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Oxygen-Fired CO₂ Recycle for Application to Direct CO₂ Capture from Coal-Fired Power Plants

FINAL REPORT

Principal Author

Thomas K. Gale

Power Systems Research Group
Southern Research Institute
2000 Ninth Avenue South
P. O. Box 55305
Birmingham, AL 35255-5305

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Prepared for

Timothy Fout
DOE Project Officer
National Energy Technology Laboratory
3610 Collins Ferry Road, P.O. Box 880
Pittsburgh, PA 15236-0940

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Abstract

The Southern Research/Southern Company 1 MWth Pilot-Scale Coal-Fired Test Facility was successfully retrofit to fire in either the traditional air-fired mode or with 100% oxygen and recycled flue gas, with a fully integrated feedback and control system, including oxygen and recycled flue gas modulation during startup, transfer, and shutdown, safety and operational interlocks, and data acquisition. A MAXON Staged Oxygen Burner for Oxy-Coal Applications produced a stable flame over a significant range of firing turn-down, staging, and while firing five different U.S. coal types. The MAXON burner design produces lower flame temperatures than for air firing, which will enable (A) Safe operation, (B) Reduction of recycle flow without concern about furnace flame temperatures, and (C) May likely be effective at reducing slagging and fouling in the boiler and super heater at full-scale Power Plants. A CFD model of the Oxy-fired Combustion Research Facility (OCRF) was used to predict the flame geometry and temperatures in the OCRF and make a comparison with the air-fired case. The model predictions were consistent with the experimental data in showing that the MAXON burner fired with oxygen produced lower flame temperatures than the air-fired burner while firing with air.

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Introduction

Between the submission of the proposal to DOE in October 2004, the award of the project in October 2005, and the completion of the project in October 2010, many changes occurred to the project team, including several changes in major partners, significant internal management and technical staff changes at Southern Research Institute, changes in the terms of agreement between the partners on the project and support provided, and an overall change in the approach pursued to accomplish the retrofit of the facility and performance of the tests required.

As the initial investigation of the project began, it became apparent that the complexity of an oxy-fired system was far greater than originally anticipated. Hence, the approach was changed to develop a more complex control system and perform a more complete overhaul and retrofit of the 1MW pilot-scale testing facility to make the project more meaningful and the retrofit facility more functional for testing on this project and potential subsequent testing.

The costs for the project and the time required to complete the project increased proportionally. In addition, portions of the system that were thought to be covered by members of the initial project team were in fact not covered, and the needed contribution for these portions of the retrofit were far greater than anticipated.

Consequently, Southern Research Institute stepped up and covered much of this additional cost, some of which was provided as cost share on the project, and some of which was not included as a cost share to the project but was paid for out of capital improvement funds at Southern Research Institute.

The retrofit was completed with all the bugs worked out in 2010 and the required testing was completed. However, the project ended (after a two-year extension) in October 2010 just as testing was completed, but before additional model runs could be completed and before awarding the last budget period from DOE that was to fund the reporting of the testing and submission of the Final Report.

Linde Gas was committed on the project to perform the Fireside Simulator runs for different testing conditions using the CFD executable code provided by REI. This was to be cost share on the project and this cost share was no longer allowed following the end of the project in October 2010. *Linde* Gas could have performed the model runs in the last quarter of 2010 and the results could have been included in this report. Unfortunately, *Linde*'s commercial business was quite busy during that time and their staff had been reduced, preventing them from completing this work. Southern Research will continue to pursue this work with *Linde* Gas and publish this information at some future time, if *Linde* is able to get to this project task.

As far as the Final Report is concerned, Southern Research has gone forward and completed a Final Report on this project without hope of reimbursement for such costs. In doing so, the integrity of the staff and the project management at Southern Research has not been compromised, yielding a report of high quality. Nevertheless, significant elements originally anticipated to be covered in the report are not present, due to the fact that the project was ended short of completion and without full project funding. The main missing component was the

additional model validation, which was anticipated to take place in the third and final budget period, either with DOE funding or cost share funding by *Linde Gas*.

In the end, the contributing partners on the project included:

NETL DOE
Southern Research Institute
Doosan Power Systems
MAXON Corporation
Southern Company
Linde Gas

The National Energy Technology Laboratory (NETL) provided overall project management and a significant portion of the funding for the project.

Southern Research performed over 95% of the work on the project, was the second most significant contributor to funding the project, retrofit the existing 1MW pilot-scale test facility, performed the oxy-fired testing, coordinated project team efforts, and was responsible for all reporting.

Doosan Power Systems provided significant funding to the project and provided valuable advice and recommendations during the retrofit and testing process. Doosan Power Systems was also the only boiler maker team member on the project team.

MAXON Corporation designed and built an advanced staged-oxygen burner that was capable of working in the pilot-scale facility, based on the burner concept previously tested in other facilities. In addition, MAXON Corporation provided significant contributions in technical discussions and project meetings.

Southern Company was the utility partner on the project, and among other things, Southern Company co-owns the 1MW pilot-scale testing facility that was retrofit, which they generously allowed to be used for this retrofit project.

Linde Gas provided safety training in relation to oxygen handling. They also donated a receiving skid that accepts the oxygen that arrives near the furnace from the liquid oxygen tank. This skid lowers the oxygen pressure and allows the flow needed for the various burner and furnace inputs. However, the modulation, direction, and flow rates of oxygen were controlled by the system created by Southern Research and its contractors.

In addition, CORR Systems provided engineering services for the retrofit and Reaction Engineering International performed CFD modeling and a stand alone fireside simulator for the project.

The following report describes the system retrofit and the equipment added as part of the retrofit, the tests conducted, the results obtained, and the modeling results insofar as they were obtained.

Executive Summary

The objective of this project was to investigate, develop, optimize, and model oxygen-fired CO₂ recycle for retrofit application to coal-fired utility boilers. Oxygen-fired CO₂-recycle combustion was investigated in the semi-industrial-scale Oxy-fired Combustion Research Facility, at Southern Research Institute, to develop a fundamental understanding of the effects of retrofitting this technology to existing air-blown coal-fired boilers, with a minimum capital expenditure. Specifically, it is intended that existing boilers, materials, and coal-feeding systems will be used.

The mechanisms elucidated in the oxy-enhanced combustion investigation were included in a model that describes temperatures, reaction rates, char burnout, and NO_x formation and/or destruction, as a function of oxygen purity, stoichiometry, coal type, staging, furnace exit oxygen, and fuel processing. The model has been used to compare the temperature profile of the oxy-fired flame with the original air-fired flame, illustrating the cooler temperature of the oxy-fired flame using the MAXON staged-oxygen burner. It is anticipated that the executable version of this model will be used in the future to provide similar comparisons of other parameters.

The initial retrofit of the 1 MW pilot-scale facility was completed in 2009. The summer of 2009 was used to shakedown the facility, discover problems, make necessary changes and fixes, and improve the programming of the control systems. During the startup testing at the end of the summer, it was determined that an additional upgrade was needed to cool the scrubber water, cool the recycled flue gas, and knockout moisture prior to testing with coal. This upgrade was completed in the first quarter of 2010, following which an extensive period of operating, improving, and patching leaks began.

In order to overcome flame instability issues associated with small fluctuations in the coal feedrate, a small amount of natural gas and oxygen flow was maintained in the pilot for all test conditions. Among other things, the furnace and convection pass were operated under positive pressure to eliminate leaks in these sections of the facility.

The parametric testing was completed, covering 65 different test conditions, while testing five different coal types, including three eastern bituminous coals, a PRB sub-bituminous coal, and a western bituminous coal. The conditions covered in the parametric investigation other than coal type included extent of recycle and recycle turndown, furnace exit oxygen percentage, oxygen staging in the burner cup, quarl, secondary recycle and overfire recycle. In addition, the load was also varied as a parameter with and without changes in the amount of recycle flow.

The temperature/time profile of the oxyfired system was not significantly different from the air-fired system when considering the temperatures of the system components and the temperature of the flue gas. The temperature/time profile was affected by four main factors, (1) the difference in load, (2) the difference in recycle flow back to the furnace and the absence of nitrogen flow, (3) the difference in the MAXON oxyburner design and an air-burner design, and (4) the difference in diffusivity of CO₂ and N₂.

Of the four factors listed above, the difference in flow rate was by far the most significant factor, which primarily affected the residence time across which the temperature of the flue gas changed. If the residence time was factored out, i.e., only looking at the temperature changes of the flue gas as a function of distance, then the only significant parameter affecting the temperature profile of the flue gas was the burner design. The furnace temperatures in the oxy-fired system were lower than in the air-fired system, because the MAXON staged-oxygen burner stretched out the heat release in the furnace and created a cooler flame.

The load and percentage of recycled flue gas injected back into the system had little effect on flue-gas emissions or CO₂ purity in the flue gas. However, it was observed for many test conditions and also during transient conditions that increases in the flow rate (through increased load, increased recycle flow to the furnace, or increased air inleakage) increased the backpass temperatures in the system by adding more mass to carry the heat downstream to the backpass components and decreased the furnace wall temperatures by increasing the thermal mass and velocity of the flue gas, which enabled the flue gas to carry more of the heat generated in the furnace downstream. These temperature changes observed were minor however to the overall temperature/time profile, which was fairly similar to the air-fired profile.

Hydrochloric acid measurements were measured continuously during most of the testing. The HCl levels measured were consistent with the concentration of chlorine measured in the coal and no buildup of HCl was observed from recycling the flue gas from the stack. An MKS 2030 FTIR was used to measure many other organic and inorganic components as well, such as benzene, methane, toluene, H₂S, NO₂, NH₃, and many others. However, under no condition were any of these unlikely flue-gas components ever found to be in the detectable range of the FTIR, which for most compounds would have been in the range of 0.1 ppmv or greater. In addition, no significant concentration of H₂SO₄ or SO₃ was measured by the FTIR.

The sulfur dioxide concentration in the flue gas was also consistent with the sulfur contained in the coal and no build up was observed via flue-gas recirculation. The carbon monoxide levels were also consistent with that of air firing, and the CO concentration had a significant correlation with only one parameter, that of furnace exit oxygen (FEO). Above 1.5% FEO, the CO concentration was around 50 ppmv. Below 0.5% FEO, the CO concentration could reach hundreds of ppmv. The relation of unburned carbon (UBC) in the ash with FEO was consistent with that of CO.

Although the MAXON burner staged the oxygen inputs and was optimized to reduce NO_x emissions, NO_x emissions were nevertheless quite high under baseline conditions. Subsequent staging of the oxygen in the secondary recycle gas and in the overfire-recycle flue gas resulted in dramatic reductions in NO_x emissions, such as would generally be observed for air firing. The UBC in the ash increased with increased furnace staging, in a similar manner as what would be observed for air firing.

Finally, the control system and retrofit concept used for retrofitting an existing power plant worked well and smoothly, allowing safe and controlled startup, changing of conditions, continuous operation without buildup of moisture, acid gases, pollutants, or other problems, and yielded efficient combustion of the coal and associated volatile gases. Furthermore, the

MAXON advanced oxygen burner performed well, providing steady flame conditions for a wide range of operating conditions.

Experimental

Oxy-Combustion Research Facility

The Southern Company and Southern Research Institute Oxy-Combustion Research Facility (OCRF) is located in Birmingham, Alabama at Southern Research Institute (Southern Research). The facility, originally designed as an air-fired coal Combustion Research Facility (CRF) using a standard swirl burner, was constructed by Southern Research under contract to Southern Company Services (SCS). Southern Research and SCS jointly own the facility, and Southern Research operates the facility under contract to SCS. However, Southern Research can also perform confidential research for outside parties, including other utilities, with the payment of a facility usage fee to SCS. The facility is designed for up to 3.6 million Btu per hour firing on natural gas or coal, which is equivalent to 1.1 MW thermal. The following description and subsequent sections up to the “System Retrofit” section describes the original CRF facility prior to the retrofit, much of which remains as part of the OCRF and essentially all of which remains as part of the CRF while the unit is in the air-fired configuration.

The design of the facility was carefully chosen to provide a close simulation of the physical processes that occur in a full-scale utility boiler. The facility in its original air-fired configuration is shown in Figures 1 and 2 and consists of a coal crushing and milling area, a coal feeding system, a vertical refractory-lined furnace, a single vertical-fired burner, a horizontal convective section pass with air-cooled tube banks, a series of heat exchangers, an electrostatic precipitator, a pulse jet baghouse, and a packed-column scrubber.

The CRF was converted in this project to allow for testing of oxy-combustion with flue-gas recycle, using a MAXON, direct-fired, staged-oxygen burner. As part of this retrofit, the computer system was upgraded to a Yokagawa CENTUM VP data acquisition and control system, and a separate flame-safeguard and burner-management system (BMS) replaced the existing CS1000 system in which the BMS was included.

Figure 1. The Southern Company / Southern Research Combustion Research Facility (CRF).

SOUTHERN RESEARCH COMBUSTION RESEARCH FACILITY

Birmingham, AL

Figure 2. The Southern Company/Southern Research Combustion Research Facility (CRF).

Fuel Preparation

The fuel preparation area includes an open area storage yard, covered on-site storage bins, a rotary drum coal crusher, a CE Raymond bowl mill, and pulverized coal storage. Eight storage bins, each capable of holding up to 25 tons of coal or other fuel, are located adjacent to the coal preparation area. Approximately one acre of additional fuel storage space is available in front of the facility. As-mined coal is loaded into the crusher with a small front-end loader and is crushed to a size of minus 3/8 inch. From the crusher, the coal is transported via a screw feeder and bucket elevator to one of two 125 ft³ storage bins located beside the mill. These bins are independently located on load cells and are equipped with integral vibrator/bridge-breakers and rotary lock feeders.

The coal mill is a refurbished and instrumented 1937 Model 352 CE-Raymond bowl mill, which has a rated capacity of 2 tons per hour. This type of mill provides representative milling simulations of the different air-swept table and roller mills normally used in power plant service. The mill air is preheated with a dedicated natural gas burner, which also helps inert the mill. For fuels that present an ignition hazard such as Powder River Basin coals and some biofuels, the facility is equipped to accept additional inerting from nitrogen tube trailers or a permanent liquid nitrogen silo. The mill is instrumented to report roller spring pressure, journal lift, motor amperage and voltage, gas flow, and mill rejects to the facility DCS.

Pulverized coal is captured in an Ultra Industries CF-41-8 pulse-jet baghouse and transported through a dedicated dense-phase transport system to either an inerted pulverized-fuel storage

hopper (adjacent to the furnace) or to an inerted, separate waste hopper. Both hoppers are located on load cells. In such small-scale pulverized coal firing, it is normal practice to use indirect firing to help eliminate coal surges that can cause flame stability problems. The mill circuit can also be used to perform stand-alone milling experiments.

Coal Feeding

The coal feeding system is designed to deliver a constant feed of pulverized coal to the burner. The storage hopper is equipped with an orbital-motion live bottom to prevent bridging or rat-holing of the fuel. An Acrison loss-in-weight auger-type feeder weighs a controlled amount of fuel that is discharged into the primary air line through a rotary airlock valve. This gravimetric feeder is suspended on a weighing mechanism, and the feed rate is controlled by varying the auger speed to maintain the desired fuel feed rate.

Radiant Furnace

The furnace is a vertical, up-fired, 28-foot high cylinder, with an inner diameter of 3.5 feet. This allows gas velocities of 10 to 15 feet per second and residence times of 1.3 to 2.5 seconds, depending upon the firing rate. The design furnace exit gas temperature is approximately 1800 °F.

The body of the furnace is built of seven 4-foot tall sections, each being a water-cooled jacket with 4 inches of cast refractory lining the fireside. This refractory lining is used to limit the heat extraction and to ensure the proper simulation of the radiation environment found inside full-scale furnaces. There is much more gas/wall contact in pilot-scale furnaces than in full-scale furnaces, and the flame would be quenched if the entire interior were lined with conventional water walls.

Convective Sections

The combustion gases exit the vertical furnace through a horizontal convection pass, which is designed to remove a substantial part of the heat from the flue gas. The extraction of heat is designed to simulate the temperature-time profile found in a utility boiler. A series of three air-cooled tube banks are installed in the convective pass, and the air cooling is used to control either the temperature profile of the flue gas or the tube metal surface temperatures for fouling/ash deposition studies. A cross-flow tubular air preheater follows the convective tube banks and is used to preheat the primary and secondary air. Finally, four tube-in-shell recuperators are used to cool the flue gas to between 300 °F and 400 °F before the flue gas enters the pilot-scale baghouse or ESP.

The convective section is 1.5 feet x 1.5 feet x 22 feet, providing gas velocities of 30 to 60 feet per second and residence times of 0.4 to 0.8 seconds, again depending upon the firing rate. The design temperature range for the convective section is 1800 °F to 1000°F.

Temperature/Time Profile

The overall air-fired temperature-time profile through the furnace, convective section, and recuperators is illustrated in Figure 3, which includes profiles from several electric utility PC boilers for comparison. As shown, the CRF temperature-time profile matches those of the full-scale units quite well.

Figure 3. Original CRF temperature/time history compared with those of full-scale Southern Company coal-fired power plants.

System Retrofit

A schematic of the original CRF system configuration is shown in Figure 4. The furnace was fired with a single up-fired air burner directly in the center of the furnace. The primary air carried the coal up through a 2.5" diameter pipe ending at the base of the refractory cone. In the center of this cone in the air-fired burner is a natural-gas pilot used to ignite the fuel when lighting off. The coal and primary air enters the air burner at the base of the refractory cone as it exits the annulus formed from the coal pipe and the pilot. The secondary air enters the wind box under the air burner where it passes through turning vanes to impart a specific burner swirl. The secondary air then travels up through the burner where it enters the air burner through the annulus formed between the hole in the center of the quarl and the primary coal pipe and mixes with the coal and establishes an attached flame at the base of the quarl cone.

The quarl itself is 2.5 feet in diameter and sits on a water-cooled metal furnace floor. The refractory walls of the furnace are 3.5 feet in the inside diameter, allowing space for any slag that drips down the furnace walls to fall on the water-cooled furnace floor.

A tube-in-shell heat exchanger located just after the third convective pass is used to preheat the primary and secondary air. The secondary air subsequently passes through ducting with inline

The diagram illustrates the air flow and heating process in a pulverized coal boiler system. Key components and temperature points include:

- Air Inlets:**
 - 1623 F (884 C) and 1418 F (770 C) at the top.
 - 1635 F (891 C), 1864 F (1018 C), 2106 F (1152 C), 2199 F (1204 C), 2271 F (1244 C), 2394 F (1312 C), and 2334 F (1279 C) along the left vertical duct.
- Heating Stages:**
 - CONVECTION COOLING AIR** and **TERTIARY AIR** sections.
 - ECLIPSE CROSS FLOW AIR HEATER** with a temperature of 1064 F (573 C).
 - ELECTRIC AIR HEATER** with a temperature of 325 F (163 C).
 - ECLIPSE RECUP-A-THERM FANS** with temperatures of 860 F (460 C), 500 F (260 C), and 325 F (163 C).
- Air Flow and Fans:**
 - FD FAN** (Forced Draft Fan) and **ID FAN** (Induced Draft Fan).
 - WET SCRUBBER** for dust collection.
 - BAGHOUSE** for final dust collection.
- Control and Monitoring:**
 - DISTRIBUTED CONTROL SYSTEM (DCS)** and **YOKOGAWA CS1000 DATA ACQUISITION** system.
- Other Labels:**
 - TO STACK** (Exhaust to atmosphere).
 - SECONDARY AIR** and **PRIMARY AIR** inlets at the bottom.
 - NATURAL GAS OR COAL** input at the bottom left.

Figure 5 contains a schematic of the retrofit system configured as the OCRF. As shown, a number of new system components were added, including a six thousand gallon liquid oxygen tank and evaporator, a new data acquisition and control system. The air-fired CRF was controlled by a Yokogawa CS1000 distributed control system. This system was replaced with a Yokogawa CENTUM VP distributed control system to handle the greater complexity of the oxy-fired system, and the flame safeguards, interlocks, and operation controls were placed in a separate burner management system (BMS) that the data acquisition and control system must communicate with in order to light the system off, change conditions, and operate continuously.

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additional oxygen is mixed with the coal at the bottom of a cup just below the quarl cone base, and oxygen is also injected through holes in the top ring of the quarl to allow the oxygen to diffuse into the flame as the flame traverses the length of the furnace. The MAXON burner does not allow for a windbox. Consequently ductwork was added to the facility to allow the flue gas to enter in through doors on either side of the quarl, which doors are used to remove ash while in the air-fired configuration. The MAXON oxyburner was constructed and the control system configured to allow natural gas and air firing during startup and heat up and between periods of testing while the system was in an idle mode to keep it hot.

The control system and components were design to transition temporarily to oxygen firing with a mixture of natural gas and flue gas before transferring entirely over to firing with coal and oxygen. The system allows flue gas to be injected into the burner as the transport fluid for the coal, in the secondary ports which are on the sides of the quarl, and in the overfire air ports (or for oxy-firing overfire recycle ports). The system is also capable of injecting additional oxygen into the secondary or overfire recycle ports along with the flue gas.

Figure 5. Configuration after retrofit to Oxy-Fired Combustion Research Facility (OCRF).

The heat exchanger used to pre-heat the combustion air when in the air-fired configuration is not used to heat process gases in the oxy-fired configuration. The air for this heat exchanger is provided by a fan and then discarded outside of the facility. However, the low-temperature heat exchangers that were only used to cool the flue gas in the air-firing configuration are now used to reheat the flue gas before reinjecting it into the furnace in the oxy-fired configuration.

The oxy-fired configuration uses a flue-gas recirculation loop taking flue gas from the stack, pulling it through the recycle fan, pushing it through a flue-gas cooler, mist eliminator, and recuperative heat exchangers and back to the scrubber inlet. Under normal operation, the flue gas flow through this loop may be several times greater than the flue-gas flow into the baghouse. Operating in this manner allows the recycle flow injection rate to be controlled by dampers and control valves while maintaining a constant recycle fan speed. This provides for greater control of flows in the system, a more robust overall control system, and more effective equipment utilization.

Finally, Figure 5 also shows a titanium scrubber cooler, a recycle flue-gas cooler and mist eliminator. It was discovered during the initial testing of the facility in 2009 that the moisture in the flue gas would cycle up in the flue-gas recirculation loop, which increased the flue gas moisture content entering the scrubber. The increasing concentration of moisture in the scrubber inlet caused the scrubber to increase in temperature, due to the heat associated with the condensation of the moisture. The increasing scrubber temperature in turn increased the saturation concentration of moisture in the scrubber outlet, which increasingly made the high moisture concentration problem even worse.

The problem in terms of operation was two fold. First, the scrubber temperature would increase rapidly to the point where it would have melted with continued operation. Secondly, the high moisture content of the recycled flue gas would have caused the primary coal feed line to clog. The addition of a flue-gas cooler and scrubber cooler solved these problems. The scrubber cooler maintains the scrubber liquid temperature at ~80 °F, while the flue-gas moisture content is maintained between 5% and 12%, depending on the coal moisture content.

Equipment Retrofit

The MAXON staged-oxygen burner with flue-gas recycle was mounted coaxially on the bottom of the furnace and up-fired using natural gas, pulverized coal, or a combination of the two. MAXON oxy-coal burners are relatively simple and smaller than air-blown burners. They can be operated in a variety of low-NO_x configurations, including furnace staging with overfire air and flame staging in a low-NO_x burner mode.

Among other things, the MAXON oxy-burner design accounts for the significant reduction in oxidant feed encountered for oxy-fired CO₂ recycle retrofit, while maintaining the coal feed rate. A closed-circuit television camera with a control-room monitor allows constant monitoring of the flame from the top of the furnace.

The MAXON burner introduces all of the oxygen right at the burner, rather than making a synthetic air. The coal is transported up to the bottom center of the burner with recycled flue gas, containing only the oxygen left in the system exhaust. The relatively pure oxygen from the cryogenic air-separation system (or the oxygen tank during testing) is introduced around the bottom of a cup that forms a transition from the coal feed pipe to the bottom of the burner quarl. The natural gas/oxygen pilot extends up through the center of the coal feed pipe with its tip ending at the bottom of the cup. The cup is wider than the coal pipe, which allows for the oxygen introduction without accelerating the coal and transport gas flow. The coal and oxygen

premix in the cup and are ignited by the oxy-pilot. This allows the oxy-coal flame to attach at the top of the cup, which is the bottom of the quarl.

The nitrogen present in an air-fired burner reduces the combustion temperature of the coal, lengthens out the flame and the release of heat through the boiler. Replacing air with oxygen in an air-fired boiler without recycle would greatly intensify the temperature of combustion and would concentrate the release of heat at and near the burner, resulting in damage to the burner and boiler, poor heat transfer characteristics, and intense slagging. A necessary feature of any oxy-fired retrofit technology is to stretch out the release of heat from the coal similar to that of an air-fired burner. The MAXON burner accomplishes the staged release of heat by first premixing the coal with a small amount of oxygen in the cup to establish a flame at the quarl bottom. Then the remaining oxygen is introduced through holes in the upper edge of the quarl on the outside of the flame. Introduction of oxygen in this manner creates a diffusion flame. Hence, the MAXON burner used in this oxy-fired retrofit system uses a flame that is initially premixed (with a small amount of oxygen) followed by the remaining part of the flame, which is a diffusion flame. The diffusion part of the flame only burns as the oxygen diffuses into the flame, which stretches out the flame and releases the heat similar to that of an air-fired burner, as shown in Figure 6 below.

In fact however, the MAXON burner has much more control than an air-fired burner. The oxy-fired flame can be adjusted to burn with a tight release of heat or stretched out to release heat over even a much longer distance than even a typical air-fired burner.

Figures 6. MAXON Burner illustrating length of oxygen-diffusion part of flame.

Figure 7 below shows a picture of the lower part of the MAXON burner, without the quarl attached. The coal is introduced through from the pipe on the right, turns through the elbow and up to the burner cup. The oxygen pilot passes straight up through the elbow into the center of the burner. The large round thick metal disk at the top of the burner is the oxygen plenum which feeds oxygen through the ports at the upper edge of the quarl. For the Oxy-Fired Combustion Research Facility (OCRF) the burner shown was constructed to allow natural-gas and air firing

through the coal pipe and burner cup, which saves considerably on the cost of heat up and while maintaining heat in the facility over night.

Figure 7. MAXON Oxy-Burner, showing the coal feed pipe, oxy-pilot input, and oxygen plenum.

Figure 8 shows a picture of the bottom of the quarl, with room for the oxygen plenum to fit into place under it, the six holes for oxygen to feed the diffusion flame, two alignment holes, and the center hole through which the burner fits. While the burner shown is based on the same design used by MAXON elsewhere, the burner design was modified to accommodate limitations of the Southern Research facility. Specifically, while the quarl was about 2.5 feet in diameter and sits on the water-cooled furnace floor, the burner itself had to extend up into the quarl from below the water-cooled floor through a round opening only 9 inches in diameter. In addition, there was limited distance between the floor of the building (made of 6 feet thick concrete) and the bottom of the furnace.

Figure 8. Bottom of MAXON Burner Quarl.

Figure 9 shows the MAXON burner (not in the furnace) with the quarl mounted in place.

Figure 9. MAXON Burner and quarl.

Figure 10 shows a series of pictures of the MAXON Burner flame taken from a port in the top of the OCRF furnace, while firing coal, oxygen, and recycled flue gas.

Figure 10. MAXON Burner Flame as tested in the OCRF at Southern Research Institute.

Figure 11 shows a picture of the oxygen receiving skid provided by *Linde* Gas that takes the oxygen from the tank after it enters the building, reduces the pressure and allows the flow rate to be increased or decreased as needed. As shown, the skid is hooked up to the pipe carrying the oxygen from the tank that extends through the wall on the right. The skid is also connected to the oxygen piping that leads to the furnace control valves and burner.

The oxygen flow system designed and implemented by CORR Systems and Southern Research allows oxygen to be introduced into the pilot, bottom of the burner cup, top edge of the burner quarl, recycled flue gas at the base of the furnace and recycled flue gas at the overfire air ports.

Figure 11. Oxygen skid provided by *Linde Gas*.

Figure 12 shows the 6000 gallon liquid oxygen tank and pad and associated evaporator.

Figure 12. 6000 gal liquid oxygen tank (left) and evaporator (right).

The picture on the left of Figure 13 shows the takeoff of recycle flue gas from the fiberglass stack. To the right of that picture is a picture of the recycle fan into which the recycle gas feeds.

Figure 13. Recycle takeoff from the stack (left) and recycle fan (right).

After the recycle fan, the flue gas passes through a flue gas cooler and subsequent mist eliminator prior to being recycled back into the furnace and used for transport media. Additional moisture tends to build up in the system when the scrubber temperature is not kept under control, which tends to increase the saturation concentration of moisture in the flue gas leaving the scrubber, which further exacerbates the problem until either the scrubber temperature exceeds its operational limit and/or the coal feeding system clogs due to increase moisture. Therefore, a scrubber cooler is used to keep the scrubber temperature in check.

Both the flue gas cooler and scrubber cooler are shown in Figure 14. The cooling tower used to cool and recycle the water used in these two heat exchangers is also shown in Figure 14.

Figure 14. Flue-Gas and Scrubber Cooler (left) and coolant recycling cooling tower (right).

From the mist eliminator, the duct connects with the recuperator cold-side flow, as shown below in Figure 15, where the flue gas is cooled and the recycled flue gas is preheated, prior to being fed to the burner and recycle injection ports.

Figure 15. Heat exchangers to cool the flue gas and preheat the recycle.

Once the flue gas has been preheated in the recuperatherms, it is metered into what was the secondary-air line (as shown in Figure 16 below on the left), where it is heated further by in-duct electrical heaters. The pneumatic valves shown in the pictures below and in other pictures of the facility are opened or closed depending on whether or not the facility is operating in oxy-fired mode or in air-fired mode. The duct in the picture on the right of Figure 16 directs the exit air from a heat exchanger (used as the air heater in air-firing configuration) out of the building.

Figure 16. Switching valves used to transition from air firing to oxy-firing.

Figure 17 shows the duct that transports excess recycled flue gas from the recuperatherm exit (from the preheating side) back to the ID fan exit and on into the scrubber. The duct is maintained under positive pressure during all testing. Since the oxy-fired control system requires fairly complex and precise control of flows, pressures and the ability to make continuous changes to the gas flows and pressures, it was not practical to try and control the flow of recycled flue gas by the recycle fan speed. Rather, the recycle fan is operated at a consistent speed and the flow of recycled flue gas is controlled by valves and dampers, and some flue gas is returned to the scrubber.

Figure 17. Recycle gas return loop to scrubber entrance.

After being heated, the recycled flue gas is injected into the two ports on either side of the burner-quarl base, through the ducting shown in Figure 18 below. The ducting was purposely designed so that the distance from the split tee is equal in distance and shape. This ensures that the pressure and flow rate of flue gas on either side of the burner is equal during operation.

Figure 18. Wrap-around duct work for main recycled flue gas introduction in furnace.

The transport gas during oxyfiring is taken from the side of one of the recuperators, as shown in Figure 19 in the left picture. The picture on the right shows the connection of the flue gas to the low-velocity eductor that entrains the coal dropped from the air-lock rotary valve and transports it to the MAXON burner where it is mixed with oxygen, ignited, and then gradually mixed with more oxygen and flue gas as the flame propagates along the length of the furnace.

Figure 19. Transport recycle takeoff (left) and connection to coal transport system (right).

Data Acquisition and Control Systems

The facility is controlled and monitored by networked combined distributed control system (DCS) and data acquisition computers, managed by Yokogawa CENTUM VP system software that runs under the Windows XP operating system. The computer control system communicates with an independent burner management system (BMS) that performs the safety monitoring needed for operation of combustion equipment, including flame scanning and interlocks, and automatic shutdown of the entire facility. Other than the burner management and flame safeguard systems, which has a stand-alone control system, this DCS performs all process control for the facility and allows complex feed-forward and calculated variable control, including all other safety systems and safety interlocks. Process data acquisition and storage is also accomplished within the Yokogawa software.

Safety System and Interlocks

As part of the retrofit from a purely air-fired system to a facility that could fire with 100% oxygen and recycled flue gas, the safety interlocks that were part of the original operational control system were replaced by a new set of safety interlocks, some of which are now located in a completely separate control system called the Burner Management System (BMS). The BMS now must be communicated with by the main operation and control system in order to light off the flame and control feed of oxygen and fuel to the burner. The BMS panel controls all flame safety functions and will shut down the furnace safely in case of a malfunction, operator error, or if unstable or unsafe operating conditions are reached. The list of safety interlocks programmed into the system is shown in Table 1.

Table 1. Safety interlocks used in the OCRF.

Description	Required for Purge	Required for Light	Master Fuel Trip
Low Gas Pressure	Y	Y	
High Gas Pressure	Y	Y	
Main Gas Valves shut	Y	Y	
Main Gas Vent shut	Y	Y	
Furnace Exit Temperature	Y	Y	Y
Convection Pass #1	Y	Y	Y
Convection Pass #2	Y	Y	Y
Convection Pass #3	Y	Y	Y
High Furnace Pressure	Y	Y	Y
Oxygen Valves Closed	Y		
Low Plant Air Pressure	Y	Y	Y
High Oxygen Temperature	Y	Y	Y
Coal Feed Off	Y	Y	
Air Valve for Pilot Closed	Y	Y	Y
Minimum Oxygen/Recycle/Air	Y	Y	Y
Minimum Air for Purge	Y		
IR Flame Scanner			Y
UV Flame Scanner			Y
Coolant Water Pump	Y	Y	Y
FD-Fan	Y	Y	Y
ID Fan	Y	Y	Y
Recycle Fan	Y	Y	Y
Low Water Flow	Y	Y	Y
High Baghouse Inlet Temperature	Y	Y	Y
High Scrubber Inlet Temperature	Y	Y	Y
Scrubber Pump Failure	Y	Y	Y
Emergency Stop Button	Y	Y	Y

In addition to the safety interlocks associated with the BMS, there are numerous alarms and interlocks in the main control system that are in place to avoid unwanted release of pollutants,

damage to the facility by exceeding high-temperature limits, damaging the bowl mill, reaching a scrubber pH that is too low, or numerous other undesirable conditions. “Required for Purge” means that the condition must be met before the purge cycle is allowed to proceed. “Required for Light” means that the condition must be met before the light off cycle is allowed to initiate. “Master Fuel Trip” means that if at any time the condition is not met, the fuel for the facility will be shut down along with a series of other trips that will shut the facility down and prevent any unsafe conditions from occurring.

An *either-or* flame scanning system using both IR and UV flame detectors is used to continuously validate the presence of a stable flame.

Continuous Emission Monitoring System

A complete extractive continuous-emission monitoring (CEM) system is installed in the facility, and it is also interfaced to the computer control system. A continuous and *insitu* measurement of the furnace exit oxygen is made with a zirconia cell. In addition, a set of gas analyzers, which analyze the flue gas for concentrations of O₂, NO_x, SO₂, CO₂, and CO, receive dry flue gas sampled from a port just upstream of the baghouse, including a CO₂ monitor that can accurately measure the concentration of CO₂ from 0% to 100% in the flue gas. The flue gas is dried prior to reaching the analyzers.

Other Flue Gas Measurements

An MKS 2030 FTIR was used to provide additional flue gas component information for species such as ammonia, hydrogen chloride, sulfuric acid vapor, trace organics, water vapor, methane, ozone, nitrogen dioxide, and nitrous oxide, and also was used to check the validity flue gas component measurements by the CEMs, such as CO and NO.

A Gas Chromatograph (GC) was used to measure the bulk concentration of oxygen, nitrogen, and carbon dioxide in the flue gas at the baghouse inlet and at other locations in the facility.

Ash and Fuel Analysis

The percentage of flyash collected in the bottom ash, convection pass, and baghouse was measured for each coal type. The Ultimate and Proximate analysis of each coal type tested was performed on a coal-feeder discharge sample taken for each coal type. The data obtained from the analysis of each coal can be found in Tables A1 through A5 of the Appendix.

Results and Discussion

Parametric Test Results

The data obtained from parametric testing in the OCRF was compiled in data Tables A6 through A12 located in the Appendix of this report. A description of each data table is provided in the Appendix along with each table. This section contains a higher level discussion of the data obtained.

Hydrochloric acid measurements were measured continuously during most of the testing. The HCl levels measured were consistent with the concentration of chlorine measured in the coal and no buildup of HCl was observed from recycling the flue gas from the stack. An MKS 2030 FTIR was used to measure many other organic and inorganic components as well, such as benzene, methane, toluene, H₂S, NO₂, NH₃, and many others. However, under no condition were any of these unlikely flue-gas components ever found to be in the detectable range of the FTIR, which for most compounds would have been in the range of 0.1 ppmv or greater. In addition, no significant concentration of H₂SO₄ or SO₃ was measured by the FTIR.

The sulfur dioxide concentration in the flue gas was also consistent with the sulfur contained in the coal and no build up was observed via flue-gas recirculation.

One of the main parameters considered during this project was the percentage of flue-gas recycle put into the furnace. It will be desirable for any plant retrofit to minimize the percentage of flue-gas recycle, because this will minimize both the capital and operation costs. The minimum flow of recycled flue gas put back into the furnace will be based on that necessary to maintain the required heat transfer to the water walls and superheater steam tubes. A reduction in the percentage of recycled flue gas up to 35% or more was examined for all of the coal types tested in this project and no correlation with any of the emissions parameters was observed.

As shown in Figure 20, it was discovered that increasing the flue gas recycle percentage injected into the furnace somewhat decreased the furnace wall temperatures and increased the temperatures in the convection pass and subsequent heat exchangers.

Figure 20. Furnace wall temperatures versus recycled flue gas turn down.

Figure 21 illustrates a correlation between increased secondary flue-gas injection and the temperatures of the flue gas in the convection pass. The scatter in the data is attributed to confounding parameters, such as inleakage, which will do the same thing as adding more flue gas to the system.

For all test conditions and certainly for the data in Figure 21, the primary flow rate was relatively constant, and for the data in Figure 21, no overfire recycle was used, so the change in secondary recycle injection represents the total change in the flow of recycled flue gas into the furnace.

The reason why the temperatures decrease in the furnace when more flue gas is injected is because there is more thermal mass to carry the heat released from combustion of coal in the furnace downstream. This is the same reason why the temperatures in the backpass increased with increasing flow of recycled flue gas. The additional mass in the flue gas carried more of the heat downstream. The higher flow rates yielded greater heat transfer to the walls of the convection pass and subsequent sections, and the temperature increased in those sections.

Figure 21. Convection section 1 exit temperature versus recycle injection rate.

Although the general trend was for the furnace temperature to increase and the convective and subsequent section temperatures to decrease with a reduction in the recycled flue gas, it was generally true that the overall temperature time profile of the facility was not significantly different than during air firing.

Figure 22 shows a comparison of the overall temperature/time profile during oxyfiring with an average temperature/time profile from air-fired testing in the same facility. As shown, the furnace temperatures are a bit lower and the residence time required to traverse the system is much longer during oxy-firing than it is during air firing. However, the actual temperature of the flue gas at each location in the system is not that much difference than for the air-fired case.

Figure 23 contains the same two plots as shown in Figure 22 and an additional plot of the oxy-fired temperature profile plotted versus the air-fired residence time. Plotted in this manner, the oxy-fired temperature profile overlays the air-fired profile from the furnace exit on, thus indicating that the flue gas temperatures in each location of the system were essentially the same as that for the air-fired system.

Even plotted versus the air-fired residence times however, the furnace temperatures were much cooler in the oxy-fired case than in the air-fired case. The furnace temperatures in the oxy-fired system were lower than in the air-fired system, because the MAXON staged-oxygen burner stretched out the heat release in the furnace and created a cooler flame.

Figure 22. Air-fired and oxy-fired temperature-time profile compared.

Figure 23. Oxy-fired temperature profile plotted versus air-fired residence time.

The temperature/time profile was affected by four main factors, (1) the difference in load, (2) the difference in recycle flow back to the furnace and the absence of nitrogen flow, (3) the difference in the MAXON oxyburner design and an air-burner design, and (4) the difference in diffusivity of CO_2 and N_2 .

Of the four factors listed above, the difference in flow rate was by far the most significant factor, which primarily affected the residence time across which the temperature of the flue gas changed. Beyond the flow rate, the most significant factor was the MAXON oxyburner design.

Figure 24 contains gas suction pyrometry measurements of the furnace during oxyfiring compared with those obtained during air firing. As shown previously, the temperatures in the lower portion of the furnace were significantly cooler during oxyfiring, as a result of the MAXON oxyburner that staged the oxygen to produce a cooler flame temperature.

Figure 24. Air-fired and oxy-fired furnace gas-temperature profiles obtained from gas suction pyrometry measurements.

Figure 25 illustrates the comparison of the temperature/time profile of the backpass for each of the five coals tested under oxy-firing conditions with that of the air-fired temperature/time profile. Once again, it is clear that the most significant difference in the temperature profile was the residence time associated with the lower gas-volume flow. Other than the residence time, the system temperatures were quite similar.

Figure 25. Convection pass temperature-time profile.

Figure 26 contains a graph of the furnace wall temperatures for each of the coals tested during oxyfiring and a comparison with a previously measured air-fired furnace wall-temperature profile. The wall temperatures were measured by thermocouples placed next to the refractory on the back side of the furnace wall. As such, the actual temperature measurement depends on where the thermocouple was placed and how it was positioned.

The wall temperatures were consistent for each of the coals tested in oxyfired mode and were similar to that of the air-fired wall-temperature profile, except for the temperature reading just past the 10 feet mark. It is supposed that this discrepancy in the wall-temperature measurement is due to a change in the position of the thermocouple inserted against the refractory for the temperature measurement. The fact that all of the other temperatures are very similar is reason to believe that the wall temperature for each condition during oxyfiring was similar to that of the air-fired case.

The significance of knowing that the wall temperatures were similar to the air-fired case is that it eliminates a variable from consideration. If the wall temperatures were much cooler than in the air-fired case, this could be a reason why the flame temperatures were cooler. However, since the wall temperatures were similar, the cooler flame temperature was due to the staged-oxygen firing of the MAXON burner.

Figure 26. Furnace wall temperatures compared between air- and oxy-firing.

Figure 27 contains a schematic of the burner and lower section of the OCRF furnace showing the locations of coal, oxygen, and flue-gas recycle injection. As shown, coal enters the bottom of a cup with the primary recycle flue gas where it is then mixed with oxygen that enters the bottom of the cup. The premixed coal and oxygen establish an attached flame at the top of the cup, which is the bottom of the quarl cone. Additional oxygen is injected through holes in the top of the quarl cone on the perimeter of the flame, where the oxygen can subsequently diffuse into the oxy-coal flame as it passes through the furnace, thus stretching out the flame length and releasing the heat over an extended area. This is why the MAXON burner flame is cooler than the air-fired flame and yet yields a stable and consistent flame.

During the parametric testing, the flow of oxygen into the cup and in through the quarl ring was adjusted as part of the test matrix. The secondary flue gas was injected through the ports on either side of the quarl as shown in Figure 27, and the tertiary flue gas was injected in the overfire air ports. The upper sections of the furnace are not included in Figure 27. The only section shown is section 1. The overfire ports are actually in the center of furnace section 4. Under baseline conditions, no recycled flue gas was injected in the overfire ports.

The amount of flue gas recycle injected into the secondary and tertiary ports was a test parameter as was the percentage of oxygen taken from the quarl and injected with the secondary recycle and the tertiary recycle flue gas.

Figure 27. Oxygen, recycled flue gas, and coal injection points.

As shown in Figures 28 and 29, there was little if any meaningful correlation between the ratio of oxygen in the cup and the quarl and the concentration of CO and NO_x in the flue gas. The burner certainly was more stable within a certain range of oxygen flows in the cup. Since there wasn't any other significant correlation between these parameters, the burner was subsequently operated in this range of greatest burner stability.

Figure 28. Carbon monoxide emissions versus oxygen flow in the burner cup and quarl.

Figure 29. NOx emissions versus oxygen flow in the burner cup and quarl.

There was a bit more of a relationship between the oxygen in the cup and the unburned carbon (UBC) in the ash, as shown in Figures 30 and 31. Consistent with burner stability, the more oxygen in the cup within the range tested, the more efficient was the carbon burnout. For PRB coal, as was the case for all test conditions in this work, the UBC was fairly low regardless of the oxygen in the cup. Powder River Basin has an active carbon type and thus tends to burn out well under most operating conditions.

The one parameter that CO concentration in the flue gas did correlate with was the furnace exit oxygen (FEO). As shown in Figure 32, below 0.5% FEO, the CO concentrations were quite high. However, above 1.0% FEO the CO concentration tended to be around 50 ppmv. There wasn't much of a correlation between NOx and FEO (see Figure 33), and the relationship between UBC and FEO, although less pronounced, was similar to that of carbon monoxide, as shown in Figure 34.

Figure 30. Unburned carbon versus oxygen flow in the burner cup.

Figure 31. Unburned carbon versus oxygen flow in the burner quarl.

Figure 32. Carbon monoxide emissions versus furnace exit oxygen percentage.

Figure 33. NO_x emissions versus furnace exit oxygen percentage.

Figure 34. Unburned carbon versus furnace exit oxygen percentage.

Again, there was little correlation between the carbon monoxide concentration in the flue gas or UBC in the ash and secondary recycle staging (see Figures 35 and 36). However, for each coal type there was a reduction in the NO_x concentration in the flue gas when oxygen was moved from the quarl and mixed with the secondary recycle flue gas, as shown in Figure 37.

Figure 35. Unburned carbon versus secondary recycle staging.

Figure 36. Carbon monoxide versus secondary recycle staging.

Figure 37. NO_x concentration versus secondary recycle.

As mentioned, the carbon monoxide concentration correlated with the FEO and little else. Consistent with that statement, Figure 38 illustrates very little correlation between the carbon monoxide concentration and staging in the overfire ports.

Figure 39 on the other hand, as expected, illustrates significant overfire staging impacts on NO_x formation in the flue gas. During every condition, the recycled flue gas contained some oxygen, and so just moving 15% of the recycled flue gas from the secondary ports to the overfire ports resulted in a decrease in NO_x formation for three out of the five coals.

However, when 15% of the oxygen in the quarl was moved to be injected with the flue gas in the overfire ports, the reduction in NO_x emissions was significant for all five coals, reducing the NO_x concentrations from levels greater than 1100 ppmv for Galatia coal to around 200 ppmv for the Blacksville coal.

This dramatic reduction in NO_x formation during furnace staging is consistent with results obtained for air-fired staging in the same facility and experienced every day at full-scale power plants. However, it is somewhat interesting that the staged oxygen in the MAXON burner did not reduce the NO_x concentrations significantly in and of itself and the furnace staging was necessary to achieve the NO_x reductions illustrated in Figure 39.

Figure 38. Effect of over-fire recycle staging on carbon monoxide emissions.

Figure 39. Effect of over-fire recycle staging on nitrous oxide emissions.

Consistent with furnace staging in air-fired systems, the UBC in the ash increased with increasing furnace staging, as shown in Figure 40.

Figure 40. Effect of over-fire recycle staging on unburned carbon in ash.

For six test conditions, a water-cooled char extraction probe was used to collect char just under the overfire ports with and without oxygen staging in the overfire flue gas. The char was then analyzed for the percent of UBC and the results are shown in Figure 41. As expected, the UBC values of the char are much greater for the conditions when oxygen was injected through the overfire ports.

The main benefit of the data shown in Figure 41 is to provide validation data for the CFD model created by REI or other models in terms of their prediction of carbon burnout.

Figure 41. Unburned carbon in char collected just under the OFR in section 3 of the furnace.

Table 2 below contains the percentage of ash recovered in the bottom ash, convective pass, and baghouse for each coal type tested in oxy-combustion. A little more bottom ash is expected in the OCRF than would be expected in a full-scale unit, because the flue gas velocities through the system are much slower than in a full-scale unit. Similarly, very little ash would be expected in the convective pass of a full-scale unit.

The flyash distribution is fairly consistent with that obtained during air firing. In addition, the distribution of ash was similar for most coal types tested, with the majority of ash being collected in the baghouse. The major exception to this is the Choctaw America coal which had only 60 percent of the ash collected in the baghouse and a much higher percentage of bottom ash than the other coal types.

Table 2. Percentage of ash recovered for each coal type.

Coal Type	Bottom Ash (%)	Convective Pass (%)	Baghouse Ash (%)
Galatia	10	3	87
West Elk	4	3	93
PRB	2	2	96
Blacksville	13	2	85
Choctaw	37	3	60

Model Description

Reaction Engineering International's proprietary CFD model, GLACIER, was used in this project. GLACIER simulates reacting and non-reacting flow of gases and particles, including gaseous diffusion flames, pulverized-coal flames, liquid sprays, coal slurries, isothermal and reacting two-phase flows, injected sorbents, and other oxidation/reduction systems. GLACIER has been applied to a wide variety of industrial and utility systems encompassing utility boilers, pyrolysis furnaces, gas turbine combustors, rotary kilns, waste incinerators, smelting cyclones and others. These applications have been used for basic design, problem solving, pollution control, etc. using many different fuels including natural gas, coal, oil, and waste.

The computational approach involves numerical discretization of the partial differential equation set which describes the physics of the system, including equations for conservation of mass, momentum, and energy. Typically 105 - 106 discrete computational nodes are needed to resolve the most relevant features of a three-dimensional combustion process. Approximately 60 variables (representing, e.g., gas velocity, temperature, concentration of various chemical species) are tracked at each node. Accurate simulation of the combustion processes requires accurate modeling of the dominant or controlling physical mechanisms. In the computer model used here, coupled equations of chemical reaction, turbulent fluid flow and mixing, and convective and radiative heat transfer are solved to give a realistic and detailed model of the processes taking place within the boiler.

Turbulence can be modeled using various traditional methods of moment closure including Prandtl's mixing length model, the two-equation k - ϵ model (Launder and Spalding, 1972) and the nonlinear k - ϵ model (Speziale, 1987). In all simulations discussed in this report, the standard k - ϵ model was used due to its general applicability in modeling the mean velocity field in reacting flows.

Within the model, the rate at which the primary combustion reactions occur is assumed to be limited by the rate of mixing between the fuel and the oxidizer. That is, the rate of chemical reactions is assumed to be fast compared to the rate of mixing (i.e. full chemical equilibrium is assumed), which is a reasonable assumption for the chemical reactions governing heat release. So, the thermochemical state at each spatial position is a function of the degree of mixing (parameterized by the mixture fraction, f), the mass fraction of coal particle off-gas (η), and the enthalpy (parameterized by the degree of heat loss, H). The effect of turbulence on the mean chemical composition is incorporated by assuming that f and η are described by a "clipped-gaussian" probability density function having spatially varying mean and variance (g). Mean chemical species concentrations are obtained by convolution over this assumed probability density function (PDF). Chemical reactions that are kinetically controlled, such as those involved in NO_x formation/destruction process are handled differently to account for the effects of their relatively slow reaction rates in comparison to the mixing rates.

Particle-phase mechanics are solved by following the mean path or trajectory for a discretized group or ensemble of particles in a Lagrangian frame of reference. Particle mass and momentum sources are converted from a Lagrangian to an Eulerian reference frame where they are coupled with gas phase fluid mechanics. The dispersion of the particle cloud is based on statistics

gathered from the turbulent flow field. Heat, mass, and momentum transport effects are included for each particle cloud.

Particle reaction processes include liquid evaporation, coal devolatilization, char oxidation and gas-particle interchange. Particle swelling is accounted for empirically. The particles are assumed to be isothermal. Particle reaction rates are characterized by multiple parallel reaction rates with fixed activation energies. Particles are defined to consist of coal, char, ash and moisture. Ash is inert by definition; volatile mineral matter is considered as part of the volatile matter of the coal. The off gas from particle reactions is assumed to be of constant elemental composition. Turbulent fluctuations and complete, local, chemical equilibrium are included in the particle reactions.

Since radiation is typically the most significant mode of heat transfer in a large boiler, it is critical that the radiation field be accurately represented. Accurately simulating radiative transfer to specific regions in a system requires a model that can account for both absorbing-emitting radiation processes and complex system geometries, including arbitrary structures such as convective tube passes. Additionally, it is desirable that any radiative model selected be computationally efficient in terms of execution time and storage to allow coupling with other routines in a comprehensive combustion model. REI's model utilizes the discrete-ordinates method, which has been shown to be a suitable choice for modeling radiation in combustion systems, both in terms of computational efficiency and accuracy. This method retains the directional dependency of the radiation intensity in a way that other flux models are unable to achieve, yet provides for a finite-difference or finite-volume solution that is more computationally efficient than zone methods and more deterministic than Monte Carlo methods. The development of the discrete-ordinates method and its application to a number of complex geometries have been presented in the literature and serve to validate the use of this method in accurately modeling radiative heat transfer in coal-fired boilers (Adams, 1993; Adams & Smith, 1993; Adams & Smith, 1995).

The Configured Fire-Side Simulator (CFS) is a Graphical User Interface (GUI) that has been developed by Reaction Engineering International for the purpose of running preconfigured reacting CFD models of industrial furnaces. By design, the CFS limits the number of input and output variables to allow the user to focus on the engineering analysis of the problem to be studied rather than the numerous details required to set up and run the computer programs on which the models are based. This CFS has been specifically configured to evaluate oxy-fuel combustion behavior in Southern Research Institute's Oxy-fired Combustion Research Facility (OCRF).

Model Results

Figure 42 below illustrates the CFD results from the REI model comparing the flame and furnace temperatures in the air-fired CRF with the oxy-fired with flue-gas recycle conditions in the same facility now modified to the OCRF configuration. As clearly illustrated in the figure, the CFD model predicts the flame and furnace temperatures to be cooler while firing with oxygen and recycled flue gas using the MAXON burner than when firing in air-fired mode with the standard air-fired burner. These temperature predictions are consistent with the experimental results obtained.

Figure 42. Comparison of air-fired and oxy-fired CRF furnace temperature profiles.

Notes Regarding Impact of Flue-Gas Recycle on Pulverizers

Typically, the pulverizers use hot air downstream of the economizer and air preheater when firing with air. This primary air serves both to dry the coal in the pulverizer as well as to transport the coal from the pulverizer to the boiler. An air inlet valve brings in ambient air to maintain the proper temperature.

As plants are converted to oxy-recycle, the following concerns must be addressed regarding the use of recycle for use in pulverizing and transport of coal:

- 1) Moisture content
- 2) Acid gas concentration
- 3) Drop out issues associated with density of transport fluid

The most straightforward approach is to use recycled flue gas that has been scrubbed of acid gasses and ash. This recycled flue gas would also require some moisture removal prior to use in the mill. Using this approach would minimize the pulverizer retrofit requirements. There may

still be minor changes to the venturies, vanes, transport lines, and other components specifically designed for the particle size distribution. However, it is unlikely that a major change will be needed.

A more challenging approach is to use recycled flue gas that has been scrubbed of ash but that has not gone through acid gas or moisture removal.

Since liquid condenses on the coolest substance, it is expected that SO_3 dewpoint conditions will not be a problem for the equipment itself. Rather, any acid gases will condense on the coal instead.

However, if too much moisture condenses in the coal, then the coal will agglomerate and ultimately foul the transport lines.

Although an increase in inlet temperature for the mill may eliminate moisture issues, such a change would significantly change the design of pulverizers. As the temperatures increase, there is an increased risk of mill fires. Minimizing air inleakage for this area would be critical for fire prevention. The oxygen injection in to the primary would need to be done downstream of the pulverizer or even in the burner itself. Increased temperatures may also require a different bearing design and additional cooling for critical pulverizer components.

An IEA report [1] makes the following suggestions concerning the operation of pulverizers with flue-gas recycle.

- 1) The FGR to the mill needs to be dried (typically by cooling to drop out the moisture, and reheating) so as to allow it to have sufficient capacity to carry the coal moisture at the mill outlet temperature - hot gas saturated with moisture cannot dry anything! Any moisture drop-out will cause problems - corrosion, wet/sticky pulverized fuel, etc.

- 2) The FGR to the mill needs to be hot; typically temperatures would be of a similar level to existing milling plant to avoid issues with materials, bearings etc. Mill inlet temperatures of 250 to 300 °C would be normal. Cold FGR or air would not dry the coal!

- 3) The flowrate of the FGR to the mill needs to be sufficient to give the same volumetric flowrate - velocities in the mill throat, classifier, and pulverized fuel piping need to be maintained to avoid drop-out etc.

- 4) The oxygen content of the FGR entering the mill must be less than 21vol% (ie lower O_2 partial pressure than air) - to avoid risk of mill fires / explosions.

- 5) Ideally the FGR will not have any acidic components (e.g. SO_3) - minimize risk of corrosion.

- 6) Possibly need to purge the mill after shutdown to get rid of potentially corrosive flue gas condensibles.

This same report emphasizes that although it would be beneficial to the mill and for safety

purposes to add the oxygen after the mill, in order to provide a stable flame it is necessary to mix the oxygen with the flue gas before the mill, so that mixing is sufficient and flame stability ensured.

However, with advanced oxygen burners such as the MAXON burner demonstrated in this project and test campaign, the oxygen is injected at the burner itself and cannot be premixed with the flue gas. Nevertheless, a stable robust flame is achieved due to the advanced staged-oxygen design. Consequently, it will be desirable to use low-oxygen flue gas (i.e., below 2% oxygen) to transport the fuel through the pulverizer, dry the pulverized coal, and heat the mill. The low oxygen content will not hinder flame stability and will dramatically improve the safe operation limits of the mill.

An additional advantage of advanced staged-oxygen burners such as the MAXON burner tested in this project is that the lower flame temperatures produced from staging the oxygen may also significantly reduce slagging and fouling in the furnace and increase the time the unit may remain on line between shut downs for maintenance.

Several sources for economic analyses of oxy-firing and flue-gas recycle for existing power plants may be found in the literature [2, 3], including both the specific references listed as well as subsequent publications from the authors listed. Another excellent source of information on oxy-fired combustion with flue-gas recycle can be found in a literature review by the International Flame Research Foundation [4].

Several previous presentations of portions of this work have been presented at technical conferences [5-7].

Conclusions

The Southern Research/Southern Company 1 MWth Pilot-Scale Coal-Fired Test Facility has been successfully retrofit to fire in either the traditional air-fired mode or with 100% oxygen and recycled flue gas, with a fully integrated feedback and control system, including oxygen and recycled flue gas modulation during startup, transfer, and shutdown, safety and operational interlocks, and data acquisition.

A MAXON Staged Oxygen Burner for Oxy-Coal Applications produced a stable flame over a significant range of firing turn-down, staging, and while firing five different U.S. coal types. The MAXON burner design produces lower flame temperatures than for air firing, which will enable (A) Safe operation, (B) Reduction of recycle flow without concern about furnace flame temperatures, and (C) May likely be effective at reducing slagging and fouling in the boiler and super heater at full-scale Power Plants.

The temperature/time profile in the OCRF was most significantly affected by lower flow rates. Otherwise, heat transfer and temperatures were not significantly changed. Furnace staging, similar to air firing, yielded the most NO_x reduction, and carbon burnout was comparable with air firing.

References

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3. Liljedahl, G., Marion, J., Nsakala ya, N., Bozzuto, C., and Palkes, M., “Technical and Economic Feasibility of CO₂ Capture on an Existing US Coal-Fired Power Plant”, *International Joint Power Generation Conference*, New Orleans, LA, June 4-7, **2001**.
4. Tan, R., Corragio, G., and Santos, S., “Oxy-Coal Combustion with Flue Gas Recycle For the Power Generation Industry – A literature Review”, IFRF Doc. No. G 23/y/1, September **2005**.
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7. De Molina, E. R., Cover, J. E., and Gale, T. K., “Control System Requirements for Recycle Gas and Oxygen Burners”, *The 34th International Technical Conference on Clean Coal and Fuel Systems*, Clearwater FL, May 31-June 4, **2009**.

APPENDIX

Tables A1 through A5 contain the analyses of the five coals tested in this project.

Table A1. Galatia HvB Bituminous coal analysis (from coal feeder discharge).

Proximate Analysis (as rec.)		Ultimate analysis (daf)		Cl Analysis (as rec.)	
% Moisture	3.1	% Carbon	75.4	Cl (%)	0.38
% Ash	6.6	% Hydrogen	4.6		
% Volatiles	33.3	% Nitrogen	1.7		
% Fixed C	57.0	% Sulfur	1.1		
HV (Btu/lb)	12,276	% Oxygen	17.2		

Table A2. West Elk HvB Bituminous coal analysis (from coal feeder discharge).

Proximate Analysis (as rec.)		Ultimate analysis (daf)		Cl Analysis (as rec.)	
% Moisture	1.9	% Carbon	75.9	Cl (%)	0.06
% Ash	8.5	% Hydrogen	5.0		
% Volatiles	37.6	% Nitrogen	1.7		
% Fixed C	52.0	% Sulfur	0.6		
HV (Btu/lb)	12,062	% Oxygen	16.8		

Table A3. NARC PRB Subbituminous A coal analysis (from coal feeder discharge).

Proximate Analysis (as rec.)		Ultimate analysis (daf)		Cl Analysis (as rec.)	
% Moisture	7.9	% Carbon	72.0	Cl (%)	0.09
% Ash	6.5	% Hydrogen	4.9		
% Volatiles	37.2	% Nitrogen	1.3		
% Fixed C	48.4	% Sulfur	0.7		
HV (Btu/lb)	11,018	% Oxygen	21.1		

Table A4. Blacksville HvA Bituminous coal analysis (from coal feeder discharge).

Proximate Analysis (as rec.)		Ultimate analysis (daf)		Cl Analysis (as rec.)	
% Moisture	2.2	% Carbon	77.5	Cl (%)	0.07
% Ash	7.6	% Hydrogen	5.0		
% Volatiles	37.9	% Nitrogen	1.5		
% Fixed C	52.3	% Sulfur	1.9		
HV (Btu/lb)	12,842	% Oxygen	14.1		

Table A5. Choctaw America HvA Bituminous coal analysis (from coal feeder discharge).

Proximate Analysis (as rec.)		Ultimate analysis (daf)		Cl Analysis (as rec.)	
% Moisture	1.7	% Carbon	79.7	Cl (%)	0.03
% Ash	5.7	% Hydrogen	4.8		
% Volatiles	34.7	% Nitrogen	1.8		
% Fixed C	57.9	% Sulfur	1.1		
HV (Btu/lb)	13,450	% Oxygen	12.6		

Tables A6a and A6b begin to define the 65 test conditions completed in the parametric testing of this project. A “GSP” in the last column of either table means that test condition was used to obtain Gas Suction Pyrometry measurements in the furnace.

Table A6a. Load, Furnace Exit Oxygen (FEO), Coal Type, and Time of each test condition.

Test Run	Load (MMBtu/hr)	FEO (%)	Coal Type	Date month/day	Time (hr:min)	Gas Suction Pyrometry (GSP)
1	2.98	3.0	Galatia	9/20	8:48 – 9:15	
2	3.18	3.9	Galatia	9/20	10:18 – 11:04	
3	3.17	1.4	Galatia	9/20	14:08 – 14:30	
4	3.17	0.2	Galatia	9/20	14:31 – 15:50	
5	3.17	0.8	Galatia	9/20	16:03 – 17:09	
6	3.17	3.7	Galatia	9/21	8:05 – 8:15	
7	3.17	0.9	Galatia	9/21	9:30 – 10:52	
8	3.18	0.9	Galatia	9/21	11:19 – 11:47	
9	3.83	0.8	Galatia	9/21	13:09 – 13:22	
10	2.85	1.0	Galatia	9/24	9:16 – 11:10	
11	2.79	1.1	Galatia	9/24	11:10 – 12:16	
12	2.79	1.0	Galatia	9/24	12:30 – 13:20	
13	2.80	1.1	Galatia	9/24	15:27 – 15:45	
14	2.79	1.1	Galatia	9/24	17:46 – 18:45	
15	2.80	1.8	Galatia	9/30	10:40 – 16:14	GSP
16	2.89	1.6	West Elk	10/1	9:47 – 16:49	GSP
17	2.89	2.3	West Elk	10/2	9:00 – 9:10	GSP
18	3.28	4.1	West Elk	10/2	11:19 – 11:50	
19	3.29	1.3	West Elk	10/2	12:02 – 13:21	
20	2.89	3.4	West Elk	10/2	14:08 – 14:21	
21	2.89	0.2	West Elk	10/2	14:49 – 15:21	
22	2.89	1.3	West Elk	10/2	15:40 – 16:34	
23	2.89	1.2	West Elk	10/2	16:59 – 17:35	
24	2.89	1.3	West Elk	10/4	10:30 – 10:54	
25	2.91	1.1	West Elk	10/4	11:31 – 12:00	
26	3.49	1.2	West Elk	10/4	12:49 – 13:15	
27	2.86	1.0	West Elk	10/4	13:41 – 14:15	
28	2.91	1.2	West Elk	10/4	14:35 – 15:20	
29	2.92	1.0	West Elk	10/4	16:12 – 16:27	
30	2.89	1.3	West Elk	10/4	16:45 – 16:54	

Table A6b. Load, Furnace Exit Oxygen (FEO), Coal Type, and Time of each test condition.

Test Run	Load (MMBtu/hr)	FEO (%)	Coal Type	Date month/day	Time (hr:min)	Gas Suction Pyrometry (GSP)
31	2.94	1.3	PRB	10/6	15:45 – 17:11	
32	2.96	2.9	PRB	10/7	8:40 – 9:07	
33	2.92	0.2	PRB	10/7	9:51 – 10:15	
34	2.95	1.2	PRB	10/7	10:50 – 11:25	
35	2.94	0.9	PRB	10/7	11:35 – 12:30	
36	2.93	0.9	PRB	10/7	12:47 – 13:36	
37	2.91	2.0	PRB	10/7	14:32 – 14:40	
38	3.59	1.0	PRB	10/7	15:30 – 16:15	
39	2.92	0.9	PRB	10/8	7:15 – 8:35	
40	2.94	1.1	PRB	10/8	8:49 – 9:00	
41	2.95	1.0	PRB	10/8	9:00 – 9:55	
42	2.94	0.8	PRB	10/8	10:40 – 11:04	
43	2.95	0.9	PRB	10/8	11:21 – 12:45	
44	2.95	1.0	PRB	10/8	13:50 – 13:40	
45	2.95	1.8	PRB	10/8	14:20 – 14:40	GSP
46	2.95	1.5	PRB	10/11	8:15 – 15:53	GSP
47	3.01	2.9	Blacksville	10/13	13:10 – 14:15	
48	3.02	0.3	Blacksville	10/13	14:38 – 15:20	
49	2.98	1.1	Blacksville	10/13	15:33 – 16:25	
50	2.98	1.0	Blacksville	10/13	16:32 – 16:53	
51	2.95	0.9	Blacksville	10/13	16:53 – 17:11	
52	3.01	0.8	Blacksville	10/14	9:10 – 9:30	
53	2.98	1.2	Blacksville	10/14	14:15 – 15:20	
54	2.99	0.8	Blacksville	10/14	16:32 – 16:45	
55	2.99	0.6	Blacksville	10/14	17:17 – 17:50	
56	2.97	3.0	Choctaw America	10/18	9:11 – 9:50	
57	2.97	0.3	Choctaw America	10/18	10:11 – 10:55	
58	2.99	0.9	Choctaw America	10/18	11:40 – 12:00	
59	2.97	1.1	Choctaw America	10/18	12:00 – 12:23	
60	2.97	1.1	Choctaw America	10/18	12:23 – 12:43	
61	2.99	1.1	Choctaw America	10/18	12:52 – 14:00	
62	2.97	0.9	Choctaw America	10/18	14:35 – 15:05	
63	2.97	0.9	Choctaw America	10/18	15:19 – 16:10	
64	2.96	1.1	Choctaw America	10/18	16:24 – 17:15	
65	3.55	1.1	Choctaw America	10/18	18:10 – 18:20	

Tables A7a and A7b contain the gas (including oxygen and recycled flue gas) and fuel input flowrates into the burner and other furnace injection ports for each test condition.

Table A7a. Fuel, Recycle, and Oxygen inputs to the furnace for each test condition.

Test Run	Coal Feed (lbs/hr)	Pilot Oxygen (scfm)	Primary Recycle (scfm)	Secondary Recycle (scfm)	Tertiary Recycle (scfm)	O ₂ in Cup (scfm)	O ₂ in Quarl (scfm)	O ₂ in Sec. Rec. (scfm)	O ₂ in Tert. Rec. (scfm)
1	243	13.7	129.3	434.9	0.0	29.2	67.0	0.0	0.0
2	259	13.6	129.5	339.6	0.0	35.0	63.3	0.0	0.0
3	258	13.5	130.0	340.4	0.0	34.7	57.5	0.0	0.0
4	258	13.5	130.0	340.0	0.0	34.7	54.7	0.0	0.0
5	258	13.5	130.0	339.9	0.0	24.0	68.8	0.0	0.0
6	258	13.7	129.6	342.9	0.0	19.1	79.1	0.0	0.0
7	258	13.6	130.0	340.2	0.0	12.2	79.5	0.0	0.0
8	259	13.5	130.0	240.0	0.0	24.2	70.0	0.0	0.0
9	312	13.5	130.0	240.1	0.0	32.8	86.7	0.0	0.0
10	232	13.6	130.0	279.7	0.0	19.6	53.6	8.3	0.0
11	227	13.6	130.0	280.1	0.0	19.6	53.5	8.5	0.0
12	227	13.6	130.0	219.1	61.1	19.6	61.9	0.0	0.0
13	228	13.6	130.0	219.1	61.0	19.6	56.0	0.0	0.0
14	227	13.6	130.0	219.0	61.0	19.6	44.8	0.0	11.7
15	228	13.7	129.5	280.0	0.0	19.6	61.7	0.0	0.0
16	240	13.7	130.1	280.1	0.0	19.6	64.4	0.0	0.0
17	240	13.9	130.0	280.1	0.0	19.6	64.3	0.0	0.0
18	272	13.8	130.2	340.3	0.0	34.9	70.1	0.0	0.0
19	273	13.8	130.0	279.3	0.0	35.0	63.9	0.0	0.0
20	240	13.7	130.0	279.7	0.0	30.5	57.4	0.0	0.0
21	240	13.7	130.0	279.7	0.0	27.6	53.3	0.0	0.0
22	240	13.7	130.1	280.1	0.0	28.8	54.9	0.0	0.0
23	240	13.7	130.0	279.9	0.0	8.8	75.0	0.0	0.0
24	240	14.0	130.0	280.1	0.0	18.3	63.7	0.0	0.0
25	241	14.0	129.9	199.8	0.0	18.3	64.9	0.0	0.0
26	289	14.0	130.0	200.0	0.0	26.7	81.4	0.0	0.0
27	237	13.9	130.0	280.2	0.0	18.3	59.2	8.8	0.0
28	241	13.9	130.0	217.9	62.0	19.4	65.8	0.0	0.0
29	242	13.9	130.0	217.6	61.7	19.1	65.2	0.0	0.0
30	240	13.9	129.8	217.9	62.0	19.1	50.0	0.0	13.8

Table A7b. Fuel, Recycle, and Oxygen inputs to the furnace for each test condition.

Test Run	Coal Feed (lbs/hr)	Pilot Oxygen (scfm)	Primary Recycle (scfm)	Secondary Recycle (scfm)	Tertiary Recycle (scfm)	O ₂ in Cup (scfm)	O ₂ in Quarl (scfm)	O ₂ in Sec. Rec. (scfm)	O ₂ in Tert. Rec. (scfm)
31	267	13.8	130.0	280.0	0.0	16.8	56.7	0.0	0.0
32	269	14.0	130.0	279.7	0.0	17.7	58.9	0.0	0.0
33	265	13.9	130.0	280.1	0.0	16.1	55.6	0.0	0.0
34	268	13.8	130.0	279.7	0.0	16.4	56.3	0.0	0.0
35	267	13.8	130.0	280.4	0.0	6.8	65.8	0.0	0.0
36	266	13.8	130.0	280.1	0.0	26.0	46.6	0.0	0.0
37	264	13.7	130.0	199.8	0.0	16.9	60.9	0.0	0.0
38	326	13.7	130.0	200.1	0.0	21.2	75.5	0.0	0.0
39	265	14.0	130.0	280.2	0.0	16.4	48.2	8.7	0.0
40	267	13.9	130.0	218.1	62.3	16.4	56.6	0.0	0.0
41	268	13.9	130.0	218.0	62.0	16.6	56.6	0.0	0.0
42	267	13.8	130.0	218.1	61.7	16.7	56.9	0.0	0.0
43	268	13.7	130.0	218.0	61.8	16.8	44.4	0.0	12.1
44	268	13.7	130.0	218.2	62.1	16.8	44.4	0.0	12.5
45	268	13.7	129.9	279.4	0.0	16.8	57.3	0.0	0.0
46	268	13.7	130.0	280.0	0.0	17.2	58.0	0.0	0.0
47	234	13.8	130.0	279.7	0.0	21.6	66.4	0.0	0.0
48	235	13.8	130.0	279.4	0.0	19.5	62.1	0.0	0.0
49	232	13.8	130.0	280.1	0.0	20.9	64.8	0.0	0.0
50	232	13.8	130.0	280.0	0.0	28.8	57.2	0.0	0.0
51	230	13.8	130.0	279.7	0.0	10.7	75.3	0.0	0.0
52	234	13.9	130.8	200.7	0.0	20.9	66.0	0.0	0.0
53	232	13.8	129.9	217.4	61.8	18.3	20.9	0.0	10.6
54	233	13.8	130.0	217.6	61.5	17.2	58.9	0.0	0.0
55	233	13.8	130.1	280.1	0.0	18.3	55.3	10.4	0.0
56	221	13.8	130.0	280.0	0.0	22.7	67.2	0.0	0.0
57	221	13.8	130.0	280.0	0.0	20.5	62.8	0.0	0.0
58	222	13.7	130.0	279.9	0.0	21.5	65.1	0.0	0.0
59	221	13.7	130.0	280.0	0.0	11.0	76.4	0.0	0.0
60	221	13.7	130.0	280.3	0.0	33.3	54.1	0.0	0.0
61	222	13.7	130.1	280.2	0.0	21.7	56.8	8.9	0.0
62	221	13.7	130.0	217.9	62.0	21.5	65.2	0.0	0.0
63	221	13.7	130.0	218.0	62.0	21.5	49.9	0.0	12.7
64	220	13.7	130.0	200.1	0.0	21.5	65.4	0.0	0.0
65	264	13.8	130.0	201.6	0.0	29.0	78.9	0.0	0.0

Tables A8a and A8b contain the flue gas temperatures at each measured location in the OCRF from the furnace exit to the exit of the last flue-gas heat exchanger for each test condition. In addition, these tables contain the measured furnace pressure, convection section 2 exit pressure, air heater exit pressure, and the pressure in the middle of the recuperative heat exchangers. For these tables, the standard deviation is separated from the measured value by a “/” symbol. For example, the measured value of the furnace exit temperature of the first test run was 1667+/-6 °F.

Table A8a. Flue-Gas Temperatures and pressures.

Test Run	Furnace Exit (°F)	CS-1 Exit (°F)	CS-2 Exit (°F)	CS-3 Exit (°F)	Air Heat Exit (°F)	Rec. 4 Exit (°F)	Furnace Pressure (in H ₂ O)	CS2 Exit Pressure (in H ₂ O)	Air Heat Exit (in H ₂ O)	Rec. 2 Exit (in H ₂ O)
1	1667/6	1445/5	1204/5	1075/3	867/4	401/0	1.0/0.9	-0.5/0.6	-0.7/1.0	-4.3/0.9
2	1642/7	1418/6	1173/6	1034/3	823/3	370/3	1.5/0.2	-0.1/0.1	0.1/0.1	-2.8/0.1
3	1608/10	1399/6	1156/5	1029/1	817/2	366/0	1.4/0.7	-0.1/0.4	0.0/0.9	-2.6/0.6
4	1671/12	1440/9	1194/8	1050/7	836/6	369/1	1.5/0.1	-0.1/0.0	0.1/0.1	-2.7/0.1
5	1727/12	1496/5	1248/5	1098/4	871/3	385/1	1.5/0.1	-0.1/0.0	0.1/0.1	-2.8/0.1
6	1560/5	1391/6	1155/5	1039/5	837/5	354/0	-0.3/1.0	-1.1/0.6	-1.8/0.9	-4.7/1.2
7	1619/5	1416/14	1176/12	1036/6	829/4	370/3	1.5/0.1	-0.1/0.0	0.2/0.1	-2.5/0.1
8	1673/18	1413/9	1155/7	998/5	780/4	333/1	1.5/0.2	0.0/0.1	0.5/0.2	-1.6/0.1
9	1883/3	1567/2	1297/1	1126/1	883/1	391/1	1.5/0.2	-0.1/0.0	0.3/0.2	-2.1/0.1
10	1684/2	1436/1	1206/1	1056/1	824/1	376/0	2.5/0.2	0.5/0.1	1.4/0.2	-1.0/0.2
11	1681/1	1443/1	1214/1	1063/1	825/1	376/0	2.5/0.1	0.5/0.1	1.4/0.1	-1.0/0.1
12	1604/2	1397/2	1180/1	1036/1	805/1	370/0	2.5/0.2	0.5/0.1	1.3/0.1	-1.0/0.1
13	1551/2	1381/4	1172/3	1032/3	806/3	375/2	0.0/0.1	-0.8/0.0	-1.2/0.1	-3.8/0.0
14	1593/9	1412/4	1198/2	1057/2	829/2	379/2	-0.2/0.3	-1.0/0.2	-1.3/0.2	-3.9/0.3
15	1647/5	1417/3	1194/3	994/2	793/2	371/1	-1.5/0.2	-1.7/0.1	-2.8/0.1	-5.4/0.1
16	1601/13	1376/14	1137/14	942/13	711/10	338/5	0.5/2.2	-0.5/1.2	-0.7/2.2	-3.2/2.3
17	1646/9	1394/9	1158/9	967/8	735/7	346/6	-0.9/1.5	-1.3/0.8	-2.1/1.5	-4.5/1.5
18	1637/18	1435/16	1207/18	1021/17	792/15	386/9	0.6/1.9	-0.5/0.8	-0.7/1.5	-3.8/1.6
19	1760/4	1494/3	1255/3	1056/3	812/1	387/1	1.7/0.9	0.1/0.6	0.6/1.3	-2.2/1.1
20	1685/2	1453/2	1221/1	1029/1	785/1	376/1	1.3/0.4	0.0/0.1	0.3/0.4	-2.2/0.1
21	1687/2	1449/2	1215/1	1026/1	785/1	372/0	1.4/0.6	0.0/0.1	0.4/0.6	-2.2/0.1
22	1680/1	1456/2	1225/2	1035/2	792/2	379/1	1.2/0.8	-0.2/0.4	0.0/0.9	-2.6/0.9
23	1709/3	1474/2	1240/1	1047/0	802/1	382/1	1.5/0.2	0.0/0.1	0.3/0.2	-2.3/0.1
24	1676/2	1417/2	1173/2	981/2	744/1	347/1	2.7/0.1	0.5/0.0	1.6/0.1	-0.6/0.1
25	1685/8	1387/4	1133/3	937/4	698/3	312/3	2.3/0.5	0.5/0.2	1.5/0.5	-0.2/0.6
26	1827/3	1498/2	1232/2	1022/2	767/2	353/1	2.5/0.1	0.4/0.0	1.4/0.1	-0.4/0.0
27	1778/2	1498/2	1253/1	1054/0	795/0	378/0	2.3/0.1	0.3/0.0	1.1/0.1	-1.0/0.1
28	1677/2	1435/2	1204/1	1017/1	771/1	369/0	2.6/0.1	0.5/0.0	1.6/0.1	-0.6/0.1
29	1640/3	1412/2	1186/1	1004/1	764/0	367/0	2.4/0.1	0.4/0.0	1.3/0.1	-0.9/0.1
30	1658/13	1436/6	1202/6	1013/5	771/4	369/1	2.5/0.1	0.4/0.0	1.5/0.1	-0.8/0.1

Table A8b. Flue-Gas Temperatures and pressures.

Test Run	Furnace Exit (°F)	CS-1 Exit (°F)	CS-2 Exit (°F)	CS-3 Exit (°F)	Air Heat Exit (°F)	Rec. 4 Exit (°F)	Furnace Pressure (in H ₂ O)	CS2 Exit Pressure (in H ₂ O)	Air Heat Exit (in H ₂ O)	Rec. 2 Pressure (in H ₂ O)
31	1548/8	1325/5	1150/3	1000/2	703/1	348/1	-0.6/0.2	-1.1/0.1	-1.6/0.2	-4.1/0.1
32	1570/3	1334/2	1151/1	1000/1	722/2	352/0	2.6/0.6	0.5/0.2	1.5/0.5	-0.9/0.6
33	1600/1	1357/2	1151/1	1000/1	720/1	355/0	2.4/0.6	0.3/0.2	1.2/0.5	-1.2/0.5
34	1601/1	1363/2	1150/1	1000/1	720/1	360/0	2.5/0.7	0.2/0.2	1.3/0.7	-1.3/0.5
35	1621/4	1379/3	1151/1	1000/1	719/1	362/1	2.2/0.5	0.2/0.2	1.0/0.6	-1.4/0.6
36	1602/2	1372/2	1150/1	1000/1	719/1	367/1	2.1/0.5	0.1/0.2	0.8/0.5	-1.7/0.5
37	1615/3	1333/3	1145/3	993/2	713/2	332/1	2.8/1.1	0.3/0.4	1.9/1.2	0.1/1.4
38	1814/2	1459/3	1174/2	1008/1	721/1	354/0	2.5/0.4	0.2/0.1	1.7/0.5	-0.4/0.4
39	1603/7	1324/5	1074/4	913/3	647/2	336/1	2.9/0.6	0.2/0.1	1.8/0.7	-0.4/0.6
40	1532/1	1293/2	1056/1	901/1	641/1	339/1	2.4/0.4	0.1/0.1	1.4/0.5	-0.9/0.5
41	1532/2	1297/3	1058/2	903/2	642/2	341/1	2.5/0.5	0.1/0.1	1.4/0.5	-0.9/0.5
42	1520/1	1302/3	1065/2	910/1	651/1	348/1	1.6/0.4	-0.1/0.1	0.7/0.5	-1.8/0.4
43	1575/6	1352/6	1106/4	945/4	676/2	362/2	1.6/0.5	-0.1/0.1	0.5/0.5	-2.0/0.4
44	1553/5	1348/6	1105/3	945/3	677/2	363/1	1.2/0.7	-0.2/0.2	0.2/0.7	-2.4/0.7
45	1585/3	1360/8	1118/8	958/8	688/7	372/5	0.3/1.6	-0.5/0.5	-0.8/1.7	-3.5/1.8
46	1641/4	1394/6	1147/6	988/6	710/6	381/5	0.0/2.0	-0.6/0.6	-1.1/2.1	-3.8/2.0
47	1643/2	1353/2	1068/1	884/1	602/1	303/1	2.7/1.0	0.3/0.4	1.5/1.0	-0.8/1.0
48	1675/3	1366/4	1083/3	899/2	615/1	307/1	2.0/1.0	0.0/0.3	1.0/1.1	-1.3/1.1
49	1694/2	1396/2	1111/2	926/2	635/1	317/1	2.1/0.9	0.0/0.2	1.0/0.8	-1.3/0.9
50	1704/2	1404/2	1121/2	936/2	644/2	321/1	1.6/0.5	-0.2/0.1	0.4/0.5	-2.0/0.5
51	1719/4	1417/3	1131/2	944/2	650/1	322/0	1.7/0.5	-0.1/0.1	0.6/0.6	-1.7/0.6
52	1589/8	1275/6	1159/7	1003/4	724/57	317/9	3.4/1.2	0.2/0.5	2.1/2.1	0.8/1.5
53	1491/5	1292/4	1191/4	1002/3	697/2	337/1	-1.0/1.8	-0.9/0.6	-1.9/1.6	-4.4/1.2
54	1490/1	1276/1	1102/18	946/15	675/11	337/2	3.1/0.9	0.1/0.1	2.1/0.3	-0.2/0.4
55	1636/10	1371/7	1113/5	950/4	677/4	336/1	2.0/0.9	-0.1/0.2	0.8/0.9	-1.6/0.9
56	1607/11	1314/9	1038/8	907/8	617/6	308/3	1.5/0.9	0.3/0.4	0.5/0.7	-1.8/0.7
57	1664/7	1345/6	1064/5	930/5	637/4	313/1	2.3/0.2	0.5/0.1	1.3/0.1	-1.0/0.1
58	1694/7	1383/1	1104/1	966/1	666/2	329/1	2.0/0.6	0.3/0.0	1.0/0.2	-1.3/0.3
59	1705/7	1395/4	1108/2	931/17	650/10	325/2	2.2/0.2	0.5/0.1	1.1/0.2	-1.2/0.1
60	1702/2	1395/2	1110/1	918/1	642/1	323/0	2.1/0.1	0.3/0.1	1.0/0.2	-1.4/0.1
61	1709/3	1406/5	1123/5	928/5	650/4	327/2	2.4/0.6	0.4/0.3	1.3/0.8	-1.0/0.6
62	1638/2	1365/1	1100/1	915/1	648/1	328/1	2.1/0.3	0.2/0.1	1.0/0.3	-1.4/0.3
63	1662/4	1385/3	1117/3	929/3	658/2	331/1	2.2/0.3	0.2/0.1	1.1/0.3	-1.3/0.3
64	1713/2	1375/2	1082/1	885/1	612/1	292/0	1.9/0.5	0.2/0.2	1.1/0.5	-0.7/0.4
65	1828/10	1453/11	1148/9	942/8	650/5	315/3	1.2/1.9	-0.3/0.9	0.1/2.3	-1.7/2.0

Tables A9a and A9b contain the measured furnace wall temperatures for each of the 65 test conditions conducted in the parametric testing associated with this project.

Table A9a. Furnace Wall Temperatures.

Test Run	Section One (°F)	Section Two (°F)	Section Three (°F)	Section Four (°F)	Section Five (°F)	Section Six (°F)	Section Seven (°F)
1	651 +/- 6	1158 +/- 6	818 +/- 1	930 +/- 2	1156 +/- 2	592 +/- 1	949 +/- 2
2	750 +/- 10	1183 +/- 12	830 +/- 1	926 +/- 3	1147 +/- 3	597 +/- 1	956 +/- 2
3	722 +/- 10	1138 +/- 11	755 +/- 2	848 +/- 5	1055 +/- 6	537 +/- 3	870 +/- 5
4	795 +/- 8	1221 +/- 9	787 +/- 7	900 +/- 9	1121 +/- 11	571 +/- 7	929 +/- 11
5	845 +/- 1	1260 +/- 2	840 +/- 5	954 +/- 4	1187 +/- 5	613 +/- 3	1002 +/- 6
6	652 +/- 3	1156 +/- 3	817 +/- 0	876 +/- 1	1076 +/- 1	544 +/- 0	825 +/- 1
7	741 +/- 23	1203 +/- 29	798 +/- 3	866 +/- 10	1074 +/- 14	546 +/- 7	856 +/- 14
8	869 +/- 17	1328 +/- 20	825 +/- 5	915 +/- 6	1139 +/- 8	582 +/- 4	924 +/- 8
9	1065 +/- 7	1544 +/- 8	896 +/- 3	1016 +/- 4	1256 +/- 4	639 +/- 2	1046 +/- 4
10	868 +/- 1	1368 +/- 0	895 +/- 2	1007 +/- 1	1223 +/- 1	632 +/- 1	983 +/- 2
11	885 +/- 1	1370 +/- 0	920 +/- 2	1023 +/- 1	1241 +/- 1	646 +/- 1	1021 +/- 2
12	924 +/- 6	1399 +/- 5	936 +/- 1	1029 +/- 0	1241 +/- 1	652 +/- 0	1039 +/- 0
13	982 +/- 1	1434 +/- 0	960 +/- 0	1015 +/- 1	1213 +/- 1	639 +/- 1	1026 +/- 1
14	968 +/- 3	1426 +/- 5	956 +/- 0	1001 +/- 2	1208 +/- 0	635 +/- 0	1020 +/- 1
15	909 +/- 1	1342 +/- 1	917 +/- 0	987 +/- 0	1218 +/- 0	639 +/- 0	1007 +/- 0
16	765 +/- 7	1288 +/- 15	727 +/- 16	820 +/- 18	1040 +/- 20	517 +/- 11	770 +/- 15
17	784 +/- 10	1317 +/- 7	852 +/- 5	936 +/- 6	1163 +/- 7	595 +/- 4	909 +/- 6
18	792 +/- 18	1223 +/- 28	877 +/- 2	926 +/- 2	1140 +/- 4	600 +/- 1	910 +/- 2
19	907 +/- 5	1394 +/- 6	891 +/- 3	979 +/- 4	1210 +/- 5	623 +/- 2	982 +/- 5
20	934 +/- 0	1389 +/- 2	923 +/- 2	1007 +/- 1	1238 +/- 0	646 +/- 1	1027 +/- 2
21	924 +/- 3	1381 +/- 0	937 +/- 1	1011 +/- 1	1241 +/- 1	651 +/- 0	1043 +/- 2
22	926 +/- 1	1383 +/- 2	944 +/- 1	1015 +/- 0	1244 +/- 0	655 +/- 0	1056 +/- 1
23	919 +/- 1	1400 +/- 3	947 +/- 1	1018 +/- 1	1248 +/- 2	657 +/- 1	1063 +/- 2
24	911 +/- 5	1357 +/- 2	855 +/- 3	942 +/- 3	1165 +/- 3	594 +/- 2	921 +/- 5
25	963 +/- 13	1402 +/- 10	890 +/- 4	972 +/- 4	1200 +/- 4	617 +/- 2	967 +/- 3
26	1108 +/- 5	1504 +/- 4	922 +/- 1	1011 +/- 2	1244 +/- 3	638 +/- 1	1001 +/- 2
27	1109 +/- 4	1478 +/- 4	963 +/- 1	1059 +/- 1	1291 +/- 1	668 +/- 1	1046 +/- 1
28	1071 +/- 0	1443 +/- 2	977 +/- 0	1062 +/- 1	1286 +/- 2	677 +/- 0	1058 +/- 1
29	1075 +/- 0	1453 +/- 0	979 +/- 0	1054 +/- 0	1264 +/- 1	669 +/- 0	1060 +/- 0
30	1073 +/- 0	1445 +/- 1	979 +/- 0	1048 +/- 0	1253 +/- 1	663 +/- 1	1058 +/- 0

Table A9b. Furnace Wall Temperatures.

Test Run	Section One (°F)	Section Two (°F)	Section Three (°F)	Section Four (°F)	Section Five (°F)	Section Six (°F)	Section Seven (°F)
31	850 +/- 11	1290 +/- 10	763 +/- 15	870 +/- 10	1118 +/- 12	542 +/- 9	855 +/- 15
32	718 +/- 5	1222 +/- 4	815 +/- 2	909 +/- 3	1155 +/- 3	568 +/- 2	900 +/- 3
33	767 +/- 1	1262 +/- 1	845 +/- 1	937 +/- 1	1190 +/- 1	590 +/- 1	941 +/- 2
34	789 +/- 2	1276 +/- 1	864 +/- 1	953 +/- 1	1210 +/- 1	604 +/- 1	969 +/- 2
35	797 +/- 1	1275 +/- 1	878 +/- 1	965 +/- 1	1225 +/- 2	614 +/- 1	989 +/- 2
36	810 +/- 3	1280 +/- 1	889 +/- 1	973 +/- 0	1234 +/- 0	622 +/- 1	1004 +/- 1
37	892 +/- 2	1359 +/- 2	897 +/- 0	983 +/- 1	1244 +/- 1	626 +/- 0	1012 +/- 0
38	1017 +/- 3	1505 +/- 2	931 +/- 1	1046 +/- 2	1317 +/- 2	651 +/- 1	1054 +/- 2
39	702 +/- 11	1242 +/- 7	826 +/- 5	951 +/- 6	1184 +/- 7	582 +/- 4	919 +/- 7
40	746 +/- 5	1268 +/- 4	844 +/- 1	970 +/- 1	1206 +/- 1	596 +/- 1	943 +/- 1
41	794 +/- 20	1305 +/- 16	859 +/- 7	979 +/- 4	1210 +/- 2	603 +/- 2	953 +/- 4
42	874 +/- 3	1357 +/- 1	899 +/- 2	996 +/- 1	1219 +/- 0	610 +/- 0	967 +/- 0
43	910 +/- 3	1366 +/- 2	924 +/- 2	1001 +/- 1	1227 +/- 3	614 +/- 1	977 +/- 3
44	922 +/- 1	1365 +/- 0	926 +/- 0	1001 +/- 0	1236 +/- 0	621 +/- 0	991 +/- 1
45	924 +/- 3	1366 +/- 3	921 +/- 0	995 +/- 1	1231 +/- 1	622 +/- 0	993 +/- 0
46	831 +/- 1	1294 +/- 0	906 +/- 3	1012 +/- 2	1268 +/- 2	639 +/- 2	1028 +/- 3
47	974 +/- 2	1390 +/- 1	856 +/- 3	963 +/- 3	1206 +/- 3	592 +/- 2	944 +/- 3
48	970 +/- 1	1404 +/- 1	896 +/- 3	996 +/- 3	1245 +/- 3	616 +/- 2	987 +/- 4
49	978 +/- 1	1413 +/- 1	925 +/- 3	1020 +/- 2	1274 +/- 3	634 +/- 2	1022 +/- 3
50	985 +/- 2	1418 +/- 1	936 +/- 2	1029 +/- 2	1285 +/- 2	641 +/- 2	1035 +/- 3
51	989 +/- 0	1421 +/- 1	943 +/- 1	1036 +/- 1	1292 +/- 1	646 +/- 1	1044 +/- 1
52	844 +/- 14	1384 +/- 12	820 +/- 3	927 +/- 5	1153 +/- 6	561 +/- 2	922 +/- 4
53	963 +/- 14	1333 +/- 7	757 +/- 5	862 +/- 6	1054 +/- 8	506 +/- 4	830 +/- 8
54	1028 +/- 2	1400 +/- 1	839 +/- 2	932 +/- 1	1129 +/- 1	554 +/- 1	912 +/- 1
55	1003 +/- 2	1376 +/- 0	879 +/- 5	962 +/- 6	1170 +/- 8	573 +/- 4	953 +/- 8
56	931 +/- 21	1302 +/- 13	757 +/- 12	938 +/- 14	1120 +/- 16	528 +/- 9	870 +/- 16
57	994 +/- 4	1349 +/- 6	819 +/- 11	999 +/- 10	1196 +/- 12	572 +/- 7	950 +/- 14
58	1039 +/- 3	1374 +/- 1	879 +/- 3	1049 +/- 2	1259 +/- 3	612 +/- 2	1026 +/- 4
59	1052 +/- 2	1381 +/- 2	895 +/- 3	1060 +/- 2	1273 +/- 3	622 +/- 2	1044 +/- 4
60	1061 +/- 4	1388 +/- 1	906 +/- 3	1069 +/- 2	1284 +/- 3	629 +/- 2	1058 +/- 4
61	1084 +/- 3	1397 +/- 3	929 +/- 6	1085 +/- 4	1304 +/- 5	643 +/- 4	1085 +/- 7
62	1141 +/- 6	1428 +/- 4	953 +/- 2	1094 +/- 0	1309 +/- 2	654 +/- 0	1104 +/- 0
63	1162 +/- 1	1441 +/- 3	967 +/- 3	1094 +/- 0	1303 +/- 1	652 +/- 1	1104 +/- 1
64	1200 +/- 2	1461 +/- 2	979 +/- 1	1106 +/- 1	1318 +/- 2	657 +/- 1	1114 +/- 1
65	1509 +/- 10	1546 +/- 2	998 +/- 1	1150 +/- 2	1367 +/- 2	675 +/- 1	1142 +/- 2

Table A10 contains the gas suction pyrometry (GSP) measurements obtained of the OCRF furnace for three different coal types.

Tables A11a and A11b contain the flue-gas composition for each test condition corrected to the furnace exit oxygen conditions. These tables also contain the measured percentage of unburned carbon (UBC) contained in the flyash for each test condition.

Table A10. Flue-Gas Temperatures in the Furnace measured by Gas Suction Pyrometry.

Test Run	Section One (°F)	Section Two (°F)	Section Three Mid (°F)	Section 3 @ 2/3 Dist (°F)	Section 3 @ 1/3 Dist (°F)	Section Four (°F)	Section Five (°F)
15	1832	2019	2111	1845	1774	---	---
16/17	1659	1787	1756	1809	1697	---	---
45/46	1657	1958	1864	1940	1755	1609	1648

Table A11a. Flue-Gas Composition at the Furnace Exit and unburned carbon (UBC) in the ash.

Test Run	O ₂ (%)	N ₂ (%)	CO ₂ (%)	CO ppmv	H ₂ O (%)	NO ppmv	SO ₂ ppmv	HCl ppmv	UBC wt%
1	2.8	26.0	65.0	58.8	6.0	1053	745	---	---
2	3.7	24.2	66.3	51.1	5.7	773	615	5.4	0.98
3	1.3	23.5	68.6	76.7	6.4	1007	944	29.8	1.33
4	0.2	24.1	68.6	255.3	6.9	657	1047	33.9	1.95
5	0.7	23.8	68.1	142.8	7.1	724	1037	47.2	6.55
6	3.5	26.4	64.0	55.1	6.0	---	590	---	---
7	0.8	25.3	66.7	122.2	7.0	1058	884	32.2	6.13
8	0.8	24.5	67.1	125.4	7.3	1163	1098	39.2	5.17
9	0.7	20.9	69.8	73.7	8.3	968	1411	43.0	3.27
10	0.9	26.6	65.7	81.2	6.5	934	1001	29.5	2.91
11	1.0	29.8	62.4	81.1	6.6	968	986	31.7	2.74
12	0.9	26.8	64.9	94.2	7.2	991	983	36.2	3.59
13	1.0	35.1	56.6	88.4	7.2	700	936	42.1	42.93 ^{CH}
14	1.0	30.6	60.9	152.3	7.4	257	1020	45.9	4.54
15	1.7	29.3	61.7	51.4	7.1	937	815	---	62.58 ^{CH14}
16	1.5	26.8	66.1	62.3	5.4	984	459	---	---
17	2.2	28.0	64.4	69.5	5.2	1169	387	---	55.04 ^{CH30}
18	3.9	19.4	71.8	55.5	4.7	1389	235	---	1.38
19	1.2	23.7	69.4	126.2	5.5	1335	472	---	1.76
20	3.2	25.2	66.6	49.0	4.9	---	246	---	1.34
21	0.2	25.8	68.1	---	5.8	695	483	---	4.19
22	1.2	27.5	65.6	88.3	5.5	1181	399	---	6.31
23	1.1	25.0	68.2	82.4	5.5	886	437	---	3.70
24	1.3	33.4	61.8	62.5	3.4	1062	302	1.0	2.64
25	1.0	30.2	63.2	85.3	5.3	1277	411	1.7	2.10
26	1.1	26.4	66.2	57.3	6.1	987	650	2.1	1.49
27	0.9	23.6	69.7	92.5	5.7	687	481	2.1	1.99
28	1.1	23.4	69.0	76.7	6.3	704	455	2.4	3.63
29	0.9	27.3	65.9	77.7	5.8	670	452	2.2	17.54 ^{CH}
30	1.2	27.7	65.3	74.0	5.6	301	492	2.4	4.17

CH = The analysis was of a char probe sample taken from just under to over-fired recycle.

CH14 = This char sample was taken during test condition 14.

CH30 = This char sample was taken during test condition 30.

All other unburned carbon data are from baghouse ash samples for the conditions indicated.

Table A11b. Flue-Gas Composition at the Furnace Exit and unburned carbon (UBC) in the ash.

Test Run	O ₂ (%)	N ₂ (%)	CO ₂ (%)	CO ppmv	H ₂ O (%)	NO ppmv	SO ₂ ppmv	HCl ppmv	UBC wt%
31	1.2	28.8	63.9	51.9	6.0	775	303	12.0	1.34
32	2.7	28.6	62.3	46.3	6.2	1188	174	18.8	1.01
33	0.2	29.3	63.1	468.6	7.2	625	302	15.8	1.15
34	1.1	29.0	63.6	44.8	6.3	813	263	12.0	1.08
35	0.8	28.2	64.2	63.3	6.6	715	286	10.8	1.25
36	0.8	29.1	63.5	65.8	6.4	888	258	9.4	0.92
37	1.9	31.2	60.4	119.8	6.4	1023	327	8.4	0.90
38	0.9	24.6	67.1	65.8	7.1	1324	403	9.1	0.68
39	0.8	28.6	64.3	131.0	6.1	849	286	4.4	0.67
40	1.0	29.3	63.5	49.6	6.1	868	284	6.6	---
41	0.9	27.8	60.9	144.7	10.2	869	306	9.7	0.65
42	0.7	28.8	60.1	97.0	10.3	836	301	7.0	10.41 ^{CH}
43	0.8	28.1	60.3	141.2	10.8	263	377	5.5	0.79
44	0.9	28.5	60.1	68.7	10.4	297	358	4.7	15.72 ^{CH}
45	1.6	25.6	62.4	44.3	10.3	961	265	4.2	---
46	1.4	25.8	63.9	56.0	8.8	881	271	5.3	---
47	2.6	30.1	57.1	53.1	9.9	1169	1526	4.5	1.09
48	0.3	30.2	59.4	330.1	9.9	602	1795	4.3	4.61
49	1.0	28.8	60.5	129.2	9.4	865	1817	3.6	6.30
50	0.9	29.6	60.0	17.4	9.2	499	1809	3.4	---
51	0.8	28.1	61.1	111.3	9.7	1695	1750	3.4	---
52	0.7	30.4	62.4	227.0	6.2	972	2152	3.7	4.14
53	1.1	32.1	60.5	217.2	6.0	175	2739	---	13.08
54	0.7	28.2	61.1	179.9	9.8	327	1230	---	9.53
55	0.5	29.0	60.3	164.6	9.9	375	2870	---	7.99
56	2.8	27.9	63.3	66.5	5.8	850	619	2.2	3.01
57	0.3	29.0	64.5	122.0	6.1	471	799	2.2	6.94
58	0.8	28.6	63.6	101.4	6.8	613	729	2.6	6.79
59	1.0	27.2	65.5	89.6	6.1	563	726	2.4	---
60	1.0	26.6	66.1	99.9	6.1	681	691	2.4	---
61	1.0	29.1	63.6	96.5	6.1	588	743	2.3	7.15
62	0.8	29.0	64.0	88.8	6.0	541	739	2.4	7.81
63	0.8	29.1	64.0	91.1	6.0	222	832	2.2	10.92
64	1.0	27.3	65.3	79.2	6.3	649	874	2.2	8.40
65	1.0	28.0	64.1	118.0	6.7	956	1170	3.0	4.00

CH = The analysis was of a char probe sample taken from just under to over-fired recycle.

Tables A11c and A11d contain the standard deviations associated with the data in Tables A11a and A11b.

Table A11c. Standard Deviations for Table A11a.

Test Run	O ₂ (+/- %)	N ₂ (+/- %)	CO ₂ (+/- %)	CO +/- ppmv	H ₂ O (+/- %)	NO +/- ppmv	SO ₂ +/- ppmv	HCl +/- ppmv	UBC +/- wt%
1	0.2	1.1	1.9	1	---	50	23	---	---
2	0.2	0.9	1.5	3	0.1	19	64	1.3	0.04
3	0.4	5.8	11.1	128	0.1	451	93	1.3	0.04
4	0.2	0.9	1.6	216	0.0	298	61	1.1	0.06
5	0.2	1.6	3.0	412	0.2	128	67	2.3	0.04
6	0.2	1.4	2.7	2	---	---	13	---	---
7	0.2	2.2	4.3	446	0.1	149	92	1.0	0.01
8	0.2	1.6	3.0	1777	0.1	132	125	1.0	0.01
9	0.1	0.9	1.7	72	0.1	59	123	1.0	0.04
10	0.2	3.5	6.8	521	0.4	248	97	0.9	0.04
11	0.1	3.0	5.8	345	0.3	183	60	1.0	0.01
12	0.1	2.1	4.1	443	0.2	346	55	1.4	0.06
13	0.2	1.0	1.7	24	0.0	114	62	0.7	0.04 ^{CH}
14	0.3	2.2	4.0	62	0.0	84	60	0.8	0.03
15	0.3	0.8	1.3	6	---	44	49	---	0.26 ^{CH14}
16	0.3	0.9	1.5	21	---	54	18	---	---
17	0.4	0.7	1.0	17	---	52	14	---	2.93 ^{CH30}
18	0.3	0.7	1.2	1	---	21	9	---	1.38
19	0.2	0.2	0.3	56	---	45	12	---	1.76
20	0.2	0.2	0.3	0	---	---	8	---	1.34
21	0.5	0.3	0.1	---	---	25	10	---	4.19
22	0.2	0.3	0.4	17	---	29	8	---	6.31
23	0.2	0.2	0.2	22	---	45	8	---	3.70
24	0.3	2.2	4.2	9	0.3	239	66	0.4	2.64
25	0.2	2.1	3.9	107	0.1	134	45	0.3	2.10
26	0.1	0.8	1.6	208	0.1	78	23	0.2	1.49
27	0.2	0.6	1.0	50	0.1	112	25	0.2	1.99
28	0.1	1.4	2.7	8	0.1	161	24	0.3	3.63
29	0.1	0.4	0.8	8	0.0	118	19	0.3	17.54 ^{CH}
30	0.1	0.3	0.5	15	0.0	29	16	0.3	4.17

For an explanation of footnotes, see explanation at the bottom of Table A11a.

Table A11d. Standard Deviations for Table A11b.

Test Run	O ₂ (+/- %)	N ₂ (+/- %)	CO ₂ (+/- %)	CO +/- ppmv	H ₂ O (+/- %)	NO +/- ppmv	SO ₂ +/- ppmv	HCl +/- ppmv	UBC +/- wt%
31	0.4	2.9	5.5	43	0.0	210	27	0.4	0.01
32	0.1	0.6	1.0	3	0.2	63	17	0.5	0.08
33	0.5	1.5	2.6	876	0.1	124	53	0.3	0.04
34	0.1	1.1	2.2	4	0.1	97	15	0.3	0.05
35	0.2	1.1	2.0	98	0.1	146	18	0.3	0.03
36	0.1	1.6	3.1	59	0.1	94	20	0.3	0.01
37	0.1	1.8	3.5	83	0.2	130	50	0.3	0.00
38	0.1	1.1	2.1	33	0.1	186	57	0.3	0.02
39	0.4	2.1	3.8	325	0.0	86	19	0.3	0.04
40	0.1	0.6	1.2	92	1.0	52	63	0.4	---
41	0.2	1.0	1.9	706	0.6	83	46	0.8	0.00
42	0.2	0.8	1.5	328	0.1	82	26	0.3	0.52 ^{CH}
43	0.2	1.1	1.9	564	0.1	54	38	0.3	0.04
44	0.1	1.8	3.5	111	0.2	90	37	0.3	0.04 ^{CH}
45	0.4	1.5	2.6	4	0.1	88	34	0.3	---
46	0.3	1.4	2.5	394	0.6	150	45	1.4	---
47	0.3	2.5	4.7	5	0.2	196	213	0.3	0.02
48	0.3	2.2	4.0	774	0.2	140	164	0.3	0.08
49	0.1	1.6	3.0	310	0.2	115	144	0.3	0.08
50	0.2	0.9	1.6	187	0.1	41	40	0.3	---
51	0.2	0.9	1.6	165	0.1	148	146	0.3	---
52	0.4	1.1	1.8	529	0.1	145	195	0.2	0.10
53	0.3	0.4	0.5	18	---	29	94	---	0.02
54	0.4	0.3	0.2	36	---	38	23	---	0.20
55	0.3	0.3	0.3	40	---	14	130	---	0.07
56	0.2	1.4	2.6	3	0.1	130	38	0.3	0.00
57	0.1	0.5	0.9	86	0.1	48	32	0.2	0.09
58	0.2	0.5	0.8	8	0.0	70	35	0.3	0.11
59	0.2	0.9	1.5	11	0.0	221	39	0.3	---
60	0.2	0.9	1.6	89	0.0	110	38	0.3	---
61	0.2	0.6	1.0	41	0.0	78	26	0.3	0.35
62	0.1	0.5	0.9	4	0.0	49	20	0.3	0.05
63	0.1	0.4	0.7	12	0.0	43	27	0.3	0.25
64	0.1	0.3	0.4	3	0.0	51	18	0.3	0.28
65	1.6	3.5	5.4	1019	0.1	253	316	0.3	0.01

For an explanation of footnotes, see explanation at the bottom of Table A11a.

Tables A12a and A12b contain the flue-gas composition for each test condition at the scrubber, after the acid gases have been removed from the flue gas but using the measured moisture values obtained upstream of the baghouse.

Table A12a. Flue gas composition at the scrubber.

Test Run	Dry Basis			Wet Basis			H ₂ O (%)
	CO ₂ (%)	N ₂ (%)	O ₂ (%)	CO ₂ (%)	N ₂ (%)	O ₂ (%)	
1	67.3	29.2	3.5	63.3	27.4	3.3	6.0
2	68.4	27.2	4.4	64.5	25.7	4.1	5.7
3	71.6	26.5	1.9	67.0	24.8	1.8	6.4
4	72.1	27.2	0.7	67.1	25.4	0.7	6.9
5	71.7	27.0	1.3	66.6	25.1	1.2	7.1
6	66.2	29.6	4.2	62.2	27.8	3.9	6.0
7	70.0	28.6	1.4	65.1	26.6	1.3	7.0
8	70.8	27.8	1.4	65.6	25.8	1.3	7.3
9	74.4	24.3	1.3	68.2	22.3	1.2	8.3
10	68.7	29.8	1.5	64.2	27.9	1.4	6.5
11	65.3	33.1	1.6	61.0	30.9	1.5	6.6
12	68.3	30.2	1.5	63.4	28.0	1.4	7.2
13	59.5	38.9	1.6	55.2	36.1	1.5	7.2
14	64.2	34.2	1.6	59.4	31.7	1.5	7.4
15	64.8	32.9	2.3	60.2	30.5	2.1	7.1
16	68.2	29.7	2.1	64.5	28.1	2.0	5.4
17	66.3	30.9	2.8	62.8	29.3	2.7	5.2
18	73.2	22.2	4.6	69.8	21.1	4.4	4.7
19	71.7	26.5	1.8	67.8	25.0	1.7	5.5
20	68.1	28.0	3.9	64.7	26.7	3.7	4.9
21	70.6	28.7	0.7	66.5	27.0	0.7	5.8
22	67.8	30.4	1.8	64.0	28.8	1.7	5.5
23	70.5	27.8	1.7	66.6	26.3	1.6	5.5
24	62.4	35.8	1.8	60.3	34.6	1.7	3.4
25	65.2	33.2	1.6	61.7	31.4	1.5	5.3
26	68.9	29.4	1.7	64.7	27.6	1.6	6.1
27	72.1	26.4	1.5	68.0	24.9	1.4	5.7
28	71.9	26.4	1.7	67.4	24.8	1.6	6.3
29	68.2	30.3	1.5	64.3	28.5	1.4	5.8
30	67.5	30.7	1.8	63.7	29.0	1.7	5.6

Table A12b. Flue gas composition at the scrubber.

Test Run	Dry Basis			Wet Basis			H ₂ O (%)
	CO ₂ (%)	N ₂ (%)	O ₂ (%)	CO ₂ (%)	N ₂ (%)	O ₂ (%)	
31	66.3	31.9	1.8	62.3	30.0	1.7	6.0
32	64.7	31.9	3.4	60.7	29.9	3.2	6.2
33	66.5	32.8	0.7	61.7	30.4	0.6	7.2
34	66.2	32.1	1.7	62.0	30.1	1.6	6.3
35	67.2	31.4	1.4	62.7	29.3	1.3	6.6
36	66.3	32.3	1.4	62.0	30.3	1.3	6.4
37	62.9	34.6	2.5	58.9	32.4	2.3	6.4
38	70.6	27.9	1.5	65.6	25.9	1.4	7.1
39	66.9	31.7	1.4	62.8	29.8	1.3	6.1
40	66.0	32.4	1.6	62.0	30.4	1.5	6.1
41	66.3	32.2	1.5	59.5	29.0	1.3	10.2
42	65.4	33.3	1.3	58.6	29.9	1.2	10.3
43	65.9	32.7	1.4	58.8	29.2	1.2	10.8
44	65.5	33.0	1.5	58.7	29.6	1.3	10.4
45	67.8	29.9	2.3	60.9	26.8	2.1	10.3
46	68.3	29.7	2.0	62.3	27.1	1.8	8.8
47	61.8	34.8	3.4	55.6	31.3	3.1	9.9
48	64.5	34.7	0.8	58.1	31.3	0.7	9.9
49	65.3	33.1	1.6	59.2	30.0	1.5	9.4
50	64.6	33.9	1.5	58.7	30.7	1.4	9.2
51	66.2	32.4	1.4	59.8	29.3	1.3	9.7
52	65.0	33.7	1.3	61.0	31.6	1.2	6.2
53	62.9	35.4	1.7	59.1	33.2	1.6	6.0
54	66.2	32.5	1.3	59.7	29.3	1.2	9.8
55	65.5	33.4	1.1	59.0	30.1	1.0	9.9
56	65.4	31.1	3.5	61.6	29.3	3.3	5.8
57	67.1	32.1	0.8	63.0	30.2	0.8	6.1
58	66.7	31.9	1.4	62.1	29.8	1.3	6.8
59	68.1	30.3	1.6	63.9	28.4	1.5	6.1
60	68.8	29.6	1.6	64.5	27.8	1.5	6.1
61	66.1	32.3	1.6	62.1	30.3	1.5	6.1
62	66.5	32.1	1.4	62.5	30.2	1.3	6.0
63	66.4	32.2	1.4	62.4	30.3	1.3	6.0
64	68.0	30.4	1.6	63.7	28.5	1.5	6.3
65	67.1	31.3	1.6	62.6	29.2	1.5	6.7