

**USE OF COAL DRYING TO REDUCE WATER
CONSUMED IN PULVERIZED COAL POWER PLANTS**

**QUARTERLY REPORT FOR THE PERIOD
January 1, 2003 to March 31, 2003**

by

Edward K. Levy

Report Issued March 2003

DOE Award Number DE-FC26-03NT41729

Energy Research Center
Lehigh University
117 ATLSS Drive
Bethlehem, PA 18015

DISCLAIMER

“This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.”

ABSTRACT

This is the first Quarterly Report for this project. The background and technical justification for the project are described, including potential benefits of reducing fuel moisture, prior to firing in a pulverized coal boiler. A description is given of the equipment and instrumentation being used for the fluidized bed drying experiments. Results of fluidization and drying tests performed with North Dakota lignite, having a 6.35 mm (1/4") top size, are presented. The experiments were performed with a 381 mm (15") settled bed depth, with inlet air and in-bed heater surface temperatures of 44.3°C (110°F), and with the superficial air velocity ranging from 0.2 m/s to 1.4 m/s. Drying rate is shown to be a strong function of air velocity, increasing seven-fold from 0.2 m/s to 1.4 m/s. Increases in velocity from 0.75 m/s (minimum fluidization velocity) to 1.4 m/s resulted in a doubling of the drying rate.

TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	1
Background	1
Previous Work	3
This Investigation	5
Task 1: Fabricate and Instrument Equipment	5
Task 2: Perform Drying Experiments	5
Task 3: Develop Drying Models and Compare to Experimental Data	6
Task 4: Drying System Design	6
Task 5: Analysis of Impacts on Unit Performance and Cost of Energy	6
EXPERIMENTAL	7
RESULTS AND DISCUSSION	10
CONCLUSIONS	17
REFERENCES	18
NOMENCLATURE	18

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Schematic of Plant Layout, Showing Air Heater and Coal Dryer (Version 1)	2
2	Schematic of Plant Layout, Showing Air Heater and Coal Dryer (Version 2)	2
3	The Effects of Coal Moisture on Cooling Tower Makeup Water	3
4	Improvement in Net Unit Heat Rate Versus Reduction in Coal Moisture Content	4
5	Project Schedule	7
6	Sketch of Experimental Bed Setup	8
7	In-Line Air Heater	8
8	Tube Bundle Support Plate	9
9	Bundle Location in Bed	9
10	Size Distribution of the Coal	10
11	Bed Pressure Drop Versus Superficial Air Velocity	11
12	Elutriated Mass as a Function of Superficial Air Velocity	11
13	Size Distribution of Elutriated Coal	12
14	Size Distribution of Elutriated Coal	12
15	Heat Transfer Coefficient Versus Air Velocity	13
16	Top and Bottom Bed Temperature Difference Versus Velocity	14
17	Coal Moisture Versus Time (wt % of Wet Coal)	15
18	Coal Moisture Versus Time (wt % of Dry Coal)	16
19	Moisture Reduction in 30 Minutes Versus Superficial Air Velocity	16

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Procedure for Drying Tests	14

INTRODUCTION

Background

Low rank fuels such as subbituminous coals and lignites contain significant amounts of moisture compared to higher rank coals. Typically, the moisture content of subbituminous coals ranges from 15 to 30 percent, while that for lignites is between 25 and 40 percent.

High fuel moisture has several adverse impacts on the operation of a pulverized coal generating unit. High fuel moisture results in fuel handling problems, and it affects heat rate, mass rate (tonnage) of emissions, and the consumption of water needed for evaporative cooling.

This project deals with lignite and subbituminous coal-fired pulverized coal power plants, which are cooled by evaporative cooling towers. In particular, the project involves use of power plant waste heat to partially dry the coal before it is fed to the pulverizers. Done in a proper way, coal drying will reduce cooling tower makeup water requirements and also provide heat rate and emissions benefits.

The technology addressed in this project makes use of the hot circulating cooling water leaving the condenser to heat the air used for drying the coal (Figure 1). The temperature of the circulating water leaving the condenser is usually about 49°C (120°F), and this can be used to produce an air stream at approximately 43°C (110°F). Figure 2 shows a variation of this approach, in which coal drying would be accomplished by both warm air, passing through the dryer, and a flow of hot circulating cooling water, passing through a heat exchanger located in the dryer.

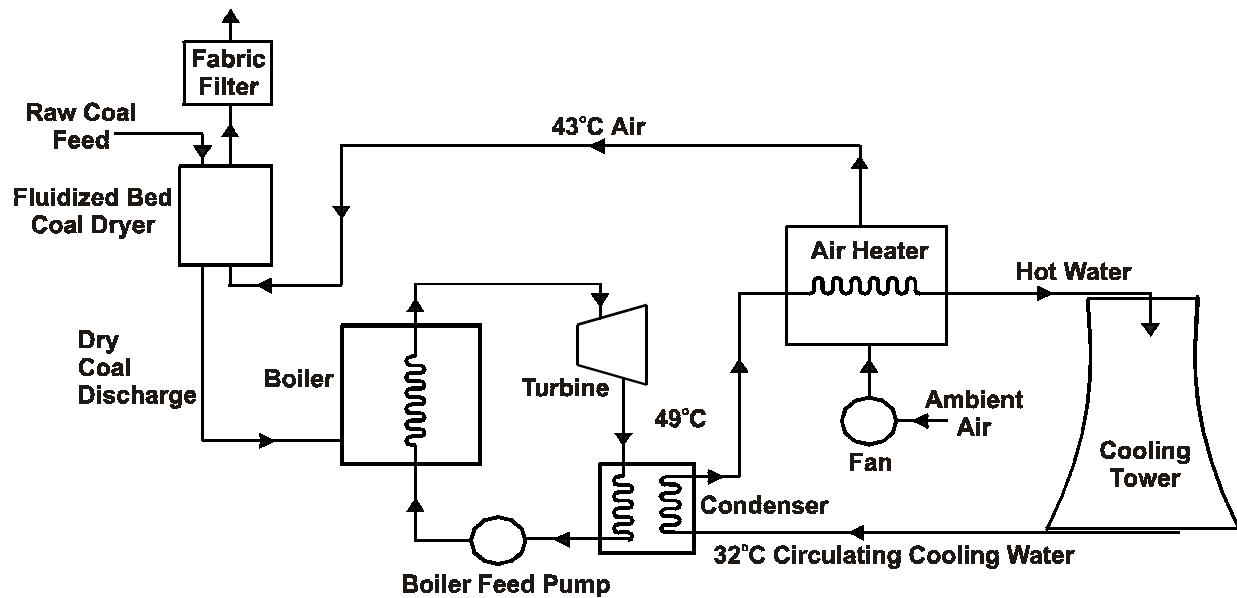


Figure 1: Schematic of Plant Layout, Showing Air Heater and Coal Dryer (Version 1)

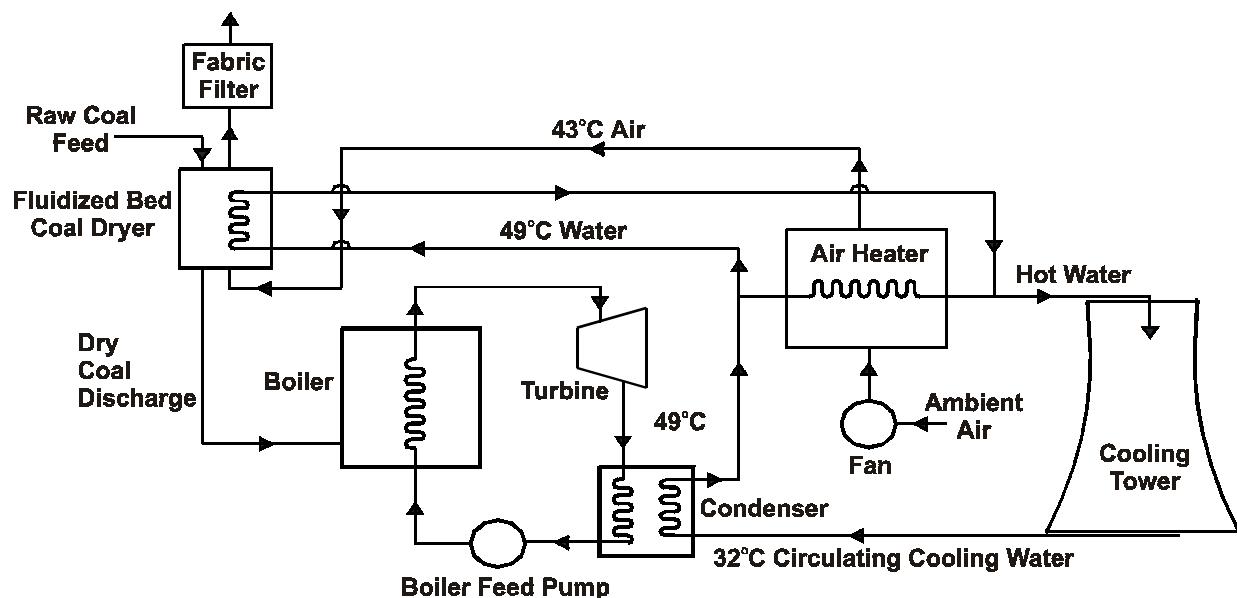


Figure 2: Schematic of Plant Layout, Showing Air Heater and Coal Dryer (Version 2)

Previous Work

Two of the investigators (Levy and Sarunac) have been involved in work with the Great River Energy Corporation on a study of low temperature drying at the Coal Creek Generating Station in Underwood, North Dakota. Coal Creek has two units with total gross generation exceeding 1,100 MW. The units fire a lignite fuel containing approximately 40 percent moisture and 12 percent ash. Both units at Coal Creek are equipped with low NO_x firing systems and have wet scrubbers and evaporative cooling towers.

The project team performed a theoretical analysis to estimate the impact on cooling water makeup flow of using hot circulating water to the cooling tower to heat the drying air and to estimate the magnitude of heat rate improvement that could be achieved at Coal Creek Station by removing a portion of the fuel moisture. The results show that drying the coal from 40 to 25 percent moisture will result in reductions in makeup water flow rate from 5 to 7 percent, depending on ambient conditions (Figure 3). For a 550 MW unit, the water savings are predicted to range from 1.17×10^6 liters/day (0.3×10^6 gallons/day) to 4.28×10^6 liters/day (1.1×10^6 gallons/day). The analysis also shows the heat rate and the CO₂ and SO₂ mass emissions will all be reduced by about 5 percent (Ref. 1).

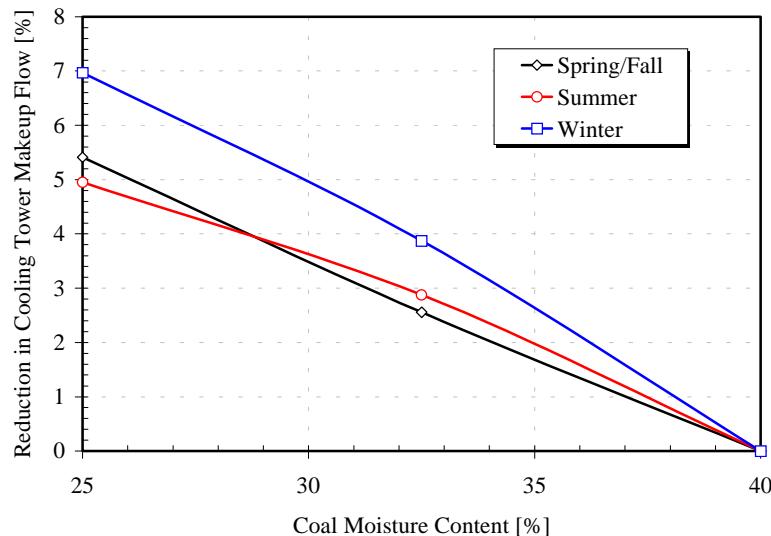


Figure 3: The Effects of Coal Moisture on Cooling Tower Makeup Water

A coal test burn was conducted at Coal Creek Unit 2 in October 2001 to determine the effect on unit operations. The lignite was dried for this test by an outdoor stockpile coal drying system. On average, the coal moisture was reduced by 6.1 percent, from 37.5 to 31.4 percent. Analysis of boiler efficiency and net unit heat rate showed that with coal drying, the improvement in boiler efficiency was approximately 2.6 percent, and the improvement in net unit heat rate was 2.7 to 2.8 percent. These results are in close agreement with theoretical predictions (Figure 4). The test data also showed the fuel flow rate was reduced by 10.8 percent and the flue gas flow rate was reduced by 4 percent. The combination of lower coal flow rate and better grindability combined to reduce mill power consumption by approximately 17 percent. Fan power was reduced by 3.8 percent due to lower air and flue gas flow rates. The average reduction in total auxiliary power was approximately 3.8 percent (Ref. 1).

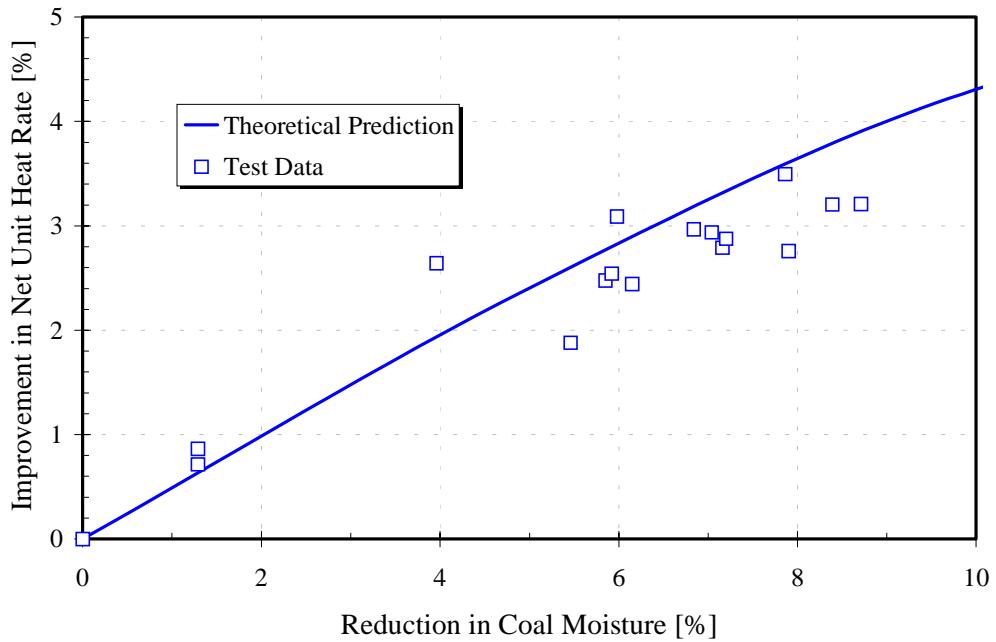


Figure 4: Improvement in Net Unit Heat Rate Versus Reduction in Coal Moisture Content

This Investigation

Theoretical analyses and coal test burns performed at a lignite fired power plant show that by reducing the fuel moisture, it is indeed possible to improve boiler performance and unit heat rate, reduce emissions and reduce water consumption by the evaporative cooling tower. The economic viability of the approach and the actual impact of the drying system on water consumption, unit heat rate and stack emissions will depend critically on the design and operating conditions of the drying system.

The present project is evaluating two alternatives (fluidized and fixed bed dryer designs) for the low temperature drying of lignite and Power River Basin (PRB) coal. Drying studies are being performed to gather data and develop models on drying kinetics. In addition, analyses are being carried out to determine the relative costs and performance impacts (in terms of heat rate, cooling tower water consumption and emissions) of these two drying options, along with the development of an optimized system design and recommended operating conditions.

The project is being carried out in five tasks:

Task 1: Fabricate and Instrument Equipment

Laboratory scale fixed bed and fluidized bed drying systems will be designed, fabricated and instrumented in this task.

Task 2: Perform Drying Experiments

The experiments will be carried out with both lignite and PRB coals, while varying superficial air velocity, inlet air temperature and specific humidity. In the fluid bed experiments, batch bed experiments will be run with different particle size distributions. The fixed bed experiments will include a range of coal top sizes. Bed depths will be varied for both the fixed and fluidized bed tests.

Task 3: Develop Drying Models and Compare to Experimental Data

In this task, the laboratory drying data will be compared to equilibrium and kinetic models to develop models suitable for evaluating tradeoffs between dryer designs.

Task 4: Drying System Design

Using the kinetic data and models from Tasks 2 and 3, both fluidized bed and packed bed dryers will be designed for 600 MW lignite and PRB coal-fired power plants. Designs will be developed to dry the coal by various amounts. Auxiliary equipment such as fans, water to air heat exchangers, dust collection system and coal crushers will be sized, and installed capital costs and operating costs will be estimated.

Task 5: Analysis of Impacts on Unit Performance and Cost of Energy

Analyses will be performed to estimate the effects of dryer operation on cooling tower makeup water, unit heat rate, auxiliary power, and stack emissions. The cost of energy will be estimated as a function of the reduction in coal moisture content. Cost comparisons will be made between dryer operating conditions (for example, coal particle feed size to fluidized beds and superficial air velocity for both fluidized bed and fixed bed dryers) and between dryer type.

The project was initiated on December 26, 2002. The project schedule is shown in Figure 5.

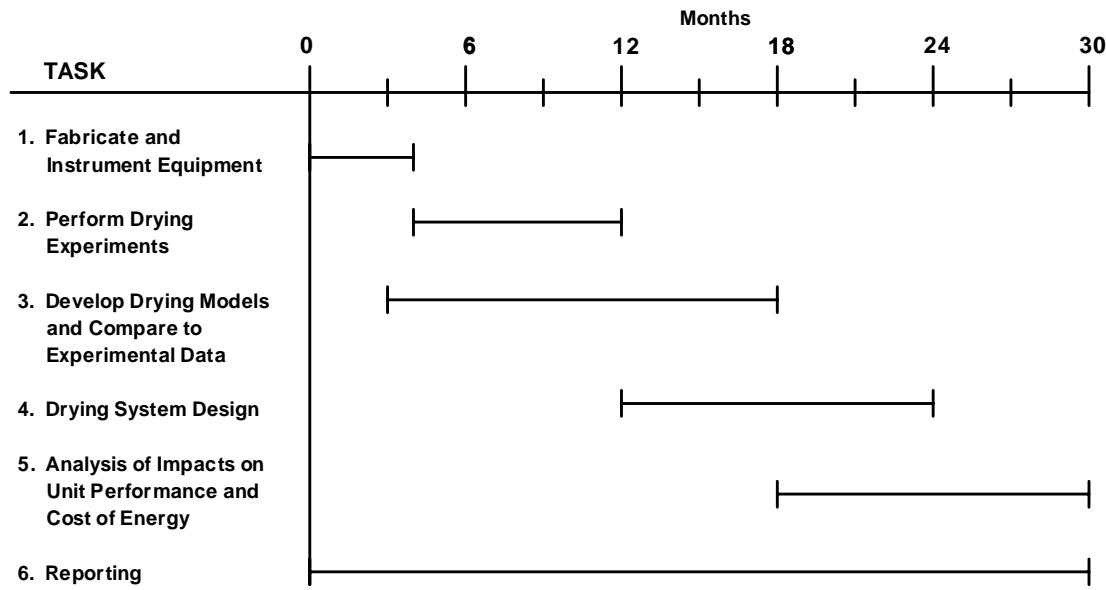


Figure 5: Project Schedule

EXPERIMENTAL

The drying experiments are being performed in the Energy Research Center's Fluidized Bed Laboratory. The bed vessel is 152.4 mm (6") in diameter, with a 1372 mm (54") column and a sintered powder metal distributor plate. The air and entrained coal particles pass through a filter bag before the air is discharged from the apparatus (Figure 6). Compressed air used in the experiments flows through a rotameter and an air heater before entering the plenum.

The heater for the inlet air was fabricated from two 304.8 mm (1-foot) long sections of 76.2 mm (3-inch) pipe joined together with pipe fittings. Each section of the heater contains a coiled 750-watt wire heater element, for a total of 1500 MW. To be able to adjust the air temperature, each wire heater is connected to a voltage regulator (Figure 7). Operating at 1.1 m/s of superficial air velocity in the 152.4 mm (6-inch) diameter bed, the air heater can attain a maximum steady state temperature of 66°C (150°F).

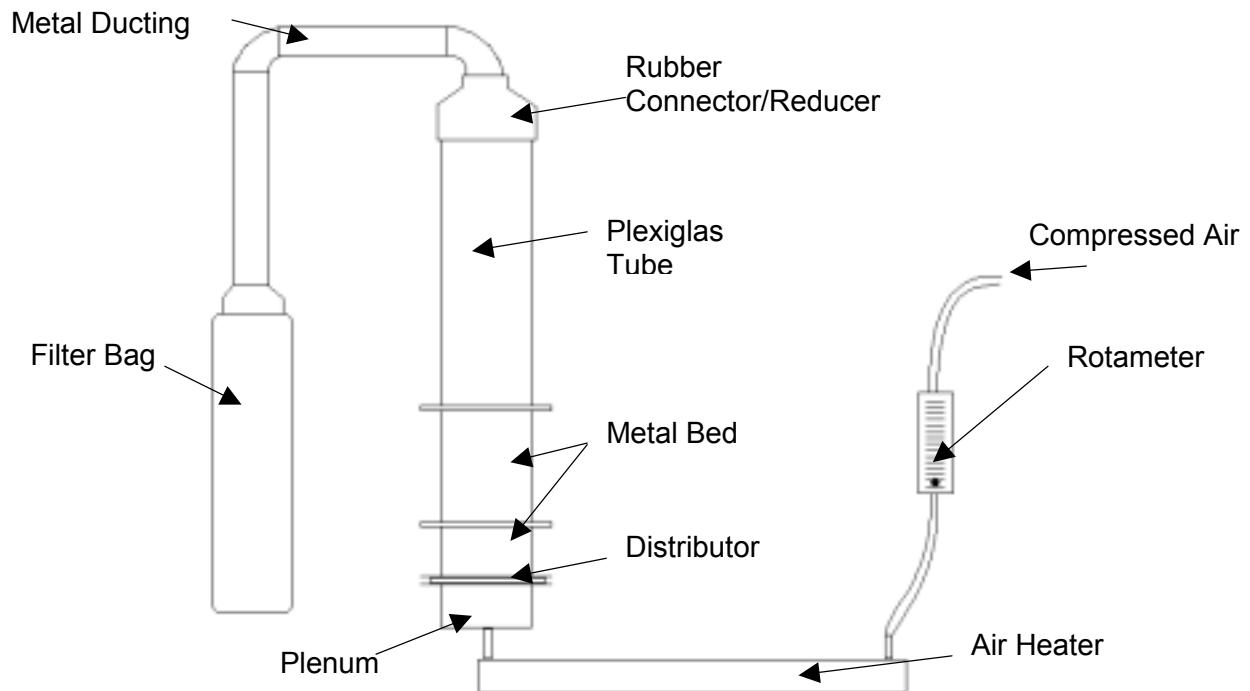


Figure 6: Sketch of Experimental Bed Setup

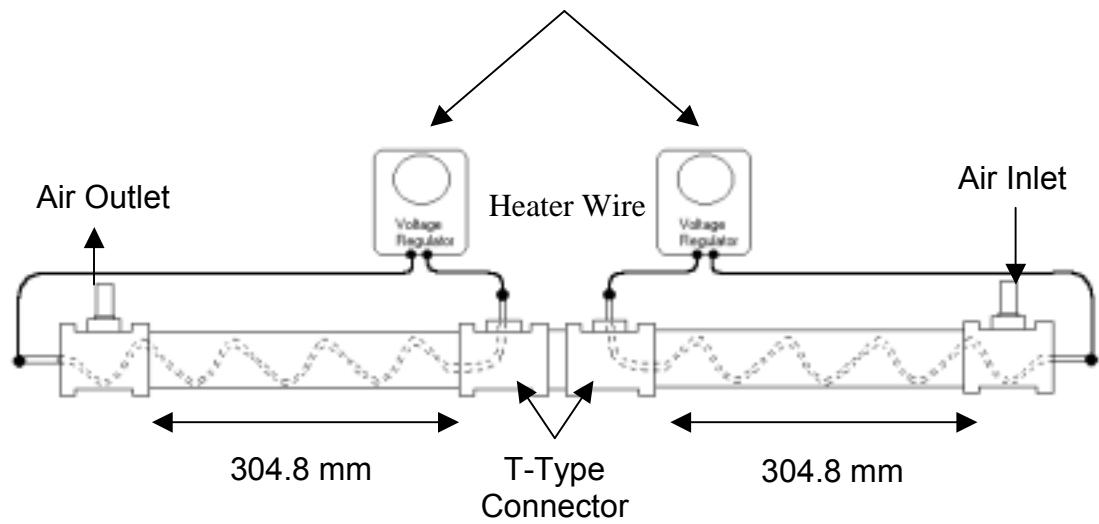


Figure 7: In-Line Air Heater

Thermocouples inserted through the bed wall are used to measure vertical distribution of bed temperature. A horizontal bundle of eighteen 469.9 mm (1/2") diameter electric heating elements is used to provide in-bed heating. The eighteen heaters consist of six 152.4 mm (6") long heaters and twelve 101.6 mm (4") long heaters, arranged in 6 rows of 3 heaters, with each row consisting of a 152.4 mm (6") heater in the center flanked by two 101.6 mm (4") heaters. Two metal plates, located inside the bed hold the heaters together and support the heater bundle (Figure 8). The heaters are located in the region from 51 mm (2") to 304.8 mm (12") above the distribution, (Figure 9) and are instrumented with thermocouples to indicate heater surface temperature. By controlling power to the heaters, the heater surface temperature can be operated in a range from 38°C (100°) to 65.6°C (150°F). At a given heater surface temperature, total heat flux to the bed can be reduced from the maximum by disconnecting selected heaters from the power supply.

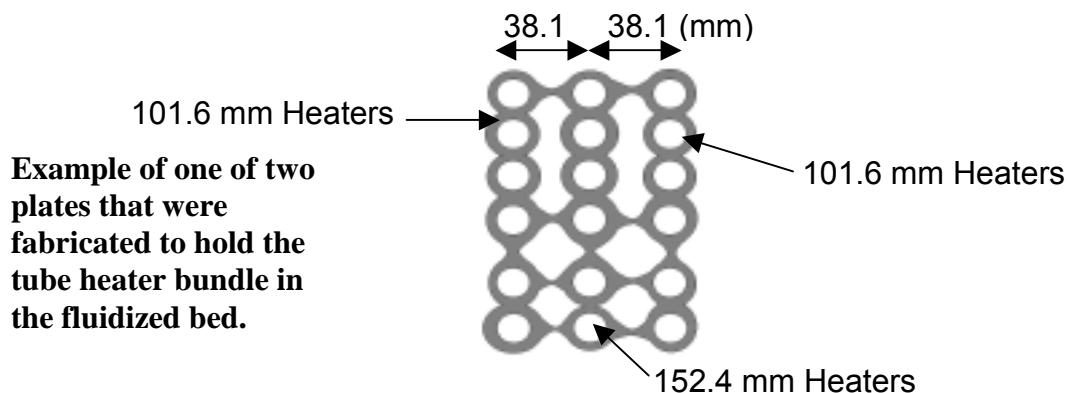


Figure 8: Tube Bundle Support Plate

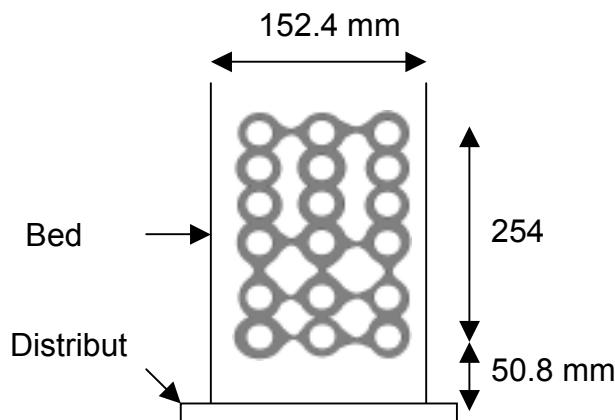


Figure 9: Bundle Location in Bed

RESULTS AND DISCUSSION

The experiments performed in this reporting period were carried out with North Dakota lignite provided by Great River Energy. This had been crushed at the mine to a 6.35 mm (1/4") top size and shipped to the Energy Research Center in barrels. Typical size distribution is shown in Figure 10. The as received moisture content varied slightly from sample-to-sample, usually ranging from 35 to 38% (expressed as mass of moisture/mass of as-received fuel) and from 54 to 58% (expressed as mass of moisture/mass dry fuel).

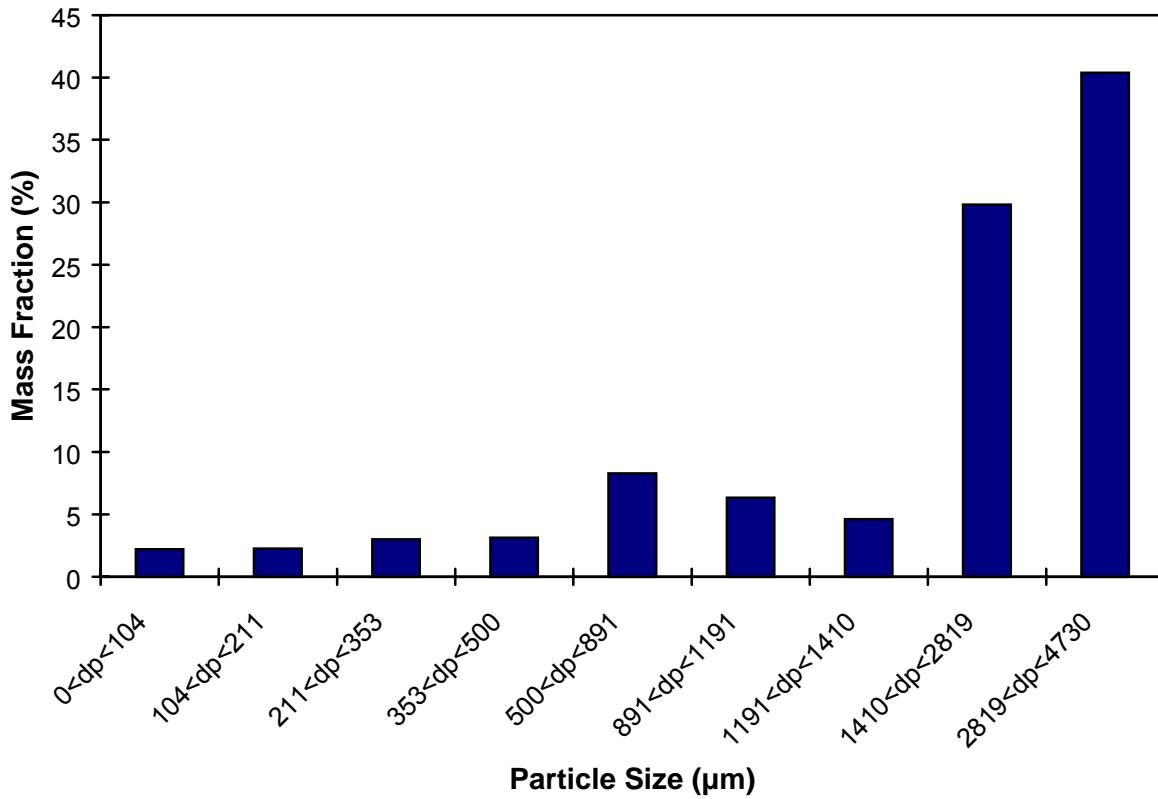


Figure 10: Size Distribution of the Coal

Minimum fluidization velocity was determined from bed pressure drop measurements performed over a range of superficial air velocities (Figure 11). These show transition from a packed bed to a fully fluidized state occurring over velocities from approximately 0.15 to 0.75 m/s. The wide transition region from packed to fluidized is due to the wide size distribution of the crushed lignite.

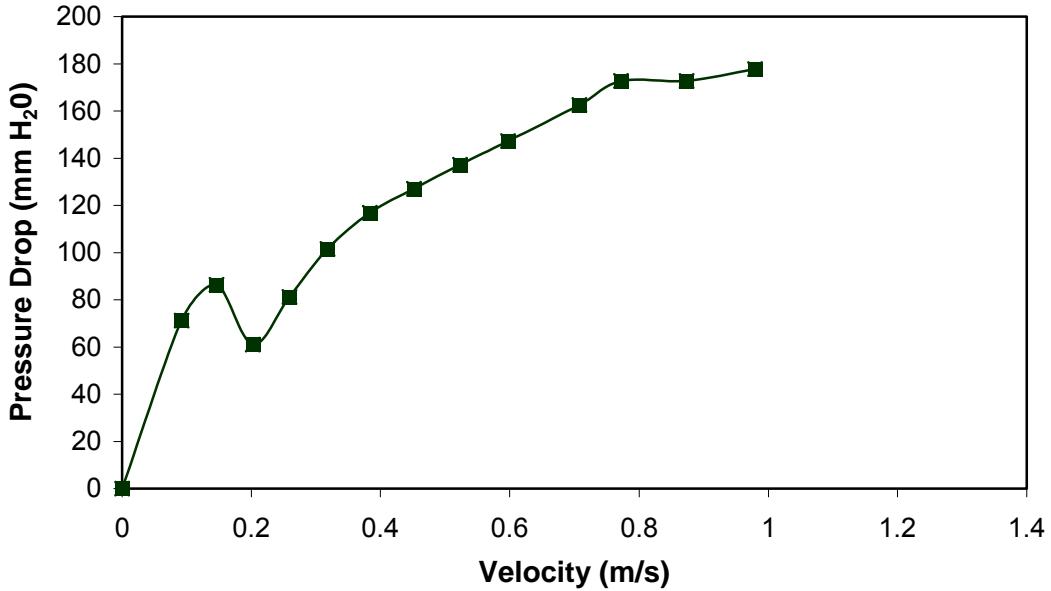


Figure 11: Bed Pressure Drop Versus Superficial Air Velocity

When the bed is fluidized, the erupting bubbles cause elutriation of particles, with the amount elutriated material depending strongly on superficial air velocity. Figure 12 shows the mass fraction of coal collected in the filter bag versus air velocity. The size distribution of the elutriated particles also varies with U_o . Figures 13 and 14 show histograms for $U_o = 0.67$ and 1.41 m/s.

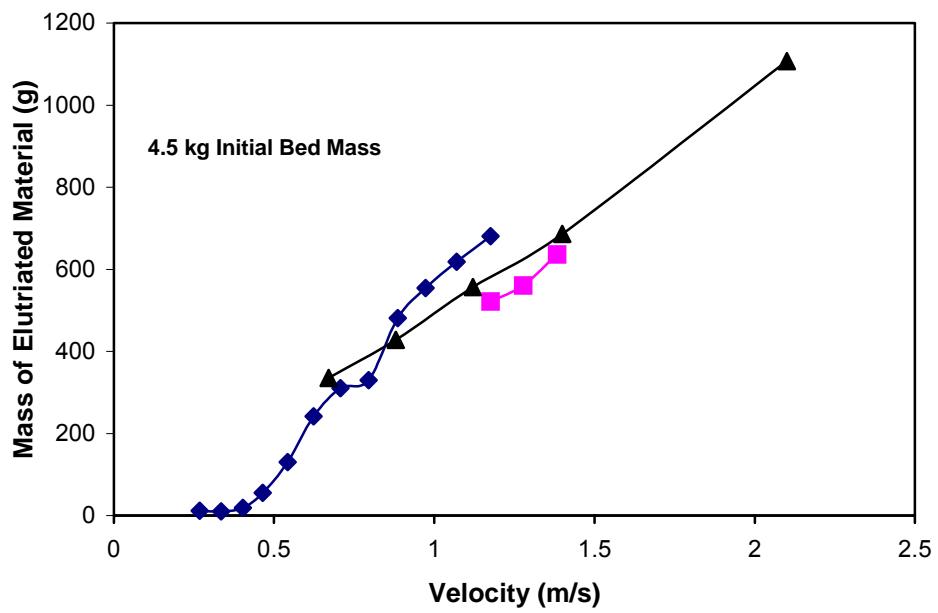


Figure 12: Elutriated Mass as a Function of Superficial Air Velocity

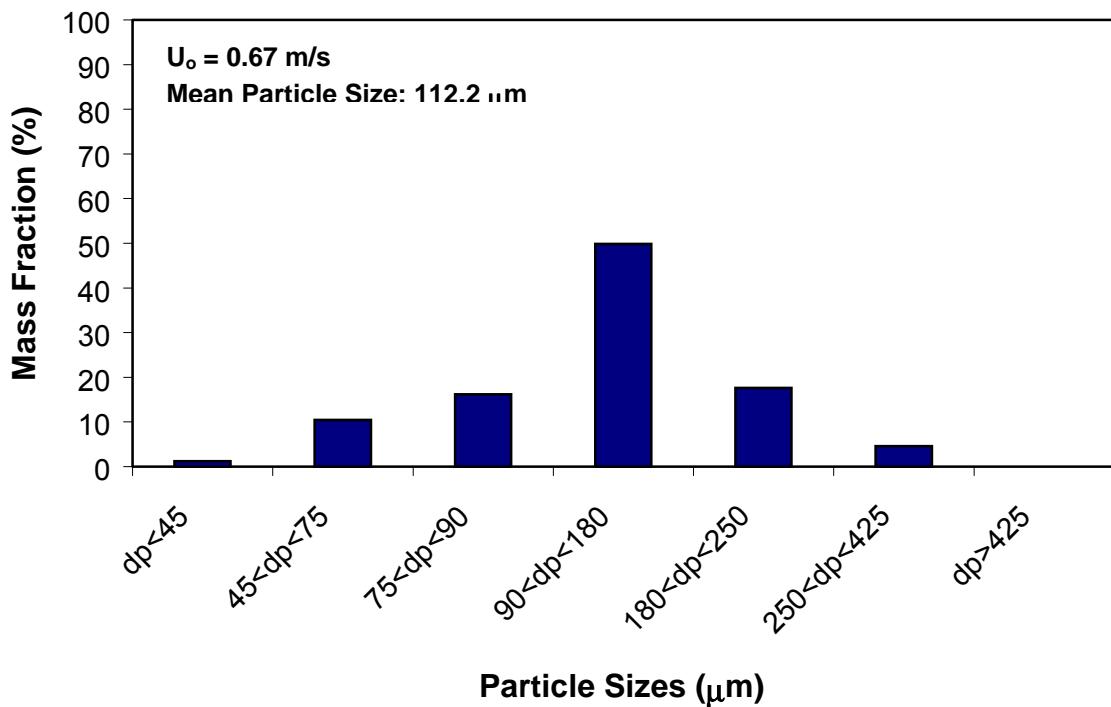


Figure 13: Size Distribution of Elutriated Coal

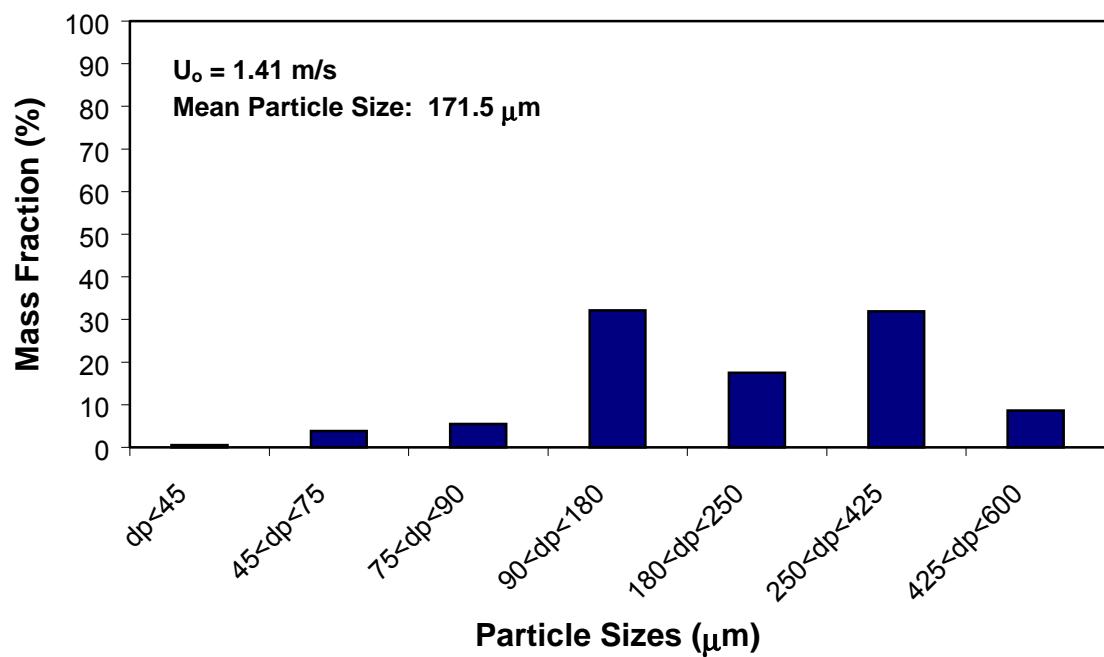


Figure 14: Size Distribution of Elutriated Coal

Average heat transfer coefficient, h , between the surface of one of the horizontal heaters and the bed was obtained from measurements of power input to the heater, heater surface temperature and bed temperature. Figure 15 shows h versus U_o . The heat transfer coefficient increased with superficial air velocity, reaching a peak of 206 $\text{w/m}^2\text{K}$ at $U_o/U_{mf} \approx 1.2$ and then staying relatively constant up to $U_o/U_{mf} = 2.4$. The rate of vertical mixing of bed material increases and the bed becomes more homogeneous as superficial air velocity increases. Figure 16 shows the temperature difference between thermocouples located near the top and bottom of the bed. This provides further confirmation of the presence of a fully fluidized bed at $U_o > 0.75 \text{ m/s}$.

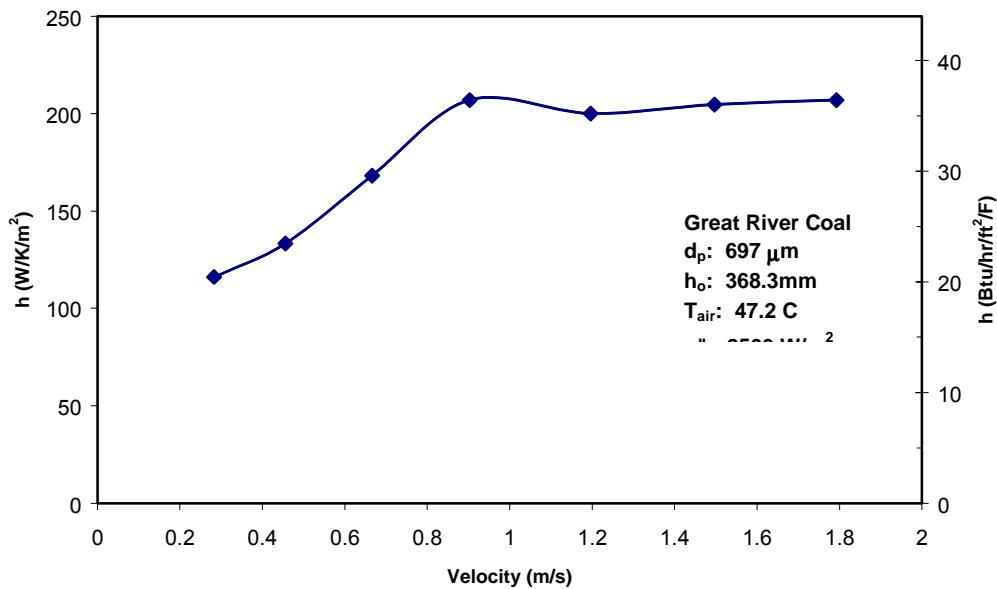


Figure 15: Heat Transfer Coefficient Versus Air Velocity

Batch bed drying tests were performed to determine the effect of superficial air velocity on rate of drying. These tests were performed with a packed bed depth of 381 mm (15"), inlet air and heater surface temperatures of 43.3°C (110°F), all eighteen heaters in operation and with specific humidity of the inlet air ranging from 0.004 to 0.008. Small samples of the coal were removed from the bed during the drying tests and coal moisture was measured. This was determined by drying samples of the coal in crucibles in an oven at 110°C for 5 to 6 hours, and weighing the samples before and after drying. The complete test procedure used in these experiments is described in Table 1.

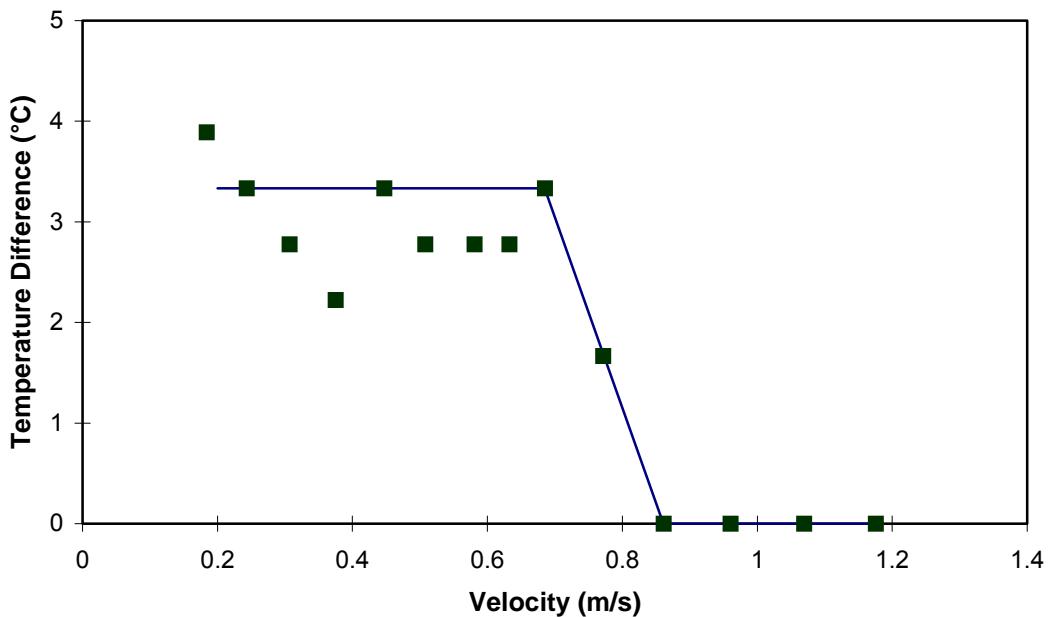


Figure 16: Top and Bottom Bed Temperature Difference Versus Velocity

Table 1
Procedure for Drying Tests

1. With no coal in bed, turn on compressor, set air flow to desired value, turn on air preheater and allow system to reach steady-state at desired temperature. Measure inlet relative humidity and dry bulb temperature of air.
2. Once air is at steady-state, turn off air preheater and air flow, load coal into bed, turn on all heaters and air flow to appropriate values, start stopwatch, and record pressure of inlet air from pressure gauge above rotameter.
3. Begin recording temperatures after 5 minutes, collect small samples of lignite from bed, measure wet and dry bulb temperatures at exit of bed, record values for temperature readings at each assigned thermocouple, adjust voltage regulators for the heaters so that surface temperatures remain steady at appropriate values, and repeat this procedure for each time interval on data sheet.
4. At end of test, shut off heaters but keep air flow on to cool the heaters, detach filter bag, load coal samples into crucibles, place crucibles into oven, set to 100°C, and leave for 5-6 hours or overnight, remove remaining lignite from the bed and weigh it.
5. Analyze results.

Figure 17 shows coal moisture as a function of time for two tests carried out at 1.1 m/s. These data, plotted as weight percent of wet coal, show that the coal moisture was reduced from approximately 36% to 26% in 30 minutes of drying and from 36% to 13% in 60 minutes of drying. The same data, presented in Figure 18 as weight percent of dry coal, show a reduction from approximately 57% to approximately 37% moisture over 30 minutes. Figure 18 also shows there was a linear variation of coal moisture with time, indicating the drying process is a “constant-rate” process.

Similar tests were performed over a range of air velocities from 0.2 to 1.4 m/s (Figure 19). These show a seven-fold increase in amount of moisture loss over 30 minutes over the velocity range. Once fully fluidized ($U_o \approx 0.75$ m/s), the amount of moisture loss was 0.15 kg/kg dry coal and this increased to 0.35 kg/kg dry coal at 1.4 m/s.

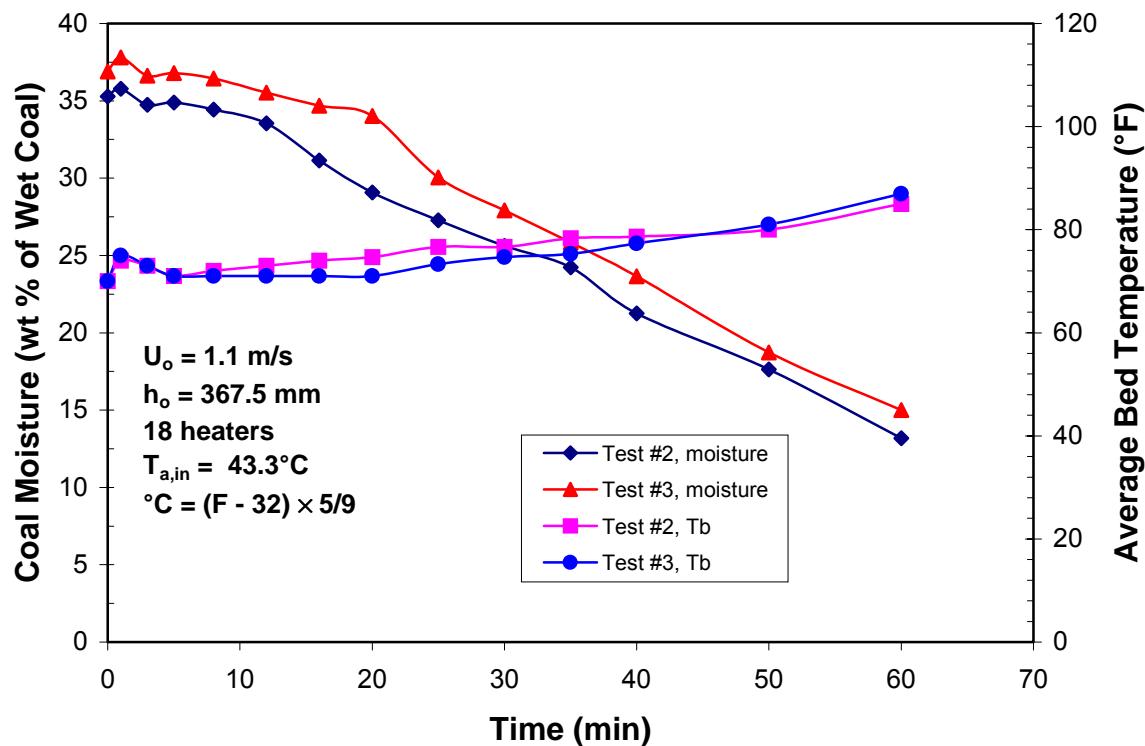


Figure 17: Coal Moisture Versus Time (wt % of Wet Coal)

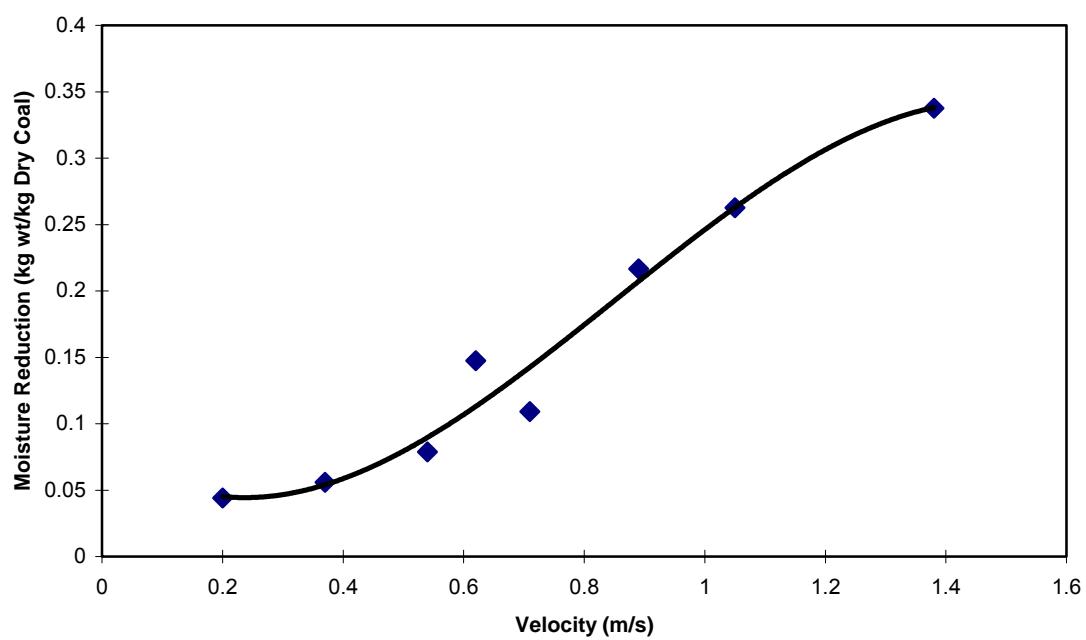
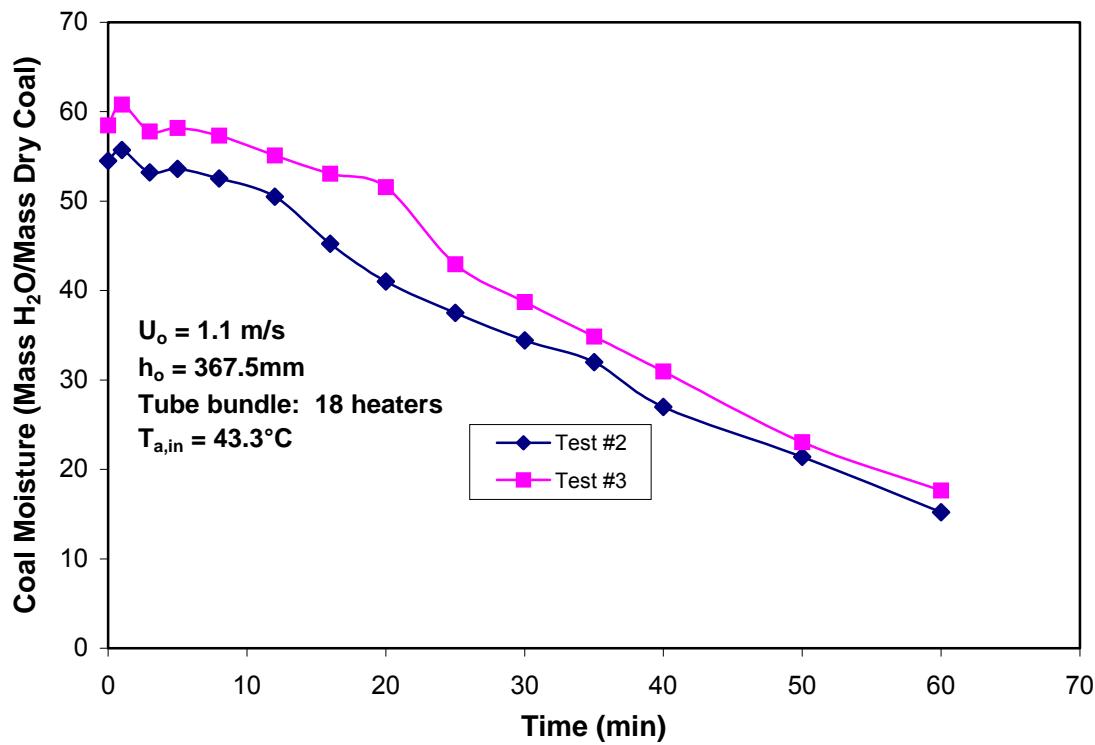


Figure 19: Moisture Reduction in 30 Minutes Versus Superficial Air Velocity

CONCLUSIONS

Much of the effort during the first year of the project focuses on the effects of dryer process conditions on drying rate. Having this information is key to being able to design dryers for this application, to estimate the costs of the drying system equipment and its operating costs, and to estimate the impacts of drying on cost of energy. Drying rate depends on superficial air velocity, bed depth, particle size distribution, drying temperature, heat flux from in-bed heat exchanger to bed material, and specific humidity of inlet air.

The experiments carried out during the first quarter were performed with 6.35 mm ($\frac{1}{4}$ ") top size lignite. The data show this material is fully fluidized at a superficial air velocity of approximately 0.75 m/s, and measurements of vertical temperature gradient in the bed show that the bed material becomes well-mixed at approximately this same velocity. Measurements of the effect of air velocity on particle elutriation show an elutriation rate of 8% at U_{mf} (8% of the feed material is carried from the bed to the bag filter), and that the elutriation rate increases to 24% at $U_o \approx 2.1$ m/s. Elutriation rate is an important consideration due to its effect on drying rate and on the design of the cyclones needed to remove particles from the air leaving the bed. Measurements made of the heat transfer coefficient between the heater surface and the bed material showed that this was approximately $206 \text{ w/m}^2\text{c}$ from 0.8 m/s to 1.4m/s. Data on heat transfer coefficient are needed for the design of in-bed heat exchangers.

Experiments on drying rate were carried out as a function of superficial gas velocity, with all other parameters held constant. At a fixed set of drying conditions, the drying rate was found to be constant over a wide range of particle residence times. The drying rate was found to be a strong function of velocity, increasing seven-fold from 0.2 m/s to 1.4 m/s. Increases in velocity from U_{mf} (0.75 m/s) to 1.4 m/s resulted in a doubling of drying rate.

Additional experiments are planned for the next quarter to measure the effects of bed depth, in-bed heating, and drying temperature on drying rate.

REFERENCES

1. Bullinger, C., M. Ness, N. Sarunac, E. Levy, "Coal Drying Improves Performance and Reduces Emissions," Presented at the 27th International Technical Conference on Coal Utilization and Fuel Systems, Clearwater, Florida, March 4-7, 2002.

NOMENCLATURE

d_p	Particle Size
h	Heat Transfer Coefficient
h_o	Settled Bed Depth
q''	Heat Flux at Heater Surface
U_{mf}	Minimum Fluidization Velocity
U_o	Superficial Gas Velocity