OPTIMIZING THE COMBUSTION PROCESS IN A COAL FIRED POWER PLANT REDUCES NOX BEYOND GUARANTEE LEVEL

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INTRODUCTION

Muscatine Power and Water (MP&W) is the largest municipal electric utility in Iowa and is owned by the City of Muscatine. The MP&W utility is committed to providing outstanding customer service and excellent reliability of power supply and boasts an incredible 99.99% rating. They have a generating nameplate capacity of 293.55 MW for all the units with a net capacity of 213 MW for its larger units 8 and 9 that have the Combustion Optimization Systems. This progressive municipal power producer, recognizing the increased focus on coal-fired plant emissions and the possible penalties for non-compliance, was looking to improve the emissions profile of its two bigger units. As part of this effort, MPW entered into a contract with Emerson Process Management Power and Water Solutions to provide an Emerson SmartProcess Combustion Optimization System for Muscatine Units 8 and 9 which would help reduce emissions and find the optimum positions for various parameters in the boiler combustion process, taking into account the changing goals of the unit as regulations change and the non-compliance cost increases. This paper outlines the successful deployment of multivariable optimization technology for reducing NOx emissions and describes the engineered solution for combustion optimization for Unit 9.

This paper describes the dynamic optimization technology applied to this tangentially fired unit utilizing Midwestern coal. The application of this new layered element to the control system will be described, with objective functions and variables that were used in the models. The system is an advanced neural fuzzy controller with state-of-the-art optimization routines to identify precise control settings for continuous optimal performance under changing conditions during startup, shutdown, load ramp and base load operation. When set in fully automated “optimizer” mode, the software sends optimum biases and setpoints directly to the distributed control system in a continually adapting closed-loop system that helps Muscatine optimize the plant’s processes seamlessly integrated into the automatic controls, assisting the operator in running the unit in the most environmentally friendly way. The successful deployment of this technology in reducing NOx emissions beyond the initial 10% target contract guarantee level are the results described.

MPW Unit 9 is a Combustion Engineering Drum Type Tangentially Fired boiler with a General Electric extraction steam generator. The unit has a net generator output of 147 megawatts and generally operates base-loaded and lower loads in the evenings and weekends at certain times of the year. There are 4 burners per elevation with 4 elevations and 4 Bowl Type coal pulverizers, A, B, C and D with either 3 or 4 of the mills required for full load. The air for combustion is supplied by fuel air dampers for each level of combustion in the boiler, auxiliary air dampers between the levels of combustion, over fire air dampers (OFAs) and secondary overfire air dampers (SOFAs).

PROJECT RATIONALE

Utilities have several methodologies available to them to reduce the NOx emissions of a generating power plant, including various options in the pre-combustion, in-combustion, and post-combustion phases of the boiler combustion process. Each of these methodologies has a cost-benefit ratio and in some cases can be implemented individually or in combination. Figure #1 shows some typical values of the cost-benefit ratios of some of these methods.

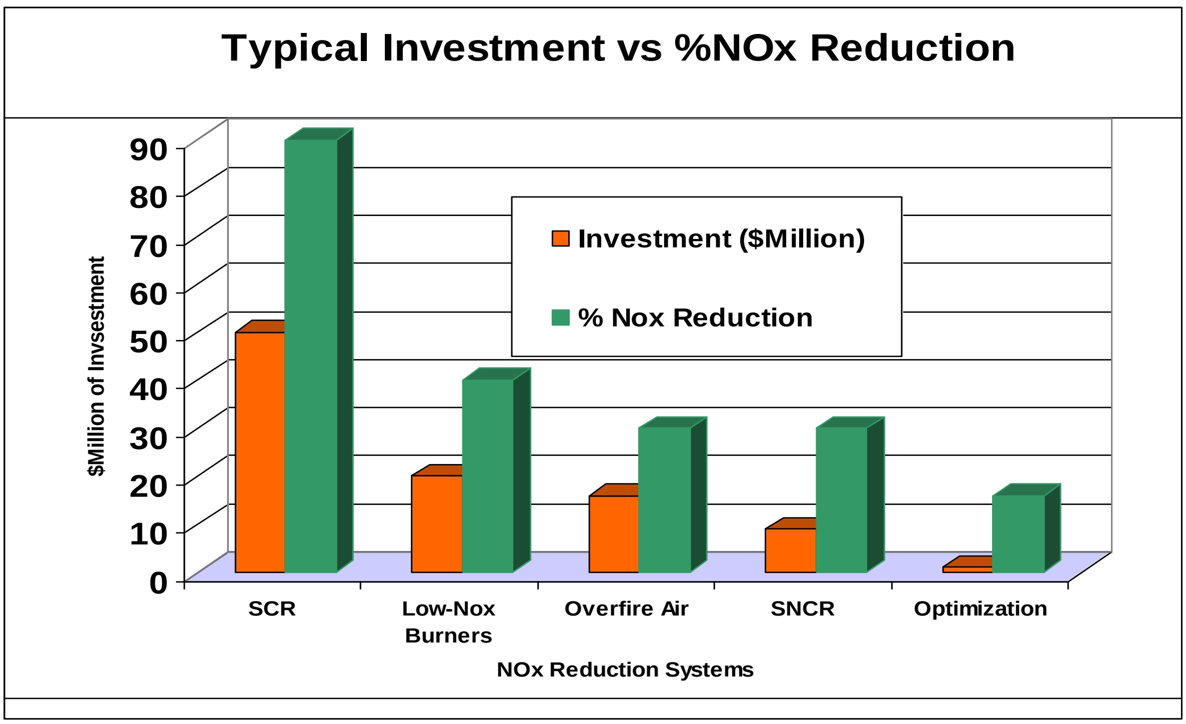

Figure # 1 Cost-Benefit Ratio of NOx Reduction Technologies

Some of the advantages of combustion optimization include:

- Very attractive cost-benefit ratio
- Can be implemented without a unit outage
- Boiler modifications are not required
- Adaptive to future changes in the combustion process
- Improvement in boiler efficiency and in turn, on unit heat rate

The decision on which methodologies to utilize is not a straight-forward one by any means and the methodologies implemented may evolve over time as the regulations become more stringent. The utility must take into account a complex model of such parameters as the current federal, state, and local emission regulations as well as what future regulations might include, the type(s) of fuel available to the utilities and the fuel and transportation costs of such fuels, the current and future demand of the power market, and the age and future operability of the unit and fleet.

MUSCATINE UNIT 9 OPERATING PROFILE BACKGROUND

The recent history of the NOx emission reductions at Muscatine Power and Water Unit 9 is shown in Figure #2 below:

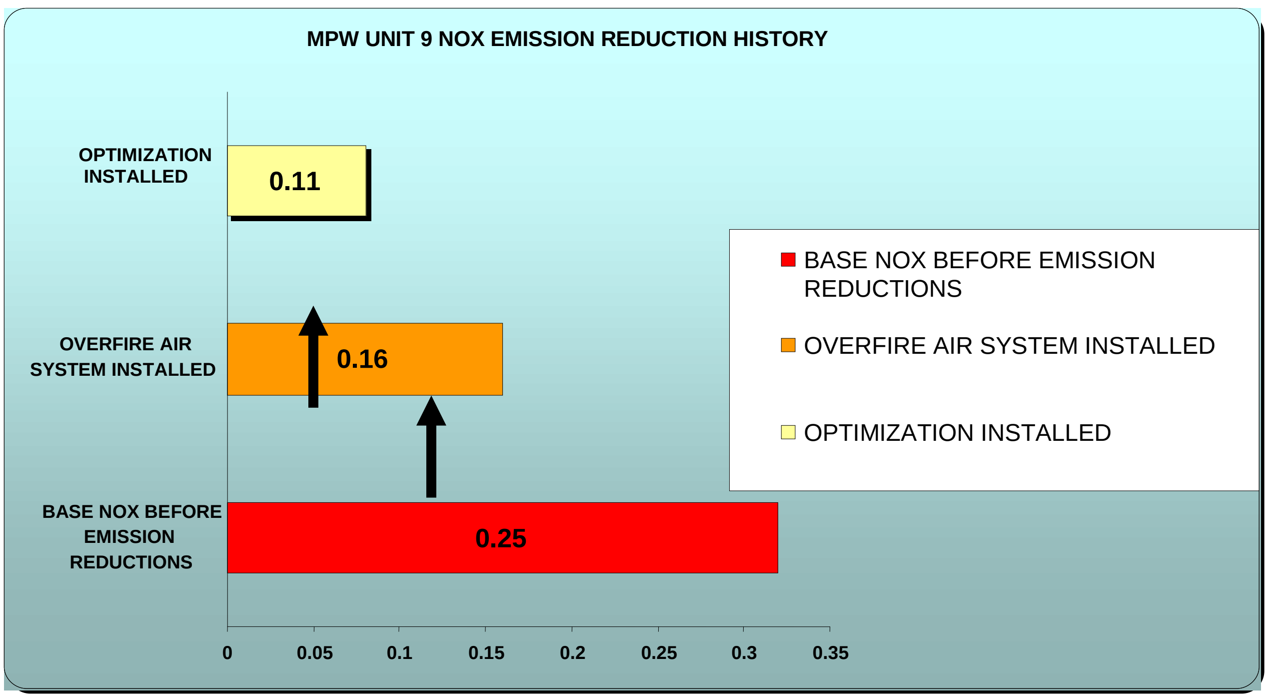

Figure # 2 Muscatine Power and Water Unit 9 Emission History

Prior to the early 2000's, MPW did not have any systems in place to reduce NOx emissions generated in the combustion process or post-combustion. The NOx emissions at this time were typically about 0.25 -0.30 lb/mmbtu.

MPW had the OFA in the upper and lower levels of the boiler to modify the air flow for better combustion in the boiler furnace. With the Optimizer, this helped to reduce the NOx to the levels of 0.16-0.18 lb/mmbtu. To further reduce emissions, they subsequently added the SOFA dampers during the spring outage in 2008 and together with the OFAs were able to bring the Nox down to about 0.11 lb/mmbtu with the Combustion Optimizer.

At the initiation of the optimization project, it was thought that the primary emission goal of the optimization system would be the reduction of NOx in the combustion process and secondary goals of the optimization system would be maintaining CO below its limit, reducing the O2 split across the boiler, and improving boiler efficiency. As the optimization project progressed and was finalized, it became apparent that the NOx and CO goals were at least equally important and in some cases the CO may require more weight than NOx in the optimization system to insure that all emission values are maintained below the required limits.

THEORY OF BOILER COMBUSTION OPTIMIZATION

Traditional DCS Base Power Plant Control System

In a typical modern power plant, the power plant process is normally controlled by an automated Distributed Control system (DCS). The DCS system normally has many individual control "loops" which utilize traditional Proportional-Integral-Derivative (PID) control to control the individual processes within the combustion process. An example of traditional PID control loop for the control of excess air is shown in Figure #3. These loops normally contain a setpoint, process value, and output for each control loop and control such parameters as the excess oxygen in the flue gas path, the flow of fuel to the boiler, the flow of combustion air to the boiler, etc. If these loops are tuned properly, they normally control the combustion process fairly well. The **KEY** difference between a traditional DCS control system and a fuzzy neural model based boiler optimization system is that in the traditional DCS system, the emission parameters such as NOx and CO formed from combustion are not directly CONTROLLED by control loops but are by-products of the combustion control loops controlling the fuel-air processes related to the combustion process.

Boiler Combustion Optimization Model Based Controls

A typical boiler combustion fuzzy neural model is shown in Figure #4. It is different from the DCS base control system described above in that it has many inputs into the model and several control variables.

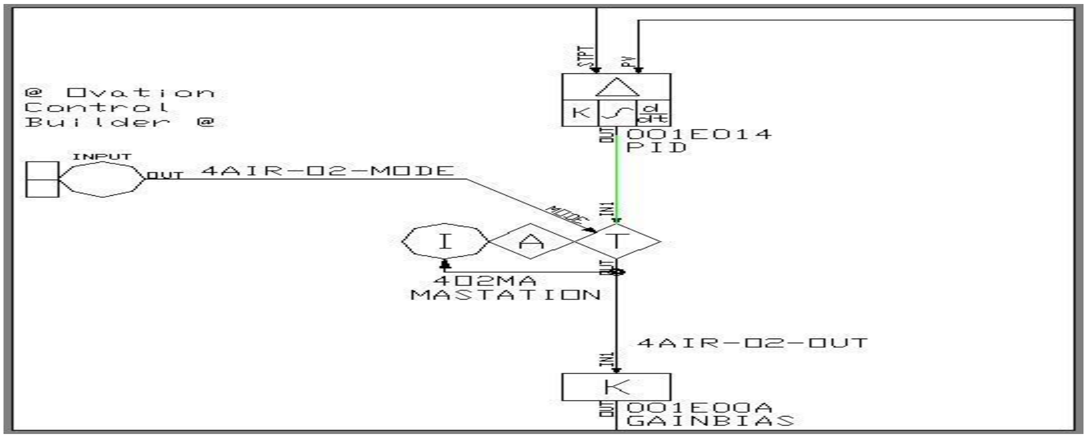

Figure # 3 Example of Traditional PID Control Loop

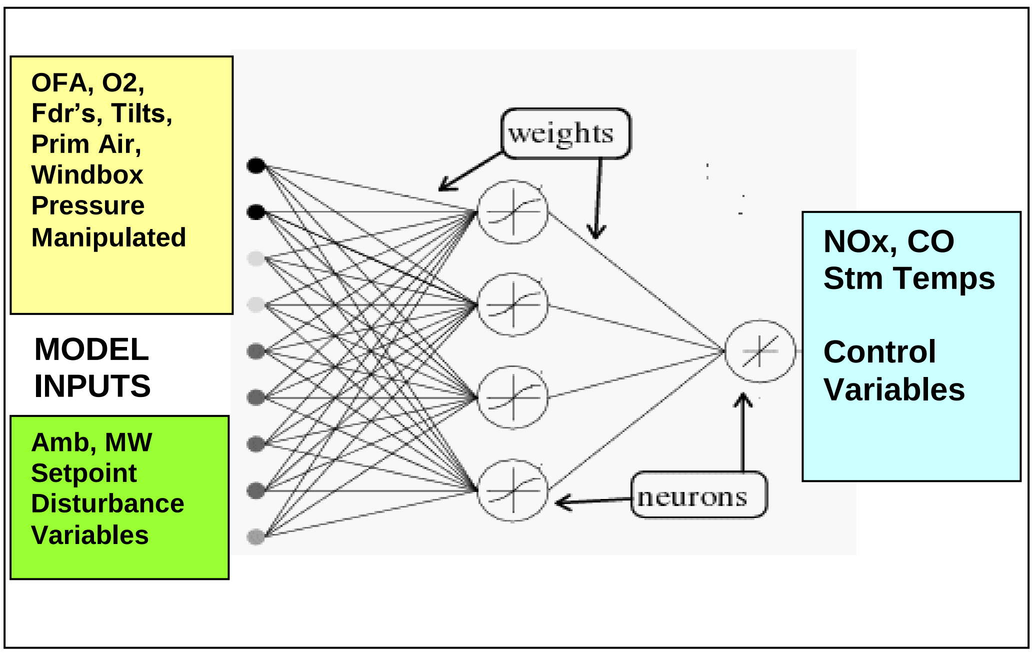

Figure # 4 Example of a Fuzzy Neural Model Optimization System

There are three types of variables that normally are included in the fuzzy neural model:

- Manipulated Variables (MV's) – these are variables which affect the combustion process and can be manipulated (moved) by the optimization system. An example in the above model would be excess air in the boiler

- Disturbance Variables (DV's) – these are variables which may affect the combustion process but cannot normally be modified by the optimization system. An example in the above model would be required generation.
- Control Variables (CV's) – these are the key combustion process variables that the optimization system desires to control. An example of a control variable would be NOx.

Optimization Model

The optimization algorithm implemented in the optimization controller software consists of state-of-the-art algorithms and methods. The two main parts are:

- Nonlinear model which is based on fuzzy neural model technology
- Constrained optimization algorithms

The model in the controller is a fuzzy neural model, characterized as a Takagi-Sugeno type fuzzy model. The model can be viewed as a fuzzy, non-linear NARMAX (Non-linear Auto Regressive Moving Average with an AuXiliary input) model, based on piecewise linear systems. Fuzzy logic is used to overcome the sharp switch between neighbor models. The Takagi-Sugeno scheme, with linear combinations as the consequences, enables the generation of fuzzy rules with a linear ARX model as the consequences.

(1): **if** x_1 **is** A_{11} **and** ... **and** x_N **is** A_{N1} **then**
$y = a^i_0 + a^i_1 x_1 + ... + a^i_N x_N$

(2): **if** y_{k-1} **is** A_{11} **and...** y_{k-n} **is** A_{n1} **and** u_{k-1} **is** B_{11} **and...** u_{k-m} **is** B_{m1} **then**
$y(k) = a^i_1 y(k-1) + ... + a^i_n y(k-n) + b^i_1 u(k-1) + ... + a^i_m u(k-m) + c^i$

The NARMAX model includes the advantages of both linear modeling in the sub-regions, and fuzziness for smooth transitions between sub-regions.

The implementation of NARMAX models can be achieved in many ways. The Fuzzy Neural Model (FNM) provides the advantages of the Takagi-Sugeno scheme along with model parameter estimation through network learning.

DESIGN, IMPLEMENTATION, AND COMMISSIONING OF THE BOILER COMBUSTION OPTIMIZATION SYSTEM

As described in the above paragraphs, when the combustion optimization project began, the primary emission goal of the optimization system would be the reduction of NOx in the combustion process by establishing the optimal combustion settings and secondary goals of the optimization system would be maintaining CO below a limit which had yet to be established, reducing the O2 split across the boiler, and boiler efficiency. As the optimization project progressed and was finalized and the CO limit was established during the project, it became apparent that the NOx and CO goals were at least equally important and in some cases the CO may require more weight than NOx in the optimization system to insure that all emission values are maintained below the required limits. The boiler combustion optimization process included the following steps:

- DCS Control Modifications
- Parametric Testing
- Model Building
- Open Loop Testing
- Closed Loop Testing
- Commissioning

DCS Control Modifications

The first major step of the optimization project was defining and implementing the DCS control modifications which would permit the optimization system to apply "biases" to the base DCS control positions for the combustion variables. Using this type of structure allows the user to maintain the base DCS controls and provides a path for combustion optimizer to inject the "optimal" settings for the combustion parameters.

The boiler combustion process on Muscatine Power and Water Unit 9 was completely reviewed and the following combustion parameters were identified as possible candidates that the optimization system might want to bias to determine and implement the optimal combustion setup in the boiler:

- Fuel Air Dampers
- Auxiliary Air Dampers
- Overfire Air Dampers

- Secondary Overfire Air Dampers
- Secondary Overfire Air Tilts
- Boiler O2 Trim
- Windbox Furnace Differential Pressure
- Coal Feeders

The DCS control drawings were marked up with the necessary modifications and implementation of these modifications occurred in March of 2007 during the unit outage. An example of a control modification is shown in Figure #5.

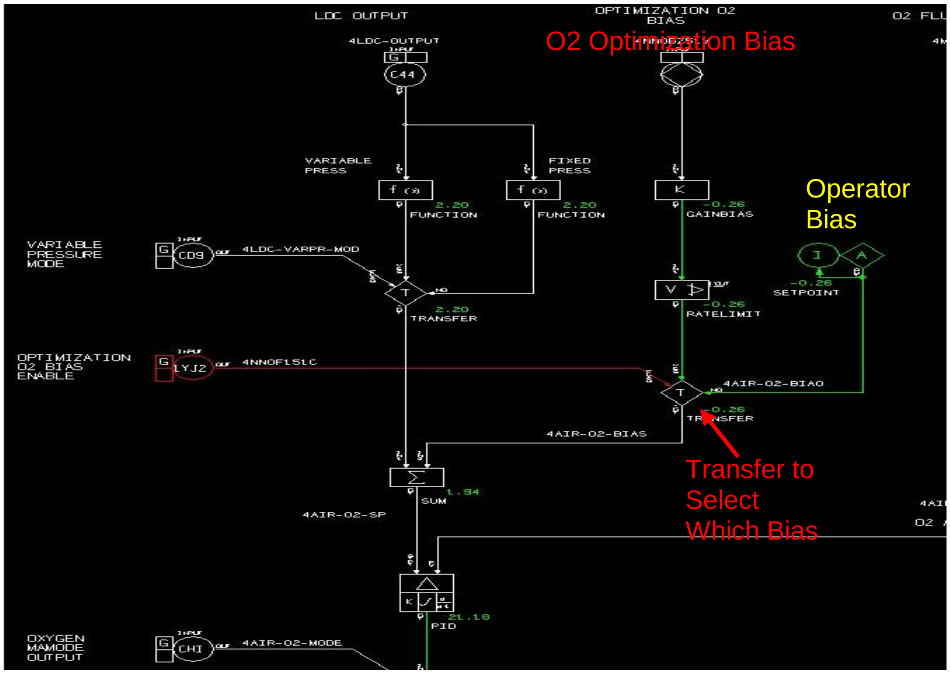

Figure # 5 Example of Optimization Control Modification

Parametric Testing

The next step in the optimization project was to define and perform the parametric tests on Unit 9 boiler. The purpose of this step is to test each of the defined combustion parameters referenced above to determine how changes in these parameters affect the key goals of the optimization project such as NOx and CO formations.

It was determined based on recent past unit operation that the parametric test points would be 4 mills and 3 mills operation at full load and 3 and 2 mills operation at partial loads. The parametric testing was executed in early June, 2007. An example of the coal feeder parametric test is shown in Figure #6.

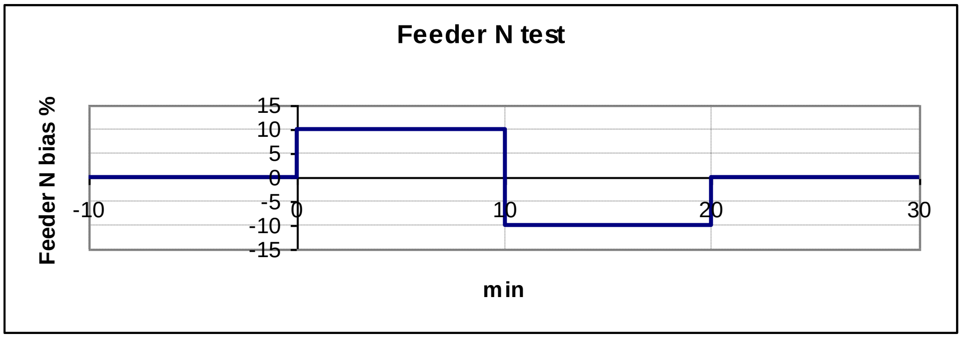

Figure # 6 Example of an Optimization Test Plan for Feeders

Model Building and Open and Closed Loop Testing

After parametric testing was completed, data analysis was performed on the test data to determine which parameters would be included in the combustion model. It was determined that the FD and ID fans did not influence any of the key optimization goals and thus were eliminated from the combustion model.

The remaining data was then input into the combustion model builder and the initial boiler combustion model was generated.

In mid June, 2007, the initial combustion model was installed on the optimization computer and open and closed loop testing were executed. When in open loop, the model was predicting what biases would be applied to the key optimization parameters while in closed loop the model was actually biasing the key values.

This testing lasted approximately two weeks and several tuning parameters were modified during the testing.

Commissioning Tests and Results

The final step in the combustion optimization project was to execute a series of “ON/OFF” tests to benchmark the results of the optimization system. The basic methodology for the ON/OFF tests was to run the unit at a stable load for a period of time (between 3-4 hours). During these time periods, the unit would run with the combustion optimization in-service for approximately ½ of the total test time period and the unit would run in "AUTO" for the remaining part of the test period. "AUTO" was defined as all key control loops associated with the combustion control system would be in automatic and would be running under the control of the DCS control system.

The Smart Process Combustion Optimizer, also called IVY, was upgraded at Muscatine Power & Water Unit 9 due to the upgrades of the DCS and the addition of SOFA Dampers and Tilts during October/November 2008 followed by the commissioning tests. The objective of these tests is to achieve long-term consistent NOx reductions over several years during periods of changes within the boiler from natural degradation of the equipment and detuning of the unit's instrumentation. It also shows the near-term results of the installation and to assist in the projection of the NOx levels during future operation of the unit.

The setpoints for the two key control variables that would carry the highest weights in the optimization system were as set as follows:

CO - less than 50 ppm

For NOx, the setpoints were set based on the mill configuration that was used.

- 160MW for 3 mills in service (BCD) - 106 ppm
- 160MW for 3 mills in service (others) - 110 ppm
- 160MW for 4 mills in service - 117 ppm

These two parameters carried the highest weights in the combustion optimization system with the CO weight being about double the NOx rate which is the same weights that had been used in the first few months of operation. During execution of the optimization project and the first few months of operation with the CO analyzer in-service, both MPW and Emerson agreed that the most important parameter in the combustion process was CO and that it should be maintained at or below 50 ppm and if the CO limit got exceeded in the combustion process, more weight would be given to CO sacrificing NOx somewhat. However, this situation never arose during and after the project was completed. It should be noted that other than the combustion optimizer, there are no other systems post-combustion that would reduce CO. Thus, the weighting was setup to have the CO control variable carry the highest weight and NOx, the second highest weight. If CO was in-check, the optimizer would configure the combustion system for NOx reduction.   If CO ran high on certain days, the optimizer would put a higher weight on CO and configure the combustion parameters accordingly. Typical results of the commissioning tests are shown in Figures #7 and #8.

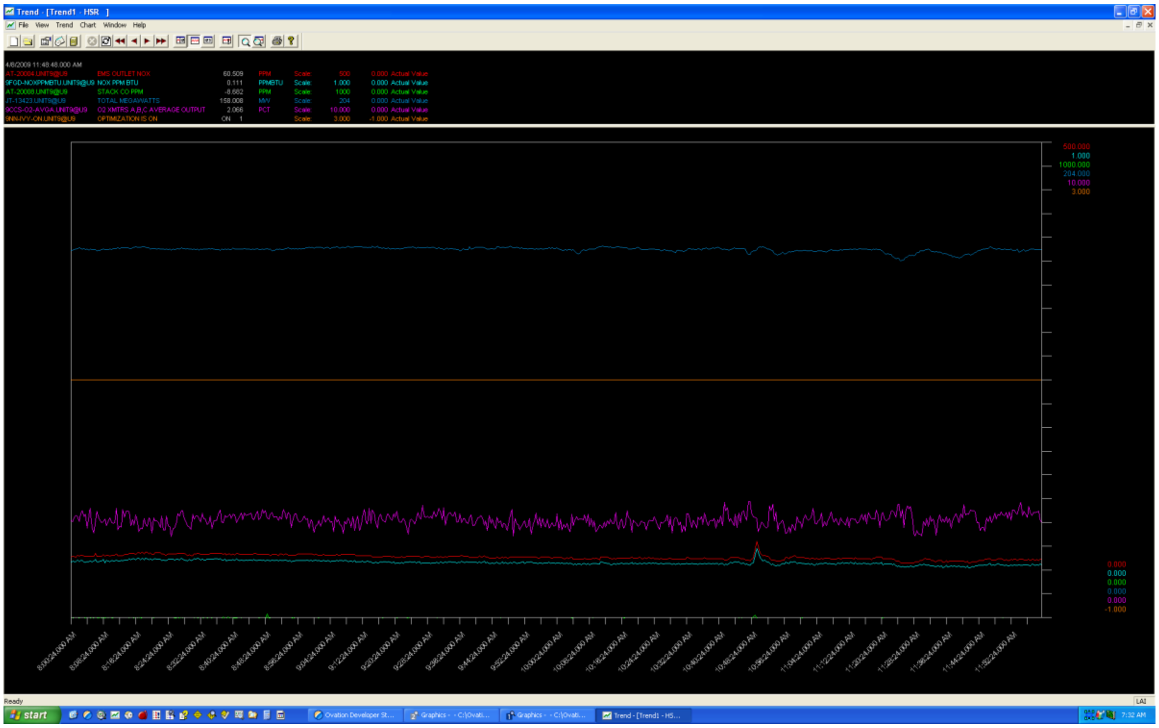

Figure # 7 Commissioning Test with the Optimizer ON

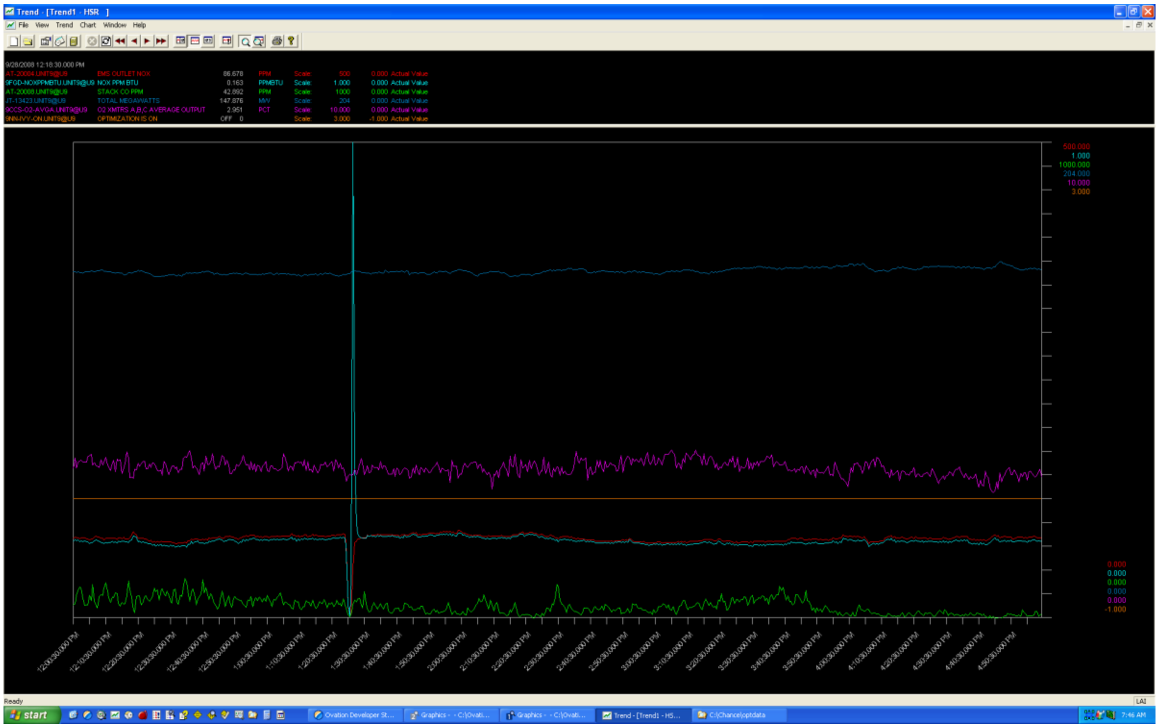

Figure # 8 Commissioning Tests with the Optimizer OFF

In the case of the upgrade of SmartProcess software on Unit 9, the commissioning test was done on Thursday, November 18th. The testing data includes time between 10:40AM and 14:55PM.

The scenario of the commissioning test was as follows:

1. OPT OFF – the boiler was operated without the Optimizer through 2 hours and 18 minutes (10:40PM – 12:58PM).
2. OPT ON – the boiler was operated with the Optimizer through next 1 hour 57 minutes (12:58PM – 14:55PM).

This report contains a results summary followed by several graphs of information which include average values (presented in the table below) and diagrams which compare results. The report also contains summary of the conclusions after the commissioning test.

Table #1 shows the major parameters' average values at unit load ~160MW that was tested. The table contains comparison for the following parameters: NOx and CO Emissions, O2 Average, Windbox to Furnace Differential Pressure, Average Unit Load, Average Auxiliary Air Demand, Average Total Air Flow and Average Total Fuel Flow.

Parameter	**IVY ON**	**IVY OFF**	Reduction
NOX	**63.11**	**75.86**	**20.20%**
CO	**6.97**	**6.95**	**Almost Same**
O2 Unit Average	**2.30**	**2.71**	**17.41%**
WBF DP	**4.49**	**4.24**	**-5.44%**
Unit Load	**160.01**	**159.72**	**Almost Steady**
AUX DMA Average	**2.08**	**46.16**	**2120.99%**
TOT AIR Average	**62.19**	**63.77**	**2.54%**
TOT FUEL Average	**67.04**	**66.91**	**Almost Same**

Table # 1 Commissioning Test Results

The statistical calculations shown above are presented in the following charts:

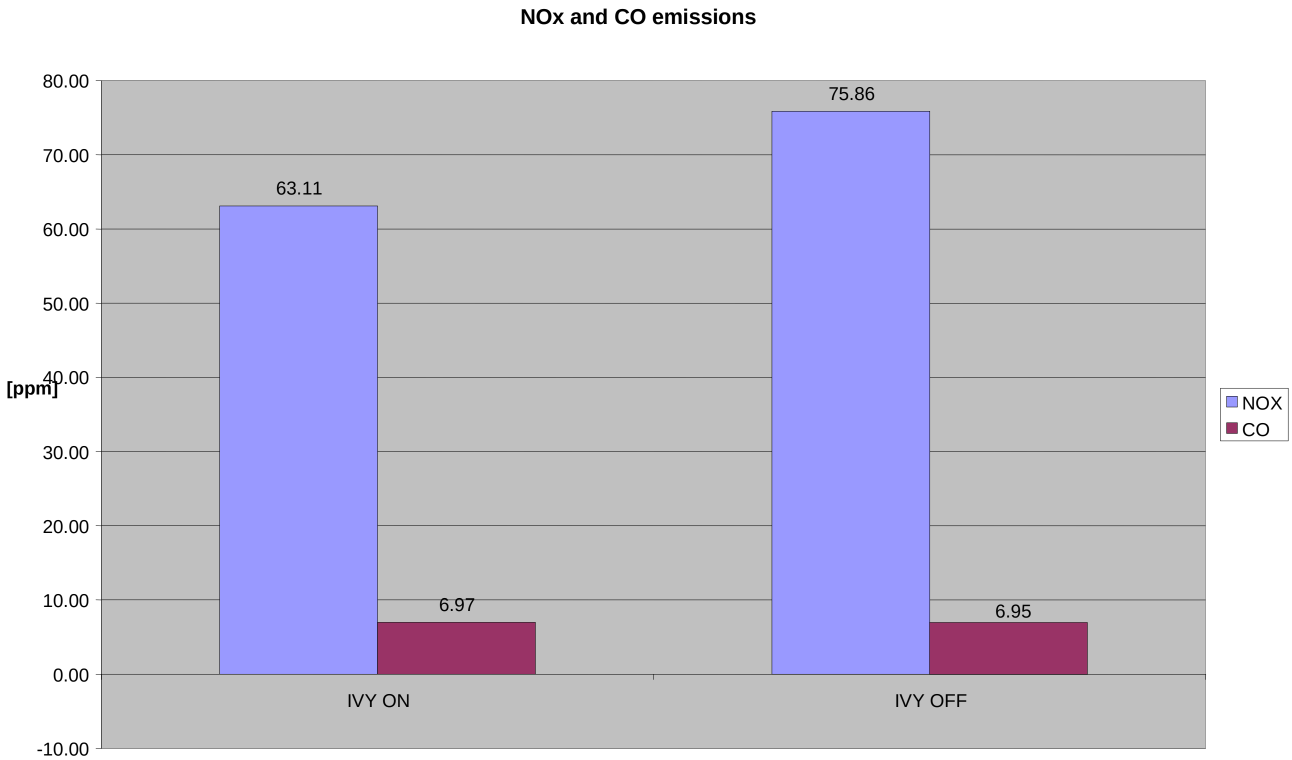

Chart 1 NOx and CO Emissions

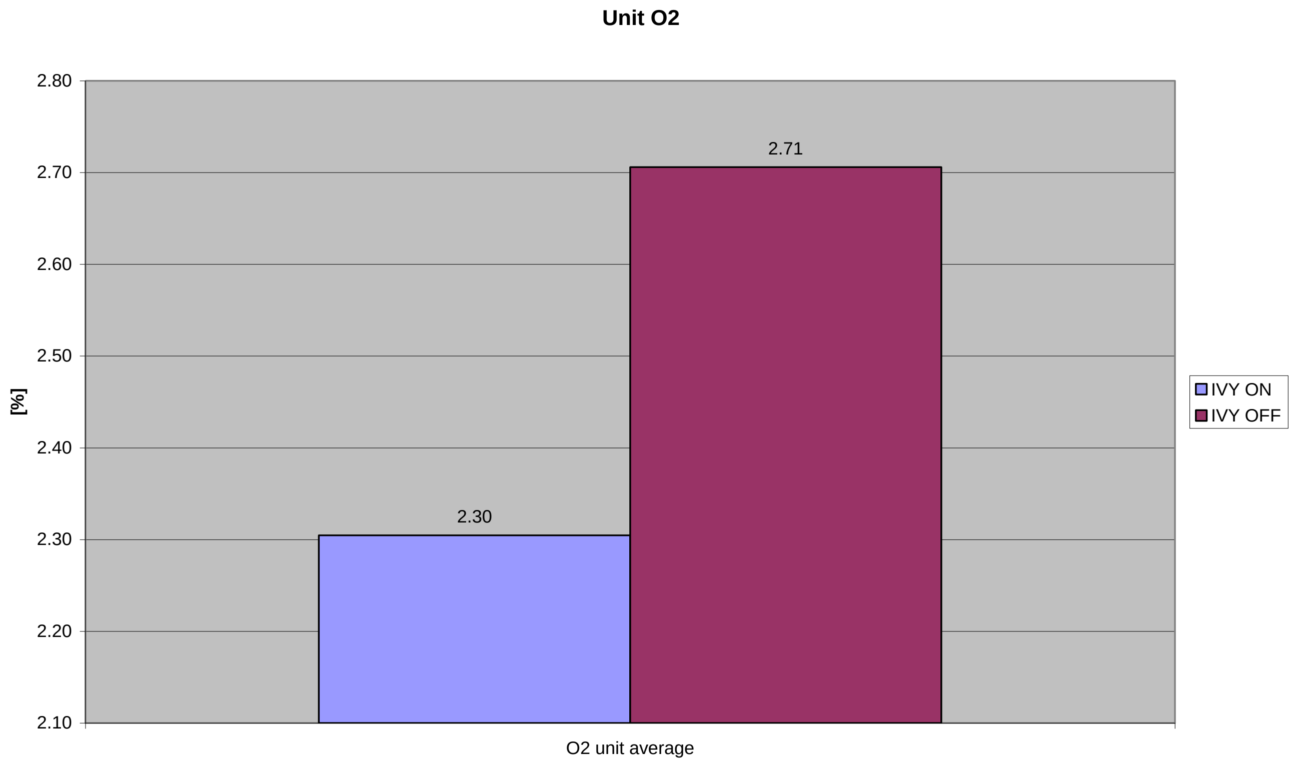

Chart 2 Unit O2 (Process Value)

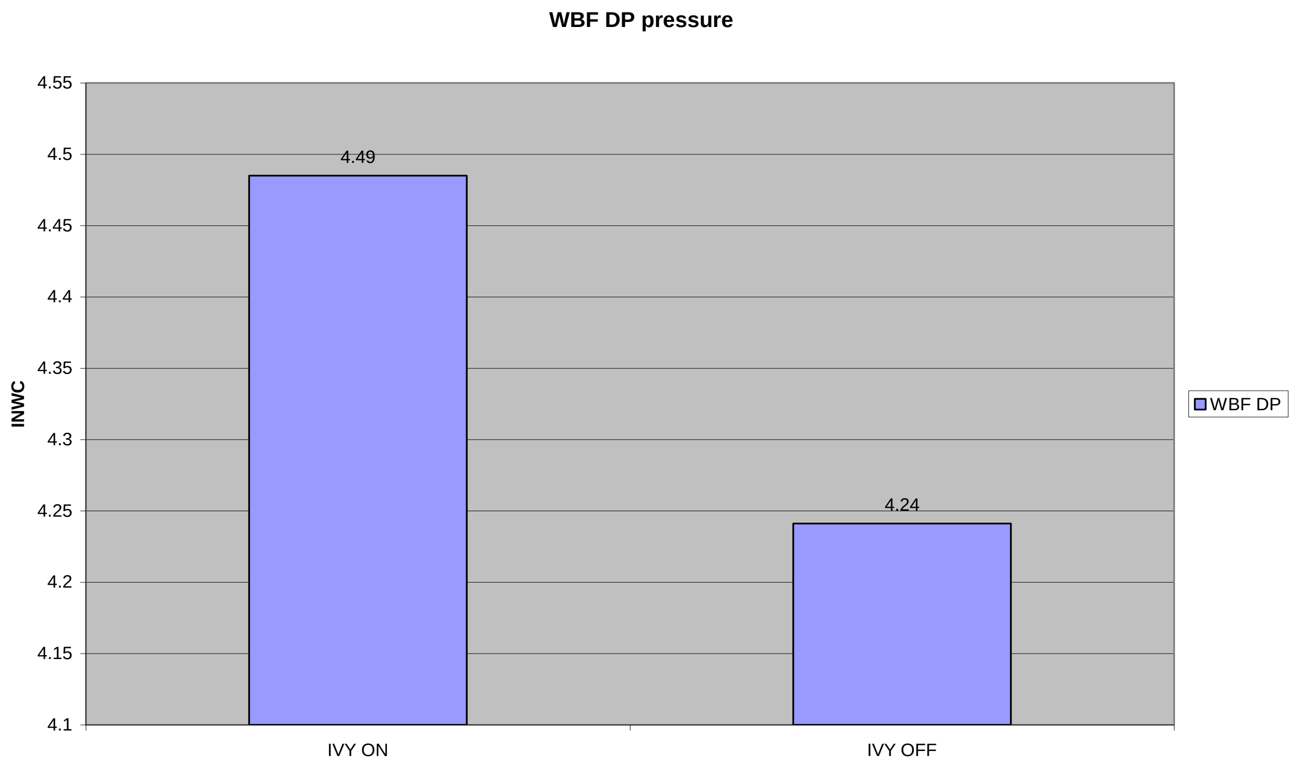

Chart 3 WBF Differential Pressure (Process Value)

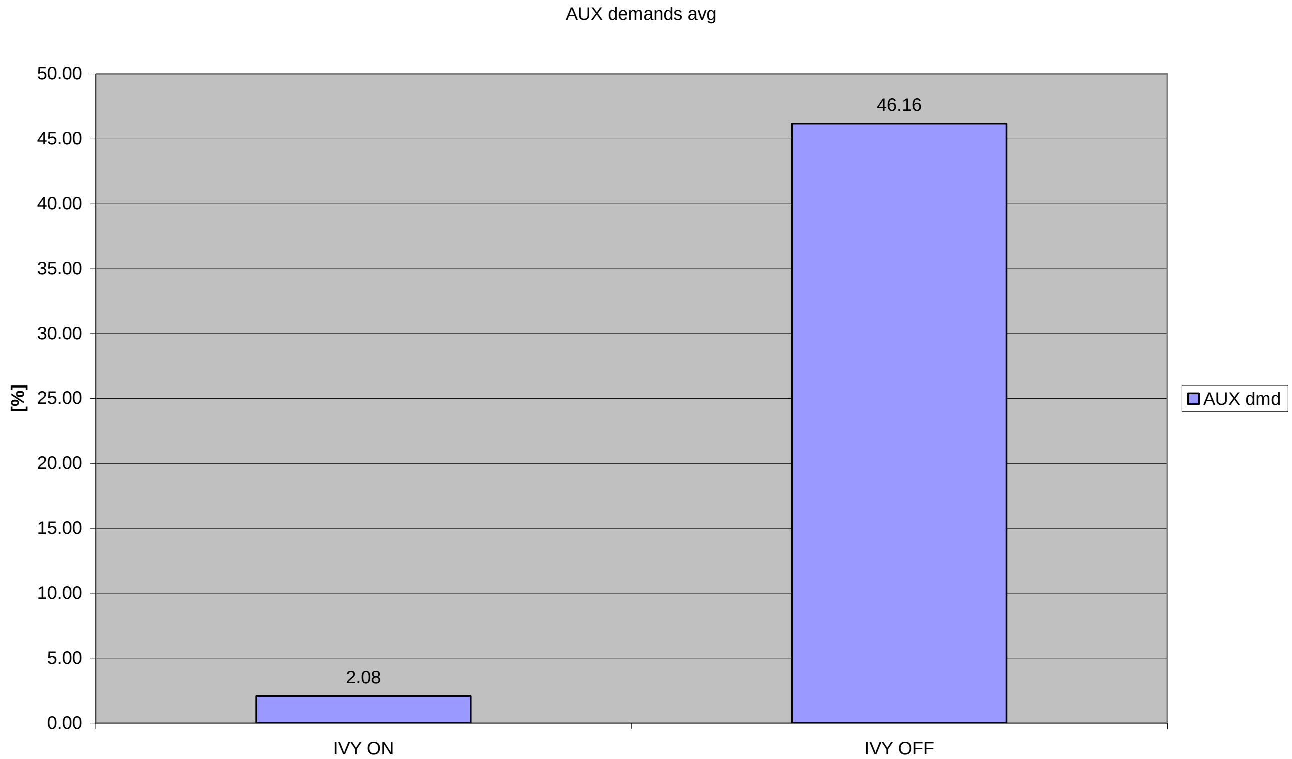

Chart 4 Auxiliary Air Average Demands

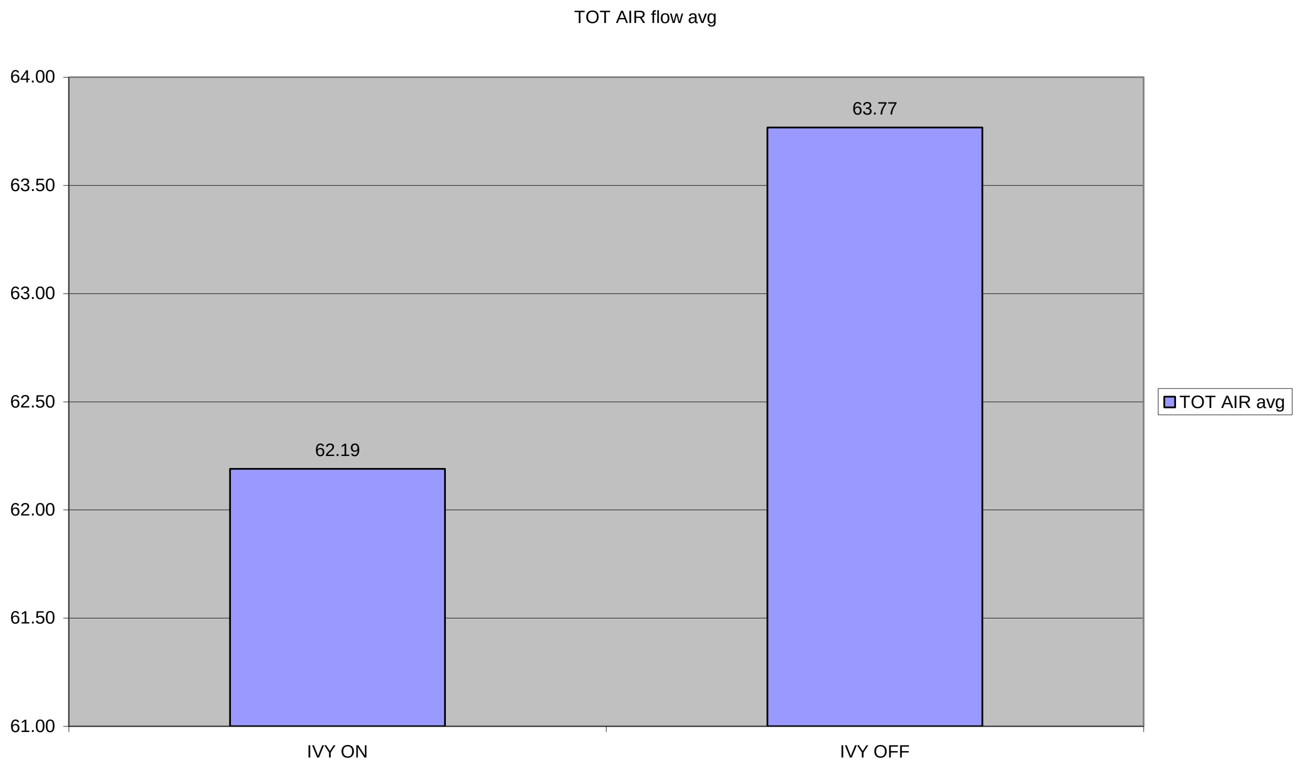

Chart 5 Total Air Flow Average Values

There were no reports from Operations about either slagging in the boiler or any change in LOI during the time the Optimizer has been on. Since the CO has been around 10 - 40ppm throughout the testing and thereafter, no LOI problems are anticipated.

SYSTEM GRAPHICS

Following graphics were provided as interface to the Combustion Optimizer to facilitate the running of the software and monitoring the various parameters that contribute to the overall reduction in NOx and CO.

The window with boiler permissives/warnings is shown below:

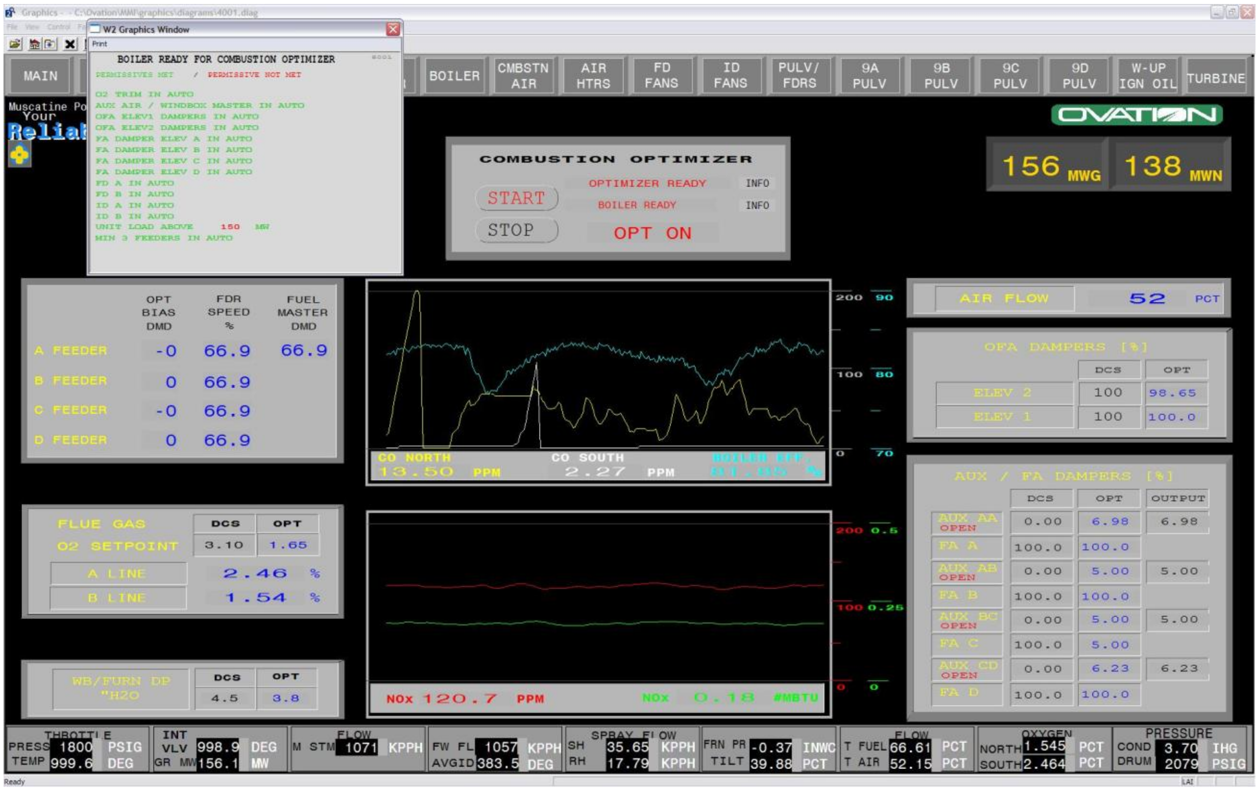

Figure # 9 Boiler Ready Signals for Combustion Optimizer

The window with permissives/warnings for optimizer is shown below:

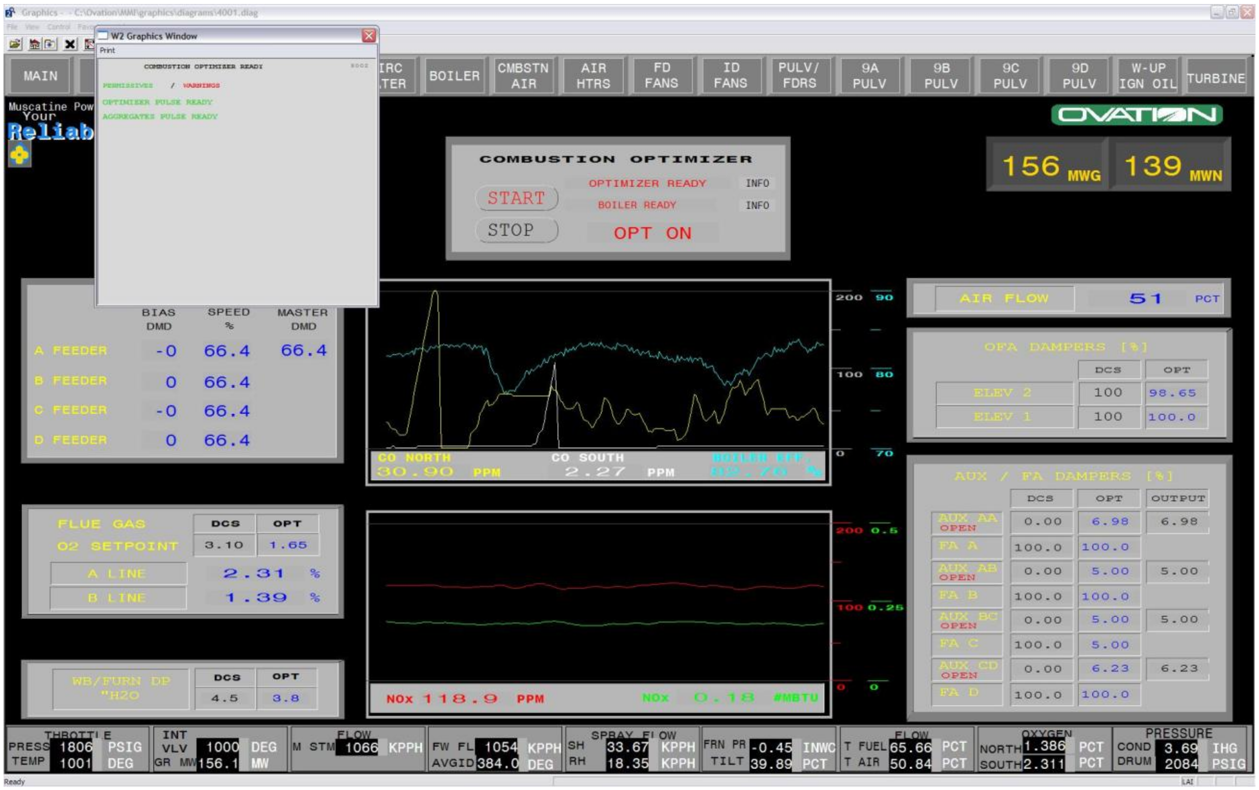

Figure # 10 Combustion Optimizer Ready Signals

NO_x Optimizer hooks can be turned ON and OFF using graphic shown below.

Figure # 11 Combustion Optimizer System Showing the Manipulated Variables Statuses

The "Combustion Optimizer" graphic is a main control graphic for Optimizer and is shown below:

Figure # 12 Combustion Optimizer Control

OVERALL PROJECT CONCLUSIONS

The combustion optimization system will help meet current emission regulations as well as more stringent regulations which may come into effect in the future. The combustion optimization system will optimize the combustion process with a software system that is very user friendly, very flexible with an easy to use web based interface for viewing and modifying the key combustion parameters, and adaptive to the changing combustion process.

The project was executed on schedule with no interruption of the operation of the unit. The cooperation between the MPW team members and the Emerson engineers was excellent and MPW provided all of the project support which was required. The unit operators seemed receptive of the system during the testing and training and the unit environmental engineer has been using and modifying the system over the past year or so.