FINAL REPORT

Contract No. DE-AC22-88PC88883

on

**DEVELOPMENT OF THE ELECTROACOUSTIC DEWATERING (EAD)
PROCESS FOR FINE/ULTRAFINE COAL**

to

**U.S. DEPARTMENT OF ENERGY
Pittsburgh Energy Technology Center**

October 31, 1991

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SUMMARY

Battelle, in cooperation with Ashbrook-Simon-Hartley (ASH), EPRI/CQ, Inc., and Professor S. Chiang of the University of Pittsburgh, conducted a two-phase research and development program to demonstrate the application of the electroacoustic dewatering (EAD) process to fine (-100 mesh) and ultrafine (-325 mesh) coals. The program was supported by the U.S. Department of Energy, Pittsburgh Energy Technology Center, and included industrial cost sharing by ASH and EPRI/CQ, Inc.

The program equally emphasized laboratory and continuous testing. In Phase I, batch EAD tests utilizing two types of coal and two feed sizes were conducted to (a) validate the technical feasibility of EAD to achieve moisture levels of 20 and 30 percent with -100 mesh and -325 mesh coals, respectively and (b) recommend operating conditions for continuous tests. In Phase II, a 1 m EAD belt press (belt width 1 m) process research unit (PRU) was modified and tested at CQ Inc., in Homer City, Pennsylvania, to (a) demonstrate the feasibility of continuous EAD, (b) obtain scale-up data and, (c) obtain process economics data. The results showed that EAD can be used to achieve final cake moisture levels as low as 22 and 31 percent for continuous dewatering of -100 mesh and -325 mesh coal, respectively. The process can be further improved by equipment modification to cost-effectively achieve potentially lower moisture levels. The laboratory results showed the minimum moisture levels to be 2 to 3 percent lower compared to the PRU, i.e., 20 percent for -100 mesh coal and 28 percent for -325 mesh coal, since the PRU could not be operated under as favorable process conditions as the laboratory unit.

THE NEED AND THE PROPOSED PROCESS

Because of the increasing emphasis on cleaning fine and ultrafine coals and the high cost and other problems with thermal drying, there is a need for enhanced, non-thermal dewatering. Commercial mechanical dewatering equipment cannot achieve moisture levels lower than about 35 and 45 percent

for -100 mesh and -325 mesh coals, respectively. The EAD process, on the other hand, was shown in this program to reduce moisture levels an additional 13 to 14 percent in continuous tests and an additional 15 to 16 percent in the laboratory tests compared with state-of-the-art equipment.

The EAD process utilizes a synergistic combination of electric and acoustic fields in conjunction with conventional mechanical dewatering processes. The main electric field mechanism is electro-osmosis caused by application of a DC potential when an anode and a cathode are brought in contact with a filter cake. The application of acoustic energy in the ultrasonic range is believed to enhance the electro-osmotic and mechanical dewatering by removing pore, capillary, and interstitial water through agglomeration.

A single-roll belt press, adapted to EAD has previously been shown to be commercially feasible for sewage sludge dewatering. A PRU based on this concept was adapted for coal dewatering. The feed to the PRU are filter cakes produced by conventional mechanical dewatering equipments such as vacuum disc filters and centrifuges. In this sense existing mechanical dewatering systems are not replaced; instead, EAD is used as a post-dewatering unit in place of thermal drying.

LABORATORY EAD TESTS

A batch-EAD system (7.6 cm I.D.) was used to simulate the belt press EAD concept. The initial tests were conducted to determine if coal flocculation was necessary to achieve satisfactory solids retention on porous, polyester filter belts used in EAD PRU. With the help of Professor Chiang, several effective coal flocculents were identified; however, the EAD belt press simulation results showed that it was neither necessary nor desirable to use flocculation. Later tests with PRU confirmed that solids retention without flocculents was high (99 percent).

Most laboratory work involved two-step parametric testing on -100 mesh and -325 mesh Upper Freeport coal samples. About two-thirds of the tests

were factorially designed to estimate the primary effects and interactions. These results were used to select variable settings to determine EAD parametric values that met target moisture objectives.

The parameters for -100 mesh coal were dewatering time, DC voltage gradient, ultrasonic intensity, and solids loading (i.e., cake thickness). Pressure was maintained at 5 psi (gauge). The EAD performance was analyzed in terms of (a) reduced moisture content of coal, (b) specific energy consumption (kWh/lb filtrate), (c) total energy cost [dollars/ton (DS) coal] at \$.05/kWh, and (d) throughput [tons (DS)/hr/m belt width]. The coal was prepared at CQ, Inc. by froth flotation and then centrifuged in the laboratory at Battelle, yielding an initial moisture level in the range of 39 to 41 percent. Dewatering for 6 minutes with pressure only (no EAD) resulted in an average final moisture level of 36.1 percent. On the other hand, the EAD tests, conducted from 1 to 6 minute dewatering intervals, resulted in final moisture levels of 32.1 to 19.8 percent. The specific energy and total energy cost increased with decreasing final cake moisture. At the lowest final moisture level (19.8 percent), the specific energy consumption was 0.250 kWh/lb filtrate, which corresponds to 10.07 dollars/ton (DS). At a lower moisture level (22.0 percent), specific energy consumption and total energy cost decreased to 0.187 kWh/lb, or 6.59 dollars/ton (DS). These specific energy values were 2 to 3 times higher than those observed for batch tests with -325 mesh coal. The difference can be attributed to the higher electrical conductivity of process water used at CQ, Inc., where the -100 mesh coal was prepared. The energy cost can be reduced by controlling the dissolved solids in process water, as was done in producing the -325 mesh coal sample.

A regression model that fit the -100 mesh EAD data, was developed. Both the observed data and regression model showed that increasing the levels of any of the four EAD parameters decreased the moisture content. Specific energy consumption increased with increasing dewatering time and voltage gradient but decreased with ultrasonic intensity from 0 to 0.88 W/cm^2 or with solids loading up to at least 12 kg (DS)/m^2 . Since an increase in solids loading also proportionately increases the throughput (capacity) of EAD belt press, it becomes a critical EAD parameter. The results also show that

increasing the dewatering time beyond about 4 minutes was ineffective and wasted energy.

The samples of the Upper Freeport -325 mesh coal were prepared at University of Kentucky by column flotation and pressure filtration, yielding a moisture level of 45 to 47 percent (average). In control tests (no EAD), the final cake moisture averaged 41.9 percent. On the other hand, the final moisture content with EAD was as low as 28.1 percent. The specific energy at this moisture level was 0.104 kWh/lb filtrate, which corresponds to 5.48 dollars/ton (DS) coal. At a somewhat higher moisture level of 29.3 percent, the specific energy consumption and total energy cost decreased to 0.059 kWh/lb filtrate and 2.90 dollars/ton (DS) coal, respectively.

The -325 mesh coal EAD parameters included the -100 mesh coal parameters as well as pressure. The observed results and a regression model showed that the moisture content as well as specific energy consumption were reduced with increasing pressure in the range of practical values for the EAD belt press (i.e., 0-6 psi). The results for other parameters were generally similar to those observed for -100 mesh coal. The ultrasonic intensity had a greater influence on reducing moisture content of -325 mesh coal than the -100 mesh coal. This difference probably results from the stronger shear-thinning effect of ultrasonics measured for -325 mesh coal than for the -100 mesh coal. The solids loading effect for -325 mesh reached an optimum at a lower value than that for -100 mesh coal. The data showed that a dewatering time greater than about 3 minutes was only marginally effective in decreasing cake moisture and wasted energy.

CONTINUOUS EAD PRU TESTS

An existing 1-m EAD belt press PRU was first modified and checked for mechanical performance at ASH facilities in Houston, Texas. The PRU was then tested at EPRI/CQ, Inc., facilities in Homer City, Pennsylvania during two test campaigns. In the first campaign, 22 tests were conducted with -100 mesh, Upper Freeport coal that had been cleaned by froth flotation and predewatered in a vacuum disc filter to a moisture level of 36 to 38 percent.

Results demonstrated the feasibility of continuous EAD in achieving a moisture level as low as 22 percent at a throughput as high as 1.35 ton (DS)/hr. The corresponding energy cost was 3.67 dollars/ton (DS) coal. The solids loading and voltage gradient had the most visible effect on final moisture content and ultrasonics had the least. The poor ultrasonics effect in the PRU tests compared to laboratory tests was probably due to poor ultrasonic coupling caused by a mechanical design problem with the ultrasonic seal in the PRU. The belt speed (dewatering time) was maintained at 1 m/min (2.7 minutes) and the maximum attainable pressure was 3.3 psi. Higher belt speeds and a cake thickness greater than 1.9 cm were desired to test the PRU at higher throughput conditions but were not possible due to a capacity limitation of the feed preparation plant.

A comparison of -100 mesh coal PRU test results with laboratory results under comparable process conditions showed that the final moisture values were about the same. However, the specific energy use in PRU was about 15 percent higher. It is believed that this difference is primarily a result of the poor ultrasonic coupling achieved in the PRU tests.

The PRU performance for -100 mesh could be improved by (a) improving the ultrasonic seal, (b) using a higher solids loading (corresponding to 3.8 cm thick feed cake), (c) employing higher pressures (greater than 3.3 psi), (d) using higher belt speeds (greater than 1 m/min) in combination with higher voltage gradients (greater than 50 v/cm), and (e) controlling the process water hardness and total dissolved solids. Based on implementing the first three improvements at two levels ("conservative" and "optimistic"), EAD performance for continuous dewatering was projected utilizing experimental results. Accordingly, the total energy costs to achieve a final moisture level of 20 percent at a throughput of 2.70 tons (DS)/hr/m belt width for the conservative (0.33 watts/cm² ultrasonics and 4.6 psi pressure) and optimistic (0.66 watts/cm² and 6 psi) cases are projected to be 3.36 and 1.48 dollars/ton (DS), respectively.

A second series of tests were performed on a 50 ton batch of -325 mesh coal. Because column-flotation- or microbubble-flotation-cleaned coals/sites were unavailable (as originally desired based on laboratory testing), a batch of -28 mesh froth-flotation-cleaned coal from the Homer City Power plant was obtained and reground at CQ, Inc. to -325 mesh size. The coal (a blend of several Upper Freeport coals) was predewatered by a solid bowl centrifuge to a moisture level that varied from 46 to 48 percent. All EAD tests were conducted at 3.3 psi pressure and 0.5 m/min belt speed (i.e., 5.4 min dewatering time). Higher belt speeds were not attempted because of the limited capacity of the grinding equipment. EAD reduced the moisture content of a 1.9-cm thick cake [corresponding to a throughput of 0.56 ton (DS)/hr], to as low as 31 percent. However, the energy cost was high, i.e., 7.77 dollars/ton (DS).

As in the case of -100 mesh coal tests, the only mechanical design problem encountered during -325 mesh coal testing was the poor ultrasonic coupling as a result of leaking ultrasonic seals. The coal feed was spread uniformly across the belt and discharged easily. All other equipment and instruments performed satisfactorily. The PRU design capacity for pressure was 3.3 psi which is below the optimum of 6 psi determined through laboratory testing. The belt speed was kept below the optimum to match the throughput of the feed plant.

The -325 mesh coal PRU results were comparable with laboratory results in terms of moisture reduction but not energy consumption. The PRU tests consumed 2 to 3 times higher specific energy than laboratory tests. This is believed to result mostly from the much higher electrical conductivity of the filtrate in the PRU tests; the poor ultrasonic coupling and lower cake pressure for PRU tests also contributed some increase in energy consumption as in the case of -100 mesh coal. The PRU specific energy consumption values for -325 mesh coal were of the same order of magnitude as for -100 mesh coal PRU tests. This probably results because the feed coals were prepared using similar process water and, therefore, had comparable electrical conductivities.

The -325 mesh coal performance is also projected to be significantly improved with the design-and-processing condition changes identified for -100 mesh coal. A thicker cake (e.g., 3.8 cm), a higher belt speed (e.g., 1 m/min), higher pressure (e.g., 4.6 psi), and improved ultrasonic seals can be implemented into a commercial EAD machine. Based on these improvements, projections of EAD performance were made for two levels of improvements, i.e., "conservative" and "optimistic". Accordingly, the total energy costs to achieve a final moisture level of 30 percent at a throughput of 2.24 ton (DS)/hr/m belt width for conservative and optimistic cases are projected to be 3.71 and 1.47 dollars/ton (DS), respectively.

EAD ECONOMICS

Economic analyses were carried out for EAD applications to -100 mesh and -325 mesh coal dewatering. Fixed capital cost estimates for EAD belt press, incorporating features to handle the desired cake thickness, pressure, belt speeds, and ultrasonic energy, were provided by ASH. The capital and operating costs were compared with thermal drying, which is the only commercial alternative to EAD. An indirect-heated dryer was selected because of the fine size of coal. Cost comparisons were made for various daily throughputs, based on a 16 hr/day operation with about 5 to 10 percent of coal preparation plant feed being in the fine/ultrafine range. The sensitivities of costs to various final moisture levels were also determined.

Based on the actual -100 mesh coal PRU operating conditions, which were suboptimal with respect to throughput and ultrasonic intensity, the EAD operating costs were found to be higher than thermal drying. On doubling the cake thickness to 3.8 cm, which can be handled in a commercial-size EAD machine with a minor redesign effort, the EAD costs were considerably lower than thermal drying at all throughputs. The economic analyses showed that EAD is more capital intensive than thermal drying, while thermal drying is much more energy intensive than EAD.

The -100 mesh coal EAD economics is projected to be further improved by design modifications to achieve pressures and ultrasonic

intensities utilized in laboratory tests. By implementing these design improvements in commercial-size EAD machine, which is expected to be 2.5 times larger than the PRU, the total operating costs for reducing the coal moisture from 37 to 20 percent are projected to be 7.50 dollars/ton (DS) and 5.80 dollars/ton (DS) for conservative and optimistic cases, respectively. Estimated thermal drying cost for such a moisture reduction for a 500 ton (DS)/day plant was \$10.50/ton (DS). There is a potential to further reduce the operating costs, but such cost projections cannot be made with confidence without obtaining additional test data.

The results of economic analysis for -325 mesh coal were similar to -100 mesh coal. The conservative and optimistic estimates of operating costs for a commercial-size EAD machine to reduce the moisture content of -325 mesh coal from 47 to 30 percent moisture are 8.70 dollars/ton (DS) and 5.90 dollars/ton (DS), respectively. Estimated thermal drying costs for such a moisture reduction was \$10.80/ton (DS). Again, the economics can be improved by further optimization in terms of throughput.

RECOMMENDED FUTURE WORK

The results of this program suggest the need to implement several design changes of minor to medium difficulty to improve EAD belt press performance. The results of the economic analyses also suggest the need to optimize the process by concentrating on operating conditions designed to maximize throughput, even at the price of increasing energy cost. Such a test program should be carried out at a commercial coal preparation plant capable of providing at least 3 tons (DS)/hr of coal.

ACKNOWLEDGMENT

The authors gratefully acknowledge the efforts of (1) Mr. Tony Bartoni and Mr. Raju Eason of Ashbrook-Simon-Hartley for operating the Process Research Unit (PRU), (2) the CQ, Inc. staff involved with the field PRU testing, (3) Dr. B. K. Parekh for supplying coal for laboratory testing, (4) Dr. J. K. Raghavan of Battelle for conducting the economic analysis, and (5) Mr. Kevin Rose of Battelle for carrying out pilot plant support activities. The many suggestions made by Dr. George Wen of DOE/PETC regarding the test program and reports were invaluable.

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FINAL REPORT
(Battelle Contract No. DE-AC-88PC88883)

on

**DEVELOPMENT OF THE ELECTROACOUSTIC DEWATERING (EAD)
PROCESS FOR FINE/ULTRAFINE COAL**

to

**U.S. DEPARTMENT OF ENERGY
PITTSBURGH ENERGY TECHNOLOGY CENTER**

Prepared by

BATTELLE

October 31, 1991

1.0 INTRODUCTION

Product coal and coal refuse dewatering has become a serious problem as a result of an increasing amount of fines (-100 mesh) in conventional coal preparation plants and an increasing emphasis on ultrafine (-325 mesh) coal cleaning to achieve very low impurity levels. Current dewatering equipment cannot dewater -325 mesh coal to less than about 45 percent moisture; but coal-water mixtures and low-cost pelletization require dewatering to 30 percent. One piece of commercial equipment is suitable for dewatering (non-thermal drying) of -100 mesh coal to the 20 percent moisture level acceptable for blending with coarse coal for use as conventional boiler fuel; but the cost is high and the process is not continuous. Thermal drying is an unattractive alternative because of its high cost, potential dust control problems, and oxidation of the coal surface. Therefore, an improved, non-thermal dewatering process is needed. To address this need, Battelle (Columbus, Ohio) undertook development of its electro-acoustic (EAD) process to demonstrate its commercial potential for continuous dewatering of fine and ultrafine coals. The pilot plant (PRU) and laboratory results, provided in this report, show that a commercial-size EAD machine is expected to economically achieve the dewatering targets for -100 mesh and -325 mesh coals.

The EAD process developed used the synergistic effect of combining electric and ultrasonic fields with mechanical pressure in a belt press arrangement. The process was patented by Battelle in 1985. It received an "IR-100" award in 1986 and the "Product of the Year" award by the American Filtration Society in 1990.

The developmental effort consisted of a two-phase project covering laboratory- and commercial-scale feasibility testing. Battelle cooperated in this effort with (a) the Electric Power Research Institute (EPRI) through its subsidiary, CQ, Inc., (b) Ashbrook-Simon-Hartley (ASH), and (c) Professor S. H. Chiang of the University of Pittsburgh. This report covers the results of a 2.5-year effort. The project objectives and approach are described below, along with the organization of the report.

1.1 OBJECTIVES

The key objectives of this project were:

- (1) Phase I--To validate, through laboratory-scale testing, the expected technical feasibility of the EAD process as applied to fine (-100 mesh) and ultrafine (-325 mesh) coal and recommend conditions for continuous testing in Phase II.
- (2) Phase II--To obtain data from a continuous, commercial-scale, process research unit (PRU) for input to conduct an economic analysis and to provide engineering data for improved design of commercial EAD belt presses, as well as to promote adaptation of the process by the coal preparation industry.

1.2. APPROACH

A two-phase project was executed that equally emphasized laboratory investigation and continuous testing. In Phase I, batch EAD tests utilizing two types of coal and two feed sizes were conducted. The tests used pressure-assisted EAD to simulate a belt press filter operation. The Phase I data were used in Phase II to make the necessary modifications of an existing belt press EAD PRU, as well as to outline a field test program. The modified PRU was then tested at EPRI's coal cleaning test facility in Homer City, Pennsylvania, operated by CQ, Inc. The results from Phase II will be useful for scale-up directly to the largest size commercial EAD belt presses.

The following targets for the product cake moisture content were set for this project:

- -100 mesh: 20 percent
- -325 mesh: 30 percent.

1.3 CONTENT OF THIS REPORT

This report covers both phases of the project and is divided into 7 sections. The need for enhanced coal dewatering, the fundamentals of the EAD process, and the concept of an EAD belt press are described in Section 2. Experimental work performed in Phases I and II is described in Sections 3 and 4. Since Section 3 is lengthy and contains voluminous data and experimental details, an extended summary is given at the beginning of this section to provide a quick overview of important laboratory EAD results and conclusions. Section 5 concerns process economics. The overall conclusions and recommendations are given in Sections 6 and 7, respectively.

2.0 TECHNICAL BACKGROUND

This section discusses the coal dewatering needs that can potentially be addressed by EAD. A theoretical background on EAD and the concept of an EAD belt press are also provided to help understand the experimental results discussed in Chapters 3, 4, and 5.

2.1 FINE/ULTRAFINE COAL DEWATERING NEEDS

There is an increasing emphasis on cleaning fine and ultrafine coal to meet stricter requirements for sulfur and mineral matter removal. This results in dewatering problems both for clean coal and refuse. The higher surface moisture in fine/ultrafine coal results in higher transportation costs, handling problems, and lower energy conversion efficiency. Thermal drying prior to shipment is undesirable because of (a) high energy use, (b) high capital and operating work, (c) dust-related problems, and (d) coal surface oxidation in case of direct heating.

The three coal cleaning areas requiring improved dewatering processes are described below.

2.1.1 Fine Coal Dewatering

Modern coal mining methods produce more fine (-28 mesh) material than do traditional coal mining methods. Even though fines may constitute 20 percent of a cleaning plant feed, they contain up to two-thirds of the product surface moisture. And with an increasing emphasis on cleaning these fines, the dewatering problems of conventional cleaning plants have increased tremendously. Traditional dewatering methods (vacuum disc filters and centrifuges) are proving inadequate for fine coal dewatering resulting in an increased need for thermal (evaporative) drying. The majority of the problem in fine (-28 mesh) coal can be attributed to the -100 mesh coal fraction. Therefore, the Electric Power Research Institute (EPRI), through its subsidiary, CQ, Inc., is studying the dewaterability of -100 mesh coal in commercially-available equipment.⁽¹⁾

The goal for fine coal dewatering for conventional coal preparation plants is about 20 percent moisture which is very difficult to achieve with -100 mesh coal using existing continuous dewatering equipment, such as vacuum disc filters, centrifuges, and belt process.⁽²⁾ Only the expensive LAROX filter, which is a batch-type filter press, can achieve this target.⁽³⁾

2.1.2 Ultrafine Coal Dewatering

In addition to enhanced dewatering needs for conventional coal cleaning, there are needs associated with advanced coal cleaning processes. The average particle size in many of these processes is in the range of 10 to 20 micron which is much smaller than -100 mesh (i.e., 149 micron and smaller) coal. Because of the very high specific surface area of these ultrafine coals, the dewatering problems are far worse than for -28 mesh or -100 mesh coal.

In some advanced processes, the ultraclean, ultrafine coal is formulated into a (CWM) where the desired moisture content is about 30 percent. But, such dewatering levels are impossible to achieve with existing continuous dewatering technology and equipment. The only solution here is thermal drying which is not desirable as discussed earlier.

2.1.3 Fine Refuse Dewatering

Closely associated with, but even more difficult than fine coal dewatering problem, is the fine refuse dewatering problem. The fine refuse contains even more ultrafine material than fine clean coal. Furthermore, the refuse contains clay minerals which makes dewatering very difficult. The ineffectiveness of current dewatering equipment then results in larger volumes of dewatered refuse. This not only increases the cost for disposal but also increases environmental concerns.

2.1.4 Commercial and Advanced Dewatering Equipment/Techniques

A variety of equipment types are currently available or under development for dewatering of coal to various levels. A number of these have been, or are being, tested at EPRI's CQ, Inc., facility in Homer City, Pennsylvania. Some of the results obtained by EPRI and others are summarized in Table 1.⁽¹⁻⁴⁾ A brief description of each is given below.

**TABLE 1. TYPICAL CLEAN COAL DEWATERING PERFORMANCE
(CAKE MOISTURE PERCENT) OF COMMERCIAL AND
ADVANCED EQUIPMENT--BITUMINOUS COAL
(Source: Ref 1-4)**

Equipment	-28 mesh	-100 mesh	-325 mesh
Vacuum Disc Filter w/o Additives w/Additives	27 ND	42 37-41 @ 0.3 lb/ton	NA NA
Bird (screen) Centrifuge	12	NA	NA
Sharples High G (solid bowl)	10	30	ND
United Coal/Sharples (High Speed Centrifugal Dryer)	12	15	ND
Belt Press (Parkson)	NA	30-34 @ 100 psi; 2-5 tph/meter	ND
LAROX	10-12	15	ND
Plate & Frame (Nutsche)	ND	ND	45

NA: Not applicable; ND: No data.

Vacuum disc filters have traditionally been used for -28 mesh coal. The dewatering performance drops considerably to about 58 percent solids (42 percent moisture) when -100 mesh coal is used. The use of silicone surfactants and other additives was investigated by Dow Chemical.⁽²⁾ The effect was a decrease in the moisture content by 1 to 5 of percent with use of about 0.3 lb of additive per ton (dry basis) of coal. Thus, vacuum disc filters are unacceptable for -100 mesh as well as -325 mesh coal since the

moisture level goals are 20 percent and 30 percent, respectively. Other researchers such as Dr. Kal Shastri at University of California at Berkeley and Professor S. Chiang at University of Pittsburgh have also done extensive amounts of work on use of chemicals to improve dewatering.^(1,2) However, the improvements have been marginal making it very clear that the targets defined above cannot be met simply by the use of additives in existing dewatering equipment.

Another traditionally used dewatering device is a screen centrifuge which gives 12 percent moisture with -28 mesh coal. This device is not applicable to finer coals. But, a high RPM (3200 g force) solid bowl centrifuge built by Sharples can dewater -100 mesh coal to 30 percent.

A new batch-type of centrifuge, called high-speed centrifugal dryer, is under development at United Coal. It is claimed to achieved about 15 percent moisture with -100 mesh coal using a very high speed ($> 10,000$ g force) centrifuge with a filter cloth. The cost is unknown, both equipment and maintenance costs are expected to be high.

A belt press made by Parkson was tested by EPRI on -100 mesh coal. Moisture levels of 30 to 34 percent at a pressure of 100 psi and throughput of 2 to 5 tons/hr for 1-meter wide belts were observed.⁽²⁾ The flocculent use was high, ranging from 0.8 to 2.0 lb/ton coal. The use of high pressure is undesirable because of the high maintenance cost. The observed performance is comparable to a high-speed solids bowl centrifuge, both falling short of the desired level. Belt presses are currently used for refuse dewatering, especially in W. Germany and their use is generally limited to average to average coal particle sizes less than about $50\text{ }\mu\text{m}$.

A high-pressure batch-type filter, made by LAROX, has been found to be quite effective on -100 mesh coal meeting the required target.⁽²⁾ However, capital cost is prohibitive because of the use of high pressures (> 200 psi) and complicated design and operation. This equipment has not been tested on -325 mesh coal.

Finally, a new plate and frame filter made by Nutsche has been tested on -325 mesh coal made by microbubble flotation process. Only a 45 percent moisture level was achieved, which is far from the desired 30 percent for CWM application or for pelletization.

The above state-of-the-art review of coal dewatering equipment clearly indicates that there is a major need for developing a reasonable cost dewatering process that can more effectively dewater fine (defined as -100 mesh from now on) and ultrafine (defined as -325 mesh from now on) coals. The EAD process has the potential to address these needs.

2.2 EAD BACKGROUND

The EAD process utilizes a synergistic combination of electric and acoustic (e.g., ultrasonic) fields in conjunction with conventional mechanical processes, such as belt presses, screw presses, plate and frame filter presses, and vacuum filters.^(5,6) The application of EAD is typically most beneficial after a filter cake is formed utilizing conventional mechanical filtration.

2.2.1 Electrically-Enhanced Dewatering

The application of a DC potential across a filter cake containing coal particles and water can result in several effects. The most desirable effect for dewatering is due to electro-osmosis. The two unavoidable side effects are resistive heating and electrolysis of water, both of which consume electrical energy. However, heating has a small positive effect on dewatering since it reduces the viscosity of water.

In electro-osmosis, which is an electrokinetic phenomena, water moves to the electrode of the same polarity as the charge on particles. In the case of raw coal or physically-beneficiated coal, the particles have a negative charge, characterized by its negative zeta potential. Therefore, application of electric field to coal suspension makes the water move to the cathode.^(6,7) Accordingly, if a conventional filter surface is made a cathode

and an anode is placed on the other side of a filter cake in contact with it, then application of a DC potential will result in enhancement of conventional, pressure-driven, filtration by electro-osmotic flow.

The liquid flow rate per unit area (Q) in idealized electro-osmosis, at a given moisture content of filter cake, can be expressed as:^(8,9)

$$Q \propto \frac{DZV}{\mu L} \quad \text{Eq(1)}$$

or

$$Q \propto \frac{DZI}{\mu L} \quad \text{Eq(1A)}$$

where,

- Q = flow rate of water per unit area of the filter cake,
- D = dielectric constant of water,
- Z = Zeta potential
- V = electric potential across the filter cake
- μ = viscosity of water
- L = filter cake thickness, and
- I = current per unit area of the filter cake.

The specific electro-osmotic flow rate (Q) is independent of capillary diameter unlike in conventional, pressure-driven-capillary flow. This is a key advantage of electro-osmosis for dewatering of suspensions containing fine particles, wherein a substantial amount of water exists as pore, capillary, and interstitial water.

The zeta potential is the most important property of a suspension (cake) subjected to electro-osmosis. The zeta potential is a function of pH

and ionic strength and arises because of the presence of an electrical double layer at a solid-liquid interface.⁽¹⁰⁾

The majority of the electrical energy consumption during electro-osmosis is due to resistive heating. The specific energy consumption can be approximated as:⁽¹¹⁾

$$E_{sp} \propto \frac{\mu \lambda V}{DZ} \quad \text{Eq(2)}$$

where,

E_{sp} = energy use (kWh) per unit (lb) of filtrate removed and
 λ = electrical conductivity of the filter cake.

Therefore, the best electro-osmotic effect is achieved with a combination of high absolute value of the zeta potential (e.g., > 30 mV) and a low electrical conductivity (e.g., < 4 millimho/cm).

2.2.2 Acoustically-Enhanced Dewatering

Acoustic or ultrasonic waves are non-ionizing elastic or pressure waves that need a material medium to propagate. They represent a form of vibratory mechanical energy in the frequency range of 20 Hz to 100 MHz. Acoustic energy in the frequency range of 1 kHz to 100 kHz has been used either alone or in combination with other standard techniques to improve the rate and degree of solid liquid separation.⁽¹²⁻¹⁴⁾

In a coal-water suspension, water is present in the following forms:

- Bulk or free water
- Pore and capillary water
- Interstitial water
- Chemisorbed water.

A significant portion of the water is filled in pores and capillaries and between particles in a tight manner due to surface tension. Conventional solid-liquid separation processes such as filtration or centrifugation are limited to removing only the bulk or free water. Acoustic energy is believed to help remove the pore and capillary water and interstitial water through agglomeration. Specifically, agglomeration leads to:

- Release of interstitial and surface water as free water
- Increase of particle size which helps to prevent clogging of the filters
- Increase in particle size which helps solid/liquid separation by conventional means.

The primary mechanisms for ultrasonic agglomeration are (a) particle collision due to orthokinetic, radiation, Oseen and Stokes forces, and (b) attraction between particles due to Bernoulli's effect.⁽²⁾ Collision of particles help form agglomerates and Bernoulli's effect further enhances this process.

It has been reported by Battelle that ultrasonic agglomeration takes place at intensities typically below 1 W/cm^2 ; at higher intensities, ultrasonic dispersion takes place. Hence it is important to carefully control the ultrasonic conditions to achieve the desired (agglomeration or dispersion) effect.¹⁵

In addition to the agglomeration effects, ultrasonics can also make microbubbles trapped in micropores and capillaries grow due to rectified diffusion and displace the trapped liquid which would otherwise be very difficult to separate. This makes more water available as bulk water.

Last, but not least, ultrasonics can reduce the apparent viscosity of a shear-thinning suspension, such that of fine coal, which can enhance the dewatering rate.

2.2.3 Combined Electroacoustic Dewatering

The synergistic effect of combining electro-osmosis and ultrasonics has been demonstrated for a number of suspensions including coal, municipal and industrial sludges, and food products.^(6,8,10,16-18) The phenomena that augment dewatering when using the combined technique are not fully understood. However, we have developed the following hypotheses.

It is believed that electro-osmosis and pressure differential across a filter cake provide driving forces for water removal out of the cake. On the other hand, ultrasonics augments electro-osmotic and pressure-driven dewatering by releasing trapped or tightly-held water into a continuum or water channel. For example, it is known that electro-osmotic flow quickly declines with the loss of the liquid continuum from the anode to the cathode as dewatering proceeds. This result is usually reflected in a rapid decline of current. However, the ultrasonic action retards the loss of continuum, thus increasing the current for a given potential gradient. This basically increases the electro-osmotic flow, without increasing the voltage gradient, in accordance with Eq 1(A). This is also the reason why the energy use with EAD is less than the energy use for electro-osmosis only.

2.3 EAD BELT PRESS CONCEPT

One way to utilize the principles of EAD on a commercial scale is to incorporate EAD in a belt press mechanism. Such a system has been successfully scaled-up by ASH, under license from Battelle, to a commercial size for sewage sludge applications.⁽⁸⁾ A belt press prototype developed for sewage sludge dewatering was modified and used as a PRU in the Phase II of the program described in this report. The design concept and the key parameters for such an EAD belt press are described below to help understand the laboratory and field test data given in Sections 3 and 4.

2.3.1 Conceptual Design

A conceptual design of an EAD belt press is shown in Figure 1. The predewatered sludge or coal is carried between two polyester belts wrapped around a cylinder of sufficient width, diameter, and wrap angle to achieve the desired range of EAD residence times and throughputs. The impervious cylinder (roll) also serves as an anode. A moving stainless steel belt, that rides on the outside of the outer filter belt serves as the cathode. On application of an electric potential between the roll and the stainless steel belt, water is removed through the outer polyester and cathode belts under the influence of electro-osmosis. This effect is enhanced by the pressure exerted on the filter cake due to the tension on the outer polyester belt as well as by application of ultrasonics.

The ultrasonic field is applied from outside the cathode belt by placing a circular vibrating plate with ultrasonic transducers. A special design is employed to provide the ultrasonic coupling between vibrating plate and the filter cake.

The dewatered filter cake can be continuously removed by separating the two polyester belts and using a scraping device.

2.3.2 EAD Belt Press Performance and Parameters

The EAD performance can be measured in terms of the following:

- (1) Effectiveness of dewatering, expressed in terms of "delta moisture" defined as;

$$\text{delta moisture} = m_1 - m_2 \quad \text{Eq(3)}$$

where m_1 and m_2 are the initial and final moisture contents, respectively, defined as pounds of water per 100 pounds of wet cake.

- (2) Efficiency of dewatering expressed in terms of specific energy consumption, E_{sp} , total energy consumption, E , and throughput per unit belt width, M , defined as:

FIGURE 1. EAD BELT PRESS DESIGN CONCEPT

E_{sp} = kWh per pound of filtrate (see Equation 2)
 E = kWh per ton (dry solids basis) of coal
 M = ton (dry solids basis) of coal per hour per meter of belt width.

These performance measures depend on the following controllable parameters:

- (1) V/L : voltage gradient, volts/cm (V/cm)
- (2) U : ultrasonic intensity, watts/cm² (W/cm²)
- (3) m_1 : Initial moisture content
- (4) τ : EAD residence time, which depends on several belt press parameters as follows:

$$\tau = \pi D_1 (\alpha/360)(1/B) \quad \text{Eq(4)}$$

where,

D_1 = roll diameter, meter
 α = wrap angle, degrees
 B = belt speed, m/min.

- (5) S_L : solids loading, kg (DS)/m², which is given as:

$$S_L = (1/10)L_1\rho_1m_1 \quad \text{Eq(5)}$$

where,

L_1 = initial cake thickness, cm
 ρ_1 = initial density of cake, g/cm³

- (6) P : cake pressure, psi, which is given as:

$$P = T \left(\frac{2}{D} \right), \quad \text{Eq(6)}$$

where,

T = belt tension, lbs/inch.

The efficiency terms can be calculated from the controllable parameters discussed above and the experimentally observed values of m_2 and I (current, amps) as follows.

$$(A) \ M = (0.132) S_L \beta \quad \text{Eq(7)}$$

$$(B) \ E_{sp} = \left(V \times I + \frac{U}{5} \right) \left(\frac{1}{1000} \right) \left(\frac{1}{F_1} \right) \quad \text{Eq(8)}$$

where,

F_1 = filtration rate, lb/hr

$$= (2000 \ M * W) \left\{ \left(\frac{m_1}{100-m_1} \right) - \left(\frac{m_2}{100-m_2} \right) \right\} \quad \text{Eq(9)}$$

where, W = Belt width, meter

$$(C) \ E = E_{sp} F_1 \left(\frac{1}{M} \right) \quad \text{Eq(10)}$$

The EAD belt press can be fairly well simulated in the laboratory batch tests, if filtration is not significantly affected by shear. The batch EAD performance measures are the same as for a continuous, PRU. The laboratory EAD results are given in the next section.

2.4 REFERENCES FOR SECTION 2

- (1) Cavalet, J. R. and R. G. Moorehead, "Fine Coal and Refuse Dewatering Projects," paper presented at the American Mining Congress, held in Chicago, Illinois (April 1984).
- (2) "Dewatering Coal and Refuse," Coal Age, 86, pp 145-152 (May 1981).
- (3) Row, R. R. and Cavalet, J. R., "Fine Coal Dewatering," paper presented at the 113th Annual Meeting of the Am. Inst. of Mining, Metallurgical and Petroleum Engineers, held in Los Angeles, CA (February 1984).

- (4) Personal communication with Jim Hervol of EPRI, now with Kaiser Engineers.
- (5) Muralidhara, H. S., Parekh, B. K., and Senapati, N., "Solid-Liquid Separation Process for Fine Particle Suspensions by an Electric and Ultrasonic Field," U.S. Patent Nos. 4,561,953 (1985), 4,747,920 (1988), and Serial No. 400,296 (1989).
- (6) Muralidhara, H. S., Senapati, N., Ensminger, D., and Chauhan, S. P., "A Novel Electroacoustic Separation Process for Fine Particle Suspensions," Proceedings of World Filtration Congress IV, held in Ostende, Belgium (April 1986).
- (7) Heath, L. and Demirel, T., "Pressurized Electro-Osmotic Dewatering," Paper presented at Engineering Foundation Conference on Flocculation, Sedimentation and Consolidation, Sea Island, GA (November 1984).
- (8) Chauhan, S. P. and Johnson, H. W., "Scale-up of Electroacoustic Dewatering of Sewage Sludges," Proceedings of Solid/Liquid Separation: Waste Management and Productivity Enhancement, held in Columbus, OH (December 1989).
- (9) Yukawa, H., Kobayashi, K., and Hakoda, H., "Study of the Performance of Electrokinetic Filtration Using Rotary Drum Vacuum Filter," J. Chem. Engr. Japan, 13 (5), pp. 390-396 (1980).
- (10) Muralidhara, H. S., Senapati, N., and Beard, R. E., "A Novel Electroacoustic Separation Process for Fine Particle Suspensions," Advances in Solid-Liquid Separation, Ed. by H. S. Muralidhara, Battelle Press/Royal Society of Chemistry, Chapter 14, pp. 335-374 (1986).
- (11) Jirjis, B., Muralidhara, H. S., Menton, R., Senapati, N., Hsich, P., and Chauhan, S. P., "Batch Electroacoustic Dewatering (EAD) of Fine Coal," Advances in Filtration and Separation Technology, 2, pp. 516-539 (1990).
- (12) Boucher, R. M. G., "Drying by Air Borne Ultrasonics," Ultrasonic News, 3, pp. 8-14 (1959).
- (13) Gregus, P., "The Mechanism and Possible Applications of Drying by Ultrasonic Irradiation," Ultrasonics, 1, pp. 83-86 (1963).
- (14) Ensminger, D., "Acoustic Dewatering," Chapter 13 in Advances in Solid-Liquid Separation, ed. H. S. Muralidhara, Battelle Press (1986).

- (15) Muralidhara, H. S., Beard, R. B., and Senapati, N., "Mechanisms of Ultrasonic Agglomeration for Dewatering Colloid Suspensions," Filtration & Separation, pp 409-413 (November/December 1987).
- (16) Chauhan, S. P., Muralidhara, H. S., Kim, B. C., "Electroacoustic Dewatering Process for POTW's (Sewage Sludges)," Proceedings of the National Conference on Municipal Treatment Plant Sludge Management, held in Orlando, Florida (May 1986).
- (17) Chauhan, S. P., Muralidhara, H. S., Kim, B. C., Senapati, N., Beard, R. E., and Jirjis, B. F., "Electroacoustic Dewatering (EAD)-A Novel Process," paper presented at 1987 Summer AIChE Meeting, Minneapolis, Minnesota (August 1987).
- (18) Chauhan, S. P., Kim, B. C., Muralidhara, H. S., Senapati, N., and Criner, C. L., "Scale-Up of Electroacoustic Dewatering (EAD) Process for Food Products," Paper No. 48a, presented at 1989 Summer AIChE Meeting, Philadelphia, Pennsylvania (August 1989).

3.0 LABORATORY TESTING

The objectives of laboratory testing were to establish the technical feasibility of EAD for enhanced dewatering of coal and to support the scale-up effort. The details on coal properties and test procedures and the results of parametric EAD testing and various support activities are given in this Section.

3.1 SUMMARY AND CONCLUSIONS FOR LABORATORY TESTING

A 7.6 cm I.D., batch EAD system was used to simulate the belt press EAD concept. The tests were conducted primarily with Upper Freeport coal from Helen Mine, Indiana, Pennsylvania, ground to two different sizes, namely -100 mesh and -325 mesh, and then beneficiated by two different flotation techniques. The coals were predewatered to levels typical of conventional mechanical dewatering systems in use today. The predewatered coal could then be used, without assistance from a flocculent, with satisfactory solids retention on a porous polyester filter belt used in EAD.

A total of 50 statistically-designed tests on the -100 mesh coal and 67 statistically-designed tests on the -325 mesh coal were carried out. About two-thirds of the tests were factorially designed to estimate the primary effects and interactions. The results from these tests were utilized to design the remaining tests, aimed at determining EAD parameter values that met target moisture objectives. The batch EAD parameters and their levels were as follows:

- Voltage gradient (0-260 volts/cm)
- Ultrasonic intensity (0-1.2 watts/cm²)
- Dewatering time (1-6 minutes)
- Solids loading (3-19 kg(DS)/m²)
- Pressure on filter cake (fixed at 5 psi for -100 mesh coal; 3-10 psi for -325 mesh coal).

The EAD performance was analyzed in terms of (a) moisture reduction, (b) specific energy consumption (kWh/lb filtrate), (c) total energy cost [dollars/ton (DS) coal], and (d) throughput [ton (DS)/hr/m belt width]. The moisture and energy data for control tests (no electric or ultrasonic field) and EAD tests that yielded minimum moisture levels as well as those that were near optimum are summarized in Table 2. As shown, the minimum moisture levels achieved with EAD were 19.8 percent and 28.1 percent for -100 mesh and -325 mesh coals, respectively; these moisture levels were 14 to 16 percent lower than those achieved in control (no electric or ultrasonic) tests. However, moisture levels about 1 or 2 percent above these minimum values for EAD tests were much more favorable with respect to energy consumption.

TABLE 2. SUMMARY OF LABORATORY EAD RESULTS ON UPPER FREEPORT COAL

	-100 Mesh	-325 Mesh
Initial Moisture, %	40	45-46
Final Moisture for Control, %	36.0	41.9
	(at 6 min.)	(at 6 min.)
Final Moisture Range for EAD, %	19.8-32.1	28.1-40.4
Energy Consumption, kWh/lb filtrate		
Range	0.067-496	0.050-0.230
At minimum moisture level	0.250	0.104
Near optimum	0.187	0.059
	(at 22% moisture)	(at 29.3% moisture)
Energy Cost, dollars/ton (DS)		
Range	1.84-15.39	1.89-10.98
At minimum moisture level	10.07	5.48
Near optimum	6.59	2.90
	(at 22% moisture)	(at 29.3% moisture)

The regression models that fit the -100 mesh and -325 mesh data were developed. Both the observed data and regression models showed that increasing the levels of any of the five EAD parameters listed above decreased the moisture content. The specific energy consumption (a) increased with increased voltage and dewatering time, (b) decreased with pressure, levelling off at about 6 psi,

and (c) and decreased with ultrasonic intensity or the solids loading up to certain levels that depended on the coal.

The ratio of the zeta potential to electrical conductivity was demonstrated to be the most important coal property determining the energy consumption. This ratio needs to be increased to reduce energy consumption. This can be achieved by reducing the dissolved solids content of the process water used for beneficiation or possibly by using a suitable additive. Two additives, namely sodium hexametaphosphate and Dowfroth 250 (a frother agent), failed to change the ratio of the zeta potential to electrical conductivity; however, it is believed worthwhile to further search for a suitable, possibly a non-ionic, additive.

The ultrasonic effect was strong for both coals; however, the effect was stronger for the finer (-325 mesh) coal. One possible reason for this observation is that the finer coal was more shear thinning, as determined with a mechanical spectrometer, and therefore, had a lower apparent viscosity under the high shear stress caused by ultrasonics.

Since a major part of the electrical energy used in EAD is converted to heat, the temperature of coal rises during EAD. This temperature rise was shown to have only a small effect on moisture reduction (less than 1 percent) when only pressure (no electric or ultrasonic field) was employed compared to the total EAD effect.

The laboratory test results were utilized to design test matrices for the PRU tests for two batches of coal.

3.2 COAL PREPARATION AND CHARACTERIZATION

The laboratory EAD tests were conducted primarily with Upper Freeport coal from Helen mine, Indiana, PA, ground to two different sizes, namely -100 mesh and -325 mesh, and then beneficiated by two different flotation techniques. The -100 mesh coal was prepared in the EPRI/CQ, Inc. facility in Homer City, PA, utilizing froth flotation. A portion of this coal, containing 84 percent

moisture was utilized for physical, chemical, and electrochemical characterization and flocculation studies. The remaining sample was centrifuged at Battelle, without the addition of a flocculent, to reduce its moisture content to 39-41 percent typically achieved by vacuum filtration of -100 mesh coal, for conducting parametric testing. Both samples were stored in a refrigerator at 4C when not in use.

The -325 mesh coal was ground and beneficiated by column flotation at the University of Kentucky, Center for Applied Energy Research (KCAER). Again a portion of the beneficiated coal, containing 78 percent moisture, was utilized for characterization and flocculation studies. The rest was predewatered at (KCAER), without use of a flocculent, in a batch filter press to about 45-47 percent moisture for EAD testing.

The following properties of coal samples were determined.

- Proximate and ultimate analyses; analyzed by Commercial Testing Labs; see Table 3
- Higher heating value (HHV) and free swelling index (FSI); analyzed by Commercial Testing Labs; see Table 3
- Electrokinetic properties; analyzed by Battelle (conductivity) and University of Pittsburgh (pH and zeta potential); see Table 3
- Particle size distribution by a Microtrac Analyzer; determined by University of Pittsburgh; see Figure 2
- Moisture content of filter cakes; determined by Battelle; see Table 3.

TABLE 3. PROPERTIES OF -100 MESH AND -325 MESH UPPER FREEPORT
COAL SAMPLES FOR LABORATORY EAD TESTING

	-100 mesh	-325 mesh
Moisture, %	39-41	45 - 47
Ultimate Analysis, % Dry Basis		
Carbon	83.01	80.21
Hydrogen	5.06	5.12
Nitrogen	1.47	1.54
Sulfur	1.65	2.65
Ash	5.73	8.15
Oxygen (diff)	3.08	2.33
Total	100.00	100.00
Proximate Analysis, % Dry Basis		
Ash	5.73	8.15
Volatile Matter	28.90	28.81
Fixed Carbon	63.37	63.04
Total	100.00	100.00
HHV, Btu/lb (MAF)	15,761	15,587
FSI	5.0	5.5
Electrokinetic Properties		
Electrical conductivity, mmho/cm	3.25	0.41
pH	7.2	6.1
Zeta Potential, mV	-36.0	-14.3

FIGURE 2. PARTICLE SIZE DISTRIBUTION OF LABORATORY EAD COAL SAMPLES

These properties were measured for one or more of the following purposes:

- To help compare EAD performance with the performance of other dewatering devices
- To help explain the EAD performance
- To determine the effect, if any, of EAD on coal properties.

A comparison of the two samples shows a big difference in the electrokinetic properties. The -100 mesh coal was about 8 times more conductive and had a zeta potential more than double that for -325 mesh. This helps explain a higher rate of electro-osmosis at a given voltage gradient and a higher DC field energy consumption for a given moisture reduction for the -100 mesh coal. The differences in two samples appear to be related to properties of water and the chemicals used for beneficiation as well as on the handling of flotation concentrates. For example, the -100 mesh coal was not washed after flotation unlike the -325 mesh coal. And the water at CQ, Inc., where the -100 mesh coal was prepared, is believed to have a high dissolved solids content compared to the laboratory water at University of Kentucky.

3.2 EXPERIMENTAL DETAILS

The laboratory EAD tests were conducted in a pressurized, batch system designed to simulate an EAD belt press system described in Section 2.3. The equipment design, test procedures, and data acquisition and reduction details are provided below.

3.2.1 Batch EAD Apparatus

A 7.6 cm diameter (I.D.), batch EAD system, shown in Figure 3, was used for all laboratory tests discussed in this report. Basically, a predewatered coal sample (cake) was placed between a polyester filter, which was supported by a perforated ultrasonic plate (also a cathode), and a floating anode. A downward force was applied on the floating anode to press the coal sample. The key components of the system are described below.

FIGURE 3. SCHEMATIC OF PRESSURIZED BATCH EAD UNIT

3.2.1.1 Double-Acting Air Cylinder

A double-wall, stainless steel body air cylinder 5.1 cm I.D. x 15.2 cm height was used to apply pressure. The cylinder was connected to a 7.6 cm diameter piston, which served as the anode, through an insulated connector to provide electrical isolation between the anode and the rest of the system. A 4-way air valve was connected to the cylinder and to an air pressure tank equipped with a 0-60 psi pressure regulator to control pressure and piston movement. The air cylinder pressure was calibrated in psi against the anode piston load in pounds.

3.2.1.2 Piston

A 7.6 cm diameter (I.D.), platinum-coated titanium piston, with an O-ring around its circumference to assure pressure seal, was used by itself as the anode. Two 1/8-inch diameter Swagelok® stainless steel fittings were vented through the piston. One fitting was used to vent the dewatering chamber and to allow trapped air and gases to escape. The other fitting was used to pass an electrically isolated thermocouple through the piston to monitor the sample temperature during dewatering.

3.2.1.3 Pressure Dewatering Chamber

A filter chamber, 3-inch I.d. x 1-5/8-inch height, made of Lucite® was used to hold the sample. This chamber was supported by four 1/2-inch all-thread screws to assure proper sealing of the O-ring seal. Two pin-shaped piezoelectric transducers (pinducers), vented through the side of the dewatering chamber were, used to monitor the ultrasonic signal penetration through the cake during dewatering. The first pinducer was located at the contact angle of cake and belt. The second pinducer was located 1/4-inch from the polyester filter.

3.2.1.4 Cathode

A stainless steel, supporting filter plate screen acted as a cathode. The screen was connected to a conical ultrasonic horn which excited the screen and produced ultrasonic vibrations. The edges of the screen were sealed with a rubber gasket to prevent leakage at the edge and provide an ultrasonic isolating support. After passing through the stainless steel screen, the filtrate was collected in a specially designed beaker sealed against the bottom of the ultrasonic transducer.

3.2.1.5 Ultrasonic Horn and Transducer

A 20 kHz piezoelectric transducer was used to produce the ultrasonic vibrations. The vibrations were amplified by a booster horn and a conical horn. The conical horn vibrated the cathode screen, which in turn, produced vibrating motion in the filter cake. The ultrasonic transducer assembly was supported by a feeding screw support plate, the location of which was controlled by the movement of the screw.

3.2.2 Batch EAD Test Procedure

The following experimental procedure was utilized for all batch EAD tests conducted with EAD unit shown in Figure 3.

1. A weighed microwipe sheet was placed under the filtering chamber around the conical ultrasonic horn in order to collect all the filtrate and its suspended solids.
2. A known quantity of coal sample was placed in the filter chamber on the polyester filter.
3. The piston (anode) was lowered using the 4-way valve to a position where the piston was in contact with the coal sample and all the air was vented through the Swagelok® vent fittings.
4. The vent fittings were capped to assure that no coal sample leaked through the top of the piston.
5. The data acquisition system, the current recorder and ultrasonic signal recorder were turned on.

6. Appropriate pressure, electrical power input and ultrasonic power were set.
7. Test was started by initially applying only pressure for 30 seconds. At the end of 30 seconds, with the pressure still applied, electrical and ultrasonic field were turned on for a set interval of time.
8. At the end of the test, air pressure was released using the 4-way valve and the anode piston was raised.
9. The dewatered cake was removed and weighed.
10. The microwipes and filtrates were removed from the filtrate chamber and were weighed.
11. The cake sample and the filtrate sample were then placed in a vacuum oven at 65 C and 5-10 inches Hg vacuum, to determine the cake moisture and filtrate solids percent.

3.2.3 Data Acquisition and Reduction

A LabTech Acquire Data Acquisition System was used to measure and record the values for the following three time-dependent parameters:

1. Electrical current
2. Cake temperature
3. Ultrasonic signals through the cake.

The system was designed to monitor and measure the above variable and produce an average value for current and ultrasonic penetration at the end of each test. The system would start monitoring as soon as it saw an electrical current of at least 20 mAmp. In addition, the following data were manually recorded for each experiment:

- Initial moisture content (m_1)
- Initial weight of sample (M_1)
- Applied voltage (V)
- Applied ultrasonic power (U)
- Applied pressure (P)
- Final weight of dewatered cake (M_2)

- Weight of liquid filtrate collected (F)
- Percent solids in the filtrate
- Final cake moisture content (m_2).

The initial cake thickness (L_1) was calculated from the initial sample weight and moisture content, assuming a specific gravity of the coal suspension at 1.2 g/cm³. During the experiments, there was a loss of about 2-4 g of filtrate. Therefore, the weight of filtrate was calculated on the basis of the moisture measurements performed before and after dewatering. The moisture content of the dewatered cake was determined immediately after the experiments were completed.

From the above mentioned data, the EAD performance was determined in terms of (a) delta moisture ($m_1 - m_2$); (b) specific energy (E_{sp}); (c) total energy (E); and (d) projected throughput (M). These calculations were based on the equations given in Subsection 2.3.

3.3 BATCH, PARAMETRIC TESTS ON -100 MESH COAL

Laboratory EAD tests were conducted with a batch of -100 mesh, Upper Freeport coal with the following objectives: (1) to determine the feasibility of achieving a final moisture level of 20 percent and (2) to determine the effects of experimental factors on EAD performance in order to establish the range of experimental conditions to be tested in the PRU. The experimental design, experimental data, a regression analysis, and the preferred ranges of conditions are discussed below.

3.3.1 Experimental Design

The laboratory tests were conducted in three stages. The first set of experiments provided useful information concerning (a) the need for flocculation and (b) EAD equipment adjustments and modifications. The flocculation tests, described later, showed that there was no significant benefit of flocculation, used during predewatering, on EAD performance.

Therefore all of the 50 parametric tests in the second and third stages of testing were done without use of flocculation.

The second set of experiments consisted of 34 tests designed to estimate main effects and interactions for the key parameters. A factorial design was used for this set of experiments. Results from the second set of experiments were then used to select variable settings in the third set to determine the EAD parameter settings which would meet the target objectives for moisture content.

3.3.2 Parameter Ranges

The following parameters and ranges of values were employed:

- Dewatering time: 1 to 6 minutes
- DC voltage gradient: 0 to 220 volts/cm
- Ultrasonic intensity: 0 to 1.0 watts/cm²
- Solids loading (initial cake thickness): 3 to 19 kg(DS)/m² (0.6 to 2.6 cm).

The voltage gradient actually increased during a test as the cake thickness decreased. The parameter values for voltage gradient refer to the initial cake thickness. The pressure was maintained at 5 psi for all tests.

3.3.2 Parametric Testing Results

The performance of EAD was analyzed using statistical analysis methods in terms of the following:

- (a) Reduction in moisture content: $m_1 - m_2$, percent
- (b) Specific energy consumption: E_{sp} , kWh/lb filtrate
- (c) Total energy cost @ 5¢/kWh: $C = 0.05E$, dollars/ton (DS) coal
- (d) Throughput per unit belt width: M tons(DS)/hr/m.

These dependent variables were defined for an EAD belt press in Subsection 2.3. The results of all the parametric tests are given in Appendix A, Table A-1.

Two control tests (no EAD), carried out at 6 minutes dewatering time, showed an average of 3.3 percent reduction in moisture content to a final moisture level of 36.1 percent (average). On the other hand, the moisture content for EAD tests, carried out at 1 to 6 minutes dewatering time, resulted in a 7.3 to 18.3 percent reduction in moisture content to final moisture levels of 32.1 to 19.8 percent, respectively.

The specific energy, for a given final moisture content, depended upon the operating conditions. Under optimum conditions with respect to specific energy, a decrease in final moisture content results in an increase in specific energy. At the lowest observed final moisture of 19.8 percent, the energy consumption was 0.250 kWh/lb filtrate, which corresponds to 10.07 dollars/ton (DS) coal. At a somewhat higher moisture level of 22.0 percent, the energy consumption declined to 0.187 kWh/lb filtrate or 6.59 dollars/ton (DS) coal. It is believed that the energy consumption can be lowered significantly by controlling the water chemistry and the zeta potential of coal, as discussed later in Subsection 3.5.2. A detailed analysis of results is provided below.

3.3.2.1 Analysis of Experimental Errors

Eight center point tests were conducted in order to estimate the error variability and the day to day variability. Results based on the final moisture content of the cake of the eight conducted tests indicate 0.77 percent experimental error. The experimental error based on energy values for the same tests indicate 0.024 kWh/lb filtrate experimental error. These data show that there are very little experimental errors associated with the above series of 50 tests.

3.3.2.2 Effect of Dewatering Time

Dewatering time is one of the critical parameters for establishing economic feasibility of the EAD process. Dewatering time affects the size of

the EAD unit and the energy consumption. Initial tests investigated both a low (1 minute) and a high (6 minute) level of time. Twelve tests were conducted at each of the two time levels; identical parameter ranges were investigated at the two levels of time for each of the parameters, namely voltage gradient, ultrasonic intensity, and solids loading. The average and standard deviation of the final cake moistures for the 12 tests conducted at 1 minute were 29.5 percent and 1.3 percent, respectively; and the average and standard deviation of the final cake moistures for the tests conducted at 6 minutes were 26.7 percent and 3.0 percent, respectively. While it was expected that the final cake moisture would decrease with increased dewatering time, it was surprising that the standard deviation would increase. The smaller standard deviation at 1 minute reflects the relatively minor differences in final cake moisture across the different voltage levels or ultrasonic power levels at 1 minute compared to at 6 minutes.

Figure 4 compares the final cake moisture contents obtained in the screening tests at dewatering times of 1 and 6 minutes for various voltage gradients and ultrasonic intensities. While final cake moistures were observed to decrease substantially with increased ultrasonic levels at 6 minute, they were relatively small with increased voltage levels at 1 minute. Also, the final moisture values at 1 minute were far from the target of 20 percent. Therefore, it was concluded that 1 minute of dewatering time was not long enough for the EAD effect to take place and, therefore, the subsequent tests concentrated on 6 minutes dewatering time.

A few tests were conducted to explore the region between 1 and 6 minutes. Results in Table 4 shows that there was no significant change in the final cake moisture contents at 4, 5, and 6 minutes. This suggests that dewatering time should be 4 minutes or less.

The specific energy consumption increased as dewatering time was increased from 1 to 6 minutes as shown in Table 4. This is basically due to the fact that electro-osmotic dewatering efficiency declines with level of dewatering. This was especially true at dewatering times greater than 4 minutes, during which period very little, if any, dewatering took place.

FIGURE 4. FINAL CAKE MOISTURE VERSUS ULTRASONIC INTENSITY FOR SELECTED VOLTAGE LEVELS AT DEWATERING TIMES OF 1 AND 6 MINUTES FOR -100 MESH UPPER FREEPORT COAL [S_L : 6.0 KG(DS)/M²]

TABLE 4. COMPARISON OF FINAL CAKE MOISTURE AND SPECIFIC ENERGY USAGE AT VARIOUS DEWATERING TIMES FOR -100 MESH UPPER FREEPORT COAL [S_L :6KG(DS)/M²; ULTRASONIC INTENSITY:0.99 WATTS/CM²]

Test No.	Dewatering Time min	Voltage Gradient volts/cm	Final Cake Moisture percent	Specific Energy kWh/lb filtrate
16 ^(a)	1	121	27.9	0.22
48	4	121	21.7	0.24
47	5	121	21.7	0.25
41	6	121	21.6	0.24
45	6	121	21.2	0.24
49	4	146	19.9	0.24
50	5	146	19.8	0.25
42	6	146	20.1	0.28

(a) Test No. 16 at 0.44 watts/cm².

3.3.2.3 Effect of Voltage Gradient and Ultrasonic Intensity

The electrokinetic potential across the cake is the electrical driving force for the electroacoustic dewatering process. Dewatering was observed to improve significantly with the application of ultrasonics in conjunction with the electric field, as shown in Figures 4 and 5 and Table 5. The final cake moisture at 6 minutes, no ultrasonics, 73 volts/cm, and 6 kg(DS)m² was 29.3 percent. When ultrasonic intensity was increased from 0 to 0.99 watts/cm², the final cake moisture decreased to 26.1 percent.

In the absence of ultrasonics, the final cake moisture decreased by only 2.4 percent when voltage gradient was increased from 73 to 121 volts/cm. However, in the presence of ultrasonics at 0.99 watts/cm², the final cake moisture decreased by 4.7 percent when voltage gradient was increased from 73 to

FIGURE 5. FINAL CAKE MOISTURE VERSUS ULTRASONIC INTENSITY AT SEVERAL VOLTAGE GRADIENTS FOR -100 MESH COAL [τ : 6 MINUTES; S_L : 6 KG(DS)/M²]

TABLE 5. EFFECT OF VOLTAGE GRADIENT AND ULTRASONIC INTENSITY ON FINAL CAKE MOISTURE AND SPECIFIC ENERGY USAGE FOR -100 MESH UPPER FREEPORT COAL [τ :6 MINUTES; S_L :6.0 KG(DS)M²; P:5 PSI]

Test No.	Voltage Gradient volts/cm	Ultrasonic Intensity watts/cm ²	Final Cake Moisture percent	Specific Energy kWh/lb filtrate
35	73	0.00	29.3	0.18
38	73	0.66	27.3	0.17
39	73	0.99	26.1	0.17
36	97	0.00	29.5	0.32
37	97	0.66	24.2	0.21
40	97	0.99	23.0	0.20
12	121	0.00	26.9	0.44
8	121	0.22	25.1	0.35
32	121	0.44	22.4	0.29
34	121	0.66	21.6	0.26
45	121	0.99	21.2	0.24
41	121	0.99	21.6	0.24
42	146	0.99	20.1	0.28

121 volts/cm. These data show a synergistic effect of DC voltage and ultrasonics on dewatering effectiveness.

While from Figure 6 and Table 5, specific energy levels are shown to increase with increased voltage, ultrasonic power is shown to markedly lower the energy consumption. The rate at which specific energy increases with voltage was found to be much higher at 0 watts/cm² than at 0.99 watts/cm² ultrasonics. Once again, this illustrates the synergistic effect of DC voltage and ultrasonics on dewatering efficiency.

3.3.2.4 Effect of Solids Loading

The solids loading, along with the dewatering time determine the throughput of an EAD machine. Prior experience with a variety of materials such as food products and sludges indicated that the final moisture content of the dewatered material increased with increase in solids loading. However, the tests on -100 mesh coal showed the opposite effect. For example, as shown in Table 6, the final moisture content declined from 26.1 percent (Test No. 39) to 21.6 percent (Test No. 44) on increasing the solids loading from 6 to 12 kg(DS)/m². It is possible that this unexpected results is due to an enhanced ultrasonic coupling, and therefore, an enhanced ultrasonic effect at higher cake thickness. In any case, this effect is of substantial economic value as the throughput is directly proportional to solids loading, according to Eq(7).

The effect of solids loading on specific energy for various levels of dewatering is shown in Figure 7. The specific energy declines with solids loading in the range of 6 to at least 12 kg(DS)/m²; there is an indication that an optimum may exist between 12 and 19 kg(DS)/m². The specific energy decline with solids loading is opposite to previously observed results with materials for which the ultrasonic effect relative to the total EAD effect was not as large as for coal. In fact, it can be shown, based on equations for idealized electro-osmosis given in Subsection 2.3, that the specific energy is proportional to the square of the solids loadings. An explanation for the observed results is that up to certain cake thickness, the ultrasonic coupling and, therefore, the ultrasonic effect improves; on increasing the thickness

FIGURE 6. SPECIFIC ENERGY VERSUS ULTRASONIC INTENSITY AT SEVERAL VOLTAGE GRADIENTS FOR -100 MESH COAL [τ :6 MINUTES; S_1 :6 KG(DS)/M²]

TABLE 6. EFFECT OF SOLIDS LOADING ON MOISTURE CONTENT AND SPECIFIC ENERGY FOR -100 MESH COAL [τ :6 MINUTES; P:5 PSI]

Test No.	Solids Loading kg(DS)/m ²	Voltage Gradient volts/cm	Ultrasonic Intensity watts/cm ²	Final Cake Moisture percent	Specific Energy kWh/lb filtrate
39	6	73	0.99	26.1	0.168
44	12	73	0.99	21.6	0.204
41,45	6	121	0.99	21.4 ^(a)	0.240 ^(a)
43	8	109	0.99	20.6	0.267

(a) Average.

FIGURE 7. EFFECT OF SOLIDS LOADING (S_L) ON THE RELATIONSHIP BETWEEN FINAL CAKE MOISTURE AND SPECIFIC ENERGY FOR -100 MESH UPPER FREEPORT COAL [7:6 MINUTES; ULTRASONIC INTENSITY: 0.99 WATTS/CM²]

beyond this optimum, the decline in electro-osmotic flow rate (Equation 1) becomes more pronounced than any improvement in ultrasonic effect due to improved coupling.

3.3.3 Regression Models

Regression models were fitted to the -100 mesh Upper Freeport data to assess the effects of voltage, ultrasonic power and solids loading on the final moisture content of the cake and specific energy usage. These models were fitted to only the tests conducted at dewatering times of 4 or more minutes. Since the effect of time on dewatering in this range was small, if any, the effects of dewatering time were not considered in the models. While initial models included terms for all possible linear, quadratic and cross-product effects, terms that were consistently statistically insignificant were dropped.

The following equations were used for the models finally selected:

$$\begin{aligned} \text{Final Cake Moisture} = & B_0 + B_1(\text{voltage gradient}) + B_2(\text{ultrasonic} \\ & \text{intensity}) + B_3(\text{solids loading}) + B_4(\text{voltage} \\ & \text{gradient})^2 + B_5(\text{voltage gradient}) * \\ & (\text{ultrasonic intensity}) + B_6(\text{ultrasonic} \\ & \text{intensity})^2 + B_7(\text{solids loadings})^2 \end{aligned} \quad \text{Eq(11)}$$

$$\begin{aligned} \text{Specific Energy} = & B_0^1 + B_1^1(\text{voltage gradient}) + B_2^1(\text{ultrasonic} \\ & \text{intensity}) + B_3^1(\text{solids loading}) + B_4^1(\text{voltage} \\ & \text{gradient})^2 + B_5^1(\text{voltage gradient}) * (\text{ultrasonic} \\ & \text{intensity}) + B_6^1(\text{ultrasonic intensity})^2 \end{aligned} \quad \text{Eq(12)}$$

The coefficients for various parameters in the above equation were estimated from the data for the set of 28 tests.

An analysis of variance was conducted to examine the effects of voltage gradient, ultrasonic intensity, and solids loading. The results from this analysis are summarized in Tables B-1 and B-2 in Appendix B. The statistical parameters were as given below.

	F-Test	P-Value	R-Square	RMSE
Final Cake Moisture	108.2	0.0001	0.97	0.67
Specific Energy	68.8	0.0001	0.95	0.023

The value of the F-test is used to determine whether or not there exists a significant relation between final cake moistures and the variables in the model. The higher the F-test, the more statistically significant the relationship between final cake moistures and the variables in the model. A measure of the statistical significance of the F-test is given by the associated P-value. The relationship is statistically significant at the 0.05 significance level when the P-value is less than 0.05. A measure of the amount of variation in the data that can be attributed to the terms in the model is R-square. An R-square value of 1 indicates that the variation in the data is exactly determined by the terms in the model. The mean square error measures the average variation in the data that is unaccounted for by the terms in the model. The square root of the mean square error (RMSE) is often used as a measure of the variability in the data. Thus, the models represent the data fairly well.

Based on the P-values for various parameters from the corresponding T-tests, the effects of voltage gradient, ultrasonic intensity, and solids loading were determined to be statistically significant at the 5 percent significance level.

The observed and predicted values for final cake moisture and specific energy for various experimental conditions are given in Appendix B. An example of predicted versus actual final cake moisture values, as a function of voltage gradient, is given in Figure 8. The predicted values at various voltage gradients are given by the solid line. The upper and lower 95 percent prediction boundaries are shown by the dotted lines. Figure 9 gives an example of dependence of final cake moisture on ultrasonic intensity.

FIGURE 8. PREDICTED FINAL CAKE MOISTURE VERSUS VOLTAGE GRADIENT FOR -100 MESH UPPER FREEPORT COAL [τ :6 MINUTES; S_L :6 KG(DS)/M²; ULTRASONIC INTENSITY:0.99 WATTS/CM²]

FIGURE 9. PREDICTED FINAL CAKE MOISTURE VERSUS ULTRASONIC INTENSITY FOR -100 MESH UPPER FREEPORT COAL [τ :6 MINUTES; $S_L=6$ KG(DS)/M²; VOLTAGE GRADIENT:121 V/CM]

The statistical (regressional) models can be used to predict EAD performance at various parameter values. For example, the dependence of final moisture content on voltage gradient and ultrasonic intensity is given in a 3-D plot in Figure 10. Accordingly, at a voltage gradient of 220 volts/cm, an ultrasonic intensity of 1 watt/cm², a dewatering time of 6 minutes, and a solids loading of 6 kg (DS)/m², the final cake moisture is predicted to be 17.1 percent.

3.3.4 Preferred Operating Conditions for -100 Mesh Coal

The observed EAD results as well as the fitted models show the following:

- (1) EAD effect in 1 minute is inadequate, but 4 minutes is probably longer than necessary.
- (2) Target objective for final cake moisture, i.e., 20 percent, can be reached with extreme levels of voltage at the expense of high-energy costs.
- (3) Both final cake moisture levels and energy costs can be reduced by increasing ultrasonics intensity up to about 1 watt/cm² or solids loading up to a value that is between 12 and 19 kg(DS)/m².

The preferred operating conditions can be defined in terms of lowest energy consumption, given in terms of specific energy or energy cost, and highest throughput for a desired final moisture content. These are given as optimum value envelopes (solid lines) in Figures 11, 12, and 13. These optima can be further improved by increasing the ratio of zeta potential to electrical conductivity. This is shown in the next subsection for -325 mesh coal, which was washed at the end of beneficiation. It is believed that such a washing steps reduces the zeta potential much less than the conductivity and also could possibly reduce the energy cost by a factor of 2 or more. It may be possible to use an additive that increases the zeta potential without increasing the electrical conductivity, as discussed later in Subsection 3.5.2.

FIGURE 10. 3-D PLOT OF PREDICTED FINAL CAKE MOISTURE VERSUS ULTRASONIC INTENSITY AND VOLTAGE GRADIENT FOR -100 MESH UPPER FREEPORT COAL [τ :6 MINUTES; S_L :6 KG(DS)/M²]

FIGURE 11. OPTIMUM FOR FINAL CAKE MOISTURE VERSUS SPECIFIC ENERGY FOR -100 MESH UPPER FREEPORT COAL

FIGURE 12. OPTIMUM FOR FINAL CAKE MOISTURE VERSUS ENERGY COST FOR -100 MESH UPPER FREEPORT COAL

FIGURE 13. OPTIMUM FOR ENERGY COST VERSUS THROUGHPUT FOR FINAL CAKE
MOISTURE RANGE OF 20 TO 22 PERCENT FOR -100 MESH
UPPER FREEPORT COAL

Based on the laboratory results for -100 mesh coal, the following range of key parameters were suggested for scale-up (PRU) testing:

- Dewatering time: 2-4 minutes
- Voltage gradient: 100-150 volts/cm
- Ultrasonic intensity: 0.6-1.1 watts/cm²
- Solids loading: 6-14 (or maximum feasible) kg (DS)/m²

3.4 BATCH, PARAMETRIC TESTS ON -325 MESH COAL

Laboratory EAD tests were conducted with a batch of -325 mesh Upper Freeport coal with the following objectives: (1) to determine the feasibility of achieving a final moisture level of 30 percent and (2) to determine the effects of experimental factors on EAD performance in order to establish the range of experimental conditions to be tested in the PRU. The experimental design, experimental data, a regression analysis, and the preferred ranges of conditions are discussed below.

3.4.1 Experimental Design

The experimental design was similar to the one for -100 mesh coal. Accordingly, the tests were conducted in three sets of experiments. In addition to the EAD parameters investigated for -100 mesh Upper Freeport coal, we investigated the effect of pressure on EAD performance. The first set of experiments consisted of 5 tests that provided useful information concerning the effect of flocculation on EAD performance. Based on these results, discussed later, it was decided to conduct the remaining batch as well a PRU tests without using flocculent. The second set of experiments consisted of 41 tests designed to estimate main effects and interactions for the pressure, electrical voltage, ultrasonic power, solid loadings, and dewatering time. Results from the second set of experiments were then used to select variable settings in the third set of 26 experiments designed to determined the EAD parameter settings that meet the target objectives for final moisture content.

3.4.2 Parameter Ranges

The batch EAD test parameters for the -325 mesh Upper Freeport coal and their ranges are listed below:

- Cake pressure: 3-10 psi
- Dewatering time: 3-6 minutes
- DC voltage gradient: 0-260 volts/cm
- Ultrasonic intensity: 0-1.2 watts/cm²
- Solids loading (cake thickness): 4-8 kg(DS)/m² (0.8-1.6 cm).

3.4.3 Parametric Testing Results

The EAD performance was measured in terms of (a) reduction in moisture content, (b) specific energy (c) energy cost, and (d) projected throughput using procedures established for -100 mesh coal. The results of the 67 parametric tests are given in Appendix A, Table A-2.

Two control tests (no EAD) showed an average of 4.8 percent reduction in moisture content to a final moisture level of 41.9 percent (average). On the other hand, the moisture content in EAD tests was reduced by as much as 18.1 percent, to a final moisture level of 28.1 percent.

As in the case of -100 mesh coal, under optimum conditions, the specific energy as well as the energy cost increased with decreasing final cake moisture content. At the lowest observed moisture content of 28.1 percent, the specific energy consumption was 0.104 kWh/lb filtrate, which corresponds to 5.48 dollars/ton(DS) coal. At a somewhat higher final moisture level of 29.3 percent, the energy consumption declined to 0.059 kWh/lb filtrate or 2.90 dollars/ton(DS) coal. A detailed analysis of results is provided below.

3.4.3.1 Analysis of Experimental Errors

Seven center point tests were conducted in order to estimate the error variability and the day-to-day variability. Results from the eight tests indicate 0.72 percent experimental error based on moisture content and 0.0095

kWh/lb filtrate error based on energy values. Again, as in the case of -100 mesh coal tests, these data indicate that there are very little experimental errors associated with the above series of 67 tests.

3.4.3.2 Effect of Pressure

It is known that the filter cake compressibility increases as the particle size decreases. Therefore, unlike for -100 mesh coal, experiments were conducted in the second stage of -325 mesh coal testing to determine the effect of pressure on combined mechanical and EAD dewatering. The effect of pressure in the range of 3 to 10 psi is shown in Figure 14. Both the moisture content and specific energy decline with pressure. This improvement in dewatering performance is most significant until about 6 psi after which the improvement is marginal.

The stage three tests were all conducted at a pressure of 6 psi which was considered the practical upper limit of the EAD belt press for commercial use. In fact, as discussed in Section 4, it was difficult to operate the PRU above 3.3 psi due to test unit design limitations.

3.4.3.3 Effect of Dewatering Time, Voltage Gradient and Ultrasonics

Among these variables, the ultrasonics had the greatest effect on improving EAD performance. As shown in Figure 15, the final moisture content decreased somewhat, i.e., about 1 percent, on increasing the time from 3 to 5.5 minutes. There was an accompanying increase in specific energy consumption as shown in Figure 16.

The effect of voltage gradient was considerably smaller than for -100 mesh coal. This is believed to be due to a 60 percent lower zeta potential for the -325 mesh coal (-14.3 mV) compared to -100 mesh coal (-36.0 mV). As shown in Figure 17, the final moisture content declined only 1.5 percent on doubling the voltage from 97 to 194. On the other hand, the specific energy more than doubled on doubling the voltage gradient.

FIGURE 14. EFFECT OF PRESSURE ON FINAL CAKE MOISTURE AND SPECIFIC ENERGY FOR -325 MESH UPPER FREEPORT COAL [τ : 4.5 MINUTES; VOLTAGE GRADIENT: 146 V/CM; ULTRASONIC INTENSITY: 0.77 WATTS/CM²; S_L : 5.4 KG(DS)/M²]

FIGURE 15. EFFECT OF DEWATERING TIME ON FINAL CAKE MOISTURE AT SELECTED CONDITIONS FOR -325 MESH UPPER FREEPORT COAL [P:5 PSI]

FIGURE 16. EFFECT OF DEWATERING TIME ON SPECIFIC ENERGY AT SELECTED CONDITIONS FOR -325 MESH UPPER FREEPORT COAL [P:5 PSI]

FIGURE 17. EFFECT OF VOLTAGE GRADIENT ON FINAL CAKE MOISTURE AND SPECIFIC ENERGY FOR -325 MESH UPPER FREEPORT COAL [τ :4.5 MINUTES; P:5 PSI; ULTRASONIC INTENSITY:0.77 W/CM²; S_L :5.4 KG(DS)/M²]

The effect of ultrasonics on final cake moisture was even stronger than in the case of -100 mesh. For example, on increasing the ultrasonic intensity from 0 to 1.21 watts/cm², the final cake moisture declined by 7.4 percent. This compares with about 5.5 percent decline for -100 mesh coal. The specific energy declined rapidly in the beginning, until 0.33 watts/cm², and then increased slowly, as shown in Figure 18. This trend for specific energy is expected and consistent with the results for -100 mesh coal; however, the optimum ultrasonic intensity level with respect to energy consumption for -100 mesh coal was roughly twice that for -325 mesh coal.

3.4.3.4 Effect of Solids Loading

The effect of solids loading on the relationship between final cake moisture and specific energy is shown in Figure 19. The data suggest that there is some sort of an optimum solids loading between 3 and 7.7 kg(DS)/m². This optimum is lower than for -100 mesh coal, the latter being between 12 and 19 kg(DS)/m².

3.4.4 Regression Models

Regression models were fitted to the 67 tests to estimate the effects of voltage, ultrasonic intensity, dewatering time, pressure and solids loading on final moisture content. The results observed on 10/25/89 were consistently superior to those predicted by the model. Upon further examination of the laboratory records, it was determined that the coal tested on 10/25/89 were prepared almost three weeks earlier, and therefore, the final cake moistures might have been affected by aging of the coal. Future investigations of coal EAD dewatering should study the effect of aging more carefully. It was also determined that the final moisture content of the cake was related to the initial moisture content of the cake. Consequently, other factors investigated included the initial moisture content of the cake, and a batch effect (AGE) for the tests conducted on 10/25/89.

FIGURE 18. EFFECT OF ULTRASONIC INTENSITY ON FINAL CAKE MOISTURE AND SPECIFIC ENERGY FOR -325 MESH UPPER FREEPORT COAL [τ :4.5 MINUTES; $S_{L5.4}$ KG(DS)M²; VOLTAGE GRADIENT:146 V/CM]

FIGURE 19. EFFECT OF SOLIDS LOADING (S_L) ON THE RELATIONSHIP BETWEEN FINAL CAKE MOISTURE AND SPECIFIC ENERGY FOR -325 MESH UPPER FREEPORT COAL [τ :4.5 MINUTES; ULTRASONIC INTENSITY:0.77 W/CM²]

The equation of the final model fitted to the data are:

$$\begin{aligned} \text{Final Moisture} = & B_0 + B_1(\text{Time}) + B_2(\text{Pressure}) + B_3(\text{Voltage} \\ & \text{Gradient}) + B_4(\text{Ultrasonic Intensity}) + B_5(\text{Solids} \\ & \text{Loading}) + B_6(\text{AGE}) + B_7(\text{Initial Moisture} \\ & \text{Content}) + B_2(\text{Ultrasonic Intensity})^2 + \\ & B_9(\text{Pressure})^2 + B_{10}(\text{Solids Loading})^2 \end{aligned} \quad \text{Eq(13)}$$

$$\begin{aligned} \text{Specific Energy} = & B_0^1 + B_1^1(\text{Time}) + B_2^1(\text{Pressure}) + B_3^1(\text{Voltage} \\ & \text{Gradient}) + B_4^1(\text{Ultrasonic Intensity}) + B_5^1(\text{Solids} \\ & \text{Loading}) + B_6^1(\text{Initial Moisture Content}) + \\ & B_7^1(\text{Ultrasonic Intensity})^2 \end{aligned} \quad \text{Eq(14)}$$

The coefficients for various parameters in the above equation were estimated from the 65 tests conducted in the presence of EAD, i.e., the models were not fitted to the two tests conducted with pressure only.

The results of variance analysis were as follows:

	F-Test	P-Value	R-Square	RMSE
Final Cake Moisture	99.3	0.0001	0.95	0.72
Specific Energy	149.4	0.0001	0.95	0.0095

The details of the analysis are given in Tables C-1 and C-2 in Appendix C.

Based on the P-values for various parameters from the corresponding t-tests, the effects of following variables were found to be significant at 5 percent level:

- (A) Final moisture content: dewatering time, pressure, ultrasonic intensity, solids loading, initial moisture content. (The effect of voltage gradient was significant at a lower, i.e., 6 percent level.)
- (B) Specific energy: dewatering time, voltage gradient, ultrasonic intensity, solids loading, and initial moisture content. (The effect of pressure was significant at a lower, i.e., 10 percent level.)

The observed and predicted values for final cake moisture and specific energy for various experimental conditions are given in Appendix C. An example is

given in Figure 20. The predicted values of final moisture at various pressures are given by a solid line and the upper and lower 95 percent prediction boundaries are shown by dotted lines.

3.4.5 Preferred Operating Conditions for -325 Mesh Coal

The observed EAD results and the fitted models show the following:

- (1) The EAD performance improves with pressure in the entire range of practical values for an EAD belt press, i.e., 0-6 psi.
- (2) Target objectives for final cake moisture, i.e., 30 percent, can be reached at moderate levels of voltage gradient and ultrasonic intensity at reasonable energy costs.
- (3) The EAD performance can be substantially improved by increasing the ultrasonic intensity or solids loading up to optimum values.
- (4) The effects of time in the range of 3 to 6 minutes and the voltage gradient between 100 to 200 V/cm are small compared to those of other variables.

The preferred operating conditions can be defined in terms of lowest energy consumption, given in terms of specific energy or energy cost, and highest throughput for desired final moisture content. These are given as optimum value envelopes (solid lines) in Figures 21, 22, and 23. A comparison with Figures 11, 12, and 13, respectively, shows that the energy costs for -325 mesh coal are less than half those for -100 mesh coal. This can be explained by Equation (2) and the fact that the $z:\lambda$ ratio for -325 mesh coal was three times higher than for -100 mesh coal.

Based on the laboratory results for -325 mesh coal, the following ranges of key parameters were suggested for PRU (scale-up) testing:

- Pressure: up to 6 psi or the highest possible for PRU (3.3 psi)
- Time: 2.5-4.5 minutes
- Voltage gradient: 70 to 140 V/cm
- Ultrasonic intensity: 0.6 to 1.0 watts/cm² or the highest possible for PRU (0.33 watts/cm²)
- Solids loading: 3.5 to 8.0 kg(DS)/m².

FIGURE 20. PREDICTED FINAL CAKE MOISTURE VERSUS PRESSURE FOR -325 MESH UPPER FREEPORT COAL [τ :4.5 MINUTES; VOLTAGE GRADIENT:146 V/CM; ULTRASONIC INTENSITY:0.77 W/CM²; S_L :5.4 KG(DS)M²]

FIGURE 21. OPTIMUM FOR FINAL CAKE MOISTURE VERSUS SPECIFIC ENERGY FOR -325 MESH UPPER FREEPORT COAL

FIGURE 22. OPTIMUM FOR FINAL CAKE MOISTURE VERSUS ENERGY COST FOR -325 MESH UPPER FREEPORT COAL

FIGURE 23. OPTIMUM FOR ENERGY COST VERSUS THROUGHPUT FOR FINAL CAKE MOISTURE RANGE OF 29 TO 31 PERCENT FOR -325 MESH UPPER FREEPORT COAL

3.5 SUPPORTING STUDIES

3.5.1 Flocculation Studies

The filter belts commonly used in a belt press are porous enough to let a -100 mesh coal slurry pass through it. To correct this problem flocculents are needed. But the EAD belt press utilizes a predewatered filter cake, which, at the beginning of this project gave some hope of eliminating flocculation. Therefore flocculation studies were carried out to identify suitable flocculents as well as to determine the effect of flocculation on solids retention on a belt and on EAD performance.

3.5.1.1 Selection of Flocculents

The flocculent types and concentrations were specified by Dr. S.H. Chiang of the University of Pittsburgh. The work was performed in two steps. First, a series of Percol flocculents supplied by Allied Collids, Inc., were tested to quickly select a suitable flocculent for laboratory EAD testing on -100 mesh coal. The following three flocculents were tested:

- Percol 726 (high molecular weight, anionic)
- Percol 757 (high molecular weight, cationic)
- Percol 525 (low molecular weight, anionic)

The single-phase permeability and the formation time of a filter cake were determined using a vacuum filtration apparatus to assess the ease of filtration. In addition, settling tests and solids capture rate calculations were carried out to determine the correct type and dosage of the polymer. The filter cake formation time decreased first with flocculent concentration and then increased after reaching a minimum value. And the opposite trend, as desired, was observed with respect to filter cake permeability. These data gave roughly the same optimum values, namely:

- Percol 726: 10 ppm
- Percol 757: 30 ppm
- Percol 525: 20 ppm

Based on these tests, Percol 726 was judged to be the most effective and efficient. The same conclusion was reached based on settling tests. Therefore, Percol 726 at 10 ppm concentration was used for the -100 mesh coal tests.

In the second step, the following three new polymeric flocculents, manufactured by Union Carbide Corp. were studied:

- WSR N-12K (1 million molecular weight, anionic)
- WSR Coagulant (5 million molecular weight, anionic)
- WSR 303 (12 million molecular weight, anionic)

A comparison with Percol 757 showed that the WSR flocculents were more efficient in terms of cake formation time as well as being more effective in terms of solids retention on the polymeric belt. The WSR coagulant was selected as the best among these for EAD studies on -325 mesh coal. A dosage of 19 ppm which corresponds to 0.17 lb of flocculent per ton of coal was selected as a practical concentration. A solids retention of about 95 percent with -325 mesh coal was expected at this concentration.

3.5.1.2 Effect of Flocculation on EAD

A number of exploratory experiments were performed to determine the effect of flocculent as EAD performance in terms of solids capture and final cake moisture. The following flocculent and coal combinations were employed:

- -100 mesh Upper Freeport Coal: Percol 726; 0.11 lb/ton (DS) coal
- -325 mesh Upper Freeport Coal: WSR Coagulant; 0.17 lb/ton (DS) coal

A bench-scale belt press predewatering system was used to predewater the flocculated coal samples to roughly the same moisture levels as achieved with the predewatered, unflocculated coal. EAD tests were performed on both flocculated as well as unflocculated coals.

The tests on -100 mesh coal showed that elimination of flocculation did not decrease the solids capture as shown in Table 7. Also flocculation appeared to have a minor effect on the final cake moisture content. For example, the average final moisture content for the two flocculation tests (1A and 3A) was 23.8 percent. On the other hand, the unflocculated test (2A) yielded a final cake moisture of 25.1 percent. Since the flocculation step involves extra equipment and operating cost and because the benefits are minor, it was decided to eliminate the use of flocculents for -100 mesh coal.

Unlike the Percol flocculent, the WSR coagulant had a marked negative influence on EAD performance as shown in Table 8. For example, the final cake moisture for the flocculated test 5A conducted at 6.5 min. dewatering time, 200.5 volts/cm, 0.99 watts/cm² and 5 psi was 37.12. While the final cake moisture for the unflocculated coal test (3B) conducted at the same above conditions was 30.65 percent. The specific energy consumption also increased from 0.15 to 0.32 kwh/lb filtrate on flocculation. Similar results were observed when comparing Test 4B (flocculated) with Test 2B (unflocculated). This decline in EAD performance with flocculation was judged to be much more than the benefit of improved solids capture. Therefore, it was decided to eliminate the use of flocculation with -325 mesh coal also. As regards to the extrusion of coal through the belt, it was decided to observe this effect further in the PRU before finding methods to improve the solids capture beyond 85-90 percent.

3.5.2 Effect of Additives on EAD Performance

The objective of examining the effect of additives was to find an additive, if any, that will increase the rate of the EAD process. Theoretically, this can be achieved by increasing the absolute value of the zeta potential of the coal particles. However, an increase of the zeta potential is often accompanied by an increase of the electric conductivity, and as a result an increase of the DC current at the same voltage. Consequently, there will be an increase of the operating costs. It is, thus, important to find an additive that will increase the zeta potential of the coal particles with little or no increase in the electric conductivity of the liquid phase of the slurry.

TABLE 7. EFFECT OF FLOCCULATION ON EAD PERFORMANCE WITH -100 MESH, UPPER FREEPORT COAL [P:7 PSI; τ :5 MIN; VOLTAGE GRADIENT:155 V/CM]

Test No.	Flocculated/ Unflocculated	Initial Sample Moisture Percent	Final Cake Moisture Percent	Percent Solids Capture
1A	Flocculated	40.1	23.2	97.4
2A	Unflocculated	38.2	25.1	97.0
3A	Flocculated	39.8	24.5	96.7

TABLE 8. EFFECT OF FLOCCULATION ON EAD PERFORMANCE FOR -325 MESH UPPER FREEPORT COAL
[P:5 PSI; τ :6.5 MIN; ULTRASONIC INTENSITY:0.99 WATTS/CM²; S_L :5.5 KG (DS)/M²]

Test No.	Voltage Gradient Volts/cm	Flocculated/ Unflocculated	Initial Sample Moisture	Final Cake Moisture %	Filtration Rate gms/min	Specific Energy kwh/lb Filtrate	Percent Solids Capture
2B	147.6	unflocculated	44.4	34.7	1.32	0.15	85.7
4B	147.6	flocculated	43.6	39.5	0.58	0.32	95.8
3B	200.5	unflocculated	44.4	30.7	1.58	0.21	87.8
5B	200.5	flocculated	43.6	39.5	0.76	0.37	98.0

Two additives were selected to be examined in this brief study: sodium hexametaphosphate and Dowfroth 250. The tests were done on -325 mesh coal at 146 v/cm, 4.5 minutes, 6 psi, and 5.4 kg (DS)/m², without any ultrasonics. The concentration of the additives were, in ppm, 10, 50, 100, 250, 500, and 1 percent, based on the total weight of the slurry. The results showed that there was no significant change in moisture contents after dewatering at different additive concentrations. The average moisture content of all samples was 33.4 percent with a standard deviation of 0.77, which is about the same as the experimental error.

During the review of the above results, Dr. George Wen of DOE/PETC suggested the use of a non-ionic flotation reagents to increase the $z:\lambda$ ratio. Such reagents should be considered in future studies.

3.5.3 Temperature Effects During EAD

The temperature of -100 mesh coal was observed to increase to about 150 F in the PRU tests. This temperature increase should favorably affect both the EAD and mechanical dewatering performance. To quantify this benefit, a special dewatering system was built to preheat a coal sample. The acoustic horn underneath the belt was removed and a heating chamber was added to hold the sample at a preset temperature (Figure 24). Coal samples were the same as those used in the -100 mesh PRU tests and were supplied by CQ, Inc. Operating parameters were chosen to represent those used by the PRU. The effect of temperature on dewatering rate was examined at two elevated temperature; 100 F and 150 F. Two different ways of heating the sample were tried. The first method was to hold a refrigerated coal sample inside a heating chamber until the sample was heated to the desired temperature. Pressure was then applied and the experiment started. In the second method, a coal sample was allowed to warm up to room temperature before adding to the heating chamber, which was at the desired, elevated temperature. Pressure was applied and the experiment started immediately after the sample was put into the heating chamber without waiting for the cake to heat up.

FIGURE 24. EXPERIMENTAL SETUP FOR EVALUATING THE TEMPERATURE EFFECT ON FINAL MOISTURE CONTENT

The coal sample had an initial moisture content of 36.1 percent. With either heating method, increasing the temperature from 110 to 150 F reduced the moisture content by less than 1 percent compared to about 10 percent moisture reduction due to application of pressure, electric field and ultrasonics. While a temperature rise due to the application of electric and ultrasonic fields may assist electroacoustic dewatering, the results show that heating without application of the fields is not of much value.

3.5.4 Belt Selection and Characterization

Choosing the right filter medium as a filtering medium is one of the most important requirements in assuring satisfactory operation of a belt press. Two polyester belts, namely IFC 6093 and IFC 6020, were selected as a filtering medium for laboratory tests with -100 mesh and -325 mesh Pittsburgh coal, respectively. Both belts were manufactured by Industrial Fabrics Corporation and supplied to Battelle by ASH. The two belts were selected primarily for their capabilities to retain the fine coal particles and reduce percent coal particles extrusion in the filtrate. The technical specifications of the selected belts are listed in Table 9. The IFC 6020 is one of the tightest belts that Industrial Fabrics produces. It has 43 percent less open area than IFC 6093. Both belts performed satisfactorily in the laboratory. However, the IFC 6020 was found to stretch too much during PRU shakedown test. A third belt, namely TEKTKO 7041 OSC, was found in the PRU test to be better than the first two belts for unflocculated, -100 mesh as well -325 mesh coal.

TABLE 9. TECHNICAL SPECIFICATIONS OF POLYMER BELTS USED FOR LABORATORY EAD TESTS

Specification	Fiber	Yarn	Weave	Weight	Tensile Strength Warp lb/in	Mesh Count Per Inch Warp & Weft	Mesh Opening Microns Warp & Weft	Air Perm CFM	Open Area %
IFC 6093	PES	Mono	Mod. Satin	35.4	1560	64 x 24	0 x 350	360	16
IFC 6020	PEB	"	Satin	22.1	445	178 x 33	0 x 250	140	9

3.5.5 Ultrasonics Effects and Shear Thinning

As discussed in Subsection 2.2.2 there are several hypothesis on the ultrasonic enhancement of dewatering. Shear thinning is believed to be one of the major factors. Ultrasonics can reduce the apparent viscosity of a shear-thinning suspension. Since the rate of electro-osmosis is inversely proportional to viscosity, use of ultrasonic can be beneficial for EAD of shear-thinning material. Therefore some measurements of the rheological properties of the -100 mesh and -325 mesh coal slurries were made.

The shear stress (T_s) versus shear rate (s) for a shear-thinning material is given as:

$$T_s \propto (s)^n \quad \text{Eq(15)}$$

where, $n < 1$

The apparent viscosity (μ) is given as:

$$\mu = T_s/s \quad \text{Eq(16)}$$

It can be shown based on these equations that

$$\mu \propto (s)^{n-1} \quad \text{Eq(17)}$$

The smaller the value of n , the more shear-thinning is the material, and greater the beneficial ultrasonic effect on EAD.

The values of n for the two coal samples were determined using a mechanical spectrometer which gives the relationship between shear modulus and angular frequency which is equivalent to a relationship between shear stress and the shear rate. The following values of n were measured for the two types of coal:

- -100 mesh : 0.79
- -325 mesh : 0.51

Thus, the -325 mesh coal had a greater shear-thinning tendency. These results are consistent with trends seen in the laboratory tests. Specifically, the effect of ultrasonics on -325 mesh coal was about 30 percent higher than for -100 mesh coal.

As explained in Section 2.2.2, factors other than shear-thinning can also contribute to the ultrasonic effect. The individual effects of these other factors have not been quantified at this time.

4.0 CONTINUOUS PRU TESTING

The objectives of the PRU (Process Research Unit) testing were to demonstrate the feasibility of continuous electroacoustic dewatering (EAD) of coal and to obtain data to perform an economic analysis as well as to design commercial EAD filters. The details of the field test setup, parametric EAD testing, and a comparison of laboratory and field test results are provided in this section.

4.1 COAL PREPARATION AND TEST SITE

Two series of PRU tests, one in summer of 1990 and another one in early winter in 1990, each one lasting about two weeks, were performed at the CQ, Inc. facility in Homer City, PA. The first series of tests were conducted with a batch of about 100 tons (DS equivalent) of -100 mesh Upper Freeport coal that was beneficiated in a froth flotation cell at CQ, Inc. The coal preparation scheme was identical to one used for preparing the sample for batch testing. The cleaned coal was predewatered in a vacuum disc filter. The feed coal moisture varied from 35 to 38 percent. The proximate and ultimate analyses are given in Table D-1 and particle size distribution is given in Figure D-1 in Appendix D.

The second series of tests was originally planned to be carried out on -325 mesh coal using an advanced flotation method. Two potential sources of column-flotation-cleaned coal, namely Powell Mountain Coal Company and Kaiser, and one source of microbubble-flotation-cleaned coal, i.e. University of Virginia in Blacksburgh, were contacted. A request was made to supply at least 50 ton (DS) of coal and a test site for 2-3 weeks. The Powell Mountain Company was not able to provide a suitable site at the time we needed it. Kaiser's column flotation system had not yet started when we contacted them. And University of Virginia could not supply sufficiently large quantities of coal for a meaningful test. Therefore, a backup plan was implemented with the help of CQ, Inc. A 50 ton (DS equivalent) sample of -28 mesh coal, which was a blend of several Upper Freeport coal seams and was froth-flotation cleaned at the Homer City Power Plant operated by PENNELEC, was shipped to CQ, Inc.

This coal was further ground in a ball mill and a pebble mill to produce -325 mesh coal. The resulting coal was then dewatered by a solid bowl centrifuge to about 46-48 percent moisture. The proximate and ultimate analyses and particle size distribution are given in Appendix D.

4.2 PRU DESCRIPTION AND SHAKEDOWN

A PRU built for and tested with sewage sludges was adapted for coal testing. The PRU is shown schematically in Figure 25 and conceptually in Figure 26. The belt press EAD unit consists of a 1 meter nominal cake width (1.2 meter belt width) system. The principle is to feed coal dewatered by conventional means, e.g. a vacuum disc filter or centrifuge, and then remove additional water (moisture) by application of DC electric and ultrasonic fields. The details of the original PRU design, the modifications, and the shakedown testing are given below.

4.2.1 Overall Arrangement

The partially dewatered coal was pumped with a Moyno pump into a specially designed chute that provided a uniform feed cake thickness across the belt. The coal was then sandwiched tightly between an outer polymer belt under medium tension and an inner polymer belt under low tension and traveled around a large roll of 1.3 meter diameter. In this manner the coal experienced a pressure in the range of 2.5 to 3.3 psi. This machine (PRU) was designed for a pressure of 4.0 psi, but was not operated above 3.3 psi because of excessive stretching of belts. Towards the end of the test program, a belt (TETKO 7041 OSC) suitable for higher pressure was identified.

The PRU system was mounted on three separate skids, as shown in Figure 27. The predewatered coal was received in a hopper (not shown) from the coal preparation plant and pumped to the feed chute by a moyno pump. The product cake was discharged into a front-end loader to facilitate quick removal from the test area.

FIGURE 25. SCHEMATIC OF EAD BELT PRESS PROCESS RESEARCH UNIT (PRU)

FIGURE 26. EAD BELT PRESS PROCESS CONCEPT

FIGURE 27. SKID-MOUNTED EAD BELT PRESS SYSTEM

4.2.2 Anode Roll

The large roll was used as the anode, and a moving stainless steel wire-mesh belt on the outside of the outer polymer belt served as the cathode as shown in Figure 26. The anode was of a special construction and was coated to minimize electrochemical and chemical corrosion. A simple design also isolated the anode from the frame of the PRU, which was grounded.

4.2.3 Ultrasonic Plate

A unique ultrasonic transducer design along with novel fluid coupling system made it possible to couple ultrasonic energy into the filter cake through belts moving in a circular path. However, the PRU was limited to delivering a maximum of 0.33 watt/cm^2 ultrasonic intensity, which was less than half of optimum based on laboratory results. A redesign effort was considered beyond the scope of the PRU test effort, which was not aimed at equipment optimization.

4.2.4 Belts

The inner, the outer, and the cathode belts were steered and tensioned independently. The hydraulic system allowed for the proper adjustment of tensions for each belt independently. Provisions were made for dewatering all these belts. The cathode belt had a wrap of about 240 degrees while the ultrasonics system covered 180 degrees with an offset towards the forward direction. This results in the following sequence of dewatering forces at a belt speed of 1 m/min.

- 0-0.3 min : pressure
- 0.3-0.7 min : pressure + electric field
- 0.7-2.7 min : pressure + electric field + ultrasonic field
- 2.7-3.0 min : pressure + electric field
- 3.0-3.2 min : pressure.

The residence times at other belt speeds can be calculated utilizing Equation (4).

4.2.5 Shakedown

The PRU system was checked out for mechanical performance at ASH facilities in Houston, Texas. The coal for the shakedown testing was prepared by CQ, Inc, and shipped in 25 drums. The shakedown effort involved the following:

- (1) The coal feeding system was modified to handle predewatered coal and to obtain a uniform-thickness feed across the belt. The modified system worked well as long as the moisture content of the -100 mesh coal was above about 43 percent.
- (2) The 900 amp D.C. power supply operated satisfactorily. (The -325 mesh PRU test used a 1600 amp power supply which was first tested at CQ, Inc.)
- (3) The ultrasonic seals had to be modified to minimize water leakage, especially when a cake thickness of more than $\frac{1}{2}$ inch was used
- (4) Several polymer belts were tested. It was decided to try two different belts, namely an IFC 6461 (310 CFM) and IFC (85 CFM), on the PRU. The IFC 6020 belt used for laboratory testing was not mechanically strong enough to be used on the PRU. The lower permeability belt was to be tried to minimize reabsorption of water towards the tail end of dewatering.

4.3 PRU INSTALLATION

The skid-mounted PRU was installed on an outdoor concrete pad at CQ, Inc., for -100 mesh testing. The predewatered slurry was piped into a hopper, which fed to the Moyno pump on the PRU. The product cake was collected in a front-end loader to quickly transport the coal away from the site. The dried coal was eventually shipped to the Homer City power plant. The filtrate was sent to CQ, Inc. clarification pond. A photograph of the overall installation is shown in Figure 28.

At the end of the first series of tests the PRU was shipped back to ASH as it was needed for tests on other materials and since the ultrasonic seal needed to be improved.

FIGURE 28 . PHOTOGRAPH OF THE PRU SYSTEM SETUP FOR -100 MESH COAL TESTING AT CO, INC. IN HOMER CITY, PENNSYLVANIA

For the second series of tests (on -325 mesh coal), the PRU was installed inside a building to protect the equipment from very cold weather. The building, however, was unheated. The feed coal was piped into the feed hopper as before. The product cake was collected in plastic bags for future use on another contract on pelletization.

4.4 EXPERIMENTAL PROCEDURES

All PRU tests were conducted utilizing the operating procedure given in Appendix E. A typical test day comprised of 4-6 tests done on a batch of coal. The beneficiated coal slurry was continuously predewatered by a vacuum filter or a centrifuge and utilized for PRU tests.

A typical test comprised of 20 minutes of steady state at a given set of conditions. It usually took about 20 minutes to reach a steady state for a new set of test conditions. Samples of feed and product cake were collected at 5-minute intervals during the steady state operation. Some samples of filtrate were also taken to determine the solids capture rate for the EAD belt press. The following analyses were performed:

1. Moisture content of all predewatered feed and product cake samples. (The averages of moisture values for the four samples of feed and product cake were used for EAD performance analysis.)
2. Proximate and ultimate analyses of composites of four samples for feed and product cake.
3. Particle size distribution of composites of the four feed samples and filtrate solids for selected tests.

The following process variables and conditions were measured and recorded during each test:

1. Cake production rate for selected tests to estimate predewatered feed and cake production rates based on cake thickness setting and moisture contents of feed and product.
2. Inlet cake thickness

3. Belt speed
4. Belt tensions
5. DC current and voltage input
6. Ultrasonic power input for the front and the back halves.

4.5 PRU RESULTS ON -100 MESH COAL

Field tests of the EAD PRU on -100 mesh Upper Freeport coal were conducted during July-August, 1990. A total of 22 tests were performed to investigate the effect of the following factors on EAD performance:

- (1) Fluid coupling (on or off)
- (2) Permeability of outer belt (85, 310 and 360 cfm of air)
- (3) Initial cake thickness (0.84, 1.27, and 1.91 cm)
- (4) Ultrasonic power (0, 4.5, and 9 kw)
- (5) D.C. voltage (0, 50, 70 and 90 volts).

The belt speed was maintained at 1 m/min, which corresponds to an EAD time of 2.7 minutes. Lower belt speeds were considered to be ineffective based on the laboratory data and higher belt speeds were not possible due to capacity limitation of the coal beneficiation system.

The mechanical and process performance results are discussed below.

4.5.1 Mechanical Performance

The feed chute and distributor worked satisfactorily to provide a fairly uniform cake across the belt. The cake discharge was also satisfactory. Very little coal squeezed out from the edges of the belt.

A mass balance based on moisture contents of feed, product cake, and filtrate showed 99 percent solids capture by the filter belts. This is an important results that confirms that as long as the coal is dewatered to a

cake-like consistency, it need not be treated with flocculents to achieve high degree of solids retention in an EAD belt press.

The main problem encountered in the testing was that the ultrasonic seal, into which water is pumped to maximize ultrasonic coupling, leaked badly. The poor ultrasonic coupling was evident as there was only a small increase in the current when an ultrasonic field was employed compared to what was expected. An attempt was made to correct this problem before the -325 mesh testing. The seal improved in the -325 mesh coal tests somewhat with an increase in belt tension but the ultrasonic coupling was still considered to be poor. This problem was further compounded by the fact that the maximum ultrasonic power input (9 kw) was less than half of the optimum value based on the laboratory tests. This reduced the effectiveness of EAD for reasons discussed in Section 3.

Despite the problems with the ultrasonic system, it was demonstrated that continuous electroacoustic dewatering (EAD) was feasible. The process performance can be improved with an equipment redesign and optimization effort.

4.5.2 EAD Process Performance

Test conditions and results are summarized in Table 10. With the feed moisture varying from 35 to 38 percent, the lowest moisture content of product cake with EAD was about 22 percent compared to a target of 20 percent. The product moisture content with pressure only (no EAD) varied from 30 to 31 percent. (It is to be noted that a somewhat lower moisture content of the predewatered feed coal could have been achieved by reducing the throughput of the vacuum disc filter. However, this may have made the feeding of the coal to the PRU unreliable. Anyway, it is believed that with EAD being used for postdewatering, the overall capital cost for predewatering plus EAD can be minimized by operating the vacuum disc filter at a high throughput without significantly compromising on the overall moisture reduction in the two dewatering steps.

4.5.2.1 Effect of Fluid Coupling

Tests were performed to assess the moisture reabsorption problem due to fluid coupling that had been experienced during the preliminary tests conducted at ASH. Test number 0720-1, 0720-3, 0720-5, 0724-1 to 0724-4 were conducted to study the effects of fluid coupling on EAD performance. These tests were run at 1.27-cm and 1.91-cm cake thickness. Tests with fluid coupling were matched with tests done at similar conditions without coupling, and their differences were statistically analyzed using a paired t-test. Results for these tests are shown in Table F-1 in Appendix F. Final moisture and delta moisture (i.e., decrease in moisture content of cake) for tests performed with fluid coupling are contained in the second and third columns of the table for tests done with fluid coupling. Differences are displayed in the last two columns.

The average paired differences were 1.21 percent and 0.81 percent for final moisture and delta moisture, respectively. The probability of the differences occurring by chance alone (p-values) are 13 percent and 29 percent for final moisture and delta moisture, respectively. From these data it is concluded that the difference between final moisture and delta moisture for tests with fluid coupling and without fluid coupling were not statistically significant at the 5 percent significance level, indicating no significant moisture reabsorption occurs under the test conditions utilized.

In Test 0727-1, a single run at 0.85-cm cake thickness, a wet streak was observed at the middle of the belt caused by moisture reabsorption during fluid coupling. Therefore, the cake thickness should be kept at 1.27 cm or greater to avoid the moisture reabsorption problem.

4.5.2.2 Effect of Experimental Factors on Moisture Content

Because the effect of fluid coupling was not determined to be statistically significant, data from tests with and without fluid coupling were pooled together to examine the effects of D.C. voltage levels, ultrasonic

TABLE 10. EAD BELT PRESS PRU TESTS ON -100 MESH UPPER FREEPORT COAL AT CQ, INC. (a)

Test no.	Outer Belt Air Perm. cfm	Inlet Cake Thickness cm	Fluid Coupling	Coal Feed ^(b) Rate ton(US)/hr	U/S ^(c) Sector	U/S Power kw	DC Voltage volts	Current amps	Initial Moisture percent	Final Moisture percent	Delta Moisture percent	Energy Cost \$/ton(US)
0720-1	310	1.90	OFF	1.33	NONE	0	0	0	35.35	30.51	5.84	0.00
0720-2	310	1.90	ON	1.36	ALL	9.0	0	0	34.83	26.80	8.03	0.33
0720-3	310	1.90	ON	1.34	NONE	0	0	0	35.80	27.65	8.15	0.00
0720-4	310	1.90	ON	1.34	ALL	9.0	90	850	35.71	22.06	13.65	3.69
0720-5	310	1.90	OFF	1.35	NONE	0	90	700	35.09	22.75	12.34	2.74
0724-1	310	1.27	OFF	0.86	NONE	0	0	0	38.01	31.08	6.93	0.00
0724-2	310	1.27	ON	0.87	NONE	0	0	0	37.14	30.00	7.14	0.00
0724-3	85	1.27	OFF	0.87	NONE	0	50	380	37.45	27.76	9.69	1.28
0724-4	85	1.27	ON	0.88	NONE	0	50	680	36.65	27.56	9.09	2.27
0724-5	85	1.27	ON	0.87	ALL	9.0	50	675	37.17	27.76	9.42	2.79
0724-6	85	1.27	ON	0.87	ALL	9.0	70	895	37.53	26.47	11.06	4.76
0726-1	85	1.27	ON	0.86	NONE	0	0	0	37.94	30.69	7.25	0.00
0726-2	85	1.27	ON	0.86	ALL	9.0	0	0	37.77	30.13	7.64	0.52
0726-3	85	1.27	ON	0.86	ALL	9.0	70	948	38.33	26.56	11.77	5.08
0726-4	85	1.27	ON	0.87	NONE	0	70	938	37.47	25.99	11.48	4.45
0726-5	85	1.27	ON	0.87	BACK	4.5	70	995	37.01	26.13	10.88	4.94
0726-6	85	1.27	ON	0.88	BACK	4.5	0	0	36.92	29.95	6.97	0.26
0726-7	85	1.27	ON	0.88	NONE	0	0	0	36.80	29.63	7.17	0.00
0727-1	360	0.84	ON	0.58	NONE	0	0	0	38.00	31.85	6.15	0.00
0727-2	360	1.27	ON	0.88	NONE	0	0	0	36.41	28.90	7.51	0.00
0727-3	360	1.27	ON	0.88	ALL	9.0	70	1035	36.71	25.98	10.73	5.36
0727-4	360	1.27	ON	0.88	NONE	0	70	1025	36.60	26.23	10.37	4.79

(a) All tests used 1 m/min belt speed, 250 psi inner belt tension, and 160 psi outer belt tension.

(b) The feed rate was back calculated based on cake thickness and initial moisture.

(c) U/S: Ultrasonics.

power levels, and cake thickness (excluding the results at 0.85 cm cake thickness) on final moisture and delta moisture. Figure 29 shows the experimental results for final moisture and Figure 30 shows results for delta moisture. For example, for test number 0724-5, at 1.27 cm cake thickness, 50 volt, and 9 kw the final moisture was 27.76 percent as plotted in the left box in Figure 29.

An analysis of variance was conducted to examine the effects of D.C. voltage, ultrasonic power, cake thickness, and belt permeability on both final moisture and delta moisture. The results from the analysis of variance are summarized in Tables F-2 and F-3 in the Appendix F for final moisture and delta moisture, respectively. The R-square and RMSE values from the variance models and means for final moisture and delta moisture models are shown below:

<u>Moisture Parameter</u>	<u>R-Square</u>	<u>RMSE</u>	<u>Mean</u>
Final Moisture	0.92	0.87	27.65
Delta Moisture	0.95	0.62	9.20

As shown in Table F-2, while the effects of D.C. voltage and cake thickness on final moisture were determined to be statistically significant at the 5 percent significance level, the effects of belt permeability and ultrasonics power were not. In summary, voltage was the most statistically significant factor on EAD performance for final moisture. Analysis of variance results agree with the experimental results shown in Figure 29 which clearly shows D.C. voltage level is the most influential factor on the percentage changes of final moisture. While final moisture does vary with cake thickness, the trend is much smaller for cake thickness than for voltage in Figure 29. Ultrasonic power, however, does not have a visible effect on final moisture in Figure 29.

FIGURE 29. MINUS 100 MESH COAL PRU RESULTS FOR FINAL CAKE MOISTURE IN PERCENT

FIGURE 30. MINUS 100 MESH COAL PRU RESULTS FOR DELTA MOISTURE IN PERCENT

As shown in Table F-3, D.C. voltage level was determined to be the only statistically significant factor (at 5 percent significance level) on the performance of EAD for delta moisture. The effects of cake thickness, belt permeability, and ultrasonic power level were not statistically significant (at 5 percent significance level). The results of analysis of variance for delta moisture also agree with experimental results shown in Figure 30. While D.C. voltage level shown in Figure 30 has a considerable effect on the percentage changes of delta solids, there was no significant effect due to ultrasonic power level.

4.5.2.3 Linear Regression Model for Moisture Content

In the final analysis, we omitted the effects of ultrasonic power and belt permeability and fitted a linear regression model to the data to estimate the linear trend between D.C. voltage and final moisture and delta moisture for the two cake thickness values. Final moisture and delta moisture levels are plotted against D.C. voltage level in Figures 31 and 32 using a different symbol for each cake thickness. The slope between final moisture and D.C. voltage level was estimated to be -0.058 with a standard error of 0.005 . The slope between delta moisture and D.C. voltage level was estimated to be 0.057 with a standard error of 0.004 . The fitted regression lines for both final and delta moisture are drawn on Figure 31 and 32, respectively. This means over the range of 0 to 90 volts, a 10 volt power increase is estimated to result in a 0.58 percent decrease and 0.57 percent increase in final moisture and delta moisture, with 0.05 percent and 0.04 percent standard errors, respectively. As indicated in Figure 31, lower final moisture levels were obtained at the thicker cake and higher voltage levels. Similarly, Figure 32 shows that higher delta moisture levels were obtained at the thicker cake and higher voltage levels.

As discussed in the laboratory tests, the rate of electro-osmotic filtration is proportional to the voltage gradient across the filter cake. Therefore the effect of the thickness, i.e. solids loading, can be better visualized by plotting final cake moisture against voltage gradient for the two values of solids loading. To do this, the entire voltage drop was assumed

FIGURE 31. FINAL MOISTURE VERSUS VOLTAGE DATA WITH FITTED REGRESSION LINES
FOR -100 MESH COAL (PRU TESTS)

FIGURE 32. DELTA MOISTURE VERSUS VOLTAGE DATA WITH FITTED REGRESSION LINES FOR
-100 MESH COAL (PRU TESTS)

to occur across the filter cake and thus values of voltage gradient were calculated. The results are shown in Figure 33. As can be seen, the effect of increasing cake thickness was quite significant, which agrees with the laboratory tests analyzed in a similar manner. A cake thickness above 1.91 cm could not be tested because of the ultrasonic plate curvature with respect to the anode roll. The design can be easily modified to allow handling thicker cakes, if necessary.

It is believed, based on laboratory studies, that effect of voltage can be enhanced by coupling more ultrasonic energy into the filter cake; this will require the redesign of the ultrasonic seal in the EAD belt press.

4.5.2.4 Energy Use

The energy cost ranged from 1 to 5 dollars/ton (DS) of coal depending on the operating conditions. The optimum energy cost versus final moisture envelopes for two throughput values are shown in Figure 34. At the higher throughput of 1.35 ton (DS)/hr/m belt width, the key costs at various moisture levels are as follows:

- 22 percent moisture: 3.67 dollars/ton (DS)
- 23 percent moisture: 2.46 dollars/ton (DS)
- 24 percent moisture: 1.64 dollars/ton (DS).

4.5.3 Effect of EAD on Coal Properties

The feed to EAD PRU and the resulting product coal were analyzed to determine if EAD affected properties of coal other than its moisture content. The properties of interest were volatile matter (VM), free swelling index (FSI), higher heating value (HHV; MAF basis), ash (MF basis), and total sulfur (MAF basis). The VM, FSI, and HHV were measured to determine if there was an electrochemical oxidation of coal. And the ash and total sulfur values were

FIGURE 33. FINAL MOISTURE VERSUS VOLTAGE GRADIENT DATA WITH FITTED REGRESSION LINES FOR -100 MESH COAL (PRU TESTS; FEED: 35-38 PERCENT MOISTURE)

FIGURE 34. CAKE MOISTURE VERSUS ENERGY COSTS AT TWO THROUGHPUTS FOR
-100 MESH UPPER FREEPORT COAL (PRU TESTS)

obtained to determine if EAD affected removal of pyritic sulfur. As shown in Table 11, these properties of coal were virtually unchanged due to EAD.

TABLE 11. AVERAGE VALUES OF SELECTED PROPERTIES OF -100 MESH COAL BEFORE AND AFTER CONTINUOUS EAD

Property	Before EAD	After EAD
VM, %	30.81	30.68
FSI	7.7	7.3
HHV, Btu/lh(MAF)	15,473	15,477
Ash, % (MF)	13.06	13.11
Total Sulfur, % (MAF)	2.46	2.51

4.5.4 Correlation with Batch Results

Since the samples of -100 mesh coal for laboratory and PRU field tests were quite comparable in terms of coal beneficiation, the laboratory and PRU data were compared to establish scale-up correlations. The conditions for tests 0720-4 and 0726-3, conducted at solids loadings of 14.0 and 9.3 kg(DS)/m², respectively, were selected for comparison. The observed values of final cake moisture and specific energy for the PRU tests were compared with values predicted by regression models based on laboratory results.

The results given in Table 12 show the final moisture values for PRU to be within about 1 percent of the laboratory values. However, the specific energy consumption for PRU tests was significantly higher than for laboratory tests, specially at the lower solids loading. The energy consumption at a solids loading of 14.0 kg (DS)/m² was about 15 percent higher for PRU. At the lower solids loading, the specific energy was about 50 percent higher for PRU. A comparison of the electrical conductivities of the filtrate shows that the coal for PRU had about the same conductivity (3.08 millimho/cm) as that for the laboratory sample (3.25 millimho/cm). Therefore, some other factors are responsible for the difference in specific energy. The

likely explanations are poor ultrasonic coupling and lower pressure achieved in the PRU.

TABLE 12. COMPARISON OF PRU EAD RESULTS WITH LABORATORY EAD RESULTS FOR -100 MESH COAL

	Final Cake Moisture, percent		Specific Energy kwh/lb filtrate	
	PRU	Laboratory ^(a)	PRU	Laboratory ^(a)
<u>Case I</u>				
PRU #0720-4 [14.0 kg(DS)/m ²]	22.1	23.6	0.150	0.128
<u>Case II</u>				
PRU #0726-3 [9.3 kg(DS)/m ²]	26.6	25.4	0.196	0.130

(a) Predicted by regression model based on laboratory results.

As discussed earlier, the ultrasonic coupling is believed to have been better at higher solids loading. This may partially explain the widening of the gap between energy consumption figures for PRU and laboratory tests as the solids loading decreased.

The PRU energy usage was higher than for laboratory test partly also because of a lower pressure (3.3 psi) used in the PRU compared to laboratory tests (5 psi). Laboratory simulations of the PRU operation, utilizing a sample from the batch of coal tested in the PRU, showed that on increasing the pressure from 3.5 to 6 psi, the moisture content was lowered by 2.25 percent and the specific energy use was reduced by 17 percent.

4.5.5 Potential for Improved EAD Performance for -100 Mesh Coal

The performance of the PRU potentially can be improved by implementing the following design improvements or processing condition modifications:

- (1) Modification of the ultrasonic plate curvature and seal to accommodate a 3.8 cm thick feed cake. This will increase the throughput and reduce specific ultrasonic energy usage.
- (2) Improve belt tensioning system to increase maximum pressure from 3.3 psi to 4.6 psi conservatively and to 6 psi optimistically. This will reduce the moisture content and specific energy usage.
- (3) Modification of ultrasonic seal and addition of more transducers to couple more ultrasonic energy. Even without adding more transducers, the EAD effectiveness could be significantly improved with a better seal.
- (4) Use of higher belt speeds in combination with higher voltage gradient may be beneficially employed to increase throughput with a disproportionately lower increase in energy cost. This needs to be studied further.
- (5) Reducing the initial moisture will reduce total energy consumption. This may however, require modification of cake feeding/distribution system to maintain uniform cake thickness across the belt.
- (6) Increasing the zeta potential (Z) to electrical conductivity (A) ratio by controlling the dissolved solids content of process water or by using a suitable additive, as discussed in Subsection 3.5.2.

It is believed that the first three items listed above are easy to implement and their benefits are quantifiable based on available laboratory data. The last three items, however, will require further testing. Based on the first three design improvements and the laboratory data, we made estimates of EAD performance. The moisture versus energy cost values for two levels of improvement, namely "conservative" and "optimistic", are compared with observed values in Table 13. As shown, a conservative estimate of projected energy cost to achieve 20 percent final moisture at a throughput of 2.70 ton

(DS)/hr/m belt width is 3.36 dollars/ton (DS). Increasing the final moisture level to 22 percent is projected to reduce energy cost to 1.50 dollars/ton (DS).

TABLE 13. COMPARISON OF OBSERVED ENERGY COST VALUES WITH PROJECTED VALUES FOR AN IMPROVED-DESIGN EAD BELT PRESS FOR -100 MESH UPPER FREEPORT COAL AT VARIOUS FINAL MOISTURE LEVELS (INITIAL MOISTURE CONTENT: 37 PERCENT)

Final Cake Moisture, percent	Observed ^(a) Energy Cost, \$/ton (DS)	Projected ^(b) Energy Cost, \$/ton (DS)	
		Conservative	Optimistic
26	0.65	NA	NA
25	1.12	NA	NA
24	1.64	0.60	NA
23	2.46	1.03	NA
22	3.67	1.50	0.59
21	NA	2.25	1.01
20	NA	3.36	1.48
19	NA	NA	2.21
18	NA	NA	3.30

NA: Not available.

(a) Observed conditions: 1.35 tons (DS)/hr/m; 2.7 min.; 1.9 cm cake thickness.

(b) Projected conditions: 2.70 ton (DS)/hr/m; 2.7 min.; 3.8 cm cake thickness.

4.6 PRU RESULTS ON -325 MESH COAL

Field tests of the EAD PRU on -325 mesh Upper Freeport coal were conducted at CQ, Inc., Homer City, PA, during November-December, 1990. A total of 25 tests were performed to investigate the effect of the following experimental factors on EAD performance:

- (1) Fluid coupling (on or off)
- (2) Cake thickness (1.27 and 1.91 cm)
- (3) Ultrasonic power (0 and 9 kW)
- (4) D.C. voltage (0, 50, 70, 80, 85, and 100 volts).

The belt speed was maintained at 0.5 m/min, which corresponds to an EAD residence time of 5.4 minutes. Higher belt speeds were desired, but were not possible due the capacity limitation of the solid bowl centrifuge used for predewatering.

4.6.1 Mechanical Performance

The feed coal was pumped from ground level up to the machine inlet using a Moyno pump. The feed distributor worked satisfactorily to provide fairly uniform cake across the belt. The cake discharge was also satisfactory. Very little coal squeezed out from the edges of the belt. In the earlier tests, there was some problem with the DC power supply, which was caused by damage during shipping. The problem was corrected in the field. The ultrasonic seal, into which water is pumped to maximize ultrasonic coupling, still leaked badly. The seal improved somewhat with an increase in belt tension.

4.6.2 EAD Process Performance

The test conditions and results are summarized in Table 14. The lowest moisture content of product cake with EAD was about 31 percent compared to 36-40 percent for pressure only (no EAD) and 46-48 percent for solid-bowl centrifugation (predewatered feed).

4.6.2.1 Effects of Experimental Factors on Moisture Content

The means and standard deviations of final cake moisture and delta moisture (decrease in final cake moisture) for each combination of cake thickness, voltage, ultrasonics, and fluid coupling are displayed in Table G-1 in Appendix G.

TABLE 14. EAD BELT PRESS PRU TESTS ON -325 MESH UPPER FREEPORT COAL AT CQ, INC. (a)

Test No.	Inlet Cake Thickness cm	Fluid Coupling	Coal Feed ^(b) Rate ton(OS)/hr	DC Voltage volts	Current amps	U/S ^(a) Power kw	Initial Moisture percent	Final Moisture percent	Delta Moisture percent	Max. Cake temp., C	Energy Coat \$/ton(OS)
1130-1	1.27	ON	0.36	0	0	0	47.86	36.40	11.46	13	0.00
1130-2	1.27	ON	0.36	50	500	0	48.05	36.04	12.01	64	4.08
1130-3	1.27	ON	0.36	50	500	9	47.83	36.01	11.82	63	5.30
1130-4	1.27	ON	0.36	80	690	9	47.82	35.57	12.25	66	10.21
1130-5	1.27	ON	0.37	0	0	0	47.34	39.31	8.04	22	1.23
1130-6	1.27	OFF	0.37	0	0	0	47.03	37.79	9.24	21	0.00
1203-1	1.27	ON	0.36	0	0	0	48.06	39.61	8.45	16	0.00
1203-2	1.27	OFF	0.36	0	0	0	47.53	38.62	8.91	16	0.00
1203-3	1.27	OFF	0.37	50	330	0	47.37	34.59	12.79	63	2.65
1203-4	1.27	OFF	0.37	85	400	0	47.25	33.74	13.51	63	5.46
1203-5	1.27	ON	0.37	85	550	0	47.32	38.50	8.81	65	7.52
1203-6	1.27	ON	0.36	85	550	9	47.46	37.18	10.28	67	8.77
1204-1	1.90	ON	0.56	0	0	0	46.00	39.63	6.37	15	0.00
1204-2	1.90	OFF	0.56	0	0	0	46.38	36.10	10.27	16	0.00
1204-3	1.90	OFF	0.55	70	425	0	46.89	33.72	13.16	69	3.16
1204-4	1.90	OFF	0.55	85	440	0	46.85	33.85	13.00	79	3.97
1204-5	1.90	ON	0.54	85	525	0	48.00	34.33	13.67	71	4.85
1204-6	1.90	ON	0.49	85	525	9	52.67	33.37	19.30	79	6.24
1205-1	1.90	ON	0.55	0	0	0	47.01	36.09	10.91	17	0.00
1205-2	1.90	ON	0.56	100	560	0	46.63	34.45	12.17	70	5.93
1204-3	1.90	ON	0.56	100	570	9	46.59	31.38	15.21	71	6.84
1205-4	1.90	OFF	0.55	100	480	0	46.87	33.23	13.64	83	5.10
1206-1	1.90	ON	0.56	0	0	0	46.60	37.13	9.48	14	0.00
1206-2	1.90	ON	0.56	100	635	9	46.30	33.03	13.27	80	7.48
1206-3	1.90	ON	0.56	100	635	0	46.85	32.81	14.04	80	6.74

- (a) All tests used 0.5 m/min belt speed, TETKO 7041 OSC (85 cfm) belt, and 140 psi inner belt tension.
 Tests 1206-1, 1206-2, and 1206-3 used 250 psi outer belt tension, all others used 240 psi belt tension.
 (b) The feed rate was back calculated based on cake thickness and initial moisture.
 (c) U/S: Ultrasonics.

Experimental results are shown in Figures 35 and 36 for final moisture and delta moisture, respectively. For example, for test number 1130-5, at 1.27 cm thick cake, 0 volt, and 9 kW final moisture is plotted as 39.30 percent in the left box in Figure 35.

An analysis of variance was conducted to examine the effects of voltage, fluid coupling, ultrasonics power, and cake thickness on both final moisture and delta moisture. These analysis of variance models included terms for the main effects of fluid coupling, cake thickness, ultrasonics, and voltage, and for the interaction between ultrasonics and cake thickness. The results from the analysis of variance are summarized in Table G-2 and G-3 in Appendix G for final moisture and delta moisture, respectively. The R-square and RMSE values from analysis of variance models, and means for final moisture and delta moisture are shown below:

<u>Moisture Parameter</u>	<u>R-square</u>	<u>RMSE</u>	<u>Mean</u>
Final Moisture	0.76	1.29	35.70
Delta Moisture	0.64	1.83	11.68

As shown in Table G-2, while the effects of voltage and cake thickness on final moisture were determined to be statistically significant (at the 5 percent significance level), the effects of fluid coupling, ultrasonics power, and the interaction between ultrasonics power and cake thickness were not. In summary, voltage was the most statistically significant factor on EAD performance for final moisture.

Analysis variance results agree with the experimental results shown in Figure 35 which clearly shows voltage level to be the most influential factor for changes in final moisture. While final moisture do vary with cake thickness the trend is much smaller for cake thickness than for voltage in Figure 35. The poor final moisture of 38.50 percent observed for test number 1203-5 at 0 kW, 85 volts, and 1.27 cm thick cake deviates from this trend, and may be due to a reabsorption of water in the presence of fluid coupling.

FIGURE 35. MINUS 325 MESH COAL PRU RESULTS FOR FINAL CAKE MOISTURE IN PERCENT

FIGURE 36. MINUS 325 MESH COAL PRU RESULTS FOR DELTA MOISTURE IN PERCENT

Ultrasonic power, however, does not have a visible effect on final moisture in Figure 35.

As shown in Table G-3, the main effects of voltage level and cake thickness level were determined to be the statistically significance factors (at 5 percent significance level) on the performance of EAD for delta moisture. Main effects of fluid coupling and ultrasonics power level were not statistically significant (at 5 percent significance level). The interaction between ultrasonics and cake thickness was marginally significant (at 5 percent significance level). This significant interaction results from the better performance of ultrasonics at 1.91 cm thick cake compared to 1.27 cm thick cake. Model predicted averages for delta moisture for selected levels of ultrasonics and cake thickness are shown below.

<u>Cake Thickness</u>	<u>Ultrasonics power level</u>	
	<u>0 kw</u>	<u>9 kw</u>
1.27 cm	11.29%	10.99%
1.91 cm	11.71%	14.90%

While delta moisture levels are predicted to increase with higher ultrasonics for 1.91 cm thick cake, they are essentially the same for 1.27 cm thick cake. This result may possibly be due to the improved fluid coupling observed with the thicker cake. Results from the analysis of variance for delta moisture also agree with experimental results shown in Figure 36. Voltage level shown in Figure 36 has a considerable effect on the percentage changes of delta moisture. The low 8.81 percent of delta moisture observed for test number 1203-5 at 0 kw, 85 volts, and 1.27 cm thick cake may be due to a reabsorption of water in the presence obtained in Test Number 1204-6 was probably due to relatively high initial moisture (52.67 percent) in this test, which was about 5 to 7 percent higher compared to other tests.

4.6.2.2 Linear Regression Models

In the final analysis, we omitted the effects of ultrasonics power and fluid coupling and fitted a linear regression model to the data to estimate the linear trend between voltage and final moisture and between voltage and delta moisture. Figures 37 and 38 plot final moisture and delta moisture against voltage level using a different symbol for each cake thickness. The fitted regression lines for both final and delta moisture are drawn on Figure 37 and 38, respectively. As indicated in Figure 37, lower final moisture levels were obtained at the thicker cake and higher voltage levels. Similarly, Figure 38 shows that higher moisture levels were obtained at the thicker cake and higher voltage levels. The slope between final moisture and voltage level was estimated to be -0.036 with a standard error of 0.007 . The slope between delta moisture and voltage level was estimated to be 0.041 with a standard error of 0.010 . This means that over the range of 0 – 100 volt, a 10 volt power increase will result in 0.36 percent decreases and 0.41 percent and 0.10 percent standard errors, respectively. These percentage changes in final and delta moisture for minus 325 mesh coal are comparable to results obtained for the minus 100 mesh coal i.e., 0.58 percent decreases and 0.57 percent increases for final and delta moisture, with 0.05 percent and 0.04 percent standard errors, respectively.

As discussed in Subsections 3.3.3 and 3.4.3, the effect of cake thickness can be better judged by plotting final cake moisture against voltage gradient measures than voltage. Assuming that the voltage drop is across the filter cake, the results shown in Figure 39 are achieved. As shown, the EAD performance improves quite significantly on increasing the cake thickness (solids loading). A cake thickness higher than 1.91 cm was desirable but not feasible without modification of the PRU.

FIGURE 37. FINAL CAKE MOISTURE VERSUS VOLTAGE DATA WITH FITTED REGRESSION LINES FOR -325 MESH COAL (PRU TESTS)

FIGURE 38. DELTA MOISTURE VERSUS VOLTAGE DATA WITH FITTED REGRESSION LINES FOR -325 MESH COAL (PRU TESTS)

FIGURE 39. FINAL MOISTURE VERSUS VOLTAGE GRADIENT DATA WITH FITTED REGRESSION LINES FOR -325 MESH COAL (PRU TESTS; FEED: 46-48 PERCENT MOISTURE)

4.6.2.3 Energy Use

The energy cost (at 5¢/kwh) ranged from 2.5 to 10 dollars/ton (DS) depending on the operating conditions. The optimum energy cost versus final cake moisture envelope is shown in Figure 40. The energy costs at various final moisture levels based on this optimum are listed as "observed" values in Table 15 along with projected values possible with two levels of design improvements.

TABLE 15. COMPARISON OF OBSERVED ENERGY COST VALUES WITH PROJECTED VALUES FOR AN IMPROVED-DESIGN EAD BELT PRESS FOR -325 MESH UPPER FREEPORT COAL FOR VARIOUS FINAL CAKE MOISTURE LEVELS (INITIAL MOISTURE CONTENT: 47 PERCENT)

Final Cake Moisture, percent	Observed ^(a) Energy Cost, \$/ton (DS)	Projected ^(b) Energy Cost, \$/ton (DS)	
		Conservation	Optimistic
35	1.34	NA	NA
34	2.58	NA	NA
33	4.10	0.88	NA
32	5.62	1.70	NA
31	7.77	2.71	0.77
30	NA	3.71	1.47
29	NA	5.13	2.34
28	NA	NA	3.20
27	NA	NA	4.43

NA: Not available.

(a) Observed conditions: 0.56 ton (DS)/hr/m; 5.4 min.; 1.9 cm cake thickness.

(b) Projected conditions: 2.24 ton (DS)/hr/m; 2.7 min.; 3.8 cm cake thickness.

4.6.3 Effect of EAD on Coal Properties

As in the case of -100 mesh coal tests, there was no significant change in the ultimate and proximate analyses of coal due to EAD application.

4.6.4 Correlation with Batch Results

A comparison of PRU tests with laboratory tests showed that while the final moisture levels were comparable to those in the laboratory tests, the specific energy values were 2 to 3 times higher. The primary reasons for this are believed to be the following, in order of decreasing importance:

- A 3 times higher electrical conductivity to zeta potential ratio for PRU tests compared with laboratory tests
- A much longer dewatering time than necessary. (The larger dewatering times were a result of low belt speeds employed to match with low feed coal production rate.)
- The ultrasonic coupling in PRU was worse than for laboratory tests.
- The maximum cake pressure in the PRU was 3.3 psi compared to 6 psi in the laboratory.

4.6.5 Potential for Improved EAD Performance for -325 Mesh Coal

The performance of the PRU for -325 mesh coal also can be significantly improved by implementing the improvements suggested for -100 mesh coal. Additionally, employing a shorter residence time, i.e., 2.7 rather than 5.4 minutes, will double the throughput, while increasing the moisture content by only 1 percent and decreasing the specific energy use by 22 percent based on laboratory data. (In making these estimates, it was assumed that the relative changes in energy with changes in processing conditions were the same for PRU as for laboratory tests. This assumption should be reasonable if the primary reason for the difference in absolute values of specific energy in PRU and laboratory test is the ratio of the electrical conductivity to the zeta potential of feed coal.) By implementing this change in operating conditions

FIGURE 40. MINIMUM ENERGY COST ENVELOPE FOR -325 MESH UPPER FREEPORT COAL (PRU TESTS)

along with design changes to obtain (a) a thicker (3.8 cm) cake, (b) a higher (4.6–6 psi) pressure, and (c) improved ultrasonic seal, the EAD performance potentially can be improved as shown in Table 15. As shown, a conservative estimate of projected energy cost to achieve 30 percent final moisture at a throughput of 2.24 ton (DS)/hr/m belt width is 3.71 dollars/ton (DS). On increasing the final moisture to 32 percent, the energy cost is projected to be \$1.70 dollars/ton (DS).

5.0 EAD VERSUS DRYING ECONOMICS

The PRU results showed that EAD can produce moisture levels as low as 22 and 31 percent for -100 and -325 mesh coals, respectively; and the laboratory tests yielded 2 to 3 percent lower moisture levels. No currently-used technology except thermal drying can produce such low coal moisture levels. Therefore, economics of EAD was compared with economics of thermal drying. The drying costs were based on the use of an indirectly-heated (steam-jacketed) rotary dryer supplied by FEECO. The indirect heating was considered necessary because of the small particle size of coals under consideration. The steam for drying was raised using clean coal, without using an FGD system. The capital and operating costs for a predewatering system, e.g., a vacuum disc filter for -100 mesh coal or a solid bowl centrifuge for -325 mesh coal, were not estimated as these were the same for EAD or thermal drying. The results are discussed below.

5.1 MINUS 100 MESH COAL ECONOMICS

The EAD capital costs were based on the use of a 2.5 meter belt width system, which has a 2.5 times higher capacity than the PRU and 1.25 times higher capacity than a commercially available EAD belt press for sewage sludges. The fixed capital investment (FCI), including installation, operating capital, startup costs, etc., was estimated by ASH to be \$632,000. The plant throughput for such a unit utilizing PRU conditions for 1.91 cm initial cake thickness, which were suboptimal, was estimated to be 55 tons (DS)/day for 16 hrs/day operation. The net annual operating costs for EAD were then estimated for final moisture levels of 22, 23, and 24 percent. The cost estimation options and breakdown of costs by various cost components for the 24 percent moisture case are shown in Table 16. The capital-related costs add up to 77 percent of the total cost, indicating that the EAD is very capital intensive under the PRU throughput conditions. For example, if either the belt speed is doubled to 2 m/min or the cake thickness is doubled to 3.8 cm, the throughput can be doubled to 110 tons (DS)/day. This can reduce the operating cost from 10.09 dollars/ton (DS) to 5.86 dollars/ton (DS). The increased belt speed option is currently feasible with the PRU, but the

TABLE 16. NET ANNUAL OPERATING COST FOR EAD FOR -100 MESH COAL (PRU TEST DATA; SUBOPTIMAL CONDITIONS; 24 PERCENT FINAL CAKE MOISTURE)

FCI \$632,000
 EAD THROUGHPUT 55 TONS (DRY SOLID)/UNIT
 PLANT CAPACITY 55 TON/DAY
 OPERATING FACTORS
 HOURS OF OPERATION PER DAY 16 HOURS/DAY
 NO. OF SHIFTS PER DAY 2
 NO. OF OPERATING DAYS PER YEAR 200 DAYS/YEAR
 COAL PARTICLE SIZE -100 MESH
 INITIAL MOISTURE 37%
 FINAL MOISTURE 24%

Cost Item	Cost Component	Basis	% of Oper. Cost	\$/Ton
Raw Materials Coal	0	0.000 per lb	0.00%	\$0.000
Utilities Electricity	18,040	\$1.64 per ton (dry solid)	16.25%	\$1.640
Labor Operating	3,000	\$30.00 per man-hr (BASED ON ONE MAN PER FOUR EAD PER SHIFT)	2.70%	\$0.273
Maintenance Supervision	750 450	25.00% of Operating Labor 15.00% of Operating Labor	0.68% 0.41%	\$0.068 \$0.041
Operating Supplies	450	15.00% of Operating Labor	0.41%	\$0.041
Maintenance Supplies	25,280	4.00% of FCI	22.78%	\$2.298
Laboratory Charges	450	15.00% of Operating Labor	0.41%	\$0.041
Patents and Royalties	0	0.00% of Product Sales	0.00%	\$0.000
Plant Overhead	2,520	60.00% of Oper and Maint. Labor and Supervision	2.27%	\$0.229
Waste Water Treatment	0	0.00% Assumption	0.00%	\$0.000
Local Taxes and Insurance	9,480	1.50% of FCI	8.54%	\$0.862
Depreciation	50,560	8.00% of FCI	45.56%	\$4.596
TOTAL ANNUAL OPERATING COSTS CONTRIBUTION TO PRICE, \$/TON DRY COAL	\$110,980 \$10.09		100.00%	\$10.089

moisture versus energy correlation for higher belt speeds is unknown. On the other hand, for the higher cake thickness option, sufficient laboratory data are available to indicate that the moisture content will not increase significantly, while the energy cost may decline by at least 5 percent; however, a minor mechanical modification of PRU is necessary in this case to accommodate a thicker cake. (A thickness above 3.8 cm may not be desirable as it will probably result in a significant degradation of the EAD performance with respect to moisture reduction level.)

The EAD operating costs were compared with thermal drying costs using published purchased equipment cost data and economic analysis procedures similar to those for EAD. The operating costs for moisture levels of 22, 23, and 24 percent with observed (suboptimal) EAD PRU energy costs and throughputs are shown in Figure 41. As shown EAD costs are lower than those for thermal drying at 55 tons (DS)/day only. The EAD costs at higher plant throughput remain the same as for 55-tons (DS)/day, while thermal drying costs decline to values below EAD costs.

If the cake thickness is doubled to 3.8 cm, and conservatively assuming no benefit in moisture or energy reduction as suggested by Figures 7 and 34, then the EAD operating costs became lower than thermal drying costs at all throughputs as shown in Figure 42. Even at the increased EAD throughput, i.e., 2.70 ton (DS)/hr/m belt width, the EAD capital cost is 2 to 3 times higher than for thermal drying as shown in Figure 43. But the EAD operating costs are lower because thermal drying is much more energy intensive than EAD.

The EAD process economics can be further improved by increasing the cake pressure above 3 psi and by coupling more ultrasonic energy. These will require minor-to medium-difficulty design modifications as discussed earlier. The operating costs for the "conservative" and "optimistic" design improvement cases discussed in Section 4.5.5 and quantified in Table 13, are shown graphically in Figure 44. The conservative case assumes increase in pressure to 4.6 psi and modification of ultrasonic seal to deliver 0.33 watts/cm^2 as opposed to a value of 0.16 watts/cm^2 (50 percent of expected) assumed arbitrarily for current design. These design improvements appear to be easily operating cost comparison with thermal drying are shown in Figure 45.

FIGURE 41. COMPARISON OF EAD AND THERMAL DRYING OPERATING COSTS VERSUS PROCESS CAPACITY FOR -100 MESH COAL (EAD COSTS BASED ON ENERGY COSTS AND THROUGHPUTS OBSERVED FOR PRU TESTS)

FIGURE 42. COMPARISONS OF EAD AND THERMAL DRYING OPERATING COSTS VERSUS PROCESS CAPACITY FOR -100 MESH COAL (EAD COSTS BASED ON PERFORMANCE PROJECTED FOR 3.8 CM CAKE THICKNESS BASED ON LABORATORY DATA)

FIGURE 43. FIXED CAPITAL COST VERSUS THROUGHPUT FOR TWO FINAL MOISTURE LEVELS FOR EAD AND THERMAL DRYING FOR -100 MESH COAL

FIGURE 44. EAD OPERATING COST VERSUS FINAL CAKE MOISTURE FOR TWO ENERGY COST SCENARIOS FOR -100 MESH COAL (BASED ON PROJECTED EAD PERFORMANCE WITH DESIGN IMPROVEMENTS)

FIGURE 45. COMPARISON OF EAD AND THERMAL DRYING OPERATING COSTS VERSUS PROCESS CAPACITY FOR -100 MESH COAL (EAD COSTS BASED ON CONSERVATIVE DESIGN IMPROVEMENT CASE)

5.2 MINUS 325 MESH COAL ECONOMICS

The operating costs for -325 mesh coal based on the PRU conditions were even higher than for -100 mesh coal because of a lower throughput, on a dry solids basis, for -325 mesh coal. The reasons for the lower throughput were a lower belt speed (0.5 m/min) and a higher initial moisture content (47 percent) for the finer coal. As mentioned earlier, operation with a belt speed greater than 0.5 m/min was not attempted due to capacity limitation of the feed preparation plant. (The PRU is capable of operating up to 2.5 m/min.) The laboratory results showed that increasing the belt speed to 1 m/min should reduce the moisture content and energy consumption values by 1.0 and 18 percent, respectively. With this change in processing conditions, which will require no design improvements, along with an increase in cake thickness to 3.8 cm and improvement in ultrasonic seal, which will require minor modifications, the EAD operating can be made lower than thermal drying operating costs, as shown in Figure 46. The throughput for this "conservative" design improvement case is 2.24 ton (DS)/hr/m belt width, which is about 18 percent lower than for -100 mesh coal.

The operating cost can be further reduced assuming that a cake pressure of 6 psi and an ultrasonic intensity of 0.66 watts/cm² can be achieved. These improvements (optimistic case) are considered to be of significantly greater difficulty than the changes for the conservative case discussed above. The projected EAD operating costs for the optimistic case are considerably lower than for thermal drying as shown in Figure 47.

In making the economic comparisons, three potential benefits of EAD were overloaded as data were not available to quantify these. First, the dust formation in thermal drying could represent some economic penalty due to loss of coal. Second, dust formation may represent exploration hazards. And third, there exists a possibility of surface oxidation of coal due to accidental overheating. The surface oxidation can hamper coal-water-slurry formulations.

FIGURE 46. COMPARISON OF EAD AND THERMAL DRYING COSTS VERSUS PROCESS CAPACITY FOR -325 MESH COAL (EAD COSTS BASED ON CONSERVATIVE DESIGN IMPROVEMENT CASE)

FIGURE 47. COMPARISON OF EAD AND THERMAL DRYING OPERATING COSTS VERSUS PROCESS CAPACITY FOR -325 MESH COAL (EAD COSTS BASED ON OPTIMISTIC DESIGN IMPROVEMENTS CASE)

6.0 CONCLUSIONS

The conclusions from the two-phase coal EAD program are as follows:

- (1) The continuous EAD of fine (-100 mesh) and ultrafine (-325 mesh) coal to achieve moisture levels of 22 and 31 percent, respectively is feasible. These PRU results are suboptimal.
- (2) The EAD operating cost under the PRU conditions employed were not attractive above 50 ton (DS)/day throughput. This is because of the capital-intensive nature of EAD and selection of low throughput conditions in PRU tests because of the limitation of the capacity of the plant supplying the coal to EAD.
- (3) The use of higher values of cake thickness (2-4 cm), coupled ultrasonic intensity (0.3-0.7 watts/cm²), belt speeds (≥ 1 m/min), and pressure (4-6 psi) should result in minimization of EAD capital and operating costs while achieving the target final cake moisture levels of 20 percent for -100 mesh and 30 percent for -325 mesh coal. The energy costs are projected to range from about 1.50 to 3.50 dollars/ton (DS) coal, depending on the level of mechanical design improvements implemented in a commercial-size EAD machine. With these improvements, the EAD is projected to be considerably cheaper than thermal drying.
- (4) A solids retention of 99 percent on polyester belts is feasible without using any flocculents.
- (5) The properties of coal (proximate, ultimate, FSI, and HHV) are unaltered by EAD.
- (6) The combination of mechanical pressure and heating effects alone contributes to less than 1 percent moisture content reduction compared to a typical 10 to 15 percent reduction as a result of all factors operative during EAD.

7.0 RECOMMENDATIONS FOR PHASE III

The results of Phases I and II point to the need for additional EAD tests to optimize the process and continuous dewatering equipment design. There is a need to (a) explore new sets of operating conditions to minimize capital cost, (b) modify the EAD belt press to achieve better ultrasonic coupling (and thus achieve the results with ultrasonics comparable to those achieved in the laboratory) and higher values of cake pressure and cake thickness, (c) test coals from several plants to determine variation in electrochemical properties versus process water chemistry, and (d) further explore use of additives to increase the ratio of zeta potential to electrical conductivity. Items (a), (c) and (d) should be studied in detail first in the laboratory, followed by PRU testing within a narrow range of conditions at no more than two sites. The modified PRU should be tested at sites capable of providing at least 3 ton (DS)/hr of coal.

APPENDIX A

LABORATORY EAD DATA SUMMARIES

A-1

APPENDIX A
LABORATORY EAD DATA SUMMARIES

The experimental results on -100 and -325 mesh Upper Freeport coals are summarized in Tables A-1 and A-2, respectively.

TABLE A-1. SUMMARY OF LABORATORY EAD PARAMETRIC TESTS ON -100 MESH UPPER FREEPORT COAL

Test Number	Date Sample prepared	Date Test Done	Initial Sample Percent	Weight Of Sample Percent	Solids Loading Kg(OS)/m2	Pressure psi	Total Test Time min	Electric Time min	Voltage Gradient volts/cm	Ultrasonic Time min	Ultrasonic Power watts/cm2	Cake Final Moisture percent	Filtrate Dry Coal gms	Average Current Amp	Cake Maximum Temperature F	Initial Cake thickness cm	Total Energy kWh/ Ton(OS)	Specific Energy kWh/ Lb.Filtrate	Cost Dollars/ Ton(OS)
1	7/18/89	7/20/89	39.37	35.13	4.7	5.00	4.00	3.50	108.9	3.50	0.33	28.42	1.63	0.69	117.00	0.64	127.46	0.225	6.37
2	7/18/89	7/20/89	39.37	35.11	4.7	5.00	4.00	3.50	108.9	3.50	0.33	29.97	1.58	0.67	117.30	0.64	124.57	0.246	6.23
3	7/18/89	7/20/89	39.37	35.14	4.7	5.00	4.00	3.50	108.9	3.50	0.33	28.48	1.83	0.65	118.00	0.64	120.12	0.210	6.01
4	7/18/89	7/20/89	39.37	35.13	4.7	5.00	4.00	3.50	108.9	3.50	0.33	29.18	1.18	0.68	117.00	0.64	125.37	0.241	6.27
5	7/18/89	7/20/89	39.37	45.09	6.0	5.00	6.50	0.00	0.0	0.00	0.00	35.24	0.00	0.00	72.00	0.83	0.00	0.000	0.00
6	7/18/89	7/20/89	39.37	25.07	3.3	5.00	6.50	0.00	0.0	0.00	0.00	36.90	0.00	0.00	72.00	0.46	0.00	0.000	0.00
7	7/18/89	7/21/89	39.37	35.13	4.7	5.00	4.00	3.50	108.9	3.50	0.33	29.18	1.57	0.72	118.00	0.64	132.50	0.247	6.63
8	7/18/89	7/21/89	39.37	45.09	6.0	5.00	6.50	6.00	121.2	6.00	0.22	25.05	1.07	0.68	142.00	0.83	232.96	0.355	11.65
9	7/18/89	7/21/89	39.37	45.13	6.0	5.00	1.50	1.00	48.4	1.00	0.44	28.68	2.70	1.59	85.00	0.83	37.38	0.065	1.87
10	7/18/89	7/21/89	39.37	25.06	3.3	5.00	1.50	1.00	218.1	1.00	0.44	31.58	1.25	1.74	126.00	0.46	177.13	0.392	8.86
11	7/18/89	7/21/89	39.37	25.10	3.3	5.00	6.50	6.00	87.1	6.00	0.22	29.61	0.79	0.40	102.00	0.46	107.07	0.214	5.35
12	7/18/89	7/21/89	39.37	45.08	6.0	5.00	6.50	6.00	121.2	0.00	0.00	26.85	0.10	0.75	158.00	0.82	247.94	0.437	12.40
13	7/18/89	7/21/89	39.37	25.13	3.3	5.00	6.50	6.00	87.0	0.00	0.00	32.06	0.10	0.42	97.00	0.46	99.08	0.274	4.95
14	7/18/89	7/24/89	39.37	35.08	4.7	5.00	4.00	3.50	109.0	3.50	0.33	29.62	2.05	0.70	123.00	0.64	129.03	0.240	6.45
15	7/18/89	7/24/89	39.37	25.10	3.3	5.00	1.50	1.00	87.1	1.00	0.44	28.27	1.98	1.20	101.00	0.46	51.51	0.084	2.58
16	7/18/89	7/24/89	39.37	45.09	6.0	5.00	1.50	1.00	121.2	1.00	0.44	27.85	1.65	2.19	126.00	0.83	123.50	0.215	6.18
17	7/18/89	7/24/89	39.37	25.13	3.3	5.00	6.50	6.00	217.5	6.00	0.22	26.03	0.56	0.50	143.00	0.46	307.83	0.496	15.39

TABLE A-1. SUMMARY OF LABORATORY EAD PARAMETRIC TESTS ON -100 MESH UPPER FREEPORT COAL
(Continued)

Test Date Number Sample prepared	Date Test Done	Initial Sample moisture Percent	Weight Of Sample gms	Solids Loading Kg(DS)/m2	Pressure psi	Test Time min	Total Time min	Electric Time min	Voltage Gradient volts/cm	Ultrasonic Time min	Ultrasonic Power watts/cm2	Cake Final Moisture percent	Filtrate Dry Coal gms	Average Current Amp	Cake Maximum Temperature F	Initial Cake thickness cm	Total Energy kWh/ Ton(DS)	Specific Energy kWh/ lb.Filtrate Ton(DS)	Cost Dollars/ Ton(DS)
18	7/18/89	7/24/89	39.37	45.14	6.0	5.00	6.50	6.00	48.4	6.00	0.22	29.55	1.61	0.41	99.00	0.83	61.12	0.120	3.06
19	7/18/89	7/24/89	39.37	45.06	6.0	5.00	1.50	1.00	48.5	1.00	0.66	28.80	3.20	1.62	89.00	0.82	39.25	0.067	1.96
20	7/18/89	7/24/89	39.37	25.16	3.3	5.00	1.50	1.00	217.2	1.00	0.66	31.07	0.32	1.68	132.00	0.46	171.97	0.413	8.60
21	7/18/89	7/25/89	39.37	45.05	6.0	5.00	1.50	1.00	121.3	1.00	0.22	27.68	1.12	2.20	120.00	0.82	122.67	0.217	6.13
22	7/18/89	7/25/89	39.37	35.06	4.7	5.00	4.00	3.50	109.1	3.50	0.33	30.08	0.66	0.72	120.00	0.64	132.42	0.285	6.62
23	7/18/89	7/25/89	39.37	25.11	3.3	5.00	1.50	1.00	87.1	1.00	0.22	29.80	0.82	1.22	93.00	0.46	50.33	0.102	2.52
24	7/18/89	7/25/89	39.37	45.05	6.0	5.00	6.50	6.00	48.5	6.00	0.44	27.56	3.36	0.41	106.00	0.82	67.23	0.106	3.36
25	7/18/89	7/25/89	39.37	25.13	3.3	5.00	6.50	6.00	217.5	6.00	0.44	24.43	1.63	0.47	140.00	0.46	303.07	0.420	15.15
26	7/18/89	7/25/89	39.37	25.13	3.3	5.00	1.50	1.00	217.5	0.00	0.00	30.89	0.13	1.84	135.00	0.46	182.50	0.443	9.12
27	7/18/89	7/25/89	39.37	45.06	6.0	5.00	1.50	1.00	48.5	0.00	0.00	29.81	0.00	1.82	90.00	0.82	40.38	0.090	2.02
28	7/18/89	7/26/89	39.37	35.09	4.7	5.00	4.00	3.50	109.0	3.50	0.33	27.97	1.99	0.65	119.00	0.64	121.34	0.204	6.07
29	7/18/89	7/26/89	39.37	25.10	3.3	5.00	1.50	1.00	217.7	1.00	0.22	30.80	1.04	1.66	129.00	0.46	166.62	0.355	9.33
30	7/18/89	7/26/89	39.37	25.08	3.3	5.00	6.50	6.00	87.2	6.00	0.44	27.07	2.46	0.35	111.00	0.46	100.11	0.160	5.41
31	7/18/89	7/26/89	39.37	45.12	6.0	5.00	1.50	1.00	48.4	1.00	0.22	28.66	1.39	1.62	89.00	0.83	36.85	0.069	1.84
32	7/18/89	7/26/89	39.37	45.11	6.0	5.00	6.50	6.00	121.1	6.00	0.44	22.41	1.60	0.63	139.00	0.83	221.57	0.292	11.08
33	7/18/89	7/26/89	39.37	25.07	3.3	5.00	6.50	6.00	87.2	6.00	0.66	28.10	2.70	0.41	121.00	0.46	133.93	0.204	6.70
34	7/18/89	7/26/89	39.37	45.06	6.0	5.00	6.50	6.00	121.3	6.00	0.66	21.58	2.74	0.58	138.00	0.82	211.86	0.264	10.59

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TABLE A-1. SUMMARY OF LABORATORY EAD PARAMETRIC TESTS ON -100 MESH UPPER FREEPORT COAL
(Continued)

Test Number	Date Sample prepared	Date Test Done	Initial Sample moisture Percent	Weight Of Sample gms	Solids Loading kg(OS)/m ²	Pressure psi	Total Test Time min	Electric Time min	Voltage Gradient volts/cm	Ultrasonic Time min	Ultrasonic Power watts/cm ²	Cake Final Moisture percent	Filtrate Dry Coal gms	Average Current Amp	Cake Maximum Temperature F	Initial Cake thickness cm	Total Energy kWh/ Ton(OS)	Specific Energy kWh/ Lb.Filtrate	Cost Dollars/ Ton(OS)
35	8/30/89	8/31/89	40.55	45.04	5.9	5.00	6.50	6.00	72.8	0.00	0.00	29.25	0.10	0.49	105.00	0.82	98.70	0.183	4.94
36	8/30/89	8/31/89	40.55	45.08	5.9	5.00	6.50	6.00	97.0	0.00	0.00	29.50	0.10	0.63	131.00	0.82	171.00	0.322	8.55
37	8/30/89	8/31/89	40.55	45.09	5.9	5.00	6.50	6.00	97.0	0.00	0.66	24.20	3.22	0.55	128.00	0.83	169.78	0.212	8.49
38	8/30/89	8/31/89	40.55	45.10	5.9	5.00	6.50	6.00	72.7	0.00	0.66	27.32	2.89	0.48	117.00	0.83	116.81	0.168	5.84
39	8/30/89	8/31/89	40.55	45.04	5.9	5.00	6.50	6.00	72.8	0.00	0.99	26.06	3.73	0.48	126.00	0.82	127.38	0.168	6.37
40	8/30/89	8/31/89	40.55	45.10	5.9	5.00	6.50	6.00	96.9	0.00	0.99	23.03	4.01	0.53	126.00	0.83	173.77	0.203	8.69
41	8/30/89	8/31/89	40.55	45.07	5.9	5.00	6.50	6.00	121.2	0.00	0.99	21.61	3.78	0.55	137.00	0.82	216.46	0.243	10.82
42	8/30/89	9/7/89	39.02	45.07	6.0	5.00	6.50	6.00	145.5	0.00	0.99	20.05	3.31	0.51	130.00	0.82	231.72	0.276	11.59
43	8/30/89	9/7/89	39.02	60.12	8.0	5.00	6.50	6.00	109.1	0.00	0.99	20.59	3.11	0.65	208.00	1.10	215.29	0.267	10.76
44	8/30/89	9/7/89	39.02	90.09	12.1	5.00	6.50	6.00	72.8	0.00	0.99	21.56	7.09	0.75	192.00	1.65	163.48	0.204	8.17
45	8/30/89	9/7/89	39.02	45.11	6.0	5.00	6.50	6.00	121.1	0.00	0.99	21.18	3.15	0.49	155.00	0.83	191.28	0.238	9.56
46	8/30/89	9/11/89	38.05	140.60	19.1	5.00	6.50	6.00	46.6	0.00	0.99	22.84	9.82	0.98	185.00	2.57	131.56	0.187	6.58
47	8/30/89	9/11/89	38.05	45.10	6.1	5.00	5.50	5.00	121.2	5.00	0.99	21.67	3.73	0.70	145.00	0.83	213.76	0.285	10.69
48	8/30/89	9/11/89	38.05	45.10	6.1	5.00	4.50	4.00	121.2	4.00	0.99	21.72	3.73	0.75	152.00	0.83	181.53	0.243	9.08
49	8/30/89	9/11/89	38.05	45.03	6.1	5.00	4.50	4.00	145.6	4.00	0.99	19.86	3.96	0.67	170.00	0.82	192.73	0.260	9.64
50	8/30/89	9/11/89	38.05	45.04	6.1	5.00	5.50	5.00	145.6	5.00	0.99	19.77	3.96	0.54	184.00	0.82	201.43	0.250	10.07

TABLE A-2. SUMMARY OF LABORATORY EAD PARAMETRIC TESTS ON -325 MESH UPPER FREEPORT COAL

Test Number	Date Sample prepared	Date Test Done	Initial Sample Moisture Percent	Weight Of Sample gms	Solids Loading kg(OS)/m ²	Pressure psi	Total Test Time min	Electric Time min	Voltage Gradient volts/cm	Ultrasonic Time min	Ultrasonic Power watts/cm ²	Cake Final Moisture Percent	Filtrate Dry Coal gms	Average Current Amp	Cake Maximum Temperature F	Initial Cake Thickness cm	Total Energy kWh/ Ton(OS)	Specific Energy kWh/ lb.Filtrate	Cost Dollars/ Ton(OS)
1	10/06/89	10/09/98	46.74	55.07	6.4	5.00	3.50	3.00	99.2	0.00	0.00	40.42	0.00	0.24	87.00	1.01	37.87	0.0951	1.89
2	10/06/89	10/09/98	46.74	45.05	5.3	5.00	5.00	4.50	145.5	4.50	0.77	32.73	3.98	0.22	121.00	0.82	93.33	0.0989	4.67
3	10/06/89	10/09/98	46.74	35.19	4.1	5.00	6.50	0.00	0.0	0.00	0.00	41.95	0.00	0.00	66.00	0.64	0.00	0.0000	0.00
4	10/06/89	10/09/98	46.74	55.06	6.4	5.00	6.50	6.00	138.8	0.00	0.00	38.63	0.10	0.22	108.00	1.01	97.04	0.1939	4.85
5	10/06/89	10/09/98	46.74	45.15	5.3	5.00	5.00	4.50	145.1	4.50	0.77	33.36	3.84	0.22	124.00	0.83	95.18	0.1042	4.76
6	10/06/89	10/09/98	46.74	35.09	4.1	5.00	3.50	3.00	217.9	0.00	0.00	38.70	0.00	0.29	118.00	0.64	98.88	0.2008	4.94
7	10/06/89	10/09/98	46.74	35.08	4.1	5.00	6.50	6.00	155.7	0.00	0.00	39.29	0.00	0.16	98.00	0.64	77.06	0.1672	3.85
8	10/06/89	10/09/98	46.74	55.13	6.4	5.00	6.50	0.00	0.0	0.00	0.00	41.83	0.00	0.00	66.00	1.01	0.00	0.0000	0.00
9	10/06/89	10/10/89	46.42	55.10	6.5	5.00	6.50	6.00	138.7	6.00	0.99	32.07	3.95	0.22	131.00	1.01	121.01	0.1323	6.05
10	10/06/89	10/10/89	46.42	45.07	5.3	5.00	5.00	4.50	193.9	4.50	0.77	31.24	2.55	0.27	144.00	0.83	142.34	0.1547	7.12
11	10/06/89	10/10/89	46.42	45.09	5.3	5.00	5.00	4.50	96.9	4.50	0.77	32.57	5.38	0.16	109.00	0.83	56.66	0.0577	2.83
12	10/06/89	10/10/89	46.42	55.14	6.5	5.00	6.50	6.00	99.0	6.00	0.55	33.85	4.51	0.15	107.00	1.01	62.64	0.0724	3.13
13	10/06/89	10/10/89	46.42	35.13	4.1	5.00	3.50	3.00	155.4	3.00	0.99	30.94	3.81	0.24	124.00	0.64	79.28	0.0779	3.96
14	10/06/89	10/10/89	46.42	45.14	5.3	5.00	5.00	4.50	145.2	4.50	0.77	32.19	3.88	0.22	127.00	0.83	95.41	0.1020	4.77
15	10/06/89	10/10/89	46.42	35.13	4.1	5.00	3.50	3.00	217.6	3.00	0.55	32.32	1.83	0.30	123.00	0.64	111.58	0.1282	5.58
16	10/06/89	10/11/89	46.28	45.06	5.3	5.00	5.00	4.50	145.4	4.50	0.77	31.62	4.14	0.22	129.00	0.83	95.11	0.0994	4.76
17	10/06/89	10/11/89	46.28	45.07	5.3	5.00	5.00	4.50	145.4	4.50	0.33	33.84	2.49	0.19	116.00	0.83	72.29	0.0898	3.61
18	10/06/89	10/11/89	46.28	35.13	4.1	5.00	6.50	6.00	155.4	6.00	0.99	30.03	3.95	0.22	146.00	0.64	149.98	0.1436	7.50
19	10/06/89	10/11/89	46.28	45.07	5.3	5.00	5.00	4.50	145.4	4.50	1.21	30.05	4.76	0.24	148.00	0.83	112.39	0.1088	5.62

TABLE A-2. SUMMARY OF LABORATORY CAD PARAMETRIC TESTS ON -325 MESH UPPER FREEPORT COAL (Continued)

Test Number	Date Sample prepared	Date Test Done	Initial Sample Moisture Percent	Weight Of Sample gms	Solids Loading kg(OS)/m ²	Pressure psi	Total Test Time min	Electric Time min	Voltage Gradient volts/cm	Ultrasonic Time min	Ultrasonic Power watts/cm ²	Cake Final Moisture Percent	Filtrate Dry Coal gms	Average Current Amps	Cake Maximum Temperature °F	Initial Cake Thickness cm	Total Energy kWh/ Ton(OS)	Specific Energy kWh/ Lb.Filtrate Ton(OS)	Cost Dollars/ Ton(OS)
20	10/06/89	10/11/89	46.28	55.07	6.5	5.00	3.50	3.00	138.8	3.00	0.99	33.42	4.87	0.30	126.00	1.01	79.18	0.0895	3.96
21	10/06/89	10/11/89	46.28	35.05	4.1	5.00	6.50	6.00	218.1	6.00	0.55	30.13	2.17	0.24	136.00	0.64	184.85	0.1926	9.24
22	10/06/89	10/11/89	46.28	55.15	6.5	5.00	3.50	3.00	99.0	3.00	0.55	34.54	4.17	0.24	102.00	1.01	44.25	0.0542	2.21
23	10/06/89	10/12/89	46.17	25.12	3.0	5.00	5.00	4.50	260.9	4.50	0.77	31.67	1.91	0.26	135.00	0.46	192.82	0.2097	9.64
24	10/06/89	10/12/89	46.17	35.07	4.1	5.00	6.50	6.00	155.7	6.00	0.55	31.02	3.30	0.19	134.00	0.64	115.78	0.1190	5.79
25	10/06/89	10/12/89	46.17	35.09	4.1	5.00	6.50	6.00	217.9	6.00	0.99	29.56	3.07	0.23	157.00	0.64	195.35	0.1929	9.77
26	10/06/89	10/12/89	46.17	65.16	7.7	5.00	5.00	4.50	100.6	4.50	0.77	33.88	4.49	0.22	114.00	1.19	64.09	0.0780	3.20
27	10/06/89	10/12/89	46.17	45.09	5.3	5.00	5.00	4.50	145.3	4.50	0.77	31.83	4.15	0.23	132.00	0.83	96.32	0.1023	4.82
28	10/06/89	10/12/89	46.17	55.11	6.5	5.00	3.50	3.00	99.1	3.00	0.99	32.27	5.79	0.26	115.00	1.01	53.39	0.0563	2.67
29	10/06/89	10/12/89	46.17	55.07	6.5	5.00	3.50	3.00	138.8	3.00	0.55	34.29	2.85	0.30	120.00	1.01	71.73	0.0929	3.59
30	10/06/89	10/13/89	45.38	45.10	5.4	5.00	4.00	3.50	145.3	3.50	0.77	32.09	3.02	0.26	130.00	0.83	82.92	0.0996	4.15
31	10/06/89	10/13/89	45.38	35.15	4.2	5.00	3.50	3.00	217.5	3.00	0.99	29.79	2.69	0.32	147.00	0.64	126.21	0.1354	6.31
32	10/06/89	10/13/89	45.38	45.09	5.4	5.00	5.00	4.50	145.3	4.50	0.77	31.60	3.53	0.23	130.00	0.83	96.85	0.1113	4.84
33	10/06/89	10/13/89	45.38	45.07	5.4	5.00	6.00	5.50	145.4	6.00	0.77	31.43	3.77	0.21	136.00	0.83	111.53	0.1260	5.58
34	10/06/89	10/13/89	45.38	55.10	6.6	5.00	6.50	6.00	99.1	6.00	0.99	31.20	5.31	0.18	136.00	1.01	81.84	0.0895	4.09
35	10/06/89	10/13/89	45.38	55.15	6.6	5.00	6.50	6.00	138.6	6.00	0.55	33.86	2.60	0.22	136.00	1.01	107.48	0.1480	5.37
36	10/06/89	10/13/89	45.38	35.08	4.2	5.00	3.50	3.00	155.7	3.00	0.55	30.07	3.05	0.24	114.00	0.64	69.78	0.0743	3.49
37	10/06/89	10/13/89	45.38	45.09	5.4	5.00	5.00	4.50	145.3	0.00	0.00	37.46	0.00	0.22	114.00	0.83	74.16	0.1599	3.71
38	10/06/89	10/13/89	45.38	45.03	5.4	3.00	5.00	4.50	145.5	4.50	0.77	35.23	2.51	0.21	126.00	0.82	90.21	0.1317	4.51
39	10/06/89	10/13/89	45.38	45.12	5.4	7.00	5.00	4.50	145.2	4.50	0.77	29.01	3.87	0.24	144.00	0.83	100.39	0.1032	5.02

TABLE A-2. SUMMARY OF LABORATORY EAD PARAMETRIC TESTS ON -325 MESH UPPER FREEPORT COAL (Continued)

#	Test Date Number Sample prepared	Date Test Done	Initial Sample Moisture Percent	Weight Of Sample gms	Solids Loading kg(OS)/m2	Pressure		Total Test Time		Electric		Ultrasonic		Cake Final Moisture Percent	Filtrate Dry Coal gms	Average Current Amps	Cake Maximum Temperature F	Initial Cake Thickness cm	Total Energy kWh/ Ton(OS)	Specific Energy kWh/ Lb.Filtrate Ton(OS)	Cost Dollars/ Ton(OS)
						psi	min	min	volts/cm	min	watts/cm2										
40	10/06/89	10/13/89	45.38	45.06	5.4	10.00	5.00	4.50	145.4	4.50	0.77	28.63	4.36	0.23	144.00	0.83	96.71	0.0959	4.84		
41	10/06/89	10/13/89	45.38	35.09	4.2	5.00	6.50	6.00	249.0	6.00	0.77	28.20	1.96	0.25	153.00	0.64	219.57	0.2296	10.98		
42	10/06/89	10/25/89	46.17	45.08	5.3	5.50	5.00	4.50	145.4	4.50	0.77	29.10	2.69	0.27	133.00	0.83	111.82	0.1135	5.59		
43	10/06/89	10/25/89	46.17	45.15	5.3	7.00	5.00	4.50	145.1	4.50	0.77	28.15	3.98	0.27	136.00	0.83	111.78	0.1054	5.59		
44	10/06/89	10/25/89	46.17	45.11	5.3	5.00	5.00	4.50	145.3	4.50	0.77	28.71	4.09	0.27	132.00	0.83	109.16	0.1044	5.46		
45	10/06/89	10/25/89	46.17	45.10	5.3	6.50	5.00	4.50	145.3	4.50	0.77	28.11	3.89	0.27	135.00	0.83	109.61	0.1035	5.48		
46	10/06/89	10/25/89	46.17	45.11	5.3	6.00	5.00	4.50	145.3	4.50	0.77	27.89	3.77	0.27	137.00	0.83	110.47	0.1040	5.52		
47	10/27/89	10/30/89	45.78	40.10	4.8	6.00	4.25	3.75	143.0	3.75	0.88	29.86	4.22	0.24	132.00	0.73	85.33	0.0851	4.27		
48	10/27/89	10/30/89	45.78	40.04	4.8	6.00	4.25	3.75	143.2	3.75	0.88	29.01	4.09	0.23	135.00	0.73	82.99	0.0809	4.15		
49	10/27/89	10/30/89	45.78	30.12	3.6	6.00	5.00	4.50	145.0	4.50	0.99	28.88	4.19	0.21	132.00	0.55	106.63	0.0983	5.33		
50	10/27/89	10/30/89	45.78	45.09	5.4	6.00	6.50	6.00	145.3	6.00	1.10	28.32	5.31	0.20	152.00	0.83	125.96	0.1177	6.30		
51	10/27/89	10/30/89	45.78	45.11	5.4	6.00	6.50	6.00	108.9	6.00	1.10	30.08	5.37	0.17	140.00	0.83	92.89	0.0913	4.64		
52	10/27/89	10/30/89	45.78	35.15	4.2	6.00	3.50	3.00	139.8	3.00	0.99	29.20	4.83	0.23	132.00	0.64	71.08	0.0663	3.55		
53	10/27/89	10/31/89	45.48	35.11	4.2	6.00	5.00	4.50	140.0	4.50	0.77	29.73	3.84	0.22	135.00	0.64	95.70	0.0965	4.78		
54	10/27/89	10/31/89	45.48	45.08	5.4	6.00	3.50	3.00	109.0	3.00	0.77	30.28	4.17	0.23	116.00	0.83	51.88	0.0548	2.59		
55	10/27/89	10/31/89	45.48	35.09	4.2	6.00	3.50	3.00	186.7	3.00	0.77	28.95	3.42	0.28	127.00	0.64	95.58	0.0957	4.78		
56	10/27/89	10/31/89	45.48	45.12	5.4	6.00	3.50	3.00	145.2	3.00	0.99	30.08	4.16	0.29	132.00	0.83	80.15	0.0841	4.01		
57	10/27/89	11/1/89	45.14	45.05	5.4	6.00	5.00	4.50	145.5	4.50	0.77	29.68	4.47	0.22	131.00	0.82	93.22	0.0977	4.66		
58	10/27/89	11/1/89	45.14	35.08	4.2	6.00	5.00	4.50	186.8	4.50	0.99	28.77	3.25	0.26	158.00	0.64	143.40	0.1472	7.17		
59	10/27/89	11/1/89	45.14	45.12	5.4	6.00	5.00	4.50	108.9	4.50	0.99	29.36	4.69	0.20	136.00	0.83	74.54	0.0767	3.73		

TABLE A-2. SUMMARY OF LABORATORY EAD PARAMETRIC TESTS ON -325 MESH UPPER FREEPORT COAL (Continued)

Test Number	Date Sample prepared	Date Test Done	Initial Sample Moisture Percent	Weight Of Sample gms	Solids Loading kg(OS)/m ²	Pressure psi	Total Test Time min	Electric Time min	Voltage Gradient volts/cm	Ultrasonic Time min	Ultrasonic Power watts/cm ²	Cake Moisture Percent	Filtrate Dry Coal gms	Average Current Amp	Cake Maximum Temperature F	Initial Cake Thickness cm	Total Energy kWh/ Ton(OS)	Specific Energy kWh/ Lb.Filtrate	Cost Dollars/ Ton(OS)
60	10/27/89	11/1/89	45.14	45.07	5.4	6.00	3.50	3.00	109.0	3.00	0.99	29.27	5.15	0.25	123.00	0.83	58.03	0.0586	2.90
61	10/27/89	11/1/89	45.14	35.12	4.2	6.00	5.00	4.50	139.9	4.50	0.99	29.47	4.28	0.21	130.00	0.64	98.40	0.0988	4.92
62	10/27/89	11/1/89	45.14	35.04	4.2	6.00	3.50	3.00	187.0	3.00	0.99	29.15	3.40	0.30	133.00	0.64	107.05	0.1105	5.35
63	10/27/89	11/1/89	45.14	35.18	4.2	6.00	3.50	3.00	139.7	3.00	0.77	28.66	3.57	0.23	117.00	0.64	66.12	0.0667	3.31
64	10/27/89	11/1/89	45.14	45.06	5.4	6.00	5.00	4.50	145.4	4.50	0.99	28.66	4.63	0.25	144.00	0.83	108.49	0.1093	5.42
65	10/27/89	11/1/89	45.14	45.12	5.4	6.00	5.00	4.50	108.9	4.50	0.77	29.08	5.12	0.20	126.00	0.83	68.50	0.0688	3.42
66	10/27/89	11/1/89	45.14	45.04	5.4	6.00	3.50	3.00	145.5	3.00	0.77	29.63	3.81	0.29	127.00	0.82	77.12	0.0826	3.86
67	10/27/89	11/1/89	45.14	35.15	4.2	6.00	5.00	4.50	186.4	4.50	0.77	29.26	2.86	0.24	150.00	0.64	126.32	0.1342	6.32

APPENDIX B

REGRESSION MODELLING RESULTS FOR LABORATORY EAD TESTS ON -100 MESH UPPER FREEPORT COAL

APPENDIX B

**REGRESSION MODELLING RESULTS FOR LABORATORY
EAD TESTS ON -100 MESH UPPER FREEPORT COAL**

The results of analysis of variance and coefficient of parameter estimates for final cake moisture and specific energy are given in Tables B-1 and B-2, respectively.

Table B-3 displays the observed and predicted final cake moistures for selected tests conducted at 6 min and 6 Kg(DS)/m² solids loading. The measured and predicted final cake moistures are shown in the fourth and fifth columns of the table. The precision of the predicted values can be assessed by the 95 percent prediction bounds for final cake moisture given in the sixth and seventh columns of the table; we are 95 percent confident that individual final cake moistures will fall between the lower and upper prediction bounds.

The effect of ultrasonic intensity on final cake moisture is presented graphically in Figure B-1.

The predicted EAD specific energy versus voltage gradient is shown in Figure B-2. A 3-D plot of predicted specific energy versus ultrasonic power and voltage gradient is shown in Figure B-3.

TABLE B-1. REGRESSION MODEL RESULTS AND COEFFICIENT OF PARAMETER ESTIMATES FOR FINAL CAKE MOISTURE BASED ON -100 MESH UPPER FREEPORT COAL LABORATORY EAD TESTS CONDUCTED AT 4, 5, AND 6 MINUTES

Dependent Variable: FINAL MOISTURE PERCENT						
Analysis of Variance						
Source	DF	Sum of Squares	Mean Square	F Value	Prob>F	
Model	7	334.89653	47.84236	108.210	0.0001	
Error	20	8.84254	0.44213			
C Total	27	343.73907				
Root MSE		Dep Mean	C.V.	R-square	Adj R-sq	
0.665		24.7	2.7	0.97	0.965	

Parameter Estimates						
Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > T	Variable Label
INTERCEP	1	43.3	1.52	28.489	0.0001	Intercept
VOLTAGE	1	-0.107	0.0196	-5.444	0.0001	VOLTAGE GRADIENT
WATTS	1	-7.67	1.86	-4.124	0.0005	ULTRASONIC WATTS
SOLIDLOAD	1	-1.51	0.204	-7.419	0.0001	SOLIDS LOADING Kg(DS)/m^2
WW	1	7.13	1.50	4.748	0.0001	WATTS-POWER QUADRATIC TERM
VV	1	0.000302	0.0000650	4.649	0.0002	VOLTS QUADRATIC TERM
VW	1	-0.0423	0.0130	-3.246	0.0040	VOLTAGE*WATTS INTERACTION
SS	1	0.0420	0.00916	4.585	0.0002	SOLID LOADING QUADRATIC TERM

DF = Degrees of Freedom
 Prob > |T| = Observed Significance Level
 C.V. = Coefficient of Variation
 MSE = Mean Square Error

TABLE B-2. STATISTICAL MODEL RESULTS AND PARAMETER ESTIMATES FOR EAD SPECIFIC ENERGY BASED ON -100 MESH UPPER FREEPORT COAL TESTS CONDUCTED AT 4, 5, AND 6 MINUTES

Dependent Variable: SPECIFIC ENERGY (kwh/lb filtrate)

Analysis of Variance						
Source	DF	Sum of Squares	Mean Square	F-test	Prob>F	
Model	6	0.21352	0.03559	68.772	0.0001	
Error	21	0.01087	0.00052			
C Total	27	0.22439				
RMS		Dep Mean	C.V.	R-square	Adj R-sq	
0.023		0.25	9.1	0.952	0.988	
Parameter Estimates						
Variable	DF	Coefficient of Variable Estimate	Standard Error	T-Test = 0	P-Value	Variable Label
INTERCEP	1	-0.158818	0.04742696	-3.349	0.0030	Intercept
VOLTAGE	1	0.005462	0.00066107	8.262	0.0001	Voltage Gradient, V/cm
WATTS	1	-0.018982	0.06263680	-0.303	0.7648	Ultrasonic Intensity, watts/cm^2
SLDLOAD	1	0.005523	0.00222655	2.481	0.0217	Solids Loading, Kg((DS)/m^2
VW	1	-0.002354	0.00043697	-5.387	0.0001	Voltage*Ultrasonic Interaction
WW	1	0.145647	0.05118979	2.845	0.0097	Ultrasonic Intensity-Power Quadratic Term
VV	1	-0.000009057	0.00000213	-4.244	0.0004	Voltage Gradient Quadratic Term

DF = Degrees of Freedom
 Prob>|T| = Observed Significance Level
 C.V. = Coefficient of Variation
 RMSE = Root Mean Square Error

TABLE B-3. EFFECT OF VOLTAGE GRADIENT AND ULTRASONIC INTENSITY ON FINAL CAKE MOISTURES AND SPECIFIC ENERGY USAGE FOR -100 MESH UPPER FREEPORT COAL [τ : 6 MINUTES; S_L : 6.0 KG(DS)/M²; P : 5 PSI]

No.	Voltage Gradient volts/cm	Ultrasonic Intensity watts/cm ²	Final Cake Moisture, %			Specific Energy (kWh/lb filtrate)				
			Observed	LPB ⁽¹⁾		Observed	Pred.	LPB	UPB	
				Pred.	UPB ⁽²⁾					
35	73	0.00	29.3	29.7	28.1	31.3	0.18	0.22	0.17	0.27
38	73	0.66	27.3	25.8	24.3	27.3	0.17	0.16	0.12	0.21
39	73	0.99	26.1	26.1	24.4	27.7	0.17	0.17	0.12	0.22
36	97	0.00	29.5	28.4	26.9	29.9	0.32	0.32	0.27	0.36
37	97	0.66	24.2	23.7	22.3	25.2	0.21	0.22	0.17	0.26
40	97	0.99	23.0	23.7	22.2	25.2	0.20	0.21	0.17	0.26
12	121	0.00	26.9	27.3	25.7	28.9	0.44	0.40	0.35	0.45
8	121	0.22	25.1	24.8	23.3	26.4	0.35	0.34	0.30	0.39
32	121	0.44	22.4	23.1	21.5	24.6	0.29	0.30	0.25	0.35
34	121	0.66	21.6	22.0	20.4	23.5	0.26	0.27	0.22	0.31
45	121	0.99	21.2	21.6	20.1	23.0	0.24	0.24	0.20	0.29
41	121	0.99	21.6	21.7	20.3	23.2	0.24	0.24	0.20	0.28
42	146	0.99	20.1	19.9	18.4	21.4	0.28	0.26	0.21	0.30

(1) Lower predicted bound

(2) Upper predicted bound

FIGURE B-1. PREDICTED FINAL CAKE MOISTURE VERSUS ULTRASONIC INTENSITY FOR -100 MESH UPPER FREEPORT [$S_L: 6 \text{ KG(DS)}/\text{M}^2$; VOLTAGE GRADIENT: 121 VOLTS/CM; $\tau: 6 \text{ MINUTES}$]

FIGURE B-2. PREDICTED SPECIFIC ENERGY VERSUS VOLTAGE GRADIENT FOR -100 MESH UPPER FREEPORT COAL [$S_L:6 \text{ KG(DS)}/\text{M}^2$; ULTRASONIC INTENSITY: $0.99 \text{ WATTS}/\text{CM}^2$; $\tau:6 \text{ MINUTES}$]

B-7

B-7

FIGURE B-3. 3-D PLOT OF PREDICTED SPECIFIC ENERGY VERSUS ULTRASONIC INTENSITY AND VOLTAGE GRADIENT FOR -100 MESH FREEPORT COAL [S_L : 6 KG(DS)/M²; τ : 6 MINUTES]

APPENDIX C

REGRESSION MODELLING RESULTS FOR LABORATORY EAD TESTS
ON -325 MESH UPPER FREEPORT COAL

APPENDIX C

REGRESSION MODELLING RESULTS FOR LABORATORY EAD TESTS
ON -325 MESH UPPER FREEPORT COAL

The results of analysis of variance and parameter estimates for final cake moisture and specific energy are given in Tables C-1 and C-2, respectively.

The predicted and observed values of moisture and specific energy as a function of ultrasonic intensity are given in Table C-3.

The predicted values of final cake moisture as a function of voltage gradient, ultrasonic intensity, and dewatering time are given in Figures C-1, C-2, and C-3, respectively.

The predicted values of specific energy as a function of pressure, dewatering time, voltage gradient, and ultrasonic intensity are shown in Figures C-4, C-5, C-6, and C-7, respectively.

The 3-D plots for final cake moisture and specific energy as a function of ultrasonic watts and voltage gradient are given in Figures C-8 and C-9, respectively.

TABLE C-1. REGRESSION MODEL RESULTS AND COEFFICIENT OF PARAMETER ESTIMATES FOR FINAL CAKE MOISTURE BASED ON -325 MESH UPPER FREEPORT COAL LABORATORY EAD TESTS

Dependent Variable: Final Cake Moisture, percent

Analysis of Variance				
Source	DF	Sum of Squares	Mean Square	P-Value
Model	10	510.76909	51.07691	0.0001
Error	54	27.77709	0.51439	
C Total	64	538.54618		
RMSE		Dep Mean	C.V.	Adj R-sq

2.3% 0.948 0.939

C-2

Parameter Estimates				
Variable	DF	Coefficient of Variable Estimate	Standard Error	T-Test = 0 P-Value
INTERCEP	1	11.879867	10.90314653	1.090 0.2807
ELECTIME	1	-0.252132	0.08697960	-2.899 0.0054
PRESSURE	1	-3.512941	0.61005238	-5.758 0.0001
VOLTAGE	1	-0.007351	0.00379345	-1.938 0.0579
WATTS	1	-13.588509	1.08947229	-12.473 0.0001
SLOAD	1	-1.519225	-0.95539966	-1.590 0.1176
AGE	1	-2.080612	0.38013123	-5.473 0.0001
INTMPCT	1	0.942948	0.20550227	4.589 0.0001
WW	1	6.396710	0.91679391	6.977 0.0001
PP	1	0.204295	0.04561429	4.479 0.0001
SS	1	0.198621	0.08785567	2.261 0.0278

DF = Degrees of Freedom
 Prob>|T| = Observed Significance Level
 C.V. = Coefficient of Variation
 RMSE = Mean Square Error

TABLE C-3. PREDICTED AND OBSERVED VALUES OF FINAL CAKE MOISTURES AND SPECIFIC ENERGY
VERSUS ULTRASONIC INTENSITY FOR -325 MESH UPPER FREEPORT COAL AT 5 PSI
AND OTHER SELECTED TESTS CONDITIONS

Test No.	Time	Solid Load	Volts	Watts	Moisture Content (%)			Specific Energy (kwh/lb filtrate)		
					Obs	Pred	UPB	Obs	Pred	UPB
6	3	4.1	218.0	0.00	38.7	38.2	36.6	0.20	0.19	0.17
15	3	4.1	217.8	0.55	32.3	32.4	30.9	0.13	0.14	0.12
31	3	4.2	217.7	0.99	29.8	29.8	28.3	0.14	0.15	0.13
37	4.5	5.4	145.4	0.00	37.5	37.6	36.0	0.16	0.16	0.14
17	4.5	5.3	145.5	0.33	33.8	34.6	33.1	0.09	0.12	0.10
*	4.5	5.3	145.5	0.77	32.2	31.7	30.2	0.10	0.10	0.08
19	4.5	5.3	145.5	1.21	30.1	31.3	29.7	0.11	0.12	0.10
7	6	4.1	155.8	0.00	39.3	37.9	36.3	0.17	0.17	0.15
24	6	4.1	155.8	0.55	31.0	31.9	30.3	0.12	0.13	0.11
18	6	4.1	155.6	0.99	30.0	30.3	28.8	0.14	0.13	0.11

Obs: Observed value
Pred: Predicted value
LPB: Lower prediction bound
UPB: Upper prediction bound.

TABLE C-4 . STATISTICAL MODEL RESULTS AND PARAMETER ESTIMATES FOR EAD
SPECIFIC ENERGY BASED ON -325 MESH UPPER FREEPORT COAL TESTS

Dependent Variable: TOTAL ENERGY (kwatt hr per lb filtrate)						
Analysis of Variance						
Source	DF	Sum of Squares	Mean Square	F Value	Prob>F	
Model	7	0.09369	0.01338	149.377	0.0001	
Error	57	0.00511	0.00009			
C Total	64	0.09879				
Root MSE		Dep Mean	C.V.	R-square	Adj R-sq	
0.00947		0.110	8.6%	0.948	0.94	
Parameter Estimates						
Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > T	Variable Label
INTERCEP	1	0.175954	0.12079236	1.457	0.1507	Intercept
ELECTIME	1	0.015039	0.00114179	13.171	0.0001	ELECTRICAL TIME
PRESSURE	1	-0.002535	0.00152393	-1.663	0.1017	PRESSURE psi
VOLTAGE	1	0.000992	0.00004825	20.569	0.0001	VOLTAGE GRADIENT
WATTS	1	-0.140690	0.01388567	-10.132	0.0001	ULTRASONIC WATTS
SLDLOAD	1	0.009053	0.00191784	4.720	0.0001	SOLIDS LOADING Kg(DS)/m^2
INTMPCT	1	-0.005791	0.00256043	-2.262	0.0275	INITIAL CAKE MOISTURE
WW	1	0.092192	0.01164259	7.919	0.0001	WATTS*WATTS

DF = Degrees of Freedom
 Prob > |T| = Observed Significance Level
 C.V. = Coefficient of Variation
 MSE = Mean Square Error

FIGURE C-1. PREDICTED FINAL CAKE MOISTURE VERSUS ELECTRICAL VOLTAGE FOR -325 MESH UPPER FREEPORT COAL (P:5 PSI; τ :4.5 MINUTES; ULTRASONIC INTENSITY:0.77 WATTS/CM²; S_L :5.3 KG(DS)/M²)

FIGURE C-2. PREDICTED FINAL CAKE MOISTURE VERSUS ULTRASONIC INTENSITY FOR -325 MESH
UPPER FREEPORT COAL [P:5 PSI; τ :4.5 MINUTES; VOLTAGE GRADIENT:146 VOLTS/CM;
 S_L 5.3 KG(DS)/M²]

FIGURE C-3. PREDICTED FINAL CAKE MOISTURE VERSUS TIME FOR -325 MESH UPPER FREEPORT COAL [P: 5 PSI; VOLTAGE GRADIENT: 146 VOLTS/CM; ULTRASONIC INTENSITY: 0.77 WATTS/CM²; S₁: 5.3 KG(DS)/M²]

FIGURE C-4. PREDICTED EAD SPECIFIC ENERGY VERSUS PRESSURE FOR -325 MESH UPPER FREEPORT COAL [τ : 4.5 MINUTES; VOLTAGE GRADIENT: 146 VOLTS/CM; ULTRASONIC INTENSITY: 0.77 WATTS/CM²; S_L : 5.4 KG(DS)/M²]

FIGURE C-5. PREDICTED EAD SPECIFIC ENERGY VERSUS DEWATERING TIME FOR -325 MESH UPPER FREEPORT COAL [P:5 PSI; VOLTAGE GRADIENT:146 VOLTS/CM; ULTRASONIC INTENSITY:0.77 WATTS/CM²; S_L:5.3 KG(DS)/M²]

FIGURE C-6. PREDICTED EAD SPECIFIC ENERGY VERSUS ELECTRICAL VOLTAGE FOR -325 MESH UPPER FREEPOR COAL
 [P:5 PSI; τ :4.5 MINUTE; ULTRASONIC INTENSITY:0.77 WATTS/CM²; S_L :5.3 KG(DS)/M²]

FIGURE C-7. PREDICTED EAD SPECIFIC ENERGY VERSUS ULTRASONIC INTENSITY FOR -325 MESH UPPER FREEPORT COAL
 [P:5 PSI; τ :4.5 MINUTE; VOLTAGE GRADIENT:146 VOLTS/CM; S_1 :5.3 KG(DS)/M²]

FIGURE C-8. 3-D PLOT OF PREDICTED FINAL CAKE MOISTURES VERSUS ULTRASONIC INTENSITY AND VOLTAGE GRADIENT FOR -325 MESH UPPER FREEPORT COAL [P: 5 PSI; τ : 4.5 MINUTES; S_L : 5.3 KG(DS)/M²]

FIGURE C-9. 3-D PLOT OF EAD SPECIFIC GRADIENT ENERGY VERSUS ULTRASONIC INTENSITY AND VOLTAGE GRADIENT FOR -325 MESH UPPER FREEPORT COAL [P:5 PSI; τ :4.5 MINUTES; S_L :5.3 KG(DS)/M²]

APPENDIX D

ANALYSES OF COALS FOR
EAD PRU TESTS

APPENDIX D

**ANALYSES OF COALS FOR
EAD PRU TESTS**

The typical proximate and ultimate analyses of the coals for -100 mesh and -325 mesh Upper Freeport coals for the PRU tests are given in Table D-1, and the typical particle size distributions of these coals are shown in Figure D-1.

**TABLE D-1. TYPICAL ULTIMATE AND PROXIMATE ANALYSES OF UPPER
FREEPORT COALS FOR PRU TESTS.**

	-100 Mesh ^(a)	-325 Mesh ^(b)
Moisture, %	35 - 38	46 - 48
Ultimate Analysis, % Dry Basis		
Carbon	74.76	79.64
Hydrogen	4.41	5.07
Nitrogen	1.48	1.27
Sulfur	2.20	1.08
Ash	13.34	6.44
Oxygen (by difference)	3.81	6.50
Total	100.00	100.00
Proximate Analysis, % Dry Basis		
Ash	13.34	6.50
Volatile Matter	30.81	29.11
Fixed Carbon	55.85	64.45
Total	100.00	100.00
Higher Heating Value, Btu/hr (MAF)	15,447.00	ND
Free Swelling Index (FSI)	7 - 8	ND

(a) Vacuum-disk-filter product

(b) Solid-bowl-centrifuge product

ND: Not determined

Figure F-1. Typical Particle Size Distributions of Upper Freeport Coals for EAD PRU Tests at CQ, Inc.

APPENDIX E

OPERATING PROCEDURE FOR THE
ASHBROOK-SIMON-HARTLEY EAD BELT PRESS PRU

**OPERATING PROCEDURE FOR THE
ASHBROOK-SIMON-HARTLEY EAD BELT PRESS PRU**

1.0 Preparing the Press for Start-up

- 1.1 Disconnect the wiring between the DC power supply and the EAD rolls. The easiest location to disconnect is at the power supply output terminals. With an ohmmeter, check the resistance between the positive and negative terminals going to the belt press to determine if a short circuit exists between the EAD rolls and the belt press frame. Investigate the cause of any short circuit and make repairs.
- 1.2 Connect all electrical cables from belt press to the control panel and check all electrical connections for tightness.

2.0 Operation of Belt Press with EAD

WARNING: During operation, rubber gloves should be worn at all times to avoid electrical shock in the event of electrical short circuit within the belt press.

CAUTION: Before turning DC power supply switch on, check for continuity between EAD roll (positive terminal) and belt press frame (negative terminal) and make sure there are no shorts in this circuit. Continuity check must be done with power supply unhooked from belt press (see 1.1).

Flashing red strobe light should immediately come on when the DC power supply or the ultrasonic power supply are energized, indicating the belt press is in the EAD mode of operation.

- 2.1 Set the DC voltage regulator to zero by turning the knob all the way to the left (this potentiometer can be wired remote, see attached wiring diagram).
- 2.2 Start the current recorder (this recorder can also be wired remote, see attached wiring diagram).
- 2.3 Set the timer, if required, located on power supply control box.
- 2.4 Make sure the cathodes are grounded to press frame.
- 2.5 Start the filtrate pump as necessary.
- 2.6 Start the DC power supply and adjust the voltage regulator to obtain desired DC current and voltage.

2.7 Set the ultrasonic power selector to desired setting:

Position 1 = ~250 watts
Position 2 = ~550 watts
Position 3 = ~800 watts
Position 4 = ~1500 watts

WARNING: The ultrasonic generator must be turned off before switching the power selector.

2.8 Start the ultrasonic power generator and adjust the frequency to obtain maximum output on the wattmeter.

2.9 The DC current can be monitored at the strip chart recorder or the DC ammeters located on the power supply control box.

2.10 The DC voltage can be monitored by the volt meters located on the power supply control box.

2.11 The ultrasonic power can be monitored by the watt meter located on each ultrasonic power generator control box.

3.0 Temporary EAD Shutdown Procedure

3.1 If feed is interrupted for 5 minutes or longer, reduce EAD voltage to zero.

3.2 Turn off ultrasonic power generator.

3.3 Red strobe light will continue to flash.

4.0 Procedure for Normal Shutdown

4.1 Turn DC power off.

4.2 Turn ultrasonic power off.

4.3 Shut off filtrate pump.

APPENDIX F

STATISTICAL ANALYSES FOR EAD PRU
TESTS ON -100 MESH COAL

APPENDIX F

STATISTICAL ANALYSES FOR EAD PRU
TESTS ON -100 MESH COAL

Table F-1 gives results of t-tests to determine the effect of fluid coupling on EAD performance.

The results of analyses of variance for final cake moisture and delta moisture are given in Tables F-2 and F-3, respectively.

TABLE F-1. PAIRED T-TEST FOR THE DIFFERENCES BETWEEN FINAL MOISTURE AND DELTA MOISTURE FOR TESTS WITH AND WITHOUT FLUID COUPLING [-100 MESH COAL; PRU TESTS]

Without Fluid Coupling			With Fluid Coupling			Difference ^(a)	
Test No.	Final Moisture Percent	Delta Moisture Percent	Test No.	Final Moisture Percent	Delta Moisture Percent	Final Moisture Percent	Delta Moisture Percent
720-1	30.51	5.84	720-3	27.65	8.15	2.86	2.31
720-5	22.75	12.34	720-4	22.06	13.65	0.69	1.31
724-1	31.08	6.93	724-2	30.00	7.14	1.08	0.21
724-3	27.76	9.69	724-4	27.53	9.09	0.20	-0.60
						(b)N	4
						Mean	1.21
						Std. Dev.	1.16
						t-test	2.08
						p-value	0.13

(a) Difference between the results of the two tests done with and without fluid coupling at similar levels of other factors.

(b)N = Sample number
Mean = Average of differences
Std. Dev. = Standard Deviation of the differences
t-test = $N \cdot 05 \text{ Mean/Std. Dev.}$, student's t test statistic.
p-value = The observed significance level for testing whether or not the average difference is statistically different from zero. The difference is significantly different from zero at the 5 percent level if the p-value is less than .05.

TABLE F-2. SUMMARY OF ANALYSIS OF VARIANCE CONDUCTED TO EXAMINE THE EFFECTS OF BELT PERMEABILITY, CAKE THICKNESS ULTRASONICS POWER LEVELS, AND D.C. VOLTAGE LEVELS FOR FINAL MOISTURE [-100 MESH COAL; PRU TESTS]

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr>F
Belt	2	1.41	0.70	0.92	0.423
Cake	1	5.06	5.06	6.65	0.024
Ultrasonics	2	0.64	0.32	0.42	0.665
Voltage	3	69.72	23.24	30.57	0.001
Total Model	8	110.97	13.87	18.25	0.001
Error	12	9.12	0.76		

Sum of squares = Total variability in the data that can be attributed to that effect.

Mean square = Sum of squares divided by degrees of freedom; measures the average variation attributed to that effect.

F value = Mean square for effect divided by the mean square for uncontrolled error. Large values indicate that effect is significant.

Pr>F = Observed significance level for the F test. The effect is statistically significant at the 5 percent level if Pr>F is less than 0.05.

Total Model = Total variability in the data that can be attributed to belt permeability cake thickness, ultrasonics power levels, and DC voltage levels.

Error = Variability that cannot be accounted for by the terms in the model

Degree of Freedom = Number of independent observations for measuring the variation across the levels of the effect

TABLE F-3. SUMMARY OF ANALYSIS OF VARIANCE CONDUCTED TO EXAMINE THE EFFECTS OF BELT COARSENESS, CAKE THICKNESS, ULTRASONICS POWER LEVELS, AND D.C. VOLTAGE LEVELS FOR DELTA MOISTURE [-100 MESH COAL; PRU TESTS]

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr>F
Belt	2	0.34	0.17	0.44	0.652
Cake	1	0.03	0.03	0.07	0.793
Ultrasonics	2	1.09	0.55	1.41	0.282
Voltage	3	68.71	22.90	59.22	0.001
Total Model	8	88.46	11.06	28.59	0.001
Error	12	4.64	0.39		

Sum of squares = Total variability in the data that can be attributed to that effect.

Mean square = Sum of squares divided by degrees of freedom; measures the average variation attributed to that effect.

F value = Mean square for effect divided by the mean square for uncontrolled error. Large values indicate that effect is significant.

Pr>F = Observed significance level for the F test. The effect is statistically significant at the 5 percent level if Pr>F is less than 0.05.

Total Model = Total variability in the data that can be attributed to belt permeability, cake thickness, ultrasonics power levels, and DC voltage levels.

Error = Variability that cannot be accounted for by the terms in the model

Degree of Freedom = Number of independent observations for measuring the variation across the levels of the effect

APPENDIX G

STATISTICAL ANALYSES FOR EAD PRU
TESTS ON -325 MESH COAL

G-1

APPENDIX G

STATISTICAL ANALYSES FOR EAD PRU
TESTS ON -325 MESH COAL

The mean and standard deviation for final and delta moisture are given in Table G-1.

The results of analysis of variance for final moisture and delta are summarized in Tables G-2 and G-3, respectively.

TABLE G-1. MEANS AND STANDARD DEVIATIONS FOR FINAL DELTA MOISTURE
[-325 MESH COAL; PRU TEST]

		Ultrasonics Power, kw											
		0						9					
		Fluid Coupling						Fluid Coupling					
		OFF						ON					
Inlet Cake Thickness, cm	Voltage	Final Moisture Percent		Delta Moisture Percent		Final Moisture Percent		Delta Moisture Percent		Final Moisture Percent		Delta Moisture Percent	
		Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
1.27	0	38.20	0.59	9.08	0.24	38.00	2.27	9.96	2.13	39.30	.	8.04	.
	50	34.59	.	12.79	.	36.04	.	12.01	.	36.01	.	11.82	.
	80 and 85	33.74	.	13.51	.	38.50	.	8.81	.	36.37	1.14	11.26	1.39
1.91	0	36.10	.	10.27	.	37.62	1.82	8.92	2.32	.	.	.	.
	70	33.72	.	13.16	.	.	.	.	.	.	.	.	.
	85	33.85	.	13.00	.	34.33	.	13.67	.	33.37	.	19.30	.
	100	33.23	.	13.64	.	33.63	1.16	13.11	1.32	32.20	1.17	14.24	1.37

Mean = Average of final or delta moisture
STD = Standard deviation of final or delta moisture

TABLE G-2. SUMMARY OF ANALYSIS OF VARIANCE CONDUCTED TO EXAMINE THE EFFECTS OF FLUID COUPLING, CAKE THICKNESS, ULTRASONIC POWER LEVELS, AND VOLTAGE POWER LEVELS FOR FINAL MOISTURE [-325 MESH COAL; PRU TESTS]

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr>F
Voltage	1	39.07	39.07	23.42	0.001
Fluid Coupling	1	6.17	6.17	3.70	0.070
Ultrasonics	1	1.91	1.91	1.15	0.298
Cake Thickness	1	19.68	19.68	11.80	0.003
Ultrasonics* Cake Thickness	1	4.05	4.05	2.43	0.136
Total Model	5	99.61	19.92	11.94	0.001
Error	19	31.70	1.67		

Sum of squares = Total variability in the data that can be attributed to that effect.

Mean square = Sum of squares divided by degrees of freedom; measures the average variation attributed to that effect.

F value = Mean square for effect divided by the mean square for uncontrolled error. Large values indicate that effect is significant.

Pr>F = Observed significance level for the F test. The effect is statistically significant at the 5 percent level if Pr>F is less than 0.05.

Total Model = Total variability in the data that can be attributed to belt permeability cake thickness, ultrasonics power levels, and DC voltage levels.

Error = Variability that cannot be accounted for by the terms in the model

Degree of Freedom = Number of independent observations for measuring the variation across the levels of the effect

TABLE G-3. SUMMARY OF ANALYSIS OF VARIANCE CONDUCTED TO EXAMINE THE EFFECTS OF FLUID COUPLING, CAKE THICKNESS, ULTRASONIC POWER LEVELS, AND VOLTAGE POWER LEVELS FOR DELTA MOISTURE [-325 MESH COAL; PRU TESTS]

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr>F
Voltage	1	41.42	41.42	12.33	0.002
Fluid Coupling	1	3.43	3.43	1.02	0.325
Ultrasonics	1	7.45	7.45	2.22	0.153
Cake Thickness	1	20.27	20.27	6.03	0.024
Ultrasonics* Cake Thickness	1	14.84	14.84	4.42	0.049
Total Model	5	114.97	22.99	6.84	0.001
Error	19	63.84	3.36		

Sum of squares = Total variability in the data that can be attributed to that effect.

Mean square = Sum of squares divided by degrees of freedom; measures the average variation attributed to that effect.

F value = Mean square for effect divided by the mean square for uncontrolled error. Large values indicate that effect is significant.

Pr>F = Observed significance level for the F test. The effect is statistically significant at the 5 percent level if Pr>F is less than 0.05.

Total Model = Total variability in the data that can be attributed to belt permeability cake thickness, ultrasonics power levels, and DC voltage levels.

Error = Variability that cannot be accounted for by the terms in the model

Degree of Freedom = Number of independent observations for measuring the variation across the levels of the effect

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