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Big Bend Power Station Neural Network-Sootblower Optimization

A DOE Assessment

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EXECUTIVE SUMMARY

The Power Plant Improvement Initiative (PPII) is a follow-up to the U.S. Department of Energy's (DOE's) Clean Coal Technology Demonstration Program (CCTDP) whose purpose was to offer the energy marketplace more efficient, cost effective and/or environmentally benign coal-fired power production options by demonstrating these technologies in commercial settings. One of the projects selected under PPII was the Big Bend Power Station Neural Network-Sootblower Optimization project, sited at Tampa Electric Company's (TECO's) Big Bend Power Station Unit 2. Tampa Electric's Big Bend Unit 2 is a Riley Stoker single drum slagging radiant boiler having pressurized furnace operation. The cost of this project was $3.4 million, with DOE's share being 27 percent. This project was a full scale demonstration of the neural network intelligent sootblowing (NN-ISB) technology on a large commercial boiler.

The overall goal of this project was to develop a NN-ISB system that initiates sootblowing in response to real-time and model predictive events or conditions within the boiler rather than relying on general rule based protocols. Other goals were to increase unit efficiency, reduce NO_x, and improve stack opacity.

In a coal-fired boiler, the buildup of ash and soot on the boiler tubes can lead to a reduction in boiler efficiency. Thus, one of the most important boiler auxiliary operations is the cleaning of heat-absorbing surfaces. Ash and soot deposits are removed by a process known as sootblowing, which uses mechanical devices for on-line cleaning of fireside boiler ash and slag deposits on a periodic basis. Sootblowers direct a cleaning medium (steam, water, or air) through nozzles against the soot/ash accumulated on the heat transfer surfaces to remove the deposits and maintain heat transfer efficiency.

Sootblowing has an impact on plant efficiency because it either uses steam that would otherwise be used to generate electric power or requires energy for pumps or compressors. Therefore, it is desirable to keep sootblowing to a minimum. On the other hand, if sootblowing is not frequent enough, redistribution or reduction of heat transfer can occur within the furnace, which again can result in reduced efficiency. Thus, optimizing sootblower operation is important to maximize unit efficiency. Typically, sootblowers operate on a specified timed cycle or else operation is initiated by an operator who believes sootblowing is needed. The purpose of an intelligent sootblowing system is to decide when to sootblow based on information from boiler instruments. The objective is to sootblow when, and only when, necessary.

The NN-ISB system uses a neural network to model the characteristics of the boiler. Neural networks can recognize patterns in input data, but before the network can associate a particular pattern with a corresponding plant state, it must be "trained," using historical data. Once a network has been trained, it can respond very rapidly to new inputs.

In order for a NN-ISB system to function effectively, a properly designed and installed control system is essential. The control system installed at Big Bend included:

- Sixteen heat flux sensors.
- Eight slag sensors.
- A Heat Transfer Advisor.
- Acoustic pyrometers.
- Sootblower control system.
- On-line efficiency Performance Monitor (OPM).
- Advanced Calibration Monitor (ACM).

Unfortunately, many of these instruments did not perform as well as expected, which was a major contributor to not achieving the anticipated performance for the overall NN-ISB installation.

- Shortly after the installation of the heat flux sensors, failures were observed. Through the efforts of the sensor supplier and project team, performance was improved throughout the course of the project, but even at the end, performance was not satisfactory.

- Slag sensors were mounted in close proximity to the heat flux sensors. After completing testing, it was determined that no statistical correlation existed between the slag sensors and the heat flux sensors.
- Because results were not sufficiently sensitive or repeatable to be usable by other parts of the project, use of the Heat Transfer Advisor was discontinued in the middle of the project.
- The acoustic pyrometers initially provided reasonable data; however, over time they developed problems. Due to the unreliable nature of the system, output data were not used as model inputs.
- The OPM was designed to help provide information necessary to run a power plant more efficiently using data collected approximately every minute. Due to problems with the OPM (poor and unrepeatable outputs), it was replaced by another efficiency calculation (PERFIndex), an indication of boiler performance and controllable losses for a plant without a rigorous heat rate monitor.
- The ACM is a computerized calibration monitoring system with capabilities to automatically assess the health and validity of instrumentation. The station reported that the ACM was an extremely difficult product to use.
- Initially, water cannons were to be used to deslag the waterwall. However, numerous problems were experienced with the water cannons, and a detailed test conducted in July 2004 indicated that the water cannon system was not suitable for this project.

The automated closed loop activation of the sootblowers during this project showed that NN adaptive sootblowing can benefit efficiency. There was a clear improvement at low loads, with the benefit decreasing as the load increased. During closed loop operation of the NN-ISB, reported efficiency gains were in the range of 0.1 to 0.4 percentage points compared to baseline. Results with open-loop (changes made by the operators based on NN-ISB recommendations, not by the NN-ISB system directly) operation were slightly poorer. A factor in this efficiency benefit was a decrease in the steam used for sootblowing. With more operating experience, gains at the high end of the load range should also be achievable.

A goal of this project was to reduce NO_x emissions through use of the NN-ISB, and it is reasonable to believe that optimizing sootblowing would be beneficial for NO_x reduction because of an improved temperature profile in the furnace. However, the data presented in the final report do not clearly show this. Although there is a great deal of scatter in the data, NO_x ranges from about 0.45 lb/million Btu at a load of 150 MW to about 0.7 lb/million Btu at a load of 450 MW. Although NN-ISB closed-loop operation is clearly better than open-loop operation, still the closed-loop data generally fall in about the same range as the baseline data.

These results are, perhaps, not unexpected, since the program originally included the use of water cannons, which experienced problems, so that the water cannons were not available during the NN-ISB tests. Water cannon problems were exacerbated because of the pressurized furnace configuration. Ideally, the water cannons would have provided cleaning and deslagging of the furnace, while concurrently optimizing heat rate. Due to the unavailability of the water cannons, the unit suffered excessive waterwall slagging, leading to higher temperatures in the combustion zone and, hence, higher levels of thermal NO_x formation. In addition, as indicated above, much of the instrumentation installed for the project did not perform up to expectations. In a system with fully functioning instrumentation and equipment, the results would be better.

Improving stack opacity was another project objective. Electrostatic precipitator (ESP) operation is sensitive to rapid changes in inlet mass concentration and total mass loading. Excessive soot removal can overload the ESP and lead to inadequate capture of particulate matter (PM), resulting in increased PM emissions. Results clearly show an improvement of 1 to 1.5 percent in opacity for closed-loop compared to open-loop operation over the entire range of sootblower steam flows.

Prior to this project, sensors and controls related to sootblowing were usually treated as isolated systems that were not fully integrated with any type of comprehensive goal in mind. What this project evaluated was a NN-ISB system that has the ability to understand, evaluate and optimize the process as an entire system with multiple, real-time objectives. Integration of the sensors went well, and communication was established to the neural network system with all sensors and elements of the project. The project proved that such systems can be linked together despite the use of proprietary networks. Further, it proved that the sensors can provide data that can be correlated and achieve a set of objectives. However, the lack of some anticipated inputs to the model limited the capabilities of the NN system to model the system as accurately as hoped and resulted in the project not fully achieving all its goals. The NN-ISB system appears to have worked well and undoubtedly improved boiler operation.

In addition to the main benefits, the following secondary benefits were observed:

- Total sootblower steam usage was lower with the optimization system engaged.
- Full integration of new sensor technology and optimization was completed.
- The operators stated that boiler drum and pressure operation was qualitatively improved.
- Steam tube temperatures benefited and showed less deviation at high loads.

There are two major potential savings from installation of a NN-ISB system. The first is a reduction in coal usage as a result of an efficiency gain. If the coal burned in Unit No. 2 cost \$40/ton, an efficiency improvement of 1 percent would decrease coal consumption by 10,000 tons/yr for a savings of \$400,000/yr. The other potential savings is in the area of NO_x reduction, which can be quantified by using the value of a NO_x allowance on the trading market. The NO_x emitted from Big Bend Unit No. 2 is estimated to be 7,000 tons/yr (0.6 lb/10^6 Btu). A 5 percent reduction in NO_x emissions would eliminate 350 tons/yr of NO_x, which, assuming that the NO_x cap and trade program is available at the plant and that the value of a NO_x allowance is \$2,000/ton, would amount to an annual revenue stream of \$700,000. Pegasus estimates that the cost of installing a NN-ISB system at a plant is in the range of $300,000 to $500,000, provided that no additional equipment or instrumentation is required. Considering only benefits from efficiency gains and NO_x reduction, the project would pay off in five to nine months. Any additional benefits from improved performance or reduced maintenance would decrease this payout period, and any additional costs would lengthen the payoff period.

The major conclusion from this project is that NN-ISB is a sound idea with significant potential, but it may take an additional project with improved equipment and instrumentation to fully quantify all the benefits. This project did successfully demonstrate NN closed-loop operation without causing unit upsets or violating any constraints and with operator acceptance.

I. INTRODUCTION

The Power Plant Improvement Initiative (PPII) is a follow-up to the U.S. Department of Energy's (DOE's) Clean Coal Technology Demonstration Program (CCTDP) that was successfully implemented in the 1980s and 1990s. The purpose of the CCTDP was to offer the energy marketplace more efficient and environmentally benign coal-fired power production options by demonstrating these technologies in commercial settings.

On October 11, 2000, the PPII was established under U.S. Public Law 106-291 for the commercial scale demonstration of technologies to ensure a reliable supply of energy from the Nation's existing and new electric generating facilities. Congress directed that PPII was to "demonstrate advanced coal-based technologies applicable to existing and new power plants… The managers expect that there will be at least a 50 percent industry cost share for each of these projects and that the program will focus on technology that can be commercialized over the next few years. Such demonstrations must advance the efficiency, environmental controls and cost-competitiveness of coal-fired capacity well beyond that which is in operation now or has been operated to date."

To fund the PPII, $95 million in previously appropriated funds were transferred from the U.S. Department of Energy's CCTDP. The PPII program solicitation was issued on February 6, 2001, and 24 applications were received. On September 26, 2001, eight applications were selected for negotiation of a cooperative agreement. One of the projects selected was the Big Bend Power Station Neural Network-Sootblower Optimization project, sited at Tampa Electric Company's (TECO's) Big Bend Power Station Unit 2. The objective of this project was to demonstrate the use of a neural network to optimize sootblower operation on a large commercial boiler. The initial cost of this project was estimated at $2.4 million, with DOE's share being 38 percent. The final cost was $3.4 million with DOE's share being 27 percent. This document is a DOE post-project assessment (PPA) of the Big Bend Power Station Neural Network-Sootblower Optimization project.

II. Project/Process Description

A. Project Site

Tampa Electric Company's Big Bend Power Station is situated on a nearly 1,500 acre site on Tampa Bay in Hillsborough County, Florida, close to Apollo Beach. Big Bend Power Station consists of four coal-fired units with a combined output of about 1,800 MW plus three combustion turbines which bring the total capacity to about 2,000 MW. The first coal-fired unit began operations in 1970; the second in 1973; the third in 1976; and the fourth in 1985. Three boilers are 445 MW Riley Turbo® opposed wall-fired, wet-bottom units, and one is a 486 MW Combustion Engineering tangentially fired coal unit. Unit 2, on which the sootblowing project is installed, is a Riley Stoker single drum radiant boiler having pressurized furnace operation, designed to serve a single turbine generator. The boiler is designed for a safe drum operating pressure of 2,875 psig and can produce 2,868,000 lb/hr of steam continuously at 2,600 psig and 1,000°F at the superheater outlet when supplied with feedwater at 487°F at the economizer inlet. The steam outlet temperatures of the superheater and high temperature reheater are both 1,000°F, and the pressures are 2,600 psig and 552 psig, respectively. The boiler is fired with bituminous coal and has a total of 48 coal nozzles on a single elevation, 24 on each side firing toward the center line of the furnace.

This project was a full scale demonstration of the neural network intelligent sootblowing (NN-ISB) technology. The NN-ISB technology was supplied and installed by Pegasus Technologies, Inc. Unit 2 has experienced many of the problems common to pulverized coal-fired units, including unplanned outages, tube leaks, weather related incidents, steam pressure adjustments, situational unit deratings, fuel condition changes, such as wet fuel days, equipment outages, and normal wear. This makes Big Bend Unit 2 a typical example of a U.S. utility boiler.

B. Project Description

The project was divided into three phases:

Phase I	Preliminary engineering
Phase II	Procurement and installation of major components and model development
Phase III	Model tuning, optimization, and demonstration of benefits

1. Phase I

The first task of Phase I was to determine whether Big Bend Unit 1 or 2 should be the demonstration unit; based upon a variety of factors, Big Bend Unit 2 was selected. A detailed and thorough review of the unit's equipment and instrumentation was conducted to define the work required to implement the project. Specific equipment was purchased and installed to permit an accurate and complete documentation of unit performance. Performance monitors were installed that collected data continuously to record changes which occurred during the course of the project. Preliminary engineering, along with material specifications for other necessary equipment, was also performed during this phase.

A third party efficiency program was installed. To facilitate reporting and comparison of baseline versus post-retrofit runtime results, the PERFIndex (Performance Efficiency Index) calculation was performed on both baseline and post-retrofit runtime data. The PERFIndex calculation is an automated calculation with results expressed in the same units as heat rate (Btu/kWh). It follows the ASME Performance Test Codes PTC 4-1988 while also including the auxiliary power, superheat and reheat steam temperatures, and spray flow loss calculations.

Baseline values for NO_x, efficiency, opacity, and operational information were taken over a longer period of time than originally planned so that data could be correctly compared to the optimization results of the NN-ISB system. The data collected post-optimization could then be compared to “as-found” conditions to allow detailed analyses to determine actual benefits from this technology.

2. Phase II

Phase II included procurement of the balance of the hardware and equipment necessary to assess the performance of the NN-ISB system. Also accomplished was the detailed software engineering necessary for building of the neural network model. Specifically, the sootblowing hardware was installed during this period. The neural network software model was built through testing of sootblowing patterns to determine optimum patterns to maximize benefits. This testing was performed by combustion experts, with the help of the TECO station personnel, who possess unique knowledge about the operation of the Unit 2 boiler. Boiler characterization information was automatically collected through an interface to the digital control system (DCS) by the neural network software installed on the Pegasus computer.

After the boiler characterization tests were completed, the information was used to build the model and define operating constraints associated with boiler operation. A significant advance in sootblowing testing was conceived, programmed, and tested during this phase. These tests were programmed to be controlled by the installed NN-ISB system to ensure that correct DCS and programmable logic controller (PLC) interfaces had been achieved, to more closely simulate the final interfaces, and to give more precision to the time stamping of the tests. This aided early operator acceptance of the technology by helping them carry out the required tests.

Software and equipment were properly and successfully installed. Limited testing was performed on this equipment during this task to ensure that it operated properly with the other systems. Communication and data needs were identified between the sensors and systems.

Pegasus was primarily responsible for development of the model to control sootblowing, with identification of unit constraints and tradeoffs by TECO personnel. This was a significant work effort and was accomplished after the results of the parametric testing had been completed. After the model was constructed, a series of tests was performed to ensure the correct variables that affect emissions and efficiency via operation of the sootblowers and combustion optimization system (COS) had been identified and prioritized within the model. Constraints within the NN-ISB system were also reviewed by TECO to ensure protection of equipment.

3. Phase III

Baseline data were collected to enable evaluation of the success of this project. Some of the variables evaluated included auxiliary power consumption, air heater inlet temperature, frequency of sootblower usage, attemperator steam use, visual fouling, overall system efficiency and reliability, and human factors, such as operator acceptance.

After verification that the core elements of the NN-ISB system were satisfactorily installed and operational, detailed model tuning began. During this task, the unit was operated at a variety of conditions, including some non-ideal variations. This helped to define acceptable operating limits and constraints that the NN uses while optimizing the system. This was a joint effort of the Pegasus and TECO teams.

During system optimization, necessary adjustments were made. This allowed the system to "learn" and make recommendations on unit operation. This task consisted of both advisory (open-loop) and closed-loop operation. The advisory mode provided recommendations to the operators and engineers, who used those results to further tune the system. This activity also proved very valuable in assessing and chronicling the performance and status of the new sensors and systems.

C. Project Goals

The overall goal of this project was to develop a NN-ISB system that initiates sootblowing in response to real-time events or conditions within the boiler rather than relying on general rule based protocols. Specific goals were to increase unit efficiency by 2 percent, reduce NO_x by 30 percent, and improve stack opacity. These goals were to be accomplished by minimizing tube erosion, minimizing auxiliary power requirements, smoothing extraction steam flow, minimizing sootblowing steam consumption, and reducing maintenance expenses. Other goals, stated in the original proposal, included promoting the use of coal, enabling the rapid deployment of the technology into the market, and expanding U.S. revenues through worldwide market acceptance.

D. Technology Description

This section discusses the technology involved in implementing the NN-ISB system.

1. Sootblowing Operations

In a coal-fired boiler, the buildup of ash and soot on the boiler tubes can lead to a reduction in boiler efficiency. Thus, one of the most important boiler auxiliary operations is the on-line, fireside cleaning of heat-absorbing surfaces. Not only is it important for proper heat transfer, but also to prevent sections of the boiler from becoming severely plugged. Plugged sections can restrict gas flow and cause load limitations. Tube erosion due to high local velocities can also occur.

Ash and soot deposits are removed by a process known as sootblowing. Sootblowers are mechanical devices used for on-line cleaning of fireside boiler ash and slag deposits on a periodic basis. They direct a cleaning medium through nozzles against the soot/ash accumulated on the heat transfer surfaces of a boiler to remove the deposits and maintain heat transfer efficiency. The type of sootblower used in an application varies with the location in the boiler, the cleaning coverage required, and the severity of the deposit accumulation. Sootblowers basically consist of (1) a tube or lance which is inserted into the boiler and carries the cleaning medium, (2) nozzles in the tip of the lance to accelerate and direct the cleaning medium, (3) a mechanical system to insert or rotate the lance, and (4) a control system.

The cleaning media used in sootblowers may be saturated steam, superheated steam, compressed air, or high pressure water. In most cases, superheated steam is the preferred cleaning medium because field experience indicates that moisture in saturated steam can cause erosion of tube surfaces. Superheated steam has a greater cleaning potential than saturated steam on an equal mass basis, due partially to the higher sonic velocity through the sootblower nozzles. This increase in sonic velocity more than offsets the loss of jet energy due to the lower density. Typical sootblower pressure is between 70 and 350 psig.

On larger boilers, compressed air is often used as the cleaning medium. The choice between air and steam is based on an economic analysis of operating and technical issues. Some of these are:

- Steam sootblowers must be designed to permit warm-up of system piping, removal of condensate from the piping, and protection from freezing, corrosion, and erosion. Availability of makeup water to replace that in the steam used must also be considered.
- Steam sootblowers typically require more maintenance, but this disadvantage may be offset by the need for compressor maintenance when air is used.
- Increasing the capacity of a steam system is usually easier than increasing the capacity of an air system.
- Air systems require higher flow rates to cool long retractable blowers because of the better heat transfer characteristics of steam.

For certain high temperature ranges in which the deposit is plastic or strongly sinters to the tube (some Western low-sulfur coals), neither steam nor air is effective and water is required as the cleaning medium.

Sootblowing has an impact on plant efficiency because it uses steam that would otherwise be used to generate electric power or else it requires energy for pumps or compressors. Therefore, it is desirable to keep sootblowing to a minimum. On the other hand, if sootblowing is not frequent enough, redistribution or reduction of heat transfer can occur within the furnace, which again can result in reduced efficiency. Thus, optimizing sootblower operation is important to maximize unit efficiency, and a reliable and flexible sootblower control system is essential to obtain optimal boiler performance. Typically, sootblowers operate on a specified timed cycle or else operation is initiated by an operator who, based on his observations and experience, believes sootblowing is needed. The purpose of an intelligent sootblowing system is to decide when to sootblow based on information from boiler instruments rather than using a timed cycle or operator experience. The objective is to sootblow when, and only when, necessary.

2. Water Cannons

Water cannons were chosen for this project because it was felt they would be most effective in cleaning the waterwall in the furnace. A water cannon directs a water jet across the furnace box, where it impinges on and removes slag from the opposite wall. Operating water pressure is typically 175 psi. The water cannon is mounted at an opening in the boiler wall that typically allows 90 degrees horizontal and 60 to 90 degrees vertical traverse; this allows a single cannon to cover a very large wall area. Cleaning is performed by sweeping the water jet across the boiler wall. Penetration of water into the outer slag layer and its subsequent expansion into steam is believed to be the primary mechanism of slag removal, although thermal shock may also play a role.

It was intended to use water cannons to meet the demanding requirements for selective sootblowing in the furnace, and the cannons and water booster pumps were installed.

The cannons were mounted with Carden joints which allowed them to pivot and direct their water lances to a distance of up to one hundred feet. Connection to the neural network was completed during the project, but mechanical failure of the mounted system occurred, which prevented verifying their application (see Section III.A.2).

3. Neural Network

The NN-ISB system, installed in this project, uses a neural network to model the characteristics of the boiler. Neural networks can have many forms. In one of the more common forms, a neural network (computer code that models a system's responses) consists of three layers: an input layer, a hidden layer, and an output layer. The input layer receives signals from the monitored variables and transmits them to the hidden layer, which contains interconnected neurons for pattern recognition. After processing, signals are sent to the output layer, which outputs recommended settings for control variables. Thus, a neural network is, in effect, a sophisticated curve fitting tool.

Neural networks can recognize patterns in input data, but before the network can associate a particular pattern with a corresponding plant state, it must be "trained." The training phase can be time consuming and usually involves feeding historical data into the program. However, once a network has been trained, it can respond very rapidly to new inputs. An advantage of a neural network is that, if any inputs are faulty, prediction capability degrades only gradually compared to most other modeling techniques.

Major components of the neural network installed for this project include an executive for coordinating all tasks associated with NN-ISB and an optimizer that determines the optimum heat distribution based on the objective functions. The innovative information analyzer normalizes the different factors in the objective list into a quantity that can be used by the optimizer. A model is included which projects the rate of soot buildup. The system includes a process for generating and maintaining the constraints of the system, both physical (e.g., only two sootblowers can be in operation at any given time) and operational (e.g., maintaining the reheat temperature or minimizing thermal transients).

4. Control System Components

In order for the NN-ISB system to function effectively, a properly designed and installed control system is essential. The control system installed at the Big Bend Power Station included the following:

- Sixteen heat flux sensors installed at appropriate locations, four on each furnace wall. Because of the relatively low slagging conditions in the upper furnace, heat flux sensors were selected to provide an indication of the level of ash buildup. Heat flux is determined by the difference in temperature across a thickness of material of known thermal conductivity (see Section III.A.1.a).
- Eight slag sensors were mounted at appropriate locations, two on each lower furnace wall. The sensors were designed to detect slag by measuring its electrical conductivity, since slag has a significantly different conductivity from ash (see Section III.A.1.b).
- A heat transfer advisor was developed. This was a software tool for determining the enthalpy changes within each boiler heat transfer section, based on steam temperatures and pressures provided by the DCS on a zone by zone basis (see Section III.A.1.c).
- Acoustic pyrometers were used to measure the temperature at two planes within the furnace, one at the traditional furnace exit and the other at a plane between the primary superheat tubes and the economizer. Acoustic pyrometers operate on the principle that the speed of sound through a medium is proportional to the temperature of the medium (see Section III.A.1.d).
- The sootblower control system was mounted in the existing control cabinet. This control system provides integrated, state-of-the-art sootblower control and a bi-directional link between the actual sequencing panel and the DCS. This allows information related to sootblower execution to be data logged and transmitted for neural network analysis, transmitted to other devices for interactive optimization, and received from the NN-ISB.

- The on-line efficiency performance monitor (OPM) is a series of computer software tools designed to help provide information necessary to run the power plant more efficiently. Data is received from the DCS and other sources about once per minute and smoothed. Validated data are sent to the performance calculation and results are logged and graphically displayed (see Section III.A.1.e).
- Data validation was performed by the Advanced Calibration Monitor (ACM), a computerized calibration monitoring system with the capability to automatically assess the performance and validity of the instruments providing data to the NN-ISB system. The pattern recognition methodology embedded in the ACM monitors a system and makes judgments based on past experience by creating a mathematical model of the system from data representing past system performance (see Section III.A.1.g).
- The NN-ISB system was installed on a Sun workstation, which uses the Solaris operating system and development environment. The neural network functions with up to six processes running in parallel. For experimental reasons, the combustion optimizing system and ISB systems were initially installed on separate workstations, but later they were installed on the same workstation.

Figure 1 shows the communications layout at Big Bend Unit No. 2. The combustion optimizing system and ISB software are loaded on one computer. For this demonstration, the models were partitioned so that they could function separately or work interactively. This is important, since this approach permits upgrades to existing power plants, as well as application to new boilers. The demonstration was carried out on a unit with the hardware and software systems described below; however, the equipment, including the DCS, could be from any manufacturer, since communications can be adapted. The Pegasus computer is interfaced to the following systems at the plant:

- **WesStation:** This is a TCP/IP (Transmission Control Protocol/Internet Protocol) communication link which utilizes WesAPI (Application Programming Interface) to read input points from the Westinghouse Distributed Processing Family Digital

Control System (WDPF® DCS) for the combustion optimizing system (COS) and ISB neural nets. It writes out neural net biases and permissives to the WesStation and, hence, to the DCS for combustion optimization. This link was installed in January 2001.

- **PI Server**: This is a TCP/IP communication link which utilizes the PI API to read heat rate and other associated inputs for the ISB software. This link was installed in the spring of 2003.
- **Solvera Sootblowing System**: This communication link utilizes the OPC standard and reads the current state of the sootblowers for input into the ISB neural net. The neural net then determines which groups of sootblowers to use and writes these results back into the Solvera System. This link was installed in the spring of 2003.
- **Advanced Calibration Monitor**: The ACM software, produced by Performance Consulting Services, allows the plant to monitor the condition of sensors throughout the plant. The ACM software indicates which sensors are failing, allowing service technicians to easily locate bad sensors. The ACM software runs on a PC card located inside the Pegasus computer. Plant technicians can view the ACM data remotely via a web-based interface.
- **Sensors:** All the sensors in the project were connected to the DCS as their main input host. From there the information was disseminated through the communications architecture.

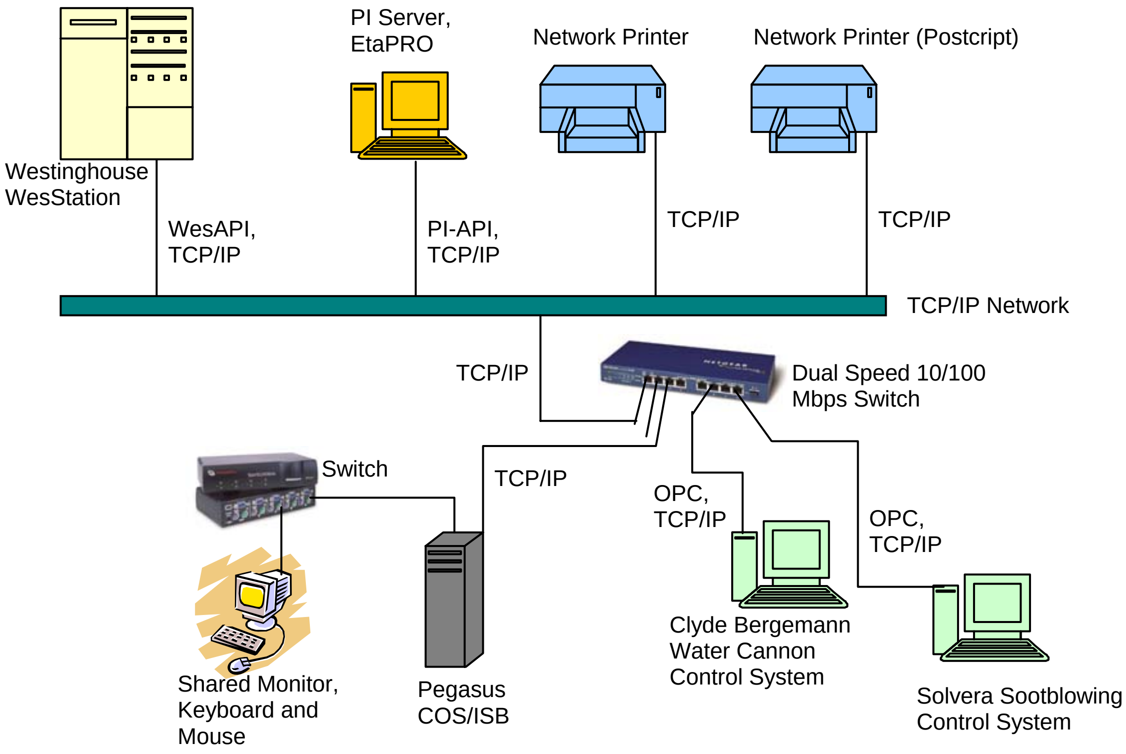

Figure 1. Communications Layout at Big Bend Unit No. 2

5. NO_x Formation

Most of the NO_x formed during the combustion process is the result of two oxidation mechanisms: (1) reaction of nitrogen in the combustion air with excess oxygen at elevated temperatures, referred to as thermal NO_x; and (2) oxidation of nitrogen that is chemically bound in the coal, referred to as fuel NO_x. For coal-fired units, thermal NO_x generally represents about 25 percent and fuel NO_x about 75 percent of the total NO_x formed. In addition, minor amounts of NO_x are formed through complex interactions of molecular nitrogen with hydrocarbons in an early phase of the flame front; this is referred to as prompt NO_x. The quantity of NO_x formed depends primarily on the “three t’s” of combustion: temperature, time, and turbulence. In other words, flame temperature, the residence time of the fuel/air mixture, and mixing, along with the nitrogen content of the coal and the quantity of excess air used for combustion, determine NO_x levels in the flue gas.

Reduction of NO_x was one of the primary objectives of this project. There is some uncertainty as to the mechanism of NO_x reduction as a result of NN-ISB operation, but it is probably due to changes in the temperature profile in the boiler. NO_x formation takes place in certain temperature ranges. Altering the cleaning of various boiler sections causes changes in the temperature profile in the furnace. With clean tubes, flue gas temperature will be lower at the top of the furnace, thus reducing the time at NO_x formation temperature and reducing NO_x. With fouled tubes, temperatures can still be high enough in the pendant and upper pass region of the boiler for thermal NO_x formation. The degree of NO_x reduction benefit from sootblowing is dependent on unit conditions, load transitions, gas flows, and unit physical and sootblowing parameters.

6. Electrostatic Precipitator (ESP) Operation

An ESP unit consists of a series of parallel vertical plates through which the flue gas passes. Centered between the plates are charging electrodes which provide an electric field. The collecting plates are typically electrically grounded and are the positive electrode components. The discharge electrodes in the flue gas stream are connected to a high voltage power source with a negative polarity. An electric field is established between the discharge electrodes and the collecting surface. As the flue gas passes through the electric field, particles in the gas take on a negative charge. As these negatively charged particles are attracted toward the grounded collection plates, they migrate across the gas flow.

Gas velocity between the plates is an important factor in the collection process since lower velocities permit more time for the charged particles to move to the collection plates and reduce the likelihood of re-entrainment. The ash particles form an ash layer as they accumulate on the collection plates. Particles remain on the collection surface due to the forces from the electric field, as well as the molecular and mechanical cohesive forces between particles.

To remove the ash layer, the collection surfaces are periodically rapped, which consists of suddenly striking the collection surface. Because particles tend to agglomerate, the ash layer is removed in sheets. This sheeting is important to prevent the re-entrainment of particles into the flue gas stream. The dislodged particles fall from the collection surface into hoppers where they remain until removed for disposal. Sootblowing increases the particle loading in the flue gas and can overwhelm the ESP, thus leading to an opacity excursion.

III. REVIEW OF TECHNICAL AND ENVIRONMENTAL PERFORMANCE

A. Technical Performance

This section discusses the performance of the neural network system installed at the Big Bend Power Station.

1. Instrument Performance

Many of the instruments did not perform as well as expected, which was a major contributor to the reduced performance for the overall NN-ISB installation. Performance of the various instrument packages that formed a part of the Big Bend project is discussed below.

a. Heat Flux Sensors

Shortly after the installation of these sensors in December 2002, failures were observed. The sensors included a redundant pair of thermocouples, so the backup set was used. However, these also failed within a short time. An investigation determined that sulfide attack was corroding the thermocouple leads. Another partial set of heat flux sensors was supplied and installed according to the supplier's recommendations; but these sensors, as well as the remaining original sensors, also failed after a short time. After further investigation, the manufacturer stated that they would use an alternative welding procedure during manufacture. A complete set of replacement sensors was supplied and installed. Although some of these sensors also failed over time, failures were not as pronounced as for the original set of sensors, and some lasted through the project.

b. Slag Sensors

Eight slag sensors were provided by Solvera/Stock Equipment and were mounted in close proximity to the heat flux sensors for evaluation. After completing testing, it was determined that no statistical correlation existed between the slag sensors and the heat flux sensors. Slag sensors represent a relatively new technology, and measurements during the project as to their effectiveness were inconclusive.

c. Heat Transfer Advisor

General Physics provided their EtaPro 8 software tool for determination of enthalpy changes within each boiler heat transfer section. Because results were not sufficiently sensitive or repeatable to be usable by other parts of the project, use of this tool was discontinued in the middle of the project.

d. Acoustic Pyrometers

The acoustic pyrometers initially provided reasonable data; however, over time they developed problems. Two sound generators were provided at each plane along with several receivers. Because Unit 2 is pressurized, each device was fitted with combination cooling and sealing air. Over the course of several months after installation, both receiver and sound generator failures were observed. In general, the receivers suffered from corrosion and high heat attack. The sound generators had problems with the amplification system that was originally provided without an oil lubrication system, which was supplied near the end of the project. Failures were also observed with the rubber hose connection that allowed the pulse of air to enter the boiler. Due to the unreliable nature of the system, output data were not used as a model input.

e. On-Line Efficiency Performance Monitor

The General Physics EtaPro 8 software package included an OPM designed to help provide information necessary to run a power plant more efficiently. Data were collected approximately once per minute from the DCS. Due to some scheduling issues and problems (poor and unrepeatable outputs) with the OPM, this system was not used.

Instead, another efficiency calculation (PERFIndex) that was in place when the model building occurred was used.

f. PERFIndex

It is not uncommon for a plant to lack some of the data necessary to calculate the unit heat rate, the number of Btu's of fuel energy required to generate one kWh of electric power. For example, units may not have all the instrumentation necessary for a rigorous heat rate calculation, or operator inputs for fuel related variables, meteorological data, and similar variables may be entered only sporadically or not at all. Furthermore, the calculated performance variable may be so noisy that the effects of control variables are lost in the noise. To achieve the desired benefit, the optimization software requires a repeatable value to represent unit performance. The Pegasus Efficiency ReFerence Index (PERFIndex) is a variable available as an indication of boiler performance for plants without a rigorous heat rate monitoring program.

Data resolution is important for enhancing online heat rate calculations. A reasonable goal is to improve heat rate by 0.25 to 1 percentage points, but heat rate inputs are inherently very noisy. Typical noise levels, even at steady state boiler conditions, are ±2 percent which is greater than the amount of expected improvement. Thus, the signal to noise ratio presents a significant problem.

Using a sum of losses approach allows separation of the factors that an automated control system can influence from the mechanical and maintenance factors that the control system cannot influence. This reduces the number of high noise variables and makes improvements more observable. The PERFIndex is designed to minimize the impact of noise and to focus on the higher resolution components affected by combustion optimization, thus providing a reliable index for measuring improvements.

The PERFIndex is not meant to be a surrogate for heat rate or to be a calculation of absolute heat rate, but rather a special purpose calculation to provide a quantifiable number to show the improvement that the optimizer has achieved. By observing the PERFIndex and the individual components of its calculation, the user can easily determine which components most affect the result, where efficiency improvements have been made, and where further efficiency improvements can be made.

g. Data Validation

The ACM, supplied by PCS, is a computerized calibration monitoring system with capabilities for automatically assessing the health and validity of instrumentation. The data validation system had two intents: to help support data review and to detect potential instrument drift. The core element of this product is pattern recognition methodology.

ACM uses an advanced pattern recognition algorithm that looks at power plant data as interdependent numbers. Since the numbers are interdependent, it is assumed that each plant parameter has some impact on all other plant parameters, although certain parameters are more closely related than others. While all data points could be modeled in a single ACM model with very good prediction results, the uncertainty of calculations would increase. ACM uses the uncertainty calculation to determine the size of the dynamic error band (alarms) for each parameter; the lower the uncertainty, the tighter the error bands will be. By grouping the points into well-correlated data sets for sub-models, uncertainties can be reduced. The data were blocked into gas-side and steam-side models. ACM communicates with other system components both to obtain input values and to write output values. ACM also provides high and low sensor limits for each point.

Whereas Pegasus supported the use of ACM for data validation for real-time inputs into the NN-ISB, the station reported that it was an extremely difficult product to use and that it also provided invalid data since it did not have the capability to extrapolate, nor could it recognize bad data during the training process.

2. Water Cannons

The purpose of the water cannons was to minimize slag in the furnace and to optimize radiant heat absorption in the waterwalls. Due to the design of the Riley Turbo® furnace, which has high heat release, numerous problems were experienced with the water cannons. For pressurized furnace applications, sealing air is absolutely critical. The system failed on several occasions due to low or no sealing air, resulting in major damage to the water cannons and loss of sealing to the furnace, which required the unit to be taken off-line for repairs. Numerous failures of the variable speed drive systems led to frequent loss of the entire water cannon system.

During periods when the water cannon system and the heat flux sensors were both in operation, it was discovered that the system could not spray water across the width of the furnace. This was in part due to the firing configuration of the Riley units, which have a total of 48 coal nozzles on a single elevation, 24 on each side firing toward the center line of the furnace. In order for the water stream to reach the other side of the unit, it had to penetrate through the gas flux of all these burners. At low- to mid-load operation, the water jets had marginal success at accomplishing the task. However, at mid- to high-load operation the water jet was easily dispersed and vaporized. A detailed test conducted in July 2004 indicated that the water cannon system was not suitable for this program.

3. Data Selection

The baseline data period was from January 1, 2002, through December 31, 2002. Unit operating data from several different time spans were reviewed to identify data periods representing comparable unit operating conditions under both open-loop and closed-loop operation. The following factors were considered in selecting data for comparative analysis:

- Periods being compared should have similar unit operating conditions, such as power production level, fuel being burned, ambient weather conditions, manual settings, etc.
- Data periods with significant gaps in operating data should be excluded.
- Data periods in close time proximity for both modes of operation should be selected to help minimize the effect of seasonal variations.
- Data periods should include days of contiguous operation for each operating mode.
- An equal number of data records for each operating mode should be selected to allow for comparative frequency analysis.

Extensive data review and analysis resulted in the selection of two monitored datasets and an extended dataset. One of the first two datasets was for open-loop operation and the other was for closed-loop operation. The extended dataset was used to offset data loss from instrument malfunction in the open-loop set and to extend the opacity data. The data set for open-loop operation comprised the period from September 14, 2004, to September 17, 2004; and the data set for closed-loop operation comprised the period from September 29, 2004, to October 2, 2004. Each data set consisted of an identical number of data records with data values averaged over 15 minute time periods. In each dataset, there were short gaps (five in the open-loop data and three in the closed-loop data) of a few minutes with no data, caused by restarting the data acquisition system. The time gaps were short enough to have no appreciable impact on data quality.

4. Coal

The coal burned during the test periods was a blend of three types of coal: Standard H, which produces higher NO_x, and Standard L and Ziegler, both of which produce lower NO_x. Table 1 gives the composition of the coal blends that were burned.

Table 1. Coal Blends Burned During Test Periods

Period	Coal Burned, tons			
	Standard H	Standard L	Ziegler	Total
10/2-4/2004	7,479.34	2,005.10	2,064.56	11,549.00
9/13-17/2004	10,066.88*	1,598.91	4,933.08	16,598.87
9/28-10/2/2004	9,832.05	656.70	5511.25	16,000.00
Total	27,378.27	4,260.71	12,508.89	44,147.87
% of Total	62.02	9.65	28.33	100.00

*Includes 100.88 tons of Pittsburgh 8 coal

5. Efficiency

One of the effects of burning coal in utility boilers is the buildup of soot and slag on the heat transfer surfaces within the boiler. This adversely affects the rate at which steam generation occurs. Fouling of the boiler leads to poor efficiency due to the resistance to heat transfer of the built-up ash. If coverage of the tube surfaces were uniform, heat that would normally be transferred to the tubes would remain in the flue gas and exit to the stack without beneficial use. In other situations (which can be encountered in the case of wall tubes), preferential coating of key areas can help overall efficiency. Non-optimal cleaning or coating can create a loss in efficiency that translates into a higher consumption of fuel for an equivalent level of electric generation and more total emissions.

Adverse efficiency impacts arise from numerous factors including, but not limited to, incomplete combustion, unbalanced steam generation, excessive use of desuperheater sprays, and high exit gas temperatures. Traditional sootblowing schemes involve activating the blowers on fixed schedules that were developed for typical operating conditions and not for unusual conditions. The unit wide heat rate calculation was not available during the baseline or during part of the run time tests. To facilitate reporting and comparing data, the PERFIndex calculation was performed on both baseline and runtime data.

Efficiency improvement was one of the modeled goals for the Neural Network; NO_x reduction was another goal. The goals of the network can be weighted against one another. In all cases the results reported cover the same data period, when the goals were evenly weighted. Thus, a feature that could subsequently be tuned by the unit personnel would be to weight NN-ISB operation more to one priority over another, similar to operations directives given by a supervisor to the operators to pay particular attention to a certain operating aspect of the unit.

The automated closed-loop activation of the blowers during this project showed that NN adaptive sootblowing can benefit efficiency. Dry gas loss (i.e., heat in the dry gas exiting the stack) was reduced. Efficiency improvement was apparent mainly at the lower end of the load range. The project improvement for the ISB portion, not counting the reduction in SB steam flow, is shown in Figure 2. The linear regressions from the data for open- and closed-loop operations have been plotted against the baseline for easier comparison.

To the extent that PERFIndex reflects the true heat rate, Figure 2 shows a clear improvement (reduction) at low loads (about 420 Btu/kWh at a load of 120 MW), with the benefit decreasing as the load increases. With more operating experience, gains at the high end of the load range should also be achievable. During closed-loop operation of the NN-ISB, reported efficiency gains were in the range of 0.1 to 0.4 percentage points compared to baseline. Results with open-loop operation were slightly poorer. These results were for NN-ISB operation only without the NN-COS system engaged; results should be somewhat better when the COS is also in use. A factor in this efficiency benefit was a decrease in the steam used for sootblowing.

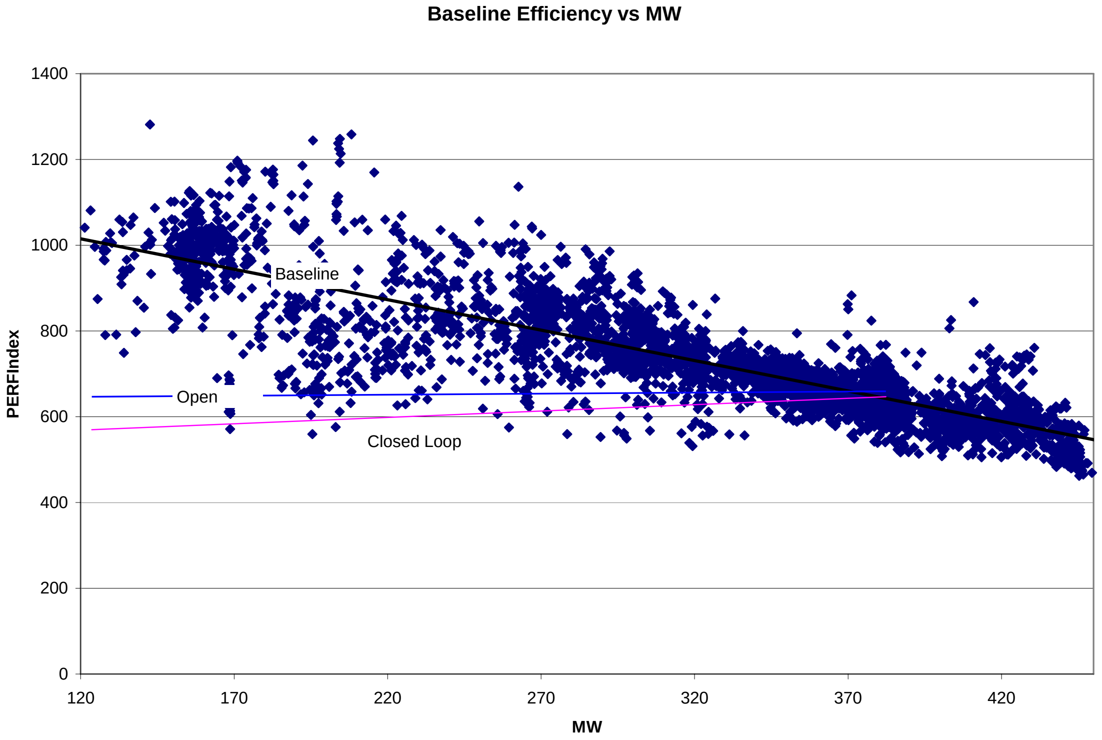

Figure 2. Efficiency (PERFIndex) as a Function of Boiler Load

B. Environmental Performance

1. NO_x Reduction

One of the goals of this project was to reduce NO_x emissions through use of the NN-ISB, and it is reasonable to believe that optimizing sootblowing would be beneficial for NO_x reduction because of an improved temperature profile in the furnace. However, the data presented in the final report do not clearly show this. Figure 3 presents baseline data as a function of unit load. Although there is a great deal of scatter in the data, NO_x ranges from about 0.45 lb/million Btu at a load of 150 MW to about 0.7 lb/million Btu at a load of 450 MW. Figure 4 presents data for NO_x rate with the NN-ISB system in operation. Although closed-loop operation is clearly better than open-loop operation, still the closed-loop data generally fall in about the same range as the baseline data. Thus, although ISB may well have valuable benefits, this project did not demonstrate a significant effect on NO_x.

These results are, perhaps, not unexpected, since the program originally included the use of water cannons, which, as explained in Section III.A.2, experienced problems and were not available during the NN-ISB tests. Ideally, the water cannons would have provided cleaning and deslagging of the furnace, while concurrently optimizing heat rate. Due to the unavailability of the water cannons, the unit suffered excessive waterwall slagging, leading to higher temperatures in the combustion zone and, hence, higher levels of thermal NO_x formation. In addition, as indicated above, much of the instrumentation installed for the project did not perform up to expectations. In a system with fully functioning instrumentation and equipment, the results may well be better.

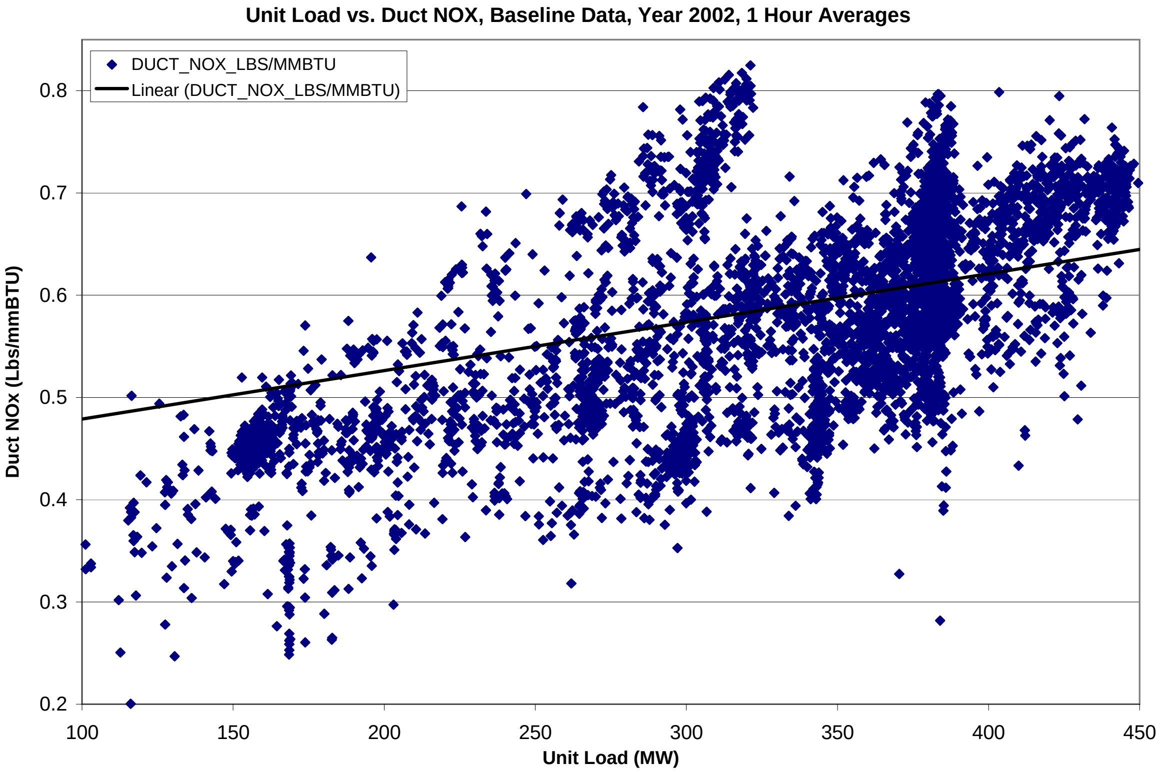

Figure 3. Duct NO_x as a Function of Unit-Load (Baseline Data)

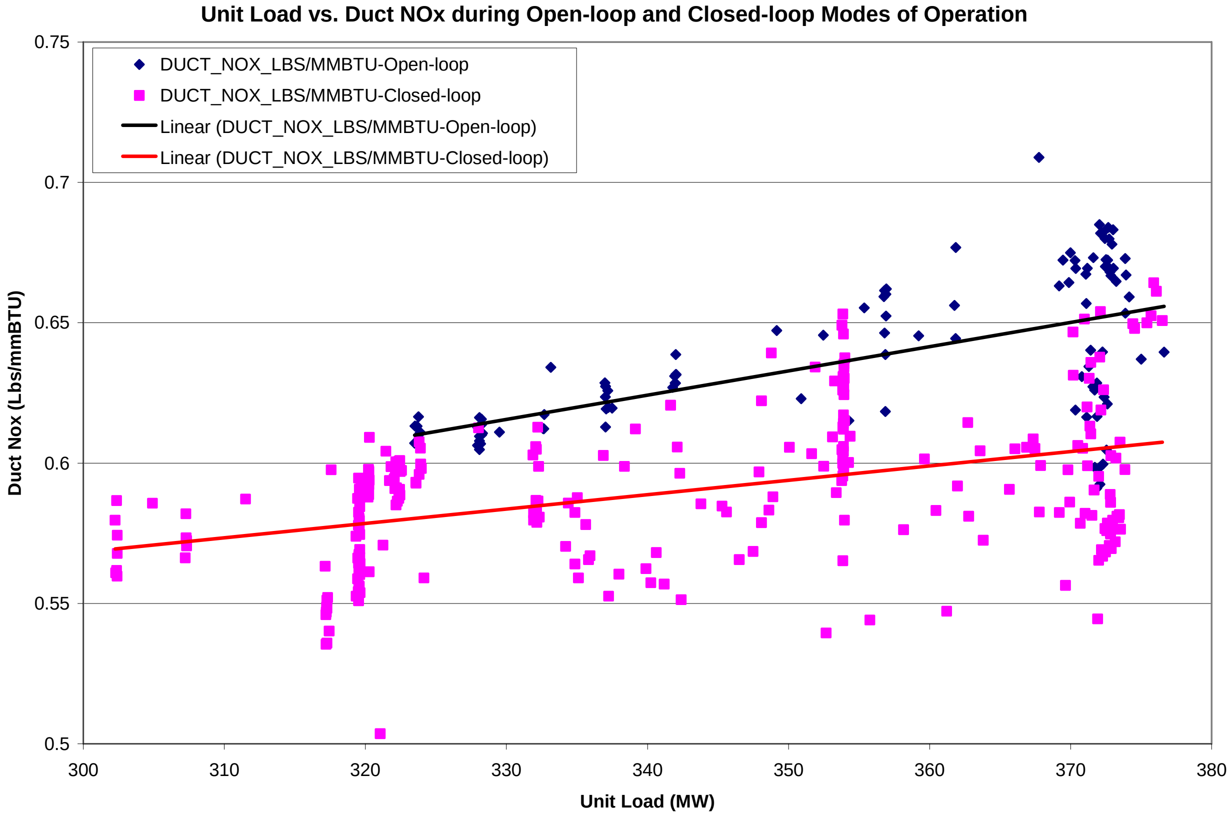

Figure 4. Duct NO_x as a Function of Unit-Load (Open-loop and Closed-loop Operation)

2. Opacity

Better management of particulate matter (PM) emissions was one of the project's objectives. ESP operation is sensitive to rapid changes in inlet mass concentration, as well as total mass loading. Excessive soot removal and/or an inappropriate cleaning strategy can overload the ESP and lead to inadequate capture of PM due to exceeding the ESP's capacity. This can result in increased PM emissions as evidenced by increased opacity and/or opacity excursions. Tighter control of inlet temperature to the ESP, coordination of sootblowing activities and ESP rapping execution, as well as reduction in unburned carbon are factors that can contribute to decreasing PM generation.

Examination of opacity results clearly illustrates opacity reduction during closed-loop operation compared to open-loop operation. Figure 5 indicates an improvement of 1 to

1.5 percentage points for closed-loop operation (lower line) over the entire range of sootblower steam flows.

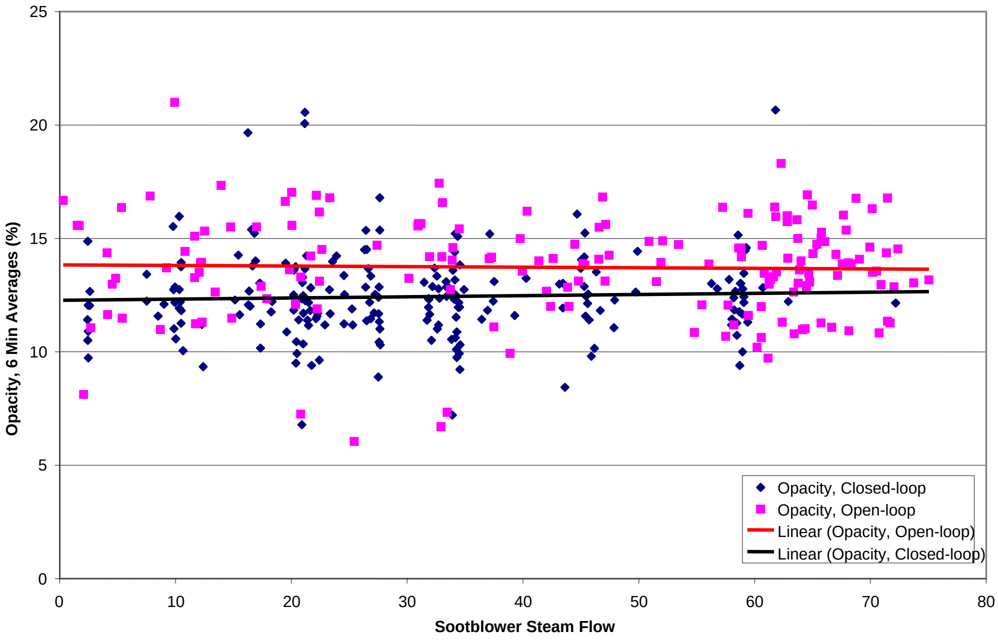

Figure 5. Stack Opacity as a Function of Sootblower Steam Flow

3. Other Benefits

Prior to this project, the sensors and controls related to sootblowing were usually treated as islands. Wall sensors would be tied only to wall blowers. Upperpass sensors would also be tied to a specific set of blowers. These components and systems had never been fully integrated with any type of comprehensive goal in mind. What was evaluated in this project was a NN-ISB system that has the ability to understand, evaluate and optimize the process as an entire system with multiple, real-time objectives. Integration of the sensors went well, and communication was established to the neural network system with all sensors and elements of the project. The project proved that such systems can be linked together without concern for communication failures between proprietary networks. Further, it proved that the sensors can provide data that can be correlated and achieve a set of objectives.

IV. DISCUSSION OF RESULTS

This project had a number of successes but was also troubled by a number of problems that prevented full achievement of its goals. A major problem was failure of the water cannons. Inability to use the water cannons meant that the waterwall in the furnace could not be effectively cleaned. This undoubtedly led to less NO_x reduction and a smaller efficiency gain than originally anticipated. The water cannon problem was compounded by failure or poor performance of much of the instrumentation installed as part of this project. The lack of anticipated inputs to the model limited the capabilities of the NN system to model the system as accurately as hoped.

Another problem was the use of the PERFIndex as a measure of efficiency. Since the exact nature of this parameter is not discussed in the final report, it is difficult to determine how accurately PERFIndex correlates with efficiency and, thus, what the true efficiency gain is.

These problems resulted in the project not fully achieving all its goals. The NN-ISB system appears to have worked well and undoubtedly improved boiler operation. However, as indicated in Section III, most of the instrumentation installed as part of this project either failed or did not perform up to expectations. Another problem was that only data for relatively short test periods (approximately 21 days total) were analyzed, and these test periods did not include all possible operating conditions. Had more data been evaluated, it is possible that benefits would be indicated more clearly.

The system was designed to optimize sootblowing on a coal-fired boiler by adjusting boiler parameters and sootblower activation signals via the control system. The main quantifiable objectives of the intelligent sootblowing system for this project were to reduce NO_x and PM emissions and improve efficiency. System operation in closed-loop mode over the demonstration period showed improvements in the targeted key parameters, as well as some secondary benefits. The NO_x emissions reduction recorded during NN application varied from zero to 8.5 percent (absolute) for closed-loop compared to open-loop operation over a variety of coal and operating conditions. Efficiency improvement of 10 Btu/kWh at high load and 50 Btu/kWh at low load were indicated, comparing the open-loop to closed-loop tests. The project improvement for the ISB portion and not counting the reduction in SB steam flow was 20 Btu/kWh at the comparable high-load points and up to 420 Btu/kWh at low-load. There is also measurable benefit for efficiency brought about by the redistribution of sootblowing steam and the ensuing average reduction of steam usage. Analysis of opacity data shows a reduction of nil to 1.5 percent (absolute) over the entire operating range during sootblowing activities.

In addition to the main benefits, several secondary benefits were observed:

- Total sootblower steam usage was lower with the optimization system engaged. This reduction in sootblower usage should help sootblower maintenance as well as tube erosion.
- Full integration of new sensor technology and optimization was completed. This shows that treating instruments as isolated systems can and should be eliminated to provide the best overall results.
- The boiler drum and pressure operation was stated by the operators to be qualitatively improved, especially in specific conditions where they previously had difficulty.
- Steam tube temperatures benefited and showed less deviation at high-load conditions for which this can be a critical parameter.

Logically, the NN-ISB system should have a number of benefits for improving power plant operations. Unfortunately, because of the problems discussed above and based on the data provided in the final report, these benefits did not turn out to be as large as expected. The major conclusion is that NN-ISB is a sound idea with significant potential, but it may take an additional project with improved equipment and instrumentation to fully quantify all the benefits. This project successfully demonstrated closed-loop operation without causing unit upsets or violating any constraints.

V. MARKET ANALYSIS

A. Commercialization

Project participant Pegasus is active in the development of the market for this technology. A marketing plan has been outlined for the sale of the NN-ISB to electrical generating organizations that primarily operate coal-fired units. A high degree of market success is anticipated, based on a plan to key in on a sector of this market that has not been addressed to date. Many executives of generating companies have expressed the desire to operate in an optimal manner and would embrace a solution that provides such capabilities.

The NN-ISB provides generating companies with an integrated solution that will assist in optimal economic and environmental real-time online operation of a unit. NN-ISB is modular in design and can be readily applied to a variety of power generating units. The solution architecture and infrastructure allow full or staged deployment, depending on the generating company's needs (plans, schedule, and budget). The technology applied throughout allows unit flexibility (i.e., existing systems can be integrated within the overall solution) and is extensible (new modules/new equipment can be readily modeled and incorporated).

This project operated as a full-scale demonstration and provided an opportunity to evaluate benefits, which will be transferred directly to other projects. The benefits, which have been demonstrated, when used in conjunction with the Pegasus NeuSIGHT combustion optimizer as an operating platform, have reduced NO_x emissions and improved efficiency and opacity. Unit operations benefited from a higher integration of sootblowing systems, less total sootblowing, and the associated less wear and tear on sootblowing equipment.

B. Economics

It is difficult to perform an economic analysis for a project such as the one discussed in this PPA because the cost of installing a NN-ISB system will vary widely from plant to plant, depending on many factors, including boiler type and size, fuel being burned, and the instrumentation and control system already in place. The following analysis is based on a new installation in a unit similar to Big Bend Unit No. 2. Although the benefits assumed in this analysis were not fully achieved by this project, it is likely that they are achievable in a new installation that incorporates the lessons learned.

There are two major potential savings from installation of a NN-ISB system. The first is a reduction in coal usage as a result of an efficiency gain. The coal burned in Unit No. 2 is estimated at one million tons per year at a cost of \$40/ton. If an efficiency improvement of 1 percent can be achieved, this would decrease coal consumption by 10,000 tons/yr for a savings of \$400,000/yr. Furthermore, this efficiency improvement would result in a reduction of SO_2 and CO_2 emissions in direct proportion to the reduction in fuel consumption.

The other potential savings is in the area of NO_x reduction, which can be quantified by using the value of a NO_x allowance on the trading market. At an assumed heat rate of 10,000 Btu/kWh and a capacity factor of 60 percent, the NO_x emitted from Big Bend Unit No. 2 is estimated to be 7,000 tons/yr (0.6 lb/10^6 Btu, see Figure 3). A 5 percent reduction in NO_x emissions would eliminate 350 tons/yr. Assuming that the NO_x cap and trade program is available at the plant installing the NN-ISB system and that the value of one NO_x allowance is \$2,000, this would amount to an annual revenue stream of \$700,000.

The cost of this project was about \$3,400,000, which included not only testing the NN-ISB system, but also testing of water cannons and various novel instruments, as discussed above. The cost of the NN-ISB system alone was about \$600,000. Because of this being a first of a kind project and the problems encountered, Pegasus estimates that costs for a new project to install NN-ISB incorporating lessons learned would be less, in the range of \$300,000 to \$500,000, provided that no new equipment or instrumentation were required at the plant. If only benefits from efficiency gains and NO_x reduction are considered, the project would pay off in five to nine months. Any additional benefits from improved performance or reduced maintenance would decrease this payout period, while any additional costs would increase the payout period.

VI. CONCLUSION

This project achieved some successes, but not all of the project goals were achieved. The successes included successful installation of a neural network and its operation in closed-loop on a full scale boiler. Furthermore, closed-loop operation of the system was accepted by the operators. This project also provided a testing ground for a number of innovative measurement devices, providing feedback on their operation that can lead to improved instruments.

The following project goals, stated in the original proposal, are considered to have been achieved:

- Promote the use of coal. Making coal use more fuel-efficient automatically reduces all pollutants on a per megawatt hour basis. In addition, reduction in NO_x emissions should lower the resistance to the use of coal for power production.

- Enable rapid deployment into the market. All coal-fired boilers employ sootblowers, and these sootblowers all require control systems. Current control systems cannot achieve the desired results. For a NN-ISB system, no new hardware needs to be developed since all of the hardware is “off the shelf.”

- Expand U.S. revenues through worldwide market acceptance. The same rapid deployment capability and acceptance will apply to offshore coal-fired boilers. Since the United States is presently the world leader in Artificial Intelligence (AI), of which the neural network system is a subset, there should be minimal competition from offshore suppliers.

On balance, the project was useful and the results should encourage other power plants to install neural networks to control sootblowing, improve efficiency, reduce NO_x, and improve other aspects of their operations.

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