OPTIMIZING THE BOILER COMBUSTION PROCESS IN A COAL FIRED POWER PLANT UTILIZING FUZZY NEURAL MODEL TECHNOLOGY

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INTRODUCTION

Tampa Electric Company (TEC), recognizing the increased focus on power plant emissions and the potential penalties for non-compliance, has undertaken several major projects at its Big Bend site in Apollo Beach, Florida to reduce the emissions being generated at the four units of Big Bend. As part of these projects, TEC has entered into a contract with Emerson Process Management Power and Water Solutions to provide an Emerson Smartprocess combustion optimization system on TEC Big Bend Unit #4 which will help reduce emissions and find the optimal positions for various parameters in the boiler combustion process, taking into account the changing goals of the unit as regulations change and the cost for non-compliance increases. This paper will discuss the combustion optimization system which was installed at TEC Big Bend Unit #4.

TEC Big Bend Unit #4 is a Combustion Engineering tangentially fired boiler design and a General Electric extraction steam generator. The unit has a capacity 450 megawatts and primarily operates in base loaded mode with some lower megawatt loads occurring in the evenings and weekends in certain parts of the year. Unit #4 has 5 coal mills providing the coal to the combustion process which are referred to as A,B,C,D,E with 4 of these mills being required to be in operation to achieve 450 megawatts of power production. The air for the combustion process is provided by fuel air dampers for each level of combustion in the boiler, auxiliary air dampers between the levels of combustion in the boiler, overfire air dampers (OFA’s) and secondary overfire air dampers (SOFA’s).

WHY BOILER COMBUSTION OPTIMIZATION??

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 ratio of some of these methods.

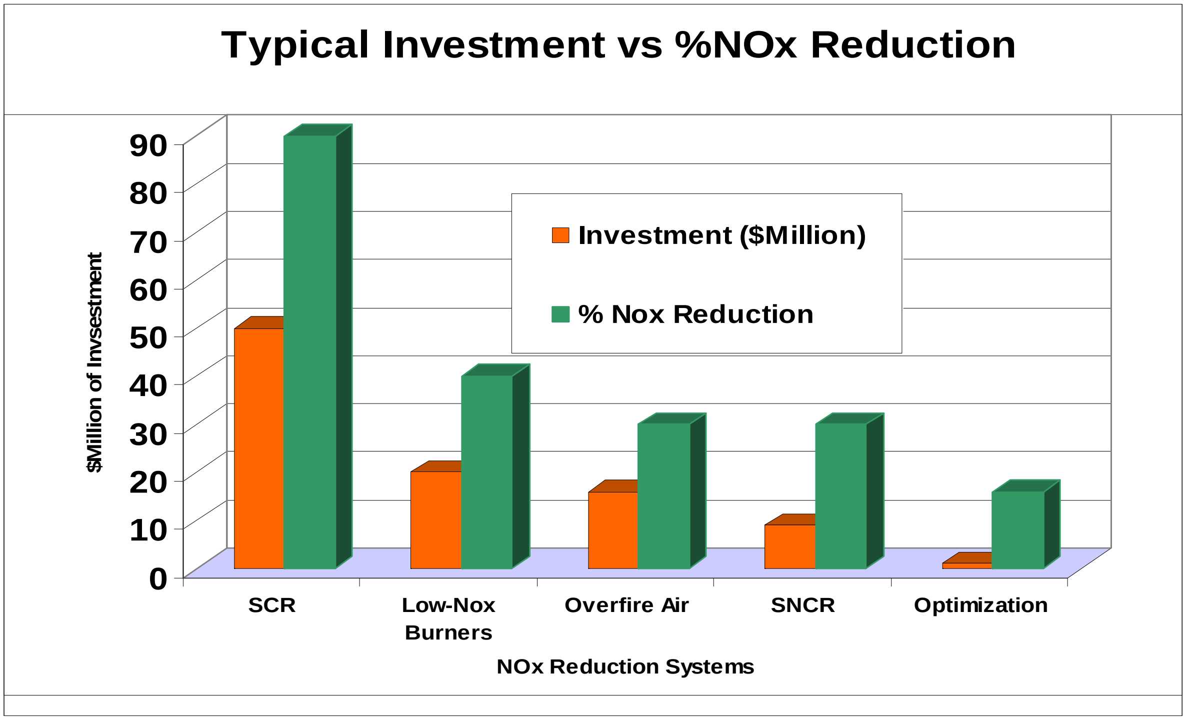


Figure #1 Cost-Benefit Ratio of NOx Reduction Technologies

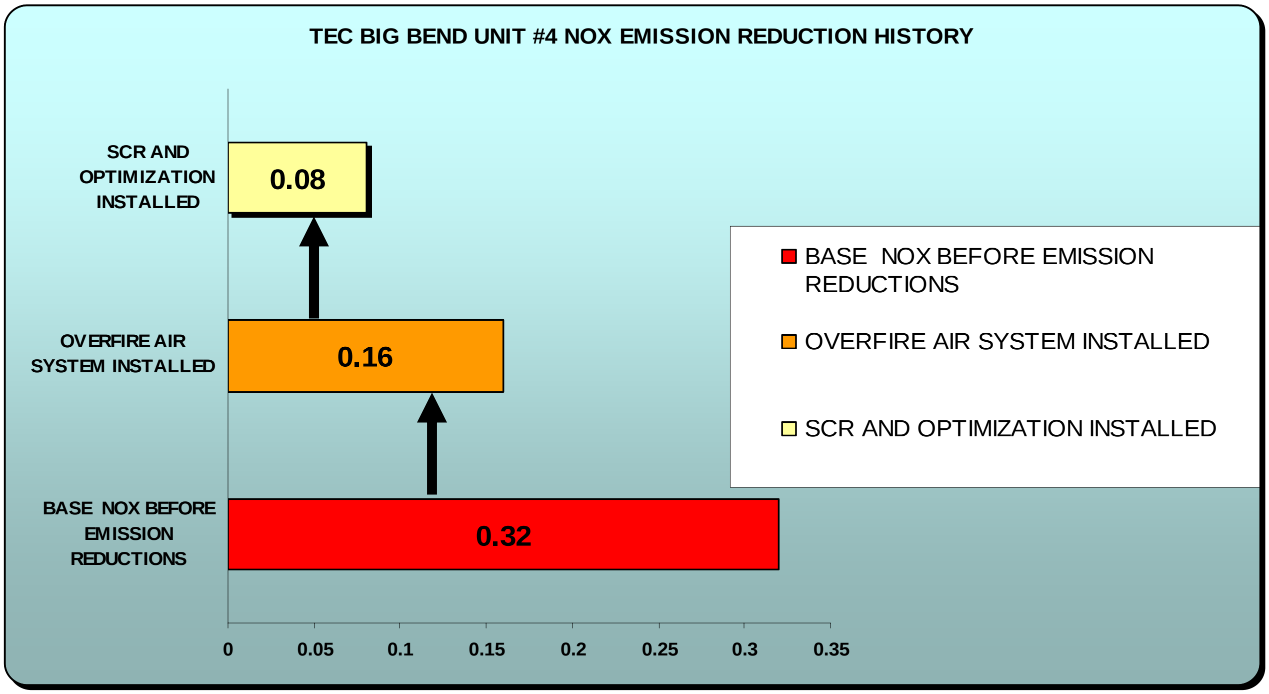
Some of the advantages of combustion optimization include:

- 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

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.

TEC BIG BEND UNIT 4 EMISSION BACKGROUND

The recent history of the NOx emission reductions at TEC Big Bend Unit 4 is shown in Figure #2 below:



Prior to the early 2000's, TEC Big Bend Unit #4 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 .27 -.35 lb/mmbtu.

TEC then chose to undertake projects to install SOFA and OFA systems in the upper levels of the boiler to modify the air flow into the combustion process and ultimately reduce the emissions of NOx. This system was installed and it was found that this system was capable of reducing NOx emissions to about .14 - .17 lb/mmbtu. However, the SOFA and OFA system were not utilized for a few years due to very strict CO limitations.

To further reduce emissions, TEC chose to install a Selective Catalytic Reduction (SCR) ammonia based system to further reduce the emissions of NOx to insure that the NOx could be maintained under the limit of 0.1 lb/mmbtu. This SCR system was installed during the spring outage of 2007 on Big Bend Unit #4.

Prior to the spring 2007 unit outage, TEC entered into a contract with Emerson to provide a fuzzy neural model based combustion optimization system. This optimization system was to be installed, configured, and tuned right after the 2007 spring outage and would be an in-combustion NOx reduction process that would reduce the generated NOx emissions and ultimately reduce the cost of the SCR operation. The primary goal of this optimization system was to determine the optimal positions for various combustion parameters to achieve multiple emission goals which are defined and can be modified by the end-user. As part of this combustion optimization and SCR projects, a new CO analyzer was purchased and installed on Big Bend 4 by TEC to provide the optimization system with critical on-line feedback for status of the boiler combustion system. It was thought, at the time, that CO would be a very important control variable in the optimization system. This was proven to be correct during implementation of the project. The CO analyzer was originally installed before the SCR inlet, but later was moved to close proximity of the FGD inlet in order to get a more realistic and less stratified value of CO across the entire boiler.

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 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.

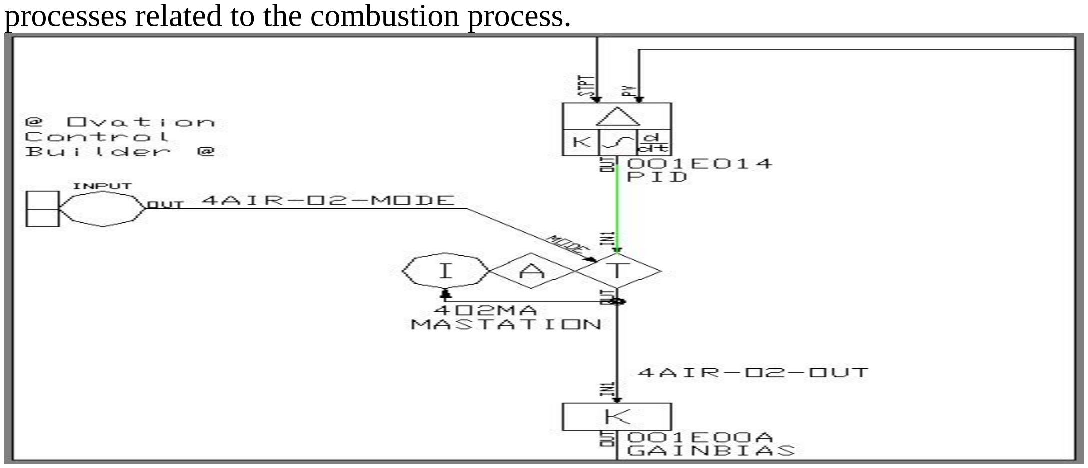


Figure #3. Example of Traditional PID Control Loop

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.

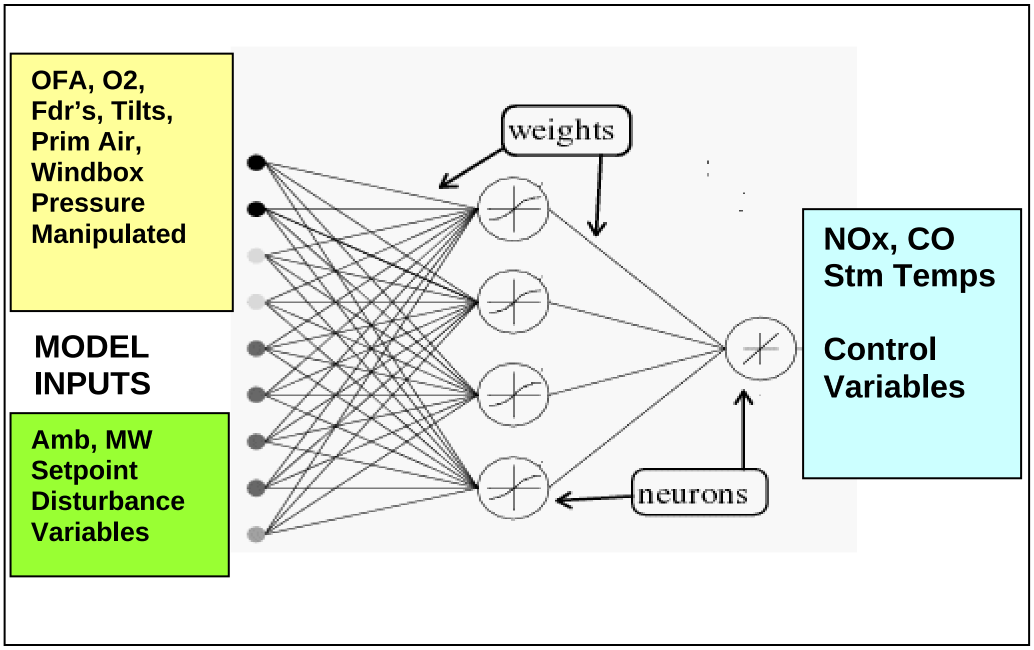


Figure #4. Example of a Fuzzy Neural Model Optimization System

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**
$y = a^i_0 + a^i_1 x_1 + \ldots + a^i_N x_N$

(2): i**f** 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**
$y(k) = a^i_1 y(k-1) + \ldots + a^i_n y(k-n) + b^i_1 u(k-1) + \ldots + a^i_m u(k-m) + c^i$

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 FOR TEC BIG BEND U4

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 Big Bend Unit 4 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:

- FD and ID Fans
- Fuel Air Dampers
- Auxiliary Air Dampers
- Boiler O2 Trim
- Coal Feeders
- Windbox-Furnace Pressure
- Overfire Air System
- Secondary Overfire Air System
- Burner Tilts

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.

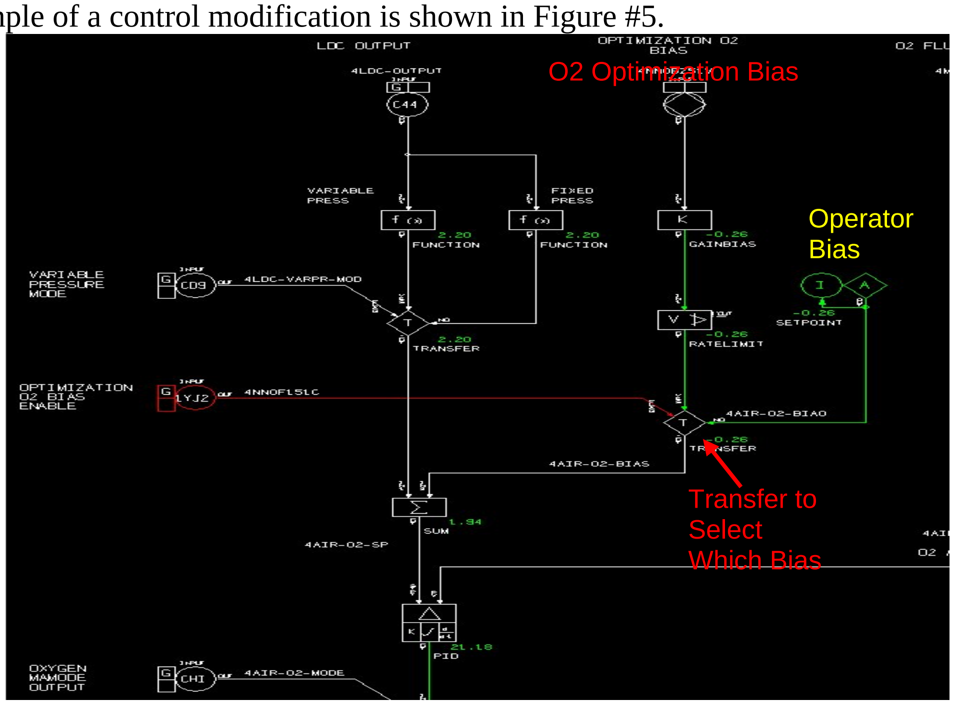


Figure #5 Example of Optimization Control Modification

Parametric Testing

The next step in the optimization project was to define and perform the parametric tests on the Big Bend Unit 4 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 mill operation and 3 mill operation. The parametric testing was executed in June, 2007. An example of the coal feeder parametric test is shown below:

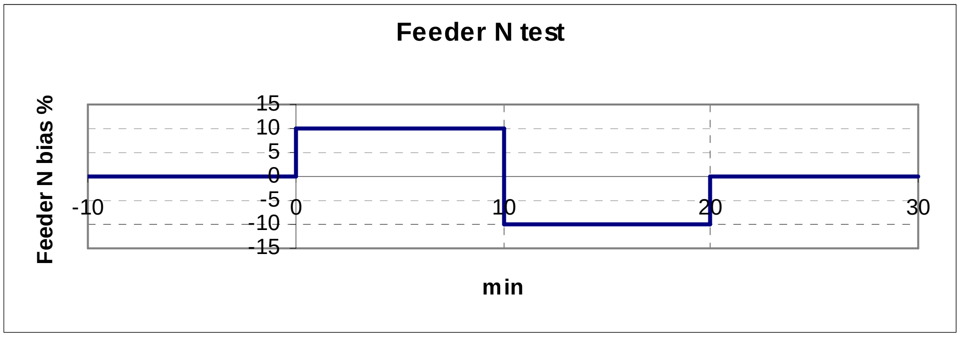


Figure #6. Example of a Optimization Test Plan for Feeders

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 July, 2007, the initial combustion model was installed on the optimization computer in open and closed loop testing was 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 three 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 (usually about 7-10 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. There were several tests ran in December of 2007.

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

CO – 150 ppm SCR Inlet NOX – 80 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 TEC engineers and Emerson engineers agreed that the most important parameter in the combustion process was CO. If the CO limit was exceeded in the combustion process, this is what would be collected and reported in the emission report. Other than the combustion optimizer, there are no other systems post-combustion that would reduce CO. If NOx ran a little high for some reason, the SCR would still be able to reduce NOx below the mandated limit. 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. Some results of the

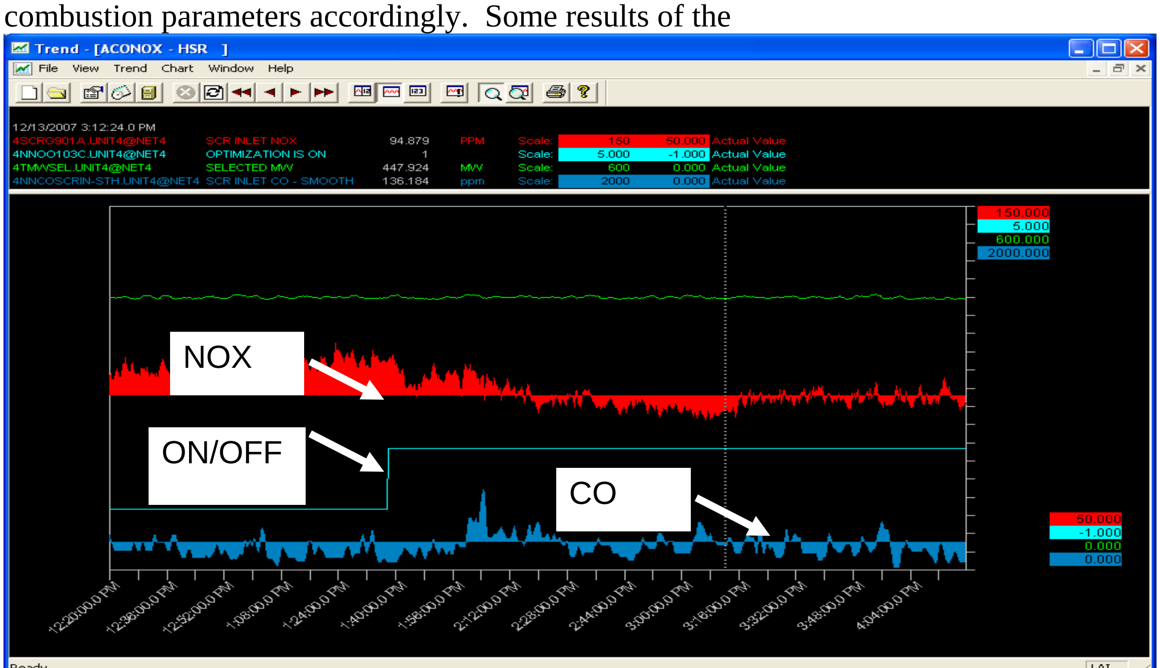


Figure #7. Commissioning Test for December 13th, 2007

commission tests are shown in Figure #7.

On this day, the combustion CO was below its limit for all of the day. The optimizer was able to keep CO in-check and lower NOx on this day. The results of the two key parameters are shown in the table below.

DATE	START TIME	END TIME	NN STAT	LOAD	NOx	CO
12/13/2007	2:20:00PM	4:19:36.0PM	ON	449.63	96.37	127.23
12/13/2007	12:20:00PM	1:37:12.0PM	OFF	449.92	105.76	106.62
		DIFF %		0.07	8.88	-19.33

Table #1. Results of Commissioning Tests for December 13th, 2007

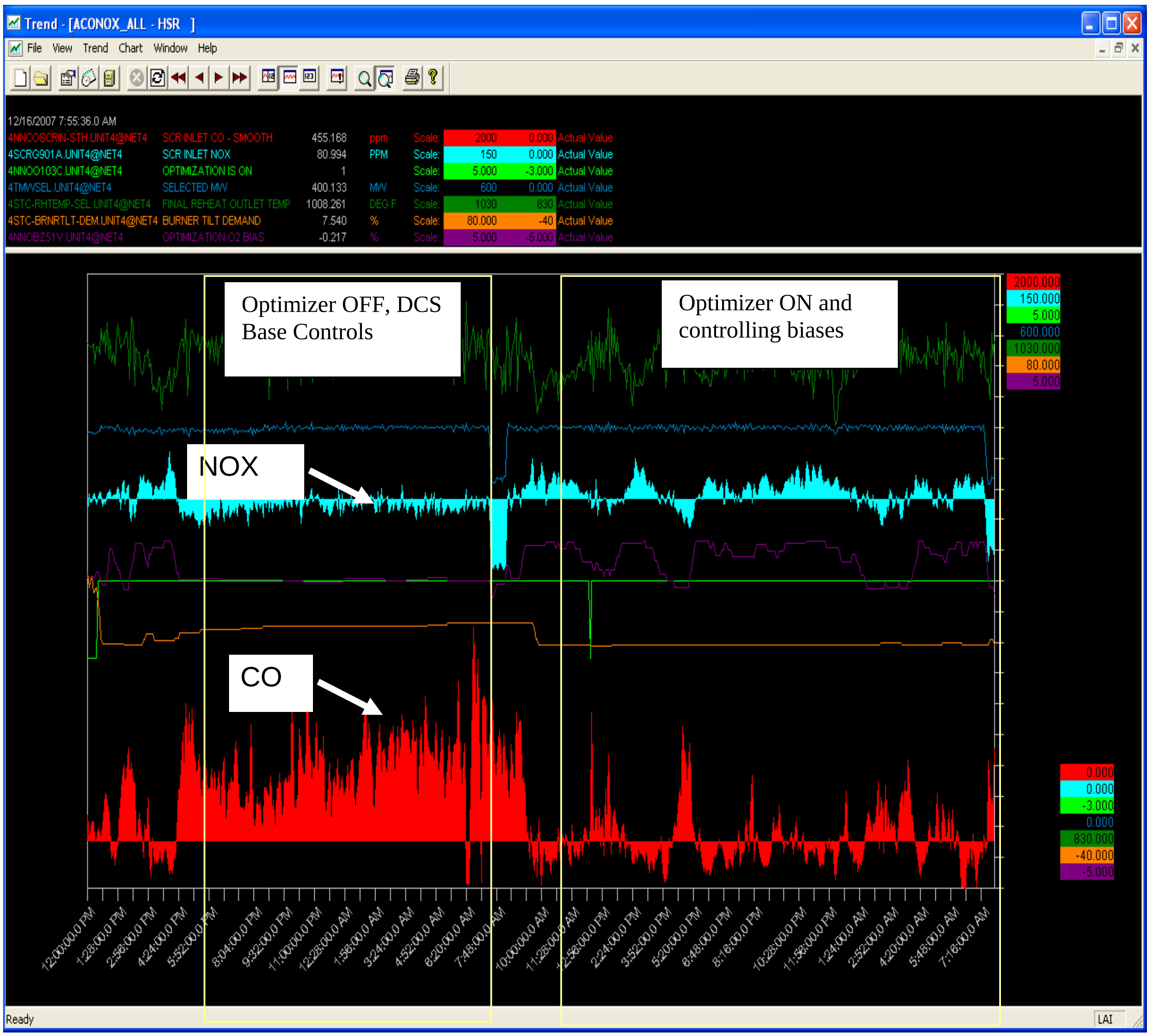


Figure #8. Commissioning Test for December 14-15, 2007

On the test above, during the OFF test and all parameters operating in AUTO, the CO was very high and above the CO limit. When the optimization system was turned on, CO was able to be controlled at or below the CO limit with small spikes. NOx was a little higher than the OFF test, but this is due to controlling CO first.

The quantitative results of this test are shown in Table #2. These results show that NOx average slightly higher with the optimizer in control but CO was much better and in-control.

START		END		OPT Status	CO PPM	NOX PPM	LOAD MW	RHT DEGF
12/14/07	5:00PM	12/15/07	07:20AM	**BIAS=0**	380.86	93.43	449.29	1006.46
12/15/07	10:00AM	12/16/07	08:00AM	**ON**	159.96	96.53	448.85	1001.42
			DIFF %		58.00	-3.33	0.10	0.50

Table #2. Results of Commissioning Tests for December 14-15, 2007

OVERALL PROJECT CONCLUSIONS

The Big Bend 4 combustion optimization system will help TECO 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 TEC team members and the Emerson engineers was excellent and TEC 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 four months.

The initial primary goal of the project was NOx reduction at BB4 but as the project was executed and the testing and tuning was executed on the optimization system, it became apparent the both NOx and CO would be the major goals of the optimization system and the system is flexible to allow the end-user to modify the goals as regulations change.

The commissioning tests showed that the CO and NOx can be controlled with CO having the higher weight and thus being controlled first and NOx reduction having the next highest weight. The tests also showed the typical variability in day to day unit operation and performance which occurs at most power plants. Things such as ambient conditions, coal quality, cleanliness of boiler, mill selection and operation, etc. affect the unit performance and the optimization system will help to minimize the impact of varying conditions.