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

FINAL REPORT

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by

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DISCLAIMER

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ABSTRACT

U.S. low rank coals contain relatively large amounts of moisture, with the moisture content of subbituminous coals typically ranging from 15 to 30 percent and that for lignites from 25 and 40 percent. High fuel moisture has several adverse impacts on the operation of a pulverized coal generating unit, for it can result in fuel handling problems and it affects heat rate, stack emissions and maintenance costs.

Theoretical analyses and coal test burns performed at a lignite fired power plant show that by reducing the fuel moisture, it is 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 evaluated the low temperature drying of high moisture coals using power plant waste heat to provide the energy required for drying. Coal drying studies were performed in a laboratory scale fluidized bed dryer to gather data and develop models on drying kinetics. In addition, analyses were 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 optimized drying system designs and recommended operating conditions.

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INTRODUCTION

BACKGROUND

U.S. low rank coals contain relatively large amounts of moisture, with the moisture content of subbituminous coals typically ranging from 15 to 30 percent and that for lignites from 25 and 40 percent (kg $H_2O \times 100$/kg wet coal). High fuel moisture has several adverse impacts on the operation of a pulverized coal generating unit, for it can result in fuel handling problems and it affects heat rate, stack emissions and maintenance costs.

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, provide heat rate and emissions benefits and reduce maintenance costs.

One drying technology addressed in this project makes use of the hot circulating cooling water leaving the condenser to dry the coal. 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). With this approach, coal drying can be accomplished by 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).

Since the rate of drying depends strongly on temperature, there may be advantages to using a higher temperature heat source from the boiler or turbine cycle in combination with condenser waste heat. This report also contains results from analyses in which heat extracted from boiler flue gas is used in combination with heat rejected by the steam condenser.

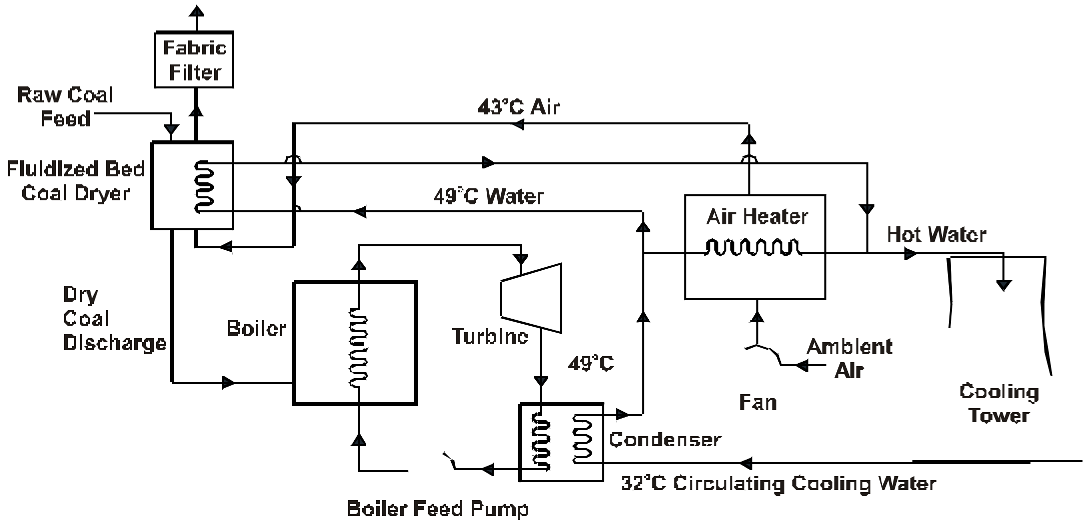

Figure 1: Schematic of Plant Layout, Showing Air Heater and Coal Dryer

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 2). 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 (Reference 1).

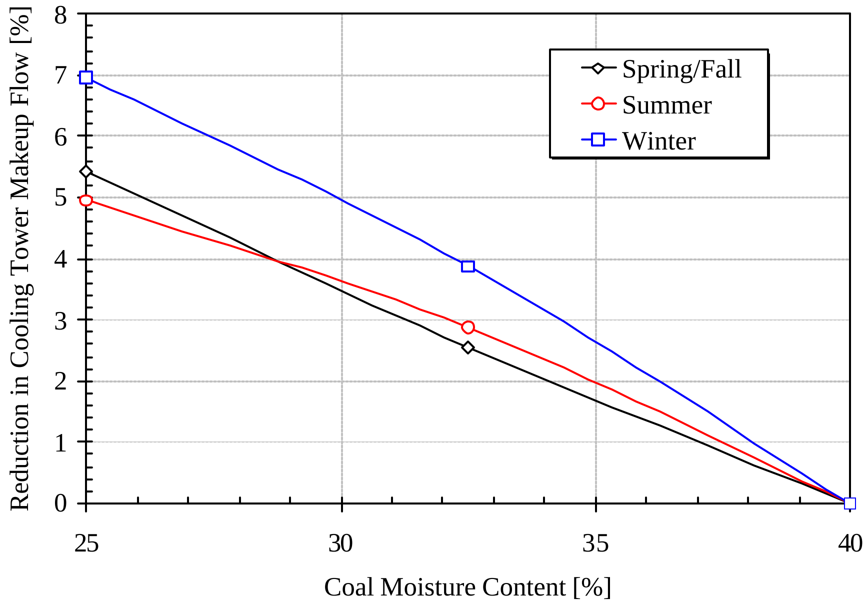

Figure 2: The Effects of Coal Moisture on Cooling Tower Makeup Water

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 show 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 3). The test data also show 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 (Reference 1).

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.

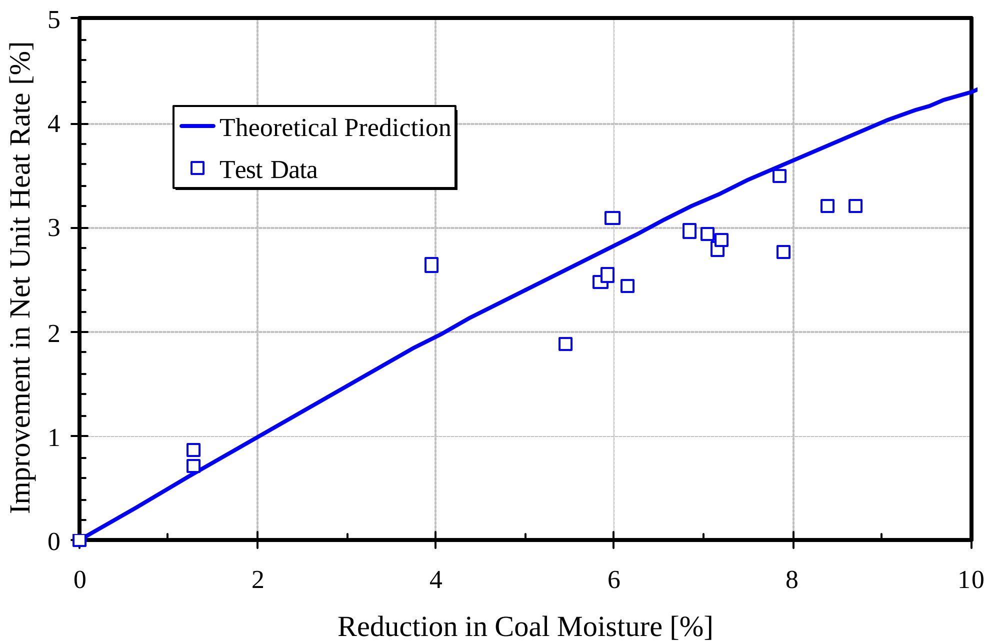

Figure 3: Improvement in Net Unit Heat Rate Versus Reduction in Coal Moisture Content

The present project evaluated the low temperature drying of high moisture coals using power plant waste heat to provide the energy required for drying. Coal drying studies were performed in a laboratory scale fluidized bed dryer to gather data and develop models on drying kinetics. In addition, analyses were 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 optimized drying system designs and recommended operating conditions.

The project was carried out in five tasks:

Task 1: Fabricate and Instrument Equipment

A laboratory scale fluidized bed drying system was designed, fabricated and instrumented in this task.

Task 2: Perform Drying Experiments

Experiments were carried out with lignite and PRB coals, while varying particle size distribution, superficial air velocity, in-bed heat flux, and inlet air temperature and specific humidity.

Task 3: Develop Drying Models and Compare to Experimental Data

A first principal drying model was developed for batch drying of coal and the results of the model were compared to the laboratory data. In addition, a second theoretical model, suitable for use with a continuously operating dryer, was developed and results were generated on dryer performance for various operating conditions.

Task 4: Drying System Design

Using the kinetic data and models from Tasks 2 and 3, fluidized bed drying systems were designed for full size coal-fired power plants. Auxiliary equipment such as fans, heat exchangers, dust collection systems and coal crushers were sized, and installed capital and operating costs were estimated.

Task 5: Analysis of Impacts on Unit Performance and Comparisons of Costs and Benefits of Drying

Analyses were performed to estimate the effects of dryer operation on cooling tower makeup water, unit heat rate, auxiliary power, and stack emissions. The costs and benefits of drying were estimated as functions of the reduction in coal moisture content.

The project was initiated on December 3, 2002. The project schedule is shown in Figure 4.

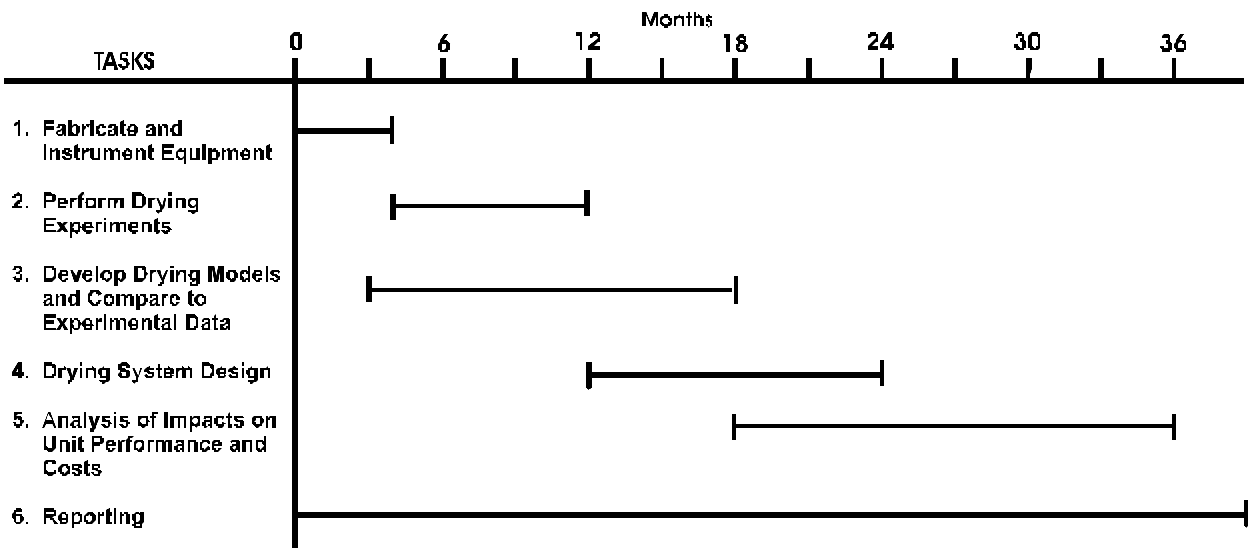

Figure 4: Project Schedule

Part I of this report describes the experiments and analyses performed in Tasks 1 through 3 on the effects of fluidized bed process conditions on rate of drying. Parts II and III describe the Task 4 and 5 analyses of the impacts of coal drying on unit performance and on the costs and benefits of coal drying.

EXECUTIVE SUMMARY

BACKGROUND

U.S. low rank coals contain relatively large amounts of moisture, with the moisture content of subbituminous coals typically ranging from 15 to 30 percent and that for lignites from 25 to 40 percent. High fuel moisture has several adverse impacts on the operation of a pulverized coal generating unit, for it can result in fuel handling problems and it affects heat rate, stack emissions and maintenance costs.

The present project evaluated the low temperature drying of high moisture coals using power plant waste heat to provide the energy required for drying. Coal drying studies were performed to gather data and develop models on drying kinetics. In addition, analyses were carried out to determine the relative costs and performance impacts of coal drying along with the development of optimized drying system designs and recommended operating conditions.

RESULTS

Effects of Process Parameters and Coal Type on Drying Rate

Laboratory scale fluidized bed coal drying experiments were performed with a North Dakota lignite and a Powder River Basin coal. The two coals exhibited similar drying characteristics, with a constant rate of drying at the beginning of the drying process, followed by a decreasing rate of drying as the coal moisture content was reduced to lower levels. The rate of drying during the constant rate period increased with superficial air velocity, inlet air temperature and in-bed heat flux and decreased with increasing levels of inlet air specific humidity. Comparisons between drying rates for lignite and PRB coals at the same process conditions show lignite dries slightly more rapidly than PRB coal. Theoretical drying models were developed for both batch and continuously operating fluidized bed drying processes, and these were found to give good agreement with laboratory and pilot plant drying data.

Impacts of Coal Drying on Unit Operations

The second part of the project involved the design of drying systems for lignite and PRB coal-fired power plants and analysis of the effects of drying system operation on cooling tower makeup water, unit heat rate, auxiliary power and stack emissions. Two drying system designs were analyzed. One, referred to in this report by the acronym, **CCW**, relies on waste heat extracted from the hot circulating water leaving the condenser for fluidized bed coal drying. The second type of drying system uses a combination of condenser waste heat and heat extracted from boiler flue gas to attain higher drying temperatures than are possible from condenser waste heat alone. This is referred to in this report by the acronym, **CCW/FG**.

The results for lignite show that as coal product moisture is reduced, boiler efficiency increases, net unit heat rate decreases and the cooling tower make up water requirements decrease for both the CCW and CCW/FG drying systems (see Table below). For a gross power generation of 572 MW and a 20 percent lignite product moisture, the station service power increases by 17 MW over the baseline for the CCW system and is relatively unchanged for the CCW/FG system. The relatively large increase in station service power for the CCW system is caused by the large dryer and consequently high fluidization air flow rates needed by the low-temperature CCW drying system.

Effects of Lignite Drying on Changes in
Key Plant Performance Parameters with a 20 Percent Product Moisture

	CCW	**CCW/FG**
Boiler Efficiency	+5.5%	+3%
Net Unit Heat Rate	-3.3%	-3.3%
Station Service Power	+17 MW	Negligible
Cooling Tower Makeup Water	-380 gallons/minute	-140/gallons/minute

The effect of coal drying on unit performance was also analyzed for identical pulverized coal-fired power plants, one firing lignite and the other a PRB coal. These calculations were performed for the CCW/FG drying system. The results show that while there are small differences due to different coal compositions, the performance impacts due to drying lignite and PRB coals follow the same trends and are very similar in magnitude.

Economic Evaluation

Analyses were carried out to determine the cost effectiveness of the CCW and CCW/FG drying systems. These analyses assumed a lignite feed and a gross electric power output of 572 MW. Installed capital costs were found to depend on product moisture, ranging up to $24.4 million for the CCW/FG drying system and up to $91 million for the CCW system.

Annual fixed costs, assuming a 20 year life and a 7.5 percent interest rate range up to $4.1 million for the CCW/FG system and up to $15.5 million for the CCW system. Use of power plant waste heat to dry coal results in a net increase in station service power of up to 16.5 MW for the CCW system and a negligibly small decrease in station service power for the CCW/FG system. Accounting for annual fixed costs, drying system operating and maintenance costs and costs associated with increases in station service power, the annual costs of drying range up to $4.6 million for the CCW/FG drying system and up to $22.1 million for the CCW system.

Analyses were carried out to estimate the annual financial benefits and at the lowest fuel product moisture levels, these ranged up to $6.6 million for the CCW/FG system and up to $7.4 million for the CCW system. Comparison of the individual parameters affected by drying shows the most important savings are the fuel savings and the avoided costs due to reduction of SO_2 and CO_2 emissions. Less important, but still significant, are savings due to avoided costs of Hg and NO_x emission control, reduced costs of mill maintenance, a decrease in lost generation due to unscheduled mill outages, reduced costs of ash disposal, and reduced use of makeup water for power plant cooling.

A comparison of costs and benefits for the CCW/FG system show that for this particular drying system and the hypothetical coal-fired generation unit which has been analyzed, the cost effectiveness of the technology increases as the coal product moisture decreases. For an annual interest rate of 7.5% and the mean cost savings scenario, the break even point is at 16 percent coal moisture reduction, with the return on investment increasing linearly to 20.9 percent at 19 percent coal moisture reduction.

In contrast, the analysis shows that due to relatively high capital costs and high station service power costs for the CCW system, the return on investment for the CCW system is negative for all moisture levels. The annual fixed costs and dryer operating costs (including station service power) for the CCW system range up to $22 million while the annual gross benefits range up to $7 million.

Additional Comments

The results from this project suggest that using power plant waste heat to dry high-moisture fuels is both technically and economically feasible. The laboratory drying tests showed that coal moisture can be reduced to less than one-half of that in the raw coal with coal residence times in the dryer small enough to be economic. Rates of drying for lignite and PRB coals were found to be of roughly the same magnitude, with slightly higher drying rates for lignite.

The cost effectiveness of drying is heavily dependent on drying temperature, with a drying system which uses a combination of heat extracted from boiler flue gas and from the steam condenser providing a significant return on investment. While the low-temperature CCW drying system, which relies exclusively on thermal energy from the steam condenser, results in significantly greater reduction in cooling tower makeup water, its relatively high installed capital costs and costs of increased station service power make this option unattractive from a financial point of view.

The benefits and costs of coal drying will depend heavily on site-specific factors, and detailed analyses would be needed to determine the most cost effective design for a particular application. All of the analyses performed here are for retrofit applications. However, a comparable study should be performed for new plant designs. Potential savings from matching the boiler design and mill, fan, ESP and scrubber capacities to a lower as-fired fuel moisture may very well lead to substantial additional reductions in installed equipment costs.

PART I – EFFECTS OF PROCESS PARAMETERS AND COAL TYPE ON COAL DRYING RATE

EXPERIMENTAL

Test Apparatus

Fluidized bed coal drying experiments were performed in the Energy Research Center's Fluidized Bed Laboratory. The bed vessel was 0.152 m (6") in diameter, with a 1.37 m (54") column and a sintered powder metal distributor plate. The air and entrained coal particles passed through a bag filter before the air was discharged from the apparatus (Figure 5). Compressed air used in the experiments flowed though a rotameter and an air heater before entering the plenum. Operating at 1.6 m/s of superficial air velocity in the 0.152 m (6-inch) diameter bed, the electrically heated, air heater could attain a maximum steady state temperature of 66°C (150°F).

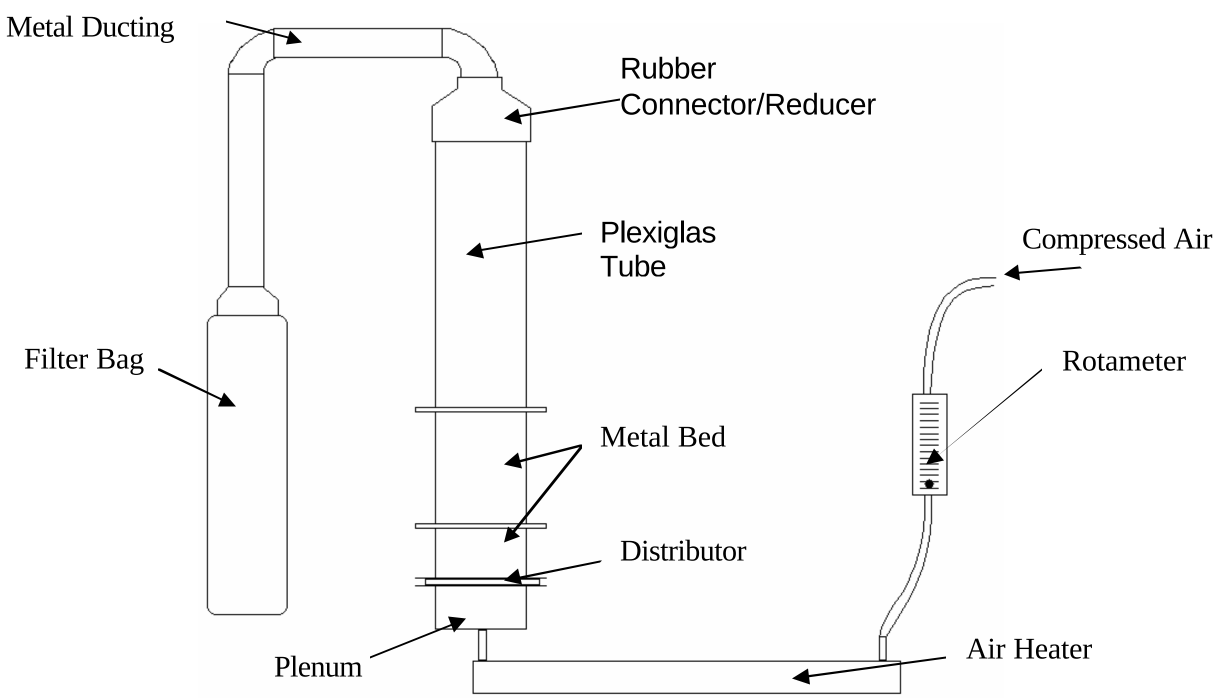

Figure 5: Sketch of Experimental Bed Setup

Thermocouples inserted through the bed wall were used to measure vertical distribution of bed temperature. A horizontal bundle of eighteen 12.7 mm (½") diameter electric heating elements were used to provide in-bed heating. The heaters were located in the region from 51 mm (2") to 304.8 mm (12") above the distributor and were instrumented with thermocouples to indicate heater surface temperature. By controlling power to the heaters, the heater surface temperature could 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 could be reduced from the maximum by disconnecting selected heaters from the power supply.

Some experiments were performed in which the specific humidity of the inlet air to the fluidized bed was increased above ambient levels. In these experiments, the inlet air flowed through a steam humidifier before entering the inlet plenum of the bed.

Test Procedure

Batch bed drying tests were performed to determine the effects of coal particle size, superficial air velocity, inlet air and heater surface temperatures and specific humidity of inlet air on rate of drying. Small samples of the coal were removed from the bed at selected intervals 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 coal 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 coal from the bed and weigh it.
5. Analyze results.

Results and Discussion

The experiments were carried out with two coals, a North Dakota lignite and a subbituminous coal from the Powder River Basin (PRB). The as-received moisture content of the lignite varied slightly from sample-to-sample, usually ranging from 54 to 58 percent and the PRB coal had a moisture content of approximately 37 percent (both 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 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.

The drying tests were performed with inlet air and heater surface temperatures up to 66°C, with superficial air velocities ranging from 0.9 to 1.7 m/s and with settled bed depths of 0.39 m. Superficial air velocity U_0 is defined here as $\frac{\dot{m}_{air}}{rA}$

where A = Bed Cross Sectional Area Without Tube Bundle

ρ = Density of Air at Standard Temperature and Pressure

The tests were performed with coal having a wide size distribution, in most cases with the top size in the 2 to 6 mm range and mean particle sizes from 300 to 600 microns. A typical particle size distribution is shown in Figure 6. The average particle size, was computed as

$$\bar{d}_p = \frac{1}{\sum \frac{x_i}{dp_i}}$$

where

x_i = mass fraction in size range i

dp_i = average particle size in size range i

$\bar{d}_p$ = average particle size for entire sample.

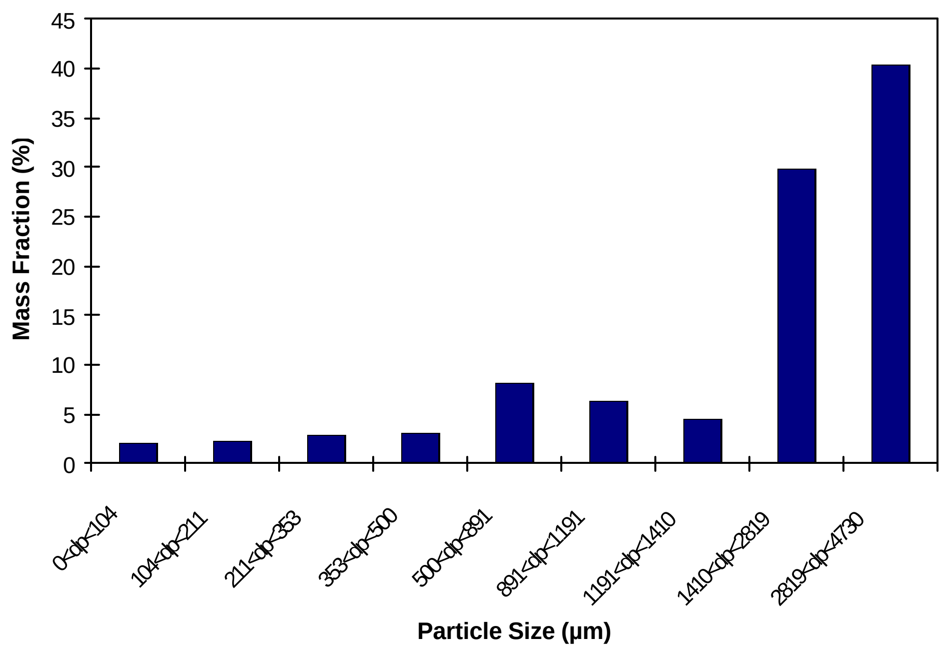

Figure 6: Size Distribution of the Coal

Drying Rate Data

Lignite Coal. Figure 7 shows lignite moisture content Γ (kg H_2O/kg dry coal) as a function of drying time for six different drying tests performed over a range of temperatures and superficial air velocities. These show characteristic drying behavior, with constant rate drying (constant slope) followed by a reduced rate of drying. The drying rates reported in this investigation are based on the constant rate slopes such as those illustrated in Figure 7.

Note that at the beginning of each test in Figure 7, the initial lignite moisture Γ was in the range of 55 to 58 percent. The moisture parameter Γ can related to the moisture content Y obtained from a proximate analysis, where Y has the units (kg H_2O/kg wet coal). Figure 8 gives the relation between Y and Γ.

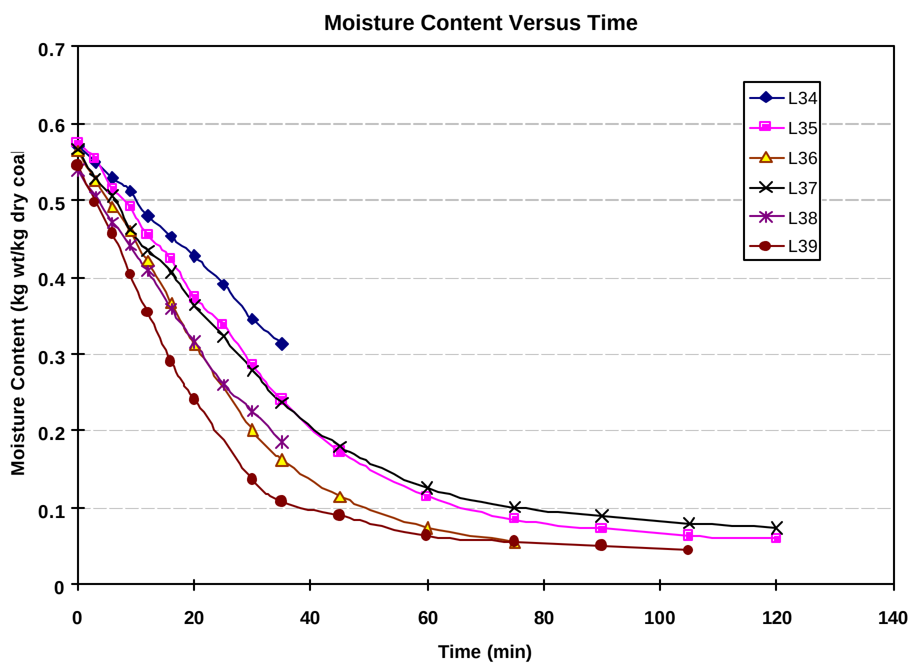

Figure 7: Moisture Content Versus Time

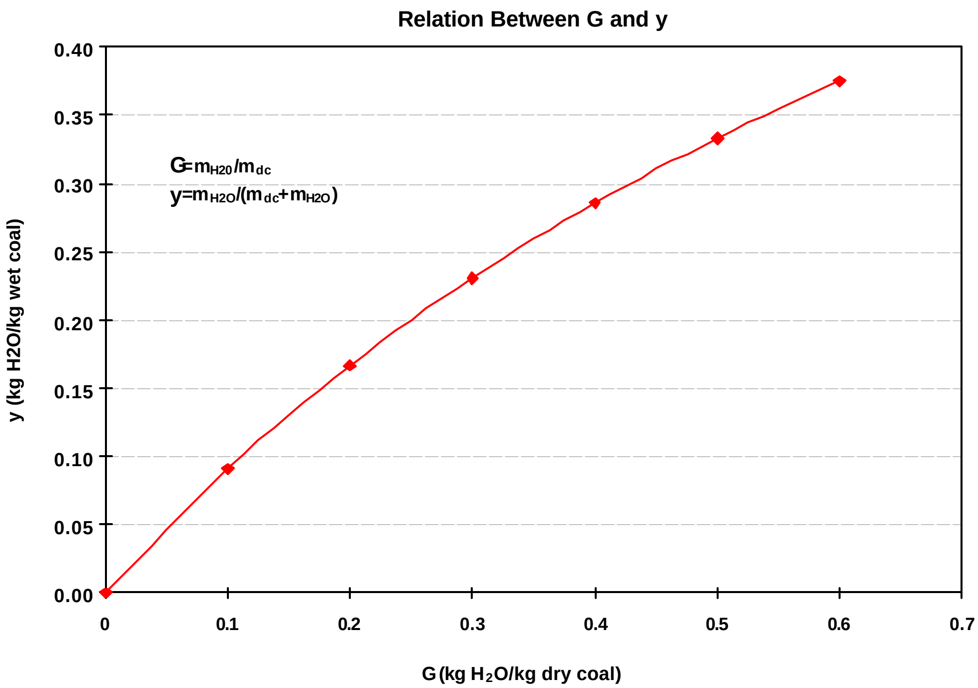

Figure 8: Relationship Between Γ and y

Repeatability and Data Consistency. Figure 9 shows three data sets for the same temperature conditions [$T_{air\ in}$ = 43°C and $T_{TUBE\ WALL}$ = 43°C] and U_0 = 1.02 to 1.6 m/s. These data indicate the degree of repeatability of the drying tests.

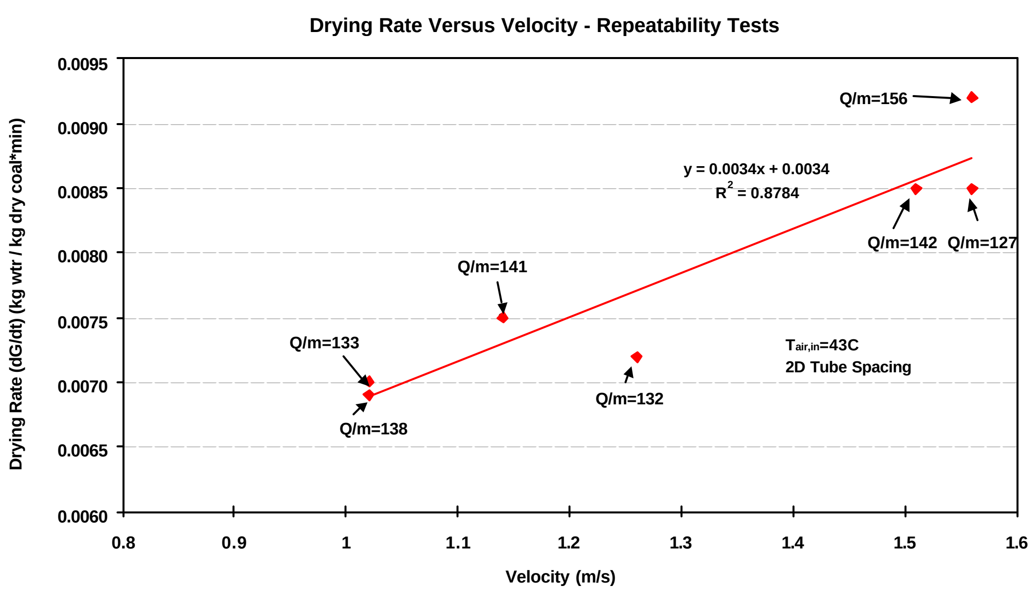

Figure 9: Drying Rate Versus Velocity – Repeatability Tests

Another way to assess the consistency of the data is to compare the measured values of moisture removed from the coal to the moisture added to the air. The mass balance for H_2O requires

$$m_{DC} \frac{d\Gamma}{dt} = -\dot{m}_{air} \left[w_{OUT} - w_{IN} \right]$$

where

ω = Specific Humidity of Air

Γ = Moisture Content of Coal $\left(\frac{\text{kg } H_2O}{\text{kg dry coal}} \right)$

$\dot{m}_{air}$ = Mass Flow Rate of Dry Air

m_{DC} = Mass of Dry Coal

$\dot{\Gamma}$ = $\frac{d\Gamma}{dt}$ = drying rate

Figure 10 compares $\dot{\Gamma}$ based on coal moisture measurements to $\dot{\Gamma}$ based on air moisture measurements. The 45° line indicates perfect agreement. The data show a small bias which ranges from approximately 9 percent at low drying rates to 3 percent at high drying rates.

Drying rate results for lignite are summarized in Figure 11, which shows the drying rate as a function of velocity, for four different particle sizes. The results show the drying rate increased with air velocity, but, 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, but not by particle size.

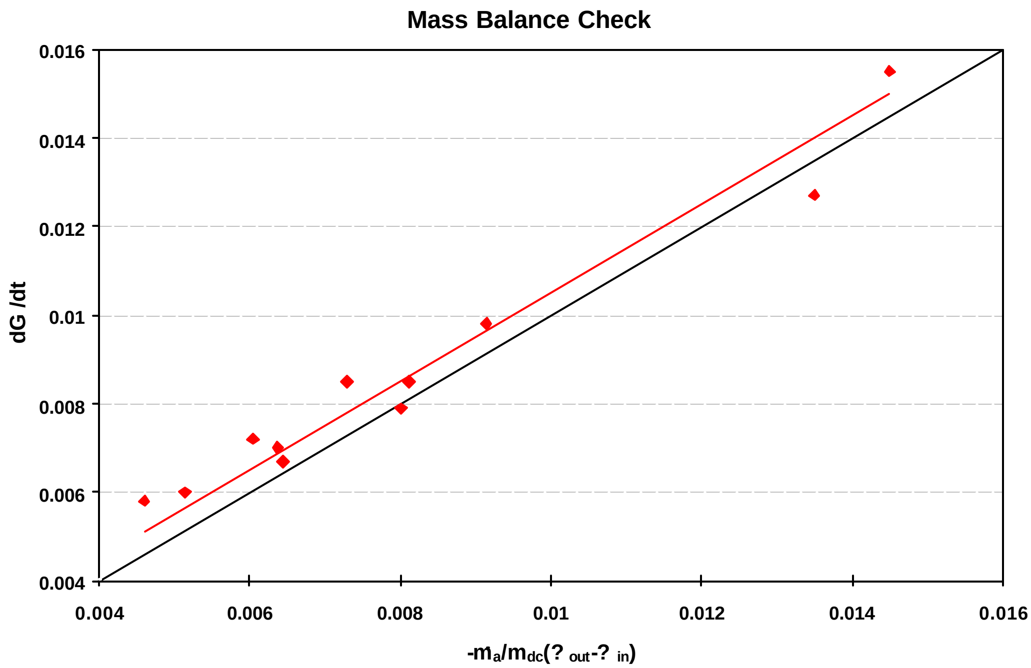

Figure 10: Mass Balance Check

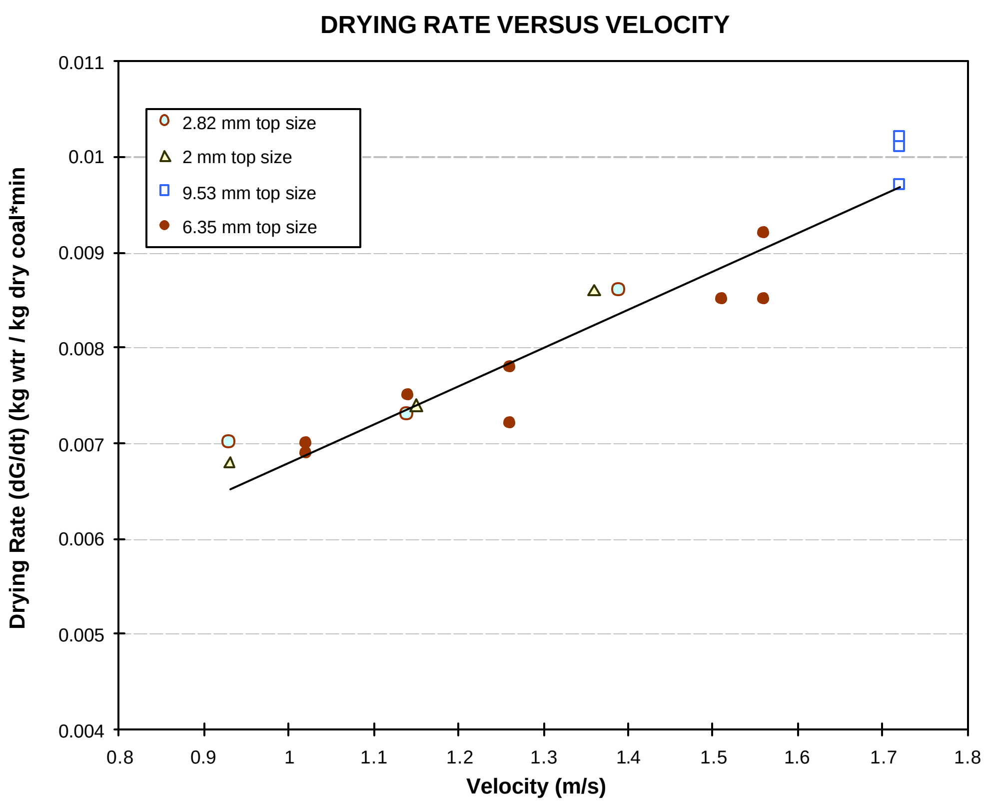

Figure 11: Drying Rate as a Function of Superficial Air Velocity and Particle Size

As to be expected, drying rate is also a strong function of temperature. Figure 12 compares drying rates of lignite and PRB coal for bed and inlet air temperatures ranging from 43 to 66°C. Both coals experienced a rapid increase in drying rate with increase in temperature.

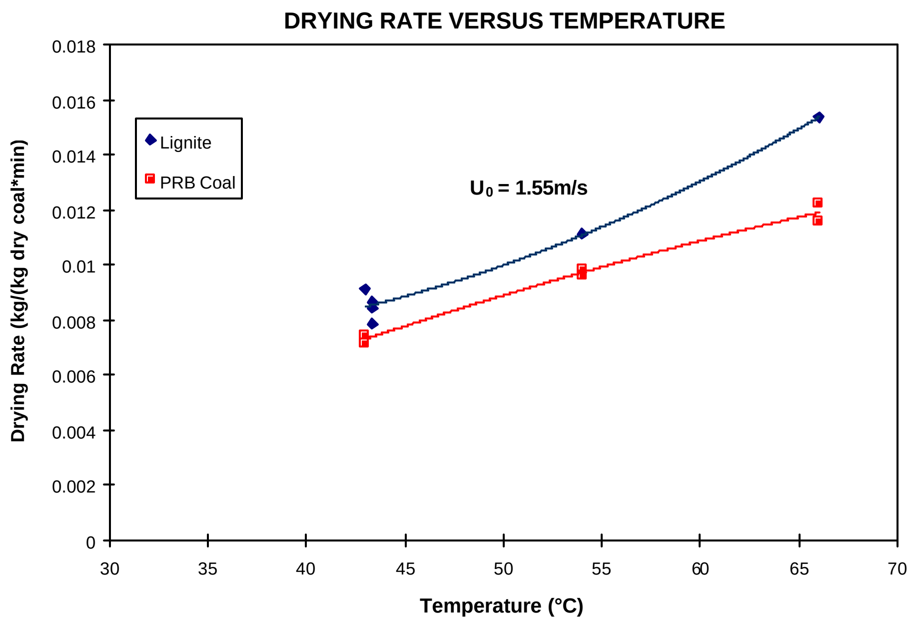

Figure 12: Effect of Bed and Inlet Air Temperature on Drying Rate

The relative humidity of air in equilibrium with coal can be expressed as a function of the coal moisture content, Γ (Reference 2). Treybal (Reference 3) presented adsorption data which are correlated well by

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

where T is absolute bed temperature and ϕ is relative humidity. As is seen in Figure 13, this gives a good fit of the data, with a relatively small scatter band.

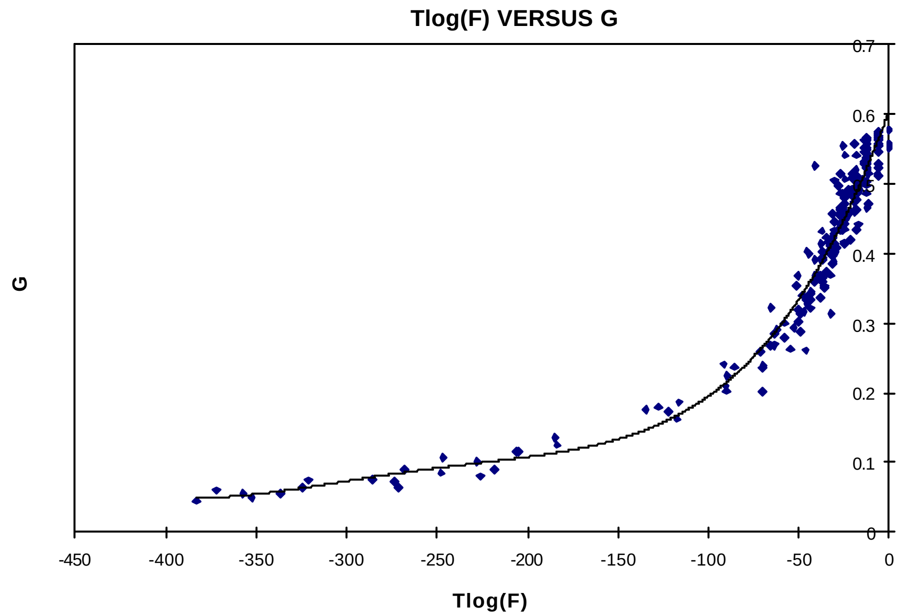

Figure 13: Equilibrium Relative Humidity of Air Versus Moisture Content of Lignite

Drying Rates with PRB Coal. The experiments with PRB coal showed a behavior very similar to that of lignite. Figure 14 shows the effect of superficial air velocity on the drying curves for a PRB coal. These tests were run with constant inlet air and heater temperatures and inlet air specific humidity; and all of them show typical drying behavior of an initial constant slope (or initial drying rate), followed by a decreasing rate of drying. The results also show that drying rate increased with increasing superficial velocity (U_0). Figure 15 summarizes the effect of U_0 on initial drying rate, $\dot{\Gamma}$, for 43° and 66°C drying temperatures.

PRB and lignite drying curves are compared for one set of process conditions in Figure 16 and a comparison of drying rates was shown in Figure 12 as a function of drying temperature.

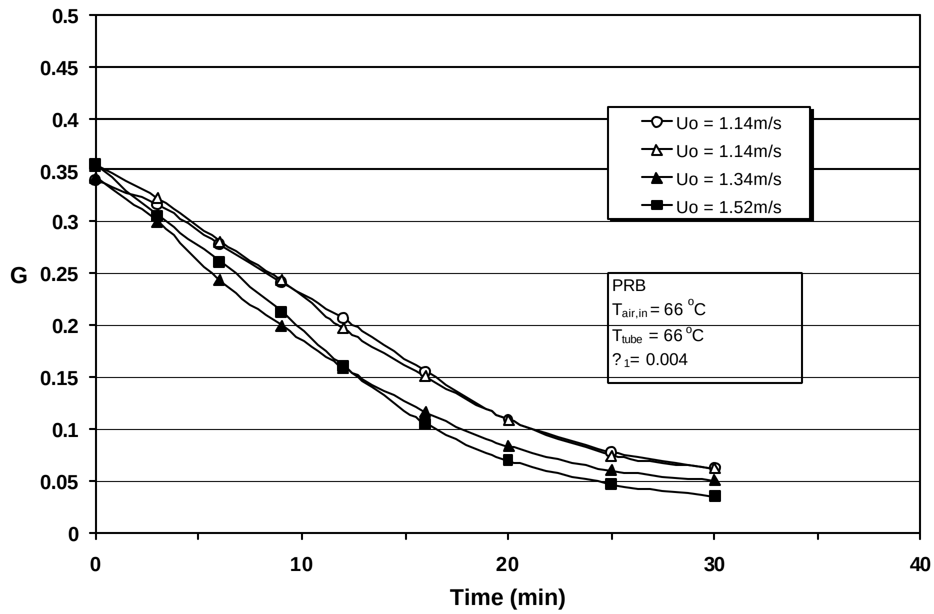

Figure 14: Moisture Content Versus Time – PRB Coal

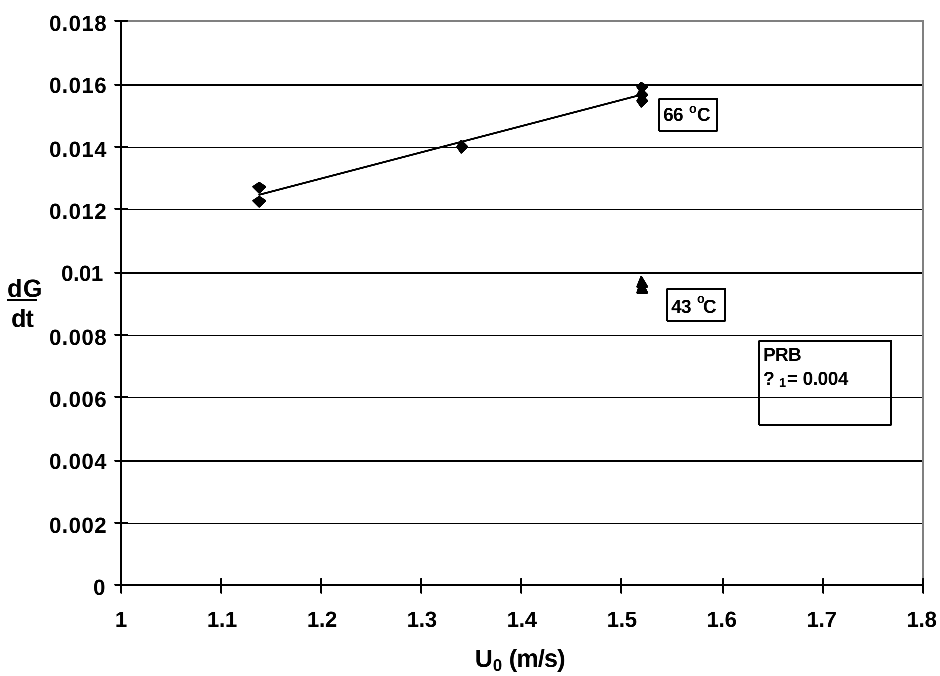

Figure 15: Drying Rate Versus Velocity – PRB Coal

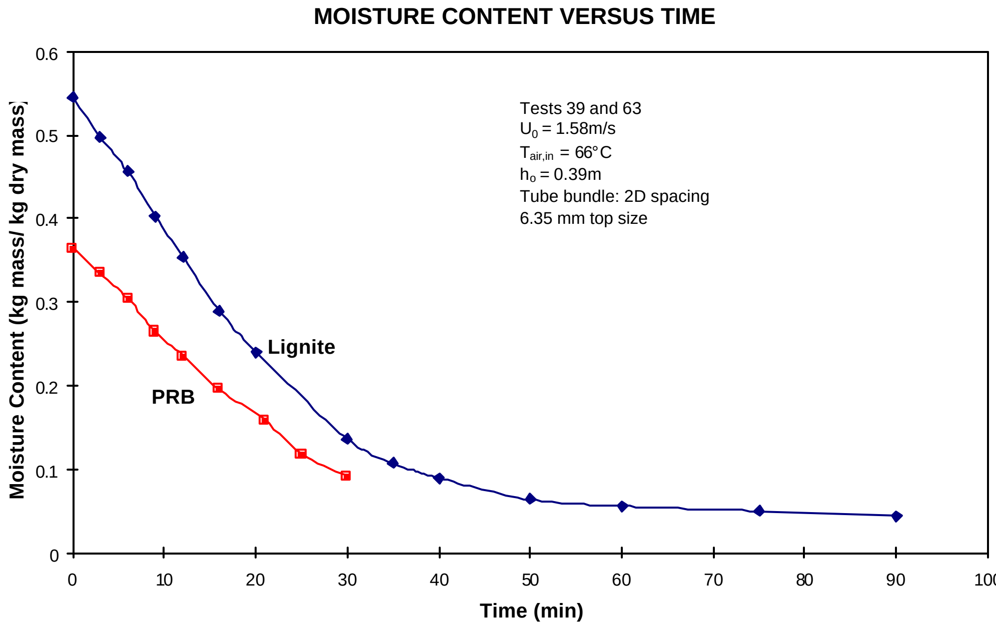

Figure 16: Comparison of Drying Curves for Lignite and PRB Coals for a 66°C Drying Temperature

Figure 17 gives the relations between equilibrium coal moisture, relative humidity of air and temperature for both lignite and PRB coals. These results show that the equilibrium relation does depend on coal type and this is important since the mathematical models for drying described later in this report require a relation for $\Gamma = \Gamma(f, T)$.

Effect of Inlet Air Humidity on Drying Rate. A series of tests was performed with both lignite and PRB to determine the effects of inlet air moisture on the drying kinetics. With these experiments, steam was injected into the inlet air to the dryer to raise the specific humidity of the inlet air (ω_1) to values greater than those leaving the compressor. The values of ω_1 ranged from 0.004 to 0.024. The lower value of ω_1 corresponds to ambient air at temperatures near freezing. An ω_1 of 0.024 occurs at 90% relative humidity and a dry bulb temperature of 30°C.

Figure 18 shows the effect of ω_1 on the drying curves for 3 tests with PRB coal with a drying temperature of 43°C. These clearly show a reduction in drying rate with increasing ω_1. With less evaporation occurring, the heat input to the bed results in an increase in bed temperature (Figure 19). The relative humidities of the air leaving the bed (Figure 20) show that during the latter stages of the drying process the air is closer to saturation with high ω_1.

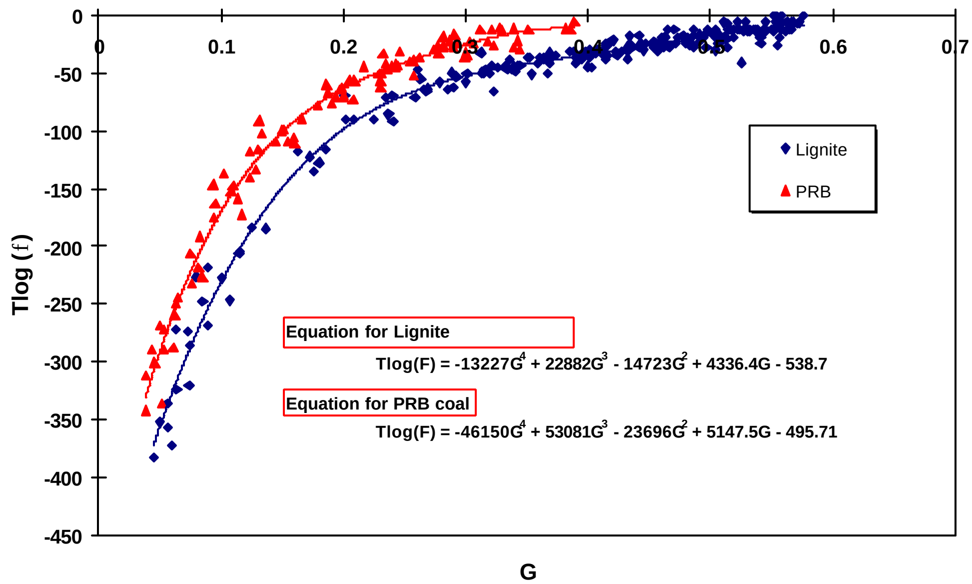

Figure 17: Γ Versus Tlog (ϕ) – Equilibrium Coal Moisture

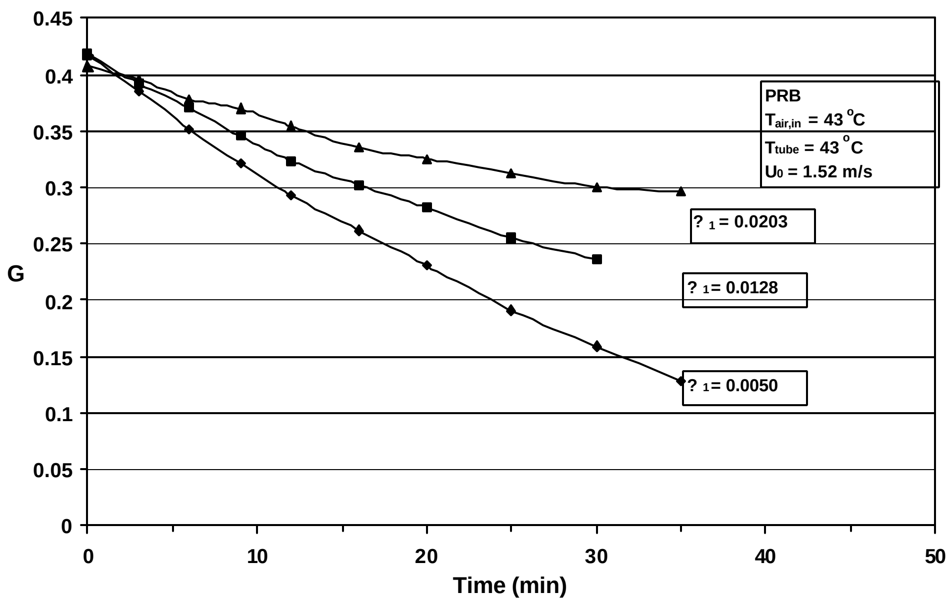

Figure 18: Coal Moisture Content Versus Time – PRB

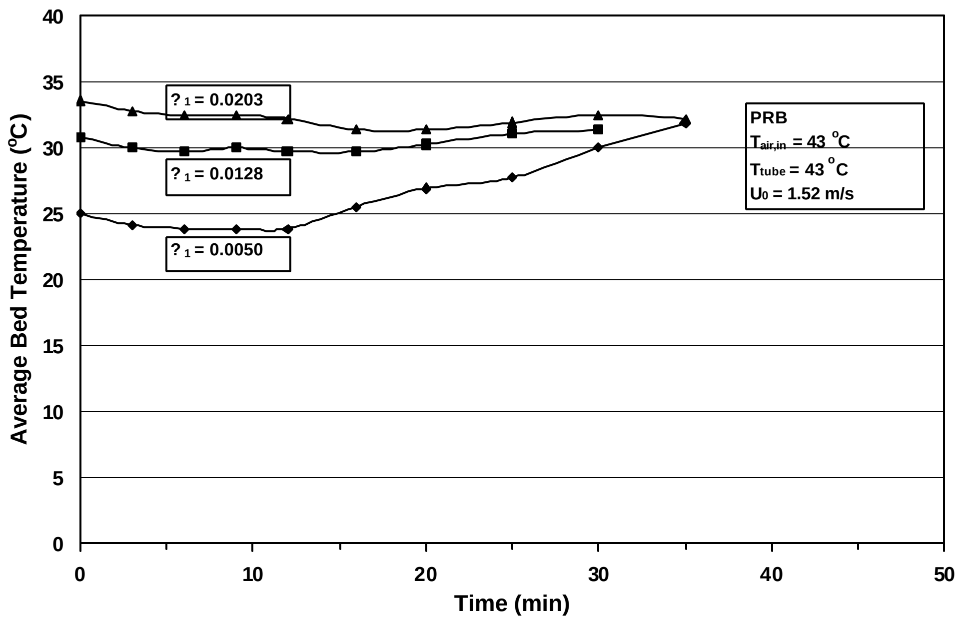

Figure 19: Bed Temperature Versus Time – PRB

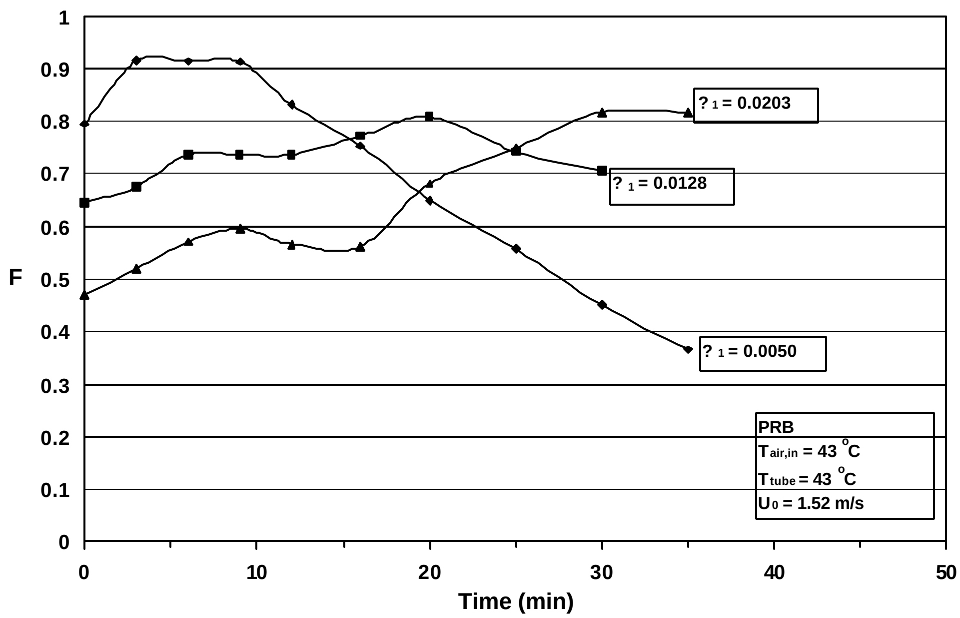

Figure 20: Relative Humidity Versus Time – PRB

Figure 21 summarizes the effects of inlet specific humidity on PRB drying rates for 43 and 66°C inlet air temperatures. At 43°C, the drying rate decreased by 60 percent as the inlet air humidity went from 0.005 to 0.022 (kg H_2O/kg dry air). At 66°C, the reduction in drying rate was 31 percent over the same range of inlet humidities.

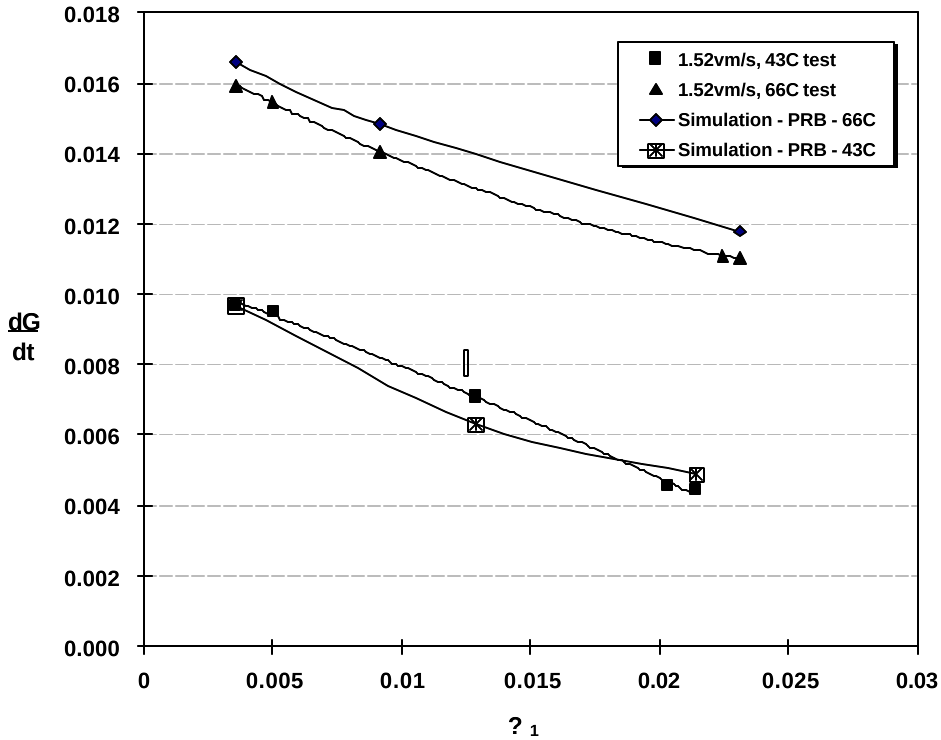

Figure 21: Drying Rate Versus Inlet Humidity – PRB

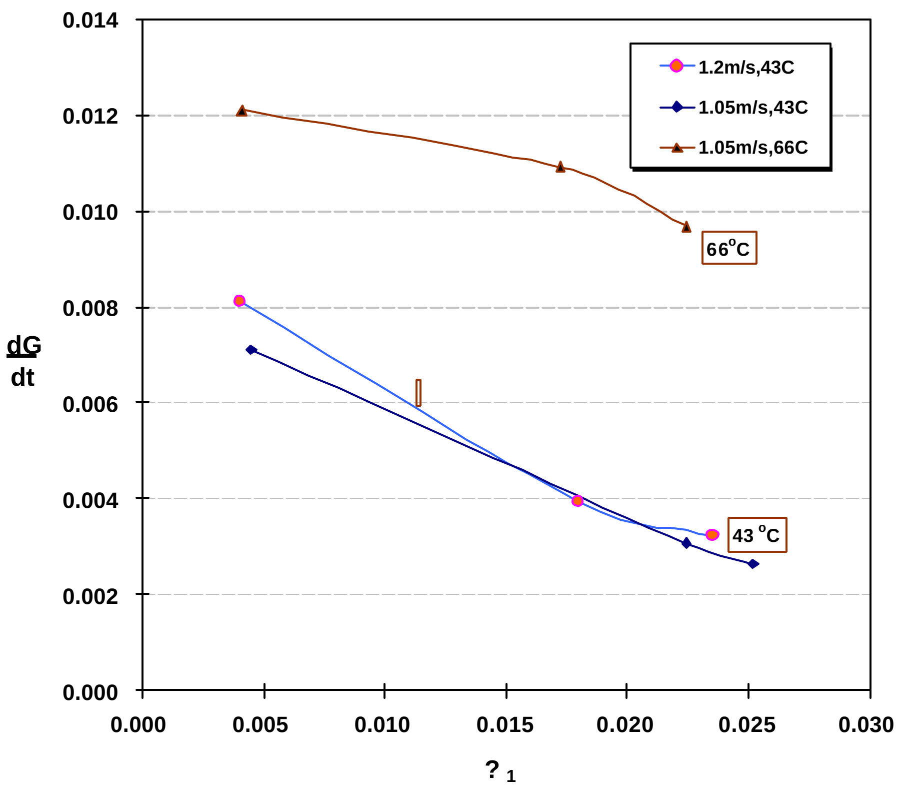

Figure 22: Drying Rate Versus Inlet Humidity – Lignite

Figure 22 shows lignite drying behavior with variations in inlet air humidity and drying temperature. Similarly to the PRB, lignite dries more rapidly with lower ω_1, and the effects of inlet air moisture on drying rate are more pronounced at lower drying temperatures.

Theoretical Model of Drying Process

The equilibrium moisture content-relative humidity relationship, described in Figure 13 was used, along with the equations of conservation of mass and energy, to develop a first principle model of the drying process. The model assumes at any instant of time, the particles and air in the bed are at the same temperature and the gas and particle properties do not vary with vertical distance in the bed. Thus for the batch bed drying process illustrated in Figure 23, conservation of mass and energy can be written:

$$\frac{d\Gamma}{dt} = -\frac{\dot{m}_a}{m_{DC}}\left(w_2 - w_i\right) \qquad \text{Eq. 1}$$

$$\dot{Q}_{TUBES} - \dot{Q}_{LOSS} = m_{DC}\left[\left(C_C + \Gamma C_L\right)\frac{dT_2}{dt} + u_L\left(-\frac{\dot{m}_a}{m_{DC}}\right)\left(w_2 - w_1\right)\right] + \dot{m}_a\left[C_{pa}\left(T_2 - T_1\right) + w_2 hg_2 - w_1 hg_1\right] \qquad \text{Eq. 2}$$

Specific humidity, ω, can be related to relative humidity ϕ and air temperature T, by

$$w = \frac{0.622\, f\, P_{sat}(T)}{P - f\, P_{sat}(T)} \qquad \text{Eq. 3}$$

while the relative humidity is an empirical function of coal moisture Γ (Figure 13).

In addition, the tube bundle heat transfer rate is

$$\dot{Q}_{TUBE} = UA\left(T_{TUBE} - T_{BED}\right) \qquad \text{Eq. 4}$$

and the parameters P_{sat} and hg are functions of air temperature.

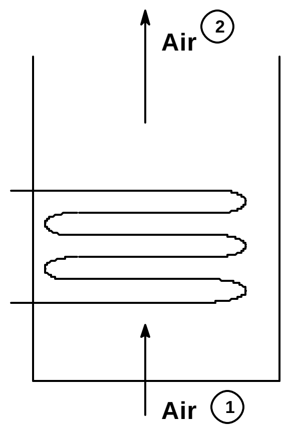

Figure 23: Sketch of Dryer Model

Equations 1 to 4 form a system of ordinary differential equations for coal moisture Γ and bed temperature T_2 as functions of time t. This was treated as an initial value problem and solved by a Runge Kutta numerical integration scheme.

Figures 24 to 27 show a comparison of the model with one set of drying data. The degree of agreement shown here is typical of the agreement obtained for the experiments with other bed operating conditions. The model is an equilibrium model and does not utilize information on bed bubbling behavior, particle-gas contacting nor mass transfer within the particle pores. For the range of fluidization conditions encountered in this process, a simple equilibrium model works very nicely.

Effect of Specific Humidity of Inlet Air on Equilibrium Moisture Curve

The data shown in Figure 13 and reproduced in Figure 28 were all obtained with relatively low inlet air specific humidities ($0.003<\omega_1<0.006$). Drying tests performed with low and high inlet air specific humidities showed the equilibrium coal moisture-relative air humidity relationship also depends slightly on the inlet air specific humidity (ω_1).

To avoid errors due to change in the character of the coal, these tests were performed using lignite from the same barrel, where the moisture content of the inlet air was alternated between low and high values in successive tests. The resulting equilibrium moisture relationships for lignite are shown in Figure 29. These show distinct equilibrium moisture curves for three inlet air humidity levels (ω_1 = 0.003, 0.01 and 0.020 to 0.025).

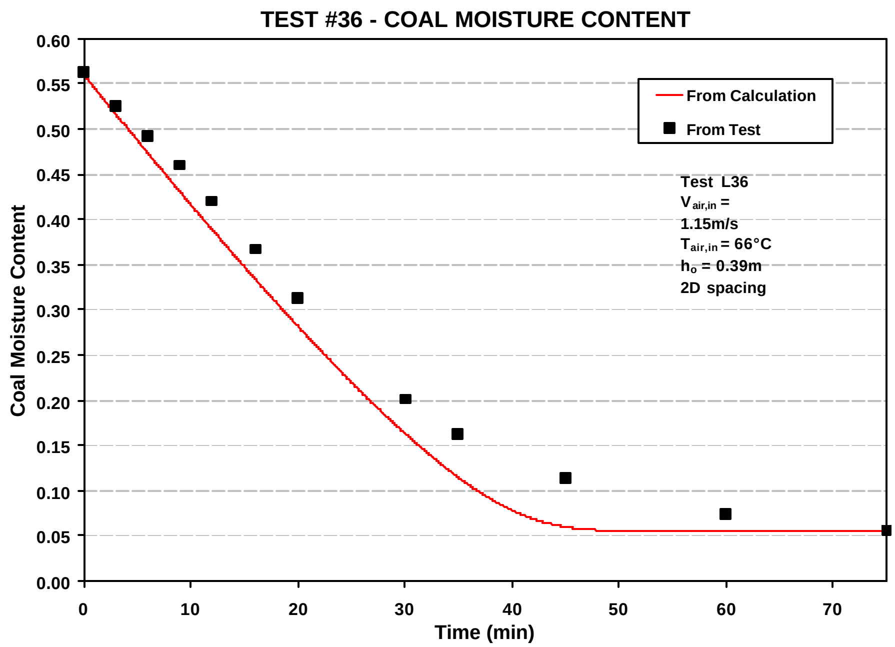

Figure 24: Lignite Drying Curve for Test 36 – Comparison Between Theory and Experiment

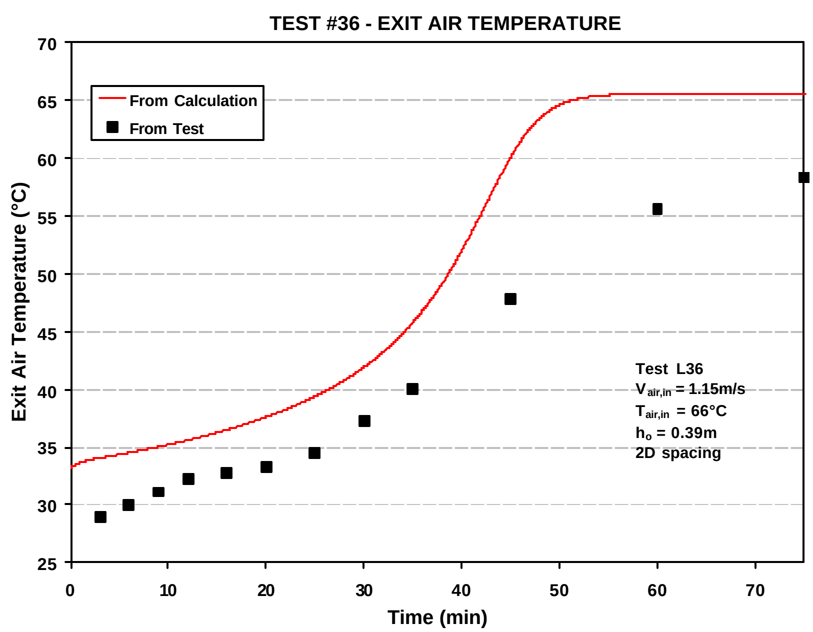

Figure 25: Exit Air Temperature for Test 36 – Comparison Between Theory and Experiment

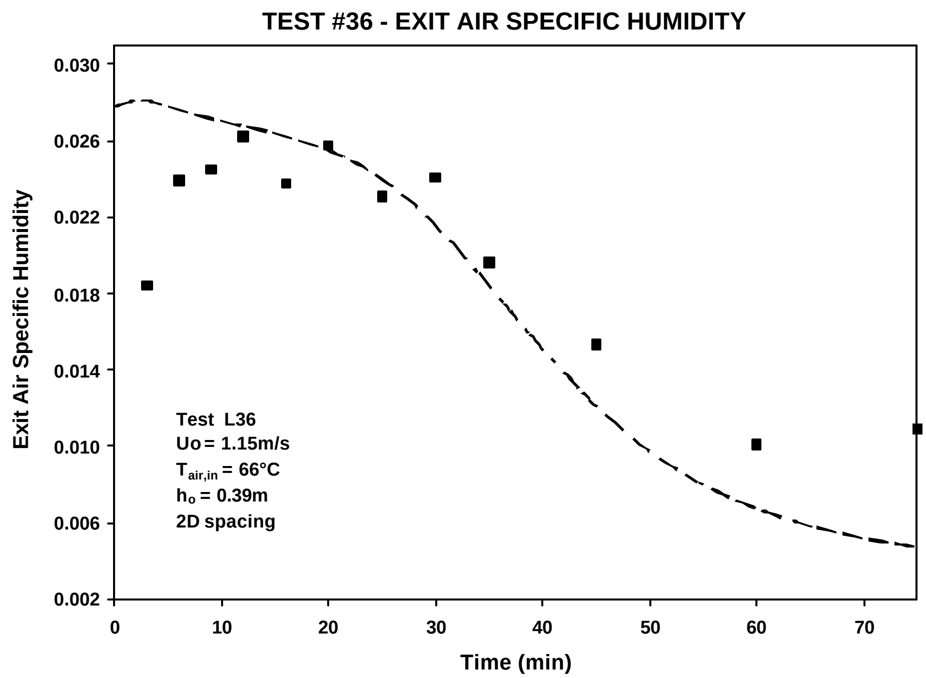

Figure 26: Exit Air Specific Humidity for Test 36 – Comparison Between Theory Experiment

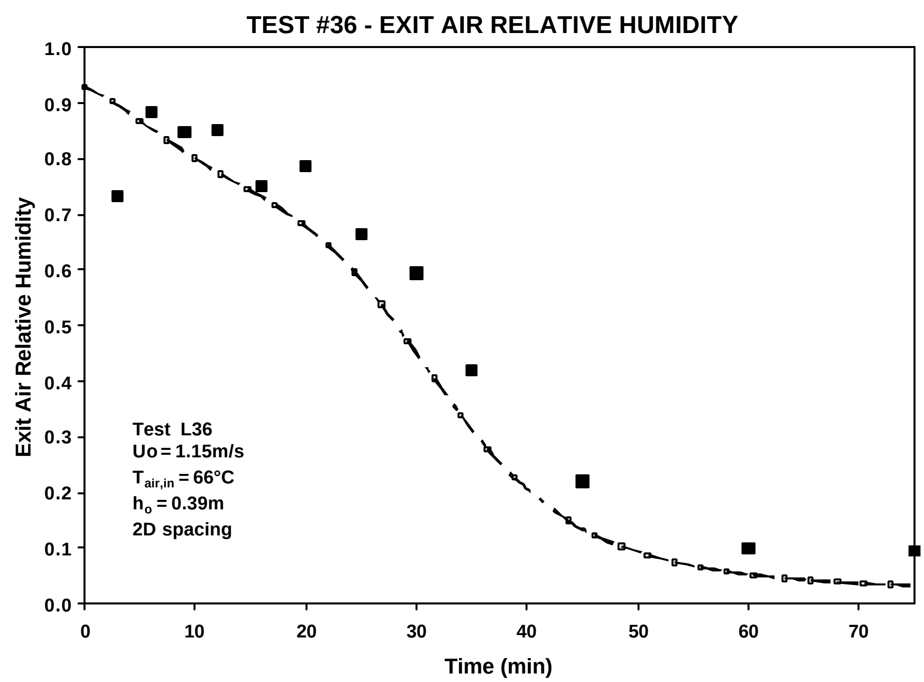

Figure 27: Exit Air Relative Humidity for Test 36 – Comparison Between Theory and Experiment

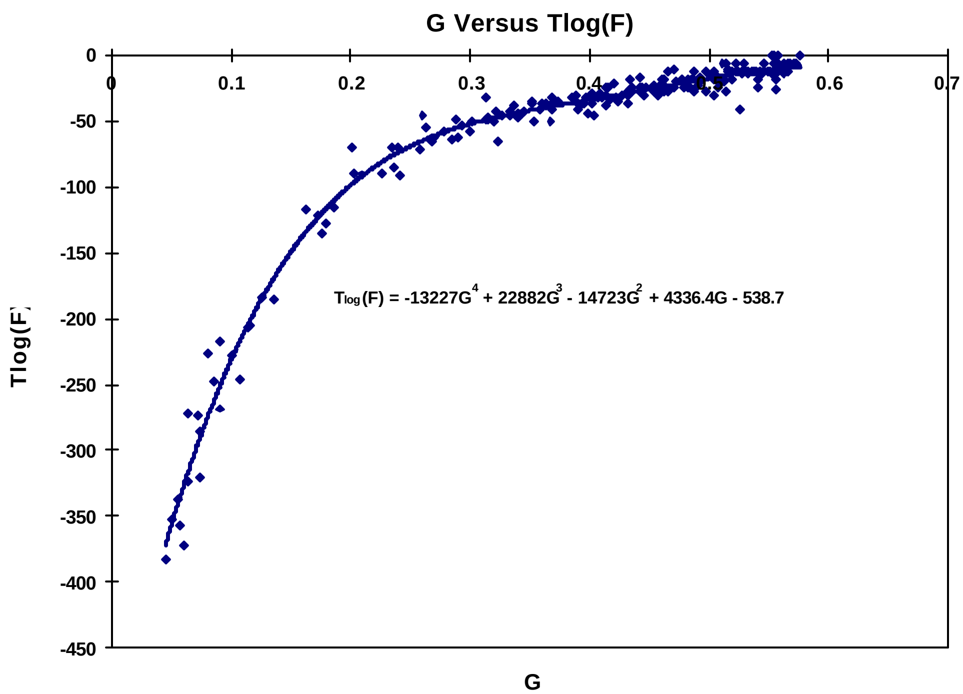

Figure 28: Equilibrium Moisture Curve for Lignite Based on Data Obtained with Low Inlet Air Specific Humidity

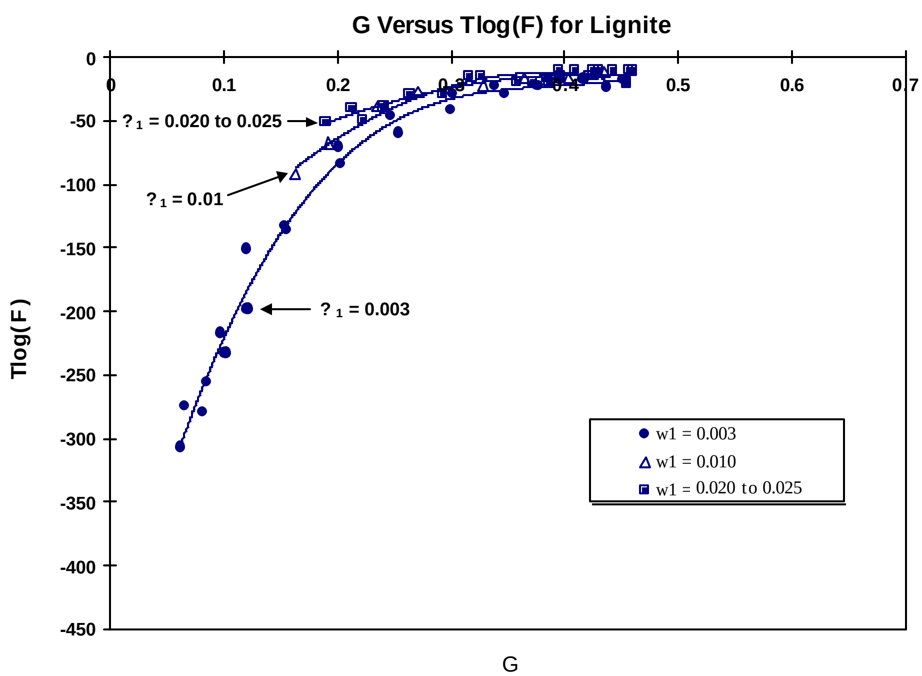

Figure 29: Effect of Inlet Air Specific Humidity on Equilibrium Moisture Curve

Calculations using the drying model were then performed to determine the effect of the choice of equilibrium moisture model on predicted values of Γ, ϕ, T and ω_2.

The conclusion from these analyses for lignite is that the choice of equilibrium moisture model does not significantly affect the computed values of coal moisture, exit air temperature or specific humidity, but it does affect computed exit air relative humidity. For best prediction accuracy for ϕ, it is thus recommended that equilibrium moisture data be used which has approximately the same inlet air specific humidity as the conditions to be modeled.

Of the coals tested, the sensitivity of the equilibrium moisture model to inlet humidity level was limited to lignite. Similar tests with PRB coal show no significant dependence of the equilibrium moisture model on inlet air specific humidity (Figure 30).

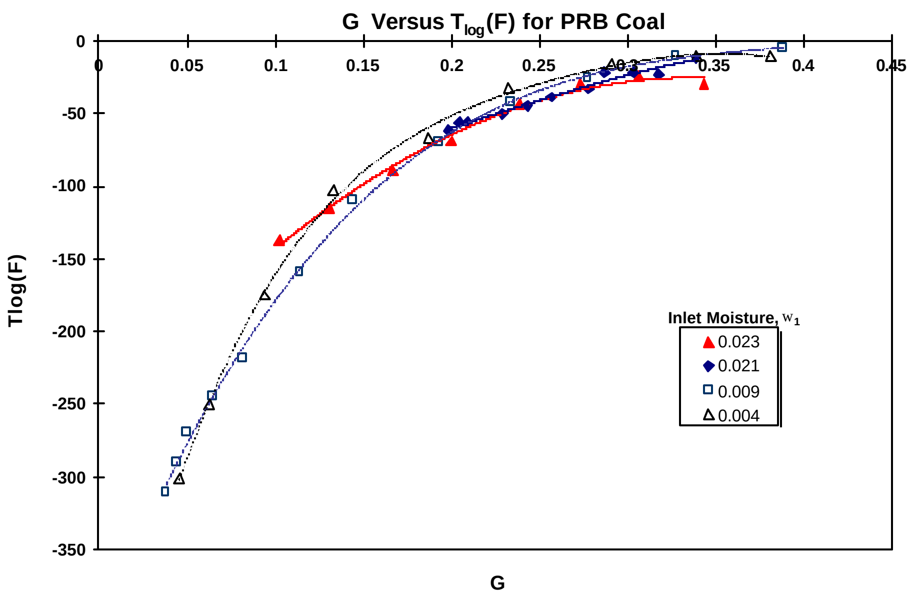

Figure 30: Effect of Inlet Air Specific Humidity on Equilibrium Moisture Data for PRB Coal

Drying Model for Continuously Operating Dryer

Results obtained in the laboratory batch dryer showed the fluidized bed is well mixed in the vertical direction, the air temperature leaving the dryer is equal to the bed temperature, and coal drying rate can be accurately predicted using a system of differential equations involving conservation of mass and energy along with an empirical expression relating equilibrium coal moisture to bed temperature and relative humidity of the air leaving the bed. This same approach was used to derive a system of equations which describe drying in the continuous flow dryer shown schematically in Figure 31. Wet coal is fed to the bed at X=0. Some is elutriated near the feed point and is carried out of the bed by the fluidizing air. The remainder flows along the bed in the X direction and is discharged at X=L. Energy for drying is supplied by the elevated temperature of the fluidizing air and by a tube bundle carrying hot fluid which is immersed in the bed.

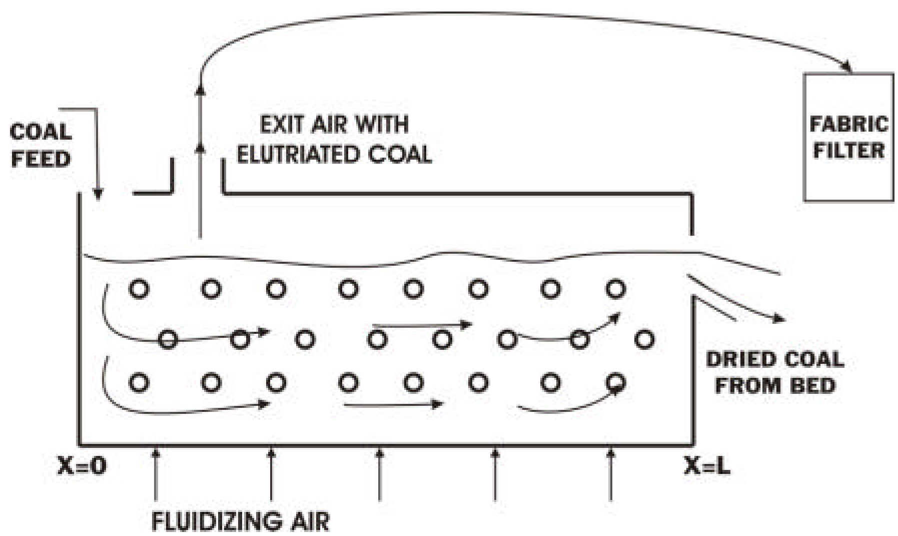

Figure 31: Sketch of Continuous Flow Dryer

The resulting system of equations is given by

conservation of mass

$$\frac{d\Gamma}{d\xi} = -\frac{\dot{m}_{air}}{\dot{m}_{DC}}\left[\omega_2 - \omega_1\right] \tag{5}$$

and conservation of energy

$$\frac{dT_2}{dx} = \left\{ h_L \frac{\dot{m}_{air}}{\dot{m}_{DC}}\left(w_2 - w_1\right) + \frac{Q_{TUBE}}{\dot{m}_{DC}} - \frac{\dot{m}_{air}}{\dot{m}_{DC}}\left[Cp_a\left(T_2 - T_1\right) + w_2\, hg_2 - w_1\, hg_1\right]\right\} / \left(C_C + GC_L\right) \tag{6}$$

where ξ = X / L

L = Length of Bed

X = Horizontal Distance from Inlet of Bed

$\dot{m}_{DC}$ = Mass Flow Rate of Dry Coal

$\dot{m}_{air}$ = Mass Flow Rate of Dry Air

Γ = Coal Moisture Content on Dry Basis $[kg\ H_2O\ /\ kg\ dry\ coal]$

ω = Specific Humidity

Q_{TUBE} = Rate of In-Bed Heat Transfer

T_1 = Inlet Temperature of Air

T_2 = Bed Temperature and Exit Air Temperature

ϕ = Relative Humidity of Air Leaving Bed

Cp_a; C_c; C_L = Specific Heats

h_L = Enthalpy of Liquid H_2O

hg = Enthalpy of Saturated Vapor

subscript 1 = Air or Coal Entering Bed

subscript 2 = Air or Coal Leaving Bed

The relation between coal moisture and temperature and relative humidity of air leaving the bed $\Gamma = f(T_2 \log \phi)$ is given graphically in Figure 17 for North Dakota lignite and PRB coals.

Equations 5 and 6 show that for given values of inlet coal temperature and moisture level and inlet air temperature and relative humidity, the solutions to the equations depend on $\frac{\dot{m}_{air}}{\dot{m}_{DC}}$ and $\frac{Q_{TUBE}}{\dot{m}_{DC}}$.

The term $\frac{Q_{TUBE}}{\dot{m}_{DC}}$ can also be written

$$\frac{Q_{TUBE}}{\dot{m}_{DC}} = U_o A_T \times DT_{avg} / \dot{m}_{DC}$$

where U_o = Overall Heat Transfer Coefficient

A_T = Tube Surface Area

ΔT_{avg} = Mean Temperature Difference Between In-Bed Coil and Bed

Comparisons of Drying Model and Pilot Dryer Data

Equations 5 and 6 were used to simulate various drying tests performed at Great River Energy's Coal Creek Station. These tests were run in a pilot scale lignite dryer with a nominal coal drying capacity of 30 kg/minute. Temperatures of fluidizing air and the in-bed tube bundle ranged from 50 to 70°C.

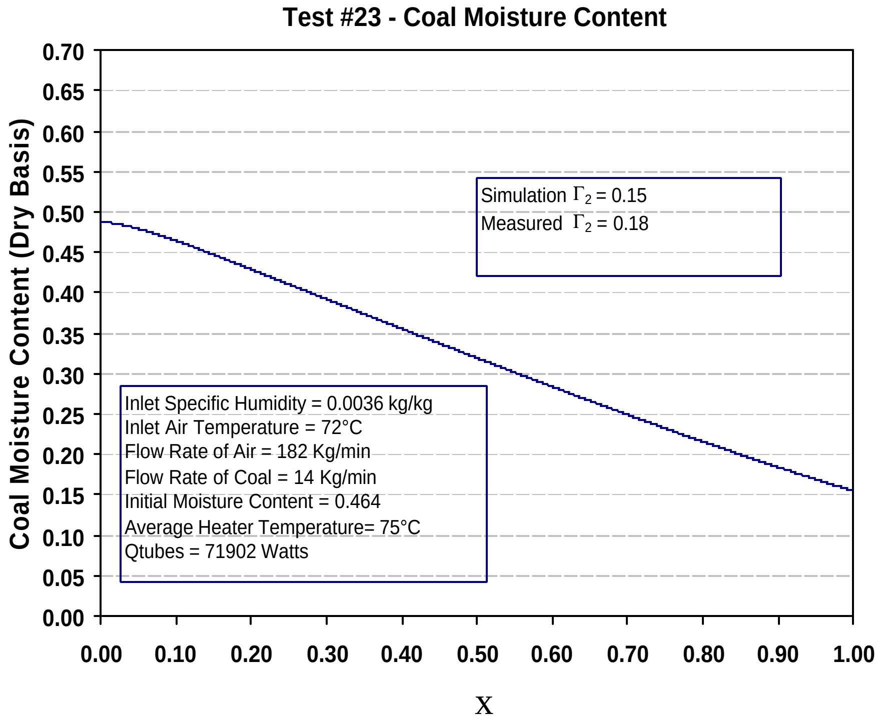

Figure 32: Axial Variation of Coal Moisture Content for Test #23.
(At ξ=1, Γ=0.15 from simulation and 0.18 from experiment.)

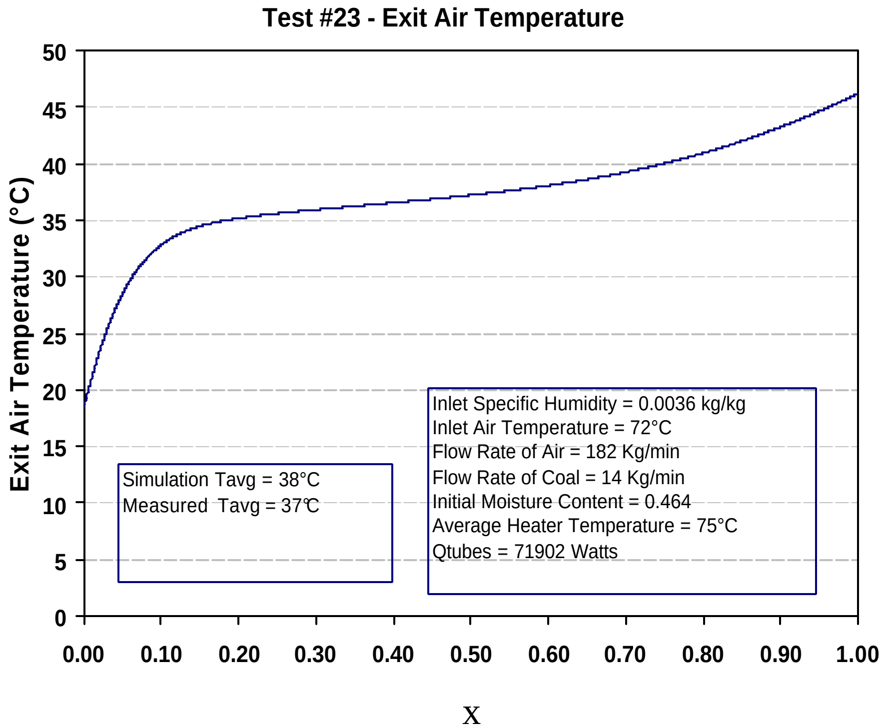

Figure 33: Axial Variation of Bed Temperature and Exit Air Temperature for Test #23. (Average Exit Air Temperature = 38°C from Simulation and 37°C from Experiment.)

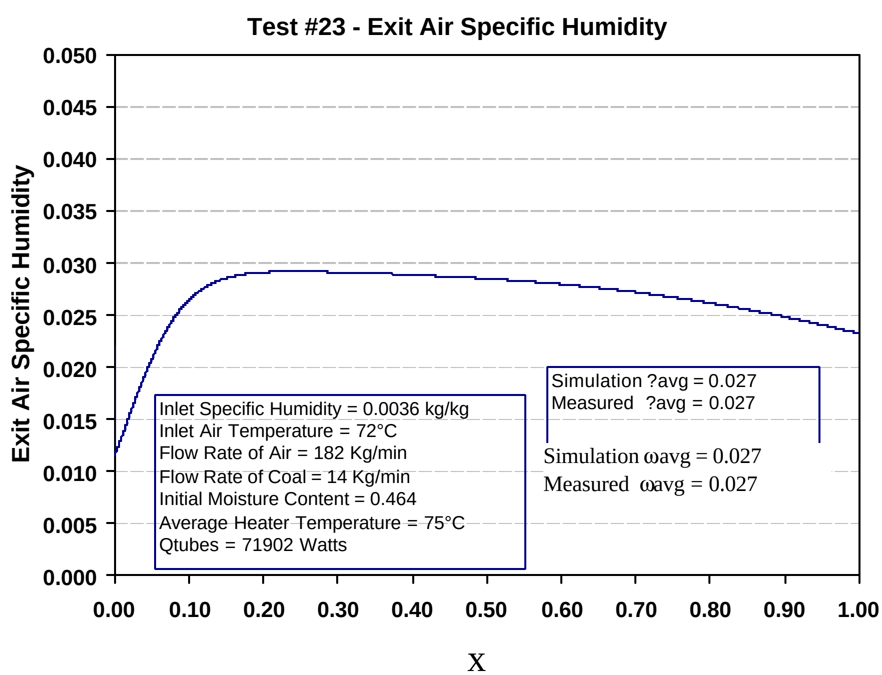

Figure 34: Axial Variation of Exit Air Specific Humidity for Test #23. (Average Exit Air Specific Humidity = 0.027 from Simulation and 0.027 from Experiment.)

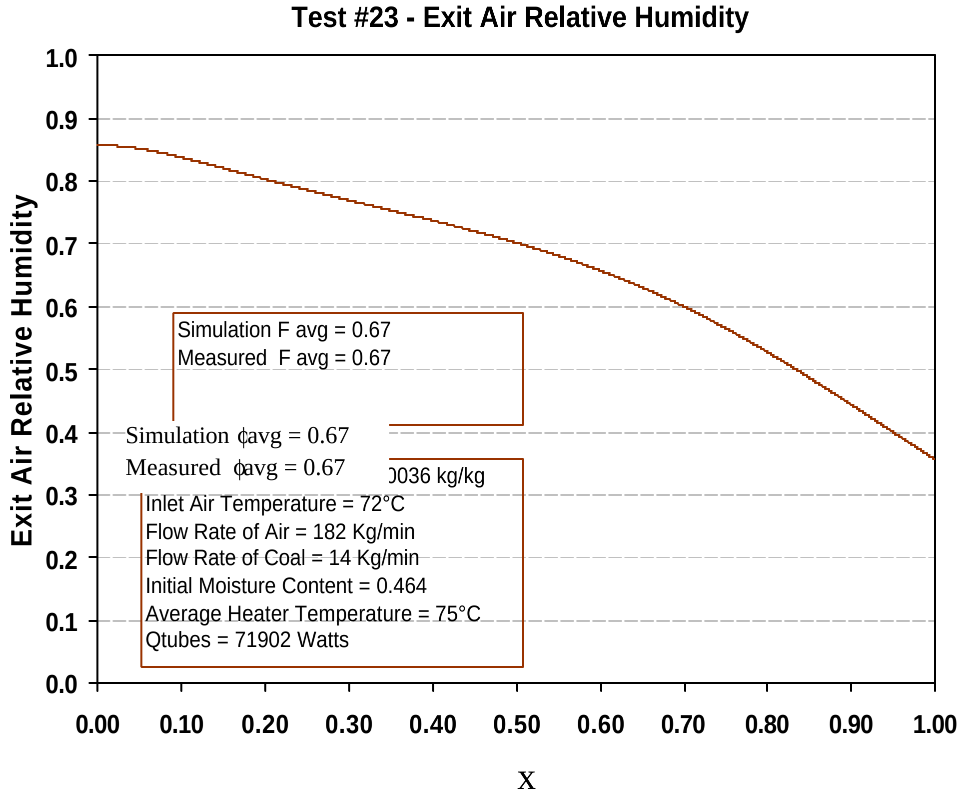

Figure 35: Axial Variation of Exit Air Relative Humidity for Test #23. (Average Exit Air Relative Humidity = 0.67 from Simulation and 0.67 from Experiment.)

Figures 32 to 35 show the results for one set of conditions, in which the axial variations of coal moisture from dryer inlet, X=0, to dryer exit, X=L, (or from $\xi = 0$ to $\xi = 1$), air temperature leaving bed, and specific humidity and relative humidity of air leaving the bed are plotted as functions of ξ.

The results show, for this range of drying conditions, coal moisture content, Γ, decreased nearly linearly with ξ, the exit air temperature increased with ξ after an initial adjustment for the inlet temperature of the coal, the relative humidity of exit air decreased with ξ, and the specific humidity either increased or decreased depending on axial variations in temperature and relative humidity.

Table 2 compares the measured and predicted results for four cases. Since the measurements for temperature and humidity are average values obtained from sensors in a duct downstream of the bed, the average values from the computer simulations were obtained by integrating air temperature and specific humidity from $\xi = 0$ to $\xi = 1$. The computed average values of relative humidity, ϕ, were obtained from the computed average values of T_{air} and ω, using a psychrometric chart.

Table 2

Comparison of Predicted and Measured Performance for Tests 4, 20, 23 and 30

TEST	G_1 - G_2		T_{air2} (avg) °C		ω_2 (avg)		ϕ_2 (avg) %	
	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted
4	0.175	0.151	25.5	26.0	0.0150	0.0144	72.5	68
20	0.134	0.217	33.5	36.7	0.0291	0.0284	86.89	70
23	0.300	0.335	36.9	37.8	0.0273	0.0276	66.7	67
30	0.107	0.150	30.2	33.3	0.0237	0.0242	86.1	72

Comparisons between measurements and predictions for the four tests are given in Figures 36 to 39. Figure 36 compares predicted and measured values of Γ_1 - Γ_2, where the scatter in the data probably reflects random sampling errors in both the Γ_1 and Γ_2 measurements. In addition to random error, Figure 36 also shows a bias error, with the predicted values of Γ_1 - Γ_2 being larger than the measured values by 10 to 15 percent.

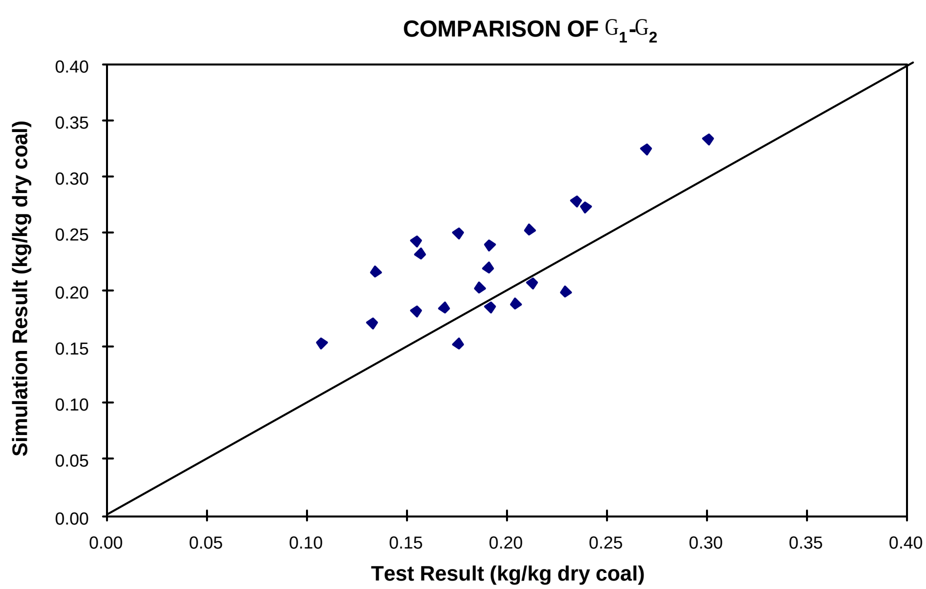

Figure 36: Comparison of Predicted Versus Measured Values – Change in Coal Moisture, (Γ_1 - Γ_2).

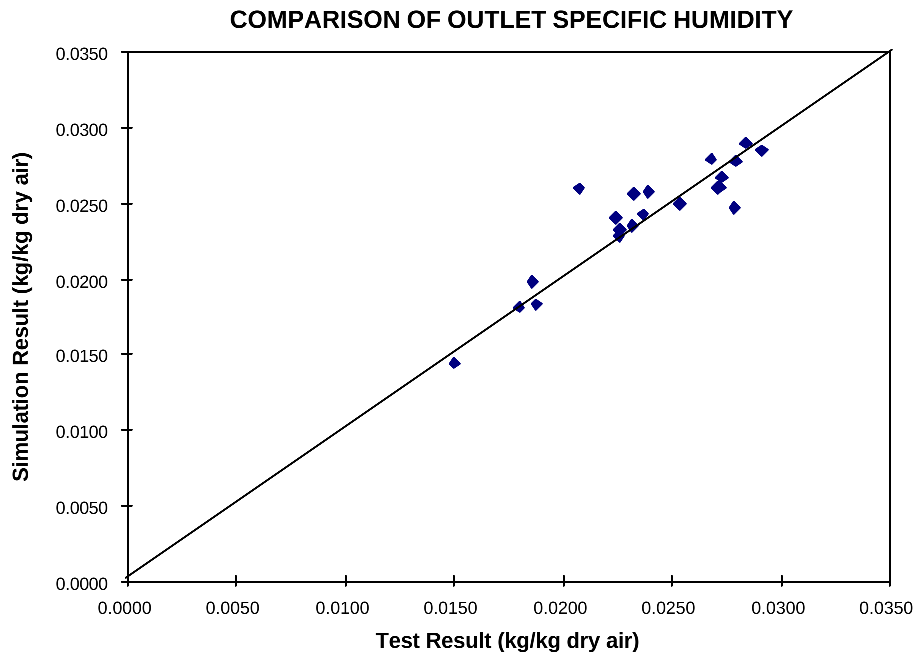

Figure 37: Comparison of Predicted Versus Measured Values – Average Outlet Specific Humidity

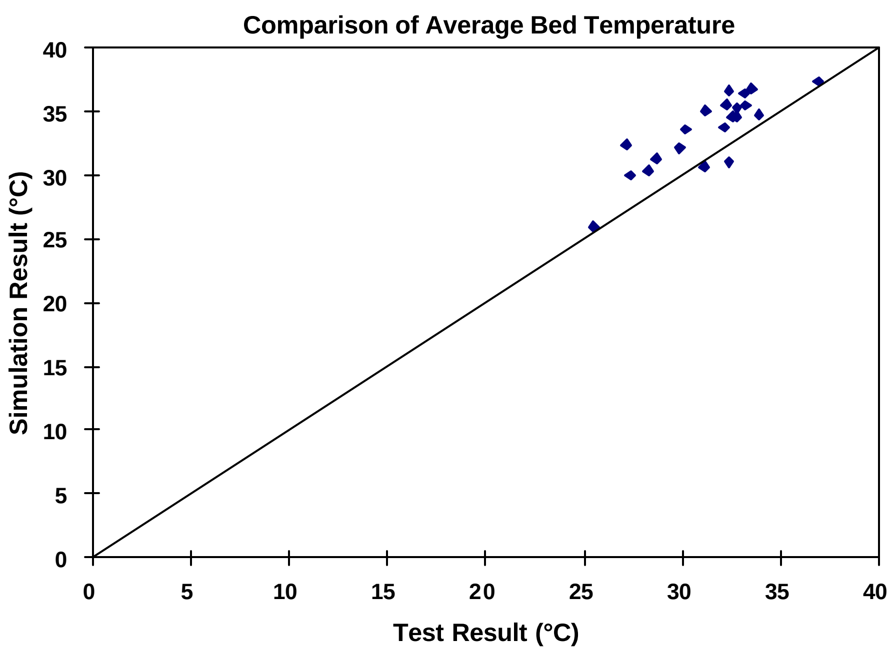

Figure 38: Comparison of Predicted Versus Measured Values – Average Bed Temperature and Exit Air Temperature

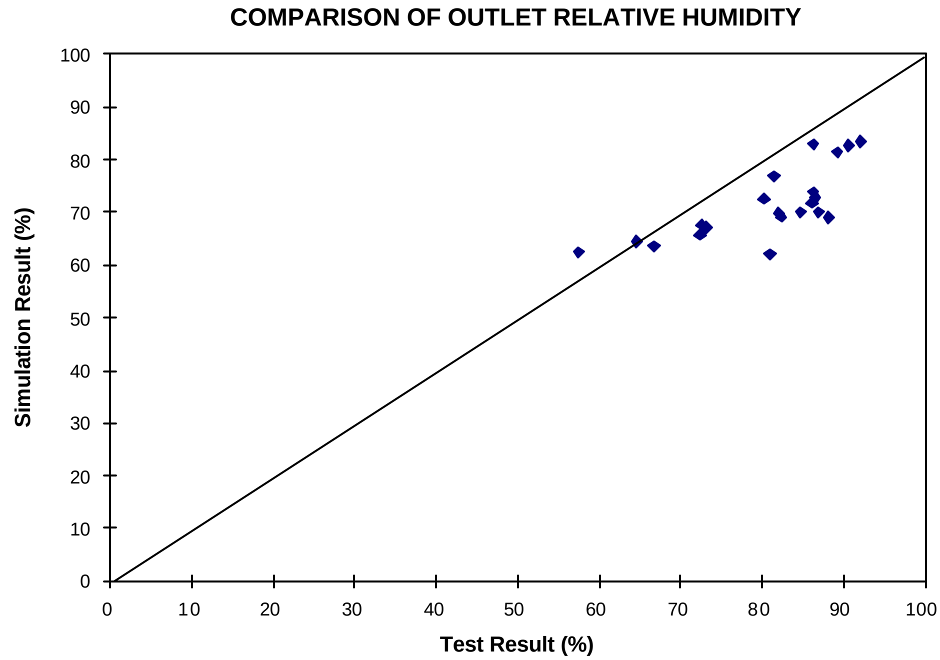

Figure 39: Comparison of Predicted Versus Measured Values – Average Outlet Relative Humidity

Figure 37, which compares measured to predicted specific humidity, shows excellent agreement between the two. Figures 38 and 39 indicate that, on average, the measured and predicted values of bed temperature differ by about 2.5°C and, on average, the measured and predicted values of relative humidity of the air leaving the bed differ by about 10 percent.

PART II – IMPACTS OF COAL DRYING ON UNIT OPERATIONS

INTRODUCTION

The second part of the project involved the design of drying systems for lignite and PRB coal-fired power plants and analysis of the effects of drying system operation on cooling tower makeup water, unit heat rate, auxiliary power and stack emissions.

Figure 40 shows the basic power plant configuration which was used in this study. The boiler is a balanced draft boiler with both forced draft (FD) and induced draft (ID) fans. A bi-sector type air preheater transfers thermal energy from the hot flue gas leaving the economizer to the relatively low temperature air leaving the FD fans. Waste heat from the steam condenser is carried by hot circulating water to an evaporative cooling tower, with cold circulating water being returned to the condenser.

Two drying system designs are described in this report. One, referred to in this report by the acronym, CCW, relies on waste heat extracted from the hot circulating water leaving the condenser for drying. This drying scheme, which is similar to that which was shown in Figure 1, involves fluidized bed dryers, where waste heat from the steam condenser is used to preheat the fluidization air and provide additional heat for drying using in-bed heat exchangers. Coal is fed to the dryers and is then transported with reduced moisture to the pulverizers before being conveyed to the burners by transport air. After leaving a dryer, the fluidization air must pass through a baghouse to remove elutriated coal particles. Besides the fan for the fluidization air, other equipment requiring station service power includes the coal crushers, pulverizers, and forced draft and induced draft fans.

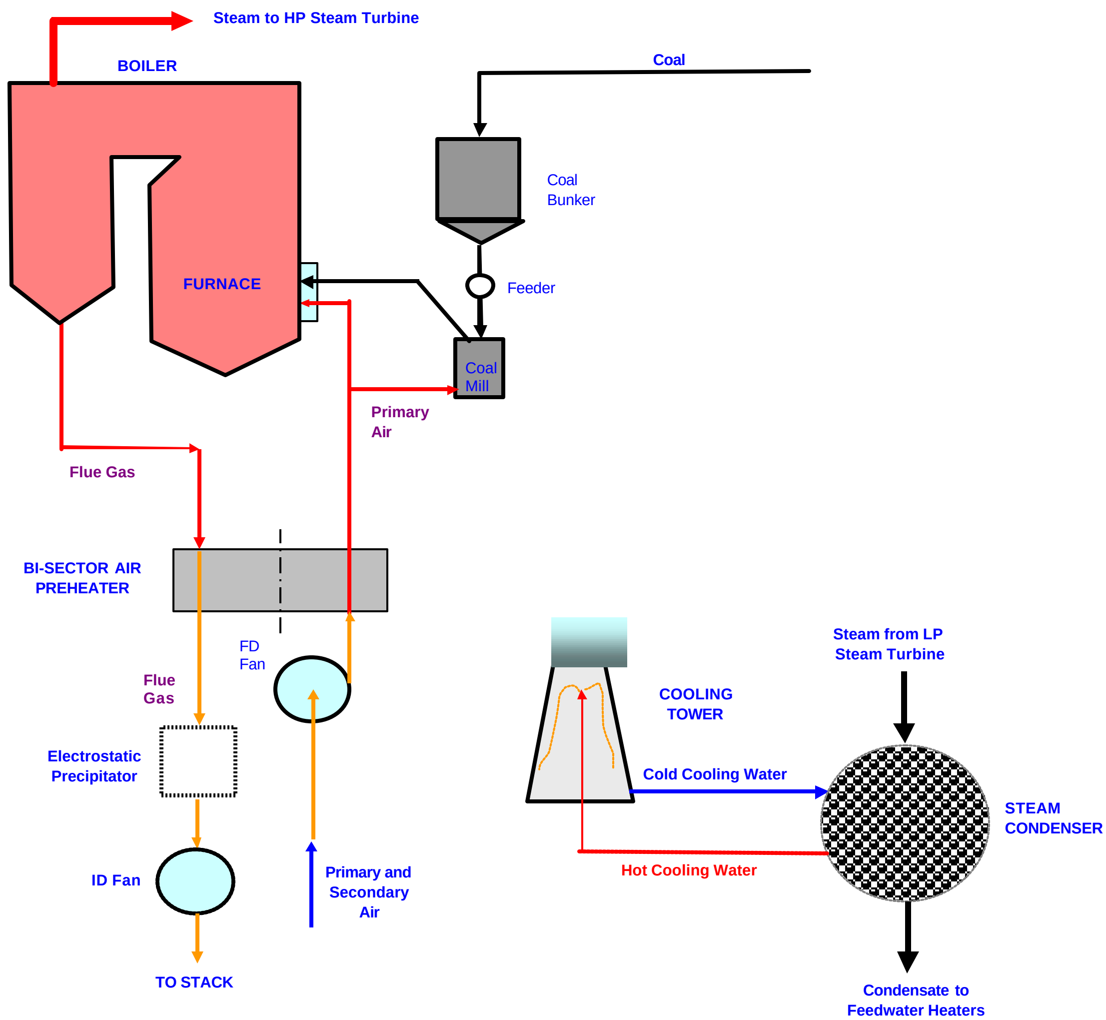

Figure 40: Basic Power Plant Configuration Used in Study

Since the steam condenser typically operates with steam temperatures in the vicinity of 49°C, the fluidization air and in-bed drying coil in the system illustrated in Figure 1 are limited to temperatures of about 43°C. The size of the dryer, flow rate of fluidizing air and the power required to drive the fluidizing air fan, are strong functions of dryer operating temperature.

The second type of drying system described here uses a combination of condenser waste heat and heat extracted from boiler flue gas to attain higher drying temperatures than are possible from condenser waste heat alone. This is referred to in this report by the acronym, CCW/FG (see Table 3).

Table 3

Drying Systems Analyzed

ACRONYM	HEAT SOURCE FOR DRYING
CCW	Hot Condenser Cooling Water
CCW/FG	Combination of Hot Condenser Cooling Water and Boiler Flue Gas

ANALYSIS METHODOLOGY AND ASSUMPTIONS

Fuel

A North Dakota lignite and a Powder River Basin coal were assumed as fuels. The as-received (wet, non-dried) fuels were assumed to be 38.5 percent moisture for lignite and 30 percent moisture for the PRB coal, where all moisture contents given in Parts II and III of this report are expressed as mass H_2O/mass wet coal. The as-received lignite has a higher heating value of 14,900 KJ/kg and the heating value of the PRB is 19,418 KJ/kg.

Dryer Design

Coal is fed to the dryer at one end, flows horizontally along the distributor and is then discharged at the downstream end (Figure 41). The mathematical dryer model described in Part I of the report was used to estimate required dryer size, flow rates of fluidizing air and amount of in-bed heat transfer as functions of drying temperature and coal product moisture.

Air Preheater (APH)

A bi-sector type APH was used for the analyses. The thermal performance of the bi-sector APH was modeled using the ε-NTU theory of heat exchangers and metal temperature software for APH analysis previously developed by the authors (Reference

4). This modeling approach allows accurate determination of outlet flue gas and air temperatures as the flow rates of flue gas and air through the APH vary.

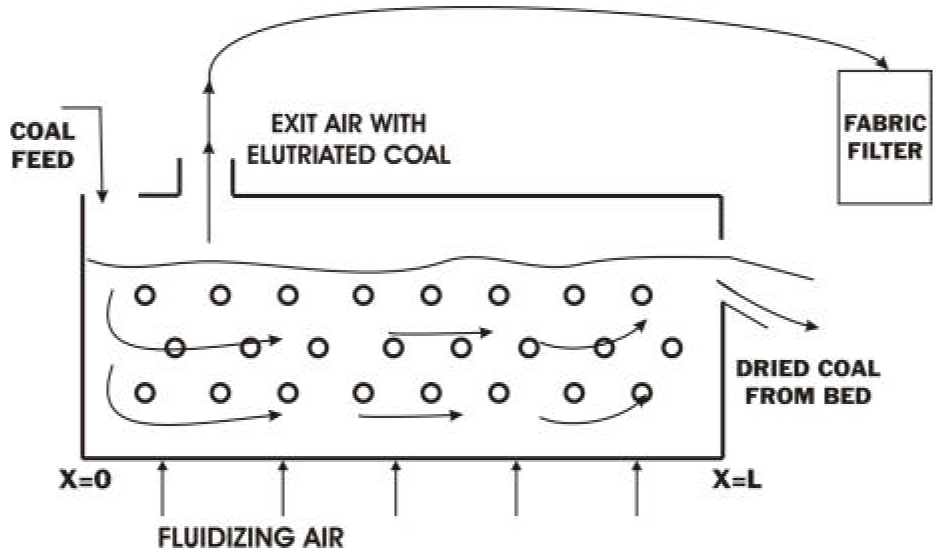

Figure 41: Sketch of Continuous Flow Dryer

Fan Power

Accurate calculation of fan power is essential in determining differences in performance between different system layouts. Fan power was calculated as per industry practice, using expressions for fan power from Reference 5. The assumed fan pressure rises were the following:

Forced Draft Fan (FD)	ΔP_{FD} = 18"	(457 mm) H_2O
Induced Draft Fan (ID)	ΔP_{ID} = 15"	(381 mm) H_2O
Fluidizing Air Fan (FA)	ΔP_{FA} = 50"	(1270 mm) H_2O

Mill Power

Mill power was calculated using software developed by the ERC for analysis of thermal performance of fossil-fired power plants (Reference 6), modified to account for the effect of drying on the energy requirement for grinding per ton of coal.

Pulverizer power requirements depend on the flow rate of coal through the pulverizers and the energy requirement for grinding per ton of coal. Coal drying results in a reduction in the energy requirements for grinding per ton of coal. This is illustrated in Figure 42a and 42b which summarize laboratory data from Reference 7 on the effect of feed moisture content on pulverizer specific power requirements for seven different lignites. These data show the power/ton of lignite feed varied linearly with coal moisture level, with the specific power at 20 percent moisture being 2/3 of the specific power at 40 percent moisture. Both the reduced coal flow rate and the reduction in grinding energy per ton of coal were taken into account in this analysis.

Combustion Calculations

Combustion calculations were also performed. The assumptions used in these calculations were the following:

Excess O_2 Level at Economizer Exit	= 3.50% by Volume
Unburned Carbon in Fly Ash	= 0.1% by Weight
CO Concentration in Flue Gas	= 10 ppm
Convection Pass Air In-Leakage	= 8 % by Weight
APH Air In-Leakage	= 10 % by Weight

In conducting the combustion calculations, a constant flue gas temperature of 825°F (441°C) at the economizer exit and an ambient temperature of 40°F (4.4°C) were assumed. These assumptions were used to conduct mass and energy balance calculations. Although beyond the scope of this investigation, for best predictions, the effect of reduced flue gas moisture content on furnace and convective pass heat transfer needs to be accounted for. The results of such an analysis would require site-specific information on the design and size of the various boiler heat transfer sections.

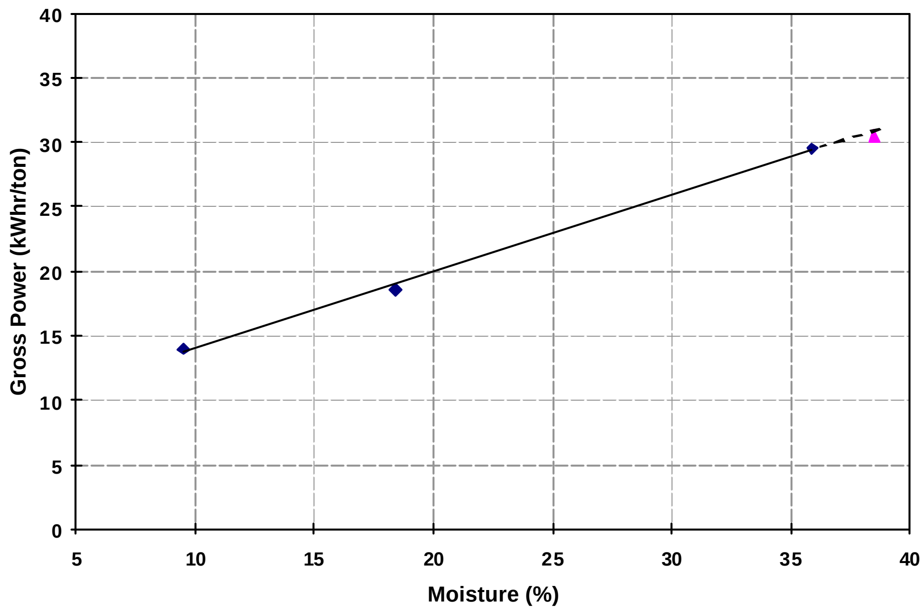

Figure 42a: Effect of Lignite Feed Moisture on Gross Pulverizer Power (kWhr/ton). Adapted from Data by Ellman et al. (Reference 7).

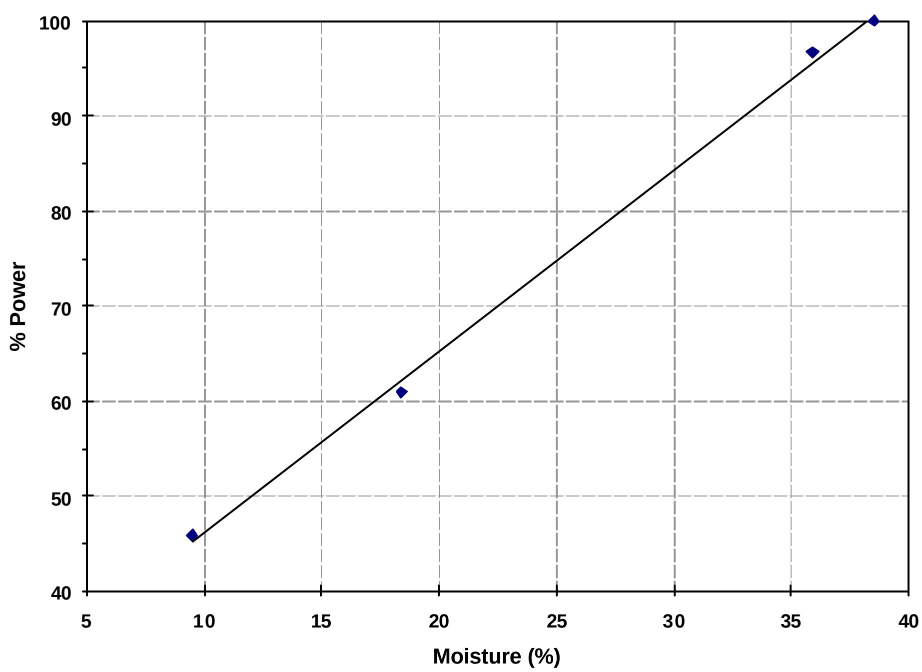

Figure 42b: Effect of Lignite Feed Moisture on Relative Pulverizer Power (kWhr/ton).

The combustion analysis provided results on the feed rate of coal (M_{coal}) and total (primary and secondary) air flow rates ($M_{air,tot}$) needed for combustion. These results were used as inputs to the overall mass and energy balance calculations.

Energy Balance

Conservation of energy was used to calculate energy flows at various locations in the power plant. From these calculations, $\dot{Q}_T$, the net energy transferred with the steam from the boiler to the turbine cycle, and $\dot{Q}_{fuel}$, the energy entering the boiler with the coal, were computed. The boiler efficiency was then found from:

$$?_B = \frac{\dot{Q}_T}{\dot{Q}_{fuel}}$$

The gross cycle heat rate, net power and net unit heat rate are:

$$HR_{cycle,gross} = \frac{\dot{Q}_T}{P_g}$$

$$P_{net} = P_g - P_{ss}$$

$$HR_{net} = \frac{\dot{Q}_{fuel}}{P_g - P_{ss}} = \frac{HR_{cycle,gross} \times P_g}{?_B \left(P_g - P_{ss}\right)}$$

$$\text{where } P_g = \text{gross electrical power}$$

$$P_{ss} = \text{station service power}$$

This procedure makes it possible to determine net unit heat rate, if the gross cycle heat rate and gross electrical power are known. Values of 7950 Btu/kWh for gross unit heat rate and 572 MW for gross electric generation were used in the analysis.

RESULTS FOR LIGNITE

The methodology described above was used to determine the effects of drying system configuration and coal product moisture on unit performance, emissions, station service power and evaporative cooling tower makeup water.

Boiler efficiency depends on the configuration of the drying system and the effects of that configuration on flue gas flow rate and temperature at the stack. Figures 43 and 44 show the gas temperature at the inlet to the induced draft fan (just upstream of the stack) and the ID fan flow rate. The results for boiler efficiency (Figure 45) show that while boiler efficiency improves with a reduction in coal product moisture, there are differences in the boiler efficiencies obtained with different drying system designs.

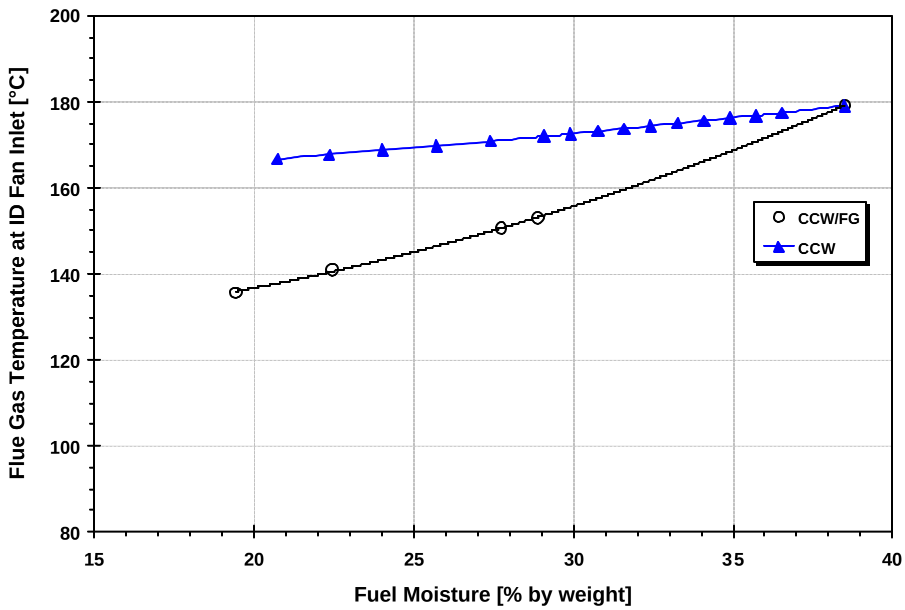

Figure 43: Flue Gas Temperature Entering ID Fan.

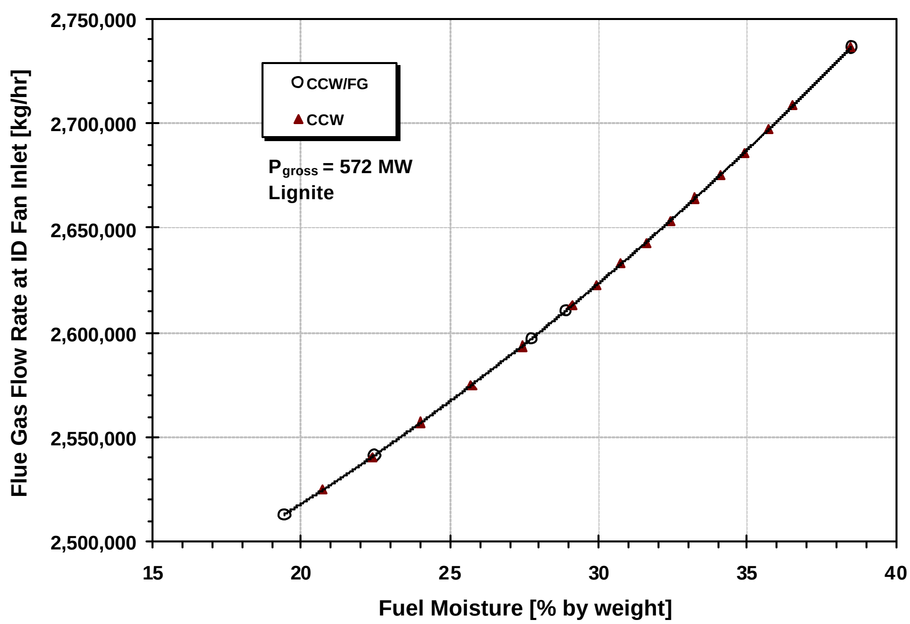

Figure 44: Flue Gas Flow Rate at ID Fan Inlet.

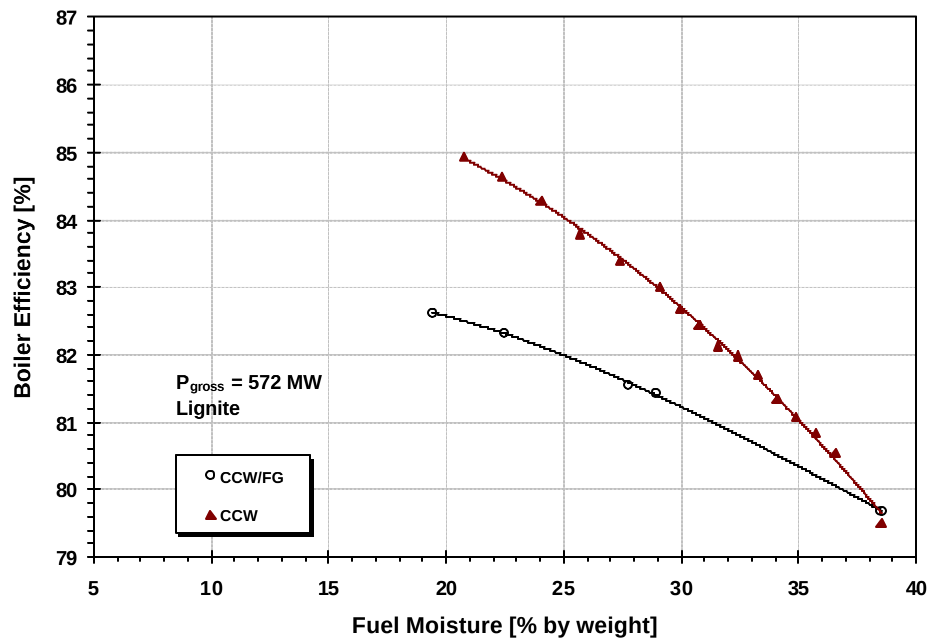

Figure 45: Boiler Efficiency.

Power requirements for the forced draft, induced draft and fluidization air fans are shown in Figures 46 to 48. The FD fan power is only weakly dependent on coal moisture level. The ID fan power depends strongly on flue gas moisture content, while the power for the fluidizing air fan is a strong function of the size of the fluidized bed dryer. Mill power depends on coal moisture level, but is otherwise independent of type of drying system (Figure 49). Station service power (Figure 50) depends strongly on type of drying system because of the impact of power required for the fluidization air fan. As a result, because of much larger dryer distributor cross sections and air flow rate requirements, the station service power requirement for the CCW system is substantially larger than for the CCW/FG system.

With information on boiler efficiency, gross electrical power and station service power, it is possible to compute the net unit heat rate. These results, shown in Figure 51 indicate lower heat rates would occur with the CCW drying system. Overall improvements in net unit heat rate due to drying lignite from 38.5 percent to 20 percent moisture in an on-site drying system are in the 3.3 percent range.

Flue gas temperature at the inlet to the induced draft fan sets a constraint on the maximum amount of drying. The acid dew point of the flue gas depends on the concentration of SO_3 and, to a lesser extent, H_2O in the flue gas. The SO_3 concentration is very site specific, varying with factors such as fuel sulfur content, concentration of alkali's in the coal, boiler design and operating conditions, and presence of a selective catalytic reactor for NO_x control. Flue gas temperatures which are too low will result in excessive acid condensation and lead to heat exchanger fouling and corrosion. Figure 52 shows the flue gas temperature entering the ID fan as a function of coal product moisture. Also shown are the sulfuric acid dewpoint temperatures for three different flue gas SO_3 concentrations. These results show the CCW system will not be affected by acid condensation as much as the CCW/FG system. A site specific study would be needed to determine the extent to which heat exchanger fouling and corrosion due to acid condensation constrains the minimum coal product moisture.

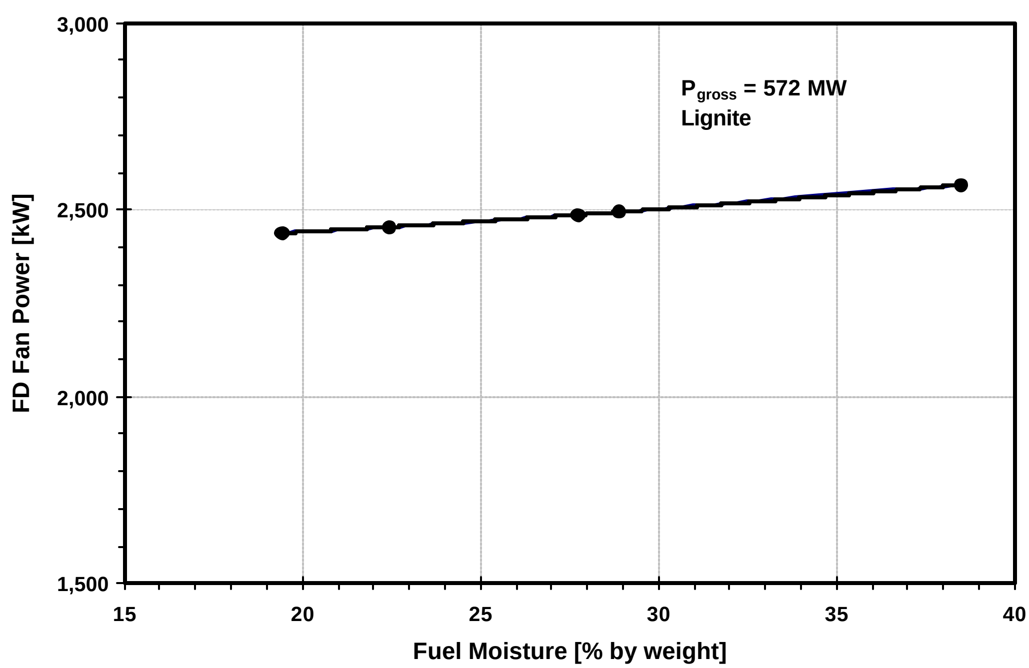

Figure 46: FD Fan Power.

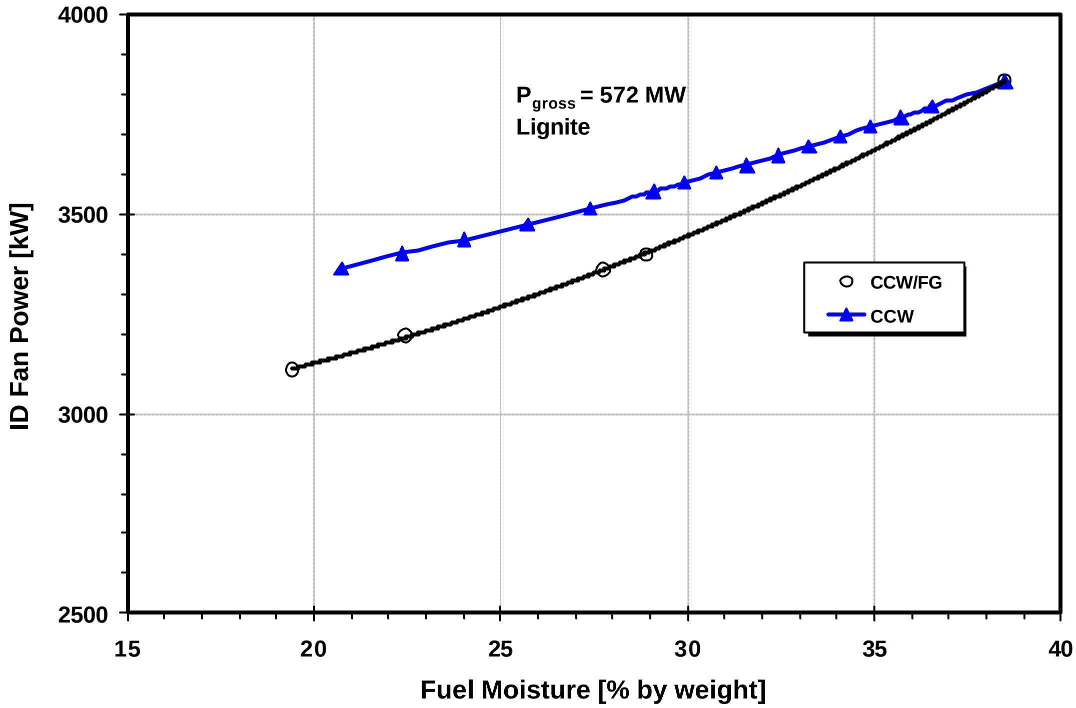

Figure 47: ID Fan Power.

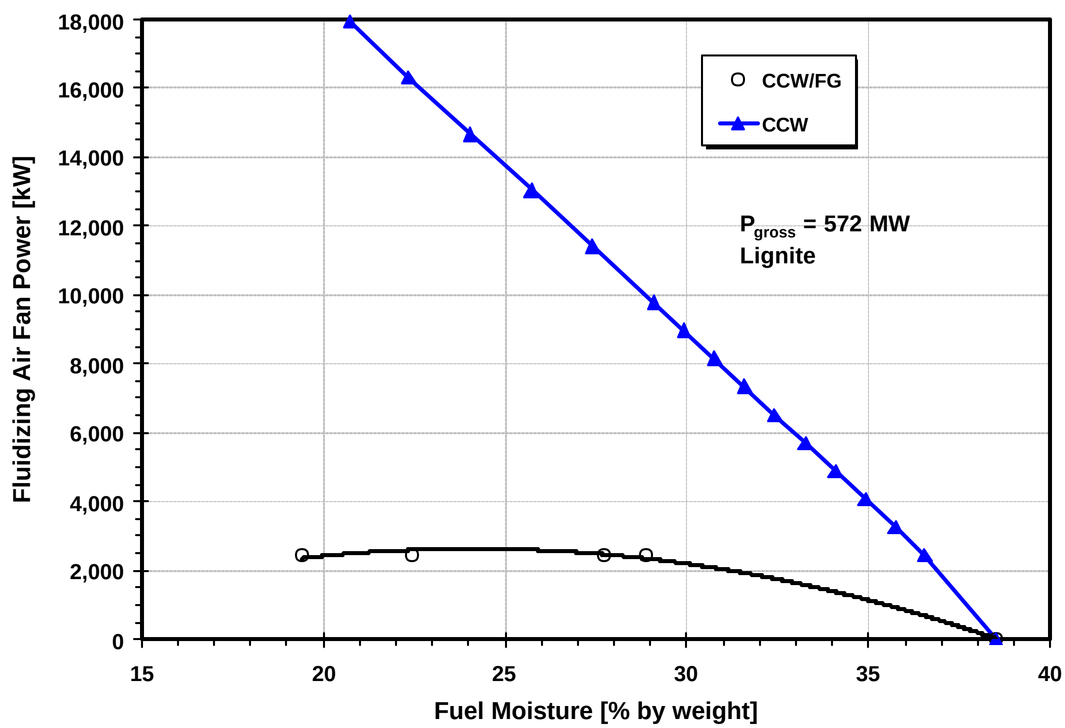

Figure 48: Fluidizing Air Fan Power.

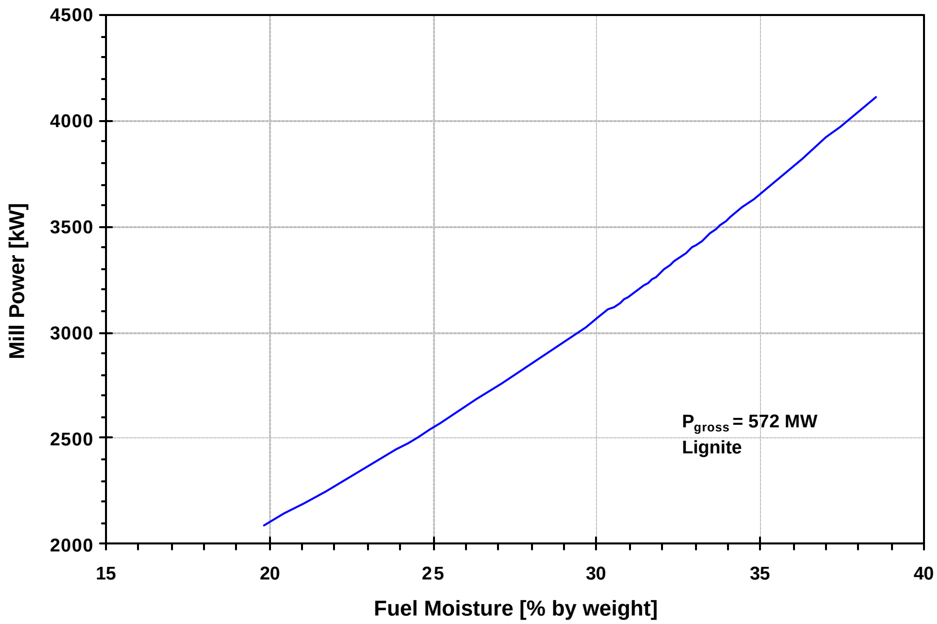

Figure 49: Mill Power.

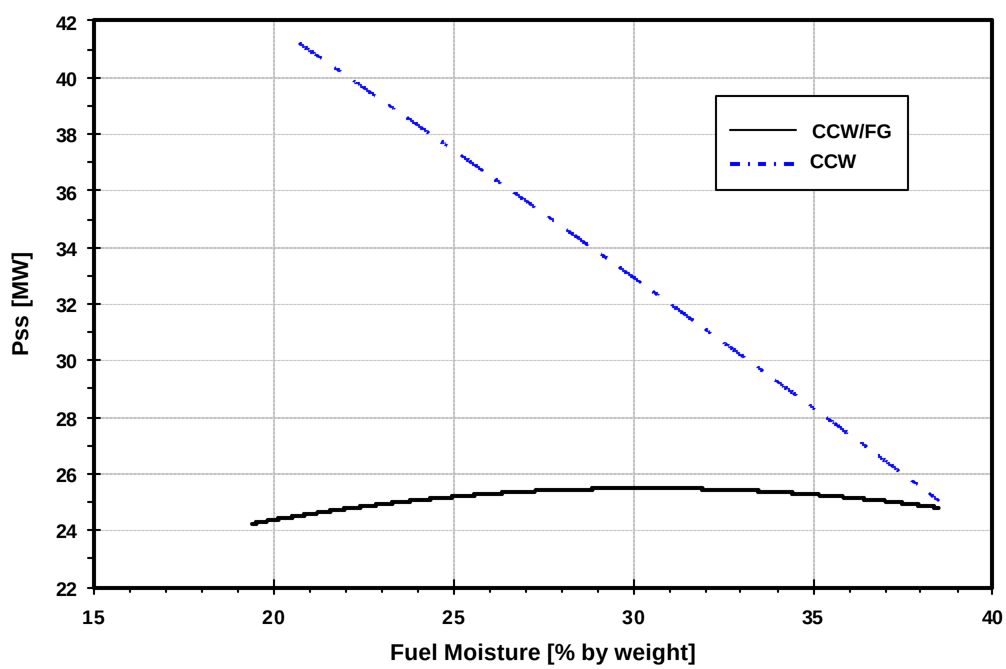

Figure 50: Station Service Power.

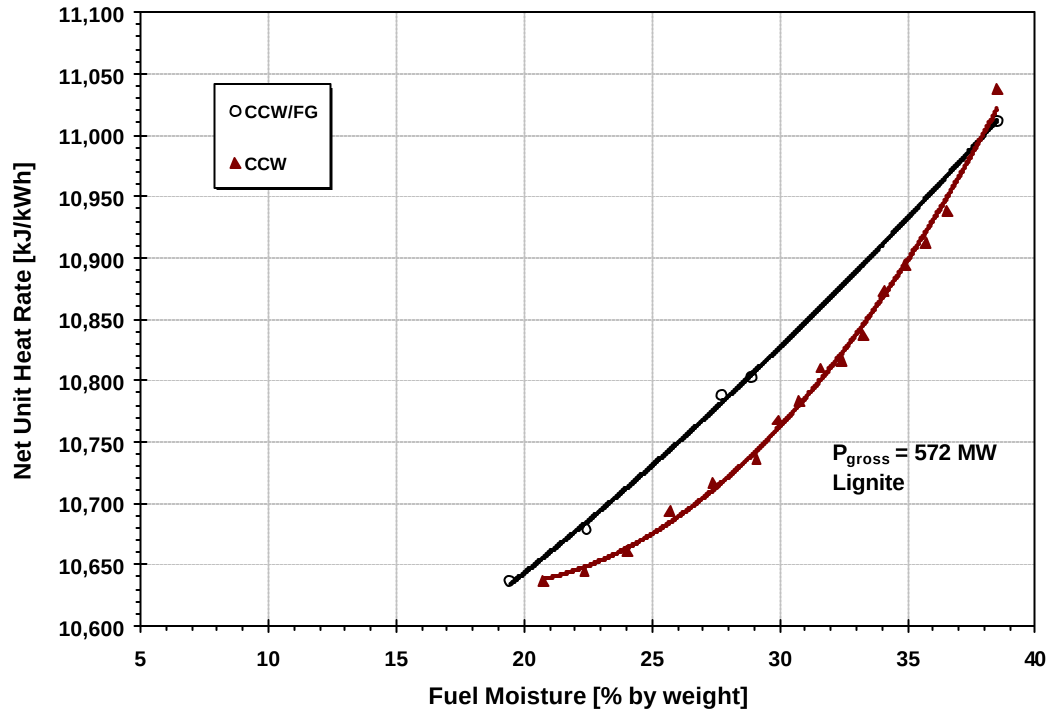

Figure 51: Net Unit Heat Rate.

REDUCTION OF COOLING TOWER MAKEUP WATER

With both the CCW and CCW/FG drying systems, a portion of the thermal energy carried by the hot circulating cooling water flowing from the steam condenser to the cooling tower is used to provide heat for the coal dryer. Figure 53 shows the rate of heat removal from the hot circulating water as a function of coal product moisture for the two drying systems.

The analysis method used for the cooling tower is based on conservation of mass and energy, where enthalpy difference is used as the driving force for mass transfer and the tower cooling capacity is specified by the number of transfer units (Reference 8).

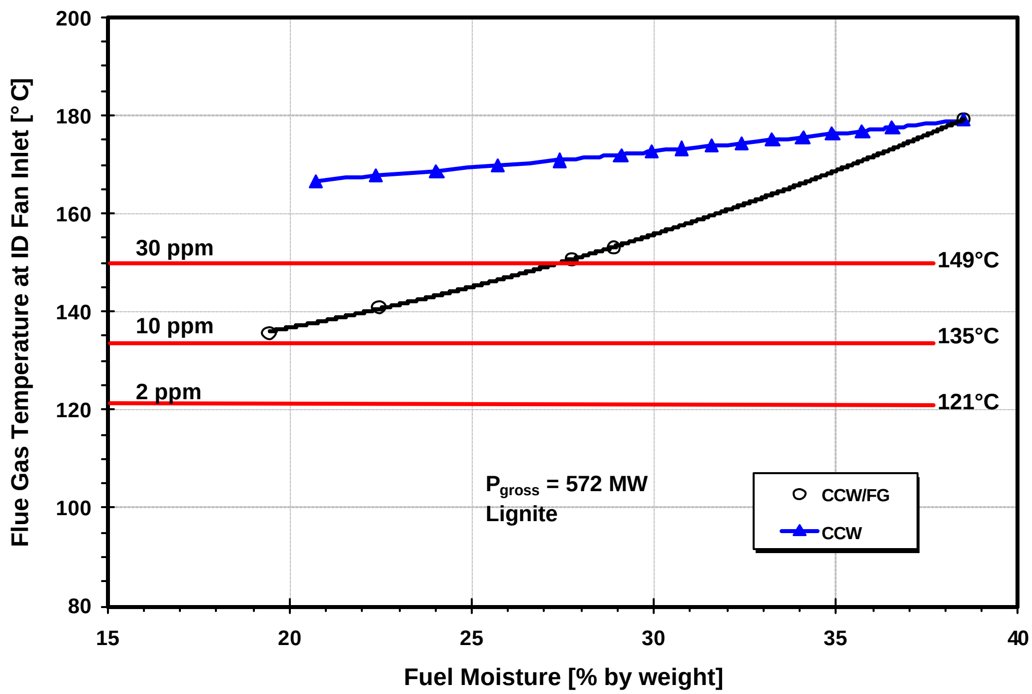

Figure 52: Flue Gas Temperature Entering ID Fan.

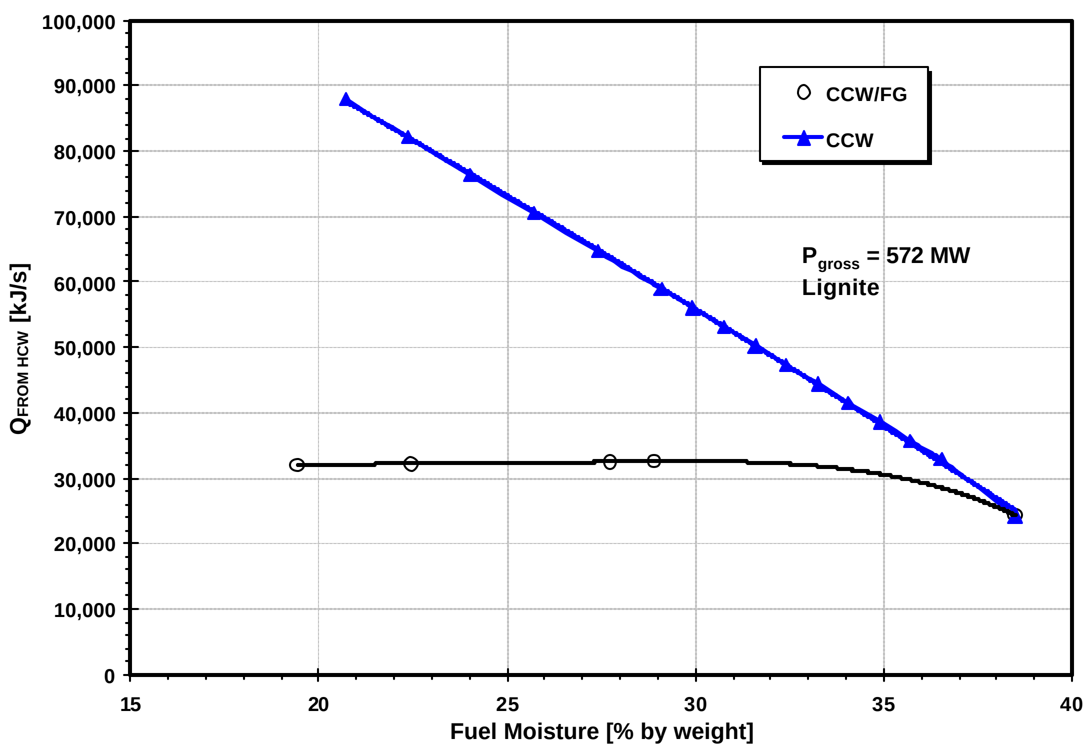

Figure 53: Rate of Heat Removal From Hot Circulating Cooling Water.

Figures 54 and 55 show the heat rejected by the cooling tower and the reduction in cooling tower makeup water depend strongly on the type of drying system. The CCW/FG drying system relies heavily on heat extracted from flue gas for drying and thus there is a relatively minor impact on cooling tower operation with this design. In contrast, all of the energy for drying comes from the hot circulating water leaving the steam condenser in the case of the CCW drying system, and this resulted in the largest reductions in cooling tower makeup water. For the conditions of these analyses (44°C ambient air temperature and reduction in lignite moisture from 38.5 to 20 percent), the reduction in cooling tower makeup water was found to range up to 6×10^5 gallons per day (2.3×10^6 liters/day).

Cooling tower analyses were also performed for Summer and Spring/Fall air temperature and humidity conditions to determine how water savings would vary with time of year. Figure 56 shows seasonal evaporation loss as a function of cooling tower heat rejection. At a given rate of heat rejection, the tower makeup water requirements increase with ambient air temperature and humidity level and are thus are greatest in the Summer. Figure 57 shows how the evaporation loss versus fuel moisture curves depend on season of the year for the two drying systems. The corresponding reduction in cooling tower makeup water due to drying with the CCW system is shown in Figure 58 for different seasons.

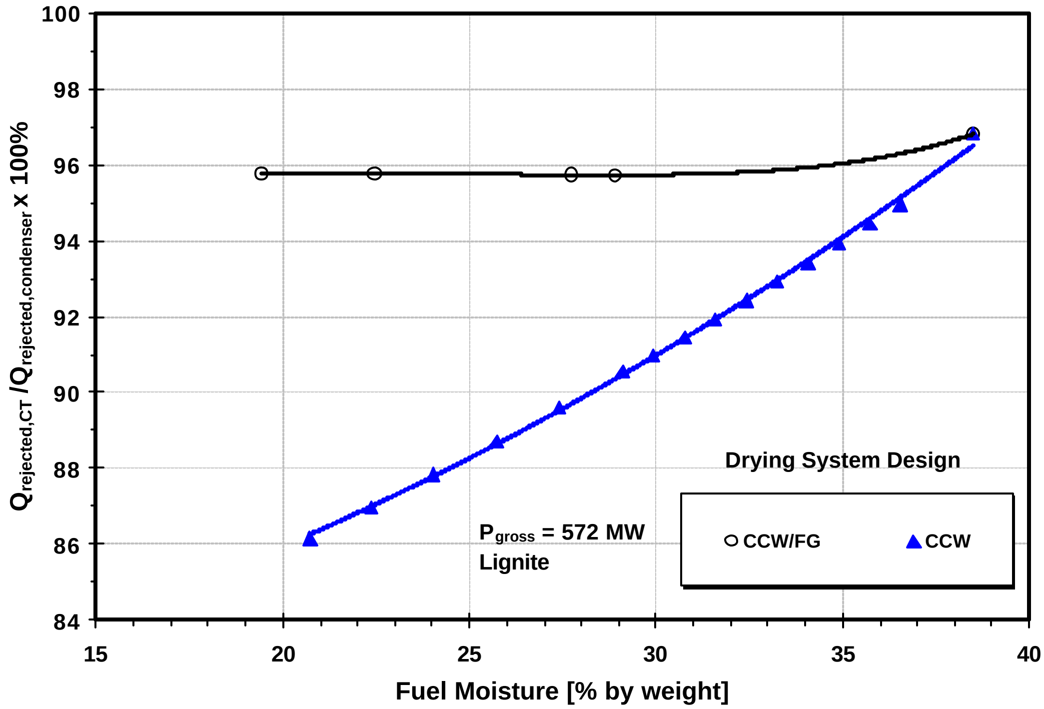

Figure 54: Ratio of Heat Rejected by Cooling Tower to Heat Rejected by Steam Condenser

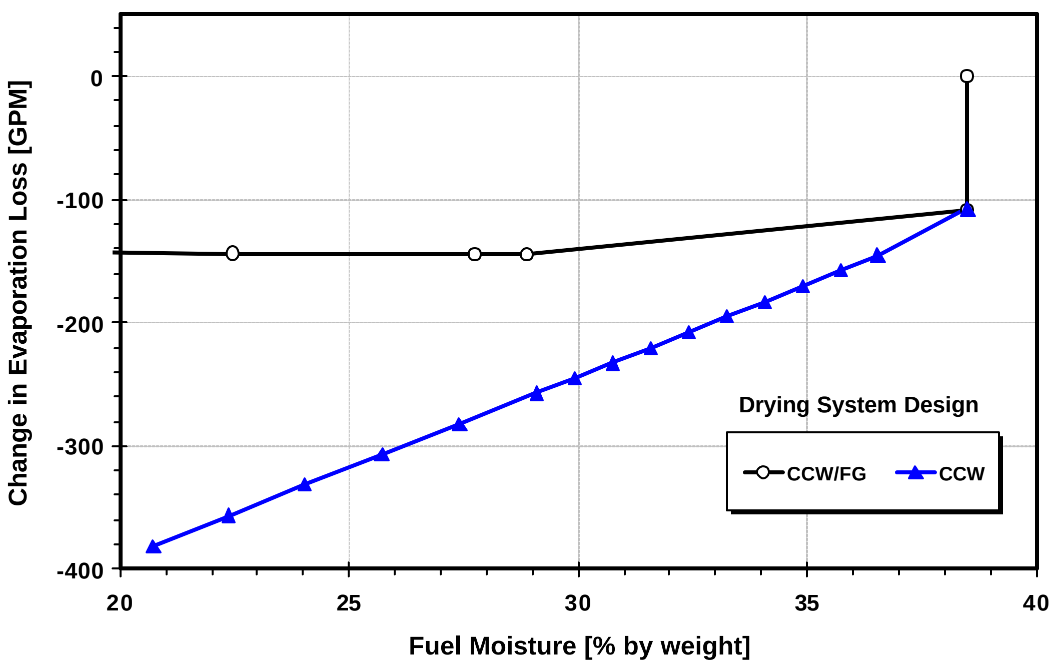

Figure 55: Reduction in Cooling Tower Water Evaporation Loss

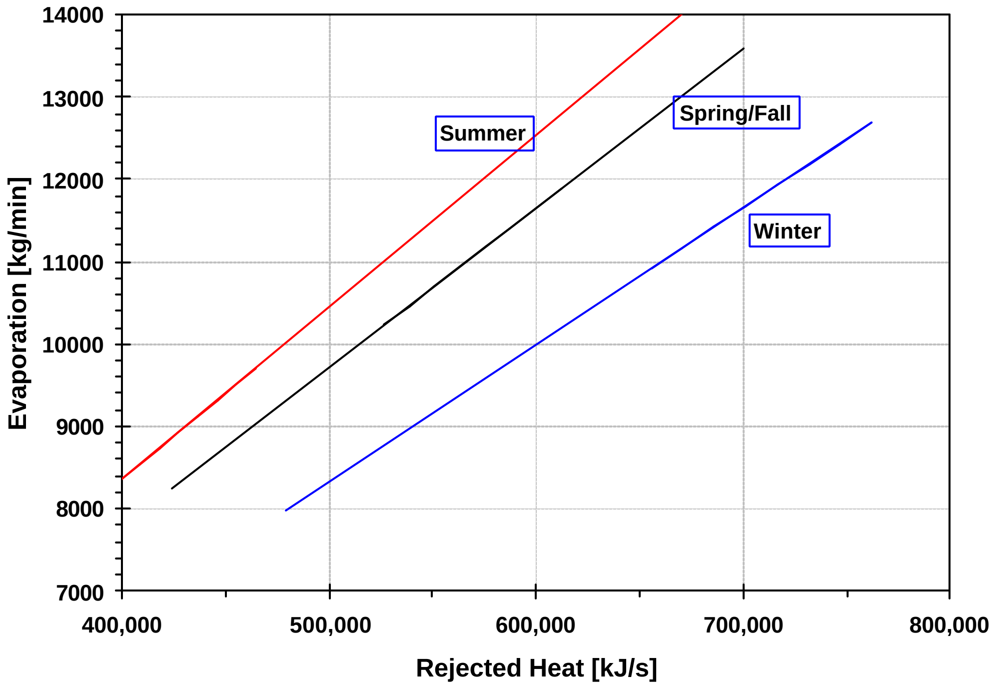

Figure 56: Variation of Cooling Tower Water Evaporation Rate with Season of Year

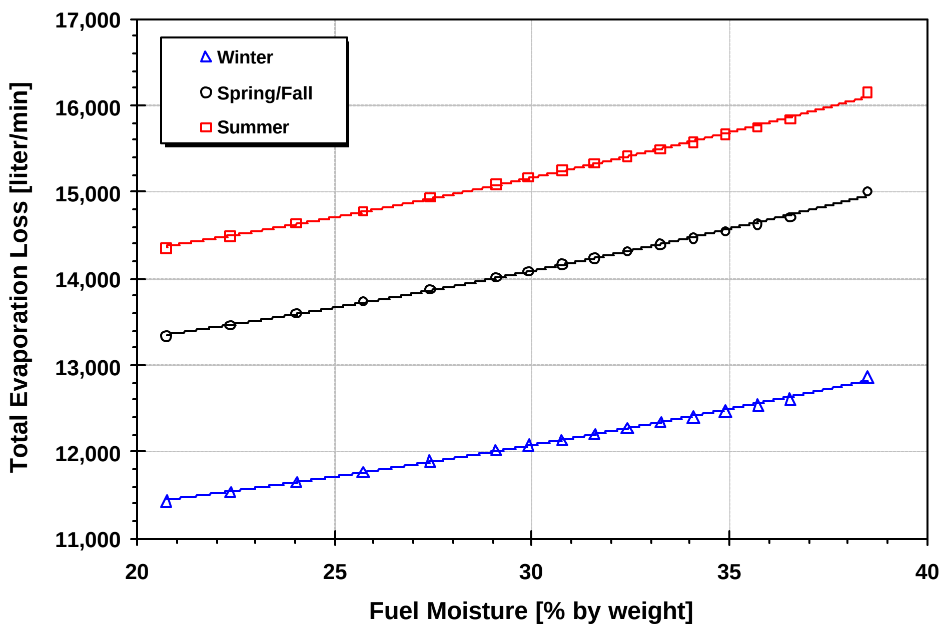

Figure 57: Effect of Time of Year on Cooling Tower Evaporation Rate. CCW Drying System.

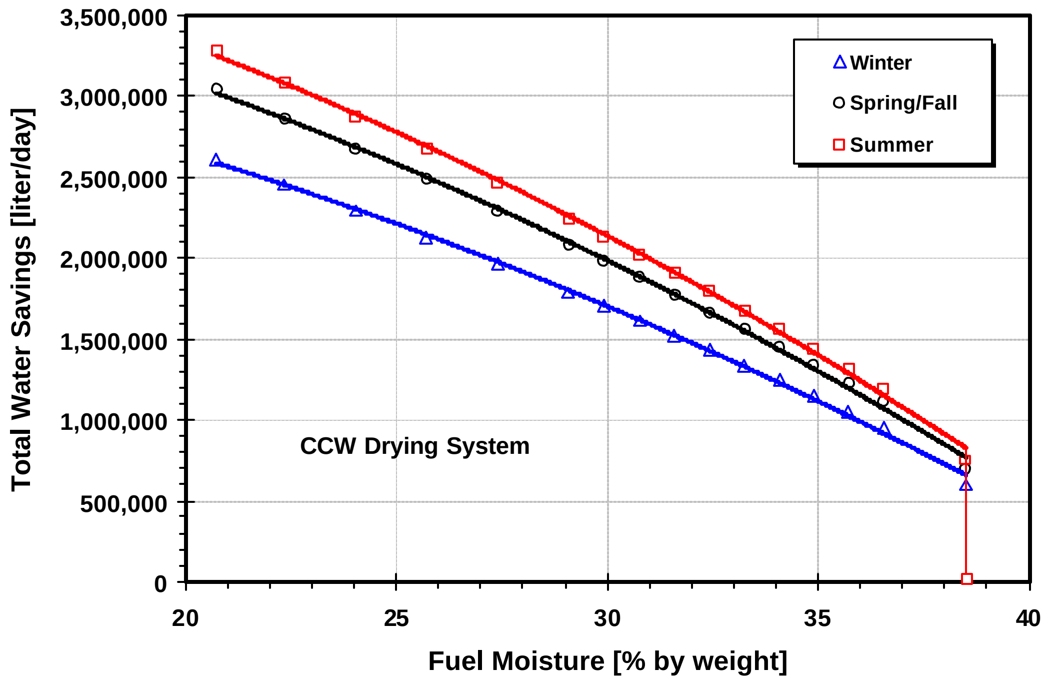

Figure 58: Effect of Coal Product Moisture and Time of Year on Reduction of Cooling Tower Makeup Water. CCW Drying System.

COMPARISONS BETWEEN LIGNITE AND PRB COALS

The effect of coal drying on unit performance was also analyzed for identical pulverized coal power plants, one firing lignite and the other a PRB coal. Calculations were performed for the CCW/FG drying system. An inlet lignite moisture content of 38.5 percent (kg $H_2 0$/kg wet coal) and an inlet PRB moisture of 30 percent were used in the calculations along with a flue gas temperature at the economizer outlet of 441°C. The gross electric power Pg was held constant at 570 MW.

The ultimate analyses of the lignite and PRB used in the analyses are given in Table 4. These show that on a moisture and ash-free (MAF) basis, the PRB has a higher carbon content, lower oxygen content and slightly lower higher heating value than the lignite. The table also gives analyses for the as-received fuels and for lignite and PRB with the same moisture content (20 percent). Figure 59 shows the variations in flue gas to coal flow rate ratio for lignite and PRB as a function of coal moisture. The results in Table 4 and Figure 59 show that, for the same coal moisture, PRB has a larger higher heating value and larger M_{fg}/M_{coal} ratio than lignite, and this is due to differences between the two fuels in carbon and oxygen content. These differences affect boiler efficiency, fan power and net unit heat rate.

Table 4

Ultimate Analyses – Comparison of Lignite and PRB Coals

		As-Received		20% Fuel Moisture			MAF	
	Units	Lignite	PRB	Lignite	PRB		Lignite	PRB
Carbon	% wt	34.03	49.22	44.27	56.25		69.17	76.05
Hydrogen	% wt	2.97	3.49	3.87	3.99		6.04	5.39
Sulfur	% wt	0.51	0.35	0.67	0.40		1.04	0.54
Oxygen	% wt	10.97	10.91	14.27	12.47		22.29	16.86
Nitrogen	% wt	0.72	0.75	0.92	0.86		1.46	1.16
Moisture	% wt	38.50	30.00	20.00	20.00		0.00	0.00
Ash	% wt	12.30	5.28	16.00	6.30		0.00	0.00
TOTAL	% wt	100.00	100.00	100.00	100.27		100.00	100.00
HHV	**kJ/kg**	**14,900**	**19,418**	**19,383**	**22,193**		**30,287**	**30,003**

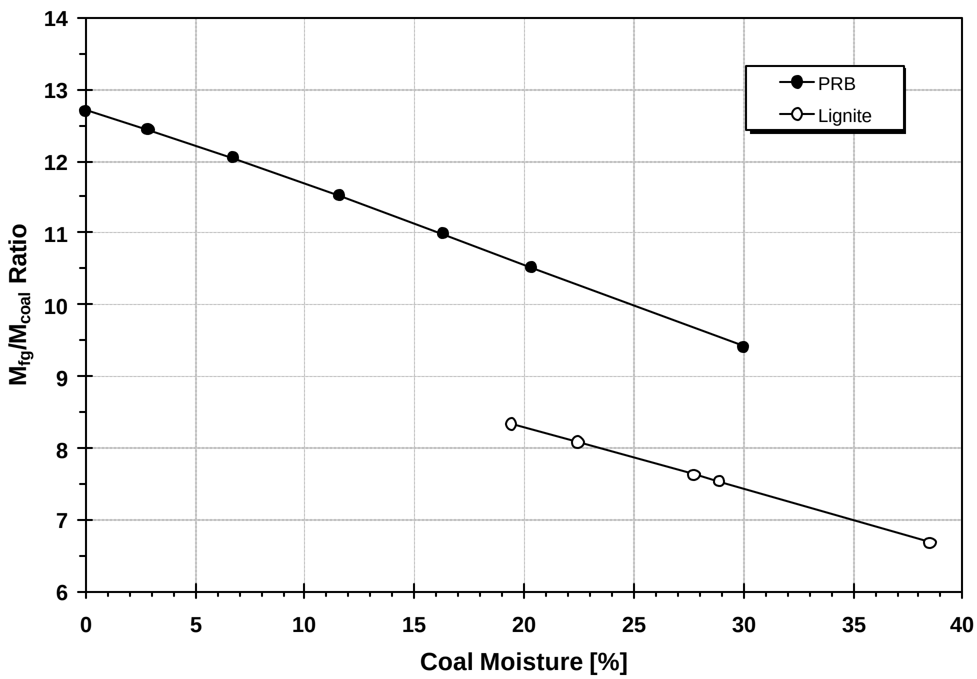

Figure 59: Effect of Coal Moisture Content and Coal Type on Mass Ratio of Flue Gas to Coal Flow Rates.

Figure 60, which shows the effect of coal moisture on boiler efficiency, shows the same trends for boiler efficiency for the two coals, but with the PRB having a larger boiler efficiency than the lignite. The percentage increase in boiler efficiency with increased coal drying is roughly the same for both fuels. The PRB calculations were taken all the way to zero percent coal moisture, and the resulting PRB curve indicates the boiler efficiency reaches a maximum and then decreases slightly as the coal moisture approaches zero.

A comparison of the heat rates for the two fuels (Figure 61) shows similar trends, but with the PRB having the lower heat rate. The heat rate trends are controlled by the variations in boiler efficiency for the high temperature drying system.

Figure 62 compares flue gas flow rates at the induced fan inlet and the inlet primary and secondary air flows. This shows that for equal fuel moistures, the PRB requires more combustion air and produces a larger flue gas flow rate. In addition, the flue gas temperature at the ID fan inlet is higher in the PRB case (Figure 63).

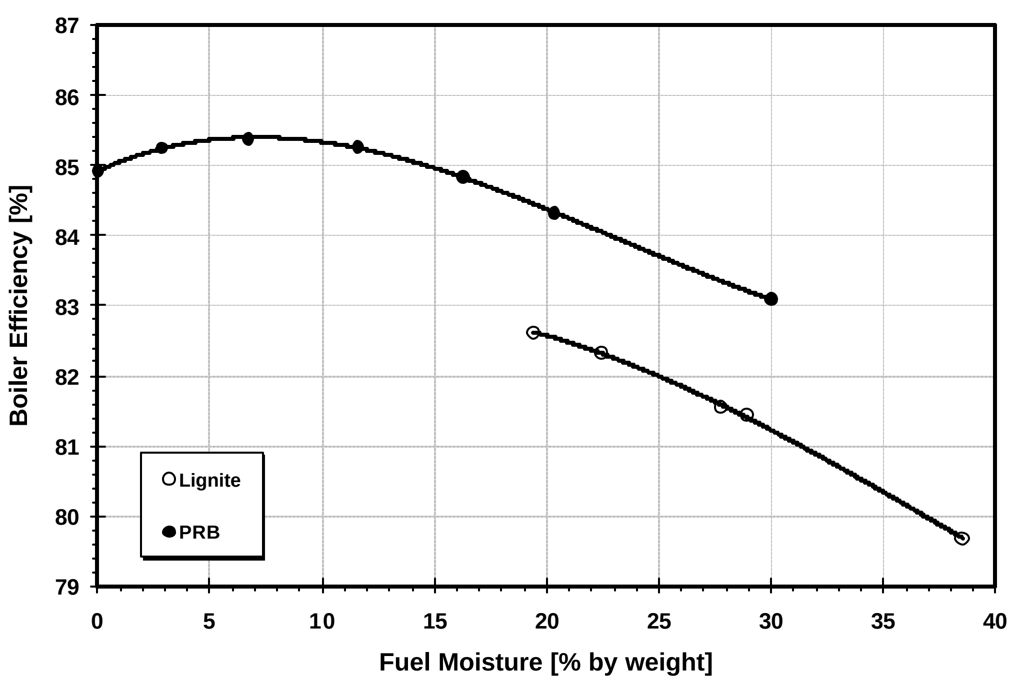

Figure 60: Effect of Coal Moisture and Coal Type on Boiler Efficiency. CCW/FG Drying System.

Station service power is also an important parameter. The FD fan power decreases as a result of coal drying and this decrease is proportional to the decrease in heat rate. Both fuels exhibit the same FD power trends (Figure 64). The decrease in ID fan power with decreasing coal moisture (Figure 65) occurs due to the reduction in heat rate and the reduction in flue gas moisture.

Coal flow rate decreases with increasing amounts of coal drying due to less moisture in the fuel and an improved heat rate (Figure 66). The mill power (Figure 67) decreases with drying due to reductions in coal flow rate and the effect of coal moisture on mill power/ton of coal (see Figure 42).

Figures 59 through 67 show that while there are small differences due to different coal compositions, the performance impacts due to drying lignite and PRB coals follow the same trends and are very similar in magnitude.

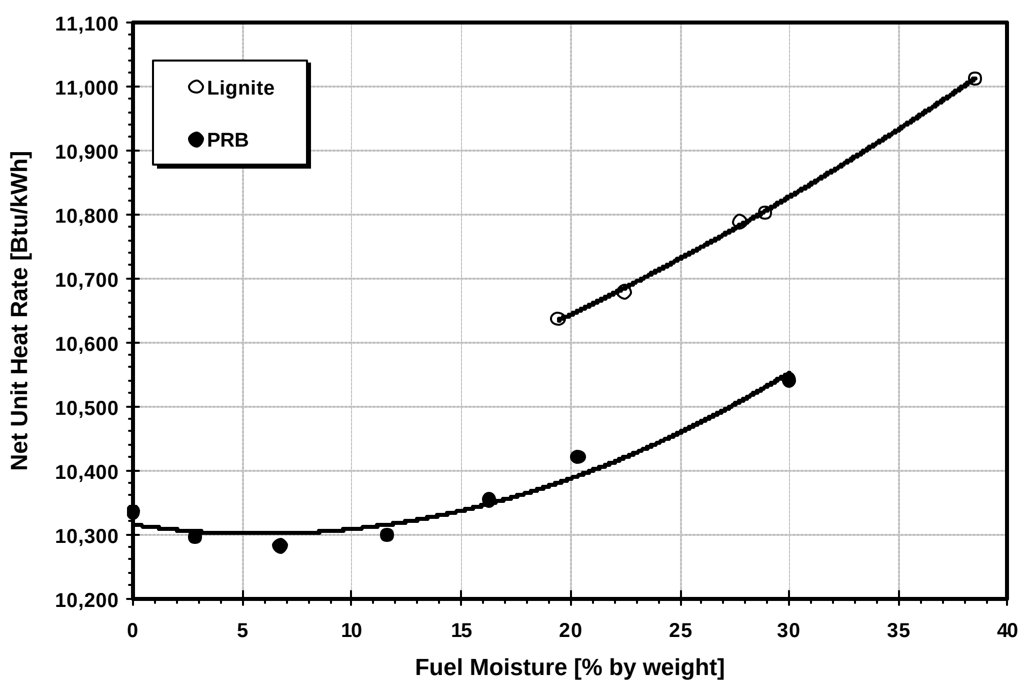

Figure 61: Effect of Coal Moisture and Coal Type on Net Unit Heat Rate. CCW/FG Drying System.

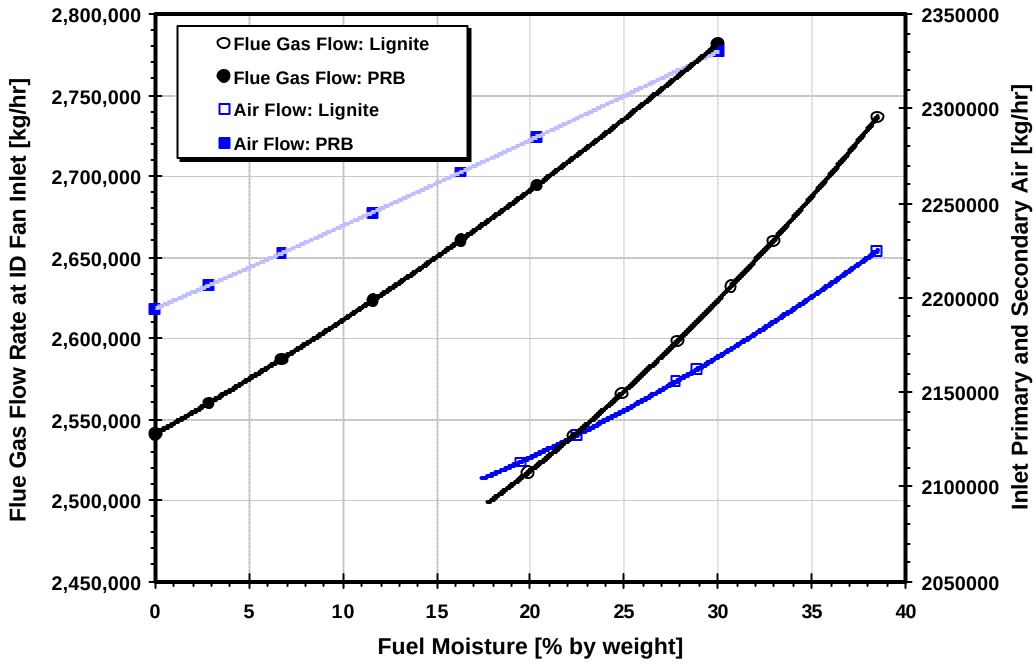

Figure 62: Effect of Coal Moisture and Coal Type on Flue Gas Flow Rate at ID Fan Inlet and Flow Rate of Inlet Combustion Air. CCW/FG Drying System.

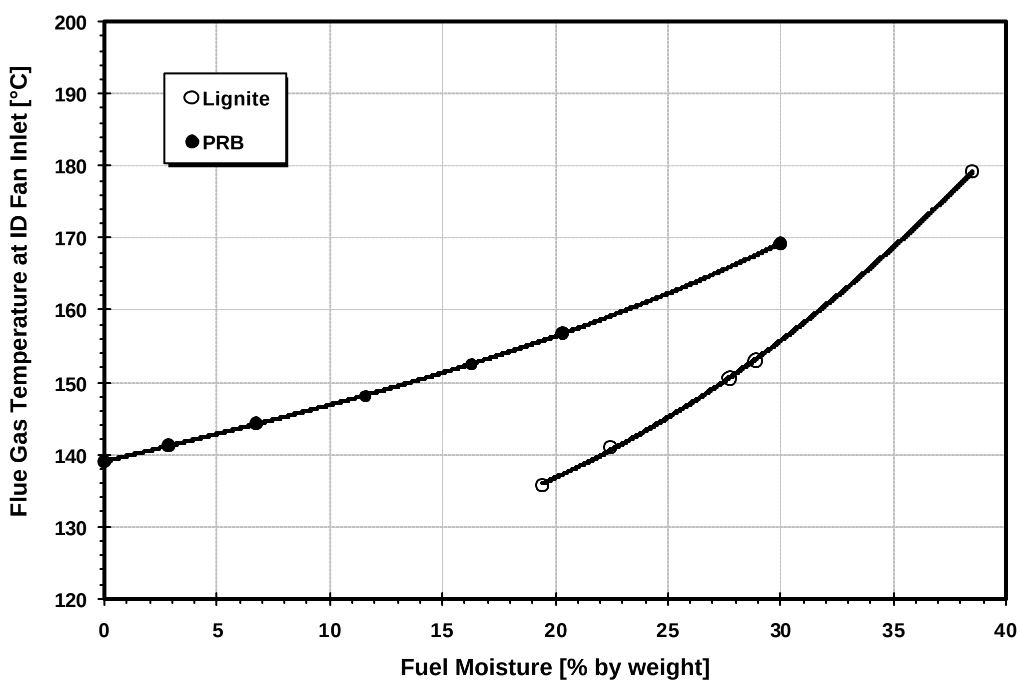

Figure 63: Effect of Coal Moisture and Coal Type on Flue Gas Temperature at ID Fan Inlet. CCW/FG Drying System.

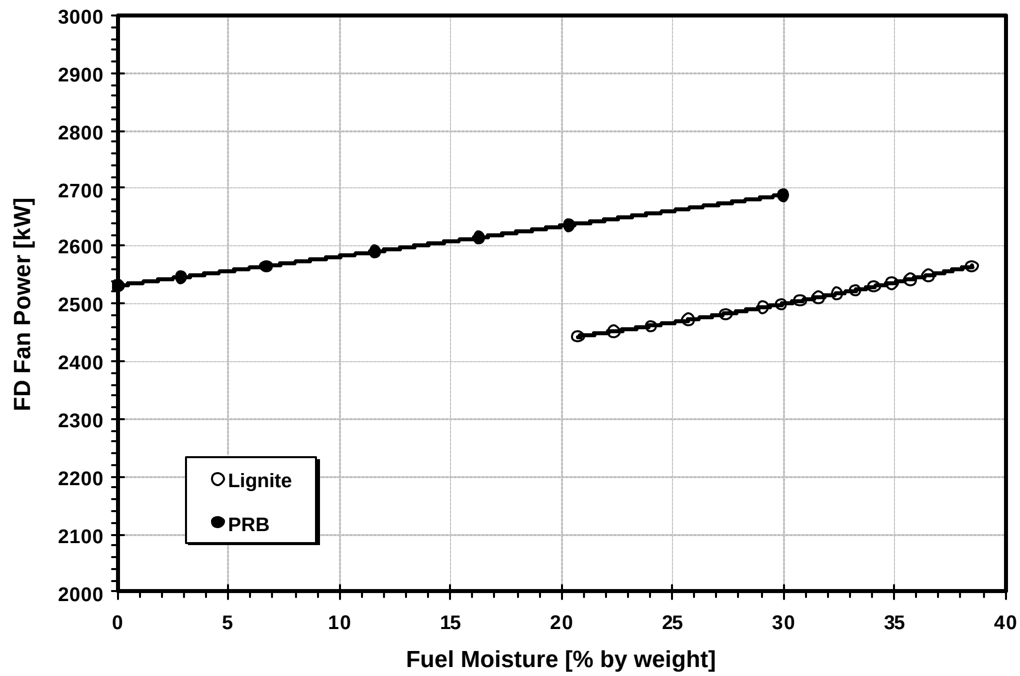

Figure 64: Effect of Coal Moisture and Coal Type on FD Fan Power. CCW/FG Drying System.

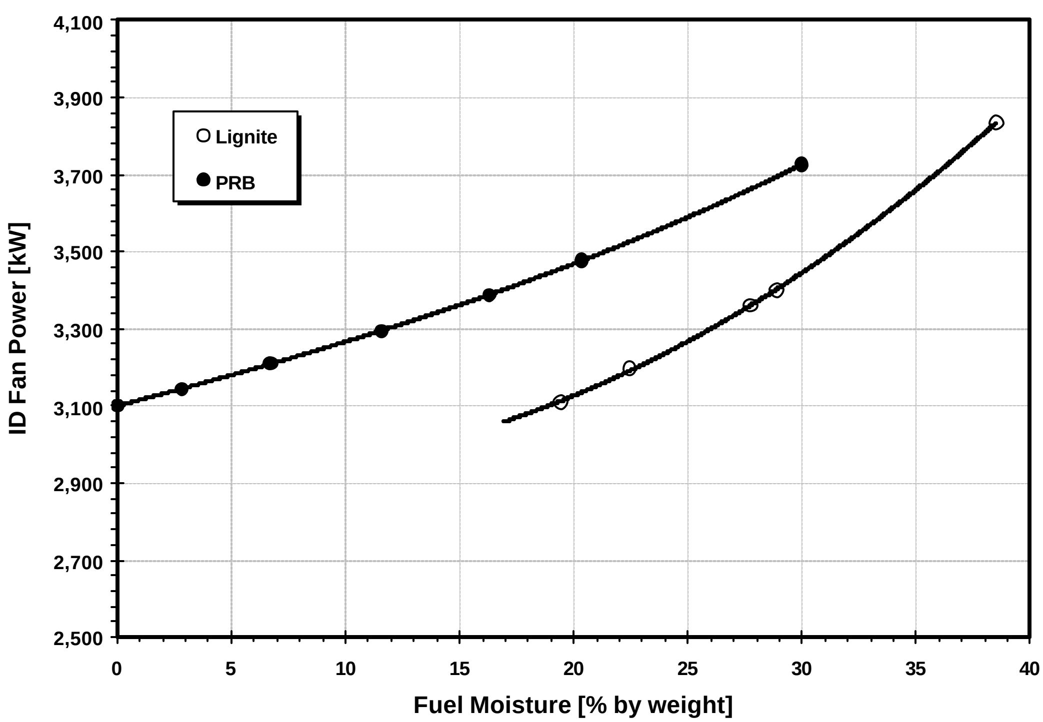

Figure 65: Effect of Coal Moisture and Coal Type on ID Fan Power. CCW/FG Drying System.

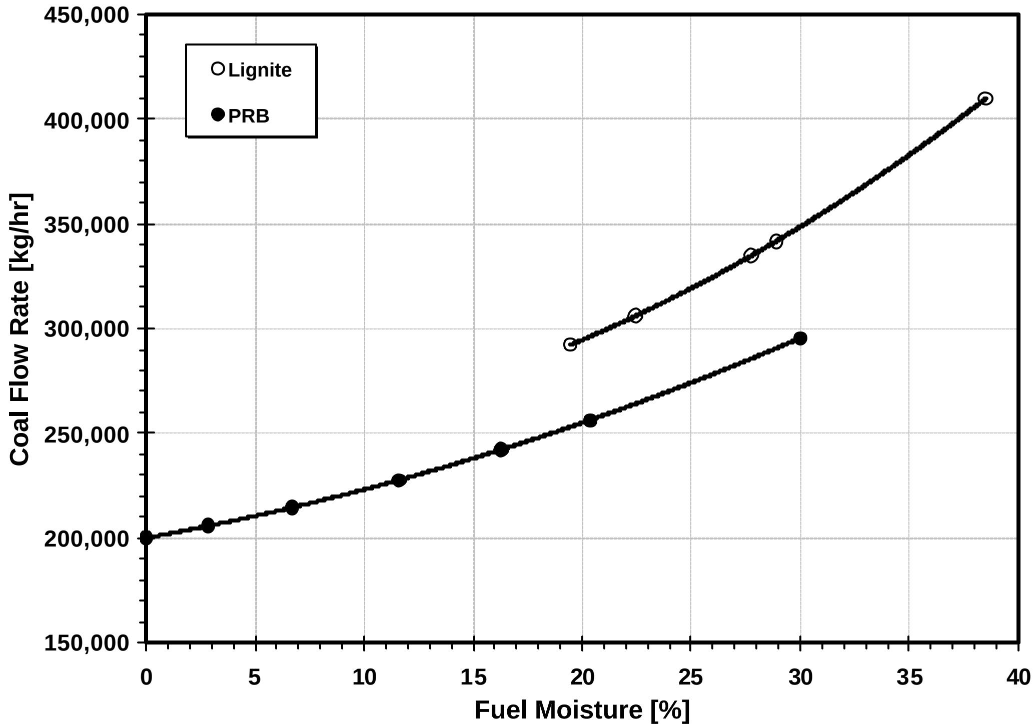

Figure 66: Effect of Coal Moisture and Coal Type on Coal Feed Rate. CCW/FG Drying System.

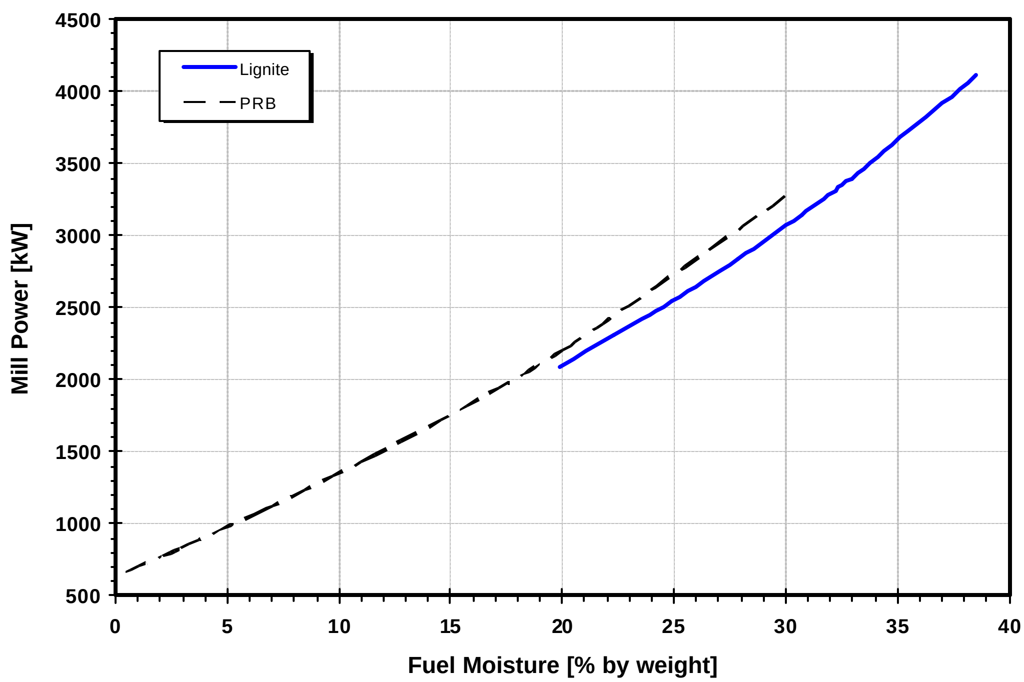

Figure 67: Effect of Coal Moisture and Coal Type on Mill Power.

PART III – ECONOMIC EVALUATION

INTRODUCTION

Part II of this report contains descriptions of analyses carried out to compute the effects of coal drying on unit heat rate, station service power, stack emissions, and water consumption for evaporative cooling. Part III contains analyses to determine the cost effectiveness of coal drying. The methodology and key assumptions used to estimate the costs and benefits of coal drying and results of analyses are described in this section. The results presented here are for two drying systems, one which utilizes a combination of waste heat from the condenser and thermal energy extracted from boiler flue gas (referred to in this report as CCW/FG) and one which relies completely on waste heat from the condenser (referred to as CCW). See Table 3. The cost analyses are for a lignite power plant with a gross electric power output of 572 MW.

INSTALLED EQUIPMENT COSTS

Installed equipment costs (in 2005 dollars) were estimated for the CCW/FG and CCW drying systems for a lignite feed and a 441°C economizer exit gas temperature. The analyses were performed to determine how equipment costs would vary as a function of coal product moisture.

Estimated costs were obtained for the heat exchangers, fans, fluidized bed dryers, baghouses, coal crushers and air flow ductwork needed for the drying systems. For component sizing purposes, this required information on parameters such flue gas, air and water flow rates, temperatures, pressure drops and rates of heat transfer, all of which had been determined as part of the analyses for heat rate described in Part II of this report.

The estimates of installed capital costs were obtained from vendors and from the open literature. Where possible, cost estimates were obtained from independent sources as a cross check on the numbers being used.

Table 5 lists equipment and installation costs per component, the quantity of each component needed and the total cost for each type of component. The dollar amounts listed in Table 4 are for a CCW/FG drying system with a 28.9 percent lignite product moisture. The total cost of this drying system was estimated to be $23,446,409.

The installed equipment costs will depend on the coal product moisture, since the size of some of the components will vary with moisture content. Figure 68 shows installed component costs for the CCW/FG system for four product moistures ranging from 28.9 to 19.5 percent. The drying system design assumed the same dryer size for all four moisture levels, but with heat exchanger capacity changing from one moisture level to the next.

Figure 69 shows the total installed costs of the CCW/FG drying system as a function of percentage change of coal moisture content from the 38.5 percent feed moisture level. These results show the estimated cost of the CCW/FG drying system is relatively insensitive to coal product moisture, ranging from $23.4 to $24.4 million.

Table 5

Component Equipment and Installation Costs for CCW/FG Drying System with 28.9 Percent Lignite Product Moisture

	Unit Material Cost	Unit Installation Cost	Quantity	Quantity Needed	Total Cost
Duct Work	$50,000.00	$253,890.90	152	1	$303,891.00
Baghouse	$184,736.00	$184,736.00	1	6	$1,940,316.00
	$202,764.00	$202,764.00	1		
	$146,256.00	$146,256.00	1		
	$113,016.00	$113,016.00	1		
FA Fan	$257,228.90	$257,228.90	1	4	$2,028,916.00
	$250,000.00	$250,000.00	1		
Heat Exchangers					
A	$392,101.40	$392,101.40	1	1	$784,203.00
B	$717,732.20	$717,732.20	1	1	$1,435,464.00
C	$1,673,362.00	$1,673,362.00	1	1	$3,346,724.00
D	$4,455,697.60	$4,455,697.60	1	1	$8,911,395.00
Crusher	$247,750.00	$247,750.00	1	1	$495,500.00
Dryer Bed	$600,000.00	$100,000.00	1	6	$4,200,000.00
TOTAL					**$23,446,409.00**

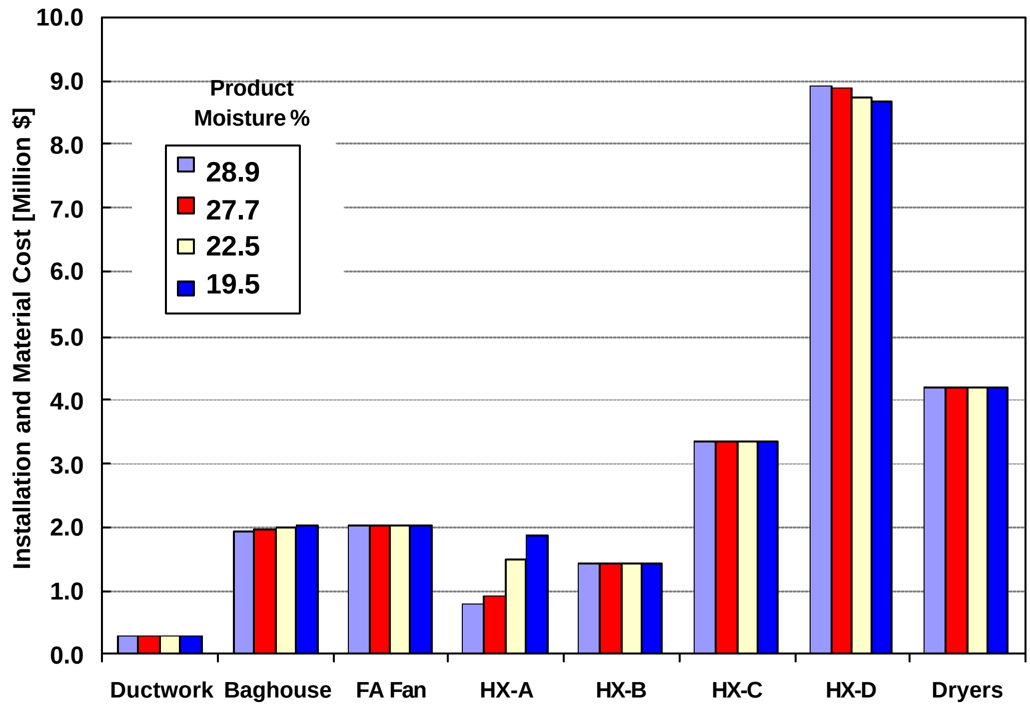

Figure 68: Estimated Installed Equipment Costs for CCW/FG Drying System at Four Product Moisture Levels.

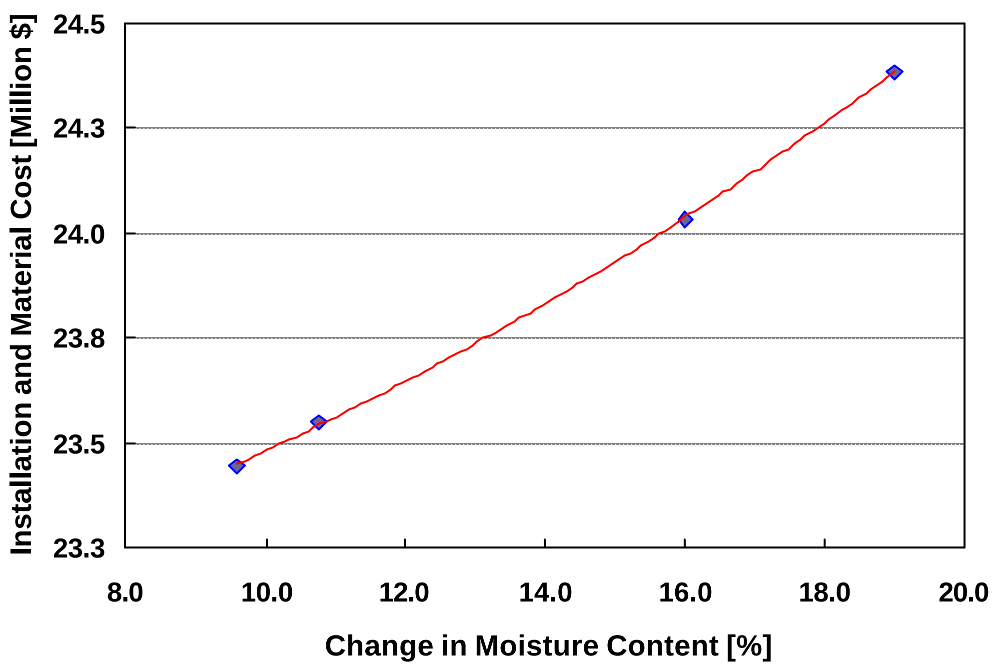

Figure 69: Total Installed Equipment Cost for CCW/FG Drying System as a Function of Coal Product Moisture.

Similar analyses were performed for the CCW drying system. In contrast to the trend for the CCW/FG system, the estimated installed costs are a strong function of coal product moisture for the CCW design. Figure 70 shows estimated installed costs for each major component for four different lignite product moisture levels. In this case, in order to achieve the product moisture targets, the size and cost of almost all of the components increased substantially as coal product moisture decreased.

Figure 71 compares the estimated installed costs for the two types of drying systems. This figure shows the CCW/FG system has a clear cost advantage, based solely on estimated installed capital costs.

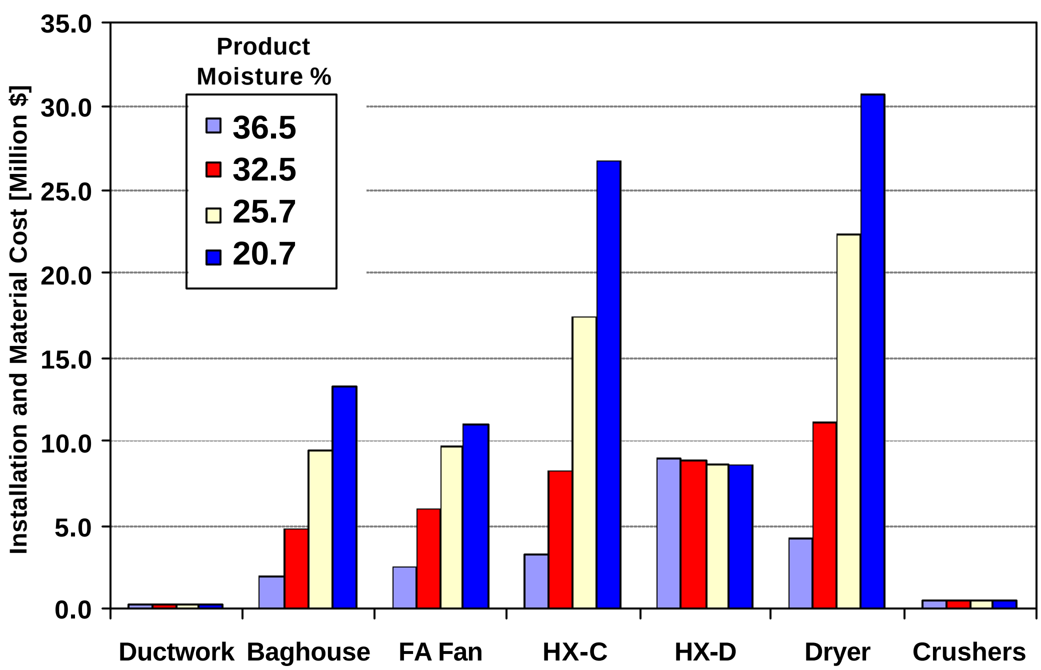

Figure 70: Installed Capital Costs for Major Drying System Components. CCW Drying System.

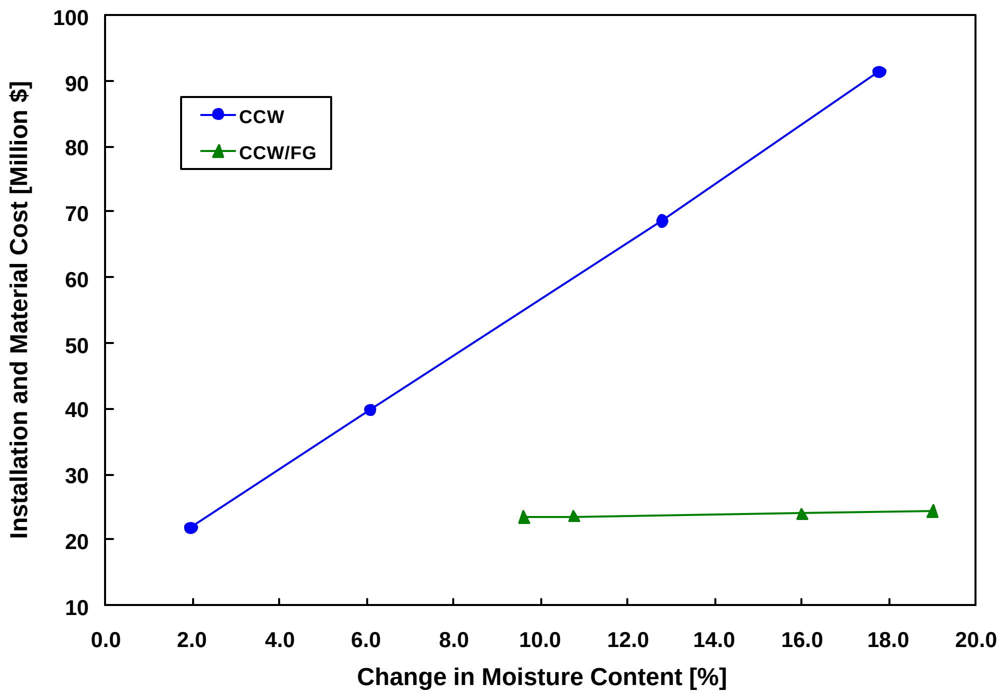

Figure 71: Comparison of Installed Capital Costs as a Function of Reduction in Fuel Moisture (2005 U.S. Dollars).

ANNUAL FIXED AND O&M COSTS

The annual fixed charge, which includes interest, depreciation, taxes and insurance, was calculated assuming a 20 year life and interest rates ranging from 6.5 to 8.5%. The total installed costs and annual fixed costs are given in Tables 6 and 7 as functions of the extent of drying and interest rate. The annual fixed costs range from $3.6 to $4.1 million for the CCW/FG system (Table 6) and from $3.4 to $15.5 million for the CCW system (Table 7).

It was assumed the drying system operates 24 hours a day and seven days a week. Costs for operating and maintenance manpower were estimated by assuming one operator for all the dryers during each operating shift and two maintenance personnel for all the dryers during one shift each day. The operating costs include salaries and wages, employee benefits, supervision, and supplies for operation and maintenance. Other operating costs include electrical power to drive the fluidization air fans and coal crushers and these are included as components in the total station service power, as described later in this report.

Excluding contributions due to station service power, the annual O&M costs were estimated to be $507,321 for all four moisture levels, and the total annual fixed and O&M costs range from $4.1 to $4.6 million for the CCW/FG system (Table 6) and from $3.89 to $16.0 million for the CCW system (Table 7).

Table 6

CCW/FG System – Capital and Operating and Maintenance Costs

% CHANGE IN MOISTURE	TOTAL INSTALLED COST	ANNUAL INTEREST %	ANNUAL FIXED COST	ANNUAL O&M COST	TOTAL FIXED[1] AND O&M COSTS
9.60	$23,446,409	6.5	$3,622,470	$507,321	$4,129,791
10.80	$23,550,919	6.5	$3,638,617	$507,321	$4,145,938
16.00	$24,034,968	6.5	$3,713,403	$507,321	$4,220,724
19.00	$24,387,259	6.5	$3,767,832	$507,321	$4,275,153
9.60	$23,446,409	7.5	$3,856,456	$507,321	$4,363,786
10.80	$23,550,919	7.5	$3,873,655	$507,321	$4,380,976
16.00	$24,034,968	7.5	$3,953,272	$507,321	$4,460,593
19.00	$24,387,259	7.5	$4,011,216	$507,321	$4,518,537
9.60	$23,446,409	8.5	$3,967,132	$507,321	$4,474,453
10.80	$23,550,919	8.5	$3,984,815	$507,321	$4,492,136
16.00	$24,034,968	8.5	$4,066,717	$507,321	$4,574,038
19.00	$24,387,259	8.5	$4,126,324	$507,321	$4,633,645

[1] Not including the effect of drying on station service power.

Table 7

CCW System – Capital and Operating and Maintenance Costs

% CHANGE IN MOISTURE	TOTAL INSTALLED COST	ANNUAL INTEREST %	ANNUAL FIXED COST	ANNUAL O&M COST	TOTAL ANNUAL[1] FIXED AND O&M COSTS
2.00%	$21,887,000	6.5	$3,381,542	$507,321	$3,888,863
6.10%	$39,884,000	6.5	$6,162,078	$507,321	$6,669,399
12.80%	$68,582,000	6.5	$10,595,919	$507,321	$11,103,240
17.80%	$91,350,000	6.5	$14,113,575	$507,321	$14,620,896
2.00%	$21,887,000	7.5	$3,599,974	$507,321	$4,107,295
6.10%	$39,884,000	7.5	$6,560,120	$507,321	$7,067,441
12.80%	$68,582,000	7.5	$11,280,367	$507,321	$11,787,688
17.80%	$91,350,000	7.5	$15,025,248	$507,321	$15,532,569
2.00%	$21,887,000	8.5	$3,703,280	$507,321	$4,210,601
6.10%	$39,884,000	8.5	$6,748,373	$507,321	$7,255,694
12.80%	$68,582,000	8.5	$11,604,074	$507,321	$12,111,395
17.80%	$91,350,000	8.5	$15,456,420	$507,321	$15,963,741

[1] Not including the effect of drying on station service power.

Costs Due to Increased Station Service Power

The components of station service power affected by coal drying include the induced draft and forced draft fan power, mill and crusher power and power for the fluidization air fans.

Coal drying results in a decreased flow rate of combustion air and a decreased flow rate of flue gas thus reducing the power requirements for the forced draft and induced draft fans. Note that fan power is proportional to the air or flue gas flow rate.

Pulverizer power requirements depend on the flow rate of coal through the pulverizers and the energy requirement for grinding per ton of coal. Coal drying results in a reduction in the energy requirements for grinding per ton of coal, as is illustrated in Figure 72, which summarizes laboratory data from Reference 7 on the effect of feed moisture content on pulverizer specific power requirements for seven different lignites. These data show the power/ton of lignite feed varied linearly with coal moisture level, with the specific power at 20 percent moisture being 2/3 of the specific power at 40 percent moisture. Both the reduced coal flow rate and the reduction in grinding energy per ton of coal were taken into account in this analysis.

As noted above, coal drying results in a reduction of the power requirements for the coal pulverizers and for the induced draft and forced draft fans. But it also leads to the addition of two new power components … the power required to drive the fans for the fluidization air and the power for the coal crushers. The flow rate of fluidization air depends on dryer size, which, in turn, depends on the temperature(s) of the heat source(s) used for drying and the difference between the inlet and exit coal moisture levels.

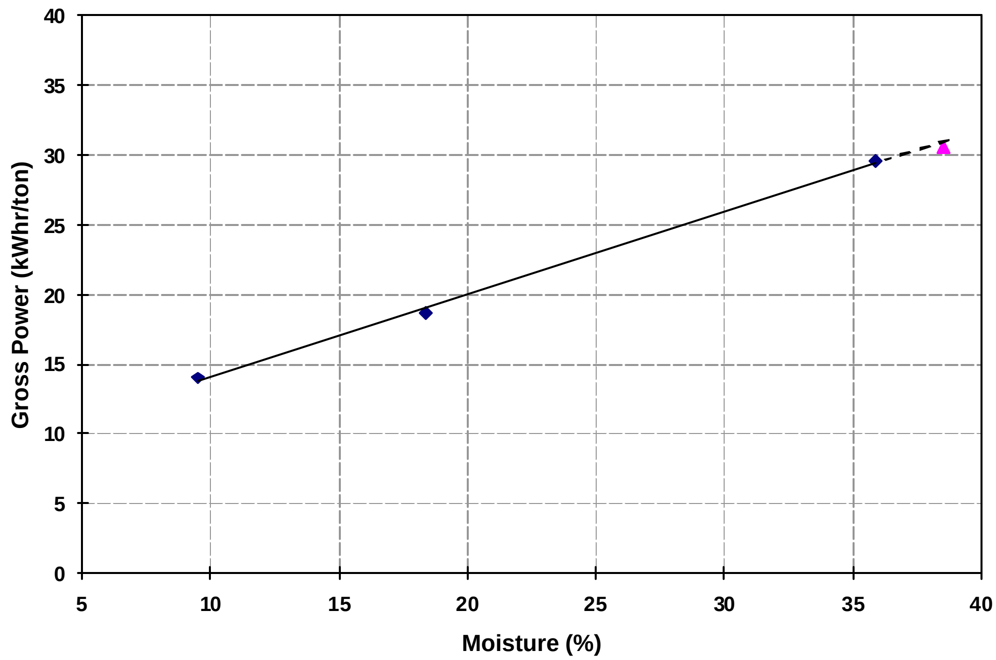

Figure 72a: Effect of Lignite Feed Moisture on Gross Pulverizer Power (kWhr/ton). Adapted from Data by Ellman et al. (Reference 7).

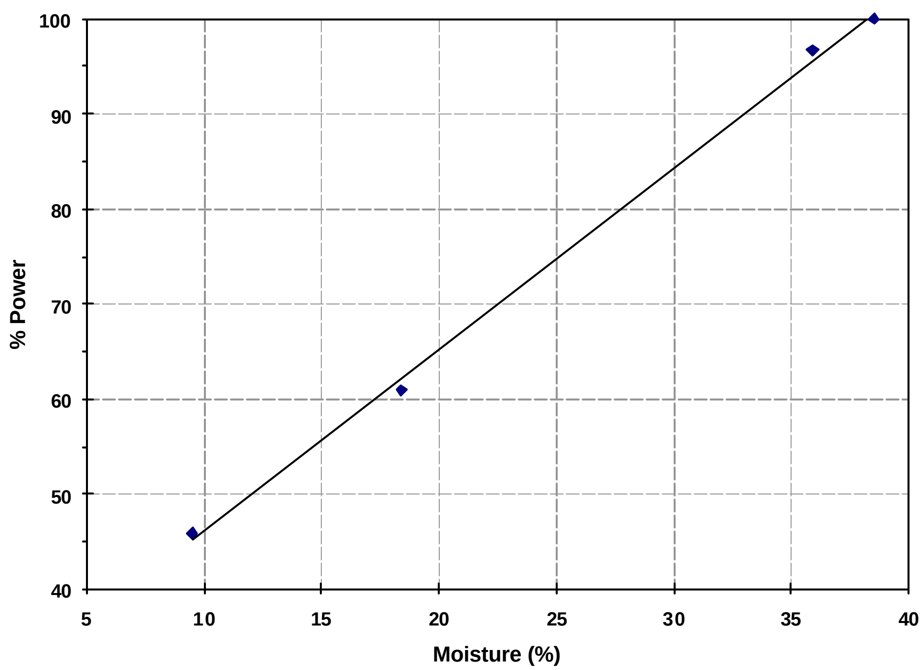

Figure 72b: Effect of Lignite Feed Moisture on Relative Pulverizer Power (kWhr/ton).

The overall impacts of drying on station service power are summarized in Tables 8 and 9. In the case of the CCW/FG system, the station service power requirements increase to values above the baseline for low levels of drying and then decrease to values below the baseline as the coal product moisture is reduced to lower levels (Table 8). Because of relatively large power requirements for the fluidization air fans with the CCW system, the CCW station service power increases steadily as percentage moisture reduction increases (Table 9). Electrical power was assumed to cost $0.05/kWh in these calculations.

Table 8

Incremental Cost of Station Service Power – CCW/FG System

% Moisture Reduction	Δ Station Service Power (MW)	$/year
0.00	0	0
9.61	+1.583	+589,350
10.76	+1.400	+521,220
16.05	+0.732	+272,524
19.07	-0.188	-69,992

Table 9

Incremental Cost of Station Service Power – CCW System

% Moisture Reduction	Δ Station Service Power (MW)	$/year
2.0	+2.25	+837,675
6.1	+5.95	+2,215,185
12.8	+11.95	+4,448,985
17.8	+16.51	+6,146,673

Finally Tables 10 and 11 and Figures 73 and 74 summarize the total annual costs for the two systems. These include fixed costs, drying system O&M costs and incremental station service costs. The tables and figures show annual costs ranging from $4.2 million to $5.1 million for the CCW/FG system and from $4.7 million to $22.1 million for the CCW system.

Table 10

Total Annual Cost – CCW/FG System

% Change in Moisture	Annual Interest %	Fixed, O&M and Station Service Power Costs
9.60	6.5	$4,719,141
10.80	6.5	$4,667,158
16.00	6.5	$4,493,248
19.00	6.5	$4,205,161
9.60	7.5	$4,953,136
10.80	7.5	$4,902,196
16.00	7.5	$4,733,117
19.00	7.5	$4,448,545
9.60	8.5	$5,063,803
10.80	8.5	$5,013,356
16.00	8.5	$4,846,562
19.00	8.5	$4,563,653

Table 11

Total Annual Cost – CCW System

% Change in Moisture	Annual Interest %	Fixed, O&M and Station Service Power Costs
2.0	6.5	$4,726,538
6.1	6.5	$8,884,584
12.8	6.5	$15,552,225
17.8	6.5	$20,767,568
2.0	7.5	$4,944,970
6.1	7.5	$9,282,626
12.8	7.5	$16,236,673
17.8	7.5	$21,679,242
2.0	8.5	$5,048,276
6.1	8.5	$9,470,879
12.8	8.5	$16,560,380
17.8	8.5	$22,110,414

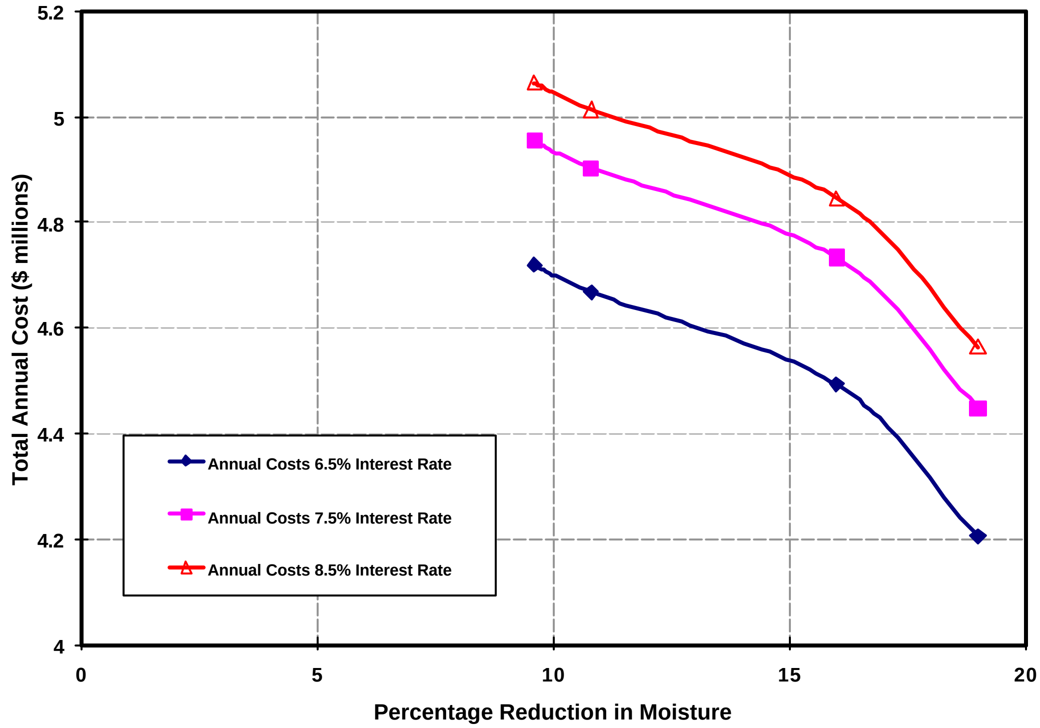

Figure 73: Total Annual Costs – CCW/FG System

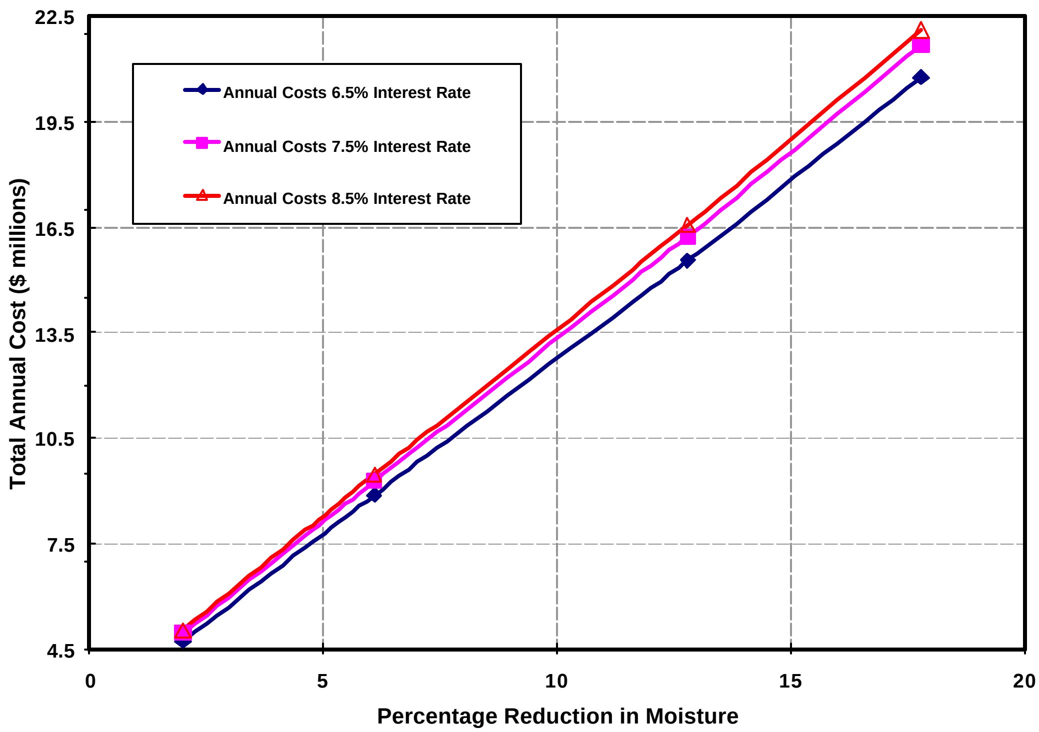

Figure 74: Total Annual Costs – CCW System

FINANCIAL BENEFITS

The potential financial benefits fall into six categories:

- Reduced Fuel Costs
- Reduced Ash Disposal Costs
- Avoided Costs of Emissions Control
- Water Savings
- Reduced Mill Maintenance Costs
- Reduced Lost Generation Due to Mill Outages

The factors considered in quantification of these benefits are described in the following sections of this report. Three estimates are listed for some of the unit cost parameters to reflect ranges of possible values. For this reason, a range of values (minimum to maximum) will be given for the total benefits.

Reduced Fuel Costs

The results presented in Part II of this report show that use of power plant waste heat to dry the coal before pulverizing it results in a reduction in unit heat rate. Thus, for a fixed gross power output, the percentage improvement in heat rate results in a proportional percentage reduction in coal use. A delivered coal cost of $17.36/ton was assumed for the analysis.

Reduced Ash Disposal Costs

A reduction in coal use results in a reduction in ash disposal costs. Ash disposal costs of $8 to $16/ton were assumed. The calculated savings due to reduced fuel and ash disposal costs are summarized in Table 12 for the CCW/FG system and in Table 13 for the CCW system.

Table 12

Annual Ash Disposal and Fuel Savings (CCW/FG System)

% Moisture Reduction	Fuel Savings	Ash Disposal Savings		
		Minimum	Mean	Maximum
9.61	$991,085	$67,869	$101,803	$135,738
10.76	$1,059,840	$75,201	$112,801	$150,402
16.05	$1,577,144	$169,202	$253,803	$338,404
19.07	$1,768,355	$217,331	$325,996	$434,661

Table 13

Annual Ash Disposal and Fuel Savings (CCW System)

% Moisture Reduction	Fuel Savings	Ash Disposal Savings		
		Minimum	Mean	Maximum
2.0	475,468	15,228	22,842	30,456
6.1	1,058,454	75,201	112,801	150,402
12.8	1,637,614	180,670	271,005	361,340
17.8	1,897,060	243,651	365,476	487,302

Avoided Costs of Emissions Control

The reduction in coal use also leads to reductions in emissions of SO_2, NO_x, CO_2 and Hg. Assuming a fixed moisture-free composition of coal fed to the plant, the rates of emissions of SO_2 and CO_2 are directly proportional to the rate at which coal, on a moisture free basis, is burned, and thus the percentage reductions in emissions of SO_2 and CO_2 are equal to the percentage reductions in heat rate. Just with the SO_2 and CO_2, the rate of emissions of Hg will be reduced due to a reduction in the rate at which moisture-free coal is burned. But in addition, there is evidence from laboratory experiments and theoretical analyses that a reduction in flue gas moisture results in enhanced Hg oxidation and thus enhanced Hg capture by particulates (References 9 and 10). If this happens, the percentage reduction in Hg emissions will be larger than the percentage reduction in heat rate. The magnitude of this effect will be site specific and field tests would be needed to quantify the magnitude of the reductions in Hg emissions. Similarly, the impact of coal drying on NO_x emissions is site specific. For purposes of the analyses carried out in this investigation, percentage reductions of the emissions of NO_x, H_g, SO_2 and CO_2 are all assumed to equal the percentage change in heat rate.

The full-load baseline emissions assumed for the analysis are shown in Table 14 and the costs of emissions used to estimate the avoided costs for each of the four gaseous pollutants are shown in Table 15. Table 16 summarizes the avoided costs due to reductions in NO_x, SO_2, Hg and CO_2 for the CCW/FG system and comparable information is shown in Table 17 for the CCW system.

Table 14

Annual Full-Load Baseline Emissions

NO_x (lb/MMBtu)	NO_x (tons/yr)	SO_2 (lb/MMBtu)	SO_2 (tons/yr)	Hg (lb/yr)	CO_2 (tons/yr)
0.22	4,486	0.864	17,625	226	4,416,093

Table 15

Unit Costs of Emissions

NO_x	$2,400/ton
SO_2	$750 to $1,500/ton
Hg	$20,000/lbm
CO_2	$9.10 to $18.20/ton

Table 16

Avoided Costs of Emissions Control (CCW/FG System)

% Moisture Reduction	NO_x	Hg	SO_2			CO_2		
			Minimum	Mean	Maximum	Minimum	Mean	Maximum
9.61	$85,240	$85,757	$251,159	$334,879	$502,318	$761,188	$1,141,782	$1,522,376
10.76	$89,726	$90,270	$264,378	$352,504	$528,756	$801,251	$1,201,876	$1,602,501
16.05	$134,590	$135,405	$396,567	$528,756	$793,134	$1,201,876	$1,802,814	$2,403,752
19.07	$152,535	$153,459	$449,443	$599,257	$898,885	$1,362,126	$2,043,189	$2,724,252

Table 17

Avoided Costs of Emissions Control – CCW System

% Moisture Reduction	NO_x	Hg	SO_2			CO_2		
			Minimum	Mean	Maximum	Minimum	Mean	Maximum
2.0	40,377	40,622	118,970	158,627	237,940	360,563	540,844	721,126
6.1	89,726	90,270	264,378	352,504	528,756	801,251	1,201,876	1,602,501
12.8	139,076	139,919	409,786	546,381	819,572	1,241,938	1,862,908	2,483,877
17.8	161,507	162,486	475,880	634,507	951,761	1,442,251	2,163,377	2,884,502

Water Savings

Reductions in makeup water requirements for evaporative cooling towers due to coal drying will result in avoided costs for water. The cooling tower analyses indicate water reductions of approximately 140 gallons per minute are possible as a result of the CCW/FG drying scheme and up to 380 gallons per minute with the CCW system. The cost of water for large industrial users varies from location to location in the United States, with water costs from \$0.50 to \$3.00 per 10^3 gallons being typical. Tables 18 and 19 list the water savings as a function of degree of drying and the unit cost of water.

Table 18

Annual Water Savings – CCW/FG System

% Moisture Reduction	Water Savings (Gallons/Year)	Water Savings (\$/year)		
		Minimum[(a)]	Mean[(b)]	Maximum[(c)]
9.61	62.5×10^6	\$31,273	\$93,819	\$187,638
10.76	62.5×10^6	\$31,273	\$93,819	\$187,638
16.05	62.5×10^6	\$31,273	\$93,819	\$187,638
19.07	62.5×10^6	\$31,273	\$93,819	\$187,638

(a) \$0.50/10^3 gallon, (b) \$1.50/10^3 gallon, (c) \$3.00/10^3 gallon

Table 19

Annual Water Savings – CCW System

% Moisture Reduction	Water Savings (Gallons/Year)	Water Savings (\$/year)		
		Minimum[(a)]	Mean[(b)]	Maximum[(c)]
2.0	71.48×10^6	35,740	107,220	214,440
6.1	98.29×10^6	49,145	147,435	294,870
12.8	138.5×10^6	69,250	207,750	415,500
17.8	169.8×10^6	84,900	254,700	509,400

(a) \$0.50/10^3 gallon, (b) \$1.50/10^3 gallon, (c) \$3.00/10^3 gallon

In some circumstances, there will be additional financial benefits if the reduction in makeup water requirements results in a decreased need to derate the unit due to a scarcity of water for cooling.

Mill Maintenance and Availability

Pulverizer maintenance requirements depend on coal feed rate, coal mineral content and the grinding characteristics of the coal. All three parameters affect wear rates of mill grinding surfaces and rates of wear and tear on components such as shafts, gear boxes and classifier blades.

This study focuses on retrofit applications, where as a result of coal drying, the existing pulverizers collectively handle lower coal feed rates than is the case without drying. Laboratory grinding studies with lignites (Reference 11) also show the grinding capacity of a mill depends strongly on moisture content, with significant increases of grinding capacity as moisture content decreases. These two factors (reduced coal feed rate to the boiler and increased mill grinding capacity) can often make it possible to take one or more mills out of service while still operating the boiler at full load conditions.

Estimates were made of the impacts of operating with fewer mills on maintenance costs and on the cost of lost generation due to unscheduled mill outages. These estimates are based on data obtained from surveying a group of coal-fired electric utility companies. The estimates assume the power plant has six pulverizers and requires all six to be in operation when firing wet coal, but with coal drying, it can operate at full load using only five pulverizers.

It is assumed each operating pulverizer is normally inspected twice a year, with each inspection costing $25,000 for parts and labor. It is also assumed each operating pulverizer normally undergoes a major overhaul every two years, with an average cost per overhaul for parts and labor of $235,000 per mill. Assuming the inspections and major overhauls are performed during low load periods or during outage periods for other maintenance work, the reduction in maintenance costs from operating five instead of six mills is $167,500 per year (Table 20).

Table 20

Annual Mill Maintenance Savings – Both CCW and CCW/FG Systems

Mill Inspections – Parts and Labor	$50,000
Major Overhaul of Pulverizer	$117,500
TOTAL	$167,500

Being able to operate at full load conditions with five instead of six mills in operation (that is, with one excess mill available for emergency situations) also leads to cost savings in the event there is an unscheduled mill outage at a time of peak power production. Table 21 summarizes the avoided costs of lost power generation due to unscheduled mill outages, where it was assumed unit derates of 1/6 x 537 MW ranging from 0.5 to 1.5 days per year with replacement power costing $0.05/ kWhr, are avoided due to coal drying.

Table 21

Mill Maintenance Savings – Lost Power Generation – Both CCW and CCW/FG Systems

Days of Lost Generation/Year	Avoided Costs/Year
0.5	$44,312
1.0	$88,623
1.5	$132,935

TOTAL FINANCIAL BENEFITS DUE TO COAL DRYING

The individual cost savings with the CCW/FG system, shown in Tables 12, 16, 18, 20 and 21, can be added to obtain the gross annual cost savings due to coal drying (see Figure 75 and Table 22). The annual savings depend strongly on the coal product moisture level and the assumptions used for individual parameters. At the largest percentage moisture reduction considered in this study, the estimated annual benefits range from $4.3 to $6.6 million. Comparison of the individual parameters affected by drying shows, for the drying system configuration analyzed here, the most important savings are the fuel savings and the avoided costs due to reduction of SO_2 and CO_2 emissions. Less important, but still significant, are savings due to avoided costs of Hg and NO_x emissions, reduced costs of mill maintenance, a decrease in lost generation due to unscheduled mill outages, reduced costs of ash disposal, and reduced use of makeup water for power plant cooling.

The gross savings due to coal drying with the CCW system (Table 23 and Figure 76) are slightly higher than those from the CCW/FG system. This is due to a slightly larger heat rate reduction and to a larger reduction in cooling tower makeup water. The estimated gross savings with the CCW system ranges up to $7.4 million for 17.8 percent moisture reduction.

Table 22

Summary of Annual Savings – CCW/FG System

% Moisture Reduction	Minimum Savings	Mean Savings	Maximum Savings
9.6	$2,485,383	$3,090,488	$3,810,587
10.8	$2,623,751	$3,256,960	$4,009,568
16.0	$3,857,868	$4,782,453	$5,870,501
19.0	$4,346,333	$5,392,732	$6,620,220

Table 23

Summary of Annual Savings – CCW System

% Moisture Reduction	Minimum Savings	Mean Savings	Maximum Savings
2.0	$1,298,779	$1,642,122	$2,060,863
6.1	$2,640,237	$3,309,190	$4,115,415
12.8	$4,030,065	$5,060,776	$6,297,332
17.8	$4,679,548	$5,895,237	$7,354,454

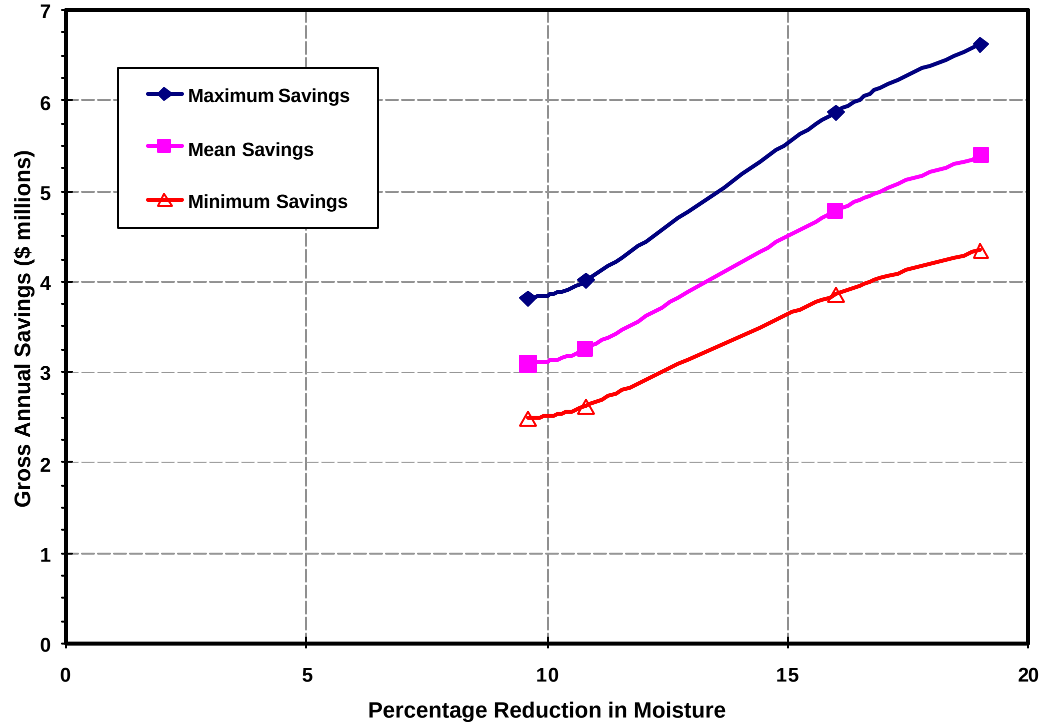

Figure 75: Gross Annual Savings – CCW/FG System.

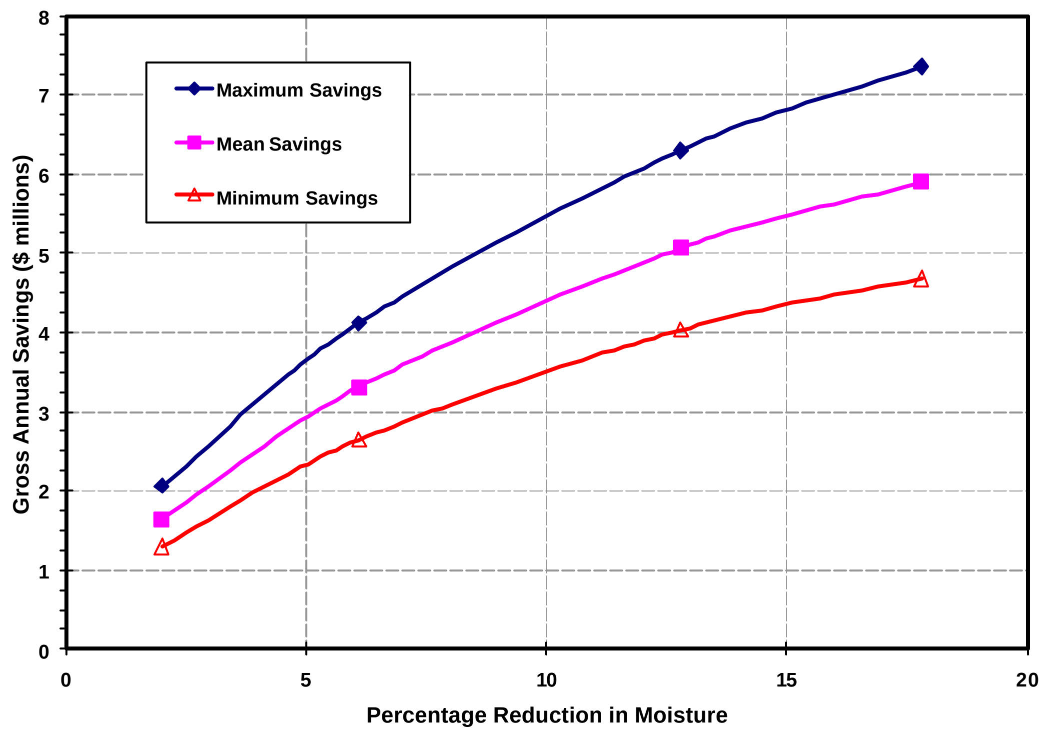

Figure 76: Gross Annual Savings – CCW System.

COMPARISON OF COSTS AND BENEFITS

The comparison of costs and benefits for the CCW/FG system is summarized in Figure 77 as annual dollars versus percentage moisture reduction. The benefits (that is, the savings) at each moisture level cover a range from the minimum to maximum savings, reflecting the range of unit costs assumed for each parameter. The costs of drying also cover a range of values, reflecting the range of interest rates used in the analysis.

These results show that for this particular drying system and the hypothetical coal-fired generation unit which has been analyzed, the cost effectiveness of the technology increases as the coal product moisture decreases. For an annual interest rate of 7.5% and the mean cost savings scenario, the break even point is at 16 percent moisture reduction, with the return on investment increasing linearly to 20.9 percent at 19 percent moisture reduction (Figure 78).

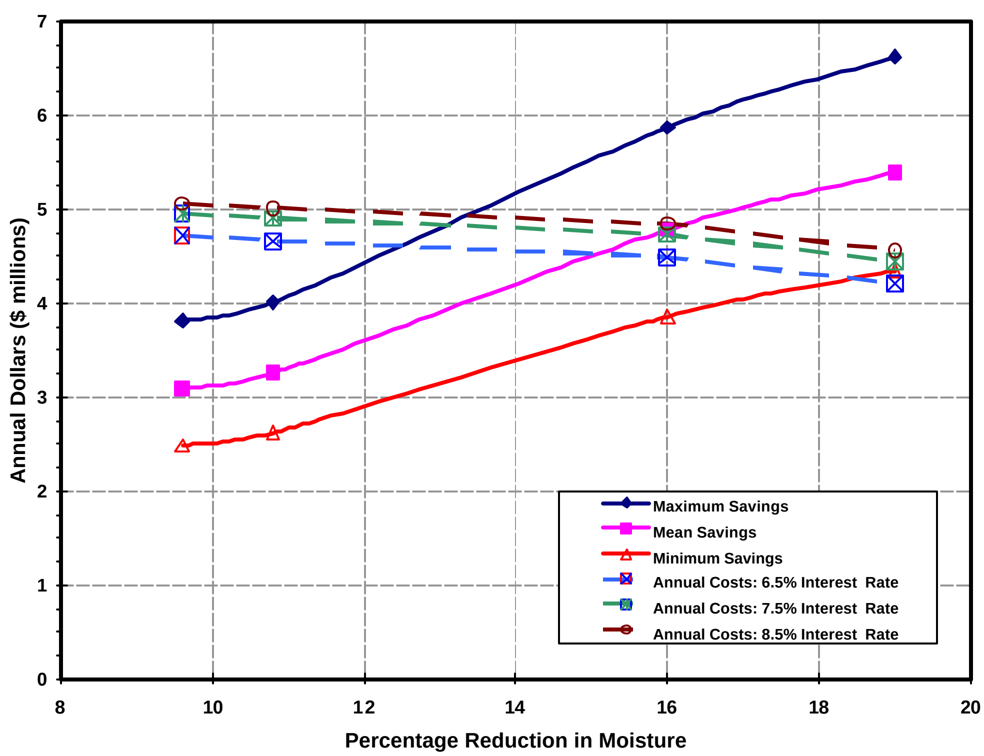

Figure 77: Comparison of Annual Costs and Benefits – CCW/FG System.

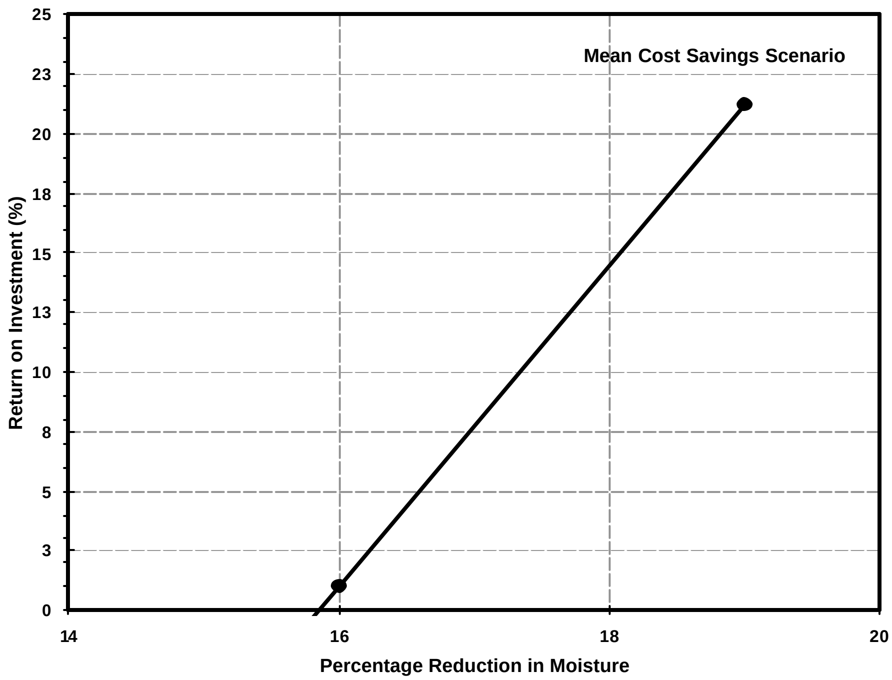

Figure 78: Return on Investment for 7.5 Percent Annual Interest and Mean Cost Savings Scenario – CCW/FG System.

In contrast, the analysis shows that due to relatively high capital costs and high station service power costs for the CCW system, the return on investment for the CCW system is negative for all moisture levels. The annual fixed costs and dryer operating costs (including station service power) for the CCW system range up to $22 million (Figure 74) while the annual gross benefits range up to $7 million (Figure 76). The costs and benefits are compared in Figure 79.

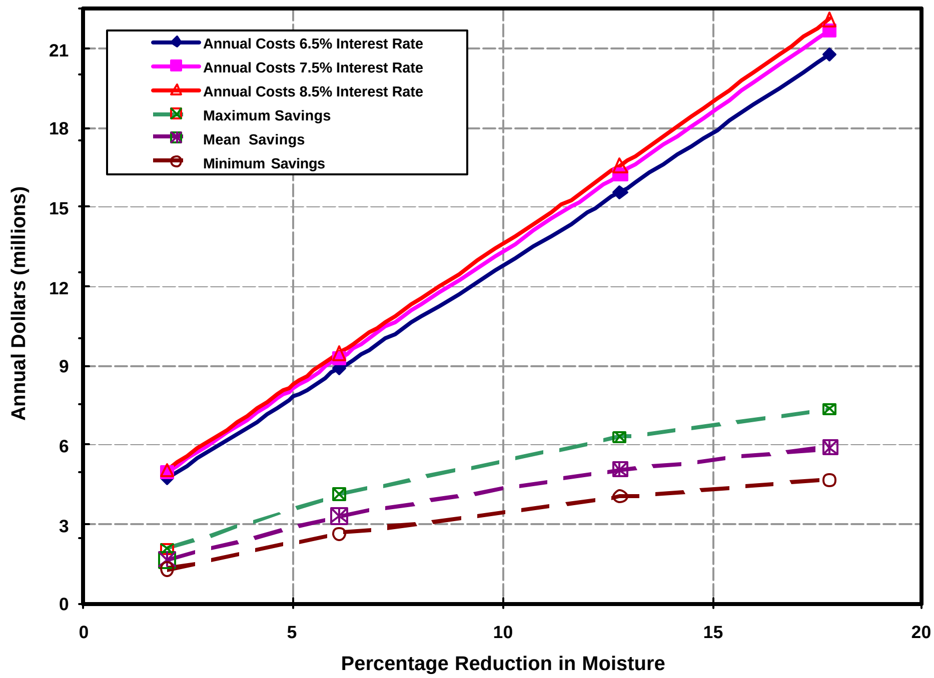

Figure 79: Comparison of Annual Costs and Benefits – CCW System

CONCLUSIONS

Effects of Process Parameters and Coal Type on Coal Drying Rate

Laboratory scale fluidized bed drying experiments were performed with a North Dakota lignite and a Powder River Basin coal to determine the effects of particle residence time, particle size, superficial gas velocity, in-bed heat flux, and temperature and specific humidity of inlet air on rate of drying. The lignite and PRB coals exhibited similar drying characteristics, with a constant rate of drying at the beginning of the drying process, followed by a decreasing rate of drying as the coal moisture content was reduced to lower levels. The rate of drying during the constant rate period increased with superficial air velocity, inlet air temperature and in-bed heat flux and decreased with increasing levels of inlet air specific humidity. Comparisons between drying rates for lignite and PRB coals at the same process conditions show lignite dries slightly more rapidly than PRB coal.

A theoretical drying model was developed for batch fluidized bed drying processes. Based on conservation of mass and energy and an equilibrium relation for air humidity and coal moisture, the model gives excellent agreement with laboratory data. A theoretical model was also developed for continuous flow fluidized bed dryers operating at steady state conditions and calculated results were found to be in good agreement with lignite drying data obtained from a pilot plant-scale dryer located at Great River Energy's Coal Creek Station.

Impacts of Coal Drying on Unit Operations

The second part of the project involved the design of drying systems for lignite and PRB coal-fired power plants and analysis of the effects of drying system operation on cooling tower makeup water, unit heat rate, auxiliary power and stack emissions. The basic power plant configuration used in this analysis consisted of a balanced draft boiler with both forced draft (FD) and induced draft (ID) fans, a bi-sector type air preheater transferring thermal energy from the hot flue gas leaving the economizer to the relatively low temperature air leaving the FD fans, and waste heat from the steam condenser being carried by hot circulating water to an evaporative cooling tower, with cold circulating water being returned to the condenser.

Two drying system designs were analyzed. One, referred to in this report by the acronym, **CCW**, relies on waste heat extracted from the hot circulating water leaving the condenser for drying. This drying scheme involves fluidized bed dryers, where waste heat from the steam condenser is used to preheat the fluidization air and provide additional heat for drying through in-bed heat exchangers. Coal is fed to the dryers and is then transported with reduced moisture to the pulverizers before being conveyed to the burners by transport air. The second type of drying system uses a combination of condenser waste heat and heat extracted from boiler flue gas to attain higher drying temperatures than are possible from condenser waste heat alone. This is referred to in this report by the acronym, **CCW/FG**.

Design and performance analyses were carried out with lignite and PRB coals having 38.5 percent (lignite) and 30 percent (PRB) as-received moisture levels. (Note that in Parts II and III of this report, coal moisture content is based on the definition used in a coal proximate analysis, that is, coal moisture equals mass of water/mass of wet coal.)

Dryer design calculations were carried out to determine dryer size as a function of process conditions and then mass and energy balance calculations were performed for the boiler and its auxiliaries to determine the effects of using power plant waste heat for coal drying on boiler efficiency, net unit heat rate, station service power and make-up water for the evaporative cooling towers.

The results for lignite show that as coal product moisture is reduced, boiler efficiency increases, net unit heat rate decreases and the cooling tower make up water requirements decrease for both the CCW and CCW/FG drying systems (Table 24). For a gross power generation of 572 MW and a 20 percent lignite product moisture, the station service power increases by 17 MW over the baseline for the CCW system and is relatively unchanged for the CCW/FG system. The relatively large increase in station service power for the CCW system is caused by the large dryer and consequently high fluidization air flow rates needed by the low-temperature CCW drying system.

Table 24

Effects of Lignite Drying on Changes in Key Plant Performance Parameters with a 20 Percent Product Moisture

	CCW	**CCW/FG**
Boiler Efficiency	+5.5%	+3%
Net Unit Heat Rate	-3.3%	-3.3%
Station Service Power	+17 MW	Negligible
Cooling Tower Makeup Water	-380 gallons/minute	-140/gallons/minute

Flue gas temperature at the inlet to the induced draft fan sets a constraint on the maximum amount of drying. The acid dew point of the flue gas depends on the concentration of SO_3 in the flue gas. Flue gas temperatures which are too low will result in excessive acid condensation and lead to heat exchanger fouling and corrosion. The results show the CCW system will not be affected by acid condensation as much as the CCW/FG system. A site-specific study would be needed to determine the extent to which heat exchanger fouling and corrosion due to acid condensation constrains the minimum coal product moisture.

The effect of coal drying on unit performance was also analyzed for identical pulverized coal-fired power plants, one firing lignite and the other a PRB coal. These calculations were performed for the CCW/FG drying system. The results show that while there are small differences due to different coal compositions, the performance impacts due to drying lignite and PRB coals follow the same trends and are very similar in magnitude.

Economic Evaluation

Analyses were carried out to determine the cost effectiveness of the CCW and CCW/FG drying systems. These analyses assumed a lignite feed with 38.5 percent moisture, product moisture levels down to 19.5 percent and a gross electric power output of 572 MW. Installed capital costs were found to depend on product moisture, ranging up to $24.4 million for the CCW/FG drying system and up to $91 million for the CCW system.

Annual fixed costs, assuming a 20 year life and a 7.5 percent interest rate range up to $4.1 million for the CCW/FG system and up to $15.5 million for the CCW system. Use of power plant waste heat to dry coal results in a net increase in station service power of up to 16.5 MW for the CCW system and a negligibly small decrease in station service power for the CCW/FG system. Accounting for annual fixed costs, drying system operating and maintenance costs and costs associated with increases in station service power, the annual costs of drying range up to $4.6 million for the CCW/FG drying system and up to $22.1 million for the CCW system.

The potential financial benefits fall into six categories:

- Reduced Fuel Costs
- Reduced Ash Disposal Costs
- Avoided Costs of Emissions Control
- Water Savings
- Reduced Mill Maintenance Costs
- Reduced Lost Generation Due to Mill Outages

Analyses were carried out to estimate the annual financial benefits and at the lowest fuel product moisture levels, these ranged up to $6.6 million for the CCW/FG system and up to $7.4 million for the CCW system.

Comparison of the individual parameters affected by drying shows the most important savings are the fuel savings and the avoided costs due to reduction of SO_2 and CO_2 emissions. Less important, but still significant, are savings due to avoided costs of Hg and NO_x emission control, reduced costs of mill maintenance, a decrease in lost generation due to unscheduled mill outages, reduced costs of ash disposal, and reduced use of makeup water for power plant cooling.

A comparison of costs and benefits for the CCW/FG system show that for this particular drying system and the hypothetical coal-fired generation unit which has been analyzed, the cost effectiveness of the technology increases as the coal product moisture decreases. For an annual interest rate of 7.5% and the mean cost savings scenario, the break even point is at 16 percent coal moisture reduction, with the return on investment increasing linearly to 20.9 percent at 19 percent coal moisture reduction.

In contrast, the analysis shows that due to relatively high capital costs and high station service power costs for the CCW system, the return on investment for the CCW system is negative for all moisture levels. The annual fixed costs and dryer operating costs (including station service power) for the CCW system range up to $22 million while the annual gross benefits range up to $7 million.

Additional Comments

The results from this project suggest that using power plant waste heat to dry high-moisture fuels is both technically and economically feasible. The laboratory drying tests showed that coal moisture can be reduced to less than one-half of that in the raw coal with coal residence times in the dryer small enough to be economic. Rates of drying for lignite and PRB coals were found to be of roughly the same magnitude, with slightly higher drying rates for lignite.

The power plant performance analyses show that coal drying would result in improved boiler efficiency, a reduced net unit heat rate, reduced stack emissions, reduced makeup water requirements for evaporative cooling, reduced pulverizer maintenance costs and improved unit availability. Savings due to decreased emissions of SO_2 and CO_2 and decreased fuel costs are particularly significant cost factors. The cost effectiveness of drying is heavily dependent on drying temperature, with a drying system which uses a combination of heat extracted from boiler flue gas and from the steam condenser providing a significant return on investment. While the low-temperature CCW drying system, which relies exclusively on thermal energy from the steam condenser, results in significantly greater reduction in cooling tower water makeup, its relatively high installed capital costs and costs of increased station service power make this option unattractive from a financial point of view.

The benefits and costs of coal drying will depend heavily on site-specific factors, and detailed analyses would be needed to determine the most cost effective design for a particular application. All of the analyses performed here are for retrofit applications. However, a comparable study should be performed for new plant designs. Potential savings from matching the boiler design and mill, fan, ESP and scrubber capacities to a lower as-fired fuel moisture may very well lead to substantial additional reductions in installed equipment costs.

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NOMENCLATURE

A	Tube Bundle Surface Area
C_c	Specific Heat of Coal
C_L	Specific Heat of Coal Moisture
C_{pair}	Specific Heat of Air
d_p	Particle Size
h_g	Enthalpy of Saturated H_2O Vapor
h_o	Settled Bed Depth
$\dot{m}_a$	Air Flow Rate
$\dot{m}_{coal}$	Coal Flow Rate
$\dot{m}_{DC}$	Mass Flow Rate of Dry Coal
$\dot{m}_{wet\ coal}$	Mass Flow Rate of Wet Coal
ΔP	Fan Pressure Rise
P	Absolute Pressure
P_g	Gross Electrical Power
P_{sat}	Vapor Pressure of H_2O
P_{ss}	Station Service Power
P_{net}	Net Electrical Power
Q	Rate of Heat Transfer
Q_{ave}	Average Heat Flux to Bed
$\dot{Q}_{LOSS}$	Rate of Heat Loss to Surroundings
$\dot{Q}_{TUBES}$	Rate of Heat Transfer in Tube Bundle
t	Time
T	Temperature
$T_{a,in}$	Air Inlet Temperature

T_b	Bed Temperature
U	Overall Heat Transfer Coefficient
u_L	Internal Energy of Coal Moisture
U_o	Superficial Air Velocity
V_{Bed}	Bed Volume
x_i	Mass Fraction of Coal with Particle Size d_{pi}
Y	Coal Moisture $\left(\dfrac{kg\ \ H_2O}{\text{kg}\,\text{H}_2\text{O} + \text{kg dry coal}}\right)$
ξ	X/L (see Figure 31)
ϕ	Relative Humidity
Γ	Coal Moisture $\left(\dfrac{kg\ \ H_2O}{\text{kg dry coal}}\right)$
$\dot{\Gamma}$	Drying Rate $\left(\dfrac{d\Gamma}{\text{dt}}\right)$
ω	Specific Humidity of Air

Subscripts

$_1$	Entering Dryer
$_2$	Leaving Dryer

Abbreviations

APH	Air Preheater
CA	Combustion Air
FA	Fluidizing Air
FB	Fluidized Bed
FD	Forced Draft
HCW	Hot Circulating Cooling Water
ID	Induced Draft

Types of Drying Systems Classified by Heat Source

CCW	Condenser Cooling Water
CCW/FG	A Combination of Condenser Cooling Water and Boiler Flue Gas