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

QUARTERLY REPORT FOR THE PERIOD
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ABSTRACT

This is the fourth 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, instrumentation and procedures being used for the fluidized bed drying experiments.

Experimental data were obtained during this last quarter on the effects of particle size on drying rate for a North Dakota lignite. Other experiments looked at drying a PRB coal. The tests comparing drying rates with lignite particles of different diameters were carried out with particle top sizes from 2 to 9.5 mm and covered a range of air velocities. The results show that drying rate increased with air velocity, but that, within the accuracy of the data, the data for all four particle size distributions follow the same curve. This suggests the higher drying rates associated with the larger particles are due to higher air velocities and not to any inherently different drying rates due to particle size.

The drying data with the PRB coal show qualitatively similar behavior to that observed with lignite. However, quantitative comparisons of the drying rate data obtained so far for the two coals show the PRB dried at rates which were 14 to 20 percent lower than the lignite, for comparable process conditions.

The equilibrium relationship between relative humidity and coal moisture was refined using a correction for temperature. This reduced the scatter in the coal moisture versus relative humidity data and improved the predictions made with the first principle drying model.

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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.

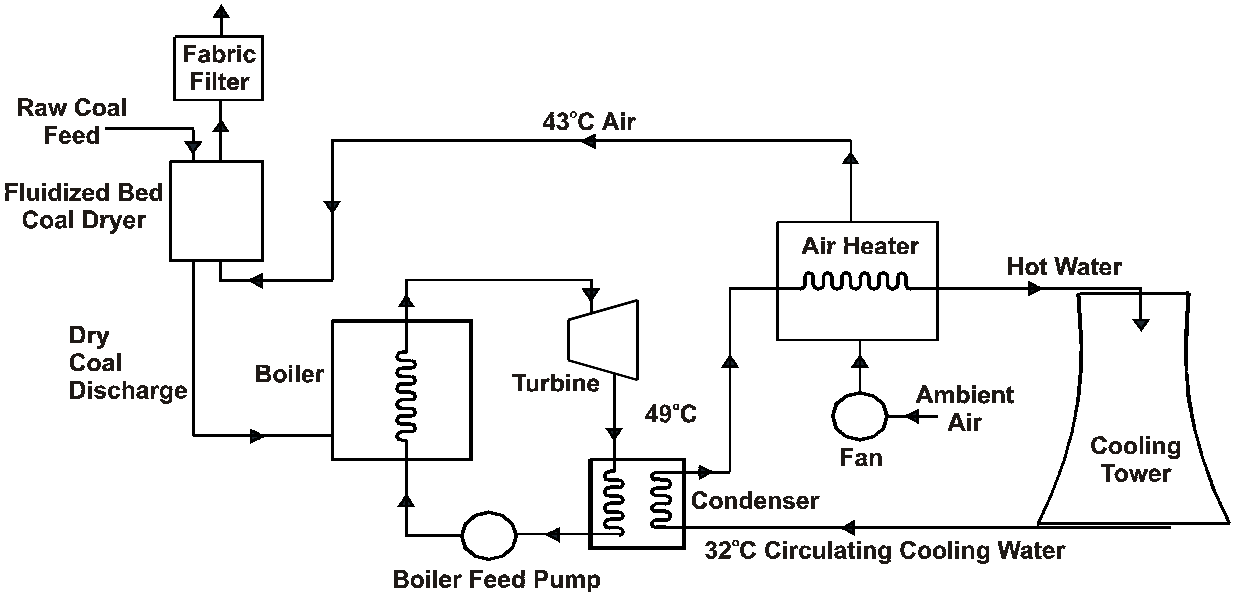

Figure 1: Schematic of Plant Layout, Showing Air Heater and Coal Dryer (Version 1)

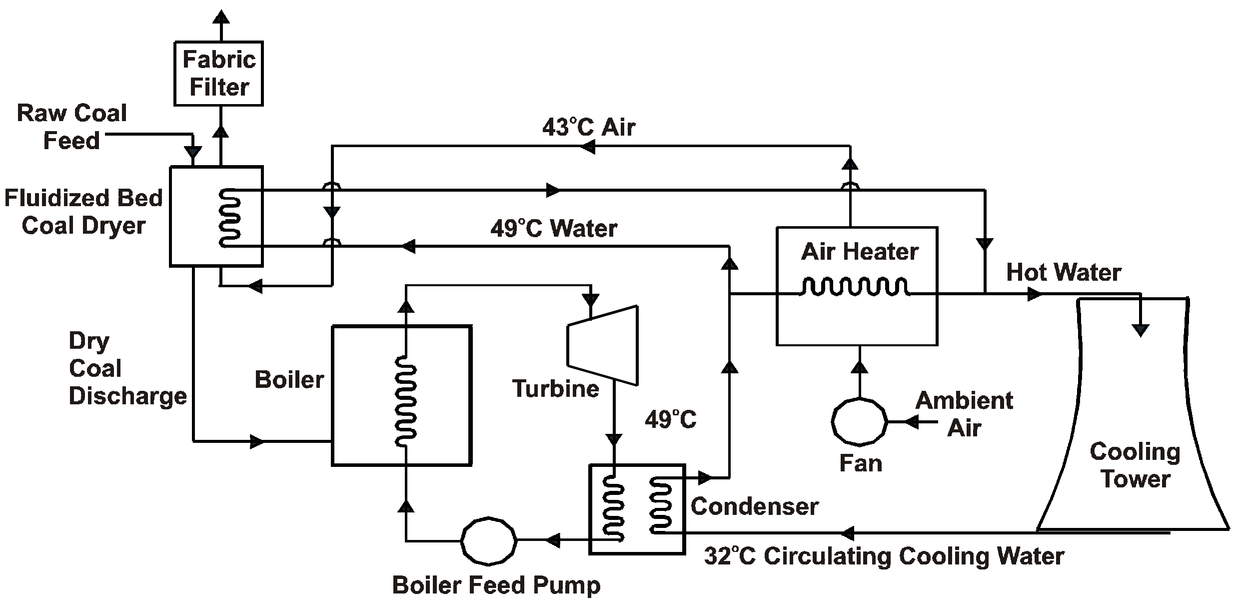

Figure 2: Schematic of Plant Layout, Showing Air Heater and Coal Dryer (Version 2)

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 CO_2 and SO_2 mass emissions will all be reduced by about 5 percent (Ref. 1).

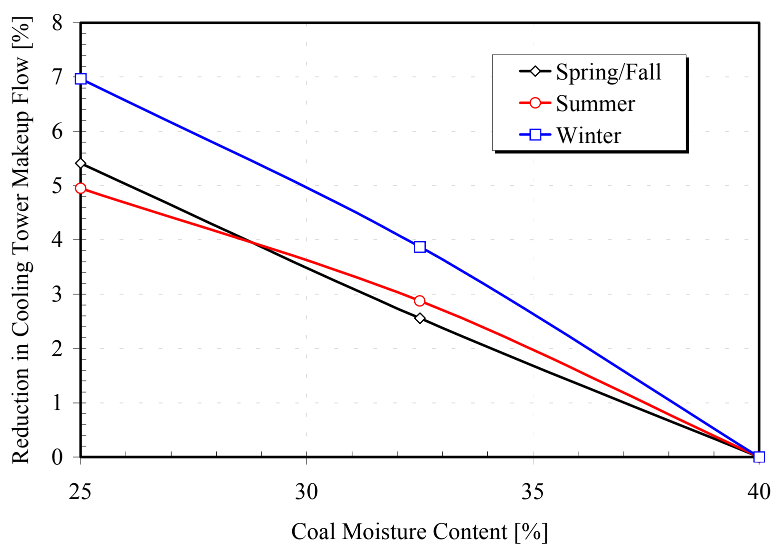

Figure 3: The Effects of Coal Moisture on Cooling Tower Makeup Water

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).

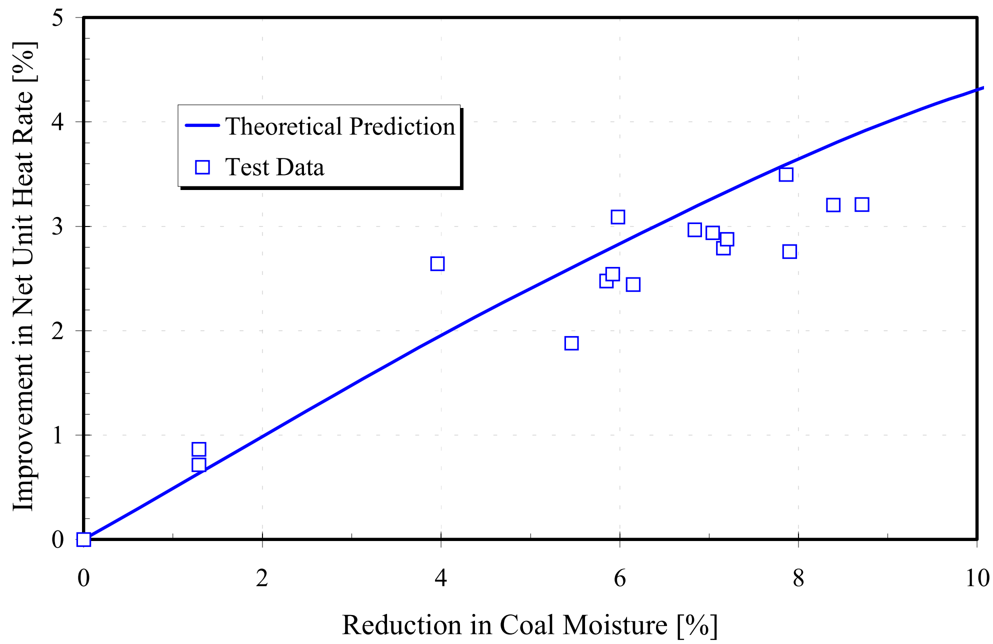

Figure 4: Improvement in Net Unit Heat Rate Versus Reduction in Coal Moisture Content

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 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 the various 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, 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.

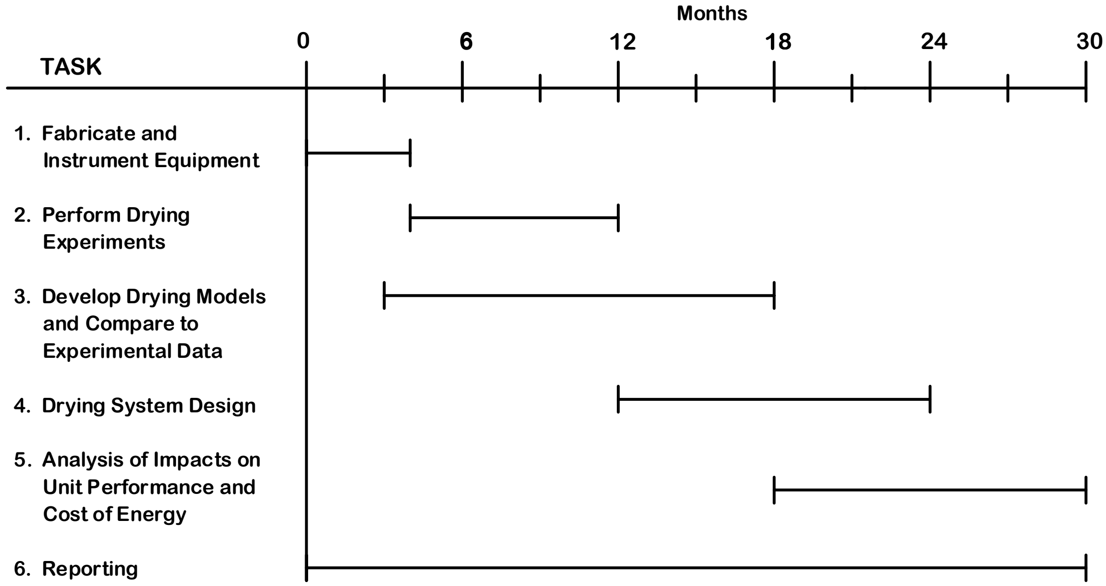

Figure 5: Project Schedule

EXECUTIVE SUMMARY

Background

Low rank fuels such as subbituminous coals and lignites contain relatively large amounts of moisture compared to higher rank coals. High fuel moisture results in fuel handling problems, and it affects station service power, heat rate, and stack gas emissions.

This project deals with lignite and subbituminous coal-fired pulverized coal power plants, which are cooled by evaporative cooling towers. The project involves use of the hot circulating cooling water leaving the condenser to provide the heat needed to partially dry the coal before it is fed to the pulverizers.

Recently completed theoretical analyses and coal test burns performed at a lignite-fired power plant showed that by reducing the fuel moisture, it is possible to reduce water consumption by evaporative cooling towers, improve boiler performance and unit heat rate, and reduce emissions. 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.

This project is evaluating alternatives for the low temperature drying of lignite and Power River Basin (PRB) coal. Laboratory 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 drying, along with the development of an optimized system design and recommended operating conditions.

Results

Experimental data were obtained during this last quarter on the effects of particle size on drying rate for a North Dakota lignite. Other experiments looked at drying a PRB coal. The tests comparing drying rates with lignite particles of different diameters were carried out with particle top sizes from 2 to 9.5 mm and covered a range of air velocities. The results show that drying rate increased with air velocity, but that the data for all four particle size distributions follow the same curve. This suggests the higher drying rates associated with the larger particles are due to higher air velocities and not to any inherently different drying rates due to particle size.

The drying data with the PRB coal show qualitatively similar behavior to that observed with lignite. However, quantitative comparisons of the drying rate data obtained so far for the two coals show the PRB dried at rates which were 14 to 20 percent lower than the lignite, for comparable process conditions.

The equilibrium relationship between relative humidity and coal moisture was refined using a correction for temperature. This reduced the scatter in the coal moisture versus relative humidity data and improved the predictions made with the first principle drying model.

During the next Quarter, it is planned to run experiments on the effects of inlet air moisture content on the drying process and to carry out additional experiments using PRB coal. In addition, the Task 4 Drying System Design study will be initiated.

EXPERIMENTAL

Test Apparatus

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 flow into a filter bag before the air is discharged from the apparatus (Figure 6). Compressed air used in the experiments flows though a rotameter and an air heater before entering the plenum. Operating at 1.6 m/s of superficial air velocity in the 152.4 mm (6-inch) diameter bed, the electrically heated, air heater can attain a maximum steady state temperature of 66°C (150°F).

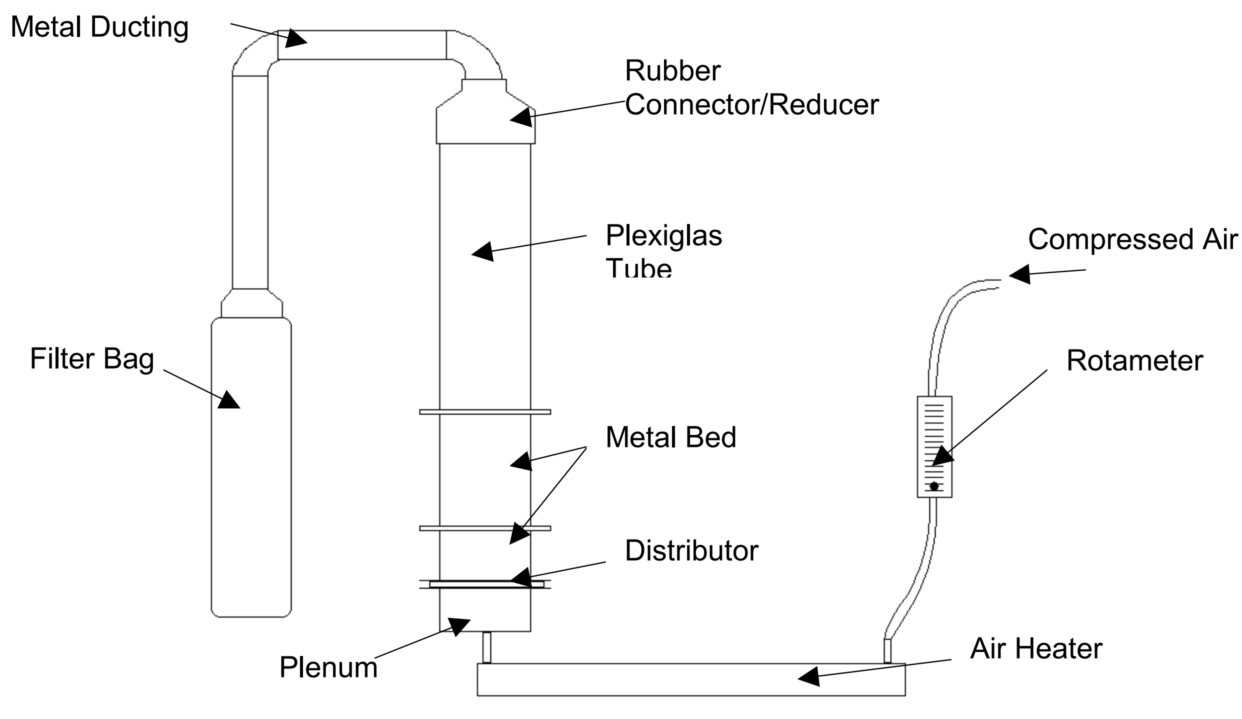

Figure 6: Sketch of Experimental Bed Setup

Thermocouples inserted through the bed wall are used to measure vertical distribution of bed temperature. A horizontal bundle of eighteen 12.7 mm (½") diameter electric heating elements is used to provide in-bed heating. The heaters are located in the region from 51 mm (2”) to 304.8 mm (12”) above the distributor 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.

Test Procedure

Batch bed drying tests were performed with specific humidity of the inlet air ranging from 0.002 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.

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.

Results and Discussion

The experiments performed in this reporting period were carried out with two coals, a North Dakota lignite and a Powder River Basin (PRB) coal. The as-received moisture content of the lignite varied slightly from sample-to-sample, usually ranging from 35 to 38 percent (expressed as mass of moisture/mass of as-received fuel) and from 54 to 58 percent (expressed as mass of moisture/mass dry fuel). The PRB coal had a moisture content of approximately 27 percent (expressed as mass of moisture/mass of as-received fuel) and 37 percent (expressed as mass of moisture/mass dry fuel).

During the first minute or two of each test, fines were elutriated from the bed. The drying rate, $\dot{\Gamma}\left(\frac{\text{kg H}_2\text{O}}{\text{kg dry coal}\times\text{min}}\right)$, presented here is based on the dry coal which remained in the bed after elutriation had occurred and after coal samples had been removed for analysis.

Effect of Particle Size on Drying Rate

Experiments were performed to determine the effect of particle size on drying rate. The tests were performed with lignite, in each case with the bed material having a wide size distribution, but with the top size ranging from 0.077" to 0.375" (2 to 9.5 mm). The bed materials were prepared by crushing the coal and sieving it to the desired top sizes. For example, Figures 7 and 8 are histograms of the size distributions for top sizes of 2 and 2.82 mm. The mean particle sizes, defined as

$$d_{pavg} = \frac{1}{\sum \frac{x_i}{d_{pi}}}$$

are given in Figures 7 and 8. The tests were performed with a settled bed depth of 0.39m, 43°C inlet air and heater surface temperature, and superficial air velocities, U_o, ranging from 0.9 to 1.7m/s. The drying curve for one of the tests is given in Figure 9,

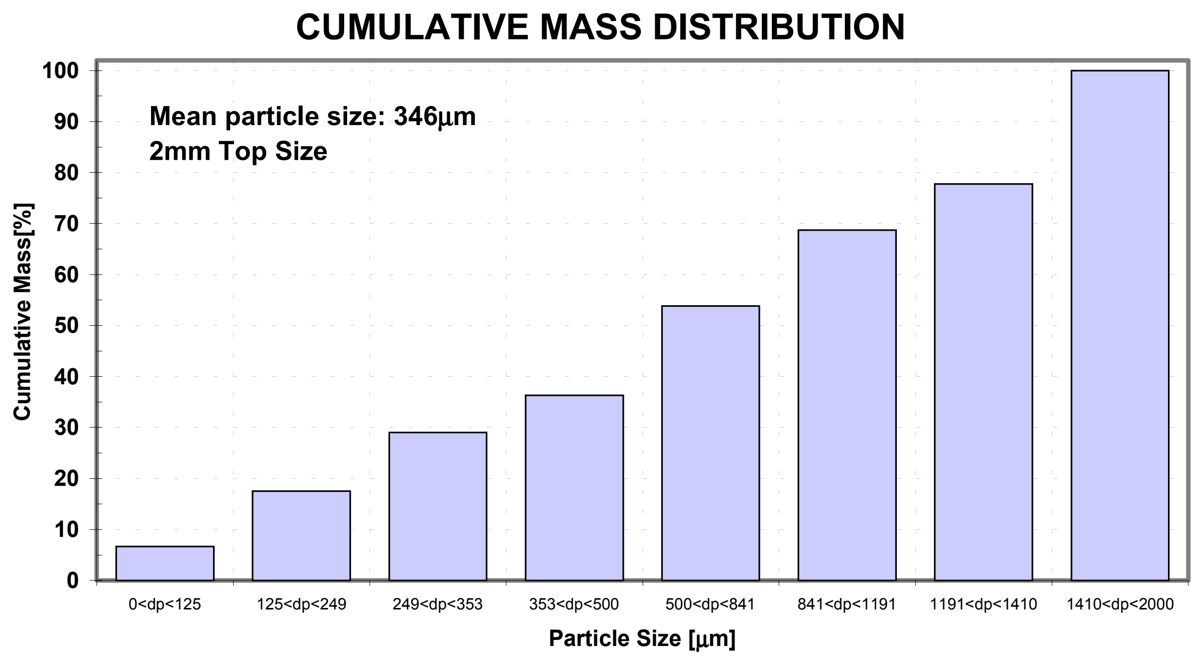

Figure 7: Particle Size Distribution of the Minus 2mm Lignite

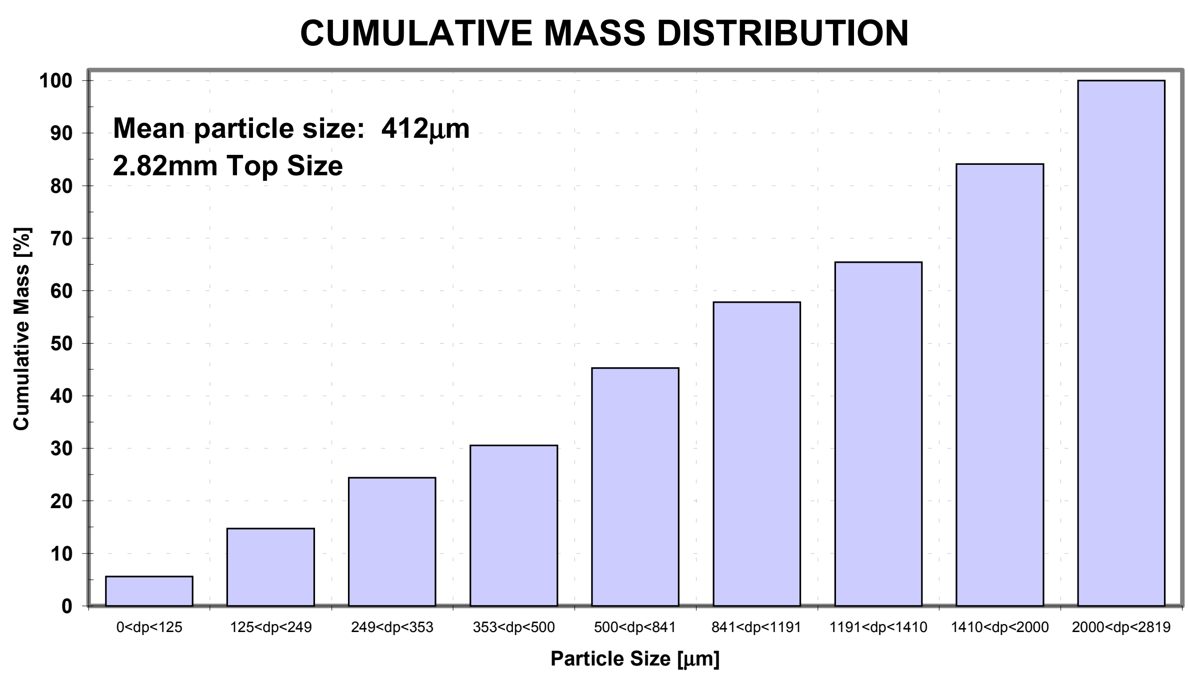

Figure 8: Particle Size Distribution of the Minus 2.82mm Lignite

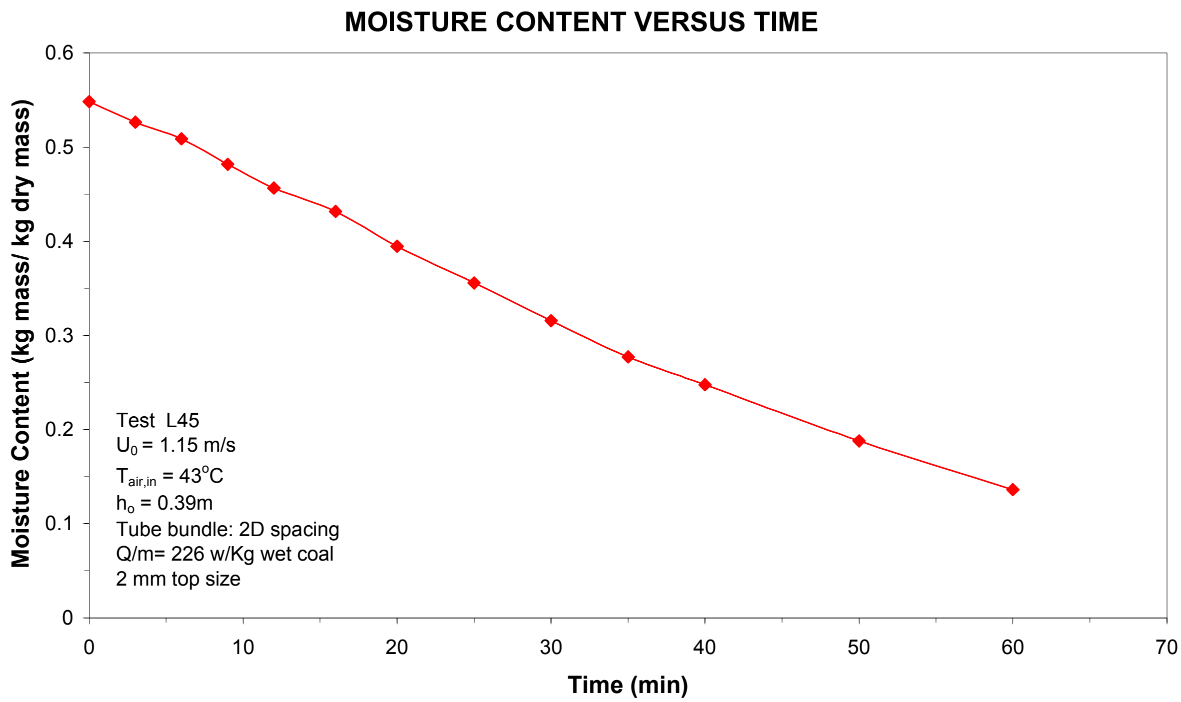

Figure 9: Drying Curve for Test L45

where the numerical value for drying rate was obtained by fitting a straight line to the drying data over the first portion of the test. The drying rate results are summarized in Figure 10, which shows the drying rate as a function of velocity, for the four different particle sizes. The results show that the drying rate increased with air velocity, but that, within the accuracy of the data, the data for all four particle size distributions are on the same curve. Thus, the larger drying rates associated with the larger particles, are due to higher air velocities and not to any inherently higher rates of drying due to particle size. This suggests that, in this particle size range, drying rate is controlled by the internal pore structure of the coal and by the ability of the surrounding air to carry the evaporated moisture away from the particle, but not by particle size.

Effect of Coal Type

Experiments were performed with both lignite and PRB coals at comparable test conditions to determine the relative rates of drying of the two fuels. Figures 11 and 12 show the drying curves for the two coals, for the same values of coal top size and

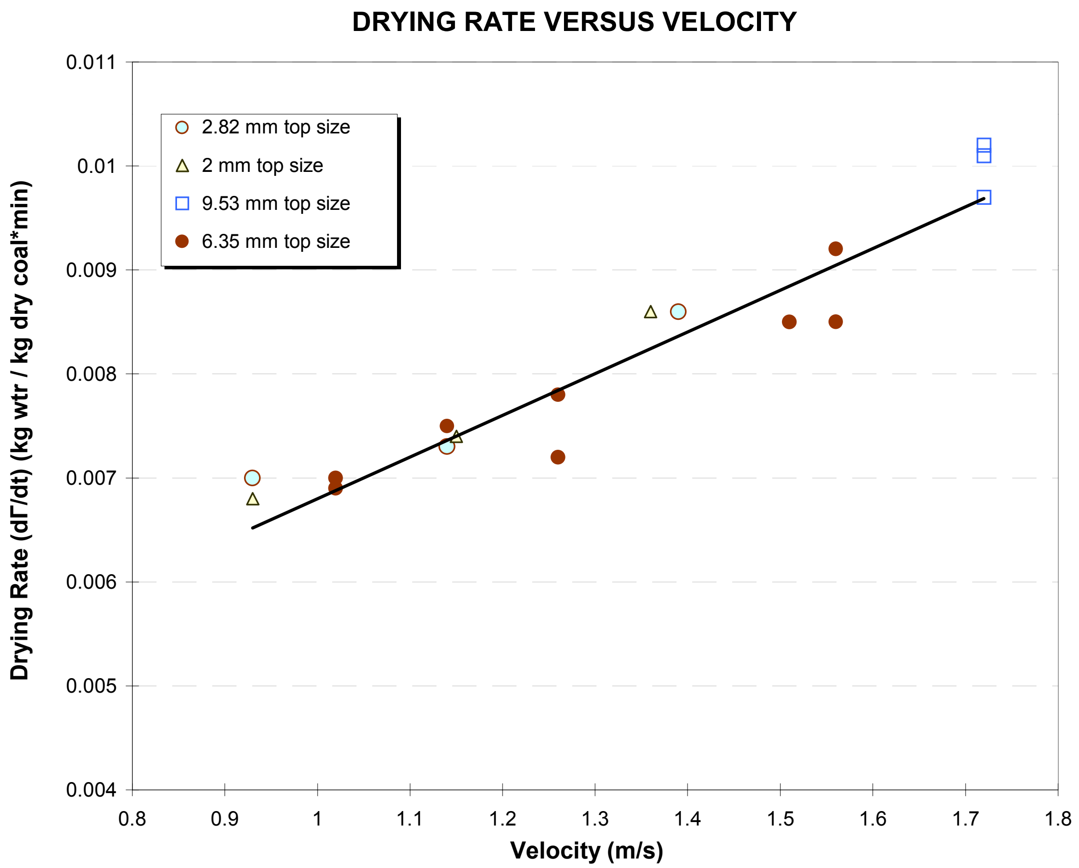

Figure 10: Drying Rate as a Function of Superficial Air Velocity and Particle Size

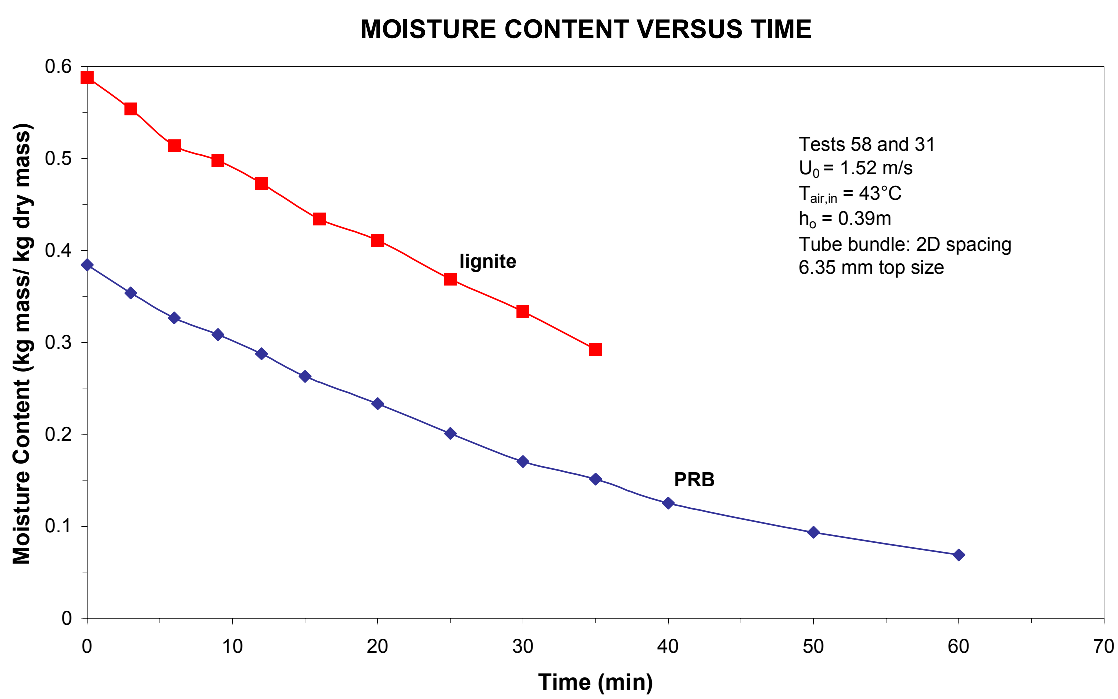

Figure 11: Comparison of Drying Curves for Lignite and PRB Coals for a 43°C Drying Temperature

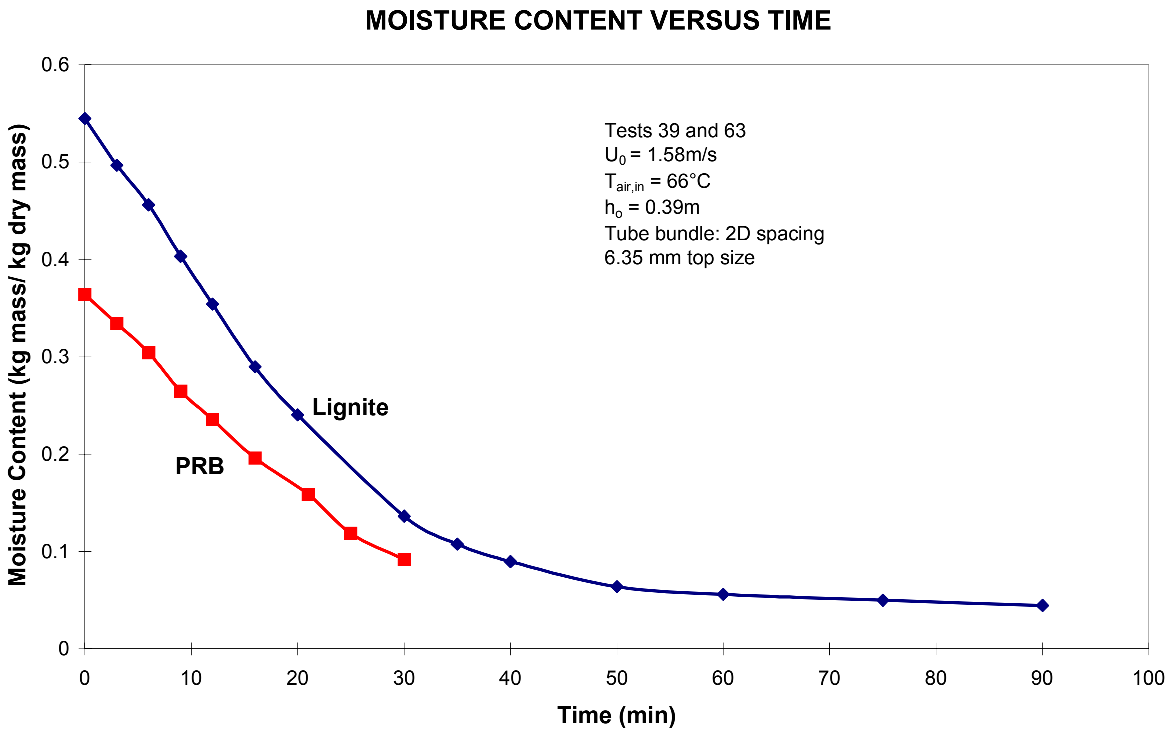

Figure 12: Comparison of Drying Curves for Lignite and PRB Coals for a 66°C Drying Temperature

settled bed depth, for two inlet air and tube wall temperatures, and approximately the same superficial air velocity. Since drying rate is the slope of the drying curve, these show a slightly lower drying rate for the PRB coal. Figures 13 and 14 compare bed temperature for the two cases, indicating almost the same bed temperatures were obtained for the two coals. The data on drying rates obtained so far, covering the range from 43 to 66°C, show that the PRB dries with the same general characteristics as lignite, but with a rate which is 14 to 20 percent lower (see Figure 15).

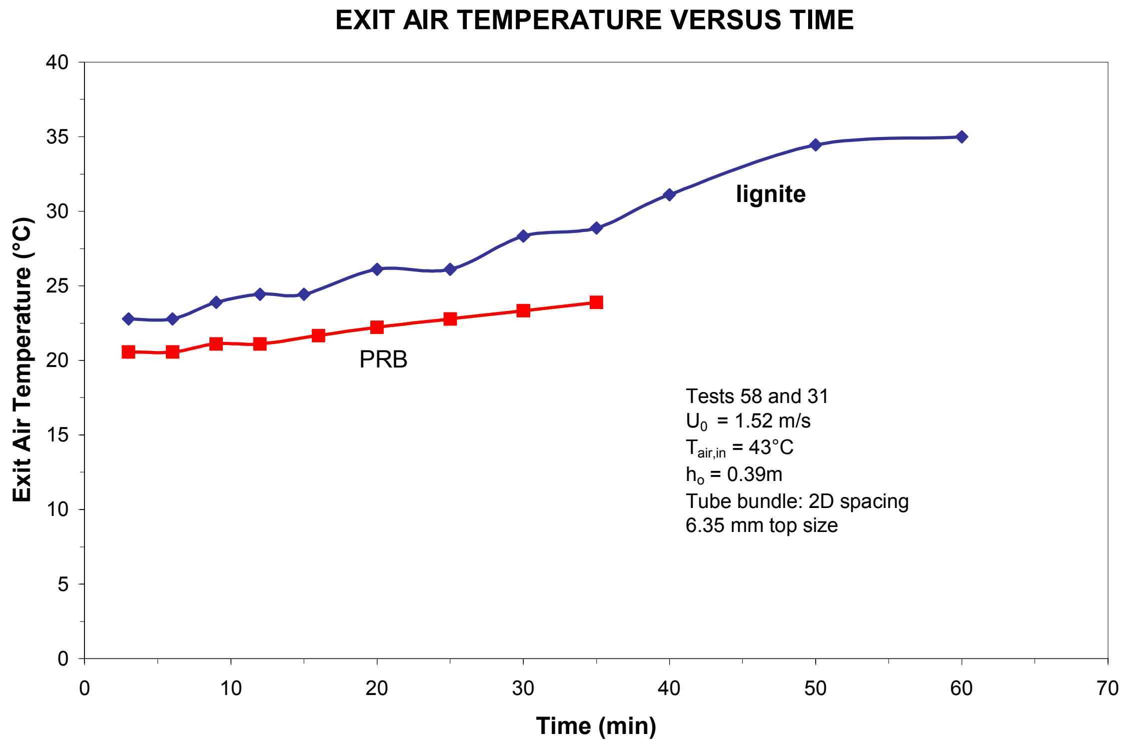

Figure 13: Comparison of Exit Air Temperatures for Lignite and PRB Coals for a 43°C Drying Temperature

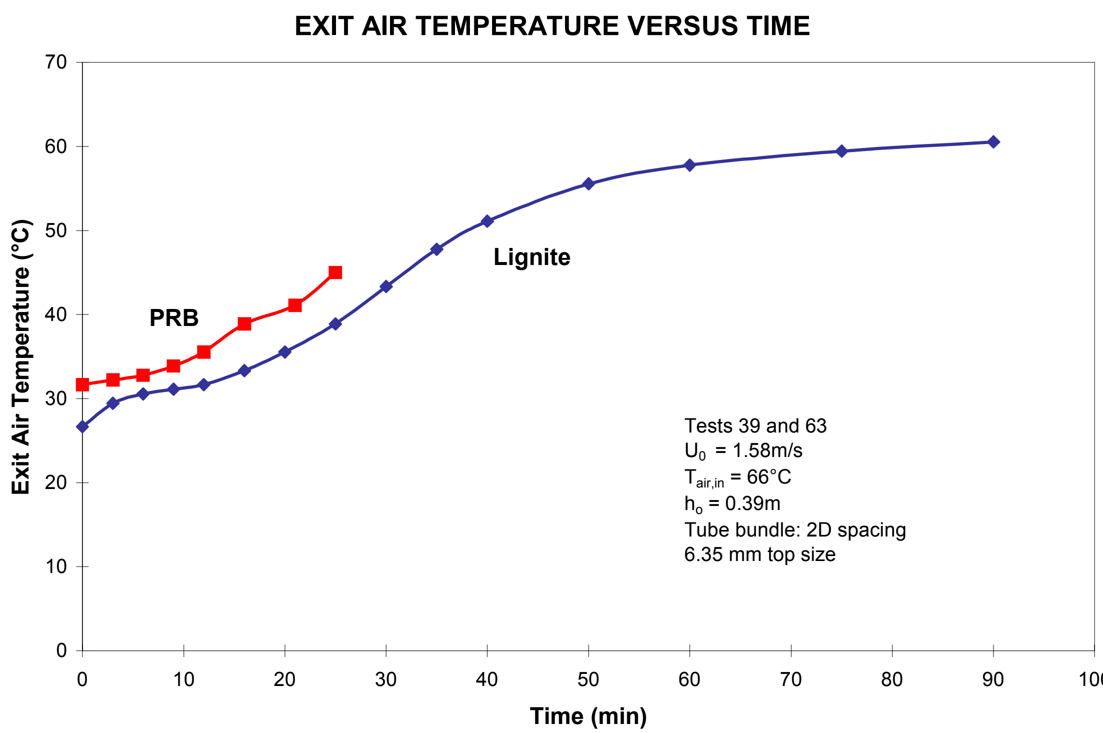

Figure 14: Comparison of Exit Air Temperatures for Lignite and PRB Coals for a 66°C Drying Temperature

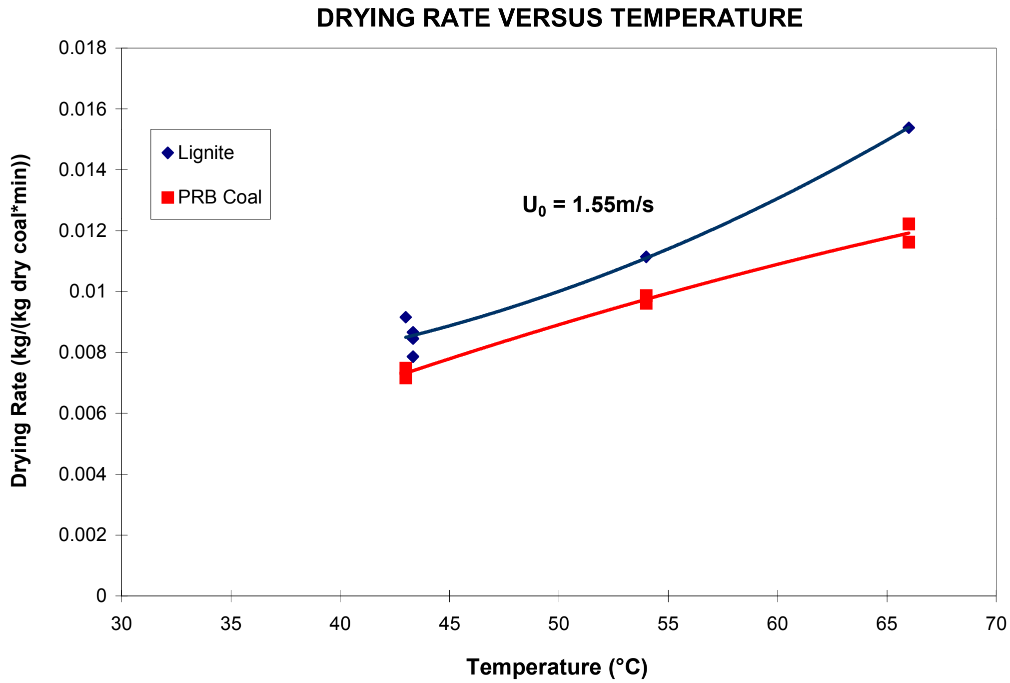

Figure 15: Comparison of Drying Rates for Lignite and PRB

FIRST PRINCIPLE DRYING MODEL

Relative Humidity of Air Leaving Lignite Dryer

Results presented in the last Quarterly report (Ref. 3) show that the relative humidity of the air in equilibrium with the coal can be expressed as a function of the coal moisture content. Figure 16, taken from the last report, shows data from a wide range of test conditions. While there is a definite correlation between coal moisture and relative humidity, the data also exhibit a degree of scatter which would be desirable to reduce, if possible.

Alternate models were explored in an effort to reduce the uncertainty in outlet relative humidity. Treybal (Ref. 2) showed that a correction for temperature improves the correlation when temperature variations are present, and he presented adsorption data which are correlated well by

$$T \log \phi = f(\Gamma)$$

where T is absolute bed temperature and ϕ is relative humidity.

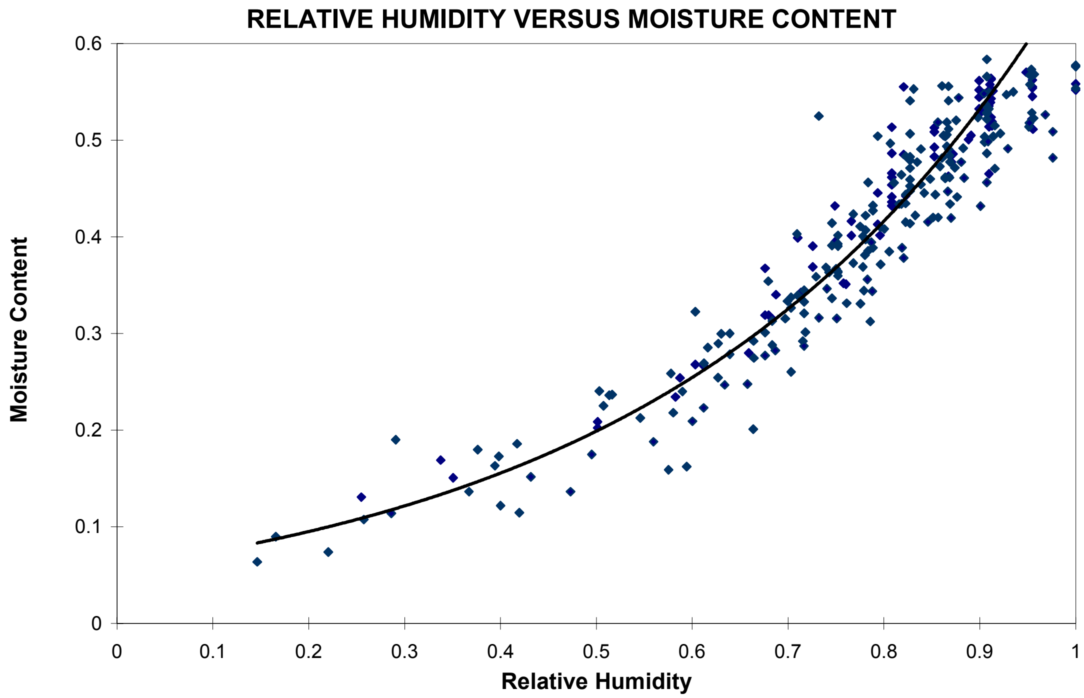

Figure 16: Equilibrium Relative Humidity of Air Versus Moisture Content of Lignite

This model was tested with the lignite drying data shown in Figure 16. As is seen in Figure 17, this gives a good fit of the data, with a relatively small scatter band. A comparison of the relative standard deviation in relative humidity ϕ for the two models is shown in Figure 18. This indicates that including temperature in the equilibrium model greatly improves the correlation.

Simulations using the first-principle drying model (see Ref. 3) were carried out with the two relative humidity models. Comparing the results to the experimental data from Test 36 shows improved predictions using the new model, particularly at bed temperatures in excess of 100°F or 38°C. (See Figures 19 to 22). However, because of lower bed temperatures and a narrower range of temperatures, there is very little difference in the predictions with the two models using the experimental conditions of Test 37 (see Figures 23 to 26).

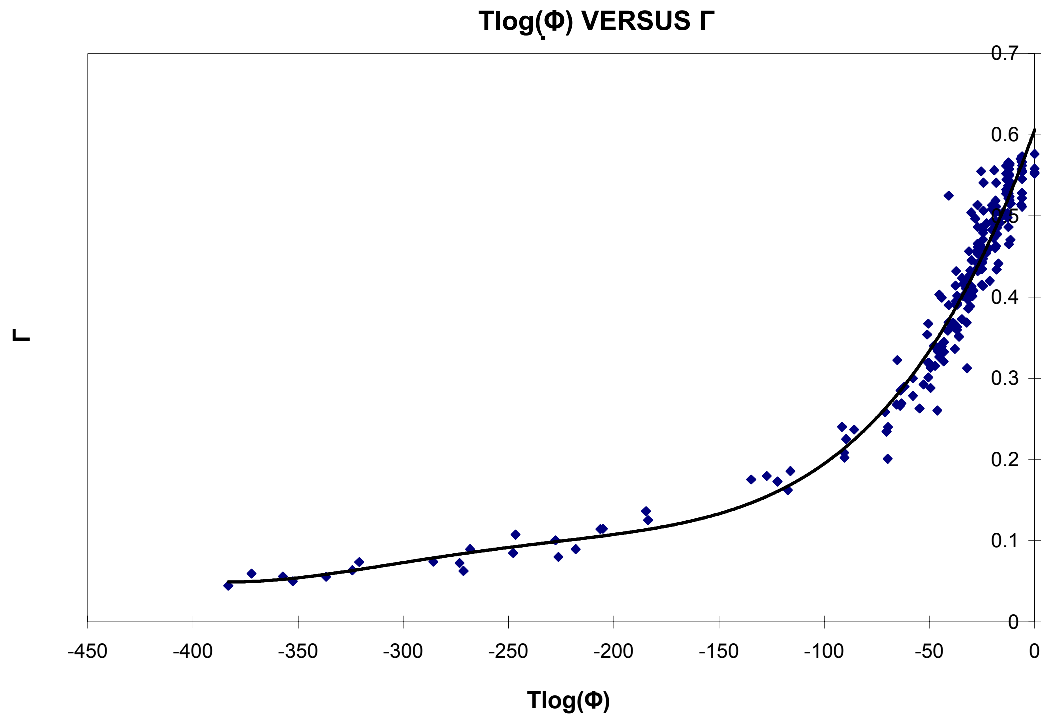

Figure 17: Improved Model for Equilibrium Relative Humidity of Air Versus Moisture Content of Lignite

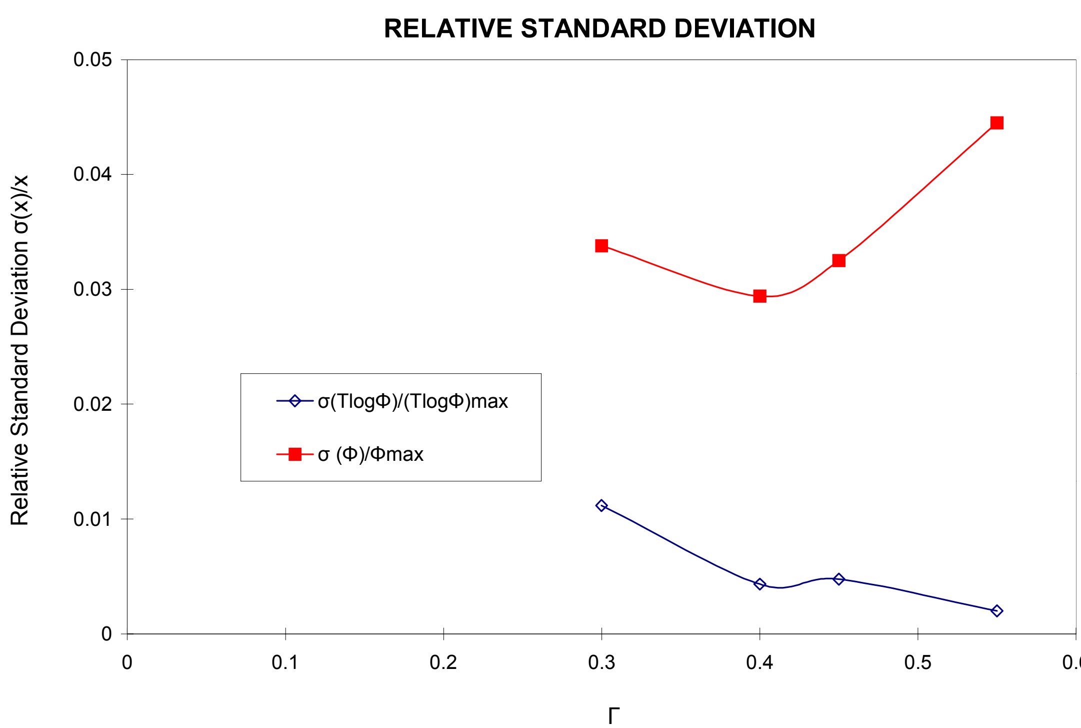

Figure 18: Relative Standard Deviation for the Two Equilibrium Moisture Models

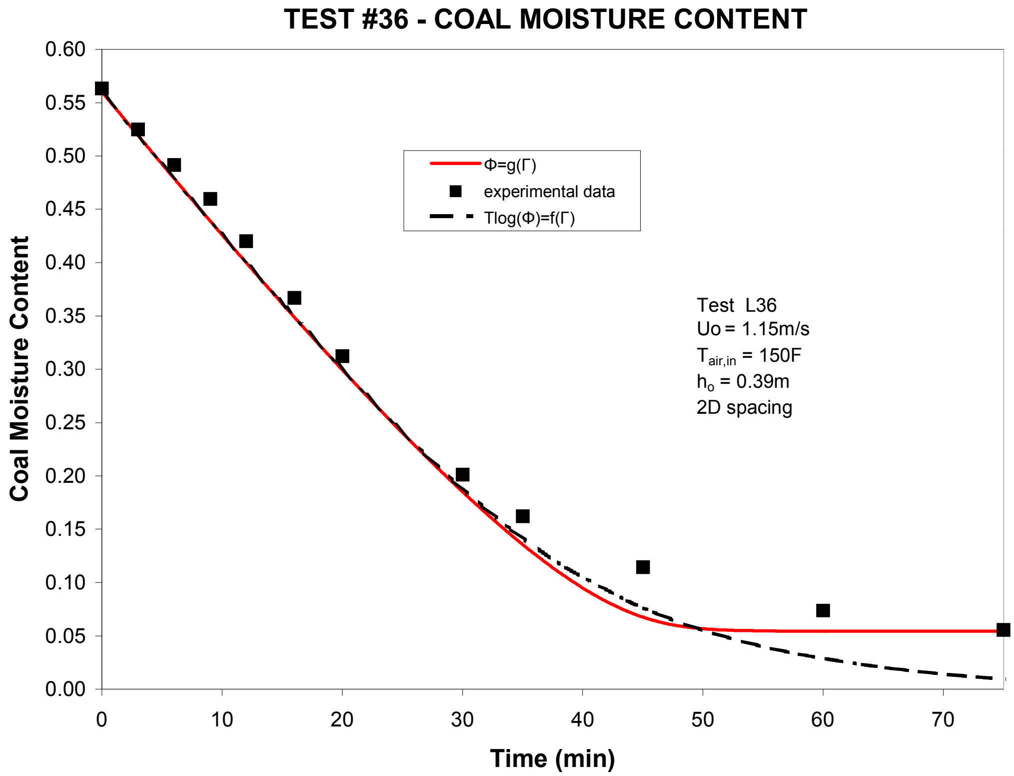

Figure 19: Lignite Drying Curve for Test 36 – Comparison of Predictions From Two Equilibrium Models

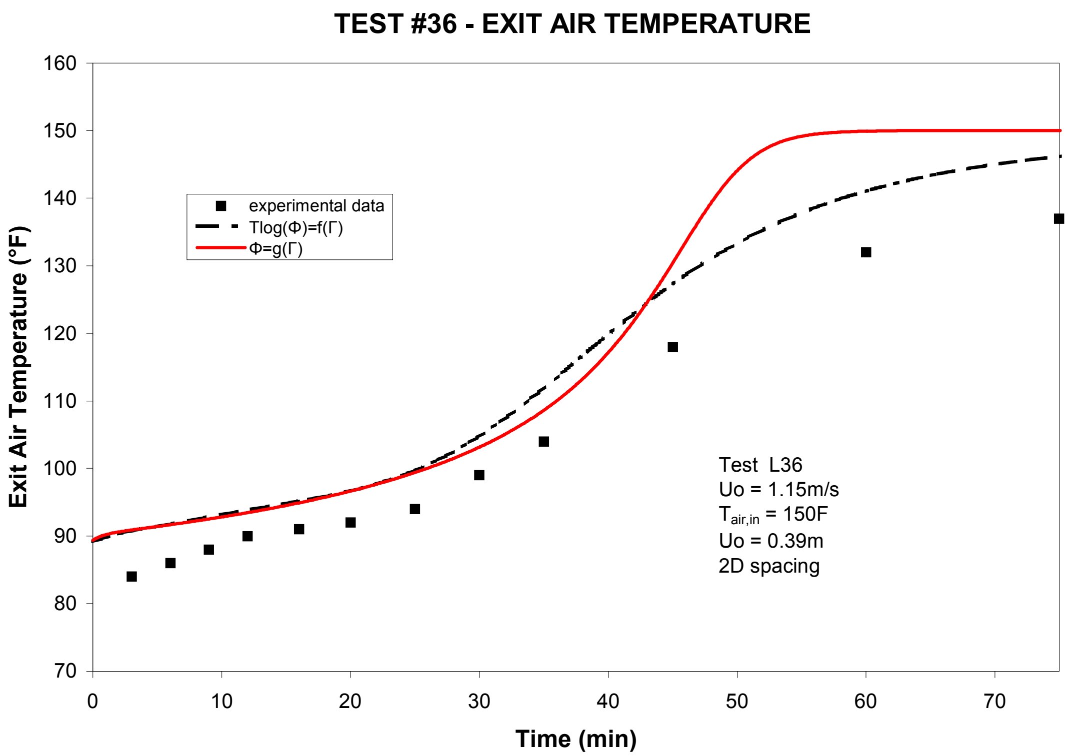

Figure 20: Exit Air Temperature for Test 36 – Comparison of Predictions From Two Equilibrium Models

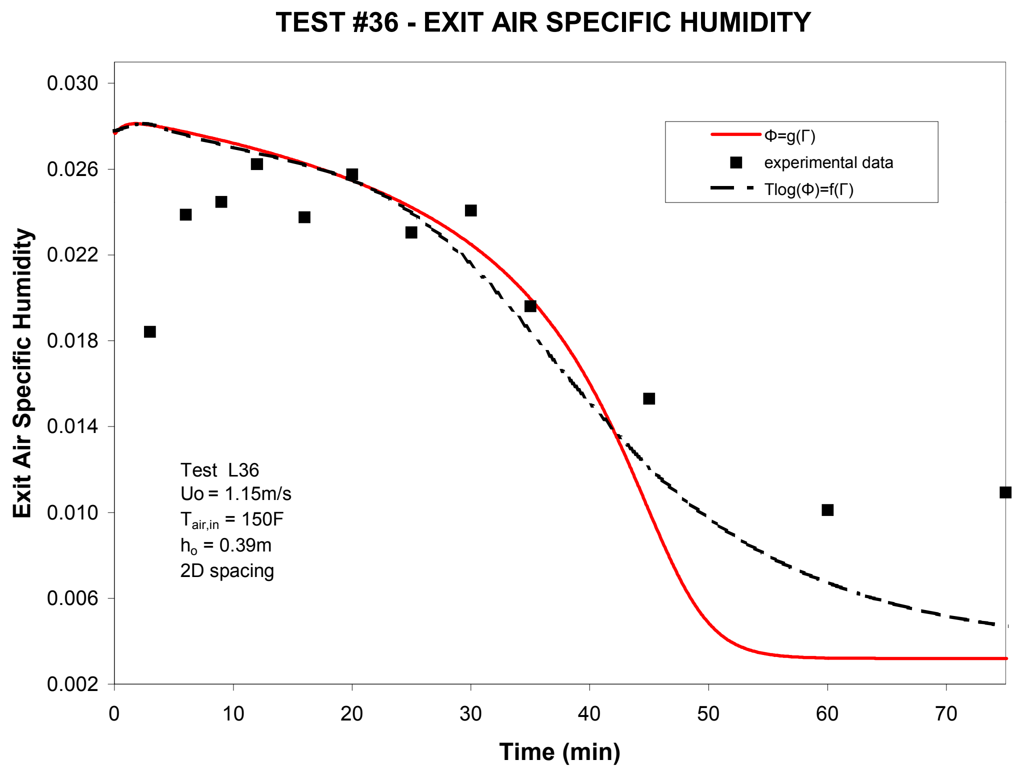

Figure 21: Exit Air Specific Humidity for Test 36 – Comparison of Predictions From Two Equilibrium Models

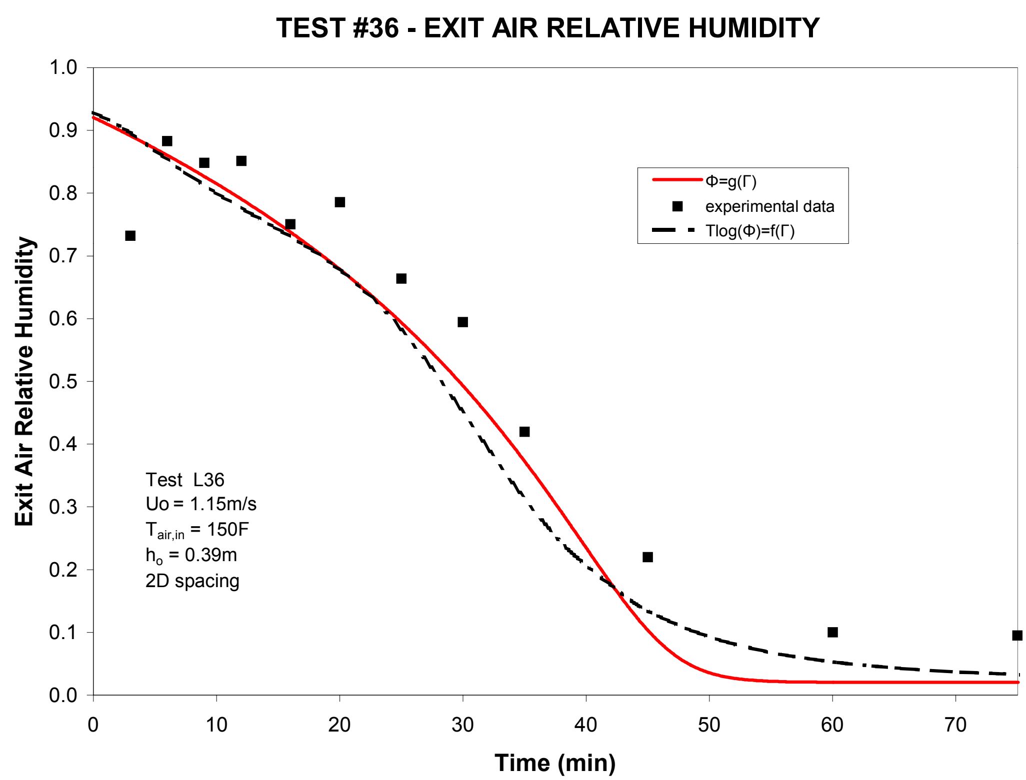

Figure 22: Exit Air Relative Humidity for Test 36 – Comparison of Predictions From Two Equilibrium Models

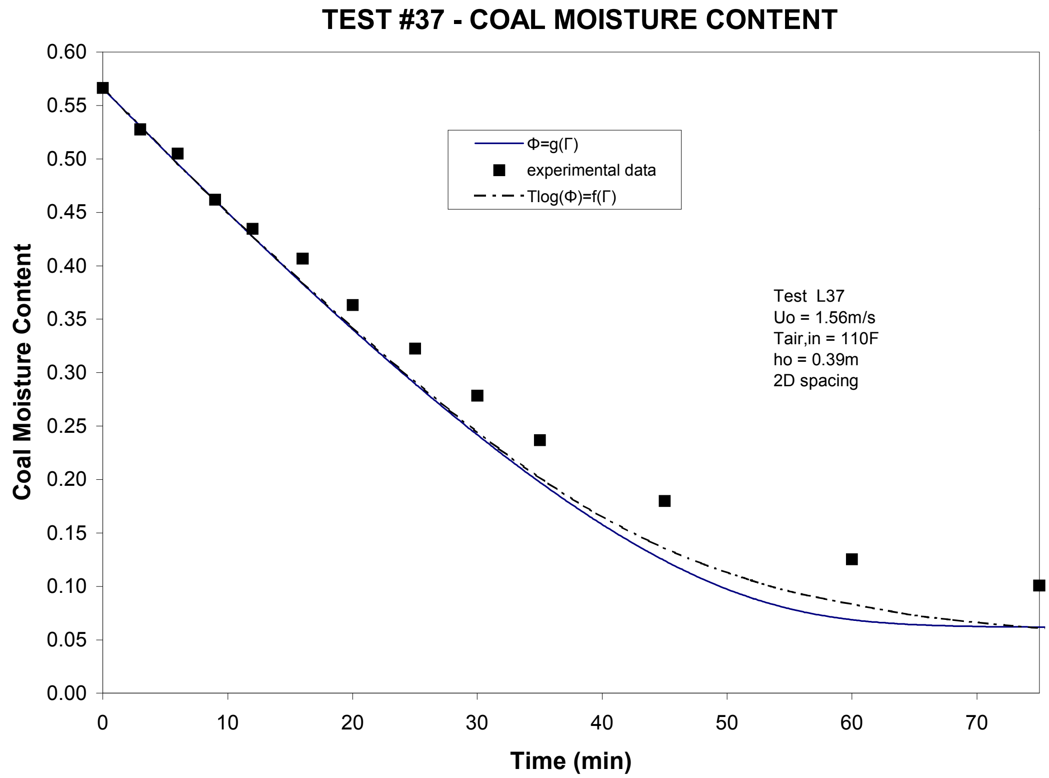

Figure 23: Drying Curve for Test 37 – Comparison of Predictions From Two Equilibrium Models

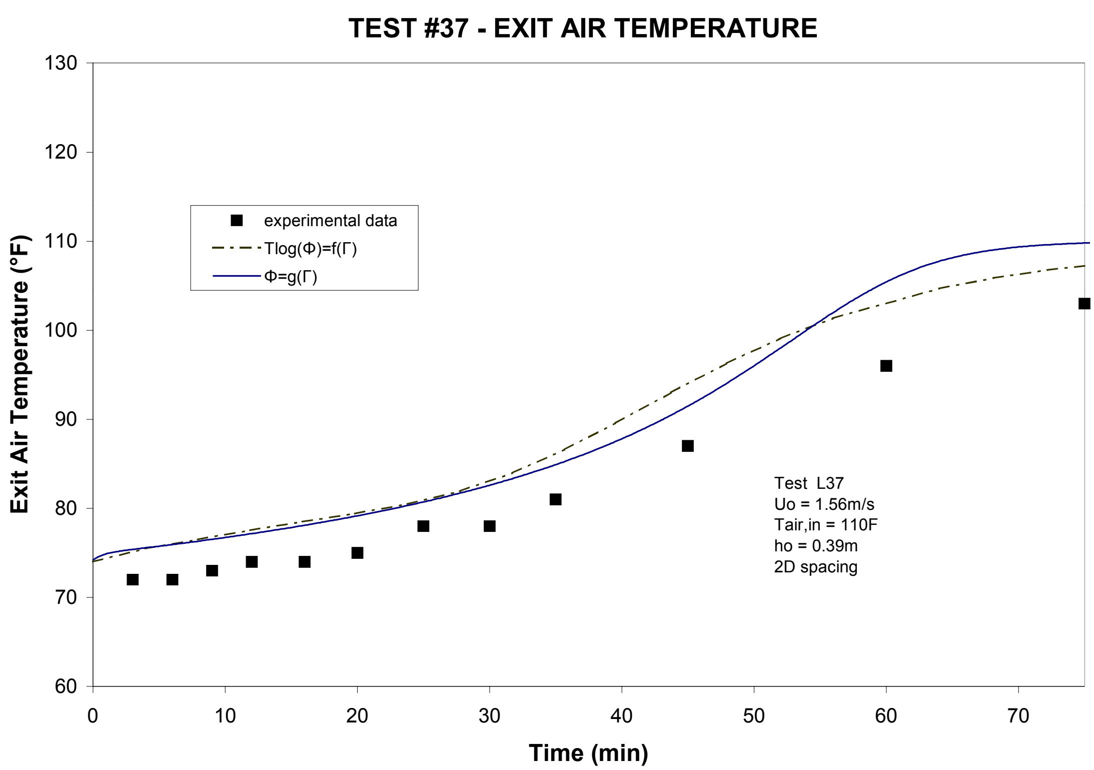

Figure 24: Exit Air Temperature for Test 37 – Comparison of Predictions From Two Equilibrium Models

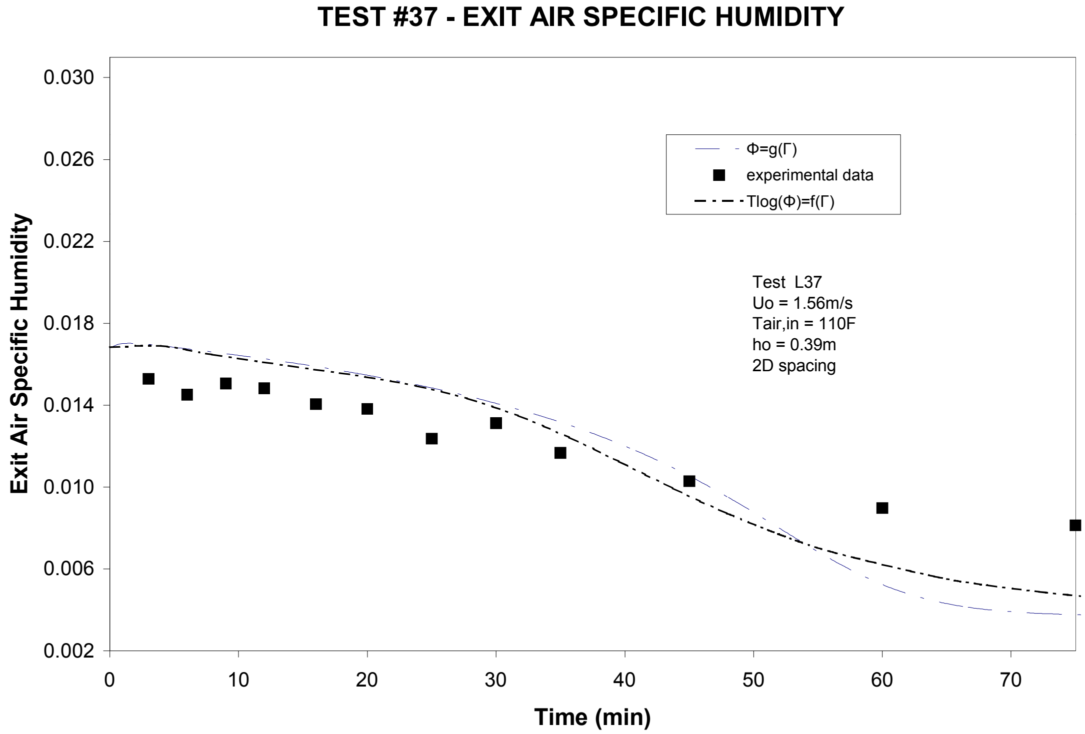

Figure 25: Exit Air Specific Humidity for Test 37 – Comparison of Predictions From Two Equilibrium Models

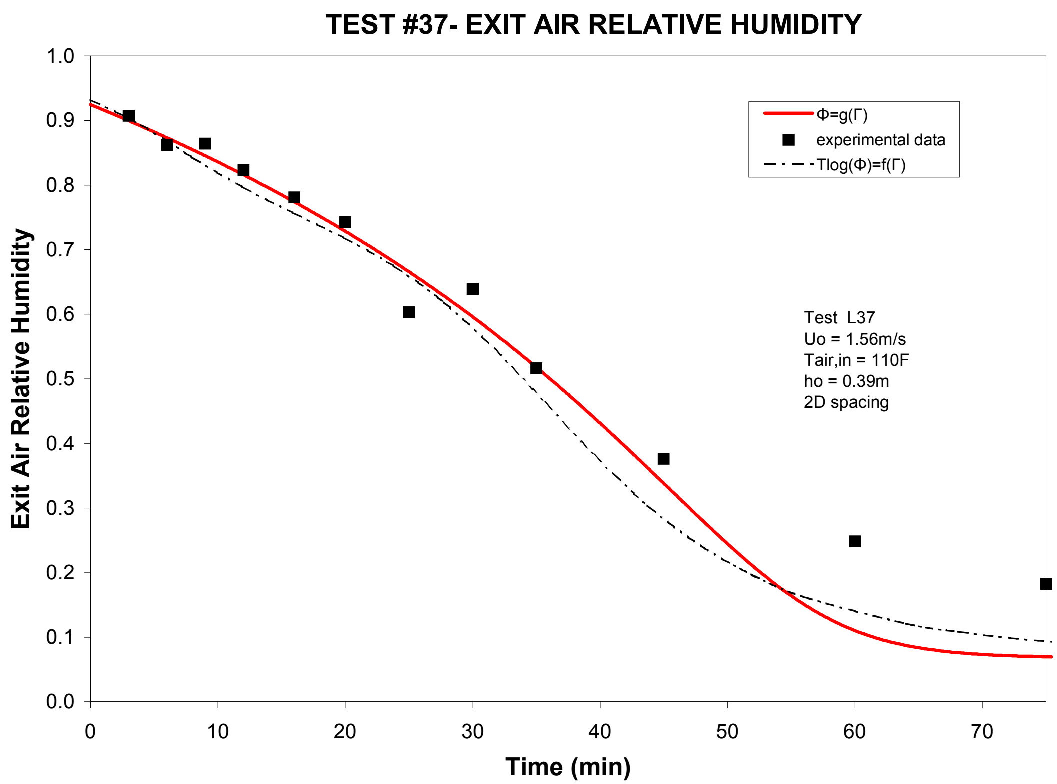

Figure 26: Exit Air Relative Humidity for Test 37 – Comparison of Predictions From Two Equilibrium Models

CONCLUSIONS

Experimental data were obtained during this last Quarter on the effects of particle size on drying rate for a North Dakota lignite. Other experiments looked at drying a PRB coal. The tests comparing drying rates with liginite particles of different diameters were carried out with particle top sizes from 2 to 9.5 mm and covered a range of air velocities. The results show that drying rate increased with air velocity, but that the data for all four particle size distributions follow the same curve. This suggests the higher drying rates associated with the larger particles are due to higher air velocities and not to any inherently different drying rates due to particle size.

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The equilibrium relationship between relative humidity and coal moisture was refined using a correction for temperature. This reduced the scatter in the coal moisture versus relative humidity data and improved the predictions made with the first principle drying model.

During the next Quarter, it is planned to run experiments on the effects of inlet air moisture content on the drying process and to carry out additional experiments using PRB coal. In addition, the Task 4 Drying System Design study will be initiated.

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2. Treybal, R., Mass Transfer Operations, second edition, McGraw Hill, page 498.

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NOMENCLATURE

d_p	Particle Size
h_o	Settled Bed Depth
$\dot{m}_a$	Air Flow Rate
M_{DC}	Mass of Dry Coal
$M_{wet\ coal}$	Mass of Wet Coal
Q_{ave}	Average Heat Flux to Bed
$T_{a,\ in}$	Air Inlet Temperature
T_b	Bed Temperature
U_o	Superficial Air Velocity
x_i	Mass Fraction of Coal with Particle Size d_{pi}
ϕ	Relative Humidity
Γ	Coal Moisture $\left(\frac{\text{kg } H_2O}{\text{kg dry coal}}\right)$
$\dot{\Gamma}$	Drying Rate = $\frac{d\Gamma}{dt}$
ω	Specific Humidity of Air
σ	Standard Deviation