Optimization of Cyclone Boilers Using Neural Network Technology

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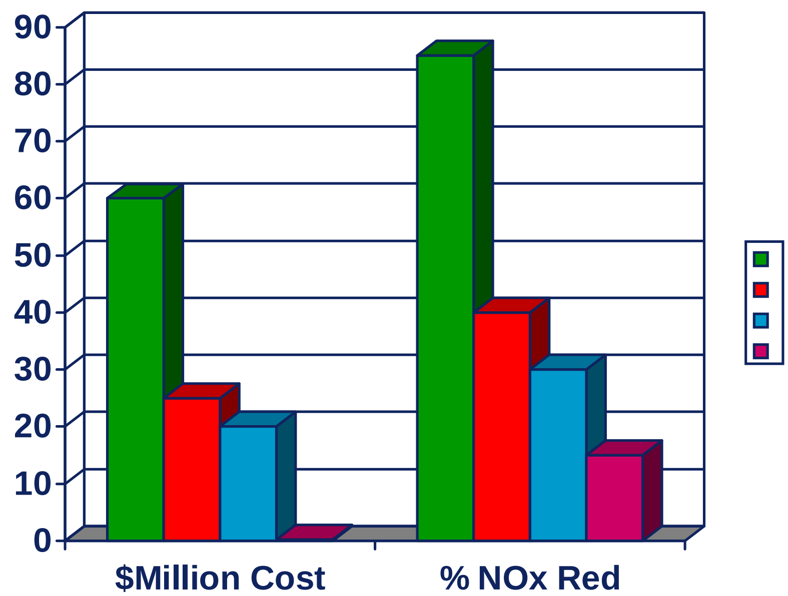
Abstract: Constellation Energy, recognizing the increased focus on power plant NO_x emissions and the benefits of reducing emissions as well as efficient boiler operation, has undertaken a project to optimize the performance of two units at its C.P. Crane station in Baltimore, Maryland utilizing advanced neural network technology. The C. P. Crane site has two (2) units, each with four (4) Babcock &Wilcox (B&W) cyclonic furnace burners in an opposed-wall firing configuration. Unit #1 is rated at 200 megawatts and unit #2 is rated at 205 megawatts. These units went into commercial service in 1961 and 1962, respectively. This project is one of the first in the United States utilizing dynamic closed-loop neural network technology to optimize performance on a load following power plant utilizing cyclone boilers for combustion. A typical characteristic of cyclone boiler design is higher than normal thermal NO_x emissions mainly due to higher than usual combustion temperatures in the cyclone. The objective of this project is to lower the NO_x emissions while improving unit heat rate and efficiency as well as improving the control on

steam temperature taking into account that these units move load continuously. This paper will discuss the design and execution of this project, unique situations that had to be overcome during the execution of the project, and the test results to date.

Background:

Constellation Energy's Charles P. Crane power station, located in Baltimore, Maryland, has two (2) units firing sub-bituminous crushed coal. Unit #1 has a megawatt rating of 200 megawatts and Unit #2 is rated at 205 megawatts (MW). These units utilize Babcock and Wilcox (B&W) cyclonic boilers for steam production and each of the units is equipped with four (4) cyclonic boilers configured in an opposed-wall firing configuration. C.P. Crane Unit #1 utilizes a "once-thru" boiler design while unit #2 utilizes the traditional drum-type boiler. Historically, these types of boilers were more efficient than traditional boiler designs (i.e., corner-fired and wall-fired boilers firing pulverized coal) but produced much higher amounts of nitrogen oxides (NO_x) than the traditional boilers. As the NO_x emission limits became more stringent and the penalties for not meeting these limits increased exponentially, it became apparent that the NO_x emissions of these two units would have to be improved or the units would be have to be retired due to unfavorable cost considerations when compared to other units in the fleet. Prior to the year 2000, typical NO_x values for these two units were in the 1.0 – 1.4 lb/mmbtu range. The two units underwent a major design change in 1999-2000, which included adding an over-fire air system (OFA) and gas reburn system to both boilers. The purpose of this redesign was to reconfigure the air flow into the

Figure 1
Cost/Benefit of various methods of NOx reduction



boilers to help reduce NO_x emissions as well as to utilize the gas reburn system to increase the efficiency of the combustion process. This new design resulted in reducing NO_x values by approximately 40 –50%. Typical NO_x values after the redesign were in the 0.55 - 0.65 lb/mmbtu range. After one year of operation, the utilization of the gas-reburn system was discontinued mainly due to the high cost of the natural gas supply. While this was a significant improvement, the NO_x values for these units were still high compared to other units and the cost of NO_x credits continued to rise. The utility began looking at various technologies to reduce NO_x emissions further.

An overfire air system had already been installed and low-NO_x burners are not an option in a cyclone boiler, therefore, the utilities choices were somewhat limited. After further study and looking at various technologies for NO_x reduction, including Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR) and the cost/benefit ratios, the utility decided in 2003 to install a neural-network based software optimization system into the distributed control system (DCS) of each unit at C.P. Crane with the goal of further reducing the NO_x emissions and increasing overall unit efficiency. This project was one of the first projects of this kind undertaken on a cyclone boiler design in the United States and it is discussed in more detail in the paragraphs below. The scope of this technical paper will be the project executed for C.P. Crane Unit #2.

Cyclone Boiler Overview

Before discussing the project, a brief overview of cyclone boilers is necessary. Each cyclone burner acts as an independent combustion chamber and is supplied with crushed coal carried to the cyclone by primary air, secondary air for the combustion process, and tertiary air, which sets the flame vortex and aids in moving the exhaust gases from the cyclone burner into the main furnace. The exhaust gases of the four cyclone burners flow into the main furnace, heating the waterwalls and other sections of the boiler for the generation of steam. The over-fire air is injected into the exhaust gases at an elevation of about 90-100 feet. There are a total of eight over-fire air ports for air injection, with four being on the front wall of the boiler and four being on the back wall. The over-fire air ports are supplied with heated air from the air heater outlet. The purpose of the over-fire air is to supply air for recombustion of the exhaust gases to reduce the NO_x production. The presence of the over-fire air system provides the capability for the redistribution of the combustion air system within the boiler. The amount of secondary air supplied directly to each cyclone can be reduced, and the additional air not supplied directly to the cyclones is then supplied to the combustion process via the over-fire air ports. This redistribution of air permits manipulation of the stoichiometric ratio of each cyclone, which plays a key part in reducing the nitrogen oxide emissions generated by the combustion process. The exhaust gases then enter the superheat and reheat sections of the boiler, followed by the economizer and air heater sections, then the baghouse for particulate removal and out to the atmosphere.

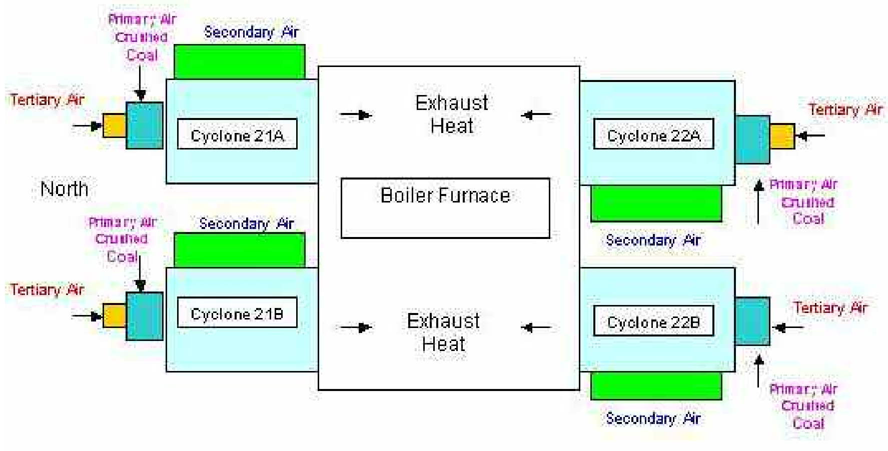


Figure 2
Crane Unit 2 is configured with 4 cyclone boilers

Boiler Optimization Project Overview

The Constellation units are under ozone-season limitations for the production of NO_x from May 1 through Sept 30 of each year, which is known as ozone-season. The utility must report the amount of NO_x produced by each unit and utilize NO_x “credits” to offset this production of NO_x. Because the project was initiated in February 2003 and the unit NO_x season began on May 1, 2003, the project was executed in two phases

- NO_x Optimization
- Steam Temperature Optimization/Unit Heat Rate Optimization

By executing the project in this fashion, the NO_x optimization portion was completed and put in-service by May 1, which allowed the utility to achieve maximum NO_x reduction for the entire 2003 ozone season. At the end of the 2003 ozone season, the steam temperature optimization/unit heat rate optimization portion of the project was executed and placed in-service in November 2003. This paper will discuss both phases of the project and report 2003 results from the NO_x optimization portion and partial 2003-2004 results for the steam temperature optimization/unit heat-rate optimization portion of the project.

NOx Optimization

The NO_x optimization portion of the project began in February 2003. The following were identified as the major tasks for the project.

- Task 1 – Unit Operation Analysis
- Task 2 – DCS Control Modifications
- Task 3 – Parametric Testing

- Task 4 – Data Analysis and Model Building
- Task 5 – Open/Closed Loop Model Testing
- Task 6 – Development of Operator Interface/Operator Training
- Task 7 - Final Commissioning

The models were placed in-service on May 1, 2003. Final tuning was completed in mid-May 2003.

NO_x Optimization Task 1 - Unit Operation Analysis

Task #1 is a critical analysis of the process and is much more than just a discovery of instrument list and plant walk down of ducting and piping although they are necessary steps. It is an analysis of the effect of parameter changes both upstream and downstream of this change. This phase included the initial visit to the plant and included several tasks. The plant and unit instrumentation were reviewed with plant personnel to determine what analog and digital measurements were available in the DCS. The design basis of the process has to be discovered to be able to test to the extremes within the design limit of the equipment, which may or may not be within the comfort zone of plant personnel. A review of the operation of the units was conducted with the plant engineer(s) and unit operator(s) to determine what parameters could be manipulated within the combustion system and what the limitations were on these parameters. Small parametric tests were then designed based on knowledge of First Principles and plant equipment limitations to provide initial feedback on how the manipulated parameters affected the combustion process. Based on these initial tests, the following parameter list was developed as parameters that potentially could be utilized in the neural network model for NO_x optimization:

- Cyclone Stoichiometry
    1. Cyclone primary air flow
    2. Cyclone secondary air flow
    3. Cyclone tertiary air flow
    4. Cyclone fuel flow
- Boiler Air Duct Pressure
- Boiler Excess Oxygen
- Over-fire Air Flow
- Forced Draft Fans
- Induced Draft Fans

This initial discovery and parametric test took one week to develop.

NO_x Optimization Task 2 – DCS Control Modifications

Modifications to the DCS control structures were designed and implemented to allow either control biases or actual control signals to be injected into the DCS from the neural network model for the parameters listed above.

NO_x Optimization Task 3 – Parametric Testing

The parametric testing phase of the project was executed in April 2003. The DCS control modifications to permit injection of the neural network model values were implemented prior to parametric testing which enabled the parametric testing to be automated thus shortened the overall time required for to complete the testing. Various tests were executed that manipulated the parameters listed above at three different load points. The purpose of the parametric testing is to obtain a large data set at various unit conditions that will be utilized in building a neural network model of the unit. The automated testing provided a consistent data set for the neural network model, thus reducing rework of additional testing for model development.

NO_x Optimization Task 4 – Data Analysis and Model Building

Analysis performed on the data collected in task #3 determined which parameters had an impact on NO_x formation and should be included with in the neural network model.

Cyclone Stoichiometry
The major contributor to NO_X generation is the flame temperature. The greatest control of flame temperature was gained through control of cyclone stoichiometry. Cyclone stoichiometry is a measure of the air to fuel ratio for the combustion process and is normally a value between 0.8 and 1.2. A value of 0.8 indicates that the amount of air supplied for combustion is less than the theoretical amount required for the complete combustion of the fuel while a value of 1.2 indicates that excess air is supplied to the combustion process. Using conventional DCS controls, the cyclone stoichiometry is a result of the amount of air and fuel supplied to the cyclone. Parametric testing showed that because of differences in each cyclone, the stoichiometric ratios that resulted from the DCS demands for air and fuel to each cyclone were different for each cyclone under normal operation. These non-uniform ratios were a result of secondary air damper position. Although the DCS signal uniformly indexed each damper by the fuel demand, the individual ductwork geometry and wear of the damper prevents uniform distribution of air to each cyclone. Figure #3 shows typical stoichiometric ratios for each cyclone when the stoichiometry was not controlled by optimization. By using the neural network model to predict and adapt to changes within the process, it was determined that NO_x production could be reduced by controlling the stoichiometric ratio of each cyclone. Figure #4 shows the typical individual cyclone stoichiometric ratios when the ratio was controlled by the neural network models. The final stoichiometric control range is 0.9 to 0.95 in the ozone season.

Figure 3
Typical uncontrolled individual cyclone stoichiometric ratios

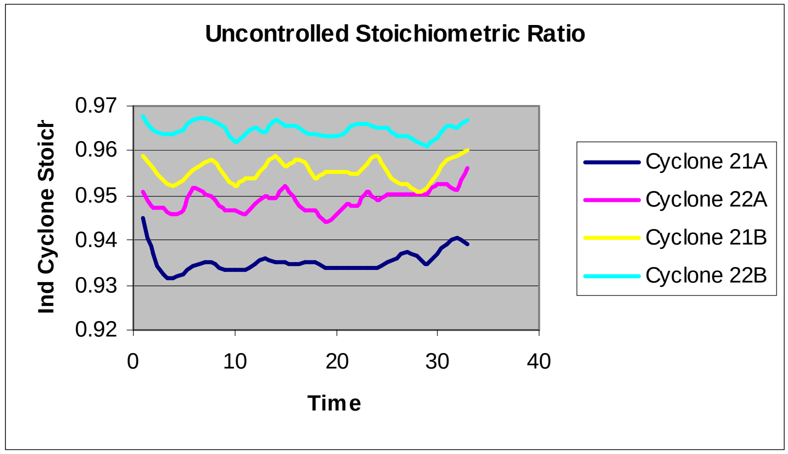
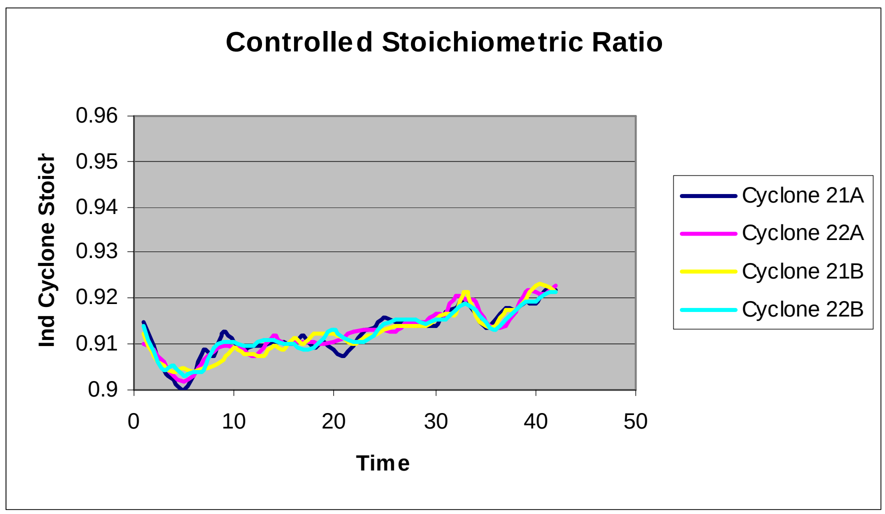


Figure 4
Typical controlled individual cyclone stoichiometric ratios



Boiler Excess Oxygen
Once cyclone air flows could be tightly controlled, the relationship between the amount of excess oxygen in the boiler and NO_x production of the boiler became apparent. This relationship was somewhat complicated for C.P.Crane's units due to the additional OFA that was injected into the boiler prior to the measurement of the excess oxygen in the boiler; however, the neural network model is able to predict the optimal process point based on load index. The final amount of excess oxygen was reduced from 3% to 2.6 to 2.8%.

Boiler Air Duct Pressure

Under the normal control structures, boiler air duct pressure had been kept in a narrow range of approximately 34 to 36 inches of water. Parametric testing showed that increasing the duct pressure allowed for greater OFA flow at higher loads and increased the cyclone air velocities necessary for complete combustion. – The final duct pressure control range is now 30 to 48 inches of water. The unit had been originally designed as a positive pressure boiler thus the ductwork was designed to support higher values of duct pressure.

Boiler Over-Fire Air Flow

Under the normal control structures, the unit operator was able to enter a percentage of total air flow that would be directed to the OFA system up to a maximum of 25% of total air flow. For the parametric testing, this maximum value was increased to 30%. Testing also determined that by increasing the boiler air duct pressure, additional air could be directed into the OFA system. Under traditional DCS control, the OFA was distributed evenly between the front and rear walls. The new neural network model developed a new paradigm based on furnace arch geometry and splits the air flow unevenly between the front and rear walls.

Boiler Forced Draft Fans

Because of the common ductwork redesigns at C.P. Crane Station, biasing the two boiler forced draft fans does not have any significant impact on the production of NO_x. For this reason, these two parameters were not included in the final neural network model.

Boiler Induced Draft Fans

As with the forced draft fans biasing, the induced draft fans do not have any significant impact on the production of NO_x. For this reason, these two parameters were not included in the final neural network model.

NO_x Optimization Task 5 – Open/Closed Loop Model Testing

After all NO_x optimization models were built, they were tested in the last week of April, 2003 in open-loop mode. Open-loop testing permitted the user to analyze what adjustments the models would make to the combustion process if it were in closed-loop operation. Because of the teams' process knowledge and the accuracy of the data collected through automated testing, minimal re-tuning was required. Closed-loop operation began on May 1, 2003. The neural network model controlled the process NO_X levels so well that at low megawatt loads, the steam temperatures dropped too low. NO_X was sacrificed in favor of steam temperature support by allowing the final oxygen level (O_2) to rise and cyclone stoichiometry control changed to 0.95. This new control scheme was implemented in mid-May and the closed-loop operation continued through September 30, 2003 with minimal time when the NO_x optimization models were not in closed-loop operation.

NO_x Optimization Task 6 - Development of Operator Interface/Operator Training

Customized DCS graphics were developed to allow the unit operator to view the current values and status of the neural network program as well as start/stop the entire neural network program or a specific loop. The main neural network DCS graphic is shown in Figure #5. New process control parameters such as monitoring the final O2 spread across the ductwork increase the operator's ability to identify combustion abnormalities such as feeder belt slipping which were previously undetected. The operations department was included in all phases of testing and implementation and had a representative on the optimization team.

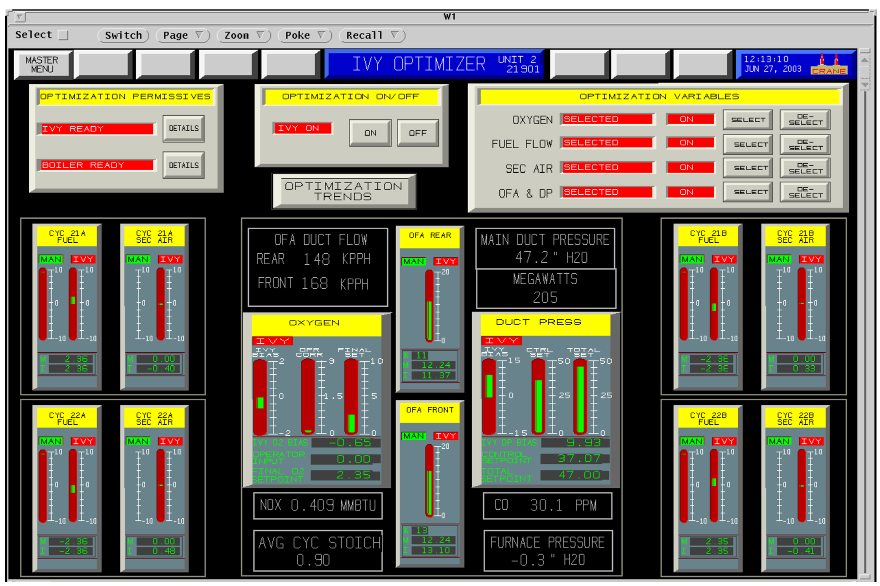


Figure 5
Neural network DCS operator interface graphic

Final training was provided to all operators on the neural network prior to placing it in-service. The acceptance level was high and was reflected in the on-time operation of the system.

NO_x Optimization Task 7 – Final Commissioning

The NO_x optimization portion of the project was commissioned by gathering all NO_x data for the years 2003(with neural network in-service) and 2002(without neural network in-service) during ozone season (May-Sept). Figure #6 shows the raw NO_x values in ten megawatt increments throughout the load range in which unit #2 normally operates.

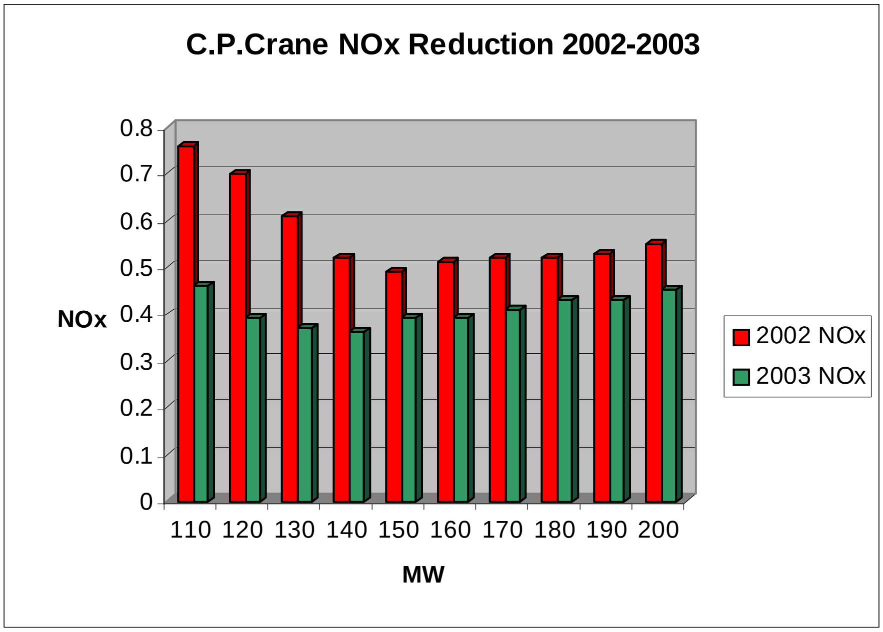


Figure 6
Raw NOx values for years 2002 and 2003

The corresponding percentage reduction of NO_x at the various loads is shown in Figure #7. The results show that higher NO_x reductions were achieved at lower loads, which was expected because lower loads normally offer more room to bias the parameters affecting NO_x formations. The unit was able to achieve these NO_X reductions without sacrificing any of the unit's 7 MW/min regulation rate throughout its normal operating load range of 110 to 205 MW.

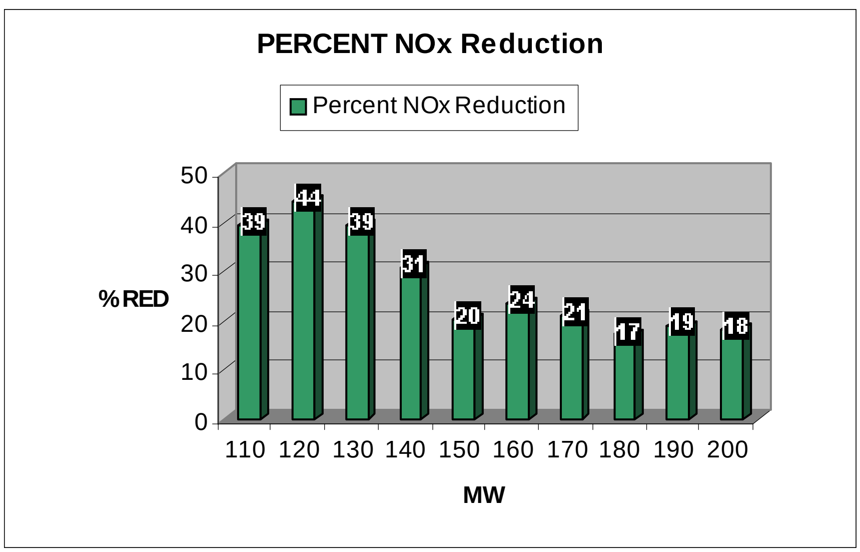


Figure 7
Percentage NOx reductions from year 2002 to 2003

Unit Performance Optimization

The C.P. Crane Unit #2 NO_x optimization neural network models were executed from May through September of 2003 in the utility's ozone season with the primary objective of NO_x reduction. To further increase the competitiveness of the units, the neural network models are now executed during the non-ozone season with the primary objective of increasing unit efficiency by optimizing the combustion process which directly affects the overall performance of the units. This part of the project required additional parametric testing to determine the combustion process parameters that could be manipulated to maximize unit performance and updating of the neural network models with the non-ozone season data set. The parametric testing was completed in October 2003 and the updated neural network models were placed in service in November. The following provides a preliminary report of the development and performance of the unit optimization neural network models.

Unit Performance Analysis

The first step in developing a neural network model that will improve unit performance of a cyclone boiler is to perform an analysis of the current performance of the unit to determine which combustion parameters can be controlled to improve the performance of the unit. Some of the typical parameters at any power plant that may be manipulated to improve the unit performance include the following:

Steam Temperature Attemporation Sprays – The use of steam temperature attemporation sprays is normally a direct loss to unit performance. Ideally, the DCS control system would be developed such that steam temperatures, both superheat and reheat, would be controlled exactly to the design conditions and no sprays would be required. However, this is normally not the case and sprays are required to control temperature excursions. By minimizing the use of sprays, the impact on the unit heat rate will also be minimized.

Combustion Air – The amount of combustion air supplied to the combustion process has a significant impact on the overall performance of the unit. Normally, an excess air curve is developed in the DCS control system and this curve is utilized to "trim" the amount of air supplied to the combustion process to the desired amount. The amount of air supplied can affect several other performance-related parameters in various ways as illustrated in the following examples:

> **Steam temperatures** - The steam temperatures that result from the combustion process can be influenced by adjusting the amount of air supplied to the combustion process. In some cases, typically at lower loads, a power plant may not be able to make the desired steam temperatures for that load. By adjusting the amount of air supplied to

the boiler (slightly increasing it), improvement in low steam temperatures can be achieved. The resulting improvement in unit performance can offset the penalty for increased air supply to the combustion process.

Loss on Ignition – The amount of air supplied to the combustion process directly affects the "loss on ignition" that results from the combustion process. The "loss on ignition", or LOI, is the amount of uncombusted carbon present in the fly-ash produced by the combustion process. The LOI is a direct penalty to the heat rate performance of the unit. By adjusting the amount of air supplied to the combustion process at various loads, the LOI can be reduced, thus improving the units' performance.

Sootblowing – Sootblowing is normally required to remove the soot buildup on the various sections of the boiler that directly affects the heat transfer capabilities of the boiler and thus the performance of the unit. The sootblowing system can be utilized in multiple ways to affect unit performance. When sootblowing is initialized, steam temperatures can be affected in various ways that impact unit performance. Parametric testing can be utilized to determine the impacts of sootblowing on steam temperature. The data collected can be utilized in the neural network models to make slight adjustments in the combustion process to anticipate and prevent major steam temperature excursions during sootblowing, thus improving unit performance.

Gas Recirculation Fans – Some cyclone boilers are equipped with gas recirculation fans, which take exhaust gas from the boiler and reinject it into the combustion process in the boiler. There are normally injection ports at two elevations for this gas. The port at the lower elevation is normally used to increase steam temperatures (especially reheat temperature) by "blanketing" the waterwalls of the boiler with the exhaust gas reducing heat influx and allowing more of the heat of combustion to enter the upper portions of the boiler. This can quickly improve steam temperatures. The port at the upper elevation is commonly know as "tempering" gas and can be utilized to decrease average gas temperatures entering the superheater section which reduces heat transfer and steam temperatures, thus preventing temperature excursions. The amount of flue gas supplied to these ports is normally controlled by the DCS and slight adjustments by a neural network model can be utilized to improve steam temperature performance, which will improve overall unit performance.

Backpass Dampers – Some cyclone boilers are equipped with dampers located in the backpass of the boiler. These dampers can be utilized to influence the path that the combustion flue gas takes as it goes through the backpass of the boiler. These dampers affectively change the surface area of the boiler that is exposed to the combustion gas and are normally used to increase reheat temperatures at low load operation of the boiler. The DCS normally has base control of the position of these dampers. Slight adjustments to the position of these dampers by a neural network model can be utilized to improve steam temperature performance, which will improve overall unit performance.

Firing Rate/Feedwater Ratio – "Once-thru" cyclone boilers are without a steam drum and the feedwater is converted directly to steam in the combustion process. These types of boilers normally have a firing-rate to feedwater ratio PID controller in the DCS used to control steam temperatures. This ratio is used to bias the amount of fuel and feedwater, which supplied to the combustion process to maintain throttle pressure and steam temperatures. Slight adjustments to this ratio by a neural network model can improve steam temperature performance, which will improve overall unit performance and reduce the thermal stress generated by overfiring the boiler to respond to frequency control through MW regulation. Boiler waterwall temperature excursions are quite common in a "once-thru" design and adjustment of this ratio in anticipation of these excursions can either prevent the excursion or limit the temperature of the excursion. The overall affect of this is to reduce stress on the waterwalls and hopefully reducing the outage time required to repair tube leaks in the waterwalls.

C.P. Crane Unit 2 Performance Analysis

An analysis was made of the C.P. Crane Unit #2 to determine what parameters described above were available on this unit and which of these would have an impact on the unit performance. The following parameters were ruled out for various reasons:

Sootblowing – Although the unit has a sootblowing system, some of the blowers were in need of repair that required a major unit outage. Also, the DCS did not have significant information as to which blowers were active. Sootblowing was ruled out as a candidate for this project.

Gas Recirculation Fans – The unit was equipped with gas recirculation fans but the fans were retired several years ago due to extremely high maintenance issues.

Firing Rate/Feedwater Ratio – Unit #2 is a drum type boiler, thus this is not an option.

Backpass Dampers – The unit's backpass dampers were not operational at the time the optimization project was initiated. Currently, the repair of these dampers is being discussed and the dampers may play a role in future optimization.

The analysis of the performance of C.P. Crane Unit #2 found the following conditions:

Relatively High LOI – C.P. Crane Unit #2 is equipped with Cegrit samplers used to collect flue gas samples in the boiler. Samples taken showed that the unit had relatively high LOI numbers, especially at lower loads.

Sagging Steam Temperatures – Analysis showed that C.P. Crane #2 had difficulty making desired steam temperatures at lower loads. In some cases, these temperatures were off design by more than 100 degrees F. The lower temperatures directly affected unit performance. Contributing to these low temperatures at lower loads was the usage of over-fire air for NO_x reduction. Thus, at low loads, the choice was to increase temperatures by decreasing OFA and increasing NOx or vice versa.

Unit Load Ramp Overshoots – C.P. Crane Unit #2 is a load following unit often performs several ramps a day from 105 MW to 205 MW at ramp rates of 7 MW/min. The analysis showed that the unit suffered from overshoots on the fuel/air system during these ramps, which resulted in temperature excursions and overshoot of megawatts. These overshoots were traced to a problem with the DCS Load Demand Center(LDC) system and were compounded by delay in the activation of the attemporation sprays to prevent temperature excursions.

Based on the performance analysis of C.P. Crane Unit #2, the following parameters were selected to be used in the neural network models to increase the unit performance.

Combustion Air – The objective in choosing this parameter was to manipulate the amount of combustion air supplied to the boiler to influence both steam temperatures and LOI. The parametric testing showed that at some loads, the amount of air might be increased by the neural network and at other loads it might be decreased.

Attemporation Sprays - This parameter was selected to manipulate the attemporation sprays to help eliminate overshoots on load ramps. The neural network would anticipate the temperature excursions and activate the sprays faster than the DCS controls.

Unit Performance Preliminary Results

Based on the information in the above paragraphs, parametric testing was executed and the neural network models were updated for the optimization parameters. Tests were conducted to determine the effectiveness of these models. The following are some preliminary results of the tests:

LOI – Tests were executed at three different loads to determine the affect of the neural network models on LOI for Unit #2. The tests were conducted in two-hour time frames with the neural network models off for one hour and active for one hour. The following table shows the results of these tests.

Load Range	LOI – Neural Net ON	LOI – Neural Net OFF
100 MW	14.00	40.00
150 MW	11.17	19.44
200 MW	5.88	6.6

Steam Temperatures – Tests were conducted to determine the affect of the neural network on the control of steam temperature. Figure #8 below shows a low-load test. As the unit settled at low load, the neural network gradually raised the steam temperatures, which were normally much below design. An improvement of 50-60 degrees F was seen, which equated to about a 0.5 - 0.6% improvement in overall unit performance.

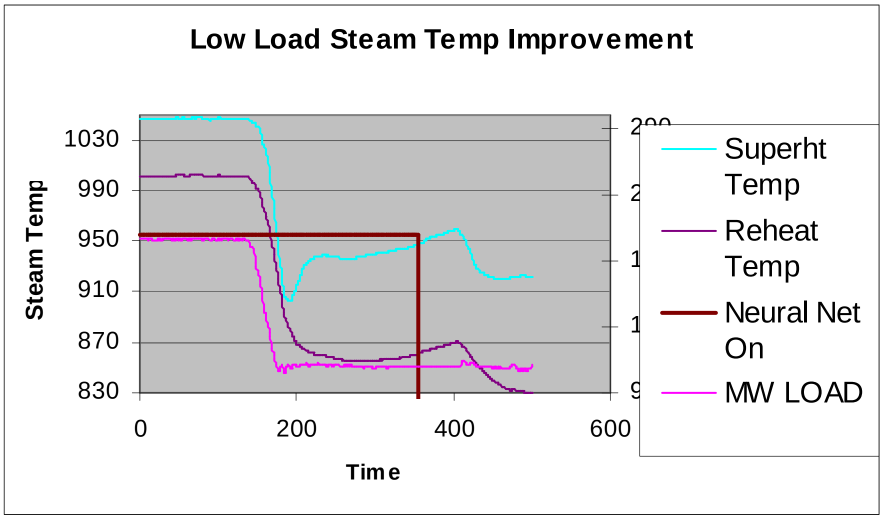


Figure 8: Low load steam temperature improvement

As the neural network was turned off, the chart shows the temperatures' gradual return to their lower values. A second test was executed at higher loads (near full load). Figure #9 below shows that steam temperatures were better maintained with the neural network on than off. When the neural network was off, temperatures oscillated and did not reach setpoint. With the neural network on, temperatures were much closer to setpoint and steadier.

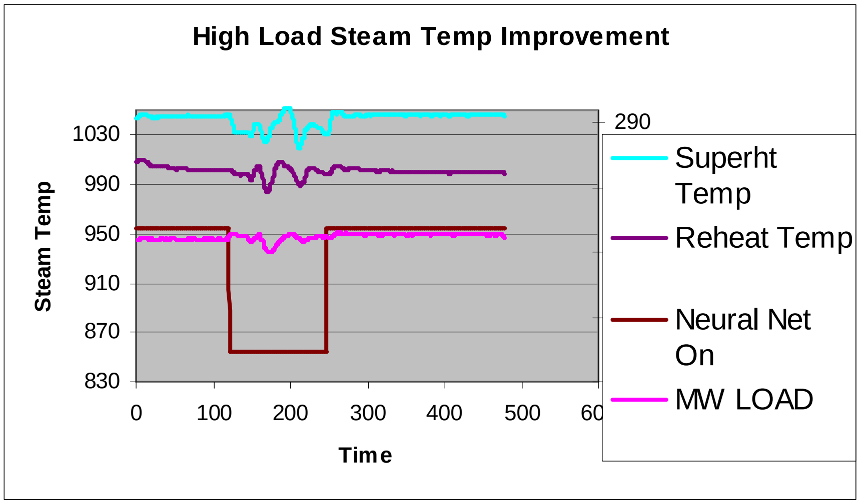


Figure 9:
High load steam temperature improvement

Conclusions

The Constellation Energy C.P. Crane Unit #2 boiler optimization project can be considered a success for the following reasons:

The project was designed, implemented, installed, and tested with very little disruption to the general operation of the unit other than scheduling the required loads for testing.

The NO_x optimization portion of the project has provided the utility with significant reduction in the NO_x emissions with a relatively small capitol investment that was recovered in the first five months of the project. This has allowed financial gains from several different aspects including the shifting of required NO_x credits to other units and lowering the units' power production costs, which has increased competitiveness in the dispatching system

The unit performance improvement also made the units more competitive in the dispatching system

As a by-product of the project, there were several items identified outside the direct scope of the neural network model, which are now being analyzed and once resolved will increase unit competitiveness even further.

- Monitor and control primary air flow indexed with load. This should help reduce LOI's at low loads and help reduce coal erosion of the cyclone metal thereby reducing boiler cyclone leaks.

- Restore the functionality of the backpass damper thus reducing the reheater temperature dip that occurs at low loads.

- Install an on-line Loss of Ignition (LOI) sensor to feed into the neural network to gain online and real time benefit of fuel firing efficiency.

As another by-product of the project, overall awareness of the impacts of operating parameters, emissions and unit performance on the future of the plant has been increased in all departments. The model clearly shows the benefits of effective operations.