Combustion Optimization: Part II – Results of Fields Studies

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ABSTRACT

Combustion optimization typically involves modifications to boiler control settings with the objective of achieving reductions in nitrogen oxide (NO_x) emissions with minimum impact on unit performance or heat rate. This technique can be used either as an alternative to or in combination with hardware modifications (low-NO_x firing systems) and post-combustion retrofit (selective catalytic and non-catalytic reductions systems, SCR and SNCR). Typical constrains include maintenance status of the combustion equipment (burners, mills, and dampers), degree of process automation, operating practices, and limitations imposed by environmental regulations. Therefore, each combustion optimization project is very much site-specific.

This paper describes results of combustion optimization studies performed by the Lehigh University Energy Research Center (ERC) on boilers of different size and design (tangentially- and wall-fired, with/without flue gas recirculation, FGR, capabilities), firing different fuels (Eastern and Western coals, oil and gas (co-)firing), and employing a variety of firing systems (conventional burners and low-NO_x systems, such as the LNCFS and TFS-2000). The results presented are case histories where Boiler OP was applied. Boiler OP is an intelligent software package developed by the ERC for combustion optimization. Over the last several years, the software has been used to identify optimal control settings for improved unit performance while meeting or reducing NO_x emissions. Depending on the application, the software has been also used to identify parameters, which most influence operational constraints such as fly ash unburned carbon content, stack opacity and carbon monoxide (CO) emissions, and combustion conditions such as flame front location, and burner tip temperatures. To date, Boiler OP has been used on over twenty-five units. Advisory application of the software for the operators is also described, as well as a practical low-cost closed-loop control approach that employs one or two control loops for the most influential operating parameters.

INTRODUCTION

Stringent restrictions in NO_x emissions and increasing pressures to improve operating efficiencies under a deregulated power generation market have motivated electric utilities in the U.S. to use intelligent software for optimization of boiler operation. This paper summarizes field results from using the Energy Research Center's combustion optimization approach (see Combustion Optimization: Part I – Methodology and Tools). Boiler efficiency and heat rate, fly ash loss on ignition (LOI), stack opacity, CO and NO_x emissions are strongly influenced by boiler controllable parameters. Boiler OP, an intelligent software package developed by the ERC for combustion optimization, has been used as part of the systematic combustion optimization approach for identifying the optimal boiler control settings that meet specific optimization objectives. Boiler OP has been used to optimize combustion on both wall and corner-fired boilers, covering a range of boiler sizes and designs, firing geometries, and fuel combinations. Results from several of these projects are described in this paper to illustrate the benefits that can be obtained from using Boiler OP for combustion optimization.

SOFTWARE DESCRIPTION

Boiler OP relies on an expert system, neural network and a mathematical optimization algorithm to guide the plant engineer through a series of parametric boiler tests, analyze the data, and identify the optimal boiler control settings. Figure 1 illustrates how the expert system, neural network and optimization algorithm are linked together within the code. The expert system portion of the code is used to guide the plant engineer, safely, through parametric boiler tests. To accomplish this, the engineer configures the software to reflect the boiler and burner design, test objectives and operating constraints. The expert system then recommends control settings for the test points, the boiler controls are adjusted by the boiler operator, and the test data are collected by the plant's data acquisition system (DAS). The test data, which are stored in a database for later use, are utilized by the expert system to determine each successive point in the testing sequence. After testing is complete, the database transfers the data to the neural network

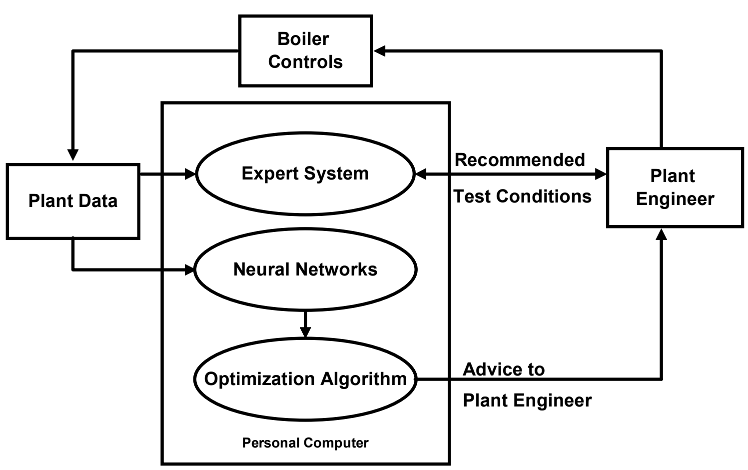

Figure 1. Boiler OP Schematic Diagram

for modeling. The optimization algorithm then determines the best combination of control settings that meets the test objectives, subject to imposed operational or environmental constraints, such as slagging, minimum steam temperatures and, maximum CO and opacity levels. The code can be used to determine boiler settings that produce minimum NO_x emissions or those which produce minimum heat rate, subject to a target NO_x level and operating constraints such as CO emissions, opacity and LOI.

FIELD RESULTS

To date, Boiler OP has been used to optimize combustion at over twenty-five units, located at eleven pulverized coal power plants of eight different utility companies. As shown in Table 1, the projects include most of the major boiler types and burner configurations. Baseline or as-found NO_x emission levels in those projects are approximately as high as 1.1 lb/MBtu to as low as 0.11 (optimized levels), with the lowest levels obtained with the newer generation of low-NO_x firing systems. The level of NO_x reduction ranges from 5 to 40 percent, with the modest reductions focusing on improving particular constraints and/or the heat rate situation. Seven of these projects are discussed in this paper.

Unit 8

Unit 8 is a 92 MW unit with a Combustion Engineering (CE) tangentially fired (T-fired) boiler, with four elevations of burners and with an ABB/CE stage III low-NO_x concentric firing system (LNCFS). Since the burner conversion, the unit was able to meet its NO_x target. However, because of the utility company-wide emphasis on reducing heat rate, a combustion optimization project that focused on heat rate was initiated at the station.

Combustion optimization of the unit was performed at full load operating conditions using Boiler OP. The results showed a large rate of increase in unit heat rate as NO_x is reduced below 0.40 lb/MBtu. The optimized results using Boiler OP identified control settings that provided consistently improved unit performance. These included boiler control settings that provided a 65 Btu/kWh heat rate improvement over the heat rate produced by the vendor's boiler control settings at a target NO_x level. In addition, the testing uncovered significant day-to-day variations in heat rate due to operator variability (Figure 2). These variations were eliminated through use of the new control settings. Both fly ash LOI and opacity were issues of concern at Unit 8. LOI was found to directly affect stack opacity. The results for minimum heat rate also gave minimum LOI values and gave values for average opacity, low enough to avoid opacity excursions.

Unit 9

Unit 9 is a supercritical opposed wall-fired Foster Wheeler (FW) boiler with a nominal output of 650 MW. The boiler has 6 mills that supply U.S. Eastern bituminous coal to 24 burners arranged in three elevations per wall with four burners per elevation. The boiler was

Table 1. Summary of Boiler OP Projects

Unit	Boiler Characteristics	Fuel Type	Unit Size (MW)	Baseline NO_x (lb/MBtu)	NO_x Reduction (%)
1, 2, 3, 4, 5	T-Fired, Four-Corner Boiler with Conventional Burners	EC	100	0.60	25
6, 7	T-fired, Eight-Corner Boiler with LNCFS-III Low-NO_x Burners	EC	600	0.75	40
8	T-Fired, Four-Corner Boiler with LNCFS-III Low-NO_x Burners	EC	90	0.45	22
9	Opposed Wall-Fired Boiler with Dual Register Low-NO_x Burners and OFA	EC	650	0.75	20
10	T-Fired, Twin-Furnace Boiler with LNCFS Low-NO_x Burners	EC	315	0.30	23
11	Front Wall-Fired, Twin-Furnace Boiler with Conventional Burners	EC WC G	280	1.13	31
12	Opposed Wall-Fired with Conventional Dual Register Burners	WC	600	0.24	34
13	Front Wall-Fired Boiler with Conventional Burners	EC WC O	150	0.68	29
14, 15	T-Fired, Eight-Corner Boiler with LNCFS-III Low-NO_x Burners	EC	250	0.36	31
16, 17	Front Wall-Fired with Conventional Burners and Flue Gas Recirculation	EC	300	1.11	21
18	Opposed Wall-Fired with Low-NO_x Cell Burners	EC WC	750	0.67	33
19	Opposed Wall-Fired with Dual Register DRB-XCL Low-NO_x Burners	EC FC	650	0.47	27
20	Separated Furnaces T-Fired Boiler with TFS-2000 Low-NO_x Burners	EC WC	285	0.14	21
21	T-Fired, Eight-Corner Boiler with Low-NO_x Burners	EC WC	535	0.22	5
22	T-Fired, Eight-Corner Boiler with Low-NO_x Burners	EC WC	240	0.21	21
23	T-Fired, Four, Four-Corner Boiler with TFS-2000 Low-NO_x System	EC FC	400	0.14	21
24	Front-Wall Fired Boiler with Conventional Burners	O G	750	Underway	Underway
25	T-Fired, Eight-Corner Boiler with Low-NO_x Burners	EC WC	500	Underway	Underway
26	T-Fired, Four Corner Boiler with Conventional Burners	O G	Steam Prod.	Underway	Underway

Fuel Types: EC - Eastern Coal, WC - Western Coal, Foreign Coals, O - Oil, G - Gas Fuel

retrofitted with dual air register low-NO_x burners and over fire air (OFA) from Phoenix Combustion. The principal goals of this project were to obtain heat rate reductions and to determine the extent to which NO_x could be reduced at full load operating conditions through combustion optimization. Control settings, found by Boiler OP, for secondary airflow, overfire air, and burner outer and inner register positions provided a 20 percent reduction in NO_x below the baseline, "as-found," condition. Due to reliability problems associated with the O_2 measurements, the secondary air flow demand parameter was used as an alternative indication of the amount of excess air in the boiler. In addition, the settings recommended by Boiler OP for the baseline NO_x level resulted in a full load heat rate improvement of 55 Btu/kWh, compared with the baseline settings used previously (Figure 3).

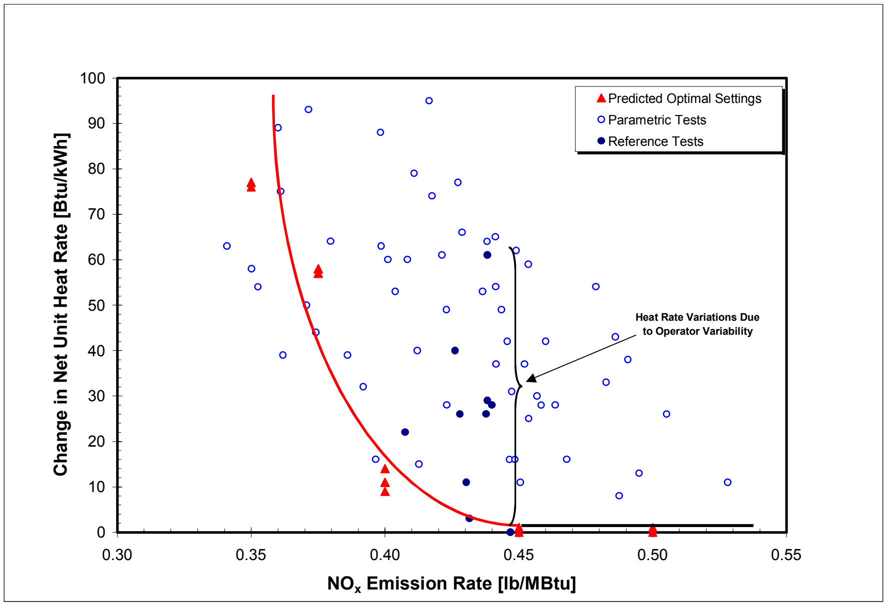

Figure 2. Boiler 8 - Optimal Heat Rate and Operator Variability

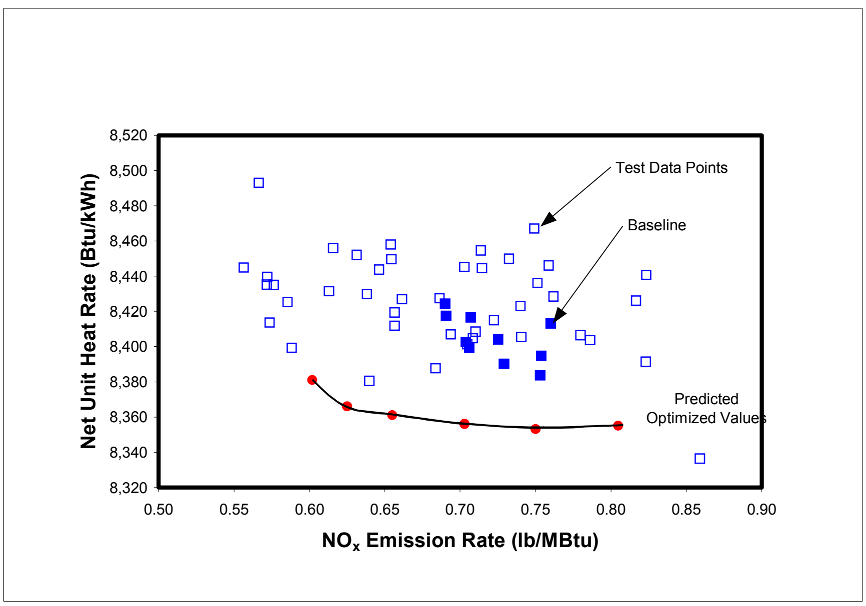

Figure 3. Boiler 9 - Optimal Heat Rate vs. Target NO$_x$ Level

Finally, the results identified means of reducing opacity excursions and high CO levels caused by furnace operating conditions. The test results shown in Figure 4 indicate that CO and opacity were affected mainly by secondary airflow (or economizer O_2). This made it possible to use Boiler OP test results to establish a closed-loop on-line control strategy, whereby corrections to optimal secondary airflow settings are implemented to maintain a balance between CO and opacity as plant conditions or fuel quality changes occur.

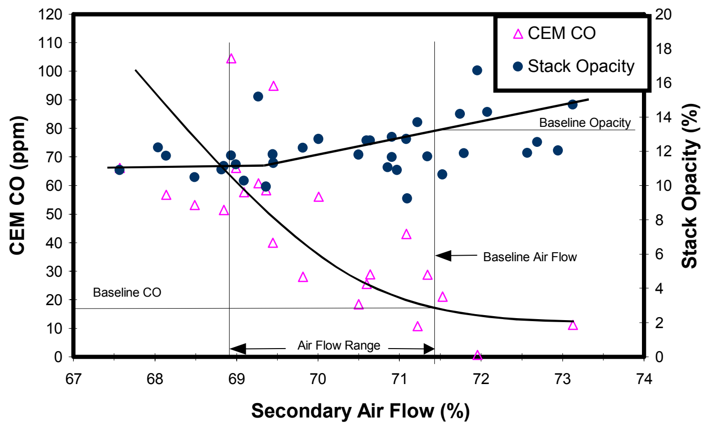

Figure 4. Boiler 9 - Secondary Air Flow Range

Unit 10

Unit 10, rated at 315 MW, has a CE T-fired, supercritical, double reheat boiler. The unit consists of twin furnaces operating in a balanced draft mode. Eight Raymond Bowl suction mills with adjustable classifiers supply U.S. Eastern bituminous coal to four elevations of four burners per furnace. The unit was retrofitted for low-NO_x operation with a LNCFS manufactured by International Combustion Ltd (ICL). The project objective was to determine boiler control settings for full load operation, which result in the minimum NO_x level, while maintaining acceptable stack opacity. Opacity was found to be a strong function of combustion conditions, with high LOI being the primary cause of opacity excursions. Combustion optimization, using Boiler OP, determined NO_x levels as low as 0.23 lb/MBtu (from a 0.30 lb/MBtu baseline level), with acceptable opacity levels, by combining changes in economizer O_2, OFA registers, auxiliary air dampers, burner tilts, mill classifier settings and mill loading patterns. As a result of mill testing, adjustments in classifier settings were recommended which resulted in reductions in the fraction of coal remaining on a 50 mesh screen to below the 0.75 percent mark, improvements in fly ash LOI and, additionally, a NO_x reduction of approximately 0.015 lb/MBtu (Figure 5).

Unit 11

Unit 11, rated at 280 MW, has a twin-furnace, front wall-fired FW boiler. The boiler has six duplex Riley Atrias suction mills, which supply a coal blend of low-sulfur U.S. Eastern and Powder River Basin (PRB) coals to 24 burners arranged in 3 elevations per furnace with four single-register burners per elevation. In addition, the boiler co-fires blast furnace gas, coke oven gas and natural gas as supplemental fuels. The objectives of this project were to determine

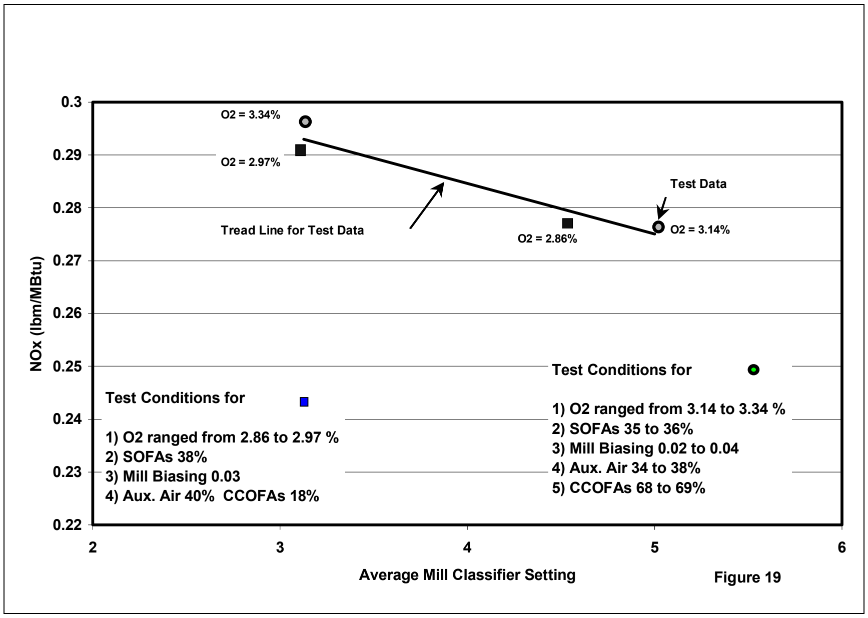

Figure 5. Boiler 10 - Effect of Mill Classifier Setting on NO_x Emissions

baseline characteristics of the unit in terms of combustion/NO_x emissions and evaluate the level of NO_x reduction achievable at full load operating conditions. Parametric tests performed with Boiler OP were used to determine baseline characteristics for NO_x, CO, LOI, opacity, and steam and flue gas temperatures (see Figure 6 for the case of CO and LOI). Maximum NO_x reductions of 23 and 31 percent from baseline levels were achieved for 100 percent coal firing and for coal/blast furnace gas/natural gas co-firing, respectively. The results demonstrated the benefit of gas co-firing for NO_x reduction without significant impact on CO and fly ash LOI (Figure 7).

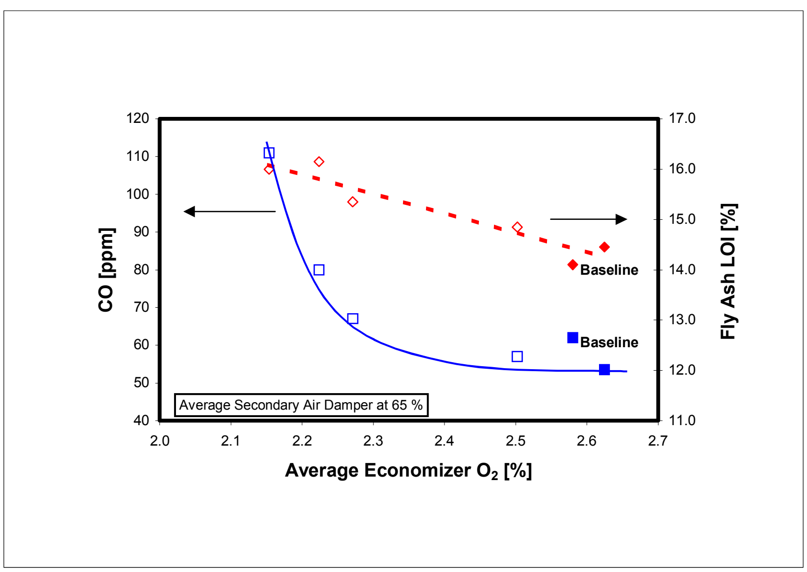

Figure 6. Boiler 11 - Effect of Excess O_2 on CO and Fly Ash LOI

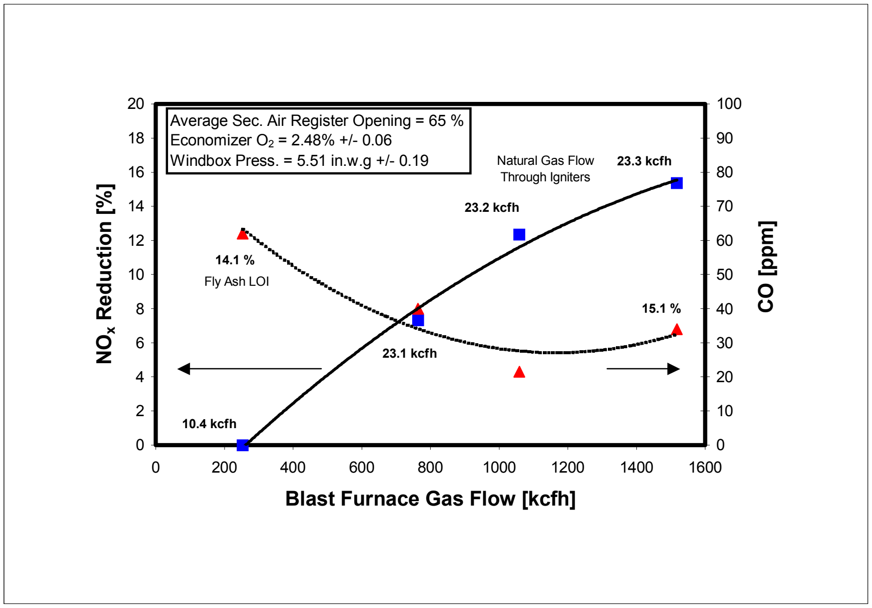

Figure 7. Boiler 11 - Effect of Blast Furnace Gas Flow on NO_x and CO

Optimal control settings were constrained to CO emissions of less than 100 ppm. Boiler OP optimization results showed that optimal net unit heat rate is a strong function of NO_x for emission levels below 1.00 lb/MBtu.

Units 16 and 17

Units 16 and 17 are 300 MW load-following sister units of a front wall-fired design and equipped with single-register conventional burners and flue gas recirculation for steam temperature control. Combustion was optimized on these units, using Boiler OP, over the load range and using combinations of excess O_2 and FGR settings, and mill loading patterns. In addition, the units were characterized for NO_x and CO emissions, fly ash LOI, stack opacity and unit performance in terms of the available boiler control parameters. Figure 8 shows an example of such characterizations, the relationship between opacity and average economizer excess O_2. Minimum opacity levels were obtained with O_2 levels in the 2.8 to 3.0 percent range at 250 MW load. For lower O_2 levels, the opacity increased due to the high fly ash LOI associated with low excess air operation. For high O_2 levels, the increase in opacity was due to the increase in flue gas flow rate (reduced residence time at the precipitator) through the precipitator and particle reintrainment.

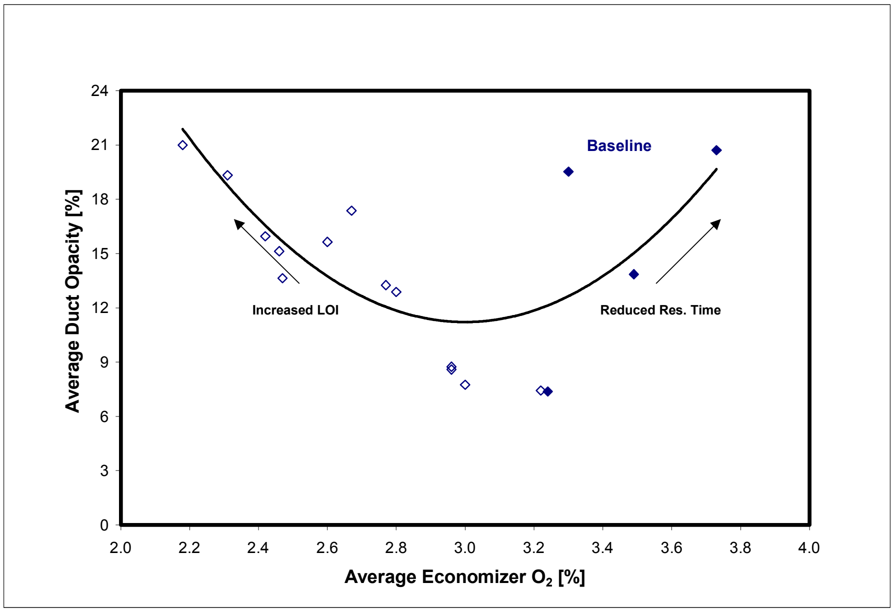

Figure 8. Boiler 16 – Effect of Excess O_2 on Stack Opacity

Boiler OP identified boiler control settings, which depending on unit load, resulted in NO_x reductions from 15 to 35 percent from baseline NO_x levels (NO_x levels corresponding to the reference boiler settings). Heat rate penalties incurred in those NO_x levels ranged from 80 to 110 Btu/kWh). Figure 9 illustrates recommendations on two boiler control settings: excess O_2 and FGR for a constant target NO_x level of 620 ppm. Recommended optimal settings are affected by mill selection, where E- and F-Mill are the top and bottom mill, respectively.

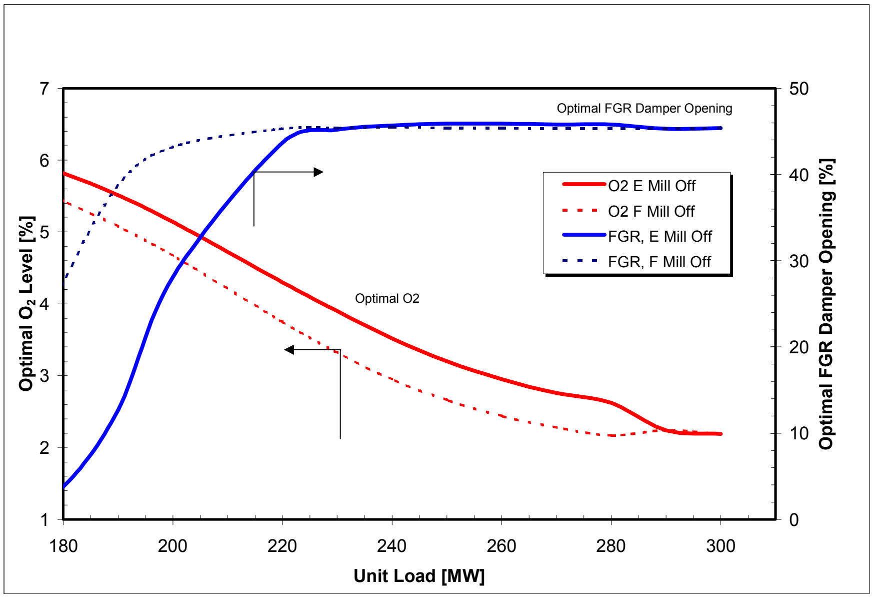

Figure 9. Boiler 16 – Optimal Excess O_2 and FGR Damper Opening Settings

Finally, an on-line advisory system (On-Line Penalty Box) was developed and implemented at these units. This system processes on-line plant data provided by a Bailey INFI-90 DAS, via a dynamic data exchange (DDE) server and a interface program, and provides advice to the operators concerning optimal control settings and actions required to eliminate deviations between the actual and recommended optimal settings. Emissions and performance penalties for not operating at optimal settings are also displayed by the system.

Unit 21

Unit 21 is 535 MW CE T-Fired boiler equipped with a Babcok & Wilcox (B&W) low-NO_x firing system with tiltable and yawable separated overfire (SOFA). The boiler has six CE 863-RS exhauster type pulverizers that supply coal to six elevations. Each mill serves one complete elevation (eight coal nozzles). The unit was originally designed to fire high-sulfur U.S. Eastern bituminous (EB) coal. The current fuel fired is a blend of coals that typically contains 40 percent medium-sulfur U.S. EB and 60 percent PRB, however, the blend fluctuates from 30/70 (EB/PRB) to 50/50 percent. With the poorer quality blend (higher moisture and lower Hardgrove grindability), six-mill operation is required to reach full load. Another problem of the current fuel blend is slagging. Slagging of the upper furnace is a major operational constraint at this unit. To control slagging, the furnace exit gas temperature (FEGT) is maintained below 1,950°F by waterwall sootblowing. Two infrared FEGT probes, located after the first superheater bank at the furnace exit, are used to monitor average gas temperatures, around the problem area. The average temperature level indicated by the optical pyrometers is maintained below an assumed ash softening temperature to prevent excessive slagging. Slagging was factored-in throughout the testing and used as constraint for combustion optimization.

The relationship between NO_x and other parameters of interest and fuel quality was correlated via measured stack SO_2, where the SO_2 concentration in the flue gas varies with coal blend. Relationships were then established between these parameters and the percent PRB coal in the fuel blend. Figure 10 shows the plot of NO_x, as well as incremental unit heat rate vs. percentage PRB in the blend. Lower NO_x emissions would be expected as the percentage of PRB coal was increased in the blend. On the other hand, an increase in unit heat rate is associated with more PRB in the blend. An increased percentage of PRB in the fuel blend was also found to negatively impact FEGT and consequently, slagging.

Boiler OP was used to provide recommendations for tight NO_x levels during the Ozone Season (May to September in the U.S.) and for the rest of year (relaxed NO_x emissions and improved unit thermal performance). Recommended settings for the Ozone Season resulted in NO_x emission levels of approximately 0.205 lb/MBtu and heat rate savings of 75 Btu/kWh with respect to baseline or reference conditions, preferentially used by the operators. For outside the Ozone Season, settings were recommended which allow better control of flue gas temperature in the furnace and increased levels of steam temperatures, as well as better improvement in unit heat rate. These settings resulted in approximately 105 Btu/kWh heat rate improvement compared to baseline operating conditions. The financial benefit of these recommendations (as

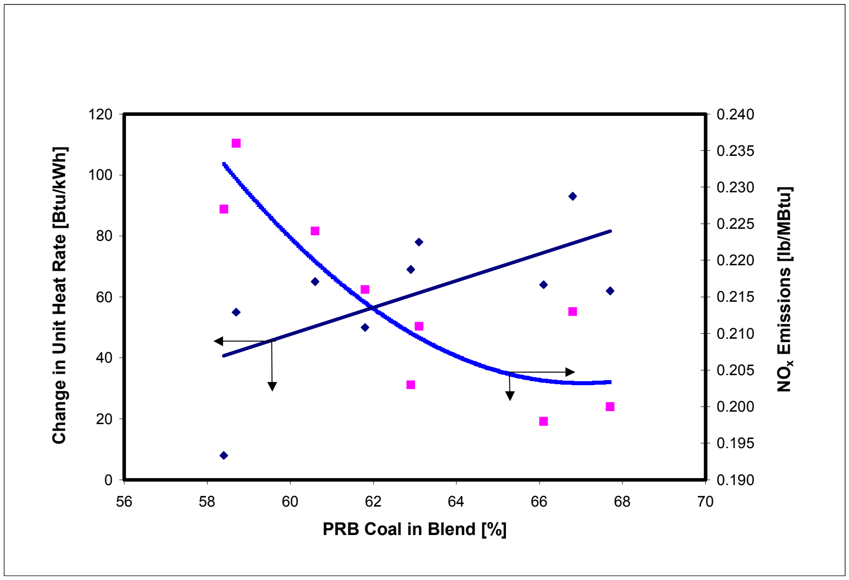

Figure 10. Boiler 21 – NO_x and Heat Range Change vs. Percentage of PRB in the Fuel

part of a "Cap-and-Trade" scheme and under 2003 U.S. NO_x and SO_2 credit values) represents approximately $680,000 and $245,000 U.S. dollars for the Ozone Season and rest of the year, respectively.

The Operator Tools in Boiler OP were configured to provide advisory information to the operators on the deviations in NO_x emissions, heat rate, FEGT (related to slagging) and hot reheat steam temperature from the levels resulting from operation at other than optimal boiler control settings and fuel blend (characterized by stack SO_2). The Operator Tools are designed to provide on-line advisory information, re-optimization capabilities and include a "What-If" feature. Figure 11 shows a sample scenario that illustrates the use of this information for compensation of the impact of fuel quality on NO_x emissions by a boiler control setting, in this case, the burner tilt parameter. In Figure 11, an increase in SO_2 of approximately 20 ppm (corresponding to approximately 3 percent change in PRB in the fuel blend) would require lowering the burner tilt approximately 8 degrees to maintain a constant target NO_x level.

Unit 23

Unit 23 is a 400 CE four-corner T-fired unit. This unit was retrofit with a CE TFS-2000 low-NO_x firing system with five elevations of burners, six elevations of SOFA and two levels of close-couple overfire air (CCOFA). This unit was designed to fire U.S. Eastern bituminous coals, however, the station switched to a foreign subbituminous coal, with lower nitrogen content, to comply with more strict NO_x regulations. Upgrades to the fuel delivery system and mills were done by the station, to be able to fire the new low-calorific value coal. Although, low NO_x emission levels were produced by this unit with the foreign coal (approximately 0.135 lb/MBtu at full unit load), operator variability at minimum loads and the financial benefit of reduced NO_x levels below baseline emissions, motivated the station to undertake a combustion optimization project.

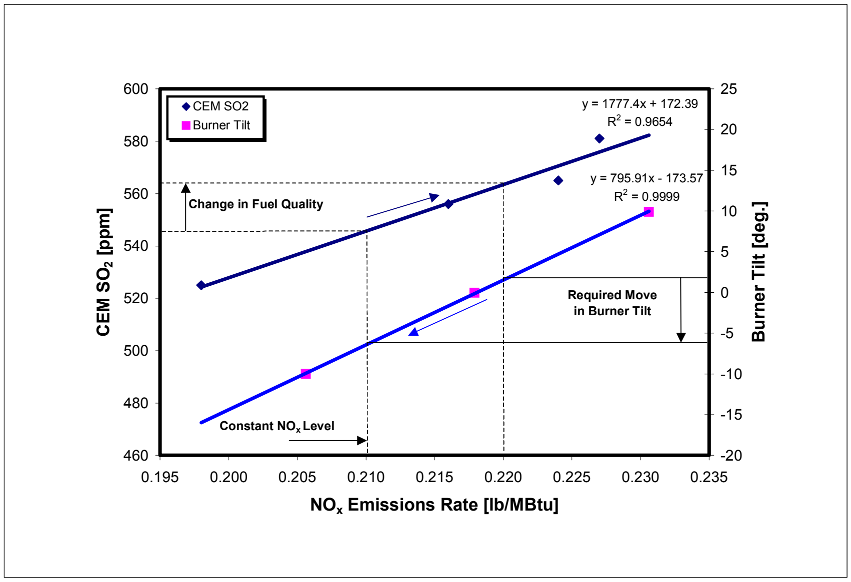

Figure 11. Boiler 21 – Use of Boiler OP Capabilities to Maintain a Target NO_x Level

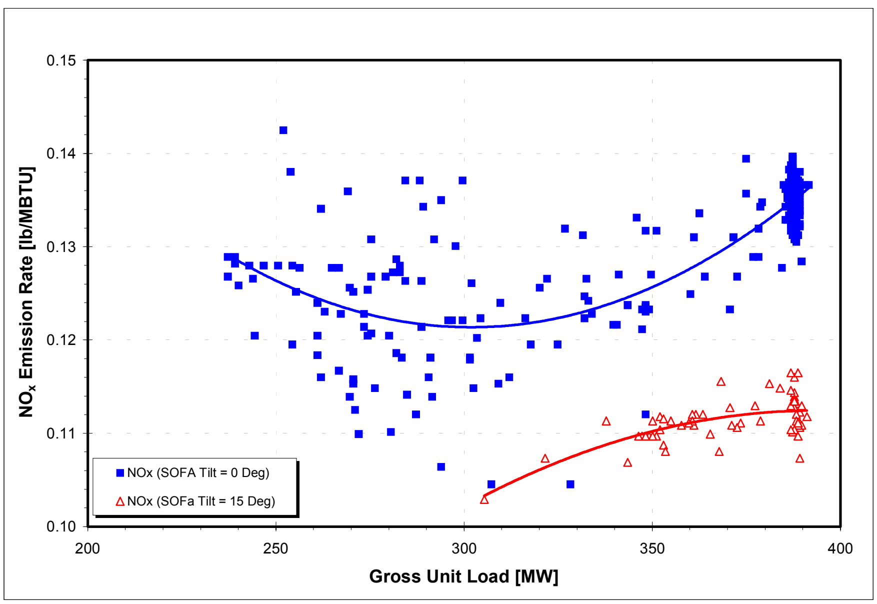

Figure 12. Boiler 23 – Baseline and Optimized NO_x Emission Levels as a Function of Unit Load

Boiler control settings were manipulated to obtain additional reductions in NO_x emissions, while keeping stack CO and opacity constraints below prescribed environmental limits. SOFA, CCOFA and secondary air registers (and windbox pressure) were found to have a major impact of controlling NO_x emissions within constraints under the high degree of staging promoted by the TFS-2000 system. Figure 12 shows a comparison of baseline and optimized NO_x emissions over the load range. Average NO_x emissions levels, as low as 0.11 lb/MBtu were achieved and maintained consistently over time across the load profile. This reduction in NO_x emissions represents approximately 20 tons of NO_x reduction per month.

SUMMARY

Boiler OP is a software product developed by the Energy Research Center to handle combustion optimization projects for NO_x emission control. The software is used in combination with a combustion optimization approach (also developed by the ERC) described in the Combustion Optimization: Part I – Methodology and Tools paper. This methodology has been used successfully to provide combustion optimization on both T-fired and wall-fired boilers burning a range of coals and supplemental fuels. The boilers tested are equipped with either conventional burners or combination of low-NO_x burners, overfire air or flue gas recirculation. The objectives of the combustion optimization process vary from project to project and include baseline characterization, finding minimum NO_x levels, minimum unit heat rate, reducing LOI and CO and avoiding opacity excursions and excessive slagging, among others. Several projects have been performed and others are currently underway which involve the deployment of Boiler OP for on-line applications. The ERC approach has also been extended to other similar applications such as combustion/SNCR systems. Research and development efforts are underway by the ERC to further expand the methodology to handle SCR's and boiler optimization for mercury emission control in coal-fired power plants.