Computational Fluid Dynamics Based Investigation of Sensitivity of Furnace Operational Conditions to Burner Flow controls

Semi-Annual Progress Report

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Abstract

This is the first Semiannual Technical Report for DOE Cooperative Agreement No: DE-FC26-02NT41580. The goal of this project is to systematically assess the sensitivity of furnace operational conditions to burner air and fuel flows in coal fired utility boilers. Our approach is to utilize existing baseline furnace models that have been constructed using Reaction Engineering International's (REI) computational fluid dynamics (CFD) software. Using CFD analyses provides the ability to carry out a carefully controlled virtual experiment to characterize the sensitivity of NOx emissions, unburned carbon (UBC), furnace exit CO (FECO), furnace exit temperature (FEGT), and waterwall deposition to burner flow controls. The Electric Power Research Institute (EPRI) is providing co-funding for this program, and instrument and controls experts from EPRI's Instrument and Controls (I&C) Center are active participants in this project. This program contains multiple tasks and good progress is being made on all fronts.

A project kickoff meeting was held in conjunction with NETL's 2002 Sensors and Control Program Portfolio Review and Roadmapping Workshop, in Pittsburgh, PA during October 15-16, 2002. Dr. Marc Cremer, REI, and Dr. Paul Wolff, EPRI I&C, both attended and met with the project COR, Susan Maley. Following the review of REI's database of wall-fired coal units, the project team selected a front wall fired 150 MW unit with a Riley Low NOx firing system including overfire air for evaluation. In addition, a test matrix outlining approximately 25 simulations involving variations in burner secondary air flows, and coal and primary air flows was constructed. During the reporting period, twenty-two simulations have been completed, summarized, and tabulated for sensitivity analysis. Based on these results, the team is developing a suitable approach for quantifying the sensitivity coefficients associated with the parametric tests. Some of the results of the CFD simulations of the single wall fired unit were presented in a technical paper entitled, "CFD Investigation of the Sensitivity of Furnace Operational Conditions to Burner Flow Controls," presented at the 28th International Technical Conference on Coal Utilization and Fuel Systems in Clearwater, FL March 9-14, 2003. In addition to the work completed on the single wall fired unit, the project team made the selection of a 580 MW opposed wall fired unit to be the subject of evaluation in this program. Work is in progress to update the baseline model of this unit so that the parametric simulations can be initiated.

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Executive Summary

The goal of this project is to systematically evaluate and quantify the sensitivity of furnace operational conditions to burner air and fuel flow controls in coal fired utility boilers to provide the type of information that the controls engineer will need to make informed decisions on the potential payoff associated with installation of burner flow controls, prior to committing to a significant financial investment in the installation of sophisticated burner controls. The approach is to utilize computational fluid dynamic (CFD) modeling to investigate the influence of variations of burner air and fuel flows under well controlled conditions on NOx emissions, unburned carbon, CO, particulate deposition on waterwalls and boiler heat transfer characteristics in two wall-fired PC units (front and opposed wall-fired), two corner-fired PC units and one cyclone-fired unit. In this project, we are utilizing REI's three dimensional, multiphase, turbulent reacting flow code *GLACIER* to perform the analyses. REI has significant experience in applying CFD modeling with *GLACIER* to aid in combustion system design, investigate impacts of combustion modifications, and evaluate performance of in-furnace and post combustion NOx control technologies in well over one-hundred utility boilers. Much of this work has involved the investigation of effects of combustion modifications on NOx emissions, CO, UBC, and particulate deposition of ash and unburned combustibles on waterwalls which can impact slagging characteristics and waterwall corrosion rates. The CFD model results provide a wealth of information on the flow patterns, temperature and species distributions, and particulate reactions, dynamics and deposition so that intelligent decisions concerning operational or equipment modifications can be made. This project has a period of performance from November 1, 2002 through October 31, 2004.

During the first six months of this project, the team nearly completed the evaluation of the single-wall fired unit and has begun simulation of the opposed wall fired unit. In particular, the following work has been accomplished during this time period:

- A project kickoff meeting was conducted as part of the DOE NETL Sensors and Control Program Portfolio Review and Roadmapping Workshop in Pittsburgh, PA on October 15-16, 2002.
- The project team met in the EPRI I&C offices in Kingston, TN to select the single wall and opposed wall-fired units for evaluation in this project as well as to develop the test matrix for the single wall-fired unit.
- The CFD evaluation of the single wall-fired unit has been nearly completed. The predictions from the baseline simulation are in very good agreement with measured data for NOx emissions, unburned carbon in fly ash, furnace exit CO, and gas temperature. Simulation results for twenty-two parametric cases to evaluate impacts of row by row biasing of secondary air and coal as well as column biasing of coal have been obtained.
- Results of the single wall-fired unit evaluation have been summarized and sensitivity analyses are in progress.
- Results for the single wall-fired unit have been presented at the 28th International Technical Conference on Coal Utilization & Fuel Systems in Clearwater, FL on March 9-14, 2003. A technical paper has also been accepted for presentation at PowerGen International, December 9-11, 2003, in Las Vegas, NV.

- Additional CFD simulations for the single wall-fired unit are in process and will aid in strengthening or qualifying the preliminary conclusions that have been proposed thus far.
- Work to update the baseline model of the opposed wall-fired unit and the parametric simulations for this unit are in progress.

1

Introduction

As aggressive reductions in boiler emissions are mandated, the electric utility industry has been moving toward installation of improved methods of burner flow measurement and control to optimize combustion for reduced emissions and improved operability in coal-fired boilers. The interest of the electric utility industry in this area is demonstrated by the number of papers presented on this topic at last years' conference (Letcavits, 2002; Cherry, 2002; Grusha, 2002). As utilities consider strategies for measuring and controlling air and coal flows, an important question is what level of control is required to improve combustion performance, particularly in low-NOx systems. For example, do flows need to be very tightly controlled at each burner or are multi-burner controls sufficient? Development of cost effective controls for burning balancing requires an understanding of how variations in air and coal flows relates to boiler impacts that are of interest. It is not cost effective to install expensive, high precision control systems if that level of precision is not necessary. On the other hand, installation of more coarse, less precise systems may not control flows to the level that is necessary. Instruments for measuring coal flows within coal pipes are currently in a state of development, and utilities have been reluctant to commit the significant financial resources necessary to purchase this equipment without having additional reliable information concerning the potential payoff associated with installation of these instruments. This project will serve to provide the type of information that the controls engineer will need to make informed decisions on the potential payoff associated with installation of burner flow controls, prior to committing to a significant financial investment in the installation of sophisticated burner controls.

The sensitivity of parameters, such as NOx and CO emissions, unburned carbon (UBC) in ash, and particulate deposition on waterwalls, to burner flows is likely dependent on furnace geometry, coal type, the specific burner location, load, as well as firing configuration. The investigation of these sensitivities through bench or pilot scale testing can be extremely time-consuming and expensive, and the amount of information acquired through such testing is often limited. In addition, the impacts of the gross furnace behavior as well as burner to burner interactions are typically ignored in these types of investigations. Testing these sensitivities in fully operating boilers is difficult due to the dynamic nature of boiler operation, which precludes the well-controlled testing warranted in this type of investigation.

The approach we are using here is to use computational fluid dynamic (CFD) modeling to quantify the impacts of variations of burner air and fuel flows on furnace operating parameters. CFD modeling provides a strategy for investigation of these sensitivities under well controlled conditions. We are utilizing REI's three dimensional, multiphase, turbulent reacting flow code *GLACIER* to perform the analyses. REI has significant experience in applying CFD modeling with *GLACIER* to aid in combustion system design, investigate impacts of combustion modifications, and evaluate performance of in-furnace and post combustion NOx control technologies. Much of this work has involved the investigation of effects of combustion modifications on NOx emissions, CO, UBC, and particulate deposition of ash and unburned combustibles on waterwalls which can impact slagging characteristics and waterwall corrosion rates. The CFD model results provide a wealth of information on the flow patterns, temperature and species distributions, and particulate reactions, dynamics and deposition so that intelligent decisions concerning operational or equipment modifications can be made.

The approach that we are planning to follow in this project will be to evaluate sensitivity of furnace conditions to burner air and fuel flows in 5 different coal fired units: 1) two wall-fired PC units (front and opposed wall-fired), 2) two corner-fired PC units, and 3) one cyclone-fired unit. REI and the project team will choose existing *GLACIER* furnace models that have been verified by comparison with plant observations and measurements. In each case, we will quantify impacts of variations in air and fuel flows on: 1) NOx emissions, 2) unburned carbon (UBC) in the fly ash, 3) furnace exit CO, 4) particulate deposition, and 5) furnace heat transfer. The predicted NOx levels at the furnace exit represent stack NOx levels. On the other hand, the predicted furnace exit CO will not represent stack CO emissions, but can still be utilized to assess sensitivities. The model simulations will predict rates of deposition of ash and unburned combustibles on the furnace walls. Thus, impacts of burner air and fuel flows on these deposition rates and patterns can be assessed. These predictions are useful for providing insight into expected changes to slagging behavior and/or rates of waterwall corrosion. In regards to furnace heat transfer, the model simulations will provide insight into impacts on furnace exit gas temperature as well as lower furnace heat flux profiles and temperature distribution.

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Experimental Methods

Within this section we present in order, brief discussions on the specific tasks that are included within this program. For simplicity, the discussion items are presented in the order of the Tasks as outlined in our original statement of work from the proposal.

Task 1 - Project Management

A number of activities were completed in this task area regarding coordination of project team efforts and presentation of results to DOE NETL and the utility industry.

- Project Kickoff Meeting: The project PI, Dr. Marc Cremer, and EPRI I&C senior engineer, Paul Wolff attended the DOE NETL Sensors and Control Program Portfolio Review and Roadmapping Workshop in Pittsburgh, PA on October 15-16, when we conducted our project kickoff meeting with our DOE COR, Susan Maley. During the first day of the meeting, a podium presentation entitled, "CFD Evaluation of Sensitivity of Furnace Conditions to Burner Flow Controls – Project Plans," was given. This presentation outlined the objectives and planned approach for this project.
- Project Team Meeting: On December 17, 2002, Drs. Marc Cremer (PI) and Brad Adams (President, REI) visited the EPRI I&C Center for a 1 day meeting with EPRI I&C project participants Dr. Paul Wolff, Rob Frank, and Cyrus Taft. Richard Brown, EPRI, participated in this meeting by phone. The outcome of this meeting was the selection of the particular wall-fired unit for evaluation as well as the definition of the test matrix for evaluation of the wall fired unit. The summary notes from this meeting are included as appendix 1.
- Presentation of Results: Dr. Marc Cremer presented a paper entitled, "CFD Investigation of Sensitivity of Furnace Operational Conditions to Burner Flow Controls," discussing preliminary project results at the 28th International Technical Conference on Coal Utilization & Fuel Systems in Clearwater, FL on March 9-14, 2003. This paper was quite well received and several contacts were made with others doing research in this area.
- Upcoming Conferences: A paper entitled, "CFD BASED EVALUATION OF THE SENSITIVITY OF COAL FIRED FURNACE OPERATION TO BURNER FLOW CONTROLS," has been submitted for presentation at PowerGen International, December 9-11, 2003, in Las Vegas, NV.
- Circulation of Reports: Semiannual and final reports on this project delivered to DOE-NETL will also be provided to EPRI, who is providing cost sharing on this project. EPRI will be circulating these reports to their members, providing an effective transfer of technology to the electric utility industry.

In summary, the project team has been very active through the first six months in coordinating our activities, performing our analyses, and presenting results to DOE and the utility industry.

Task 2 – CFD Evaluation for a PC Single Wall-Fired Boiler

The purpose of this task is to utilize REI's proprietary CFD code GLACIER to evaluate the impacts of burner air and/or coal flow variations in a single wall-fired PC unit. Subtasks for this effort include:

2.1 Selection of furnace model
2.2 Definition of test matrix
2.3 Parametric simulations
2.4 Analysis of results

Task 2.1 Selection of single wall-fired furnace model

All units to be evaluated in this study will be selected from REI's existing database of furnace models and each selection will attempt to represent the power industry as a whole. REI has modeled approximately 20 single wall-fired utility boilers, 15 opposed wall fired units, and 20 tangentially fired units burning pulverized coal. In addition over 35 cyclone fired units burning crushed coal with blends of tire derived fuel (TDF) and petroleum coke have been simulated. Unit capacities have ranged from 30 to 1300 MW. In addition to unit size, other parameters including firing configuration (e.g. burner type, overfire air design, concentric vs. nonconcentric firing, corner vs. non-corner tangential firing), coal type (bituminous, subbituminous, lignite), and whether the unit is supercritical vs. subcritical will be considered. In regards to the cyclone units, burner type (scroll, vortex, radial), barrel size (8, 9, or 10 ft. diameter), and the existence of a target wall will also be taken into account in the unit selection. EPRI's participation in the selections will assure that the units selected for evaluation will represent the industry as a whole.

Out of a database of approximately 20 single wall fired pulverized coal furnace models ranging in size from 35 to 350 MW, the project team selected a 16 burner, 150 MW Riley-Stoker furnace. This unit is equipped with Riley Combustion Controlled Venturi (CCV) single register low NOx burners as well as a single row of overfire air (OFA) ports on the front wall. The average full load NOx emissions are approximately 0.40 lb/MBtu and typical measured loss on ignition (LOI) is 22%. The firing configuration as well as the boiler geometry is symmetric about the center of the unit. The fuel fired in this unit is a 1.3% sulfur, 6.6% ash containing bituminous coal.

A number of factors made this particular boiler a good selection for this study. The 16 burner layout provides complexity enough so that burner to burner interactions exist, but not excessive complexity that would preclude accurate simulation. EPRI reports show that of all single wall fired units with low NOx systems, those equipped with Riley CCV burners and OFA contribute a significant fraction. In addition, our understanding of full load firing conditions, as provided by the utility, is believed to be quite good. In all, the furnace geometry, low NOx firing system, the type of coal, as well as the unit size, make this particular furnace a good choice for inclusion in this evaluation.

Task 2.2 Definition of test matrix

A key task in performing the parametric evaluations for this project is identification of appropriate cases that will provide a basis for completion of a sensitivity analysis. The number of possible cases involving variations in air and fuel flow rates for all sixteen burners is uncountable. So it is important to define a test matrix of limited size that will provide a representative range of conditions.

The project team held several discussions on this issue. On December 17, 2002, the team met in the EPRI I&C offices at the Kingston plant of Tennessee Valley Authority (TVA) to establish the test matrix. The team agreed that to keep the number of simulations to a realistic number, certain furnace conditions would remain fixed including: coal composition and grind, air temperature, primary air to fuel ratio, furnace stoichiometry, furnace firing rate, burner secondary/tertiary air ratio, waterwall and convective surface properties, and burner type. However, it was agreed that the test matrix may change subject to preliminary results. Given these constraints, the group agreed that the specific variations to consider are: 1) biasing only the secondary combustion air, keeping the overall burner zone stoichiometry fixed, 2) biasing the coal flow rates only, keeping the overall burner zone stoichiometry and firing rate fixed, and 3) biasing the coal and secondary air flow rates together to keep the stoichiometry of each burner fixed. In addition, the team agreed that these variations should be carried out under two different burner zone stoichiometries representing "typical" conditions and "low NOx, deeper staged" conditions.

Based on these constraints, the team developed the following matrix of simulations for the 16 burner single wall-fired unit:

1. Base case – all burners uniform (1 case)
2. -25% fuel in each of four rows (fuel evenly redistributed to other burners) (4 cases)
3. -25% fuel in each of two burners in the most sensitive row (determines maximum sensitivity) (2 cases)
4. -25% fuel in each of two burners in the least sensitive row (determines minimum sensitivity) (2 cases)
5. -10% fuel to most sensitive row and burner (2 cases)
6. Repeat four row tests in item 2 with air biasing (same stoichiometric ratio as fuel change) (4 cases)
7. Repeat row test in item 5 with air biasing (1 case)
8. Repeat four row tests in item 2 with air and fuel biasing (constant stoichiometry) (4 cases)
9. Repeat row test in item 5 with air and fuel biasing (1 case)
10. Run new uniform burner case at deeper staging (1 case)
11. Depending on previous results, vertically bias either coal or air flow at the more deeply staged conditions (2 cases)
12. Bias burner groups horizontally (-25% fuel) (2 cases)
13. Fill in sensitivity curves as necessary

The team members will periodically assess whether any changes to the test matrix are necessary.

Task 2.3 Parametric Simulations

The CFD model utilized in this evaluation is REI's proprietary multi-phase turbulent reacting flow code, *GLACIER*. *GLACIER* was originally developed to simulate solid fuel combustion and has been used to model more than 100 utility scale boilers over the last decade, including cyclone, wall, tangential, and turbo fired configurations burning a range of fuels including coal, oil, gas, biomass, and tire-derived fuel. Figure 1 shows the distribution of units modeled by REI as a function of firing system and size. The motivation for the majority of the simulations has been NOx reduction, including evaluation of the boiler impacts associated with combustion and post combustion based NOx controls. The application of these tools to the evaluation of NOx reduction strategies (Cremer, 2000a; Cremer, 2000b; Cremer, 2001; Cremer, 2002) and their impacts on coal fired boiler operation (Valentine, 2000; Davis 2002) has been well documented.

GLACIER employs a combination of Eulerian and Lagrangian reference frames (Adams, 1995; Baxter, 1996; Adams, 1993; Jain, 1998; Smoot, 1985). The flow field is assumed to be a steady-state, turbulent, reacting continuum field that can be described locally by general conservation equations. The governing equations for gas-phase fluid mechanics, heat transfer, thermal radiation and scalar transport are solved in an Eulerian framework. Gas properties are determined through local mixing calculations and are assumed to fluctuate randomly according to a statistical probability density function (PDF) which is characteristic of the turbulence. Turbulence is typically modeled with a two-equation non-linear k-ε model that can capture secondary recirculation zones in corners. Gas-phase reactions are assumed to be limited by mixing rates for the major species as opposed to chemical kinetic rates for kinetically limited species such as oxides of nitrogen. In regards to predictions of NOx, REI's methodology is to utilize a reduced mechanism approach, which employs assumptions of certain chemical species being in steady state (Cremer, 2000a; Cremer, 2000b). REI has successfully applied this model to predict impacts of low NOx burners, staging with OFA, RRI, SNCR, water injection, flue gas recirculation, and reburning on NOx emissions in coal fired boilers (Adams, 2001; Cremer, 2001a; Cremer 2001b; Cremer, 2002).

The governing equations for particle-phase mechanics are solved in a Lagrangian reference frame. This approach to modeling fuel/ash particles provides a convenient basis for implementing descriptions of phenomena such as unburned carbon, deposition, and corrosion. The mean path and dispersion of an ensemble of particles, referred to as a "particle cloud," are tracked. Dispersion of the cloud is determined with input from the turbulent gas flow field. Particle mass, momentum, and energy sources are coupled to the gas flow field through a particle-source-in-cell technique (Crowe, 1977). Particle reaction processes include coal devolatilization, char oxidation, and liquid evaporation. Waterwall deposition is accounted for through evaluation of particle/wall interactions. Since each particle cloud originates within a particular location within a particular burner, particulate deposition on waterwalls and unburned carbon on the fly ash can be traced back to its source.

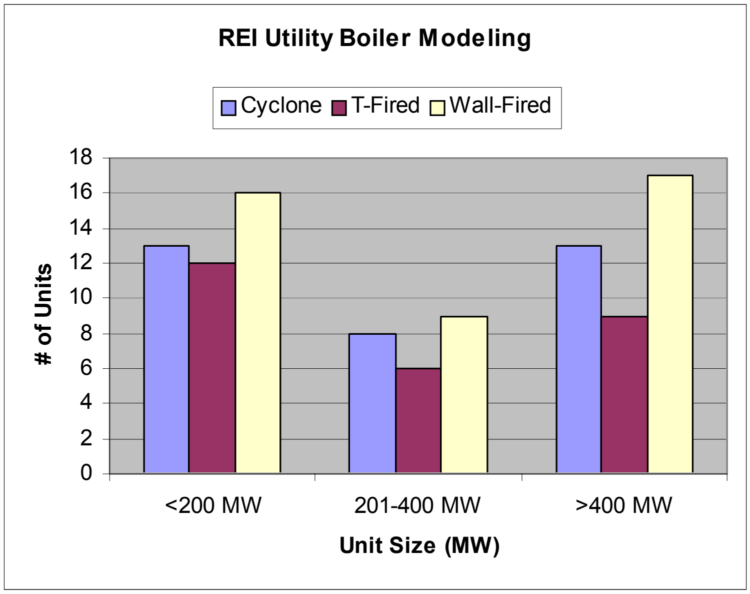

Figure 1: Distribution of utility boilers modeled by REI as a function of size and firing configuration.

Task 2.4 Analysis of Results

Each simulation that is completed provides a significant amount of data for analysis. The simulations not only provide information at the model exit, but spatial distributions of parameters are provided throughout the furnace. For this study, detailed analyses focus on the predicted furnace exit (model outlet) results. The detailed gas and particle phase distributions are helpful in understanding the trends seen in the furnace exit conditions

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Results and Discussion

The majority of the simulations for the evaluation of the single wall-fired unit have been completed, and we have begun evaluation for the opposed wall-fired unit. Evaluation for one tangentially fired unit will likely begin in parallel with that of the opposed-wall fired unit. The following sections describe the results of the front wall-fired unit evaluation.

Unit Selection

Out of a database of approximately 20 single wall-fired pulverized coal furnace models ranging in size from 35 to 350 MW, the project team selected a 16 burner, 150 MW Riley-Stoker furnace with specifications as shown in Table 1. This unit is equipped with Riley Combustion Controlled Venturi (CCV) single register low NOx burners as well as a single row of overfire air (OFA) ports on the front wall. The average full load NOx emissions are approximately 0.40 lb/MBtu and typical measured loss on ignition (LOI) is 22%. The firing configuration as well as the boiler geometry is symmetric about the center of the unit. The fuel fired in this unit is a 1.3% sulfur, 6.6% ash containing bituminous coal.

Baseline Simulation

A baseline CFD model of this unit was previously developed in cooperation with the utility. Figure 2 shows an outline of that furnace model. The simulation extends from the ash hopper up through the burner column, OFA ports, radiant superheater, and exits in the vertical plane immediately downstream of the high temperature reheater. Although the entire lower furnace is shown in Fig. 2, only one-half of the furnace was simulated by placing a symmetry plane through the center of the furnace parallel to the side walls. Color contours are shown in Fig. 2 for the predicted gas temperature distribution in the baseline case. Baseline operation includes all 16 burners in service as seen in Fig. 2. However, the wing OFA ports are closed under baseline full load conditions.

Figure 3 shows predicted mean coal particle trajectories as a function of initial size and burner location. Also shown is the predicted particle deposition flux on the rear waterwall. The particle trajectories are colored according to the remaining char fraction in the particle cloud. By analysis of the char remaining in the particulates at the furnace exit, the total unburned carbon (UBC) in the fly ash as well as the UBC as a function of starting location and particle size can be computed. Similarly, the simulation also allows analysis to compute the contribution of each burner to total waterwall deposition.

Figure 4 shows the predicted distributions of CO and O_2 for the baseline simulation. The predicted NOx distribution is provided in Figure 5. The simulated NOx emissions, furnace exit gas temperature, CO, and unburned carbon in the fly ash at the model exit are provided in Table 2. The predicted NOx and LOI levels agree well with the typical full load emissions as seen by comparison with Table 1.

Table 1: Specifications for Single Wall, Coal Fired Utility Boiler Model

Parameter	Value
Gross Output	150 MW
Number of burners	16
Burner arrangement	4 rows, 4 columns
Burner Type	Riley CCV
OFA Arrangement	Front Wall, single elevation, 6 ports
Coal	Bituminous, 1.3% S
UBC in fly ash	22%
NOx (lb/Mbtu)	0.4

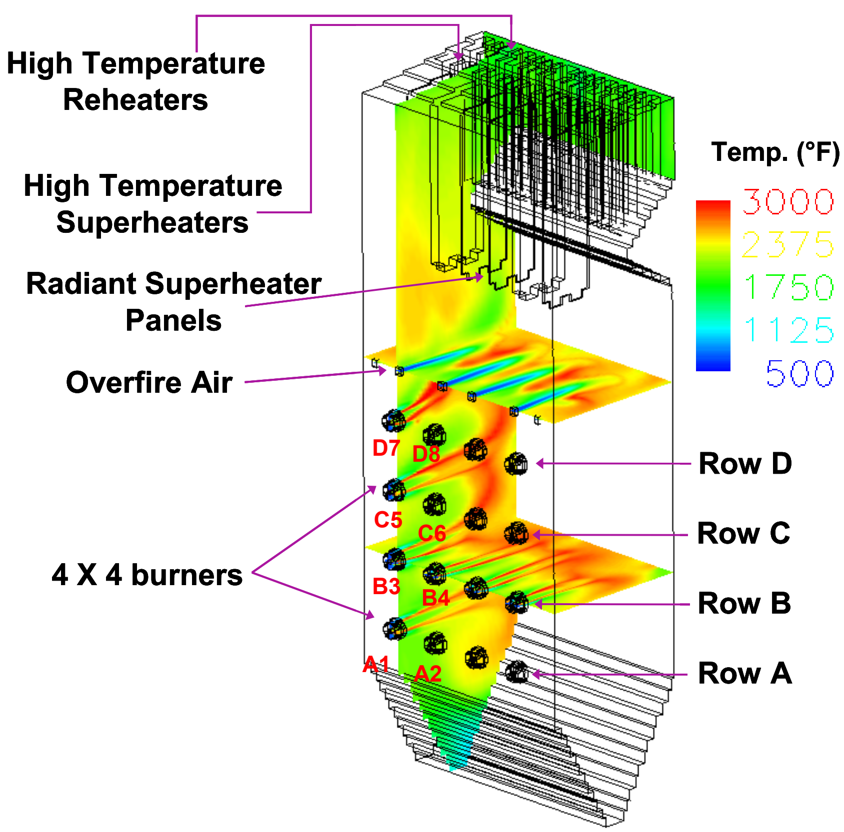

Figure 2: Predicted gas temperature distribution for 150 MW front-wall fired coal boiler.

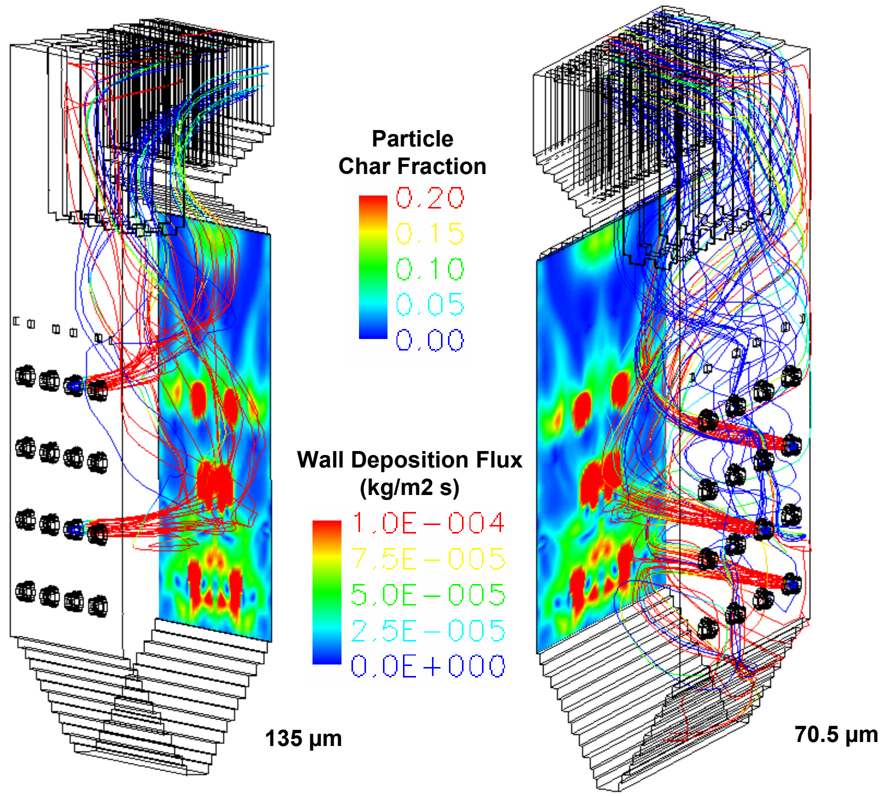

Figure 3: Predicted deposition flux on the rear wall and remaining char fraction as a function of particle size and burner starting location.

Parametric Simulations

The test matrix of cases that has been completed for the evaluation of the single wall-fired unit was based on adjustment of air and fuel between burners on a burner row or column basis. The majority of the simulations have involved adjustments on a row basis. The completed simulations are:

1. Base case – all burners uniform (1 case)
2. -25% fuel in each of four rows (fuel evenly redistributed to other burners) (Cases 1-4)
3. -25% fuel in each of two burners in the most sensitive row (Cases 5-6)
4. -10% fuel to most sensitive row (Cases 7-8)
5. Repeat four row tests in item 2 with air biasing (Cases 9-12)
6. Repeat four row tests in item 2 with air and fuel biasing (Cases 13-16)
7. Column fuel biasing in row B (Case 17)
8. Deeper staging with and without firing rate increases (Cases 18-22)

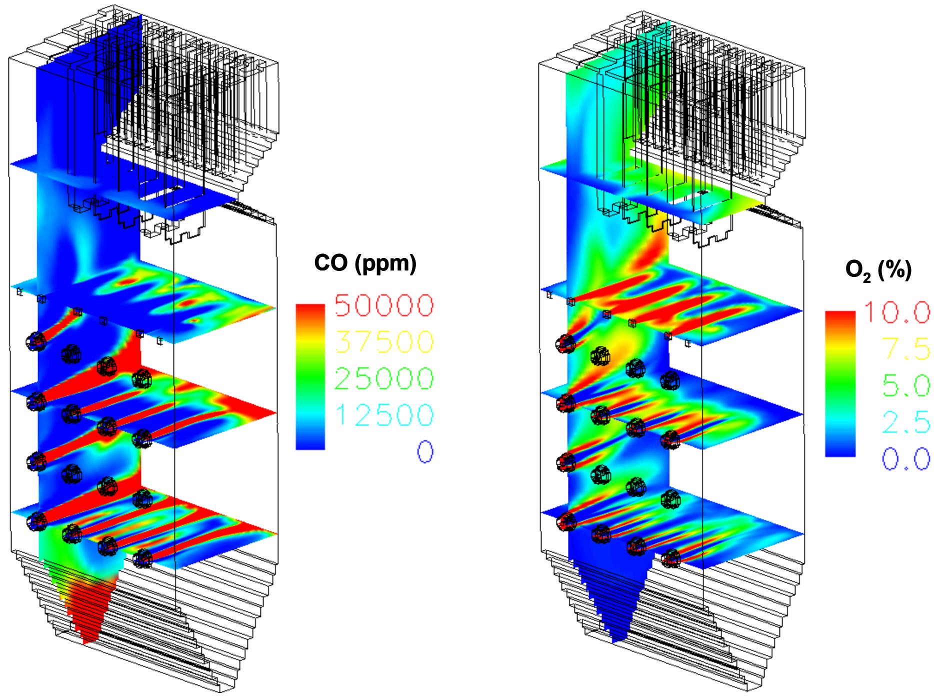

Figure 4: Predicted CO and O_2 distribution for 150 MW front wall-fired coal boiler under full load conditions.

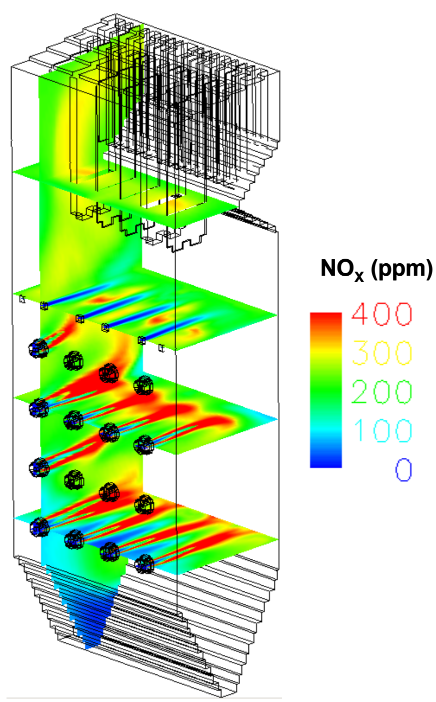

Figure 5: Predicted NO_x distribution for 150 MW front wall-fired coal boiler under full load conditions.

Table 2: Model exit predicted values for the single wall-fired unit under baseline operation.

Model Exit	Baseline
Gas Temperature (°F)	1910
CO Concentration, dry ppm	581
O_2 Concentration, dry %	3.90
NOx Concentration, dry ppm	267
lb-NOx/MMBtu	0.37
LOI (%)	27

Table 3 contains a detailed summary of the input data for the simulations. Figure 2 shows how the burner rows and individual burners are numbered. Row A is the bottom burner elevation and row D is the top. The baseline case assumed uniform coal and air flow to all 16 burners. Cases 1-4 evaluated the impacts of reducing the coal flow rate by 25% sequentially to each of the four burner rows. In each case, the coal that was removed from a selected burner row was uniformly redistributed to the burners in the remaining three rows to keep the total coal flow rate to the furnace unchanged from the baseline case. Cases 5-8 evaluated the impact of reducing the coal flow rate to two pairs of the four burners in the row that yielded the greatest change in NOx from cases 1-4. Coal flow rates were adjusted in pairs since the model utilizes a symmetry plane. Both 25% and 10% reductions in coal flows were evaluated. In these cases, the coal removed from the burner pairs was uniformly redistributed to the burners in the remaining three rows, without modifying the coal flow to the two remaining burners in the affected row. In cases 9-12, the same evaluation from cases 1-4 was repeated except that the secondary air was increased sequentially to each of the four burner rows. This evaluation was carried out to obtain the same burner row stoichiometric ratio as that obtained in cases 1-4. Thus, the adjustment to the secondary air flow rate was approximately 33%. In cases 13-16, both the secondary air flow rate and coal flow rate was adjusted sequentially in each of the four burner rows in a manner to keep the burner stoichiometric ratio unchanged. A reduction in coal flow rate of 25% (with the stoichiometric equivalent quantity of air) was evaluated. In case 17, row B biasing of the coal flow rate was evaluated in a manner to keep the row fuel flow rate fixed. The row B wing burner coal flow was reduced 25% while the interior burner coal flow was increased 25%. Cases 18-22 evaluated deeper staging conditions achieved either through fuel flow increases or burner air flow reductions. These cases were carried out to evaluate sensitivities under more deeply staged conditions as well as to provide results that would lend themselves to the sensitivity analyses being carried out.

Table 3: Simulated parametric cases for single wall-fired unit.

INPUTS	Baseline	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Furnace Case 'Group'	baseline	fuel biasing	fuel biasing	fuel biasing	fuel biasing	fuel biasing	fuel biasing	fuel biasing	fuel biasing
"Case Description"	uniform burners	D row leaner	C row leaner	B row leaner	A row leaner	D7 leanest	D8 leanest	D7 leanest	D8 leanest
Overall Furnace SR	1.193	1.193	1.193	1.193	1.193	1.193	1.193	1.193	1.193
Burner SR	0.950	0.950	0.950	0.950	0.950	0.950	0.950	0.950	0.950
Furnace Firing Rate (MMBtu/hr)	1500	1500	1500	1500	1500	1500	1500	1500	1500
Total Furnace Coal Flow Rate (kpph)	113.0	113.0	113.0	113.0	113.0	113.0	113.0	113.0	113.0
Total Furnace Air Flow Rate (kpph)	1366.0	1366.0	1366.0	1366.0	1366.0	1366.0	1366.0	1366.0	1366.0
Primary Air Flow Rate (kpph)	204.9	204.9	204.9	204.9	204.9	204.9	204.9	204.9	204.9
Primary Air (% of total air)	15%	15%	15%	15%	15%	15%	15%	15%	15%
Secondary Air Flow Rate (kpph)	882.9	882.9	882.9	882.9	882.9	882.9	882.9	882.9	882.9
Secondary Air (% of total air)	65%	65%	65%	65%	65%	65%	65%	65%	65%
OFA Flow Rate (kpph)	278.2	278.2	278.2	278.2	278.2	278.2	278.2	278.2	278.2
OFA (% of total air)	20%	20%	20%	20%	20%	20%	20%	20%	20%
OFA Port Jet Velocity (ft/s)	244	244	244	244	244	244	244	244	244
ROW A									
Burner 1									
Coal Flow Rate (kpph)	7.063	7.651	7.651	7.651	5.297	7.357	7.357	7.180	7.180
Coal Carrier Air Flow Rate (kpph)	12.806	13.873	13.873	13.873	9.604	13.339	13.339	13.019	13.019
Secondary Air Flow Rate (kpph)	55.180	55.180	55.180	55.180	55.180	55.180	55.180	55.180	55.180
Burner Air Flow Rate (kpph)	67.985	69.052	69.052	69.052	64.784	68.519	68.519	68.199	68.199
Burner SR	0.950	0.891	0.891	0.891	1.207	0.919	0.919	0.937	0.937
Burner 2									
Coal Flow Rate (kpph)	7.063	7.651	7.651	7.651	5.297	7.357	7.357	7.180	7.180
Coal Carrier Air Flow Rate (kpph)	12.806	13.873	13.873	13.873	9.604	13.339	13.339	13.019	13.019
Secondary Air Flow Rate (kpph)	55.180	55.180	55.180	55.180	55.180	55.180	55.180	55.180	55.180
Burner Air Flow Rate (kpph)	67.985	69.052	69.052	69.052	64.784	68.519	68.519	68.199	68.199
Burner SR	0.950	0.891	0.891	0.891	1.207	0.919	0.919	0.937	0.937
ROW B									
Burner 3									
Coal Flow Rate (kpph)	7.063	7.651	7.651	5.297	7.651	7.357	7.357	7.180	7.180
Coal Carrier Air Flow Rate (kpph)	12.806	13.873	13.873	9.604	13.873	13.339	13.339	13.019	13.019
Secondary Air Flow Rate (kpph)	55.180	55.180	55.180	55.180	55.180	55.180	55.180	55.180	55.180
Burner Air Flow Rate (kpph)	67.985	69.052	69.052	64.784	69.052	68.519	68.519	68.199	68.199
Burner SR	0.950	0.891	0.891	1.207	0.891	0.919	0.919	0.937	0.937
Burner 4									
Coal Flow Rate (kpph)	7.063	7.651	7.651	5.297	7.651	7.357	7.357	7.180	7.180
Coal Carrier Air Flow Rate (kpph)	12.806	13.873	13.873	9.604	13.873	13.339	13.339	13.019	13.019
Secondary Air Flow Rate (kpph)	55.180	55.180	55.180	55.180	55.180	55.180	55.180	55.180	55.180
Burner Air Flow Rate (kpph)	67.985	69.052	69.052	64.784	69.052	68.519	68.519	68.199	68.199
Burner SR	0.950	0.891	0.891	1.207	0.891	0.919	0.919	0.937	0.937
ROW C									
Burner 5									
Coal Flow Rate (kpph)	7.063	7.651	5.297	7.651	7.651	7.357	7.357	7.180	7.180
Coal Carrier Air Flow Rate (kpph)	12.806	13.873	9.604	13.873	13.873	13.339	13.339	13.019	13.019
Secondary Air Flow Rate (kpph)	55.180	55.180	55.180	55.180	55.180	55.180	55.180	55.180	55.180
Burner Air Flow Rate (kpph)	67.985	69.052	64.784	69.052	69.052	68.519	68.519	68.199	68.199
Burner SR	0.950	0.891	1.207	0.891	0.891	0.919	0.919	0.937	0.937
Burner 6									
Coal Flow Rate (kpph)	7.063	7.651	5.297	7.651	7.651	7.357	7.357	7.180	7.180
Coal Carrier Air Flow Rate (kpph)	12.806	13.873	9.604	13.873	13.873	13.339	13.339	13.019	13.019
Secondary Air Flow Rate (kpph)	55.180	55.180	55.180	55.180	55.180	55.180	55.180	55.180	55.180
Burner Air Flow Rate (kpph)	67.985	69.052	64.784	69.052	69.052	68.519	68.519	68.199	68.199
Burner SR	0.950	0.891	1.207	0.891	0.891	0.919	0.919	0.937	0.937
ROW D									
Burner 7									
Coal Flow Rate (kpph)	7.063	5.297	7.651	7.651	7.651	5.297	7.063	6.356	7.063
Coal Carrier Air Flow Rate (kpph)	12.806	9.604	13.873	13.873	13.873	9.604	12.806	11.525	12.806
Secondary Air Flow Rate (kpph)	55.180	55.180	55.180	55.180	55.180	55.180	55.180	55.180	55.180
Burner Air Flow Rate (kpph)	67.985	64.784	69.052	69.052	69.052	64.784	67.985	66.705	67.985
Burner SR	0.950	1.207	0.891	0.891	0.891	1.207	0.950	1.036	0.950
Burner 8									
Coal Flow Rate (kpph)	7.063	5.297	7.651	7.651	7.651	7.063	5.297	7.063	6.356
Coal Carrier Air Flow Rate (kpph)	12.806	9.604	13.873	13.873	13.873	12.806	9.604	12.806	11.525
Secondary Air Flow Rate (kpph)	55.180	55.180	55.180	55.180	55.180	55.180	55.180	55.180	55.180
Burner Air Flow Rate (kpph)	67.985	64.784	69.052	69.052	69.052	67.985	64.784	67.985	66.705
Burner SR	0.950	1.207	0.891	0.891	0.891	0.950	1.207	0.950	1.036
Total Coal Flow Rate (kpph) (1/2 model)	56.500	56.500	56.500	56.500	56.500	56.500	56.500	56.500	56.500
Total Coal Carrier Air Flow Rate (kpph) (1/2 model)	102.445	102.445	102.445	102.445	102.445	102.445	102.445	102.445	102.445
Total Burner Sec Flow Rate (kpph) (1/2 model)	441.436	441.436	441.436	441.436	441.436	441.436	441.436	441.436	441.436
Total Burner Air Flow Rate (kpph) (1/2 model)	543.881	543.881	543.881	543.881	543.881	543.881	543.881	543.881	543.881
OFA Flow Rate (kpph) (1/2 model)	139.100	139.100	139.100	139.100	139.100	139.100	139.100	139.100	139.100
Cumulative Furnace Stoichiometric Ratio									
Burner Row A	0.950	0.891	0.891	0.891	1.207	0.919	0.919	0.937	0.937
Burner Row A+B	0.950	0.891	0.891	1.020	1.020	0.919	0.919	0.937	0.937
Burner Row A+B+C	0.950	0.891	0.972	0.972	0.972	0.919	0.919	0.937	0.937
Burner Row A+B+C+D	0.950	0.950	0.950	0.950	0.950	0.950	0.950	0.950	0.950
Burner Row A+B+C+D+OFA	1.193	1.193	1.193	1.193	1.193	1.193	1.193	1.193	1.193

Table 3: Simulated parametric cases for single wall-fired unit (continued).

INPUTS	Case 9	Case 10	Case 11	Case 12	Case 13	Case 14	Case 15	Case 16
Furnace Case 'Group'	air biasing	air biasing	air biasing	air biasing	air+fuel	air+fuel	air+fuel	air+fuel
"Case Description"	D row leaner	C row leaner	B row leaner	A row leaner	D row low flow	C row low flow	B row low flow	A row low flow
Overall Furnace SR	1.193	1.193	1.193	1.193	1.193	1.193	1.193	1.193
Burner SR	0.950	0.950	0.950	0.950	0.950	0.950	0.950	0.950
Furnace Firing Rate (MMBtu/hr)	1500	1500	1500	1500	1500	1500	1500	1500
Total Furnace Coal Flow Rate (kpph)	113.0	113.0	113.0	113.0	113.0	113.0	113.0	113.0
Total Furnace Air Flow Rate (kpph)	1366.0	1366.0	1366.0	1366.0	1366.0	1366.0	1366.0	1366.0
Primary Air Flow Rate (kpph)	204.9	204.9	204.9	204.9	204.9	204.9	204.9	204.9
Primary Air (% of total air)	15%	15%	15%	15%	15%	15%	15%	15%
Secondary Air Flow Rate (kpph)	882.9	882.9	882.9	882.9	882.9	882.9	882.9	882.9
Secondary Air (% of total air)	65%	65%	65%	65%	65%	65%	65%	65%
OFA Flow Rate (kpph)	278.2	278.2	278.2	278.2	278.2	278.2	278.2	278.2
OFA (% of total air)	20%	20%	20%	20%	20%	20%	20%	20%
OFA Port Jet Velocity (ft/s)	244	244	244	244	244	244	244	244
ROW A								
Burner 1								
Coal Flow Rate (kpph)	7.063	7.063	7.063	7.063	7.651	7.651	7.651	5.297
Coal Carrier Air Flow Rate (kpph)	12.806	12.806	12.806	12.806	13.873	13.873	13.873	9.604
Secondary Air Flow Rate (kpph)	49.048	49.048	49.048	73.573	59.778	59.778	59.778	41.385
Burner Air Flow Rate (kpph)	61.853	61.853	61.853	86.378	73.651	73.651	73.651	50.989
Burner SR	0.864	0.864	0.864	1.207	0.950	0.950	0.950	0.950
Burner 2								
Coal Flow Rate (kpph)	7.063	7.063	7.063	7.063	7.651	7.651	7.651	5.297
Coal Carrier Air Flow Rate (kpph)	12.806	12.806	12.806	12.806	13.873	13.873	13.873	9.604
Secondary Air Flow Rate (kpph)	49.048	49.048	49.048	73.573	59.778	59.778	59.778	41.385
Burner Air Flow Rate (kpph)	61.853	61.853	61.853	86.378	73.651	73.651	73.651	50.989
Burner SR	0.864	0.864	0.864	1.207	0.950	0.950	0.950	0.950
ROW B								
Burner 3								
Coal Flow Rate (kpph)	7.063	7.063	7.063	7.063	7.651	7.651	5.297	7.651
Coal Carrier Air Flow Rate (kpph)	12.806	12.806	12.806	12.806	13.873	13.873	9.604	13.873
Secondary Air Flow Rate (kpph)	49.048	49.048	73.573	49.048	59.778	59.778	41.385	59.778
Burner Air Flow Rate (kpph)	61.853	61.853	86.378	61.853	73.651	73.651	50.989	73.651
Burner SR	0.864	0.864	1.207	0.864	0.950	0.950	0.950	0.950
Burner 4								
Coal Flow Rate (kpph)	7.063	7.063	7.063	7.063	7.651	7.651	5.297	7.651
Coal Carrier Air Flow Rate (kpph)	12.806	12.806	12.806	12.806	13.873	13.873	9.604	13.873
Secondary Air Flow Rate (kpph)	49.048	49.048	73.573	49.048	59.778	59.778	41.385	59.778
Burner Air Flow Rate (kpph)	61.853	61.853	86.378	61.853	73.651	73.651	50.989	73.651
Burner SR	0.864	0.864	1.207	0.864	0.950	0.950	0.950	0.950
ROW C								
Burner 5								
Coal Flow Rate (kpph)	7.063	7.063	7.063	7.063	7.651	5.297	7.651	7.651
Coal Carrier Air Flow Rate (kpph)	12.806	12.806	12.806	12.806	13.873	9.604	13.873	13.873
Secondary Air Flow Rate (kpph)	49.048	73.573	49.048	49.048	59.778	41.385	59.778	59.778
Burner Air Flow Rate (kpph)	61.853	86.378	61.853	61.853	73.651	50.989	73.651	73.651
Burner SR	0.864	1.207	0.864	0.864	0.950	0.950	0.950	0.950
Burner 6								
Coal Flow Rate (kpph)	7.063	7.063	7.063	7.063	7.651	5.297	7.651	7.651
Coal Carrier Air Flow Rate (kpph)	12.806	12.806	12.806	12.806	13.873	9.604	13.873	13.873
Secondary Air Flow Rate (kpph)	49.048	73.573	49.048	49.048	59.778	41.385	59.778	59.778
Burner Air Flow Rate (kpph)	61.853	86.378	61.853	61.853	73.651	50.989	73.651	73.651
Burner SR	0.864	1.207	0.864	0.864	0.950	0.950	0.950	0.950
ROW D								
Burner 7								
Coal Flow Rate (kpph)	7.063	7.063	7.063	7.063	5.297	7.651	7.651	7.651
Coal Carrier Air Flow Rate (kpph)	12.806	12.806	12.806	12.806	9.604	13.873	13.873	13.873
Secondary Air Flow Rate (kpph)	73.573	49.048	49.048	49.048	41.385	59.778	59.778	59.778
Burner Air Flow Rate (kpph)	86.378	61.853	61.853	61.853	50.989	73.651	73.651	73.651
Burner SR	1.207	0.864	0.864	0.864	0.950	0.950	0.950	0.950
Burner 8								
Coal Flow Rate (kpph)	7.063	7.063	7.063	7.063	5.297	7.651	7.651	7.651
Coal Carrier Air Flow Rate (kpph)	12.806	12.806	12.806	12.806	9.604	13.873	13.873	13.873
Secondary Air Flow Rate (kpph)	73.573	49.048	49.048	49.048	41.385	59.778	59.778	59.778
Burner Air Flow Rate (kpph)	86.378	61.853	61.853	61.853	50.989	73.651	73.651	73.651
Burner SR	1.207	0.864	0.864	0.864	0.950	0.950	0.950	0.950
Total Coal Flow Rate (kpph) (1/2 model)	56.500	56.500	56.500	56.500	56.500	56.500	56.500	56.500
Total Coal Carrier Air Flow Rate (kpph) (1/2 model)	102.445	102.445	102.445	102.445	102.445	102.445	102.445	102.445
Total Burner Sec Flow Rate (kpph) (1/2 model)	441.433	441.433	441.433	441.433	441.436	441.436	441.436	441.436
Total Burner Air Flow Rate (kpph) (1/2 model)	543.877	543.877	543.877	543.877	543.881	543.881	543.881	543.881
OFA Flow Rate (kpph) (1/2 model)	139.100	139.100	139.100	139.100	139.100	139.100	139.100	139.100
Cumulative Furnace Stoichiometric Ratio								
Burner Row A	0.864	0.864	0.864	1.207	0.950	0.950	0.950	0.950
Burner Row A+B	0.864	0.864	1.036	1.036	0.950	0.950	0.950	0.950
Burner Row A+B+C	0.864	0.979	0.979	0.979	0.950	0.950	0.950	0.950
Burner Row A+B+C+D	0.950	0.950	0.950	0.950	0.950	0.950	0.950	0.950
Burner Row A+B+C+D+OFA	1.193	1.193	1.193	1.193	1.193	1.193	1.193	1.193

Table 3: Simulated parametric cases for single wall-fired unit (continued).

INPUTS	Case 17	Case 18	Case 19	Case 20	Case 21	Case 22
Furnace Case 'Group'	fuel biasing	air biasing	fuel flow increase	fuel flow increase	air biasing	fuel flow increase
"Case Description"	B3 rich, B4 lean	all burners richer	all burners richer	uniform burners	all burners richer	all burners richer
Overall Furnace SR	1.193	1.193	1.193	1.193	1.107	1.115
Burner SR	0.950	0.864	0.891	0.950	0.864	0.891
Furnace Firing Rate (MMBtu/hr)	1500	1500	1625	1625	1500	1625
Total Furnace Coal Flow Rate (kpph)	113.0	113.0	122.4	122.4	113.0	122.4
Total Furnace Air Flow Rate (kpph)	1366.0	1366.0	1479.8	1479.8	1063.0	1161.1
Primary Air Flow Rate (kpph)	204.9	204.9	222.0	222.0	204.9	222.0
Primary Air (% of total air)	15%	15%	15%	15%	19%	19%
Secondary Air Flow Rate (kpph)	882.9	784.8	882.9	956.5	784.8	882.9
Secondary Air (% of total air)	65%	57%	60%	65%	74%	76%
OFA Flow Rate (kpph)	278.2	376.3	375.0	301.4	278.2	278.2
OFA (% of total air)	20%	28%	25%	20%	26%	24%
OFA Port Jet Velocity (ft/s)	244	330.0	328.9	264.3	244.0	244.0
ROW A						
Burner 1						
Coal Flow Rate (kpph)	7.063	7.063	7.651	7.651	7.063	7.651
Coal Carrier Air Flow Rate (kpph)	12.806	12.806	13.873	13.873	12.806	13.873
Secondary Air Flow Rate (kpph)	55.180	49.048	55.180	59.778	49.048	55.180
Burner Air Flow Rate (kpph)	67.985	61.853	69.052	73.651	61.853	69.052
Burner SR	0.950	0.864	0.891	0.950	0.864	0.891
Burner 2						
Coal Flow Rate (kpph)	7.063	7.063	7.651	7.651	7.063	7.651
Coal Carrier Air Flow Rate (kpph)	12.806	12.806	13.873	13.873	12.806	13.873
Secondary Air Flow Rate (kpph)	55.180	49.048	55.180	59.778	49.048	55.180
Burner Air Flow Rate (kpph)	67.985	61.853	69.052	73.651	61.853	69.052
Burner SR	0.950	0.864	0.891	0.950	0.864	0.891
ROW B						
Burner 3						
Coal Flow Rate (kpph)	8.828	7.063	7.651	7.651	7.063	7.651
Coal Carrier Air Flow Rate (kpph)	16.007	12.806	13.873	13.873	12.806	13.873
Secondary Air Flow Rate (kpph)	55.180	49.048	55.180	59.778	49.048	55.180
Burner Air Flow Rate (kpph)	71.187	61.853	69.052	73.651	61.853	69.052
Burner SR	0.796	0.864	0.891	0.950	0.864	0.891
Burner 4						
Coal Flow Rate (kpph)	5.297	7.063	7.651	7.651	7.063	7.651
Coal Carrier Air Flow Rate (kpph)	9.604	12.806	13.873	13.873	12.806	13.873
Secondary Air Flow Rate (kpph)	55.180	49.048	55.180	59.778	49.048	55.180
Burner Air Flow Rate (kpph)	64.784	61.853	69.052	73.651	61.853	69.052
Burner SR	1.207	0.864	0.891	0.950	0.864	0.891
ROW C						
Burner 5						
Coal Flow Rate (kpph)	7.063	7.063	7.651	7.651	7.063	7.651
Coal Carrier Air Flow Rate (kpph)	12.806	12.806	13.873	13.873	12.806	13.873
Secondary Air Flow Rate (kpph)	55.180	49.048	55.180	59.778	49.048	55.180
Burner Air Flow Rate (kpph)	67.985	61.853	69.052	73.651	61.853	69.052
Burner SR	0.950	0.864	0.891	0.950	0.864	0.891
Burner 6						
Coal Flow Rate (kpph)	7.063	7.063	7.651	7.651	7.063	7.651
Coal Carrier Air Flow Rate (kpph)	12.806	12.806	13.873	13.873	12.806	13.873
Secondary Air Flow Rate (kpph)	55.180	49.048	55.180	59.778	49.048	55.180
Burner Air Flow Rate (kpph)	67.985	61.853	69.052	73.651	61.853	69.052
Burner SR	0.950	0.864	0.891	0.950	0.864	0.891
ROW D						
Burner 7						
Coal Flow Rate (kpph)	7.063	7.063	7.651	7.651	7.063	7.651
Coal Carrier Air Flow Rate (kpph)	12.806	12.806	13.873	13.873	12.806	13.873
Secondary Air Flow Rate (kpph)	55.180	49.048	55.180	59.778	49.048	55.180
Burner Air Flow Rate (kpph)	67.985	61.853	69.052	73.651	61.853	69.052
Burner SR	0.950	0.864	0.891	0.950	0.864	0.891
Burner 8						
Coal Flow Rate (kpph)	7.063	7.063	7.651	7.651	7.063	7.651
Coal Carrier Air Flow Rate (kpph)	12.806	12.806	13.873	13.873	12.806	13.873
Secondary Air Flow Rate (kpph)	55.180	49.048	55.180	59.778	49.048	55.180
Burner Air Flow Rate (kpph)	67.985	61.853	69.052	73.651	61.853	69.052
Burner SR	0.950	0.864	0.891	0.950	0.864	0.891
Total Coal Flow Rate (kpph) (1/2 model)	56.500	56.500	61.208	61.208	56.500	61.208
Total Coal Carrier Air Flow Rate (kpph) (1/2 model)	102.445	102.445	110.982	110.982	102.445	110.982
Total Burner Sec Flow Rate (kpph) (1/2 model)	441.436	392.383	441.436	478.222	392.383	441.436
Total Burner Air Flow Rate (kpph) (1/2 model)	543.881	494.828	552.418	589.204	494.828	552.418
OFA Flow Rate (kpph) (1/2 model)	139.100	188.154	187.479	150.692	139.100	139.100
Cumulative Furnace Stoichiometric Ratio						
Burner Row A	0.950	0.864	0.891	0.950	0.864	0.891
Burner Row A+B	0.950	0.864	0.891	0.950	0.864	0.891
Burner Row A+B+C	0.950	0.864	0.891	0.950	0.864	0.891
Burner Row A+B+C+D	0.950	0.864	0.891	0.950	0.864	0.891
Burner Row A+B+C+D+OFA	1.193	1.193	1.193	1.193	1.107	1.115

Table 4 provides a summary of results for the parametric simulations. Average predicted gas temperature, CO, O_2, and NOx at the horizontal nose plane and at the vertical plane at the model exit are provided. These locations are as shown in Figure 6. In addition, predicted unburned carbon on the fly ash (LOI) is provided. Figure 7 plots the predicted average NOx, LOI, and CO emissions at the model vertical exit plane for all cases, as comparisons against the baseline results.

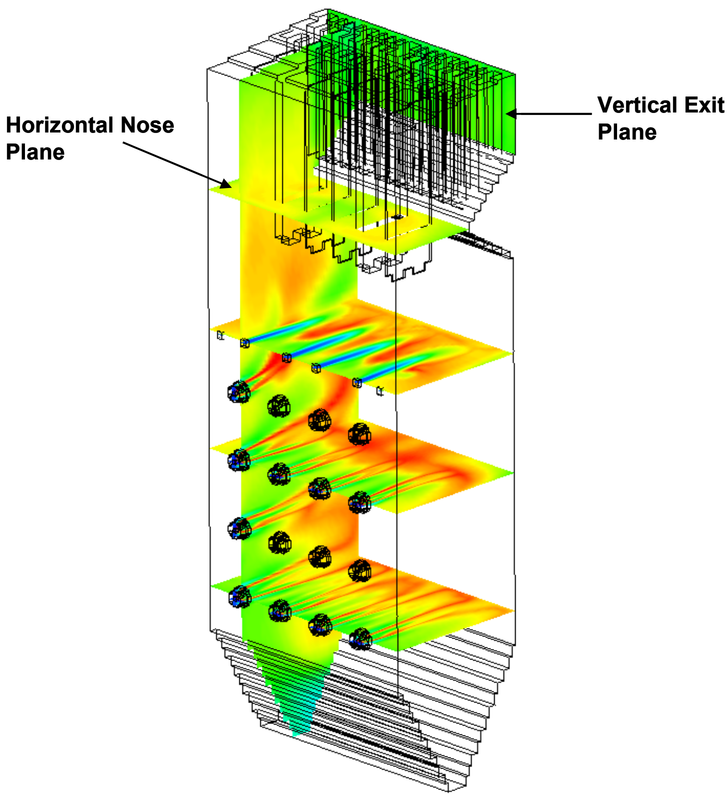

Figure 6: Locations of horizontal nose plane and vertical exit plane where average scalar values are computed and entered in Table 4

Row by Row Coal Biasing

For cases 1-4, which involve 25% decreases in burner coal flow to each burner row, the predicted impact to the NOx emissions ranges from -8% to +5%. Similarly, the impact to the predicted LOI ranges from -4% to +13%. In case 4, the NOx, LOI, and furnace exit CO were all predicted to increase, whereas in cases 1-3 the predicted change to CO and LOI had opposite sign to that of NOx. At the vertical exit plane, the largest change to the average gas temperature was a decrease of 11^{o}F.

Figure 7 shows that out of cases 1-4, the largest changes to furnace exit conditions are associated with case 1. In that case, 25% coal is removed from the top most burner row (row D) and evenly distributed to the lower three burner rows. Thus, the theoretical stoichiometric

Table 4: Summary of CFD results for wall-fired unit.

RESULTS	Baseline	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Vertical Exit:									
Gas Temperature (K)	1313	1307	1316	1314	1314	1311	1308	1312	1311
Gas Temperature (°F)	1904	1893	1909	1906	1905	1901	1895	1903	1900
CO Concentration, dry ppm	37	234	12	19	95	123	98	59	48
del CO, ppm	0	197	-25	-18	58	86	61	22	11
O2 Concentration, dry %	3.96	4.07	3.93	3.96	3.98	4.02	4.02	3.98	4.00
NOx Concentration, dry ppm	267	246	273	280	279	257	255	263	262
lb-NOx/MMBtu	0.375	0.346	0.383	0.393	0.391	0.360	0.359	0.369	0.368
del NOx, relative %	0.0	-7.7	2.1	4.8	4.3	-4.0	-4.3	-1.6	-1.9
Horizontal Nose Plane:									
Gas Temperature (K)	1534	1521	1539	1536	1533	1530	1526	1533	1530
Gas Temperature (°F)	2302	2278	2310	2305	2300	2294	2286	2300	2295
CO Concentration, dry ppm	1481	2249	1165	1349	2057	1705	2057	1500	1686
O2 Concentration, dry %	4.23	4.37	4.19	4.24	4.30	4.29	4.32	4.25	4.28
NOx Concentration, dry ppm	260	241	264	270	273	251	250	256	256
LOI (%)	29.4	33.2	28.1	29.0	30.2	31.3	31.9	29.9	30.7
del LOI, relative (%)	0.0	12.9	-4.4	-1.4	2.7	6.5	8.5	1.7	4.4
Total Deposit Rate (kg/s)	2.60E-01	2.92E-01	2.71E-01	2.63E-01	1.67E-01	2.92E-01	2.92E-01	2.71E-01	2.71E-01
Hopper	2.32E-01	2.57E-01	2.39E-01	2.42E-01	1.45E-01	2.57E-01	2.62E-01	2.41E-01	2.45E-01
Above hopper to OFA	2.15E-02	2.18E-02	2.52E-02	1.80E-02	1.72E-02	2.41E-02	2.28E-02	2.21E-02	2.25E-02
Avove OFA to Nose	6.59E-03	1.29E-02	6.08E-03	3.66E-03	4.95E-03	1.10E-02	6.83E-03	8.39E-03	4.06E-03

RESULTS	Case 9	Case 10	Case 11	Case 12	Case 13	Case 14	Case 15	Case 16
Vertical Exit:								
Gas Temperature (K)	1315	1315	1306	1313	1305	1308	1312	1317
Gas Temperature (°F)	1908	1907	1891	1904	1890	1894	1902	1910
CO Concentration, dry ppm	85	4	4	4	19	62	29	4
del CO, ppm	48	-33	-33	-33	-18	25	-8	-33
O2 Concentration, dry %	4.07	3.81	3.77	3.81	3.93	4.01	3.94	3.86
NOx Concentration, dry ppm	249	278	286	306	274	264	274	276
lb-NOx/MMBtu	0.349	0.390	0.401	0.429	0.384	0.371	0.384	0.387
del NOx, relative %	-6.9	4.0	6.9	14.4	2.4	-1.1	2.4	3.2
Horizontal Nose Plane:								
Gas Temperature (K)	1531	1546	1529	1536	1527	1521	1531	1542
Gas Temperature (°F)	2297	2322	2293	2305	2288	2278	2296	2315
CO Concentration, dry ppm	2582	524	687	1405	1038	2034	1519	1031
O2 Concentration, dry %	4.45	4.01	3.99	4.10	4.18	4.34	4.24	4.12
NOx Concentration, dry ppm	242	270	277	296	265	257	265	267
LOI (%)	33.2	23.4	21.6	22.8	28.6	31.1	28.6	24.6
del LOI, relative (%)	12.9	-20.4	-26.5	-22.4	-2.7	5.8	-2.7	-16.3
Total Deposit Rate (kg/s)	2.68E-01	2.80E-01	2.97E-01	1.56E-01	2.65E-01	2.29E-01	2.49E-01	2.23E-01
Hopper	2.42E-01	2.49E-01	2.33E-01	1.30E-01	2.37E-01	2.03E-01	2.25E-01	1.84E-01
Above hopper to OFA	2.01E-02	2.29E-02	5.72E-02	2.28E-02	2.28E-02	2.33E-02	2.22E-02	3.21E-02
Avove OFA to Nose	5.85E-03	7.73E-03	7.10E-03	3.00E-03	4.51E-03	2.42E-03	1.95E-03	6.94E-03

RESULTS	Case 17	Case 18	Case 19	Case 20	Case 21	Case 22
Vertical Exit:						
Gas Temperature (K)	1308	1324	1350	1336	1320	1344
Gas Temperature (°F)	1895	1923	1970	1945	1916	1959
CO Concentration, dry ppm	51	2	3	59	347	691
del CO, ppm	14	-35	-34	22	310	654
O2 Concentration, dry %	3.94	3.74	3.76	4.01	2.89	3.05
NOx Concentration, dry ppm	270	278	284	269	228	240
lb-NOx/MMBtu	0.380	0.390	0.398	0.377	0.296	0.315
del NOx, relative %	1.3	4.0	6.1	0.5	-21.1	-16.0
Horizontal Nose Plane:						
Gas Temperature (K)	1528	1551	1577	1553	1550	1571
Gas Temperature (°F)	2291	2332	2379	2336	2330	2368
CO Concentration, dry ppm	1617	329	254	1694	3874	3833
O2 Concentration, dry %	4.21	3.96	3.98	4.29	3.32	3.44
NOx Concentration, dry ppm	264	269	273	263	226	239
LOI (%)	28.4	19.2	20.0	31.1	38.2	37.9
del LOI, relative (%)	-3.4	-34.7	-32.0	5.8	29.9	28.9
Total Deposit Rate (kg/s)	2.51E-01	2.85E-01	3.06E-01	2.90E-01	2.65E-01	2.88E-01
Hopper	2.24E-01	2.47E-01	2.58E-01	2.52E-01	2.37E-01	2.57E-01
Above hopper to OFA	1.78E-02	2.40E-02	2.58E-02	2.78E-02	1.67E-02	2.29E-02
Avove OFA to Nose	9.43E-03	1.36E-02	2.20E-02	1.05E-02	1.11E-02	8.20E-03

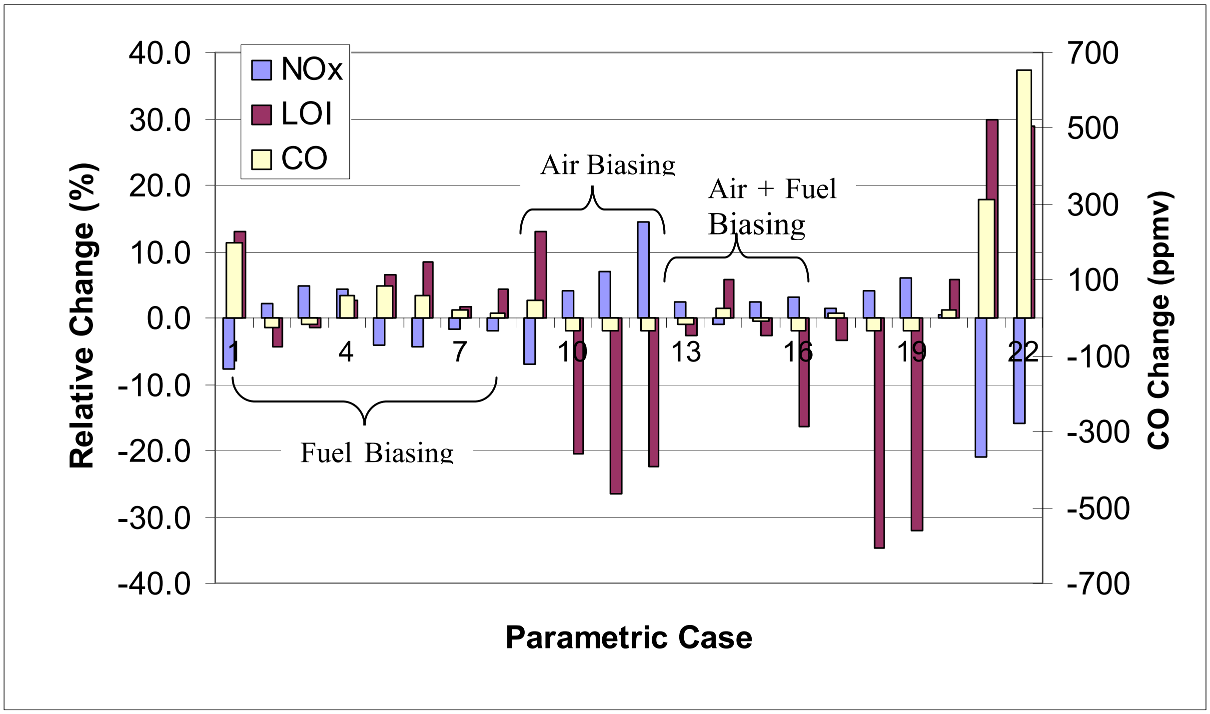

***Figure** 7*: Predicted changes to furnace exit NOx and LOI for all parametric cases in comparison with the baseline case.

ratio associated with the lower furnace below the elevation of row D is reduced from the baseline level of 0.95 to 0.891, the lowest of all cases 1-4. This case results in the greatest level of NOx reduction, but also the greatest increase in LOI, furnace exit CO, as well as the greatest reduction to the furnace exit gas temperature. Figure 8 shows the predicted NOx flow rates as a function of furnace elevation comparing the baseline case with parametric cases 1-4. Figure 9 shows the predicted LOI for these same cases plotted as a function of each burner's contribution to the total LOI. Figure 9 shows that a large fraction of the LOI is due to the row C wing burner (C5). Thus, biasing the coal flow to reduce the coal flow to row C reduces the overall LOI (case 2). Increasing the coal flow to row 3 tends to increase the predicted LOI.

Since cases 1-4 indicated that reduction of coal flow to row D exhibited the largest impact to furnace exit conditions, cases 5-8 were simulated to determine which burner in row D yielded the largest impact. The results as shown in Table 4 indicate that the differences between D7 and D8 are very small. There is a slightly larger increase in LOI and larger reduction in NOx through adjustment to D8 than adjustment to D7. This is consistent with the LOI data shown in Figure 7 since there is a larger fraction of LOI due to burner D7 than D8. Reducing the coal flow rate to D7 rather than D8 would be expected to reduce the overall increase in LOI. In cases 7 and 8, the level of reduction of coal flow rate to D7 and D8 was reduced from 25% in cases 5 and 6 to 10%. Thus, the predicted impacts to furnace exit conditions were reduced accordingly.

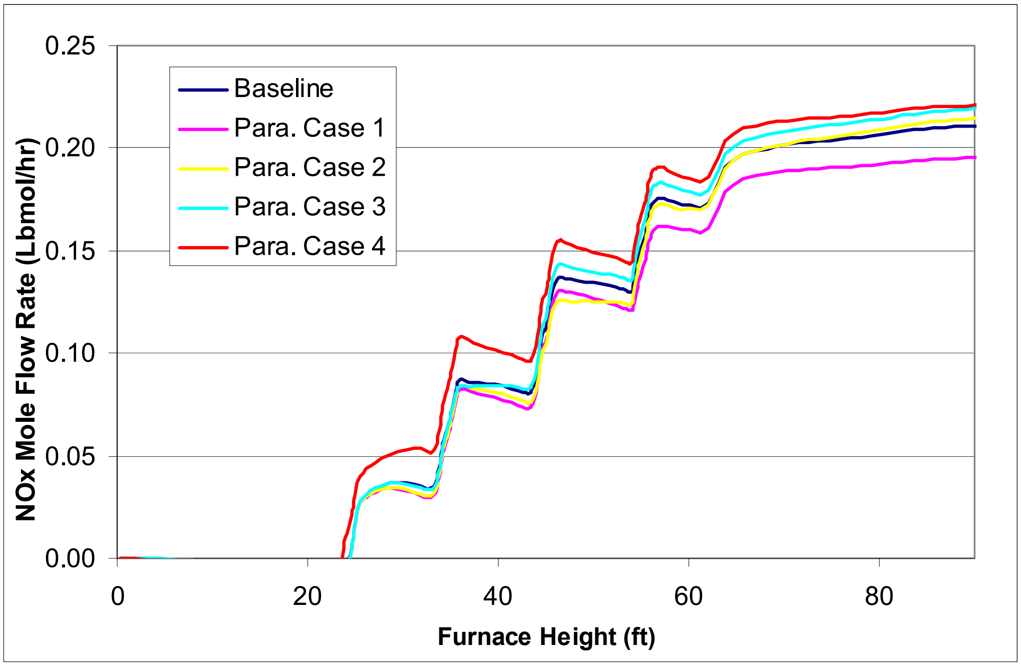

Figure 8: Predicted NOx molar flow rate vs. furnace height. The flow rates shown are for one-half furnace due to the use of a symmetry plane

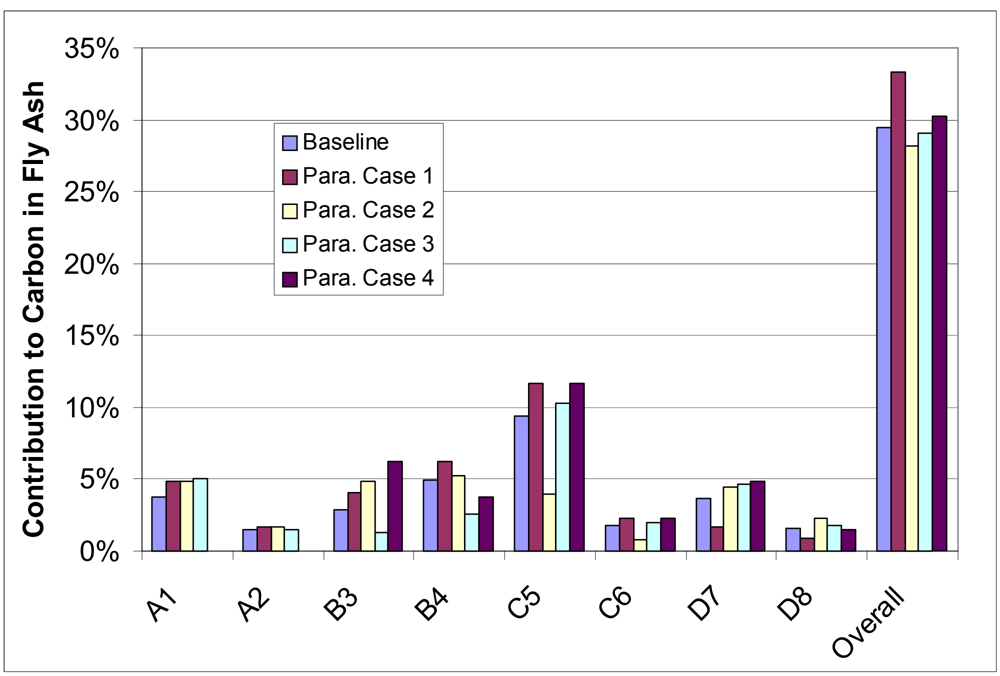

Figure 9: Predicted LOI for the baseline case and parametric cases 1-4 shown as a function of burner location.

Case 17 examined the impacts of coal biasing in a different manner to that evaluated in cases 5-8. In this case, the coal flow rate to burner B3 was increased by 25% while the coal flow rate to burner B4 was reduced by 25%. The impact of this +/- 25% variation to burners within B row yielded only a 1% increase in NOx and a 3% decrease in LOI. This result suggests that in a front wall fired furnace of the type simulated here, large variations in coal flow from burner to burner within a given row may not lead to significant variation in furnace exit conditions including NOx emissions and LOI. More simulations will be necessary to evaluate impacts of column biasing before this conclusion can be made.

Row by Row Air Biasing

Impacts of secondary air biasing on NOx and LOI emissions (cases 9-12) appear to be more significant than those associated with coal biasing (cases 1-8). In cases 9-12, the burner secondary air was increased to one burner row at a time to achieve the same burner SR (1.207) as that achieved in the coal biasing cases 1-4. The secondary air used to increase the flow rate to the one burner row was uniformly taken from all burners in the remaining three rows, thereby reducing their associated burner SRs. Figure 10 shows the predicted CO contours for the baseline and cases 9-12. The impact on local CO concentration of reducing the secondary air to the lower burner rows can be clearly seen. Biasing the secondary air in this manner resulted in variations in NOx emissions, compared to the baseline case, from -7% to 14%. The predicted NOx profiles compared to the baseline case are provided in Fig. 11. The most dramatic difference can be seen for case 12, where additional secondary air is supplied to the row A burners. Figure 12 shows the NOx molar flow rate as a function of furnace elevation. The four large jumps in NOx flow rate are associated with the four burner elevations. It can be seen that the level of NOx production associated with the burner elevations is strongly dependent on the burner stoichiometric ratio.

Variations in predicted LOI ranged from -27% to 13%. Case 9 was the only case resulting in a decrease in NOx, with an associated increase in LOI and CO. This is consistent with the results of the coal biasing in case 1. In both case 1 and case 9, the stoichiometric ratio of the D row was increased from 0.95 to 1.207 while that of the three lower burner rows decreased from 0.95 to 0.891 and 0.864 for case 1 and case 9, respectively. In cases 10-12, the impact of increasing secondary air to burner rows C, B, and A was a larger increase in NOx and a larger decrease in LOI than compared to that of cases 2-4, in which coal was biased to achieve the same burner row SRs.

Row by Row Air + Coal Biasing

The predicted impacts of biasing coal and secondary air equally (cases 13-16), to keep the burner stoichiometric ratio unchanged, yielded changes to predicted NOx emissions of less than 4%. In case 14, the predicted NOx decreased at the expense of increased CO and LOI. On the other hand, in cases 13, 15, and 16, the opposite trends were seen. The largest impact was a 16% reduction to LOI in case 16. These results suggest that varying coal and secondary

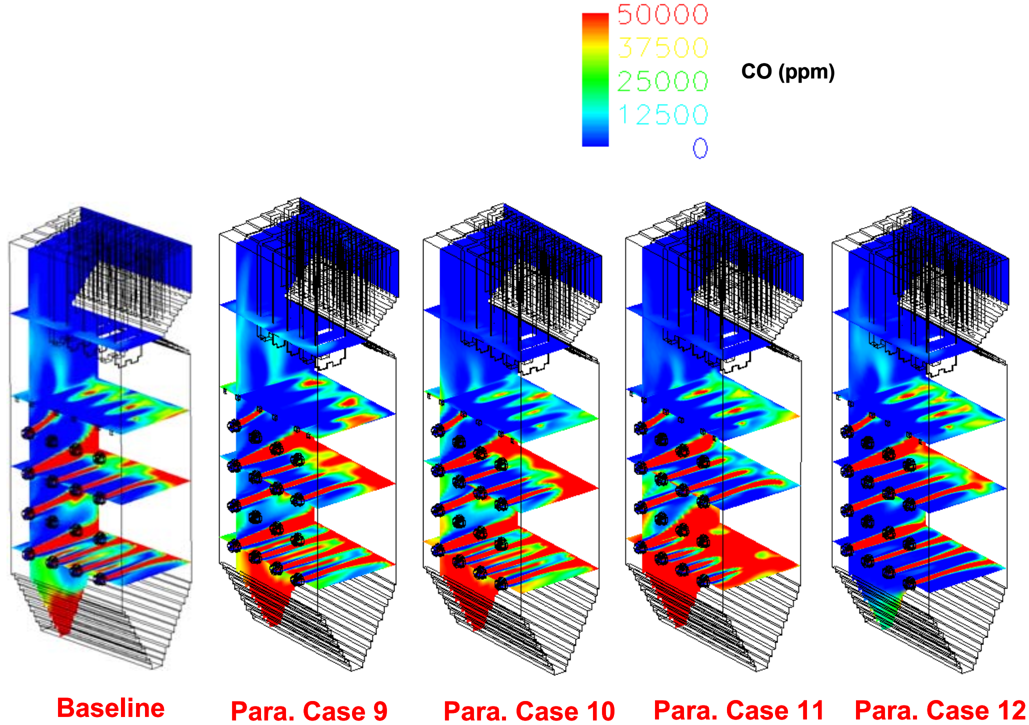

Figure 10: Contour plots showing the predicted distribution of CO throughout the furnace comparing the baseline (uniform air) case with cases 9-12 in which secondary air was removed sequentially from the four burner rows starting with the top row (D). The secondary air removed from the affected row was uniformly distributed to all burners in the other three rows.

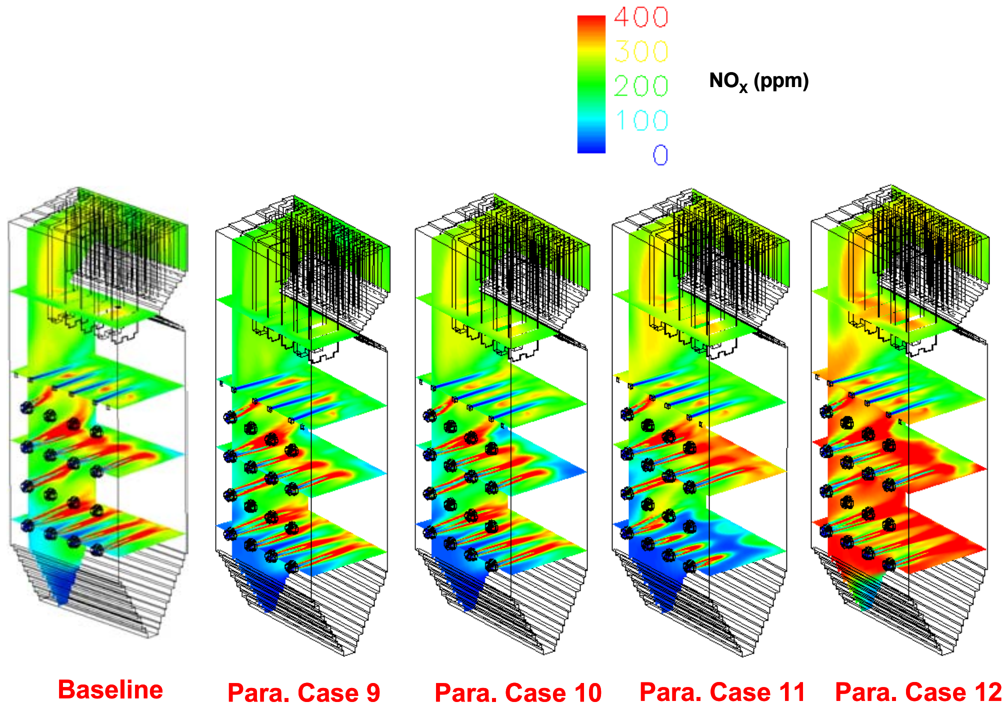

Figure 11: Contour plots showing predicted NOx distribution for same cases as in Figure 10.

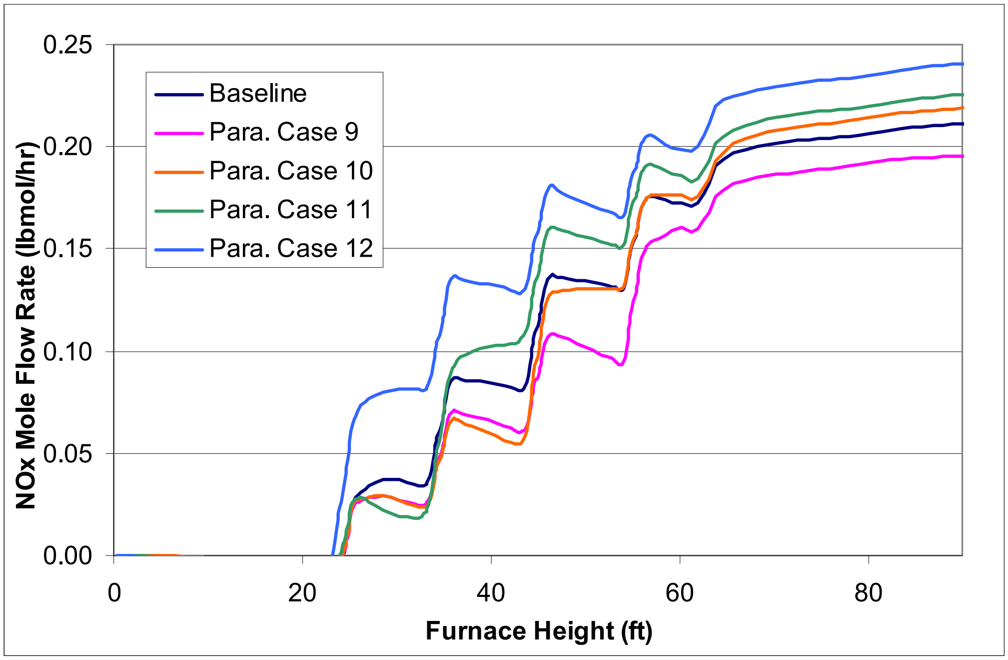

Figure 12: Predicted NOx molar flow rate vs. furnace height for the baseline and cases 9-12. Reducing the secondary air flow to the bottom three burner rows (case 9) resulted in the lowest NOx formation. The associated NOx distributions for these cases are shown in Fig. 9.

air in a stoichiometrically balanced fashion will have significantly reduced impact to furnace exit conditions than through variations of coal or air flow leading to changes in local stoichiometric ratios. In other words, changes to burner row or individual burner stoichiometric ratios appears to lead to more significant impacts than changes in firing rate alone.

Deeper Staging

Cases 18, 19, 21, and 22 were simulated to investigate impacts of reducing the burner zone stoichiometric ratio below 0.95. In case 18, this was achieved by simply reducing the secondary air to all burners equally to achieve a burner zone SR=0.864. The reduced burner zone air was then added to the overfire air flow to keep the total furnace SR fixed. In case 19, the burner zone SR was reduced by increasing the coal flow rate to all burners. The OFA flow rate was increased accordingly to keep the total furnace SR fixed. In case 21, secondary air was removed from the burners as in case 18. However, this air was not added to the OFA, thereby reducing the total furnace SR. Finally, in case 22, the coal flow rate was increased as in case 19, but the OFA flow rate was not increased, thereby reducing the total furnace SR. The primary objective in carrying out these four simulations was to provide results that would support the sensitivity analyses described in the following section.

A number of observations can be made from the results of these simulations. Figure 13 shows the predicted NOx molar flow rate vs. furnace height for cases 18 and 21. It is surprising that the predicted NOx emission for case 18 exceeds that of the baseline case, given that the unit is assumed to be more deeply staged in case 18. Figure 13 shows that the NOx generation is indeed significantly lower throughout the three lower burner elevations. However, the NOx generation increases significantly at the fourth burner elevation as well as at the elevation of the OFA The model results show that the mechanism causing this behavior is that the increased air flow rate and velocity through the four open OFA ports leads to increased penetration and splashing of air on the rear wall which circulates down into the row D burner zone. The increased air concentration there leads to a dramatic increase in NOx formation. Note that in case 21, the air flow to the OFA was not increased beyond that of the baseline case. Thus, there is no increased NOx generation at the row D burners, and the furnace exit NOx is predicted to decrease by 15%. However, the reduced furnace excess air (SR) leads to a predicted increase in LOI of 30%. Similar impacts to NOx and LOI are seen in the results of cases 19 and 22.

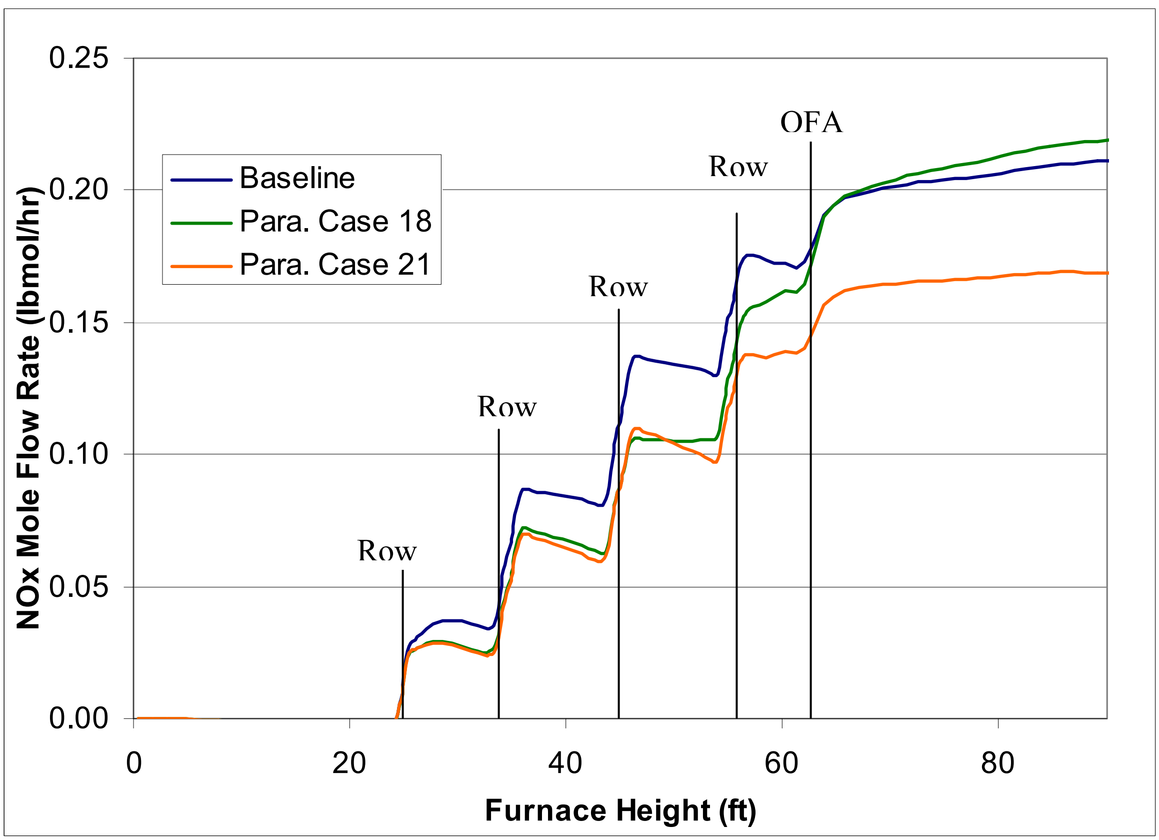

Figure 13: Predicted NOx molar flow rate (one-half furnace) vs. elevation for cases 18 and 21, in comparison with the baseline case.

Sensitivity Analysis of Results

The discussion of simulation results provided above illustrates the value of the results in quantifying the impacts of burner air and fuel variations on furnace operational conditions. Simple analysis of the results suggests a number of preliminary conclusions including:

1. Coal and air variations that impact burner stoichiometric ratio lead to more significant impact in furnace operation than variations that impact burner firing rates alone.
2. Variations in burner secondary air flows lead to more significant impacts in furnace operation than variations in burner fuel flows
3. Column biasing of burner coal flows between burners within a given row may be much less significant than biasing coal flows between burner rows.
4. At a fixed firing rate, fixed lower furnace stoichiometry, and fixed furnace excess O_2, the predicted impacts to NOx emissions were at least less than 15% and typically less than 10% for variations in coal and/or secondary air flows of up to 25%, indicating that NOx emissions are relatively insensitive to large variations in burner and coal variations (sensitivity coefficients are small).

Although the simulation results provide a wealth of information that can be useful for assessing furnace operational sensitivities to burner air and coal flows, it is important that the matrix of simulations be formulated in a manner that results can be rigorously analyzed to quantify sensitivities that are meaningful to control and optimization systems engineers and designers. To this end, results of specific simulations have been utilized to compute sensitivity coefficients through a linear analysis. The analysis is based on solution of the system:

$$\frac{\partial \varphi}{\partial SR_i} dSR_{i\,j} = d\varphi_j \qquad \text{(Eq. 1)}$$

where i indicates burner row, j indicates the specific simulation, and φ refers to the impacted scalar quantity (i.e. NOx, LOI, CO, etc.). In practice, Eq. 1 reduces to:

$$\frac{\partial \varphi}{\partial SR_A}\Delta SR_{Aj} + \frac{\partial \varphi}{\partial SR_B}\Delta SR_{Bj} + \frac{\partial \varphi}{\partial SR_C}\Delta SR_{Cj} + \frac{\partial \varphi}{\partial SR_D}\Delta SR_{Dj} = \Delta\varphi_j \qquad \text{(Eq. 2)}$$

Defining the ΔSR's and the Δφ's as relative changes from the baseline case, sensitivity coefficients ($\partial \varphi / \partial SR_i$) have been computed. Table 5 contains results for NOx and LOI using the results of simulations 1-4 (coal biasing). These results provide a number of insights:

1. The sensitivity coefficients for both NOx and LOI are quite small.
2. The sensitivity coefficients provide a mechanism for optimization.
3. Row B actually has the largest sensitivity coefficient for NOx (not row D).

Table 5: Computed sensitivity coefficients based on results of cases 1-4.

Row	$\frac{\partial NOx}{\partial SR}$	$\frac{\partial LOI}{\partial SR}$
D	-0.15	0.61
C	0.15	0.09
B	0.23	0.18
A	0.22	0.30

The sensitivity coefficients computed through solution of Eq. 2 as given in Table 5 are rates of change for each of the four burner rows. Assuming the sensitivity coefficients for all burners in a row are equal, then the burner sensitivity coefficients are a factor of four smaller than the row coefficients (4 burners per row). These values are quite small and indicate very low sensitivity of both NOx and LOI to fuel variations within the burner rows.

The values of the sensitivity coefficients can be useful in terms of providing input for optimization. The values of the NOx coefficients indicate that the best way to reduce NOx emissions is through reduction of coal to burner row D and increasing coal flow to row B. However, a better overall solution may involve increasing the coal flow to row A rather than row B if LOI is taken into account. The row A LOI sensitivity coefficient suggests that the increase in LOI would be smaller if the coal removed from row D was transferred to row A. The NOx reduction may be somewhat reduced. Additional CFD simulations could be completed to confirm or to improve this analysis.

The results of cases 13-16 (fuel and air biasing) indicated that the furnace exit conditions were somewhat sensitive to burner row changes in firing rate in the absence of changes to burner row stoichiometric ratio. In addition, the results of cases 9-12 indicated that biasing secondary air flow alone, which impacts burner row SR but not firing rate, were different from those obtained in cases 1-4, where both burner row SR and firing rate were varied. This indicates that the assumption that changes to furnace exit conditions only depends on changes to burner SRs is not strictly correct. Thus, the analyses outlined in this section are not complete and improvements can be made. An additional complication is that when the same analysis as that described by Eq. 2 is attempted to evaluate impacts of secondary air changes (cases 9-12) or impacts of secondary air and fuel changes (cases 13-16), the coefficient matrix is singular. Better consistency between the test matrix development and the sensitivity analysis procedure will help to avoid this in future evaluations.

Conclusions

Good progress has been made on several fronts during the first six months of this project. In particular:

- A project kickoff meeting was conducted as part of the DOE NETL Sensors and Control Program Portfolio Review and Roadmapping Workshop in Pittsburgh, PA on October 15-16.
- The project team assembled in the EPRI I&C offices in Kingston, TN to select the single wall and opposed wall-fired units for evaluation in this project as well as to develop the preliminary test matrix for the single wall-fired unit evaluation.
- The CFD evaluation of the single wall-fired unit has been completed.
- Results of the single wall-fired unit evaluation have been tabulated and sensitivity analyses are in progress.
- Results of the project have been publicly presented at the 28th International Technical Conference on Coal Utilization & Fuel Systems in Clearwater, FL on March 9-14, 2003. A technical paper has also been written and submitted for presentation at PowerGen International, December 9-11, 2003, in Las Vegas, NV.

The project team has selected the single wall fired unit to be evaluated, a 150 MW front wall fired unit with 16 Riley CCV low NOx burners and OFA. The predictions from the baseline simulation are in very good agreement with measured data for NOx emissions, unburned carbon in fly ash, furnace exit CO, and gas temperature. Simulation results for twenty-two parametric cases to evaluate impacts of row by row biasing of secondary air and coal as well as column biasing of coal have been obtained. Preliminary conclusions from this investigation include:

1. Coal and air variations that impact burner stoichiometric ratio lead to more significant variations in furnace operation than variations that impact burner firing rates alone.
2. Variations in burner secondary air flows lead to more significant variations in furnace operation than variations in burner fuel flows
3. Column biasing of burner coal flows between burners within a given row may be much less significant than biasing coal flows between burner rows.
4. Computed sensitivity coefficients describing variation of furnace exit NOx and LOI are quite small indicating relatively low sensitivity to variations in burner air and coal flows in the single wall fired furnace under investigation, subject to a fixed overall furnace firing rate, fixed lower furnace SR, and fixed furnace excess O_2.

Additional CFD simulations for the single wall-fired unit are in process and will aid in strengthening or qualifying the preliminary conclusions that have been proposed thus far. Similar evaluations for an opposed wall-fired furnace are currently in process.

Plans for the next six months include: completion of the evaluations of the opposed wall-fired unit, and the first tangentially-fired unit, refine our sensitivity analyses for application to the results of these units, perform additional simulations for the single wall-fired unit to support the on-going sensitivity analyses.

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Appendix

Summary of Meeting Notes

REI/EPRI I&C Meeting
December 17, 2002
EPRI I&C Center in Kingston, Tennessee

Meeting Attendees: Rob Frank, Rabon Johnson, Cyrus Taft, Paul Wolff, EPRI I&C
Brad Adams, Marc Cremer, REI

Meeting Objectives: Review DOE Burner Flow Control program objectives
Identify single-wall fired unit for modeling study
Develop test matrix for single-wall unit numerical tests

Program Objectives

Using REI's combustion simulation software, systematically quantify the sensitivity of furnace conditions (CO and NOx emissions, UBC, particulate deposition, boiler heat transfer characteristics) to burner air and fuel flows for:

- Two wall-fired PC units
- Two tangentially-fired PC units
- One cyclone-fired unit

Single Wall-fired Unit Selection

Units considered were Unit A, Unit B, Unit C, Unit D, and Unit E. Unit specifications were summarized in a previous spreadsheet. The following guidelines were used by the team in determining unit selection:

- No boundary air
- No mixed OEM hardware
- Typical furnace configuration, specifically furnace cross section
- Current operation consistent with previous models
- No duplication of effort between CFD modeling

These guidelines led to the following decisions on each unit:

Unit A – good choice except uses boundary air
Unit B – has Riley burners with B&W air registers, also has 24 burners making modeling more time consuming and sensitivity tests more extensive
Unit C – atypically shallow furnace, have changed burners since initial modeling, uses boundary air

Unit D – good choice except uses boundary air and has been previously modeled by EPRI for sensitivity analysis
Unit E – recommended choice (no boundary air, typical dimensions and firing rates)
The recommendation of Unit E was to be further reviewed by all team members including Rich Brown of EPRI who was unable to attend the meeting.

A test matrix was developed for the initial modeling studies. The tests were to focus on the effects of moving air and fuel between different burners under baseline and deeper staged conditions. The tests do not include sensitivity to coal grind, air temperatures, primary air/fuel ratio, furnace stoichiometry, furnace firing rate, coal quality and type, burner secondary/tertiary air ratios, furnace surface properties, and burner type.

The test matrix identified for the single-wall fired unit was (4 x 4 burner array):

1. Base case – all burners uniform (1 case)
2. -25% fuel in each of four rows (fuel evenly redistributed to other burners) (4 cases)
3. -25% fuel in each of two burners in the most sensitive row (determines maximum sensitivity) (2 cases)
4. -25% fuel in each of two burners in the least sensitive row (determines minimum sensitivity) (2 cases)
5. -10% fuel to most sensitive row and burner (2 cases)
6. Repeat four row tests in item 2 with air biasing (same stoichiometric ratio as fuel change) (4 cases)
7. Repeat row test in item 5 with air biasing (1 case)
8. Repeat four row tests in item 2 with air and fuel biasing (constant stoichiometry) (4 cases)
9. Repeat row test in item 5 with air and fuel biasing (1 case)
10. Run new uniform burner case at deeper staging (1 case)
11. Depending on previous results, vertically bias either coal or air flow at the more deeply staged conditions (2 cases)
12. Bias burner groups horizontally (-25% fuel) (2 cases)
13. Fill in sensitivity curves (e.g., percent bias) (if possible)

Total cases identified was 26. A review discussion will be held after the models are completed in step 3 to determine if any changes to the test matrix are needed. There was some sentiment that perhaps one of the t-fired test sets could be dropped or reduced to allow more testing of other units. This will be considered after the wall-fired tests are completed.

Finally, the group identified a 500 MW with 24 Foster Wheeler burners and advanced OFA as a likely candidate for the opposed-wall firing case.

Modeling is to begin after first of the year when all parties have agreed on the test unit and sensitivity cases.