appear to be significant reductions in SO₂ emissions, in the one test in which the burn rate was kept under control, NO_x emissions were 126 ppm, or about 32% less than from the control sample.

7. ECONOMICAL FEASIBILITY

7.1 Goals and Objectives

The goal of this task was to conduct an economic feasibility study on the production of a premium fuel using fine clean coal and wood waste. The economic evaluation considered the briquetting operation as an integral part of an operating preparation plant where quality benefits provided by the briquettes could be used to positively enhance recovery in the coarser coal cleaning circuits of a traditional coal preparation plant.

7.2 Introduction and Background

Many studies have been conducted by professionals in the coal industry to quantify the economical benefits of producing coal briquettes from fine coal. Without tax incentives, the economics, in general, have not justified the capital expenditure. However, the evaluations were based on the incremental gains in production provided by the briquette operation without considering the possible benefits that the added briquette quality could have on the recovery achieved in the coarser coal cleaning circuits.

The target market for the premium fuel produced in this study is the electric generation industry where heating value is the most important fuel characteristic. The heating value of a given coal is directly proportional to its ash and moisture contents. An increase in both factors reduces the heating value. As such, decreasing the value of both quantities during coal preparation is equally important. To simplify the targeted reduction, the sum of the ash and moisture contents are generally referred to as the *total inert content*.

To achieve the most efficient reduction in the total inert coal, the run-of-mine (ROM) coal is typically separated into different size fractions and cleaned in separate circuits that utilize coal cleaning technologies most appropriate for the given particle size fraction. Three processing circuits are commonly employed in coal preparation plants, i.e., coarse circuit (100 x 10 mm), intermediate circuit (10 x 1 mm) and fine circuit (-1 mm). Based on washability analysis data and available coal cleaning technologies, the efficiency of ash rejection generally improves with a decrease in particle size. In other words, the lowest product ash content material can be realized

from the fine coal cleaning circuit while recovering the most coal depending on the separation technology employed. However, moisture content in the plant product exponential increases with a decreasing particle size as shown by a plant water balance in Table 7.1. Therefore, the use of advanced fine coal circuit to reduce plant product ash content and yield may be countered by the negative effect of increasing moisture content and thus total inert content. As a result, optimum plant operations needed to produce a required total inert content while maximizing mass yield to the product often results in a decision to limit or complete remove the fine coal circuit production.

Table 7.1. Product moisture balance for a 1000 ton/hr preparation plant; 7.8% total product moisture (Meenan, 2005).

	Plant Feed	Plant Mass	Product Surface	Plant Product	Product
Circuit	Mass Weight	Yield	Moisture	Water	Moisture
	(%)	(%)	(%)	(tons/hr)	Distribution (%)
Coarse	50.0	65.0	4.0	13.5	22.0
Intermediate	38.0	80.0	5.0	16.0	26.0
Fine	12.0	80.0	25.0	32.0	52.0
Total	100.0			61.5	100

A more clear understanding of the problem can be realized by an evaluation of Figure 7.1. To optimize the plant mass recovery, the incremental grade from each process circuit must be maintained at a constant value. The incremental grade refers to the quality of the last unit of weight recovered or the quality of the 'dirtiest' particle. If the requirement to achieve a certain heating value requires a 30% incremental inert content, no fine coal recovery could be realized in the hypothetical example unless coal recovery in the coarser circuits is reduced to achieve lower inert contents. This example further explains the abundance of plants that currently do not recover the -150 micron (-100 mesh) coal. However, it is noted that, if the quality requirements were mainly associated with the product ash content, fine coal recovery would be very beneficial due to an increased yield, which can be visual understood by removing the water components from Figure 7.1 and plotting as a function of ash content.

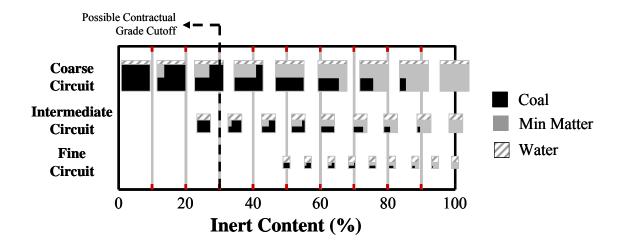


Figure 7.1. Schematic showing the inability to recover the fine coal due to the need to maintain constant incremental inerts and the amount of water associated with fine coal.

As stated previously, partial fine coal recovery is often used when product moisture is an issue. The majority of the water associated with -1 mm (16 mesh) coal is associated with the -45 micron (-325 mesh) fraction as shown in Table 7.2. In this case, 2.7% (= mass of -45 micron material in product) of the total plant product is associated with 33.9% (= 27.7 + 6.2) of the total water in the product. As such, it is common to employ gravity-based technologies to clean the nominal 1 x 0.15 mm (16 x 100 mesh) size fraction and froth flotation systems for the nominal 150×45 micron (100×325) fraction.

Table 7.2. Water distribution in the -1 mm size fraction of a 1000 tph plant (Meenan, 2005).

Particle Size Fraction	Weight	Water Mass Rate	Percent of Total Plant
(mesh)	(%)	(tons/hr)	Product Water Content
+28	26	2.9	4.8
28 x 100	28	4.7	7.6
100 x 200	10	1.9	3.1
200 x 325	8	1.7	2.7
325 x 500	13	3.8	6.2
-500	15	17.0	27.7
Total	100	32.0	52.0

Briquetting the fine coal provides the benefits of reducing the moisture of the final product as well as alleviating other concerns with fine coal recovery such as transportation and handleability issues. As indicated by the quality analysis of the laboratory (Table 2.4) and pilot-scale (Table 6.6) briquettes produced from a coal and sawdust blend, the premium fuel contained low amounts of ash and total moisture. Total moisture values were less than 5% by weight.

Based on the benefits of producing a fine premium fuel product containing low ash and total moisture contents as discussed in the above paragraphs, an economic analysis was performed which included the briquetting operation as an integral component of an operating preparation plant as indicated in the flowsheet of Figure 7.2. Briquettes formed from coal flotation concentrate and a blend of flotation and spiral concentrates were considered. Also, an evaluation of a stand-alone fine coal recovery and briquetting operation was completed as represented by the dashed lines in Figure 7.2.

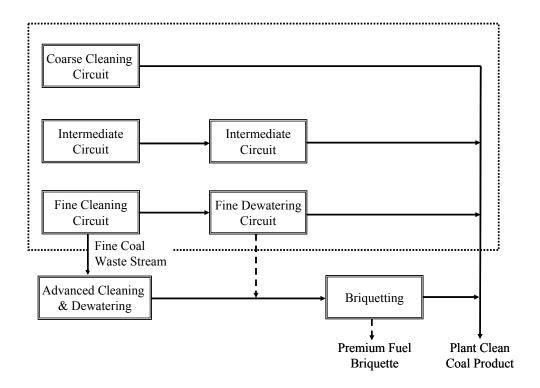


Figure 7.2. Flow diagram showing the advanced cleaning, dewatering and briquetting operation as an integral component of a coal preparation plant operation; dotted lines = typical plant flow.

7.3 Plant Performance

The technical and economical benefits of the coal and sawdust briquette production were based on integration into the operations at the James River Leatherwood preparation plant. The plant feed weight distribution according to particle size and separator circuit type is provided in Table 7.3. The -100 mesh material is not treated to recover the coal in the current plant and thus reports to the thickener and subsequently to the fine coal waste impoundment. According to release analysis data (Figure 2.1), about 54% or 50 ton/hr of high quality coal can be recovered from the current waste stream. The performances achieved by the dense medium vessel and dense medium cyclone are provided as a function of separation density in Table 7.4.

Table 7.3. Feed particle size distribution and separators used in the 1400 ton/hr preparation plant.

Particle Size	Weight Distribution		Separator
Fraction	Percentage	Tons/hr	Separator
+1/4-in	59.15	828.1	DM Vessel
1/4-in x 28 mesh	25.54	357.6	DM Cyclone
28 x 100 mesh	8.51	119.1	Spirals
-100 mesh	6.80	95.2	none
Total	100.00	1400.0	

Table 7.4. Dense medium vessel and cyclone performances for the 1400 ton/hr plant.

Relative Separation	DM Vessel Performance		DM Cyclone P	erformance
Density	Product Ash %	Yield %	Product Ash %	Yield %
1.30	4.47	24.96	4.48	34.15
1.35	5.70	34.78	5.12	44.32
1.40	6.60	43.21	5.80	51.69
1.45	7.62	48.31	6.50	56.85
1.50	8.60	52.24	7.14	60.52
1.55	9.55	55.35	7.69	63.03
1.60	10.46	57.88	8.19	64.81

Since the performance achieved by spiral concentrators is not normally controlled to achieve variable product grades, a single set of performance data was used in the analysis, i.e., product ash content = 8.51% at a mass yield of 66.1%. Likewise, the performance projected for the flotation column system based on release analysis data included a product ash content of 5.41% while recovering 53.7% of the feed mass.

As indicated in the introduction section, the evaluation was conducted on the basis of total inert content in the product where the total inert content is the sum of the ash and moisture contents. The total moisture contents in the products from each circuit were maintained at constant values and were not changed with variations in ash content. The total moisture contents used for the DM vessel, DM cyclone and spiral products were 2.5%, 6.5% and 12.0%, respectively. When flotation columns were considered without a briquetting operation, a moisture content of 22.0% was used for the -100 mesh material assuming a plate and frame press or similar filtration technology was employed to ensure a high recovery of the ultrafine -325 coal. A significantly lower total moisture content of 8.0% was considered when the coal and sawdust briquetting operation was evaluated, which was based on the laboratory (Table 2.4) and pilot-scale (Table 6.6) data presented in this report. The 8.0% value was considered a conservative estimated since significantly lower moisture values were actually achieved in this study.

The optimum performance of the plant was determined on the basis of maintaining a constant incremental total inert content from each circuit. The constant incremental grade approach is a proven methodology for maximizing the mass yield to the product stream. However, in this case, the spiral and froth flotation performance could not be varied and thus the total inert contents from each circuit were fixed. The total inert content for the spiral product was 20.5% whereas a value of 27.41% was considered for the flotation product when briquetting was not included. The briquette product has a total inert content of 13.4%.

The addition of column flotation to recover the 51 tons/hr would seemingly have a positive impact on overall plant yield. However, due to the relatively high amount of moisture that reports with the flotation product, even after using an efficient dewatering device such as the plate-and-frame press, the coarse circuit separation gravity values must be lowered to decrease the total inert values to a level that meets contract specifications. As a result, the overall plant yield decreases significantly after the addition of the flotation product as shown in Figure 7.3. However, by combining the fine coal with the sawdust through a briquetting process, the additional tons recovered in the plant product does not negatively affect the total inert content. As such, an increase in the overall plant yield is obtained at an equivalent heating value. At a

constant inert value of 13.1%, the plant yield is increased by 51 tons/hr as indicated by the performance data in Table 7.5, whereas a 36 ton/hr reduction is incurred when flotation is added without briquetting.

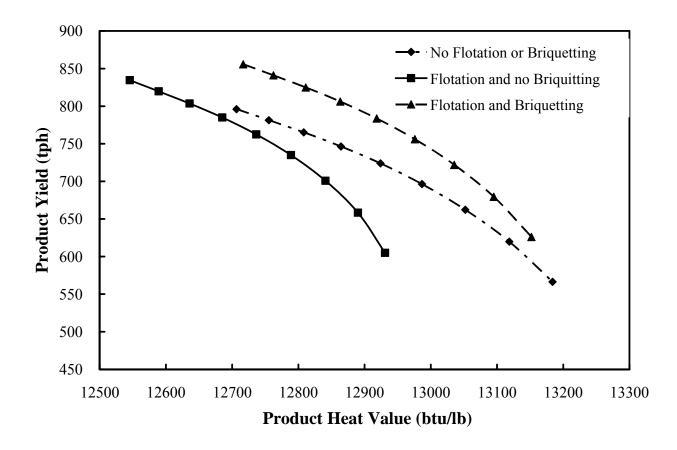


Figure 7.3. Comparison of plant performances as a function the product heating value when the plant i) excludes -100 mesh coal recover, ii) includes column flotation without briquetting and iii) includes column flotation with briquetting.

Table 7.5. Plant production improvement using a 50 tph coal-wood briquetting system.

Process	Current (Operation	Add F	lotation	Add Flotation	& Briquetting
Circuit	Inerts (%)	Yield (tph)	Inerts (%)	Yield (tph)	Inerts (%)	Yield (tph)
DM Vessel	11.5	443.0	9.9	386.3	11.5	443.0
DM Cyclone	13.9	185.9	12.5	155.5	13.9	185.9
Spirals	20.51	78.8	20.5	78.8	20.5	78.8
Flotation	0.0	0.0	27.5	51.1	13.5	51.1
Total	13.1	707.7	13.1	671.7	13.1	758.8

7.4 **Economic Evaluation**

7.4.1 **Capital and Operating Costs**

Based on the performance evaluations (Section 7.3), the economic evaluation was performed for a 50 ton/hr plant addition. Since the fine coal to be recovered is a waste stream, the assessment was based on incremental costs. As such, the cost of mining and processing the coal already incurred were not included. Only the capital and operating costs of the addition flotation and briquetting system were included.

The total capital costs for the major equipment items are listed in Table 7.6. Where possible, manufacturers of the equipment provided to cost data based on the characteristics of the James River coal and the desired production rate. Other capital cost values were obtained from a cost estimate guide for mineral processing equipment. The total major equipment cost was \$3.62 million.

The costs of auxiliary equipment and facilities, site modification and installation were considered as a function of the total major equipment cost using standard estimation guidelines for mineral processing facilities (Mular, 2002). As shown in Table 7.7, the total capital cost for the 50 ton/hr facility was determined to be 2.23 times the major equipment cost or \$8,075,811.

Table 7.6. Major Capital Equipment Cost for 50 tph fine coal-sawdust briquetting system.

Major Equipment	Quantity	Unit Cost	Total Cost
Komarek DH 500- 28x27x2	1	\$795,000 ¹	\$795,000
Pug Mill	1	$67,800^2$	67,800
Dryer/Curing Chamber	1	$1,150,000^3$	1,150,000
Conveying System	3	$82,880^2$	248,640
Plate-and-Frame (1000 ft ²)	2	$500,000^2$	1,000,000
Column Flotation Cells	2	$180,000^4$	360,000
Total Major Equipment Cost			\$3,621,440

¹ Quote provided by Komarek ² Western Mining Cost Estimate Handbook

⁴ Quote provided by Eriez Manufacturing

Table 7.7. Total capital cost estimate for 50 ton/hr coal-sawdust briquetting system.

	Component Cost	Fixed Capital
Plant Cost Component	Ratios (cost/equip.	Cost
	capital cost)	(\$)
Equipment Capital	1.00	3,621,440
Equipment Installation	0.17	615,645
Piping, materials & labor	0.07	253,501
Electrical, materials & labor	0.13	470,787
Instrumentation	0.03	108,643
Process Buildings	0.33	1,195,075
Plant Services, water & air	0.07	253,501
Site Improvements	0.03	108,643
Field Expenses, construction	0.10	362,144
Project Management	0.30	1,086,432
Total Fixed Capital Cost	2.23	\$8,075,811

As apparent from the research findings discussed in Chapters 5 and 6, the operating cost associated with briquetting is highly variable due to the dependency on binder type, coal characteristics and the required strength of the briquette. As such, the economic evaluation was performed over a range of briquette operating costs from \$2 to \$15/ton.

Estimates of the other operating costs are provided in Table 7.8. These costs are based on general experience and estimations. The addition of two labor position was considered, one for each operating shift at a cost of \$75,000 annually each. The sawdust was assumed to be provided at a cost that was associated with transportation only. Using a 40 ton payload, a single truck load per day would fill the needs of the briquetting operation. The cost was estimated to be \$150/load based on a 40 mile round trip. The total operating cost including an administrative cost but minus the briquetting cost was estimated to be \$6.83/ton produced.

Table 7.8. Operating cost estimate for the coal-sawdust system minus briquetting and impoundment recovery costs.

Item	Description	Cost(\$)
Column Flotation		\$2.41
Fuel Oil	1 lb/ton treated; \$2.00/gallon; \$0.50/ton	
Frother	0.5 lb/ton; \$0.75/lb; \$0.75/ton	
Power	\$0.20/ton	
Maintenance	40% of total operating costs	
Plate and Frame Filter		3.00
Manpower	2 additional positions; \$75,000/year	0.60
Sawdust Transportation	1-40 ton payload/day; 20 mile;\$150/load	0.20
Subtotal Operating Costs	6.21	
Administrative Costs (10% of subtotal) 0.62		
Total Operating Cost minus Briquetting Costs \$6.83		

7.4.2 Economic Assessment

The projected increased revenue was determined based on a current steam coal market value of about \$1.40/Mbtu and a premium fuel briquette material with a heating value of 12,900 btu/pound as received. The equivalent per ton price is about \$36. The annual operating hours for the 50 ton/hr addition was expected to coincide with current plant operations which run 16 hours/day, 6 days/week, 52 weeks/year. As shown in Table 7.9, the estimated annual revenue is approximately \$9 million.

Table 7.9. Annual revenue estimate.

Item	Description	
Throughput Capacity	Flotation and Briquette System	50 tons/hr
Annual Operating Hours	16 hrs/day*6 days/wk*52 wks/yr	4992 hrs
Annual Production	50 tons/hr * 4992 hrs/yr	249,600 tons
Briquette Heating Value	Based on laboratory and pilot-scale data	12,900 btu/lb
Annual Recovered Btu	12,900 btu/lb * 249600 tons*2000 lbs/ton	$6.44 \times 10^6 \text{ Mbtu}$
Market Value	Based on current steam market value	\$1.40/Mbtu
Estimated Annual Revenue	$6.44 \times 10^6 \text{ Mbtu/yr} * \$1.40/\text{Mbtu}$	\$9,016,000

Since the tax rates and incentives vary from state-to-state and local-to-local, tax costs were not considered in the analysis. As such, the total annual net profit was determined by subtracting the estimated operating cost including the briquette process costs from the estimated annual revenue (Table 7.9). The total life for the operation was considered to be 10 years.

Two scenarios were considered: i) froth flotation and briquetting treatment of a current plant fine coal tailings stream and ii) froth and briquetting treatment of a waste impoundment. For the waste impoundment case, an extra operating cost of \$12/ton was considered for extracting and management of the impoundment.

When treating the current fine coal waste stream, the internal rate of return (IRR) is attractive for all briquette operating costs evaluated as shown in Figure 7.4. However, the IRR falls below a minimum attractive value of 12% at a briquetting cost level above \$8/ton when recovering coal from an impoundment. The analysis clearly indicates potential of realizing a significant economical benefit from recovering coal that is currently rejected to the fine waste stream due to the inability of achieving acceptable moisture levels as well as handleability and transportation issues. Additional incentives would be realized by reducing the total waste material requiring placement into impoundments or other approved areas.

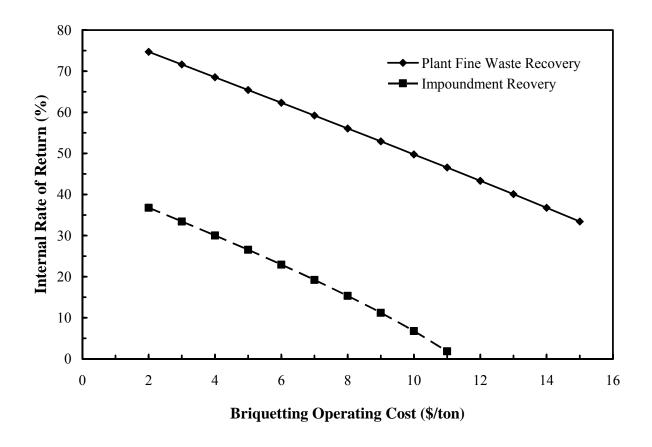


Figure 7.4. A comparison of internal rate of return values as a function of briquetting operating costs for two treatment scenarios: i) fine coal waste stream treatment and ii) fine coal waste impoundment treatment.

If a briquette operating cost of \$12/ton is assumed, the annual profit before tax would be slightly greater than \$4 million as shown in Table 7.10. The binder cost used to establish binder concentration throughout the investigation as described in Chapters 5 and 6 was \$8/ton. Considering power and other operating expenses, a \$12/ton value should be fairly conservative. Based on the total capital cost (Table 7.7), the return on investment would occur in approximately 2 years. In this case, the IRR would be an attractive 43%.

Table 7.10. Economic benefit summary for a 50 ton/hr coal-sawdust briquette addition to an operating preparation plant assuming a \$12/ton briquette operating cost.

Total Annual Revenue		\$ 9,015,552
Annual Briquette Operating Costs Annual Other Operating Costs	\$3,294,720 1,705,018	¢ 4 000 729
Total Operating Costs		\$ 4,999,738
Total Annual Profit		\$ 4,015,814
Total Capital Cost		\$8,075,811
Return on Investment		2 years
Internal Rate of Return		43%

7.5 Summary and Conclusions

An evaluation was conducted to access the economic benefits of producing a premium fuel from sawdust and fine coal recovered from a process waste stream. The analysis was performed based on integration of the coal recovery and briquetting operation into an existing coal preparation facility. Specifically, the installation of the process was evaluated using the operating and performance data of the James River Leatherwood preparation plant located in eastern Kentucky. Conclusions derived from the analysis are as follows:

- i. Characteristic data indicated that about 50 tons/hr of high quality, high btu coal (> 13,000 btu/lb) can be readily recovered from the fine coal waste stream of a 1400 ton/hr preparation plant located in eastern Kentucky. Recovering the fine coal would result in an increase in annual production of 249,600 tons, which equates to an energy gain of 6.5 trillion btu annually at a single mining operation.
- ii. Considering the using of flotation and an advanced dewatering technology to recover the coal in the -100 mesh size fraction would cause a decrease in the overall plant yield due to the moisture recovered from the fine coal recover. When considering a 22% moisture level for the dewatered flotation product of a 1400 ton/hr preparation plant, the overall plant yield decreased by about 37 tons/hr while ensuring a constant product heating value.

- iii. An increase in mass yield to the product stream of about 50 tons/hr may be realized when the fine coal and sawdust are blended into a briquette product. The low moisture content of the coal-sawdust briquettes allows the material to be blended with the overall plant product without negatively affecting the product heating value and thus plant yield.
- iv. The briquette production of 50 tons/hr includes the use of sawdust at a 5% concentration by weight. As such, the annual use of sawdust for the single operation would total 4992 tons. Given a heating value contribution from sawdust of around 6000 btu/lb, the total energy recovered from the wood waste product would be 59,900 Mbtu annual. Considering a market value of \$1.40/Mbtu, the total market value recovered at one operation would equate to \$83,866.
- v. The total capital cost including installation for the 50 ton/hr fine coal recovery and briquetting operation was determined to be \$8,075,811.
- vi. The incremental operating cost for the fine coal recovery and briquetting operation was estimated to be \$6.83/ton of briquettes plus the cost of the briquetting process.
- vii. Assuming a steam coal market value of \$1.40/Mbtu, the net gain in revenue was calculated to be about \$9 million annually.
- viii. For an installation treating directly treating the current fine coal waste stream from an operating preparation plant, the internal rate of return was greater than 30% over the entire range of briquetting costs from \$2 \$15/ton.
 - ix. When the fine coal waste material is extracted from an impoundment at a cost of \$12/ton, the internal rate of return becomes unattractive for briquette operating costs above \$8/ton.
 - x. An increase in the annual profit before taxes of about \$4 million was estimated for the 50 ton/hr operation treating an active waste stream based on a briquetting cost of \$12/ton of

product. Thus, the return of investment would occur in approximately 2 years. The internal rate of return was 43%.

8. SUMMARY AND CONCLUSIONS

8.1 Accomplishments

Goals or Objectives	Accomplishments
Goal: Produce a premium fuel from the waste products of the coal and timber industries containing around 9,000 to 10,000 btu/lb.	Durable briquettes with a heating value greater than 14,000 btu/lb were produced from blends of 10% sawdust and 90% coal fines at a binder addition equating to \$8.00/ton.
Objective 1: Clean fine waste coal using advanced separation technologies	 i. Column flotation efficiently recovered greater than 90% of the coal in two fine coal waste streams while providing clean coal products with less than 10% ash. ii. Binders were not found to be effective as flotation collectors. iii. Selectivity of the froth flotation process was improved by the novel concept of adding highly hydrophobic particles into the froth zone to encourage selective detachment of low grade particles. A 5

absolute percentage point reduction in the

iv. The performance of centrifugal teeter bed

separator was improved by a unique

technique involving the injection of air

bubbles into the feed stream, which

aggregates and a lower medium density. A 10 - 20 absolute percentage increase in

density coal-bubble

product ash content was realized.

low

resulted

in

recovery was obtained.

Objective 2: Dewater clean coal to lower moisture levels than currently realized by adding wood fibers utilizing an enhanced dewatering technique

- Moisture reductions to approximately 20%
 by weight were achieved on -150 micron flotation concentrate using advanced filtration techniques.
- ii. Pressure filtration with the addition of 0.25 kg/ton of a cationic surfactant reduced the moisture content to 15% by weight.
- iii. Based on a detailed test program, the addition of sawdust reduced the dewatering performance of vacuum and pressure filters.
- iv. In general, the binders did not improve dewatering performance.

Objective 3: Combine and reconstitute clean, dewatered coal and sawdust through briquetting to form a utility fuel that can be easily handled through the transportation process

- i. Based on relative performance, the most cost-effective binders were identified from a list of over 50 formulations using batch laboratory and continuous pilot-scale briquetting devices.
- ii. Briquettes were evaluate for compressive strength, drop shatter strength, water resistance and attrition resistance.
- iii. The impact of a number of briquetting parameters on the physical properties of the briquettes was evaluated.
- iv. The optimum blending ratio for obtaining the maximum briquette packing efficiency from mixtures of spiral and froth flotation products was determined.

Objective 4: Evaluate burn characteristics and assess emission impacts by performing combustion tests on the final premium fuel product

- Three larger-scale combustion tests of briquettes prepared from blends of fine coal and sawdust were completed. The combustion tests were performed on a significantly larger scale combustion unit than originally proposed.
- ii. No difficulties were encountered during these tests
- iii. The test results indicated that the combustion properties of the three briquette samples were similar with the exception that one of the formulations burned much more rapidly and with a significantly higher level of bed burnout relative to a control sample of binderless briquettes.

Objective 5: Perform a detailed economic evaluation of the total process.

- An economic analysis was conducted on the basis of recovering 50 tons/hr of high quality coal from the fine waste stream of a currently operating 1400 ton/hr coal preparation plant.
- ii. The capital cost for a 50 ton/hr fine coal recovery plant and coal-sawdust briquetting system was estimated to be around \$8 million.
- iii. Based on a briquetting operation cost of \$12/ton, the internal rate of return was determined to be an attractive 43% with a return on investment in about 2 years.

8.2 Conclusions

8.2.1 Sample and Briquette Characterization

The analysis results obtained for coal samples collected from the fine waste streams in two coal preparation plants located in eastern Kentucky revealed that a significant amount of high heating value coal is currently being disposed into the slurry impoundment. At one operation, about 22% of the material had a particle size greater than 37 microns (400 mesh) and a heating value exceeding 13,900 btu/lb on an air-dried basis. Given a plant feed rate of 1,400 tons/hr, the amount of high quality coal being disposed was around 50 tons/hr. Likewise, the +37 micron fraction of another waste stream represented 39% of the total mass and had a heating value of around 9,000 btu/lb. Both coal sources were found to respond well to froth flotation. Product ash values below 10% were achieved by flotation on both fine coal waste materials while achieving combustibles-recovery values greater than 90%.

Sawdust generated from several wood types and sources was analyzed for heating value, particle size analysis and surface charge. The sawdust from oak wood provided the highest heating values of around 7,000 Btu/lb as received. The average heating value of all wood types was 6,700 Btu/lb. Given that 35,000 tons of sawdust is discarded in Kentucky annually, the monetary value of the wood waste is \$656,000.

8.2.2 Fine Coal Recovery

A pilot-scale advanced flotation unit commercially known as the Jameson Cell was used to recover coal from active fine coal waste streams in two eastern Kentucky coal preparation plants (i.e., James River's Leatherwood facility and Cooke & Sons' Sapphire facility). Product ash values less than 5% were achieved which resulted in enhanced heating values of around 14,000 Btu/lb on an air-dried basis. The clean coal samples were used in the majority of the laboratory dewatering and briquetting tests.

For the continuous briquette tests performed on a pilot-scale unit, the flotation concentrate samples were collected from the product stream of a flotation column at TECO's Clintwood-Elkhorn No. 3 coal preparation plant. The coal was originally from the Elkhorn No. 3 coal seam.

The flotation concentrate contained about 14% ash and had a heating value of around 14,000 Btu/lb on an air-dried basis.

Two briquetting binders that were identified as potential flotation collectors were tested by quantifying their effects on coal flotation rates. The REAX binder had a negative impact on flotation rates with the rates decreasing with increasing reagent concentration. Selectivity also deteriorated with the use of REAX as compared to the performance provided by fuel oil No. 2. On the other hand, tall oil provided good collector performance. However, the overall flotation rate was three-to-five times less than that realized by fuel oil. Based on these findings, it was concluded that the binder reagents are not suitable for use as a collector in coal flotation.

Improvement in the selectivity achieved by froth flotation processes was achieved by the addition of coal having a higher degree of hydrophobicity into the froth zone of a flotation column. The more hydrophobic material attaches to the bubbles and, as bubbles coalesce and decrease surface area availability, the more weakly hydrophobic mixed-phase material and coal pyrite are selectively detached due to lower binding energies with the bubble surface. The detached particles report to the collection zone where they are more likely to move into the tailings stream. The result was a 5 absolute percentage point decrease in the product ash content at equal recovery values.

Teeter-bed technologies have reportedly achieved exceptional separation performance when treating 1 x 0.15 mm coal. In this study, a centrifugal teeter-bed technology known as the Knelson Concentrator was evaluated for its potential to improve the selectivity of cleaning -150 micron coal. Fundamentally, gravity-based separations should always be superior to those obtained by froth flotation. Tests conducted on a relatively 'easy-to-clean' coal and a 'difficult-to-clean' coals showed that this unit has can provide significant reductions in ash content. The ash content for the 'difficult-to-clean' coal was reduced from nearly 22% to values approaching 8% while recovering approximately 70% of the combustibles. This equates to a performance that was superior to that achieved by froth flotation.

Evaluation of the process separation efficiencies revealed that the Knelson unit has the ability to provide a wide range of relative separation densities from a low value of 1.46 RD to a high value of 2.18 RD. However, low-density separations resulted in a significant amount of coal being bypassed to the underflow tailings stream while high-density separations provided a substantial amount of ash-bearing material being bypassed to the overflow product stream. The probable error values (E_P), which defines the overall separation efficiency, varied within the range of 0.245 to 0.300. Based on a particle-size performance analysis, inefficiencies appear to be associated with the cleaning performance achieved on the finest-size fraction (i.e., 75 x 44 μ m).

To improve the performance achieved by the Knelson Concentrator, air-bubbles were generated in the feed coal stream and injected into the unit. The hypothesis was that the air bubbles would collide with and attach to the coal particles and create low-density aggregates which are more likely to report to the clean coal product stream. For the 'easy-to-clean' Powelton coal which had a high degree of floatability, air bubble injection was found to have a significant effect on the operating characteristics of the Knelson Concentrator and the separation performances. A 10 – 20 percentage point improvement in recovery was obtained by injecting air bubbles into the feed stream while also providing the ability to lower the product ash by 2 percentage points. The improvement in recovery was largely due to a decrease in coarse-coal losses to the tailings stream. Lower product ash values are attributed to enhanced particle settling rates caused by a reduced medium density, which is a result of the high population of micron size bubbles. By manipulation of the operating parameters, the relative separation densities were varied from 1.3 to 1.8 with corresponding probable error values around 0.20.

The injection of air bubbles into the feed stream of Coalberg coal having weak flotation characteristics did not provide an improvement in the separation performance. However, the Knelson Concentrator reduced the ash content from about 18% to 8% while recovering almost 80% of the energy value. In addition, the separation performance was superior to that achieved by froth flotation, the process used to clean the fine coal at the test site. In conclusion, the exploitation of both density and surface-based property differences provided improvements in the separation performances achieved by an enhanced gravity concentrator when treating ultrafine, hydrophobic coal.

8.2.3 Advanced Dewatering

Using a vacuum dewatering technique, a filter cake with about 25% moisture was obtained. The addition of surfactants and flocculants had minimal affect in lowering the moisture; however pretreating the slurry with about 125 kg/t of water/oil emulsion (97% water, 2% fuel oil, and 1% cetyl pyridinium chloride (CPCL), a cationic surfactant) lowered the filter cake moisture to 19%. Using a relatively low pressure of 3.4 bar (50 psi), a filter cake with 18% moisture was obtained. Pressure filtration with the addition of 0.25kg/t of the CPCL reagent lowered the moisture to 15%. Using a combination of low pressure 1.3 bar (20 psi) for cake formation and high pressure 3.4 bar (50psi) for cake drying provided a filter cake with 19% moisture. Thus, it can be concluded that the best dewatering condition of the fine coal slurry was obtained using 3.4 bar (50 psi) pressure with the addition of a cationic surfactant.

A thorough experimental program was performed to evaluate the potential of improving dewatering performance by adding sawdust to the feed stream. The test results revealed that saw dust was detrimental to the filter cake moisture. Likewise, the use of briquette binders as a dewatering aid did not prove to be beneficial.

8.2.4 Laboratory Briquetting Studies

Guar gum, wheat starch, and REAX/lime were identified as the best performing binders for briquetting coal and sawdust when applied on an equivalent-cost basis. Over 50 formulations were investigated. The parameters that exhibited the greatest impact on briquette performance were binder concentration; sawdust concentration, particle size, and type; cure temperature; and ash content. Parameters that had the least impact on briquette properties, at least over the ranges studied, were moisture content, briquetting force, and briquetting dwell time. More efficient compaction and higher briquette densities and cured strengths could be obtained by blending coarser coal fines with fine flotation fines, both with and without added sawdust. These effects were more pronounced when a binder was added.

8.2.5 Pilot-Scale Testing

Continuous Briquetting: To determine the potential of producing a premium fuel from cleaned fine coal and wood waste, an evaluation in a continuous briquetting unit (i.e., Komarek Model B-

100) was conducted. The investigation included a parametric study and a re-evaluation of the binders that were chosen on the basis of laboratory data in a batch unit. The most effective binders were identified and the optimum conditions quantified and used to produce the briquettes for the combustion studies. The conclusions from the evaluation were:

The main goal of the project was achieved, i.e., the production of a premium fuel from fine coal and wood waste having a heating value between 9,000 and 10,000 btu/lb. The briquettes produced by the 200 lb/hr Komarek briquette unit contained 5% sawdust and had a heating value of about 12,700 Btu/lb as received.

Although the main focus of the project was to combine coal and wood waste into durable briquettes, it was found that the addition of sawdust to the clean coal deteriorated the strength of the briquettes. The highest compressive strength values were obtained using no sawdust. To maintain the briquette strength when adding sawdust, binder concentration must be increased.

Optimizing the mass feed flow rate to the briquetting roll press is a critical issue. A flow rate lower than the optimum value results in a lower compressive force being applied during briquette formation and, in turn, in production of briquettes with poor handling characteristics. Feed rates exceeding the optimum may result in a stoppage of the briquetter. As such, erratic mass flow behavior, which is related to high feed-moisture values, produces briquettes of varying quality.

The upper limit of moisture that can be tolerated in the continuous briquetter is determined by the ability to consistently flow the feed blend through the hopper chute that feeds the screw conveyor. The use of moisture values greater than the upper limit results in the inability of the solids to free flow through the chute. Laboratory briquetting studies indicate that maximum briquette strengths are achieved with relatively high moisture levels of 20-25% by weight. A study of the relation between moisture content and briquette strength in the continuous unit indicated that higher moisture values are not detrimental, and in fact can be beneficial to briquette strength. However, due to the problems in attaining consistent feed rates, the practical upper limit for the Komarek unit was in the range of 12-14% moisture.

Binder type has a significant effect on the maximum feed-blend moisture that can be tolerated. For example, blends containing guar gum binder were found feed at a reasonably consistent rate at moisture levels as high as 15% by weight. Other binders, e.g., molasses/lime and the BF2 mixture, provide superior briquette strength when added to low moisture feeds (<12% by weight). As such, these latter binders could be used to provide maximum briquette strength under the required feed conditions of the Komarek unit. However, significant costs will be incurred to achieve the required moisture level with -150 micron (-100 mesh) coal.

Combustion Tests: Combustion tests were conducted on three batches of briquettes using a Stoker simulator unit at The Energy Institute of The Pennsylvania State University. Two briquette batches were formed from 95% clean coal and 5% sawdust using two different binder multi-component binder formulations (i.e., BF1 and BF2) as were identified in the laboratory and continuous briquetting studies. The third batch was used as a control material for comparison purposes and thus was comprised of fine clean coal and sawdust with no binder.

For the control briquettes made with the fine clean coal and sawdust without binder, the bed burnout was about 87.3%. CO and CO₂ emissions were 240 ppm and 15.5%, respectively. Average SO₂ and NO_x were 705 ppm and 186 ppm, respectively.

For the BF1 briquettes, the bed burn out was about 85%; the CO and SO_2 emissions were 257 ppm and 658 ppm, respectively. The NO_x emission averaged 185 ppm. There were no statistically significant reductions observed in SO_2 and NO_x emissions relative to the control sample.

The BF2 briquettes burned with high intensity and starved the system of oxygen resulting in high CO emission. The bed burnout was about 97%. There were no significant reductions in CO or SO₂ emissions; however, the NO_x emission was reduced by about 32% relative to the control sample.

8.2.6. Economic Feasibility Analysis

An evaluation was conducted to access the economic benefits of producing a premium fuel from sawdust and fine coal recovered from a process waste stream. The analysis was performed based on integration of the coal recovery and briquetting operation into an existing coal preparation facility. Specifically, the installation of the process was evaluated using the operating and performance data of the James River Leatherwood preparation plant located in eastern Kentucky.

Characteristic data indicated that about 50 tons/hr of high quality, high Btu coal (> 13,000 Btu/lb) can be readily recovered from the fine coal waste stream of a 1,400 ton/hr preparation plant located in eastern Kentucky. Recovering the fine coal would result in an increase in annual production of 249,600 tons, which equates to an energy gain of 6.5 trillion Btu annually at a single mining operation.

The use of flotation and an advanced dewatering technology to recover the coal in the -100 mesh size fraction would cause a decrease in the overall plant yield due to the moisture recovered from the fine coal recover. When considering a 22% moisture level for the dewatered flotation product of a 1,400 ton/hr preparation plant, the overall plant yield decreased by about 37 tons/hr while ensuring a constant product heating value.

On the other hand, an increase in mass yield to the product stream of about 50 tons/hr may be realized when the fine coal and sawdust are blended into a briquette product. The low moisture and ash contents of the coal-sawdust briquettes allows the material to be blended with the overall plant product without negatively affecting the product heating value and thus plant yield.

The total capital cost including installation for the 50 ton/hr fine coal recovery and briquetting operation was determined to be \$8,075,811. The incremental operating cost for the fine coal recovery operation was estimated to be \$6.83/ton of briquettes. Since the briquetting process cost is highly dependent on binder concentration required, which varies from site-to-site, the economic evaluation was performed over a range of briquette operating costs. Assuming a steam coal market value of \$1.40/Mbtu, the net gain in revenue was calculated to be about \$9 million annually. For an installation directly treating the current fine coal waste stream from an operating

preparation plant, the internal rate of return was greater than 30% over the entire range of briquetting costs from \$2 - \$15/ton.

An increase in the annual profit before taxes of about \$4 million was estimated for the 50 ton/hr operation treating an active waste stream based on a briquetting cost of \$12/ton of product. Thus, the return of investment would occur in approximately 2 years with an attractive internal rate of return of 43%.

PRODUCTS DEVELOPED

Publications

- Honaker, R. Q., Taulbee, D., Parekh, B. K. and Tao, D., "Premium Fuel Production from Coal And Timber Waste," SME Annual Meeting, Denver, Colorado, Preprint No. 04-142, February 2004.
- ii. Honaker, R. Q., Taulbee, D., Parekh, B. K., and Patil, D., "Energy Recovery from Coal And Timber Waste," *Proceedings*, 30th International Technical Conference on Coal Utilization & Fuel Systems, Clearwater, Florida, ISBN 0-932066-30-6, April 17 21, 2005, pp. 89 100.
- iii. Honaker, R. Q., Taulbee, D., Parekh, B. K. and Tao, D., "Premium Fuel Production from Coal and Timber Waste," *Minerals and Metallurgical Processing Journal*, Volume 21, No. 4, 2004.
- iv. D. Taulbee, D.P. Patil, Rick Q. Honaker, and B. K. Parekh, "Briquetting of Coal Fines and Sawdust"; Proceedings of the 29th Biennial Meeting of the IBA, Clearwater, FL, Oct. 16-19, 2005.
- v. D. Taulbee, D.P. Patil, B.K. Parekh and R. Honaker, "Briquetting of Coal Fines and Sawdust: Part 2. Compaction and Combustion Studies," Proceedings of 29th Biennial Meeting of the IBA, Clearwater, FL, Oct. 16-19, 2005.

Collaborations

i. TECO Coal, James River Coal, and Cooke & Sons Mining; Coal companies that provided manpower, technical expertise, fine coal waste and flotation concentrate samples for the project.

- ii. H&S Lumber, Pine Mountain Lumber and Sandy Gaye Lumber; Timber companies that provided timber waste in the form of sawdust for the briquetting studies.
- iii. ADM, Meade-Westvaco, Northway Lignin, Omni Materials, ABC Coke, US Sugar Corporation, Marathon-Ashland, Anhauser-Busch, Hase Petroleum, PQ Corp., Akzo-Nobel, the Heritage Group, and Bob Rooksby; Companies and individuals who provided technical advice and binders for the briquetting study.
- iv. KR Komarek, Inc., briquetting equipment manufacturing company, discussions regarding the technical and economical aspects of briquetting, especially in regards to coal.
- v. Bruce G. Miller, Associate Director, The Energy Institute, College of Energy & Mineral Sciences, The Pennsylvania State University, C214 Coal Utility Laboratory, University Park, Pennsylvania 16802; Institute that performed the briquette combustion studies.

Technologies/Techniques

- i. Method of improving fine coal recovery by a froth flotation process. Specifically, the technique enhances the selectivity of the process which will provide benefits for fine coals sources containing pyritic sulfur and a significant amount of mixed-phase particles. The results obtained in this study show higher recovery and lower product ash contents when highly hydrophobic material is added directly to the froth zone to encourage a competitive bubble-particle attachment environment.
- ii. Air injection into a centrifugal fluidized bed separator to improve gravity based separations achieved on fine coal. Recovery was improved by 10 to 20 absolute percentage points for +45 micron (+325 mesh) coal.

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