CLEAN COAL TECHNOLOGY (CCT)

500 MW DEMONSTRATION OF ADVANCED WALL-FIRED COMBUSTION TECHNIQUES FOR THE REDUCTION OF NITROGEN OXIDE (NOx) EMISSIONS FROM COAL-FIRED BOILERS

Phase 4 - Digital Control System and Optimization

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ABSTRACT

This report presents the results of a U.S. Department of Energy (DOE) Clean Coal Technology (CCT) project demonstrating advanced wall-fired combustion techniques for the reduction of nitrogen oxide (NOx) emissions from coal-fired boilers. The project was conducted at Georgia Power Company's Plant Hammond Unit 4 located near Rome, Georgia. The DOE Cooperative Agreement Number for this project is DE-FC22-90PC89651.

The Clean Coal Technology Program is a jointly funded effort between government and industry to move the most promising advanced coal-based technologies from the research and development stage to the commercial marketplace. The Clean Coal effort sponsors projects that are different from traditional research and development programs sponsored by the DOE. Traditional projects focus on long-range, high-risk, high-payoff technologies with the DOE providing the majority of the funding. In contrast, the goal of the Clean Coal Program is to demonstrate commercially feasible, advanced coal-based technologies that have already reached the "proof-of-concept" stage.

As originally planned, the primary objective of the demonstration at Hammond Unit 4 was to determine the long-term effects of commercially available wall-fired low NOx combustion technologies on NOx emissions and boiler performance. In supporting this objective, baseline testing was conducted on the unit followed by installation and testing of an advanced overfire air system and low NOx burners, separately and in combination. These tests constituted Phases 1 through 3 of the project. These results were reported previously in the final report for these phases [SCS 1998].

An important result from Phase 1-3 testing was that combustion optimization had the potential to enhance boiler performance. Based on these results, a scope addition was proposed to the project funders (DOE, EPRI, and Southern Company) to add another task to the project. This task, added as Phase 4 of the project, evaluated advanced digital control and optimization techniques as applied to (1) reduction of NOx emissions, (2) mitigation of adverse impacts of low NOx burners and advanced overfire air system, and (3) improvement of boiler efficiency. The purpose of this report is to provide a technical account of Phase 4 of the project.

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LIST OF ABBREVIATIONS

acfm	actual cubic feet per minute
AGC	automatic generation control
AMIS	All mills in service
AOFA	Advanced Overfire Air
ASME	American Society of Mechanical Engineers
ºC	degrees Celsius
C	carbon
CAA(A)	Clean Air Act (Amendments)
CCT	U.S. Department of Energy's Clean Coal Technology Program
CEM	Continuous emissions monitor
CFSF	Controlled Flow/Split Flame
CIA	carbon-in-ash
Cl	chlorine
CO	carbon monoxide
DAS	data acquisition system
DCS	digital control system
DOE	U.S. Department of Energy
ECEM	extractive CEM
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ESP	electrostatic precipitator
ºF	degrees Fahrenheit
FC	fixed carbon
fps	feet per second
FWEC	Foster Wheeler Energy Corporation
GNOCIS	Generic NOx Control Intelligent System
GPC	Georgia Power Company
H	hydrogen
h	hour
HHV	higher heating value
HVT	High velocity thermocouple
I&C	Instruments and Controls
ID Fan	Induced draft fan
kW	kilowatt
kWh	kilowatt hour
(k)lb	(kilo) pound
lb	pounds
lbm	pounds mass
lb/MBtu	pounds per million Btu of fuel burned
LNB	low NO_x burner
LOI	loss on ignition
(M)Btu	(million) British thermal unit
MOOS	Mills out of service
MW	megawatt

N	nitrogen
NO	nitrogen oxide
NOx	nitrogen oxides
NSPS	New Source Performance Standards
O, O_2	oxygen
OFA	overfire air
O&M	operation and maintenance
PA fan	primary air fan
ppm	parts per million
psia	pounds per square inch absolute
psig	pounds per square inch gauge
PTC	Performance Test Codes
RSD	relative standard deviation
s	second
S	sulfur
SCS	Southern Company Services
SO_2	sulfur dioxide
THC	total hydrocarbons
UARG	Utility Air Regulatory Group
UBC	unburned carbon
VM	volatile matter
w.c.	water column

EXECUTIVE SUMMARY

This report discusses the results of a U.S. Department of Energy Clean Coal Technology (CCT) demonstration of advanced wall-fired combustion techniques for the reduction of nitrogen oxide (NOx) emissions from coal-fired boilers. The project was conducted at Georgia Power Company's Plant Hammond Unit 4 located near Rome, Georgia. Hammond Unit 4 is a Foster Wheeler Energy Corporation (FWEC) opposed wall-fired boiler, rated at 500 MW. The primary goal of this project was the characterization of the low NOx combustion equipment through the collection and analysis of long-term emissions data. The project was funded by the Electric Power Research Institute, Southern Company, and U.S. Department of Energy.

As originally planned, the primary objective of the demonstration at Hammond Unit 4 was to determine the long-term effects of commercially available wall-fired low NOx combustion technologies on NOx emissions and boiler performance. In supporting this objective, baseline testing was conducted on the unit followed by installation and testing of an Foster Wheelers advanced overfire air system and Controlled Flow / Split Flame low NOx burners, separately and in combination. These tests constituted Phases 1 through 3 of the project. These results were reported previously in the final report for these phases [SCS 1998].

An important result from Phase 1-3 testing was that combustion optimization had the potential to enhance boiler performance. Based on these results, a scope addition was proposed to the project funders to add another task to the project. This task, added as Phase 4 of the project, evaluated advanced digital control and optimization techniques as applied to (1) reduction of NOx emissions, (2) mitigation of adverse impacts of low NOx burners and advanced overfire air system, and (3) improvement of boiler efficiency. For the optimization effort, the principal effort was placed on the application of GNOCIS (Generic NOx Control Intelligent System).

Based on competitive bidding, a Foxboro I/A DCS was selected for installation at Hammond replacing the pneumatic control system. The DCS was installed at Hammond during a nine-month outage starting in September 1993 and continuing to June 1994. Since there had been major modifications to the unit during the outage (precipitator replacement, mill replacements, turbine upgrades), testing was conducted on the unit following this outage to reevaluate the performance of the unit in particular with regards to NOx emissions. This testing was conducted over an extended period lasting from third quarter 1994 and continuing to first quarter 1996. The major findings were that although the DCS greatly improved the dynamic performance of the unit and the ease of which process data could be accessed and analyzed, the DCS did not appear to actually improve unit performance.

The second part of Phase 4 of the project was the installation and demonstration of GNOCIS. GNOCIS is an enhancement to digital control systems (DCS) targeted at improving utility boiler efficiency and reducing emissions. GNOCIS utilizes a neural-network model of the combustion characteristics of the boiler that reflects both short-term and longer-term trends in boiler characteristics. A constrained-nonlinear optimizing procedure is applied to identify the best set points for the plant. These recommended set points can be implemented automatically without operator intervention (closed-loop), or, at the plant’s discretion, conveyed to the plant operators for implementation (open-loop). The software is designed for continuous on-line use. GNOCIS development was funded by the Electric Power Research Institute, PowerGen, Southern Company, Radian International, U.K. Department of Trade and Industry, and U.S. Department of Energy. GNOCIS was under development at Alabama Power's Gaston Unit 4 and PowerGen's Kingsnorth Unit 1 from 1994 through 1996 (PowerGen, 1997).

Following the work at these two sites, GNOCIS was installed and became fully operational at Hammond during first quarter 1996. At Hammond, GNOCIS was designed to operate in either open-loop (advisory) or closed-loop (supervisory) modes, although more emphasis was placed on the latter. During first quarter and second quarter 1996, short-term testing on the unit was conducted. The results from this testing were similar to that observed at the other GNOCIS sites with NOx reductions of around 10 to 15% and efficiency improvements of about 0.5%. Additional GNOCIS testing at Hammond was hoped for; however, due in part to the relative unavailability of the unit for testing, this testing never materialized. Although testing was not as extensive as first hoped, numerous GNOCIS tests have been conducted at Hammond and other sites and it is felt that the results obtained at Hammond are representative of the true performance of the technology.

Using the available short-term test results, model studies further predict that GNOCIS could, at least for this unit, simultaneously reduce NOx emissions and improve unit heat rate. The results of these studies are shown in Table ES-1 through Table ES-4 for several operating mode/load profile combinations. In most scenarios, GNOCIS improved both unit heat rate and reduced NOx emissions.

Table ES-1 NOx and NOx Reduction vs. Load Profile and Operating Mode

		GNOCIS Operating Mode		
Load Profile (lb/Mbtu / % Reduction)	Baseline	Minimize NOx	Maximize Efficiency	Minimize LOI
Phase 1	0.42	0.37 / 11%	0.39 / 6%	0.45 / -9%
Base Load	0.43	0.38 / 12%	0.39 / 7%	0.46 / -9 %
Peaking Load	0.41	0.35 / 13%	0.43 / -6%	0.42 / -3%
Cycling Load	0.40	0.36 / 10%	0.39 / 4%	0.43 / -8%
Flat Load	0.40	0.36 / 11%	0.40 / 0%	0.43 / -6%

Table ES-2 Average Heat Rate Deviation vs. Load Profile and Operating Mode

		GNOCIS Operating Mode		
Load Profile (Btu/kWh)	Baseline	Minimize NOx	Maximize Efficiency	Minimize LOI
Phase 1	--	-47	-78	38
Base Load	--	-56	-88	47
Peaking Load	--	1	-37	-6
Cycling Load	--	-43	-71	18
Flat Load	--	-25	-56	5

Positive number indicates poorer heat rate, negative numbers improved heat rate.

Table ES-3 Fuel Cost Deviation vs. Load Profile and Operating Mode

Load Profile	Baseline	GNOCIS Operating Mode Minimize NOx	Maximize Efficiency	Minimize LOI
Phase 1	--	-$237,610	-$391,804	$190,685
Base Load	--	-$280,727	-$446,273	$237,479
Peaking Load	--	$4,483	-$187,014	-$28,909
Cycling Load	--	-$216,281	-$356,717	$90,939
Flat Load	--	-$127,076	-$283,833	$26,589

Positive number is an expenditure.
Negative number is a savings.

Table ES-4 NOx Reduction Cost Effectiveness vs. Load Profile and Operating Mode

Load Profile ($/lb NOx removed)	Baseline	GNOCIS Operating Mode Minimize NOx	Maximize Efficiency	Minimize LOI
Phase 1	--	-$261	-$684	n/a
Base Load	--	-$277	-$627	n/a
Peaking Load	--	$43	n/a	n/a
Cycling Load	--	-$293	-$975	n/a
Flat Load	--	-$177	-$2,403	n/a

n/a – There was a net NOx emission increase for these load/mode combinations.
Negative numbers indicate a net saving.

Again, the above tables are based on the extrapolation of available test data to various long-term operating profiles.

Based on GNOCIS testing at this site and others, at plant management's request, GNOCIS is being incorporated into the unit's standard operating procedures. Also, consideration is being given to applying GNOCIS to other plant processes.

1 INTRODUCTION

1.1 Purpose of this Report

This report presents the results of Phase 4 of a U.S. Department of Energy (DOE) Clean Coal Technology (CCT) project demonstrating advanced wall-fired combustion techniques for the reduction of nitrogen oxide (NOx) emissions from coal-fired boilers. Phase 4 consisted of the installation and testing of a digital control system and on-line combustion optimization system. The project was conducted on Unit 4 at Georgia Power Company's Plant Hammond, located near Rome, Georgia. The technologies demonstrated on this unit include Foster Wheeler Energy Corporation's advanced overfire air system and Controlled Flow/Split Flame low NOx burner. The DOE Cooperative Agreement Number for this project is DE-FC22-90PC89651.

The project was managed by Southern Company Services, Inc. (SCS) on behalf of the project co-funders: Southern Company, U.S. Department of Energy (DOE), and Electric Power Research Institute (EPRI). Southern Company, the largest producer of electricity in the United States is the parent firm of Alabama Power, Georgia Power, Gulf Power, Mississippi Power and Savannah Electric. Based in Atlanta, Southern Company supplies electricity in nine countries on four continents and provides energy-related marketing, trading and technical services and wireless telecommunications. SCS provides engineering, research, and financial services to Southern Company.

The Clean Coal Technology Program is a jointly funded effort between government and industry to move the most promising advanced coal-based technologies from the research and development stage to the commercial marketplace. The Clean Coal effort sponsors projects that are different from traditional research and development programs sponsored by the DOE. Traditional projects focus on long range, high risk, high payoff technologies with the DOE providing the majority of the funding. In contrast, the goal of the Clean Coal Program is to demonstrate commercially feasible, advanced coal-based technologies that have already reached the "proof of concept" stage. As a result, the Clean Coal Projects are jointly funded endeavors between the government and the private sector, conducted as cooperative agreements in which the industrial participant contributes at least fifty percent of the total project cost.

1.2 Overview of Project

The primary objective of the demonstration at Hammond Unit 4 was to determine the long-term effects of commercially available wall-fired low NOx combustion technologies on NOx emissions and boiler performance. Short-term tests of each technology were also performed to provide engineering information about emissions and performance trends. A target of achieving fifty percent NOx reduction using combustion modifications was established for the project.

Specifically, the original objectives of the project were:

- Demonstrate in a logical stepwise fashion the short-term NOx reduction capabilities of the following advanced low NOx combustion technologies:

- ❑ Advanced Overfire Air (AOFA)
- ❑ Low NOx burners (LNB)
- ❑ LNB with AOFA

- Determine the dynamic, long-term emissions characteristics of each of these combustion NOx reduction methods using statistical techniques.
- Evaluate the progressive cost effectiveness (i.e., dollars per ton NOx removed) of the low NOx combustion techniques tested.
- Determine the effects on other combustion parameters (e.g., CO production, carbon carryover, particulate characteristics) of applying the NOx reduction methods listed above.

To accomplish these evaluations, the project was partitioned into the following test phases:

- Phase 1 - Baseline
- Phase 2 - Advanced Overfire Air
- Phase 3A - Low NOx Burners
- Phase 3B - Low NOx Burners plus Advanced Overfire Air

Each of the phases of the project involved three distinct testing periods - short-term characterization, long-term characterization, and short-term verification. The short-term characterization testing established the trends of NOx versus various parameters and establishes the influence of the operating mode on other combustion parameters. The long-term characterization testing (50 to 80 continuous days of testing) established the dynamic response of the NOx emissions to all of the influencing parameters encountered. The short-term verification testing documented any fundamental changes in NOx emissions characteristics that may have occurred during the long-term test period. The results from Phases 1-3 can be found in the final report for these phases [SCS 1998].

Over the course of the project, several tasks not part of the original project scope were included:

- Chemical Emissions Testing - Chemical emissions testing was conducted during Phases 2 and 3A.
- Demonstration of On-Line Carbon-in-Ash Monitors.
- Digital Controls / Optimization - This task, added as Phase 4 of the project, evaluated advanced digital control and optimization techniques as applied to (1) reduction of NOx emissions, (2) mitigation of adverse impacts of low NOx burners and advanced overfire air system, and (3) improvement of boiler efficiency.

The results of the chemical emissions testing and on-line carbon-in-ash monitors are presented in other reports [Radian 1993][SCS 1997]. This report is the subject of Phase 4 – the digital control / optimization phase.

1.2.1 Host Site Description

Georgia Power Company's Plant Hammond Unit 4 is a Foster Wheeler Energy Corporation (FWEC) opposed wall-fired boiler, rated at 500 MW gross, with design steam conditions of 2500 psig and 1000/1000°F superheat/reheat temperatures, respectively. Hammond 4 was placed into commercial operation on December 14, 1970. Prior to the LNB retrofit, six FWEC Planetary Roller and Table type mills provided pulverized eastern bituminous coal (12,900 Btu/lb, 33% VM, 53% FC, 1.7% S, 1.4% N) to 24 pre-NSPS, FWEC Intervane burners. During the LNB outage, the existing burners were replaced with FWEC Control Flow/Split Flame burners. The unit was also retrofit with six Babcock and Wilcox MPS 75 mills during the course of the demonstration (two each during the spring 1991, spring 1992, and fall 1993 outages). The burners are arranged in a matrix of twelve burners (4 wide x 3 high) on opposing walls with each mill supplying coal to 4 burners per elevation. As part of this demonstration project, Hammond 4 was retrofit with a FWEC designed Advanced Overfire Air System. The unit is equipped with a coldside ESP and utilizes two regenerative secondary air heaters and two regenerative primary air heaters. Designed for pressurized furnace operation, Hammond 4 was converted to balanced draft operation in 1977. The unit was equipped with a Bailey pneumatic boiler control system during the baseline, AOFA, LNB, and LNB+AOFA phases of the project. Further details on the unit configuration and operating performance can be found elsewhere [SCS 1998].

1.2.2 Project Schedule

Figure 1-1 shows the overall schedule for the project. Baseline, AOFA, LNB, and LNB+AOFA installation and testing were conducted from 1989 through 1993. On December 6, 1994, DOE approved a project scope addition to demonstrate the use of advanced on-line control and optimization techniques to combustion optimization.

1.2.3 Project Cost

The total estimated cost of the project is $15,853,890. The Participants' cash contribution and the Government share in the costs of this project are shown in Table 1-1. The costs quoted are those submitted in the most recent Cooperative Agreement modification. A summary of funding by contributor is shown in Table 1-2.

1.3 Report Organization

The purpose of this report is to provide a technical account of Phase 4 of the project. The following is a brief description of the information provided in each section:

- Section 1 - Introduction - Background and funding information.

- Section 2 - Technology Descriptions of the DCS and GNOCIS

- Section 3 - Basis for Installing the DCS and GNOCIS
- Section 4 - DCS Testing
- Section 5 - Optimization
- Section 6 - Conclusions

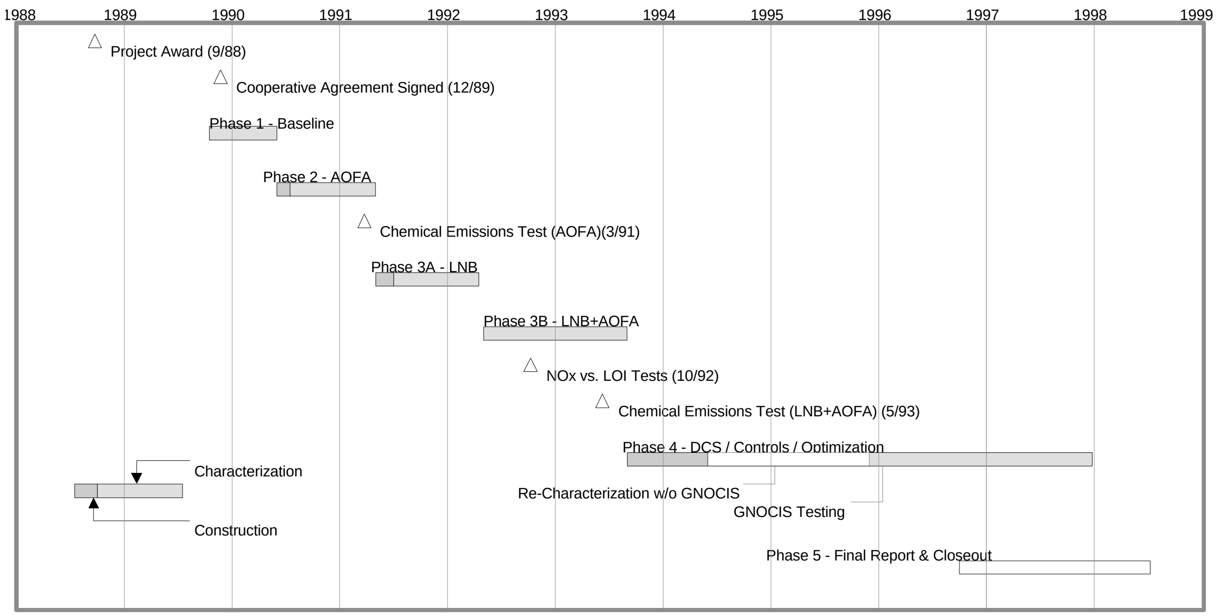


Figure 1-1 Overall Project Schedule

Table 1-1 Project Costs by Phase

Phase	Dollar Share ($)	Percent Share (%)
Phase 0 - Pre-Award		
Government	$122,311	41%
Participant	$179,637	59%
	$301,948	
Phase 1 - Baseline Testing		
Government	$660,426	45%
Participant	$813,739	55%
	$1,474,165	
Phase 2 - AOFA Installation and Characterization		
Government	$1,712,745	45%
Participant	$2,110,346	55%
	$3,823,091	
Phase 3 - LNB Installation and Characterization		
Government	$2,571,446	45%
Participant	$3,168,389	55%
	$5,739,835	
Phase 4 - Digital Control System		
Government	$1,076,000	30%
Participant	$2,522,338	70%
	$3,598,338	
Phase 5 - Project Close-out and Final Reporting		
Government	$410,598	45%
Participant	$505,915	55%
	$916,513	
Total Project Funding	$15,853,890	

Table 1-2 Project Funding by Participant

Participant	Dollar Contribution	Percent
DOE	$6,553,526	41.3
EPRI + Southern Company	$9,300,364	58.7
Total	$15,853,890	100

2 TECHNOLOGY DESCRIPTION

Three FWEC low NOx technologies were tested at Hammond: the Advanced Overfire Air (AOFA), the CF/SF Low NOx Burners (LNB), and the LNB+AOFA. These NOx control technologies were tested during Phases 1-3 of the project and the results are described elsewhere [SCS 1998]. The objective of Phase 4 of the project at Plant Hammond was to evaluate and demonstrate the effectiveness of advanced digital control/optimization methodologies as applied to the NOx abatement technologies installed at this site (LNB and AOFA). The combustion optimization system chosen for demonstration was GNOCIS (Generic NOx Control Intelligent System). This section provides an overview of the digital control system and GNOCIS.

2.1 Digital Control System

An integral part of Phase 4 of the project was the design and installation of a digital control system to be the host of the advanced control/optimization strategies being developed. SCS Engineering had overall responsibility for the following major activities:

- Preliminary engineering
- Procurement
- Detail engineering
- Digital control system configuration
- Installation and checkout

In general, the system consisted of Unit Master, Fuel Control, Air Flow Control, Furnace Pressure Control, Feedwater Control, Steam Temperature Control, Condensate Control, Auxiliary Control, DCA Heater Level Control, Ash Handling System, Precipitator Energy Management System, Precipitator Fire Protection, and Burner Management System. In total, the digital control system was configured for 2352 input/output points consisting of 572 analog inputs, 116 analog outputs, 1032 digital inputs, and 632 digital outputs with the balance being allocated spares.

Based on a competitive evaluation, a Foxboro I/A Series System DCS was selected for installation. The Foxboro I/A Series System is a fully distributable, digital control system designed to address a broad range of application requirements. The DCS provides nodes of interchangeable hardware and software modules that can be matched to the process application. Although not necessarily unique to the Foxboro I/A System, the following are some of the important characteristics of this digital control system:

- Fully distributable, both functionally and physically, allowing installation of the control system hardware in the field (i.e. near the burner front and mills) -- no special environment for the control system hardware is needed.

- Extensive use of standard communication networks. I/A Series nodes communicate with each other using a MAP compatible network. Gateways are provided for communication to other devices via RS-232-C, RS-485, X.25, Modbus, Allen-Bradley Data Highway, IEEE 802.3 (CSMA/CD), IEEE 802.4 (token passing) and others.

- Open system architecture. The digital control system is built using the following constructs: (1) operating system - "VENIX", a version of "UNIX", (2) development language - "C", (3) relational data base - "INFORMIX", and (4) network - IEEE 802.3 and 802.4. Adherence to these standards facilitates software portability from and to other platforms and allows current software to be utilized as new hardware technology is introduced.

- Increased reliability from the use of sealed modules interconnected by serial communications and the application of redundant hardware modules on critical control loops.

An overview of the system installed at Hammond Unit 4 is shown in Figure 2-1.

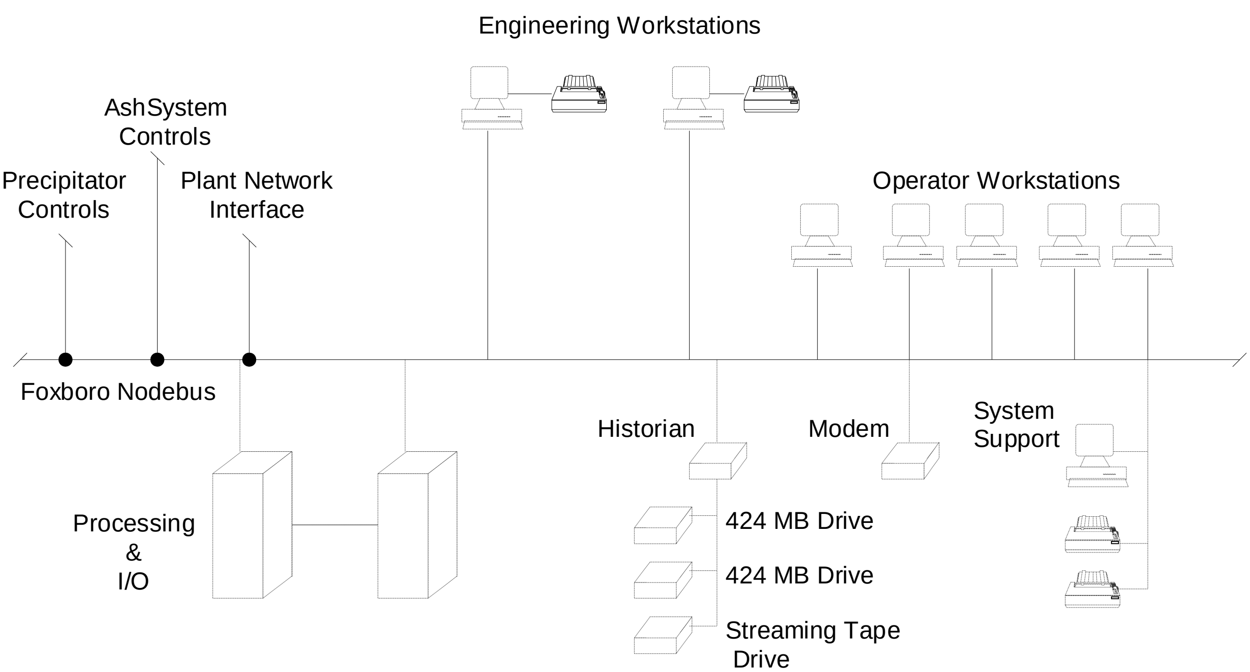


Figure 2-1 Unit 4 DCS Overview

As part of this project, the control room was modified to accept the new Unit 4 digital control system. A plan drawing of the retrofitted Unit 1-4 control room is shown in Figure 2-2. As shown, the pre-existing Unit 4 benchboards were removed and replaced with a CRT based control panel. Also shown in this figure is the retrofitted Unit 3 benchboard that was upgraded during fall 1993. In addition to the upgrades to Units 3 and 4, Georgia Power is also considering upgrading the digital control systems on Units 1 and 2. Figure 2-3 shows the control room as envisioned following upgrades on all four units. Digital control system and control room modifications for Units 1, 2, and 3 are not a part of the Wall-Fired Project. A schematic of the new Unit 4 benchboard is shown in Figure 2-4 and a photo in Figure 2-5. As can be inferred from this figure, operator interaction with the digital control system is almost exclusively through the operator displays.

In addition to the inter-DCS network, the Unit 4 DCS (and the others also), are connected through a router to the plant's token-ring PC engineering and administrative LAN and the corporate wide area network (WAN) (Figure 2-6). The latter enables remote access of process data and facilitates software maintenance. A Sun Sparcstation 5, hosting the advanced control/optimization software, is connected to this network.

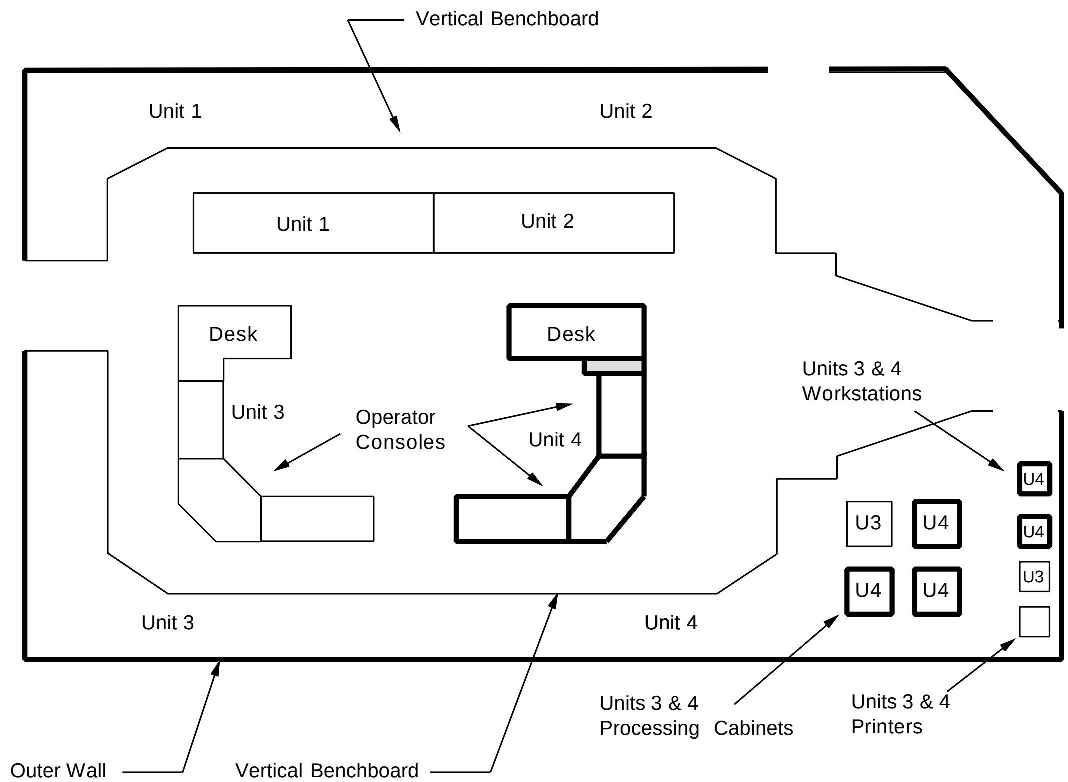


Figure 2-2 Unit 1-4 Control Room Layout as Currently Implemented

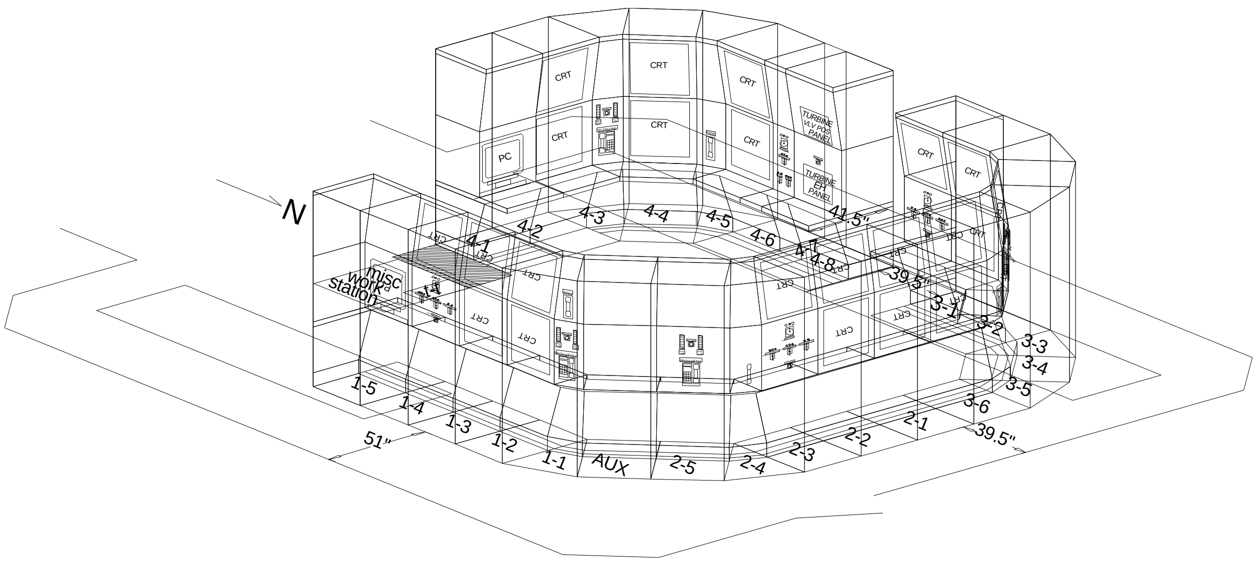


Figure 2-3 Unit 1-4 Control Room Layout (Planned)

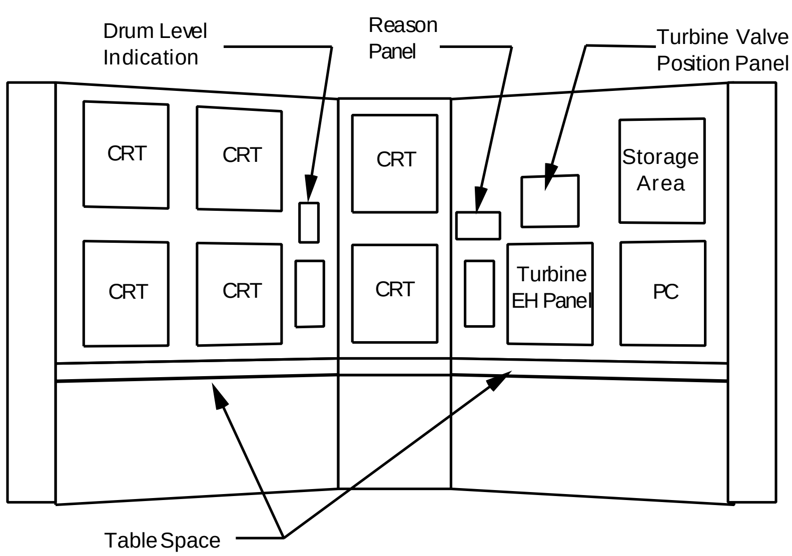


Figure 2-4 Unit 4 Benchboard

Figure 2-5 Photo of Unit 4 Benchboard

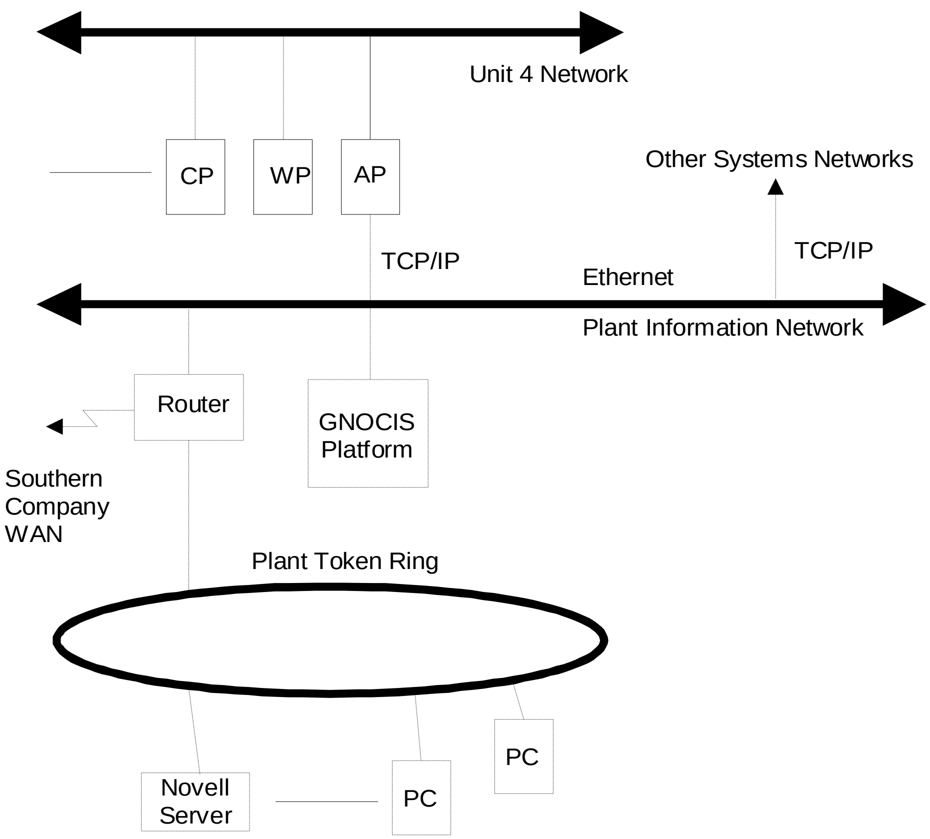


Figure 2-6 Hammond Plant Network

2.2 GNOCIS

GNOCIS (Generic NOx Control Intelligent System) is an enhancement to digital control systems (DCS) targeted at improving utility boiler efficiency and reducing emissions. GNOCIS is designed to operate on units burning gas, oil, or coal and is available for all combustion firing geometries. GNOCIS development was funded by a consortium consisting of the Electric Power Research Institute, PowerGen, Southern Company, Radian International, U.K. Department of Trade and Industry, and U.S. Department of Energy.

GNOCIS utilizes a neural-network model of the combustion characteristics of the boiler that reflects both short-term and longer-term trends in boiler characteristics. A constrained-nonlinear optimizing procedure is applied to identify the best set points for the plant. These recommended set points can be implemented automatically without operator intervention (closed-loop), or, at the plant's discretion, conveyed to the plant operators for implementation (open-loop). The software is designed for continuous on-line use. The major elements of GNOCIS are shown in Figure 2-7.

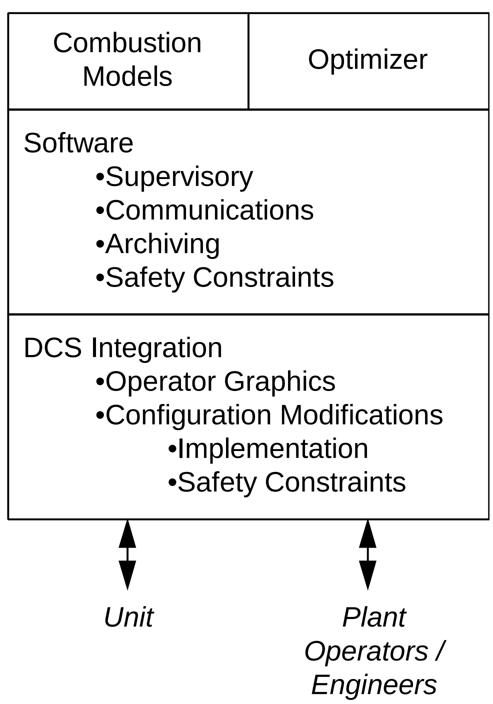


Figure 2-7 Major Elements of GNOCIS

The recommendations provided by GNOCIS, whether open- or closed-loop, are supervisory in nature and are ideally implemented via the DCS. As shown in Figure 2-8, GNOCIS utilizes process data collected from the DCS. Once determined, the recommendations are provided to the operator through the DCS or other displays. The operator can then make the final determination on whether these recommendations should be implemented. Alternatively, the recommendations are automatically implemented via the DCS.

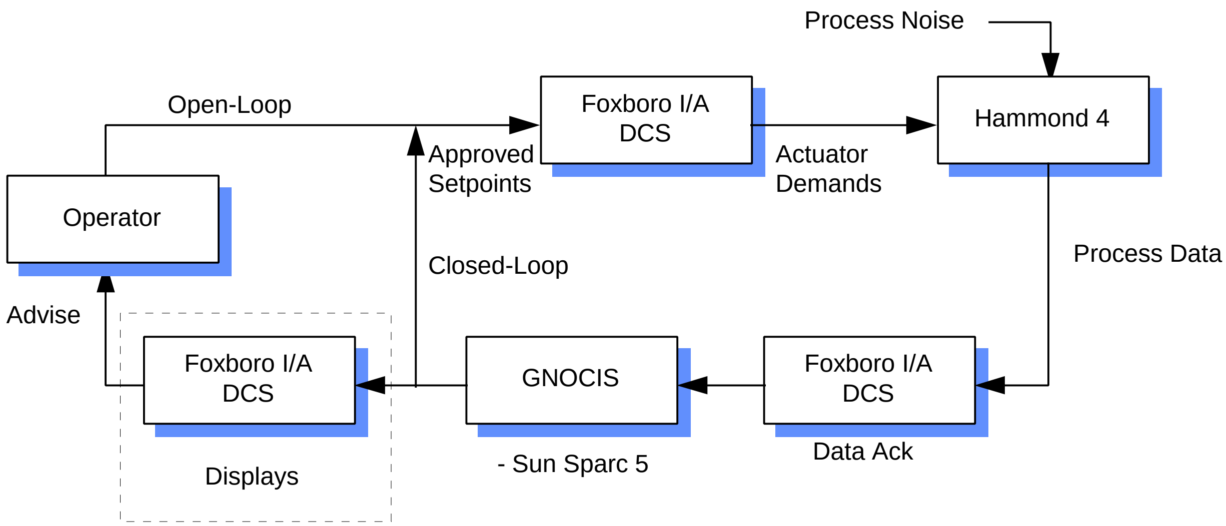


Figure 2-8 Hammond 4 GNOCIS Implementation

Combustion optimization difficulty at Hammond has increased dramatically since the installation of the low NOx burners and advanced overfire air system. This added difficulty is a result of the increase in the number of adjustments and sensitivity of these burners to operating conditions (Table 2-1). Using this list as a starting point, GNOCIS was designed to make use of the variables shown in Table 2-2. The control variables in the first tier have been implemented, and, if successful, additional variables from the subsequent tiers will be considered if their inclusion improves the performance of the system significantly. Software hooks were designed into the DCS to facilitate the incorporation of these signals into the control logic.

Sample operator graphics for GNOCIS are shown in Figures 2-9 and 2-10. Typically, the DCS operator displays are the principal interface to GNOCIS. These displays must (1) clearly convey to the operator the recommendations and predicted benefits and (2) allow the operator flexibility in setting constraints. As shown, the operator is presented with the current operating conditions and two sets of recommendations and predictions. One set corresponds to the current mills-in-service operating condition. If accepted, the operator can either implement the recommendations by individually setting the manipulated parameters to the targets or have the DCS automatically implement the recommendations (*Implement Recommendations*). When clamped, the operating parameter is assumed clamped to the current operating condition, and the optimization is performed with the remaining parameters. The operator can also remove or add parameters from the optimization by using this screen (*Clamped / Free).*

Since in many instances the mill selection can affect performance and emissions, it is important to provide recommendations concerning the mills in service. However, due to many externalities not measurable by the DCS or best judged by the operator, the mill configuration cannot be achieved or is not desirable. As a compromise, another set of recommendations are provided as to the optimum mills-in-service and the performance/emissions benefits. Given the predicted improvement and the current state of the plant, the operator can decide whether it is of overall advantage to change the mills in service. Close-loop mode, if implemented, is obtained by selecting the *Close Loop* button from this screen.

Table 2-1 Combustion Tuning Control Points at Hammond 4

Pre-LNB+AOFA Retrofit	Post-LNB+AOFA Retrofit
Burners	Burners
Sleeve registers (24)	Sleeve registers (24)
Secondary air	Tip Positions (24)
Windbox balancing dampers	Inner registers (24)
Mill Biasing	Outer registers (24)
	Advanced overfire air
	Can-in-can dampers (8)
	Flow control dampers (4)
	Secondary air
	Windbox balancing dampers
	Boundary air
	Mill Biasing

Table 2-2 GNOCIS Control Points

Parameter of Interest	Controlled Parameter	Advisory Mode Open-Loop	Supervisory Mode Close-Loop
First Tier			
Overall Furnace Air / Fuel Ratio	Excess O_2 Bias	Y	Y
Overall Furnace Staging	AOFA Flow (4)	Y	Y
AOFA Distribution	AOFA Flow (4)	Y	Y
Mill Biasing	Mill Coal Flow (6)	Y	Y
Mills-in-Service	Mill Coal Flow (6)	Y	Advise
Second Tier			
AOFA Distribution	AOFA Can Dampers (8)	Y	Y
Furnace Secondary Air Distribution	Burner Sleeve Dampers by Banks (8)	Y	Y
Third Tier			
Furnace Secondary Air Distribution	Burner Sleeve Dampers (24)	Y	Y

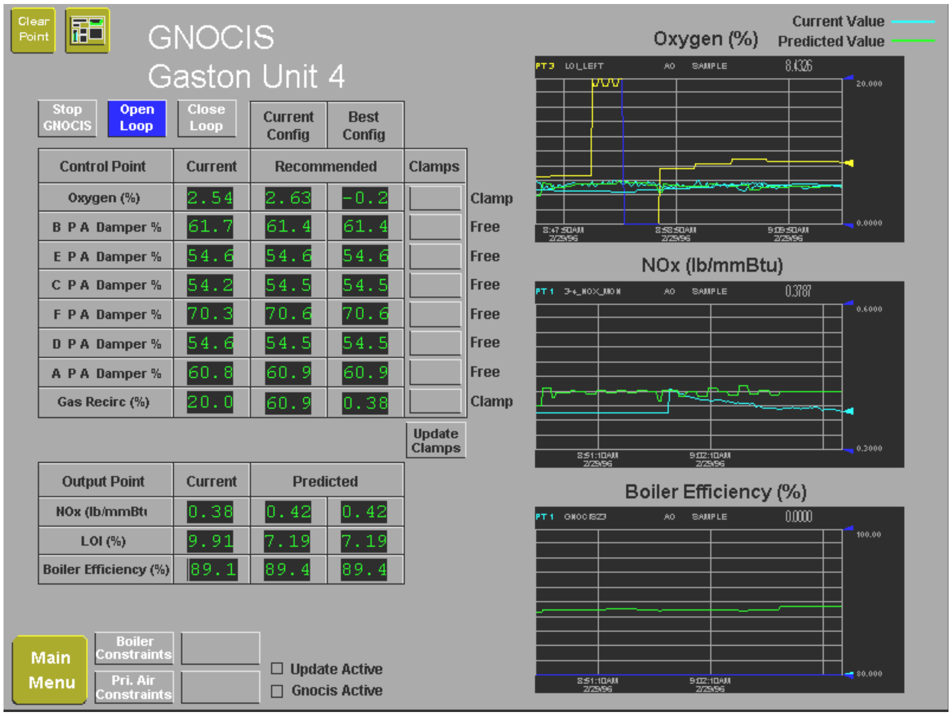


Figure 2-9 GNOCIS Recommendation Screen

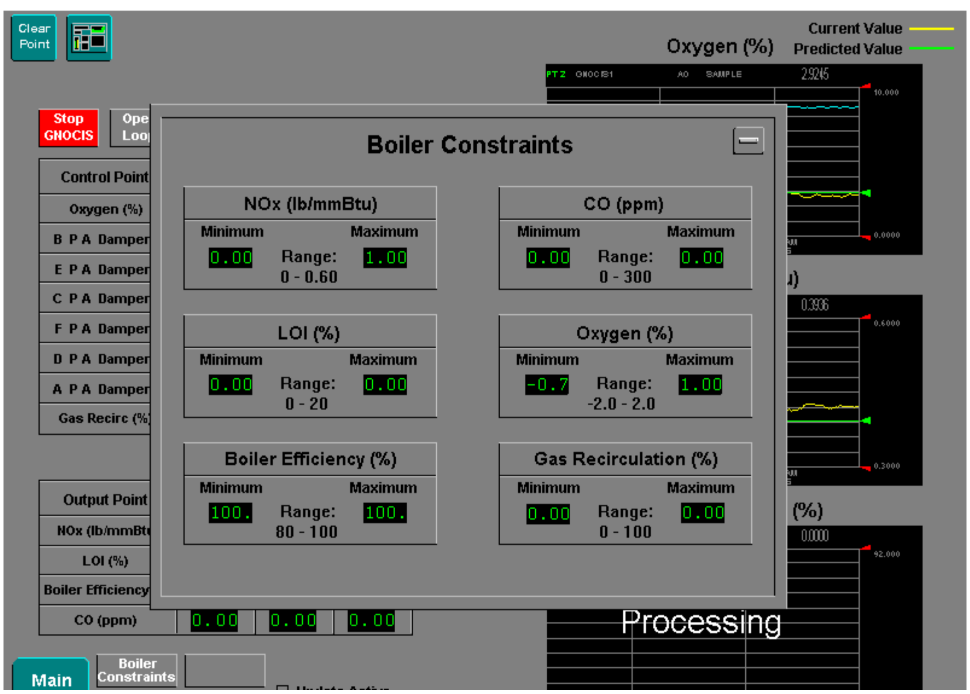


Figure 2-10 GNOCIS Constraint Screen

3 BASIS FOR INSTALLING GNOCIS AND THE DCS

3.1 Potential Benefits of Continuous Optimization

Unlike SO_2 emissions that are primarily a function of the sulfur content of the fuel, NOx emissions are highly dependent on a number of parameters (Table 3-1). Nitrogen oxides (NOx) are formed in combustion processes through the thermal fixation of atmospheric nitrogen in the combustion air producing "thermal NOx" and the conversion of chemically bound nitrogen in the fuel producing "fuel NOx". NOx emissions can theoretically be reduced by lowering: (1) the primary flame zone O_2 level, (2) the time of exposure at high temperatures, (3) the combustion intensity, and (4) primary flame zone residence time. NOx emission rates are strongly influenced by the apportionment of the air to the burners and AOFA system.

Table 3-1 Factors Controlling the Formation of NOx

Primary Equipment and Fuel Parameters	Secondary Combustion Parameters	Fundamental Parameters
Inlet temperature & velocity		
Furnace design	Combustion intensity	
Fuel composition	Heat removal rate	Oxygen level
Injection pattern of fuel & air	Mixing of combustion products	Peak temperature
Size of particles	Local fuel/air ratio	Exposure time at peak temperature
Burner swirl	Turbulent distortion of flame zone	

As with NOx emissions, boiler performance is heavily influenced by boiler operating parameters, both controllable and non-controllable. The performance includes efficiency, steam temperatures, unburned combustibles, and air heater exit air temperatures. The operating parameters that can affect the performance include among others excess oxygen, fuel quality, mills-in-service, and fuel and combustion air distribution.

An example of the interdependencies and conflicting goals that must be considered can be seen in Figure 3-1. As shown, as excess air (or equivalently, excess oxygen) decreases, NOx decreases while LOI increases. High LOI is indicative of poor combustion and therefore poor boiler performance. Also, on units which sell their fly ash, an increase in fly ash LOI can change the fly ash from a marketable commodity to an undesirable byproduct. A decision must be made as to what is the optimum operating condition based on economic and environmental considerations. Similar comprises must also be made when optimizing boiler efficiency (Figure 3-2). In this case, the optimum operating condition is clear as long as the performance index is defined as boiler efficiency and other parameters (such as NOx emissions) are not considered. Conflicting objectives such as these have been observed on Hammond Unit 4 and other units. For example, it has been thoroughly documented that NOx production rate is an increasing function of the excess oxygen level while fly ash LOI is a decreasing function. Therefore using this control alone, to reduce LOI, excess oxygen levels would need to be raised, however, this would also result in an increase in NOx emissions. These dependencies have been and continue to be well documented in the industry [EPRI, 1993][Sorge, 1993][SCS, 1998][Tavoulareas, 1993][SCS 1993][Petrill, 1993].

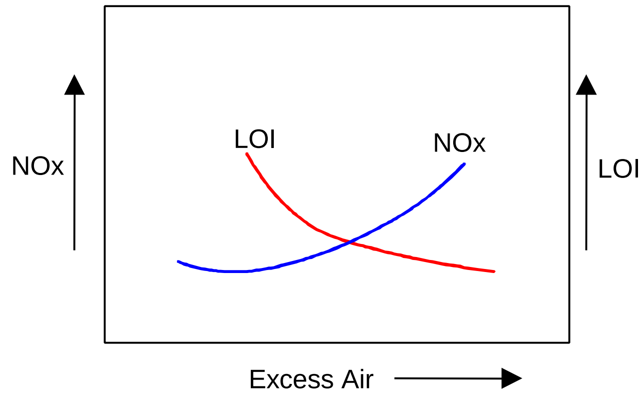


Figure 3-1 Typical NOx and LOI vs. Excess Oxygen Characteristics

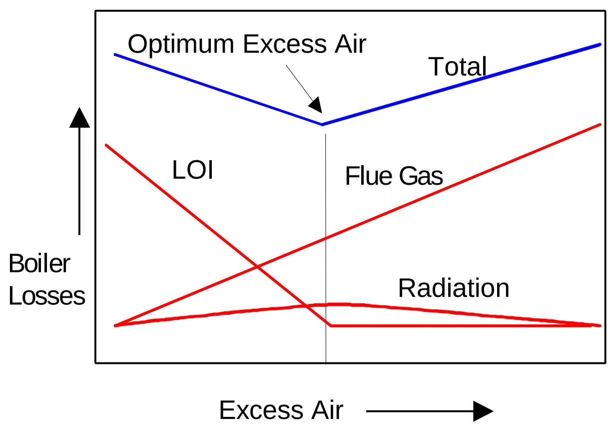


Figure 3-2 Typical Boiler Efficiency Losses vs. Excess Air Characteristic

These tradeoffs in performance have been evident at Hammond 4 since the start of project testing. A strong example of possible improvement in performance by operational adjustments can be seen in Figure 3-3. This data is from the NOx vs. LOI testing conducted on Hammond Unit 4 during October 12 - 28, 1992 [SCS, 1998]. The primary purpose of these tests was to determine the effects of various burner settings and mill operation on NOx emissions and unburned carbon levels in the fly ash. To assess the effects of each parameter, the test matrix was designed so that a single parameter was varied each test day and all other parameters were held constant to the extent possible. The parameters tested were (1) excess air, (2) mill coal flow bias, (3) burner sliding tip position, (4) burner outer register position, and (5) burner inner register position. The range of values tested is shown in Table 3-2.

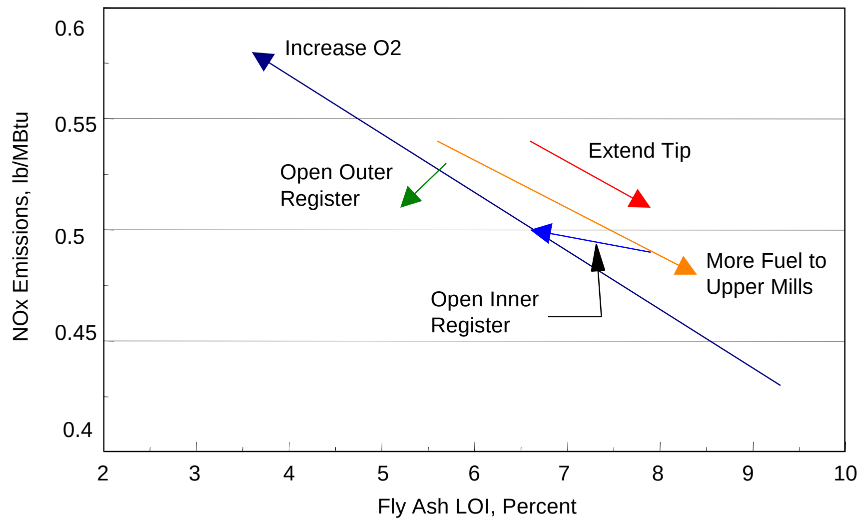


Figure 3-3 NOx vs. LOI Testing / All Sensitivities (Phase 3A)

Table 3-2 Hammond 4 / NOx vs. LOI Tests / Parameters Tested

Parameter	Nominal Value	Range Tested	
		Low	High
Excess Air	4%	2.8%	5.0%
Sleeve Damper	7" Outer burner columns 4" Inner burner columns	Not Adjusted	Not Adjusted
Inner Register	~15%	Nominal	Nominal + 40%
Outer Register	~60%	-20% of nominal	+20% of nominal
Sliding Tip	+4 inches	+2 inches	+4 inches
Mill Bias	No bias	Upper Mills +10% Lower Mills -10%	Upper Mills -10% Lower Mills +10%

The NOx emissions and LOI levels varied from approximately 0.44 lb/MBtu to 0.57 lb/MBtu and 10% to 3%, respectively. As expected, excess O_2 level had a considerable effect on both NOx and LOI. For the other parameters considered, within the range of adjustments tested, mill bias and sliding tip position had the greatest influence on NOx and LOI. As can be seen from these graphs, there is some flexibility in selecting the optimum operating point and making tradeoffs between NOx emissions and fly ash LOI; however, much of the variation was the result of changes in excess O2. This figure shows for excess O2, mill bias, inner register, and sliding tip, any adjustments to reduce NOx emissions are at the expense of increased LOI. In contrast, the slope of the outer register characteristic suggests that an improvement in both NOx emissions and LOI can be achieved by adjustment of this damper. However, due to the relatively small impact of the outer register adjustment on both NOx emissions and LOI, it is likely that the positive NOx / LOI slope is an artifact of process noise.

In addition to the short-term effects, operating conditions also vary significantly during long-term operation and it is evident that a number of uncontrolled and unidentified variables greatly influence NOx production. These influencing variables are believed to be mill operating conditions (primary air temperatures, air/fuel ratios, flows, grind, and moisture), secondary air non-uniformity (air register settings, forced draft fan bias, and windbox pressure differential), coal variability, etc. The long-term NOx emission vs. load characteristics for the Phases 1 through 3B at Hammond are shown in Figure 3-4 and Figure 3-5. As can be seen in these figures, there are significant variations in the NOx emissions although it is believed there were (1) no changes in burner adjustments and (2) operating procedures did not vary during the data collection periods. Further evidence of this long-term variation is shown in Figure 3-6. As shown, NOx emissions increased over the approximate five-month test period by nearly 10%. This increase is likely the result of a general rise in excess oxygen levels that occurred over the period. The cause of the increase in oxygen is not known.

As evidenced above, NOx emissions can be affected by a number of operation factors, especially excess oxygen levels and mills biasing /mills-in-service. The impact of mills-in-service on NOx emissions for the four phases are shown in Figure 3-7 to Figure 3-10. For Phase 1 (Baseline), on average, during the long-term period, NOx emissions were less when “C” mill (top elevation /front wall) was out of service and greater when “B” mill (bottom elevation / rear wall) was out of service, implying that the “C” mill was more of a contributor of NOx than “B” mill. At lower loads, the difference between the best and worse configuration for NOx was approximately 0.3 lb/MBtu or 30% of the nominal level (~ 1.0 lb/MBtu). The spread was similar during the AOFA phase (Figure 3-8). However for this phase, the best configuration for NOx excluded “D” mill while the worse configuration for NOx excluded “F” mill. During both of these phases (Baseline and AOFA), the unit was equipped with FWEC Intervane burners. For the LNB and LNB+AOFA phases, the NOx dependency on mills-in-service was much reduced in absolute terms from that which had been previously observed (Figure 3-9 and Figure 3-10, respectively). However, on a percentile basis, the variation remained in the neighborhood of 25% at low loads. During the LNB and LNB+AOFA test phases, FWEC’s CF/SF low NOx burners were on the unit.

As with NOx emissions, parameters which affect boiler efficiency, and thereby unit heat rate, varied considerably during the long-term test periods. Boiler efficiency can be estimated by either the input/output method or loss method, with the latter method generally considered the most robust for coal-fired boilers. The major losses are dry flue gas, moisture in fuel, moisture from combustion, unburned combustibles, and radiation. The magnitudes of these losses vary with numerous parameters including boiler design, fuel type, load, and ambient conditions. Typical levels are as follows:

Loss	Typical Level
Dry flue gas	4.5
Moisture in fuel	1.5
Moisture from combustion	3.7
Unburned combustibles	0.2
Radiation and convection loss	0.2
Manufacturer margin and unaccounted	1.5

[CE, 1991]

Of these losses, the dry flue gas loss and unburned combustibles are the ones impacted by operating conditions which may be subject to optimization. For example, a basic calculation for dry flue gas loss can be expressed as follows [Hill, 1987]:

$$L_{dfg} = (T_{go} - T_{ai}) \cdot \left[k_1 + k_2 \cdot (1 + O_2)^2\right]$$

where:

L_{dfg} = Dry flue gas loss

T_{go} = Gas outlet temperature

T_{ai} = Air inlet temperature

O_2 = Excess oxygen

k_1 , k_2 = Constants

In addition to the direct impact on this loss, excess oxygen can also affect the economizer outlet and air heater outlet gas temperatures. More detailed procedures can be found in the ASME Performance Test Codes and other references [ASME, 1985] [CE, 1991] [B&W, 1992]. An example of the variations of some of these process variables from Phase 1 testing are shown in Figure 3-11. The dry flue gas loss variation (upper 95th to lower 95th percentile) averaged about 0.5% and in general was greater at the lower load ranges. This increased variation is likely the result of more operating flexibility (such as mill selection) at the lower loads.

More detail on the excess oxygen and economizer outlet temperatures for Phase 1 are shown in Figure 3-12 and Figure 3-13. As shown, the bias between the “A” and “B” sides was nearly 1% for most of the load range with the “B” side being the higher for all circumstances. The “B” side economizer outlet temperatures were also higher than the “A” side temperatures for most of the load range. Although it varies from furnace to furnace, balancing the furnace tends to improve overall boiler performance.

In summary, it was evident from results from Hammond 4 and elsewhere that operational adjustment has the potential for reducing NOx emissions, improving boiler performance, and mitigating the adverse impacts of low NOx burner retrofits.

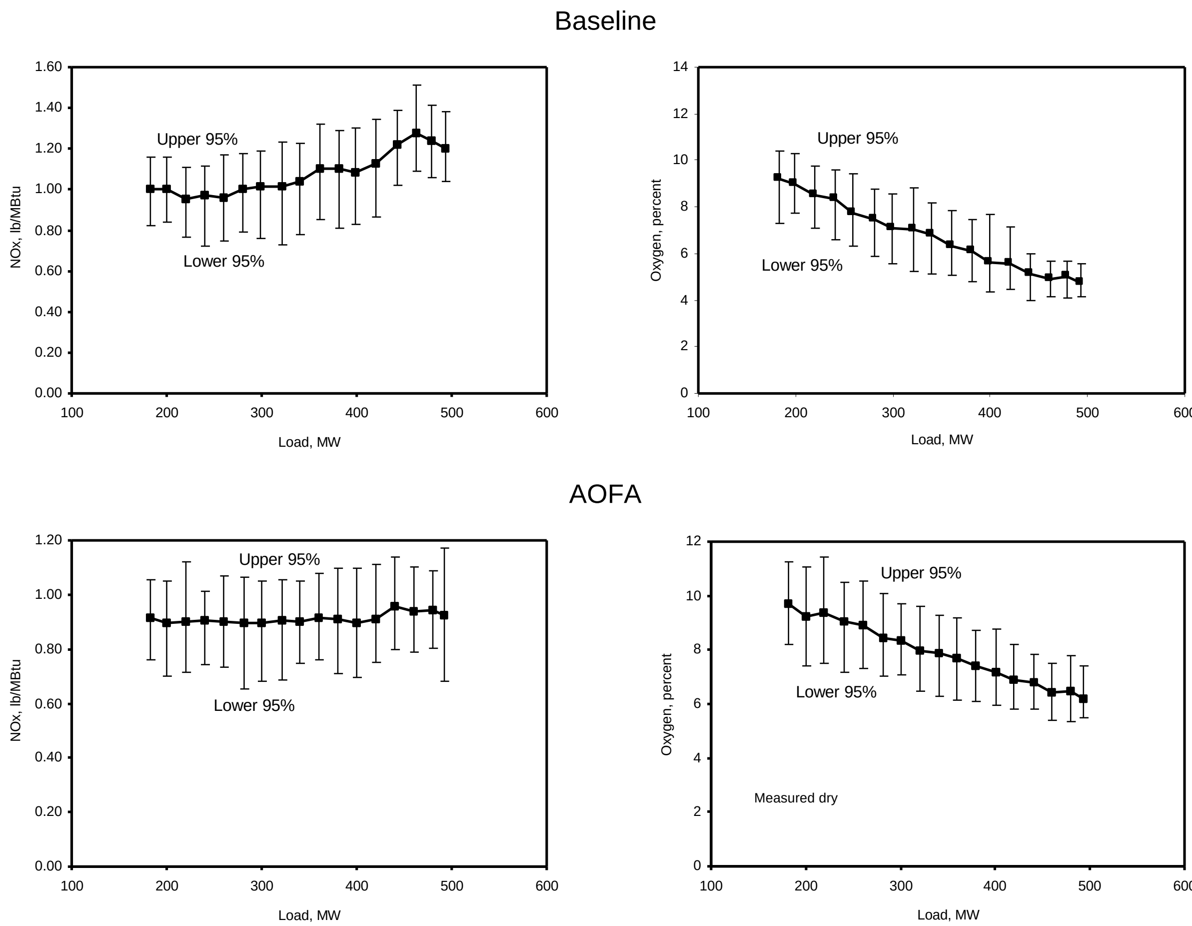


Figure 3-4 NOx and Stack O2 vs. Load (Phases 1 and 2)

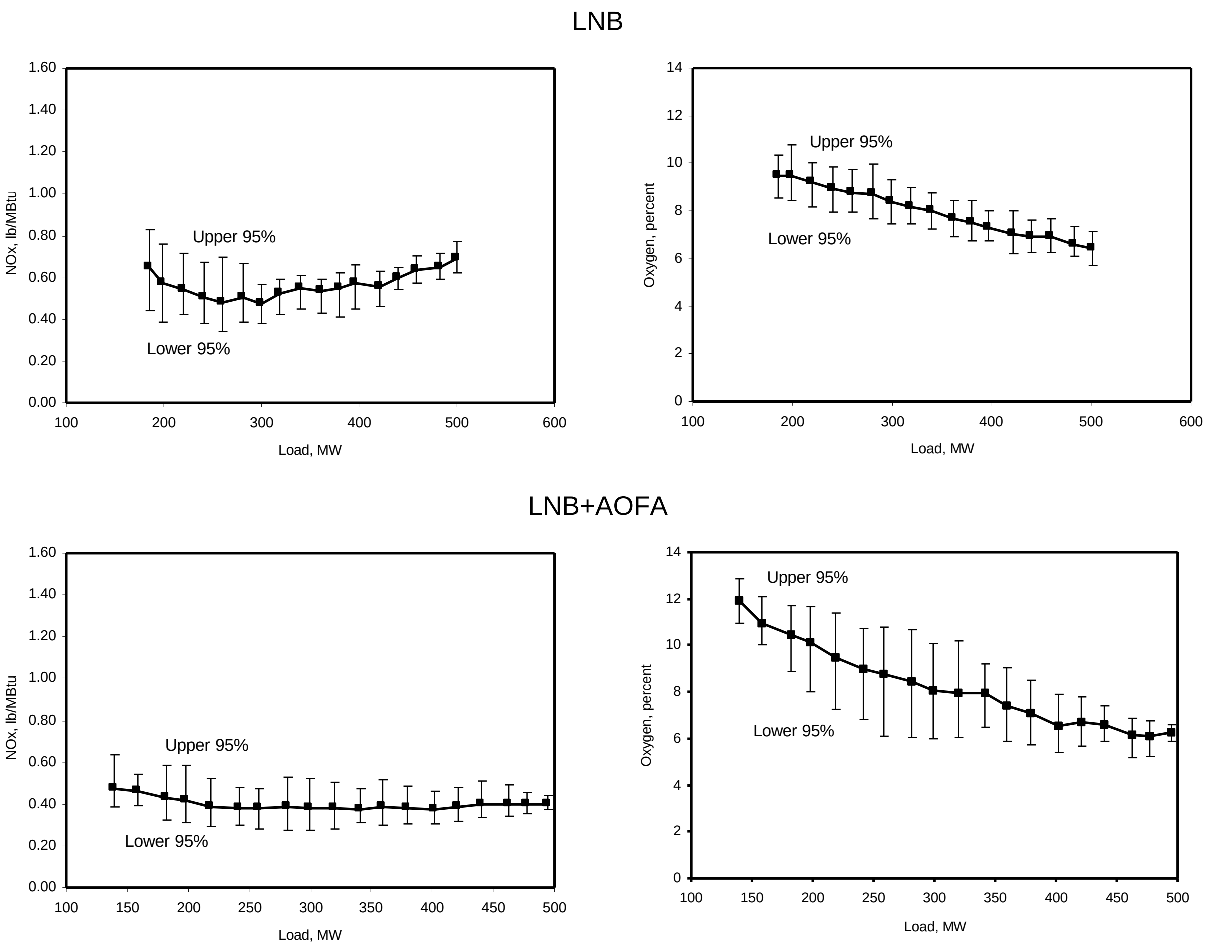


Figure 3-5 NOx and Stack O2 vs. Load (Phases 3A and 3B)

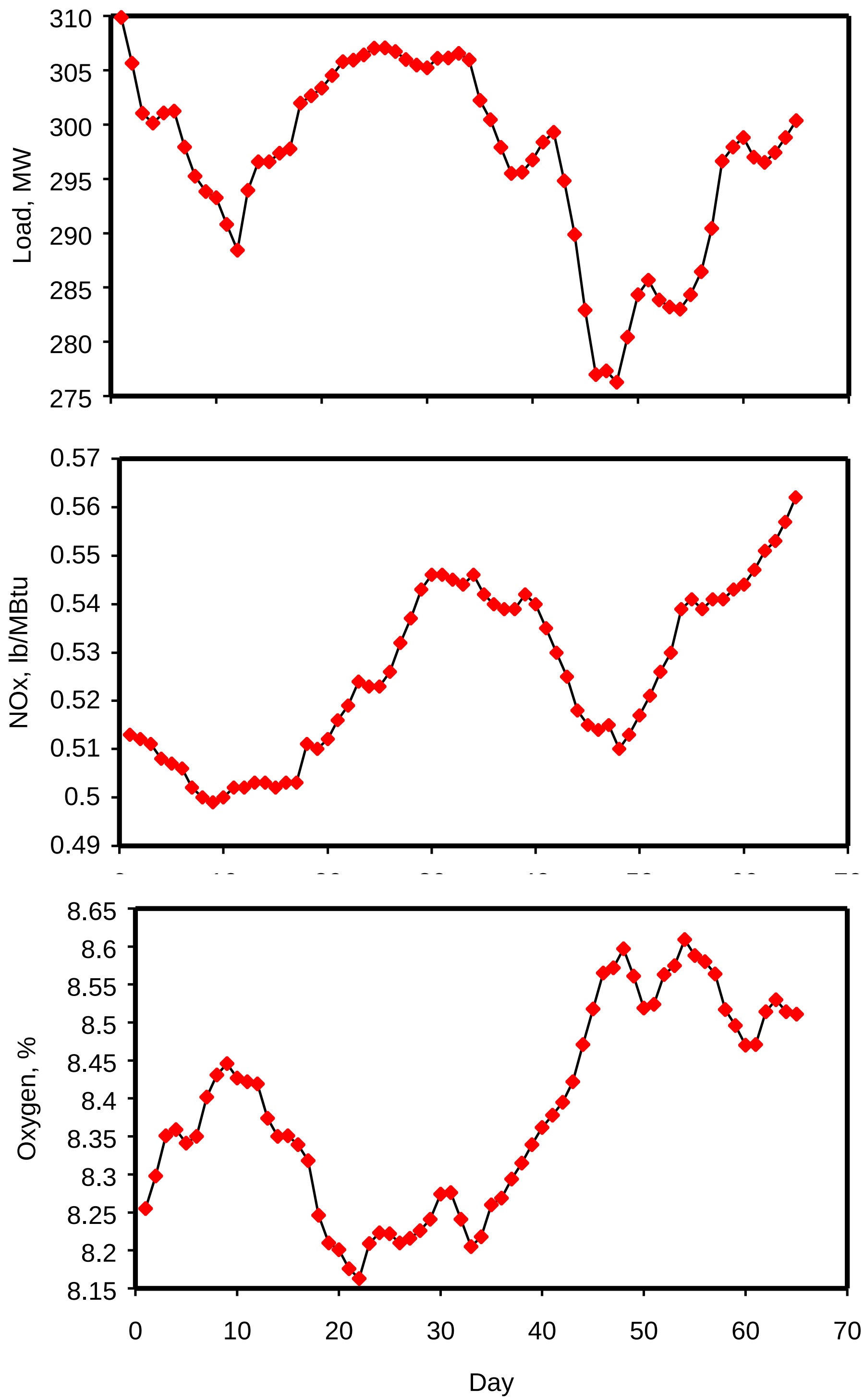


Figure 3-6 LNB / Long-Term 30 Day Rolling Average

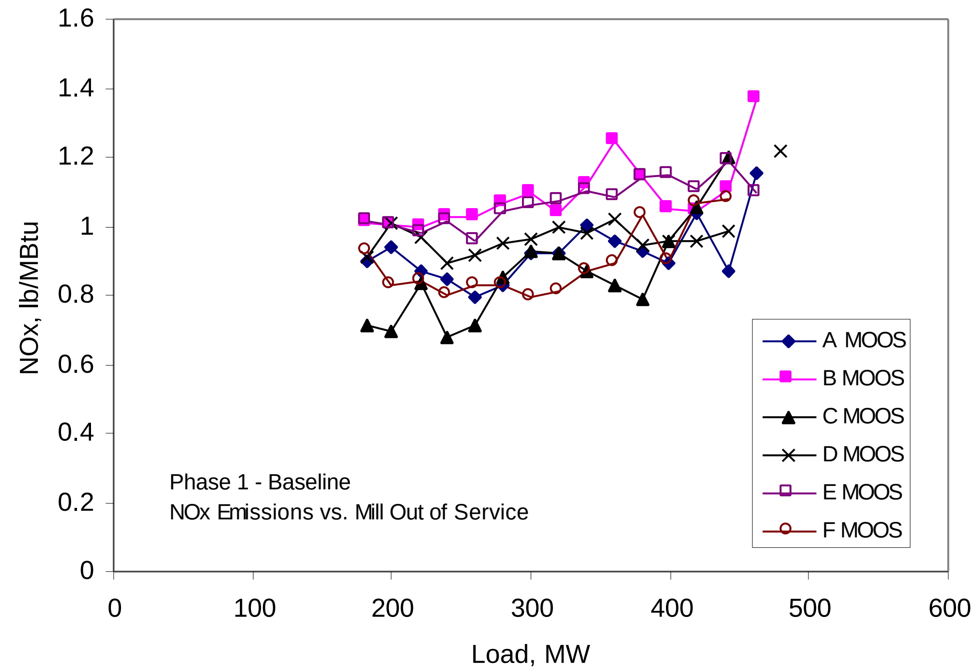


Figure 3-7 NOx vs. Load vs. MOOS (Phase 1)

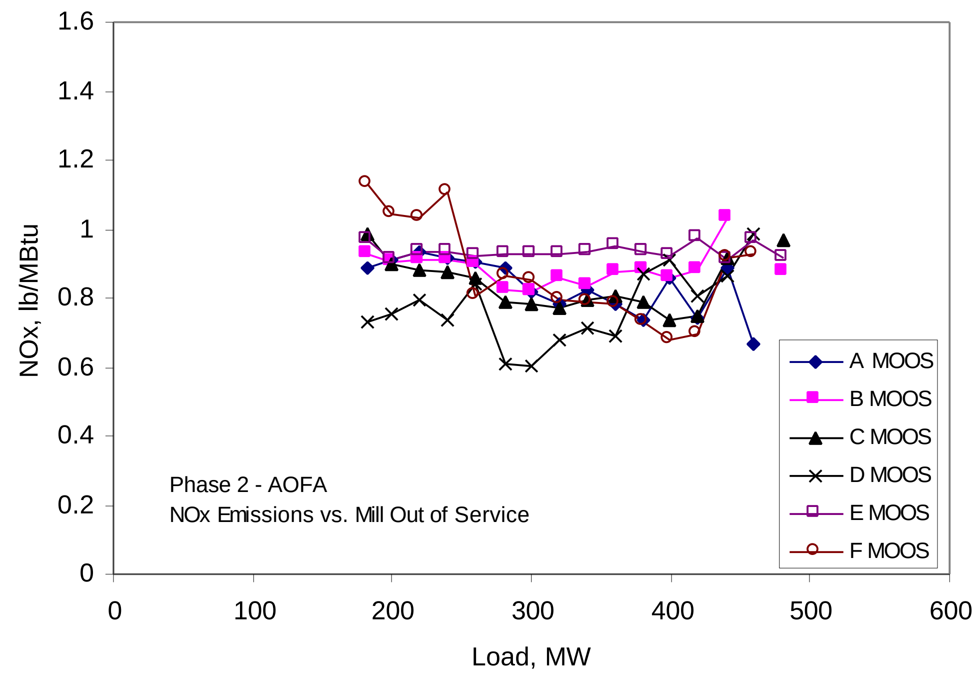


Figure 3-8 NOx vs. Load vs. MOOS (Phase 2)

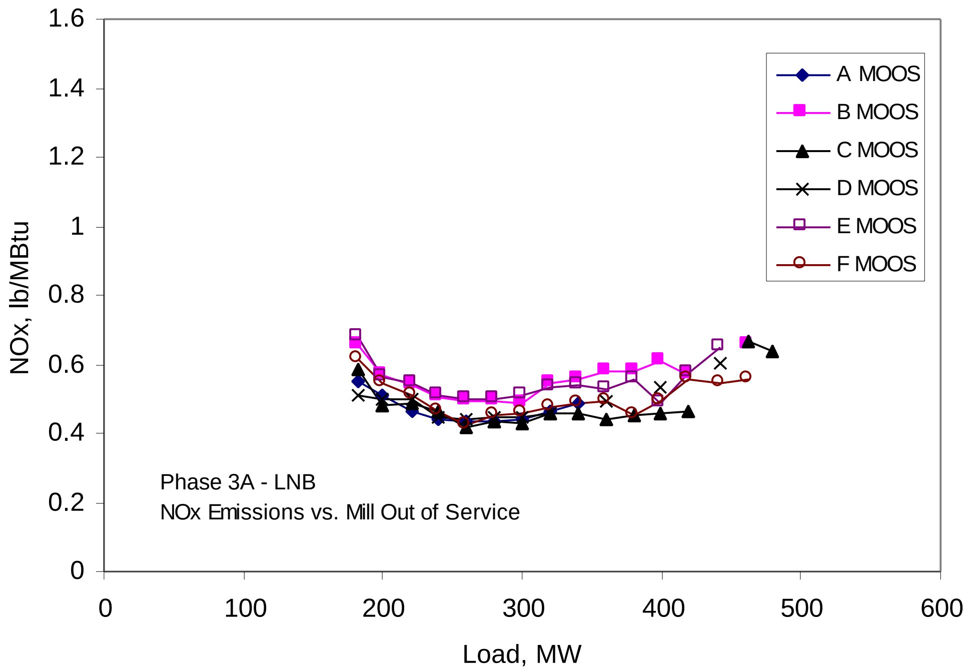


Figure 3-9 NOx vs. Load vs. MOOS (Phase 3A)

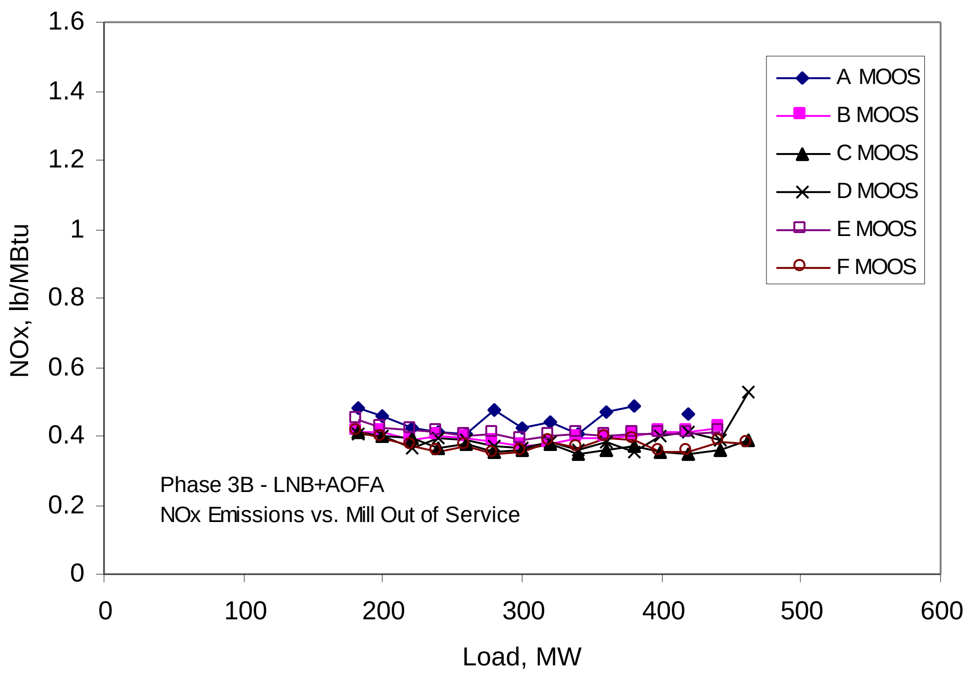
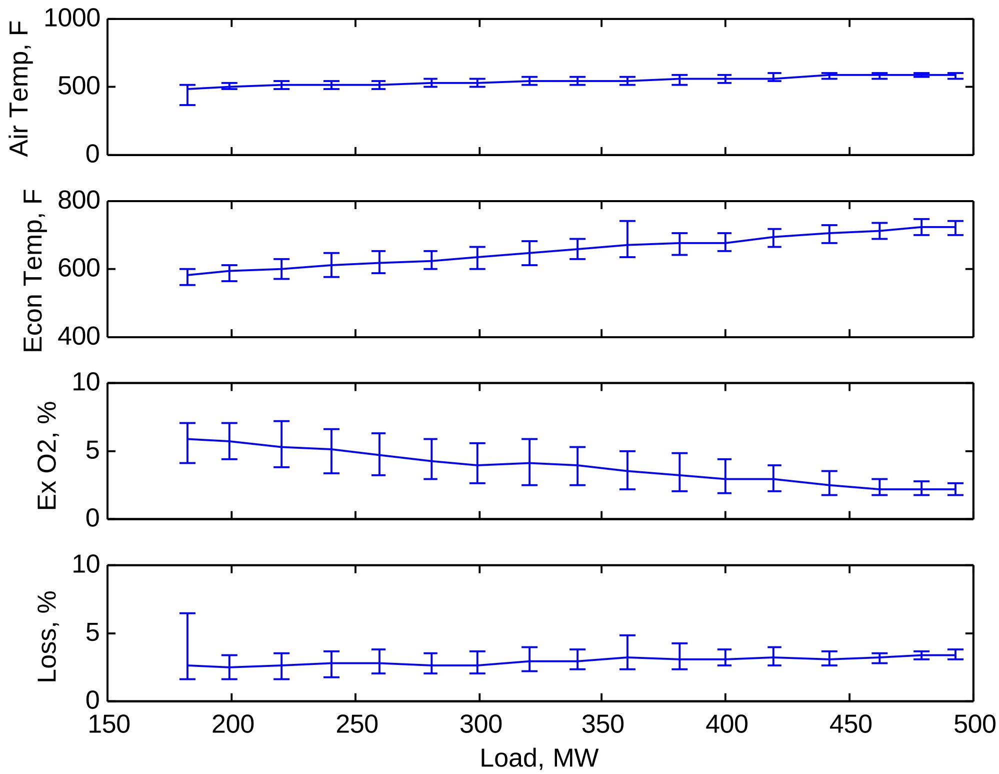


Figure 3-10 NOx vs. Load vs. MOOS (Phase 3B)



Mean, upper 95th, and lower 95th percentiles shown

Figure 3-11 Dry Flue Gas Loss Variations with Load (Baseline)

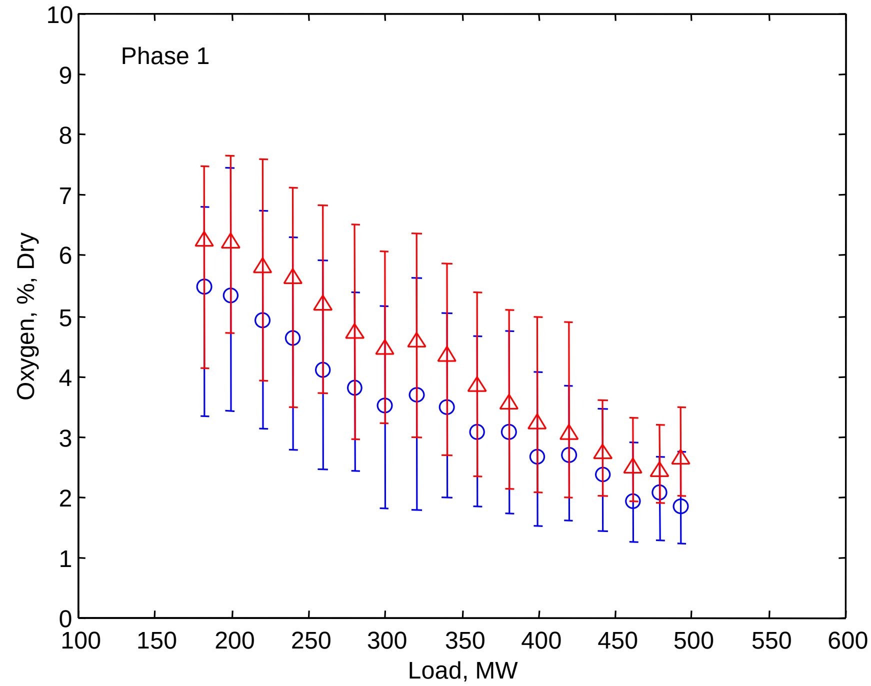


Figure 3-12 Excess Oxygen Variations with Load (Baseline)

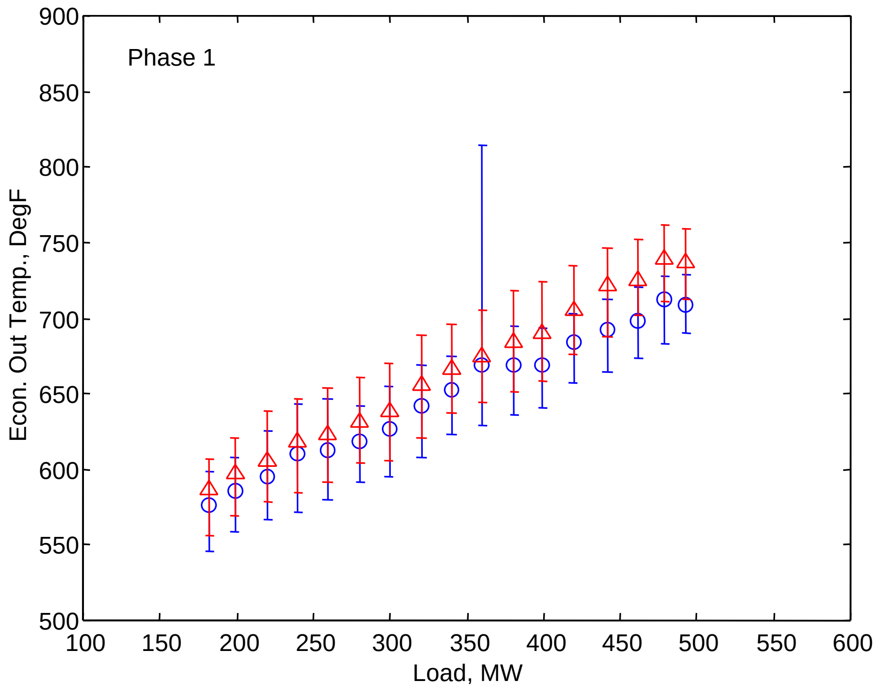


Figure 3-13 Economizer Outlet Temperature Variations with Load (Baseline)

3.2 Potential Benefits of the DCS

In addition to the potential benefits that on-line continuous optimization might provide during steady-state unit operation, there was also reasonable probability that the installation of the DCS might itself provide benefits. Potential benefits include improved unit heat rate, extended equipment life, improved capability, improved availability, and faster loading rate [EPRI, 1992].

Improved plant heat rate. A DCS should provide better control of plant parameters than the control system (typically pneumatic or electronic) that it replaces. If the DCS does better control the unit to setpoint then there is some likelihood that there may be efficiency improvements, however, this is not always the case. These possible improvements can relate to either (1) eliminating the bias between desired operating point and actual operating point, (2) better dynamic control and reduced oscillation of the process, and (3) improved process information.

An example of the possible improvement that may result from the elimination of process bias is shown in Figure 3-14 in which three scenarios for steam temperatures are shown. For the lower trend, the control system controls steam temperature to an average of 990°F with ±5°F. The offset could be the result of a combination of (1) instrument inaccuracies, (2) control system inaccuracies (especially for pneumatic systems), or (3) setting of the setpoint to 990°F by plant staff to minimize transients above 1000°F. If the DCS produces the temperature trend shown in the middle, there would be a heat rate improvement due to higher steam temperatures all else being equal. In general, a 10°F increase in steam temperature produces a 0.15% increase in turbine cycle heat rate [ASME, 1985]. On the other hand, the pre DCS retrofit trend could be as shown in the top. If this were the case, the DCS' better control of steam temperature would tend to decrease heat rate (the heat rate correction is linear about the design point, and therefore, a 10°F decrease in steam temperature produces a 0.15% decrease in turbine cycle heat rate). This same argument also applies to reheat temperature, steam pressure, excess oxygen, and perhaps others. Michael has reported that heat rate improvements of up to 1.5% may be achieved if the unit is controlled better to setpoint [EPRI, 1992], however the assumption in this report is that reducing the biases are all to the advantage of heat rate.

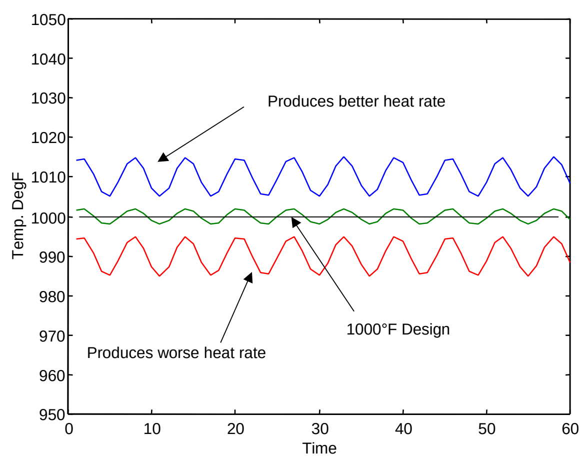


Figure 3-14 Steam Temperature vs. Heat Rate

As to the benefits to heat rate from reduced oscillation, based on dynamic computer modeling studies performed by Anderson, heat rate improvements of 0.5% would be obtainable on gas fired units [Anderson, 1989]. Another study by Chang found that unit dynamics had little impact on heat rate during unit regulatory dispatch with the majority of the impact occurring in the boiler [EPRI, 1982]. Chang speculated that the cause of the heat rate insensitivity to unit dynamics were due to (1) the changes in the stored energy of the boiler are very small as compared to the absolute level of stored energy and (2) the relative linearity of the stored energy changes as a function of input energy change. Note that the Chang study was different from the Anderson work in that the latter addressed degradations from process oscillations while the former looked at transients resulting from load dispatching. Chang also found that the effect of short duration transient mismatches between air and fuel resulted in only small cycling losses. Although Chang found that the transient inefficiencies were small, the difference between the heat rate when the unit is ramping down as opposed to ramping up is on the order of 7 to 10% (700 – 1000 Btu/kWh).

As pointed out by Michael, a consideration in evaluating this benefit is if the better control allowed the setpoint to be brought closer to the design point [EPRI, 1992]. The example given in this report is that when main steam temperature is not adequately controlled, the plant operator may lower the setpoint below the design value to prevent the steam temperature at the high excursions from exceeding the design value (Figure 3-15).

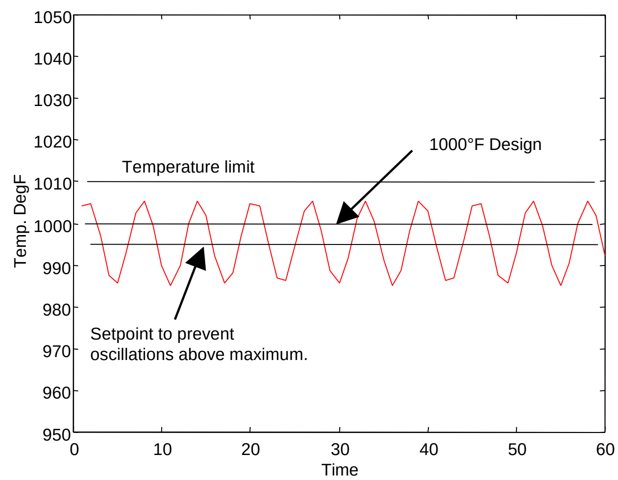


Figure 3-15 Steam Temperature vs. Heat Rate

Perhaps the most important factor in the DCS ability to improve heat rate is that process data is more readily available and tends to be of higher quality than that available from older control systems and therefore plant staff can better manage the unit's performance.

It is difficult to generalize whether a DCS will improve unit heat rate, due to varying fuels, capacity factors, equipment type, and equipment conditions. However, previous data collected on Southern Company units have found that on similar units, DCS equipped units tend to have better heat rates than those units without a DCS.

Extended plant equipment life spans. There is potential for lengthening the life spans of plant equipment by reducing the cycling (thermal and other) of the unit. There have been numerous studies which have dealt with these issues [EPRI, 1987][Riccardella, 1987][Weinstein, 1988].

Improved unit availability. Trips associated with the control system should be reduced with a DCS. Also, the time required to correct problems with a DCS should be less than that of either pneumatic or other control systems. A secondary effect is that equipment is less stressed thus improving availability since these components are less likely to fail [EPRI, 1992].

Improved unit flexibility and loading rate. Improved AGC response and wider operating ranges should be achievable with a DCS. For the latter, a lower unit minimum may be achievable due to better unit control than may be achieved with a non-DCS control system. As for AGC response, there is general recognition that an improved AGC response is of monetary benefit to a utility; however, there is no consensus on a methodology for calculating these benefits. In their report *Control System Retrofit Guidelines*, EPRI provides one approach [EPRI, 1992].

A description of these benefits and methodology for calculating the benefits can be found elsewhere [EPRI, 1992].

Pre-DCS retrofit data specific to Hammond 4 is shown in Figure 3-16 through Figure 3-28 for the period March 2, 12:00 noon to March 3, 12:00 noon. The load, excess O_2, stack O_2, and NOx emissions for a twenty-four hour period during baseline are shown in Figure 3-16 through Figure 3-19. As shown, the unit operated from minimum (~170 MW) to maximum (~480 MW) during this period. Excess O_2 varied from nearly 2% to 8% with considerable bias between the "A" and "B" ducts. Stack O_2 varied from a low of about 5.5% at the higher loads to near 10% at minimum load. There was a "high" frequency (peak-to-peak cycle of about 15 minutes) component to the stack O_2 of about 0.5 percentage points. The cause of this component is not known, but it appears not to have affected the NOx readings (Figure 3-19). Finer time resolution is provided in Figure 3-20 through Figure 3-28. Although the 5-minute storage rate on the data acquisition somewhat limits dynamic analysis, several possible control related features are evident in these plots:

- There was a considerable split in excess oxygen between the "A" and "B" sides, especially at lower loads (2 percentage points) (Figure 3-20).
- Excess oxygen (both at the economizer outlet and stack) exhibited some overshoot at both the start and end of the low load period (Figure 3-21 and Figure 3-22).
- NOx emissions at the start and end of the low load period were greater than the nominal NOx level during this period (Figure 3-23). However, NOx emissions showed a sharp decrease during the high-to-low and low-to-high transitions. The control system is generally set up to cross-limit the combustion airflow during these load transitions, thereby supplying more combustion air than is normal for steady-state operation. Although it is normally expected that increased combustion air results in increased NOx emissions, this was not the case for these transitions.
- Superheat and reheat temperatures showed considerable variation from design values (1000°F) especially at the load transitions (Figure 3-25 and Figure 3-26). On average, the temperatures were below design thereby adversely affecting heat rate (for superheat and reheat, there is approximately 15 Btu/kWh penalty for 10°F temperature deviation from design).
- Throttle pressure varied considerably, especially at the load transitions (Figure 3-27). The low-to-high transition produced higher throttle pressures, which tend to decrease heat rate (100 psi deviation yields 40 Btu/kWh change in heat rate).
- The "B" air heater gas outlet temperature was positively biased over the "A" side, as was the excess oxygen (Figure 3-28). Not necessarily control related, this temperature and excess differential could be the result of (1) differing air heater performance, including air inleakage, (2) furnace backpass air inleakage, (3) burner imbalances, and (4) secondary combustion air maldistribution. Air heater gas inlet temperatures also showed a bias from side-to-side (Figure 3-29).

3.3 Summary

In summary, there was considerable evidence that the installation of a DCS and an on-line combustion optimization system such as GNOCIS had a high likelihood of improving unit performance both in terms of emissions and heat rate.

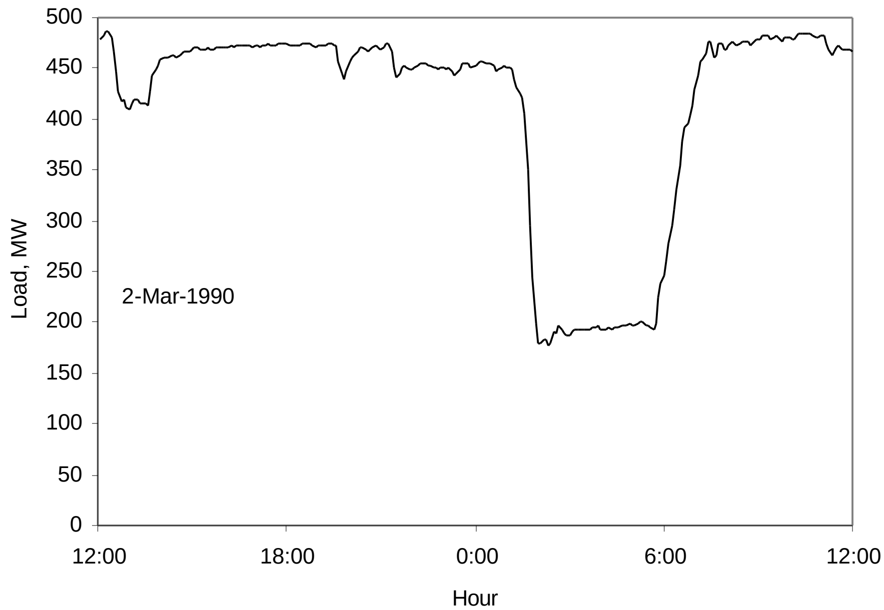


Figure 3-16 Load Response (Baseline)

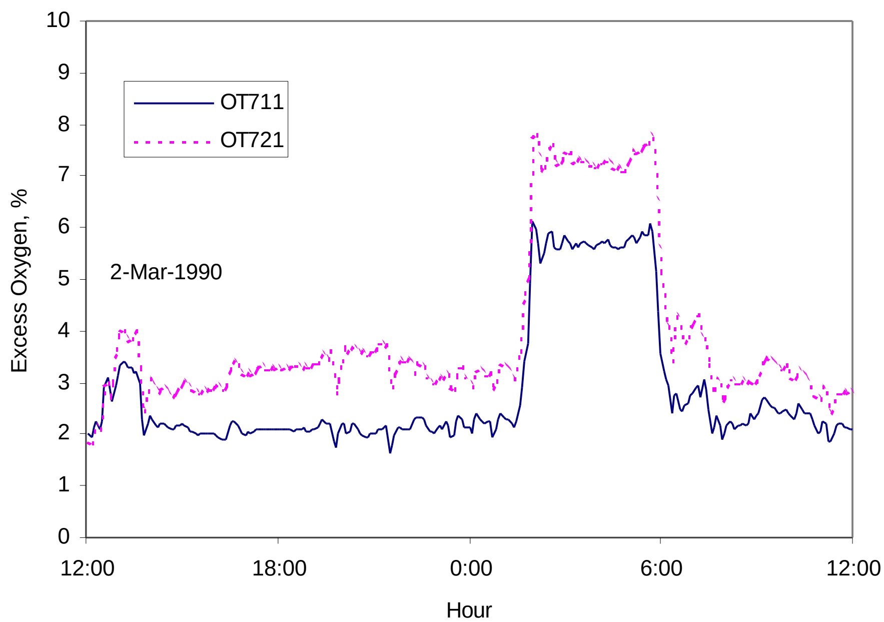


Figure 3-17 Excess Oxygen Response (Baseline)

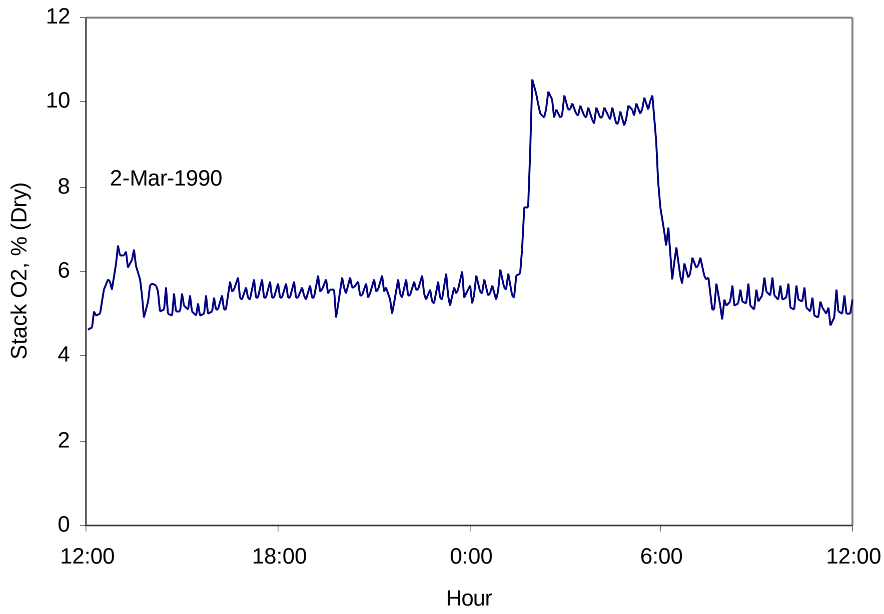


Figure 3-18 Stack O_2 Response (Baseline)

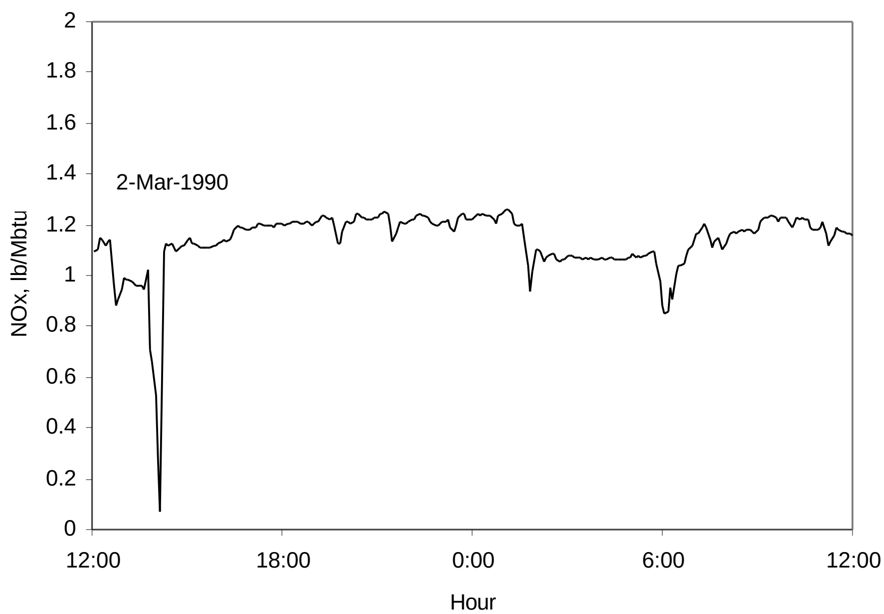


Figure 3-19 NOx Emissions Response (Baseline)

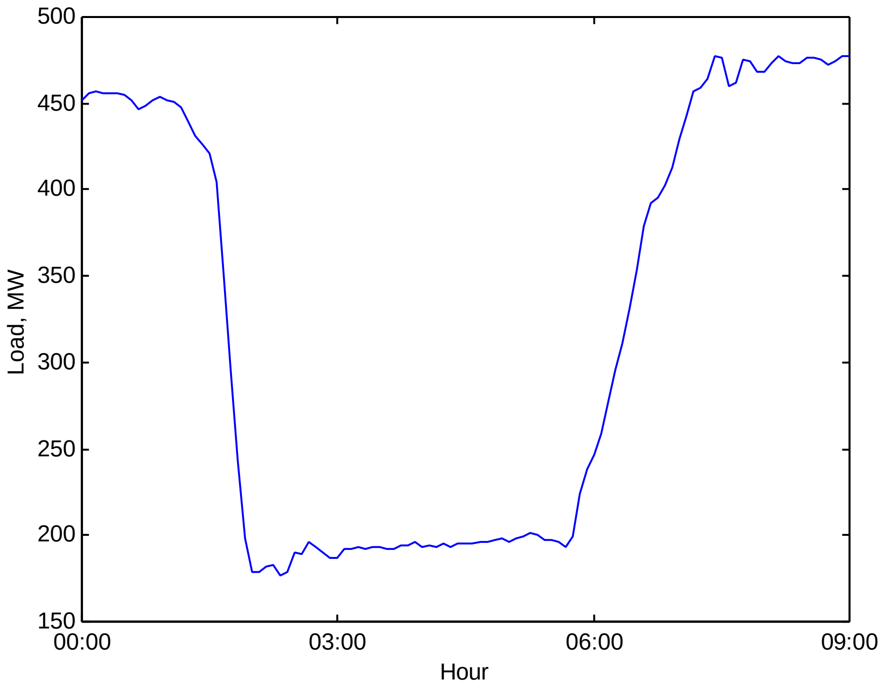


Figure 3-20 Load Response (Baseline)

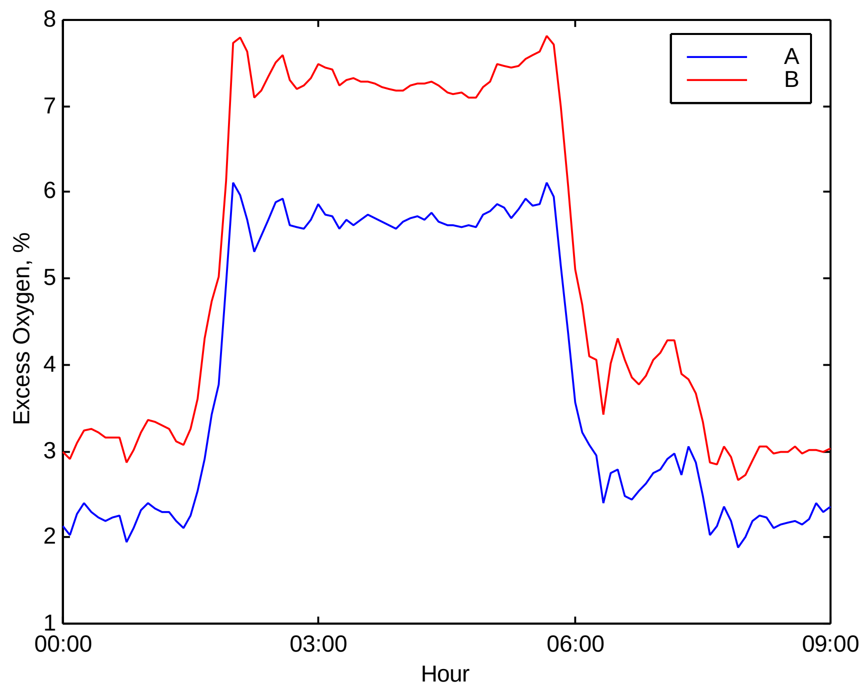


Figure 3-21 Load Response (Baseline)

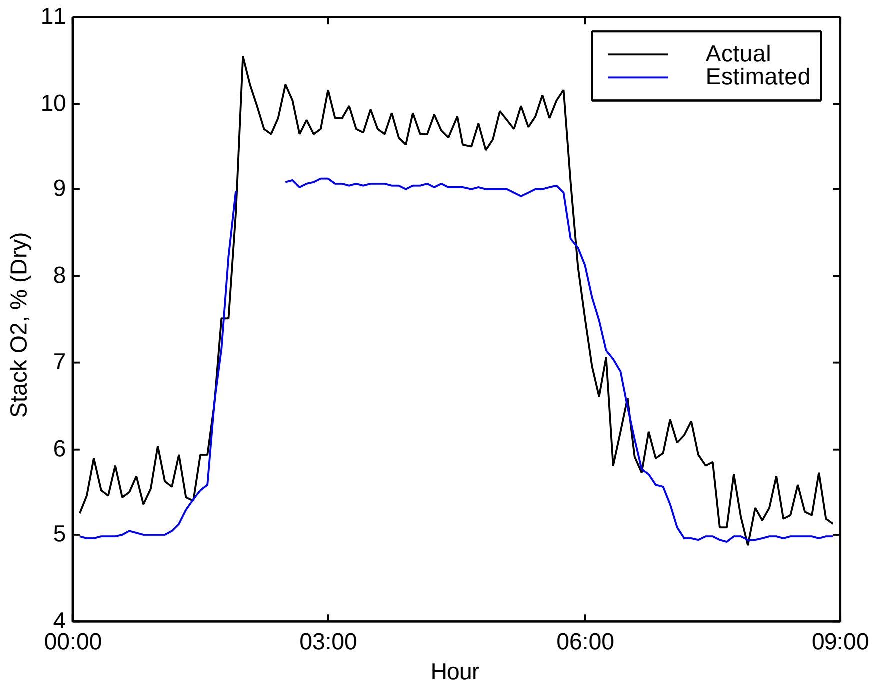


Figure 3-22 Stack O_2 Response (Baseline)

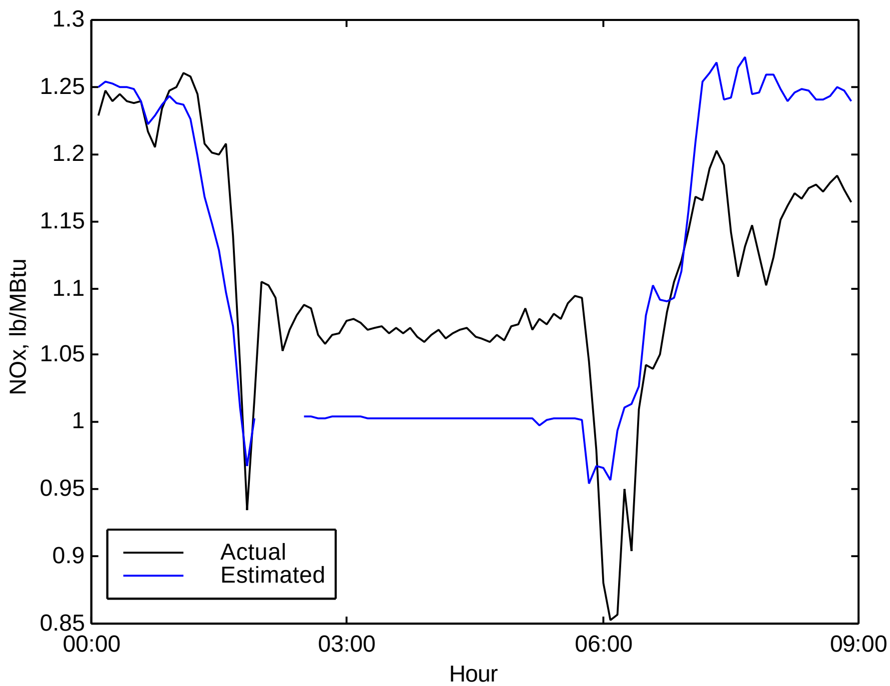


Figure 3-23 NOx Response (Baseline)

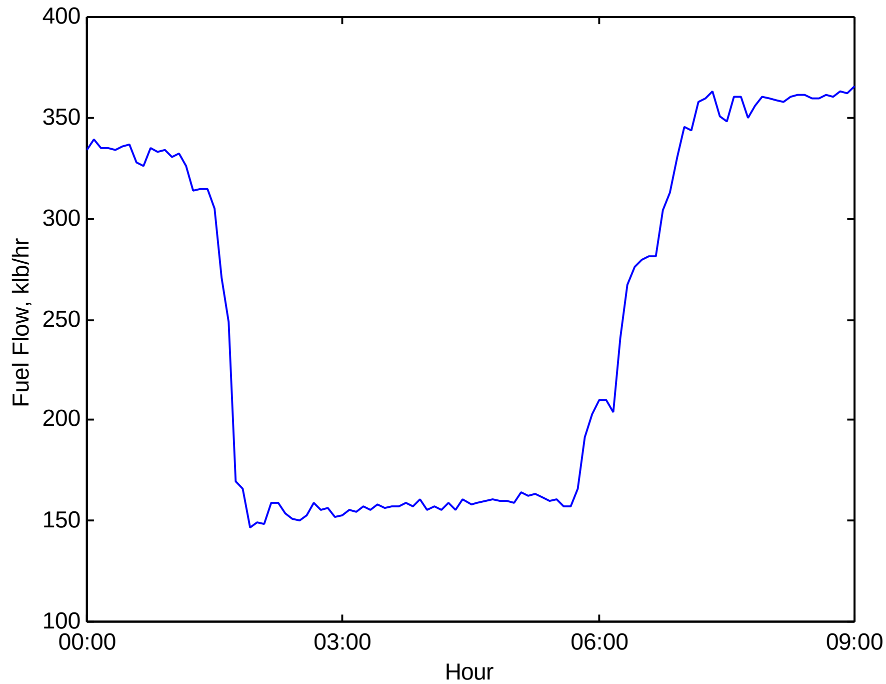


Figure 3-24 Fuel Flow (Baseline)

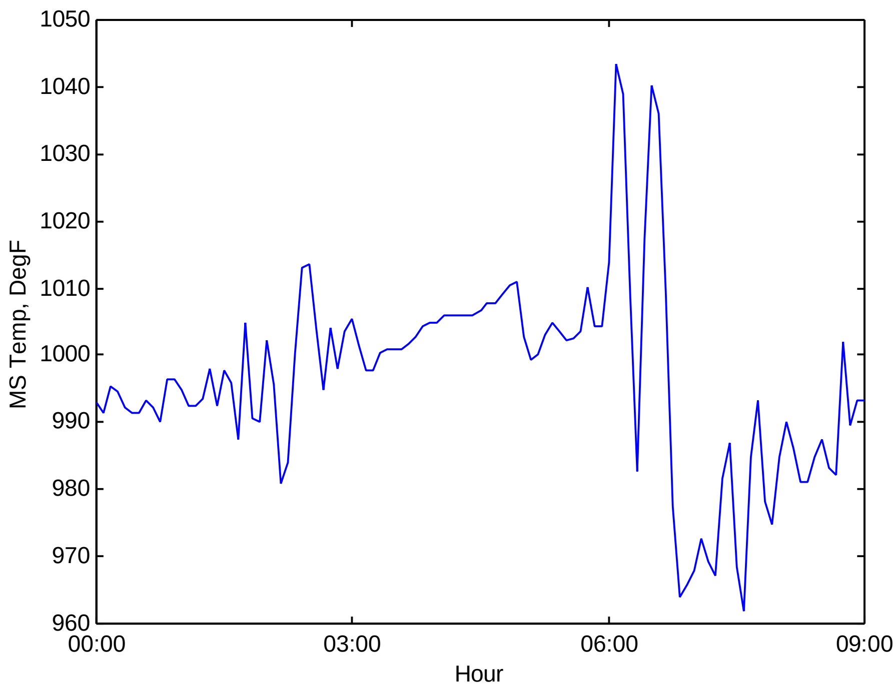


Figure 3-25 Throttle Temperature Response (Baseline)

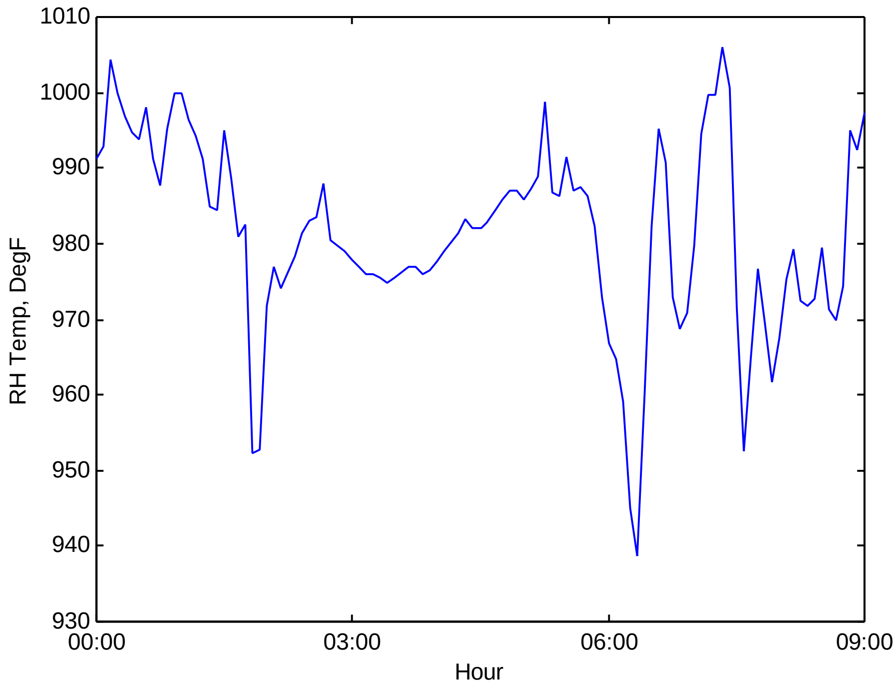


Figure 3-26 Reheat Temperature Response (Baseline)

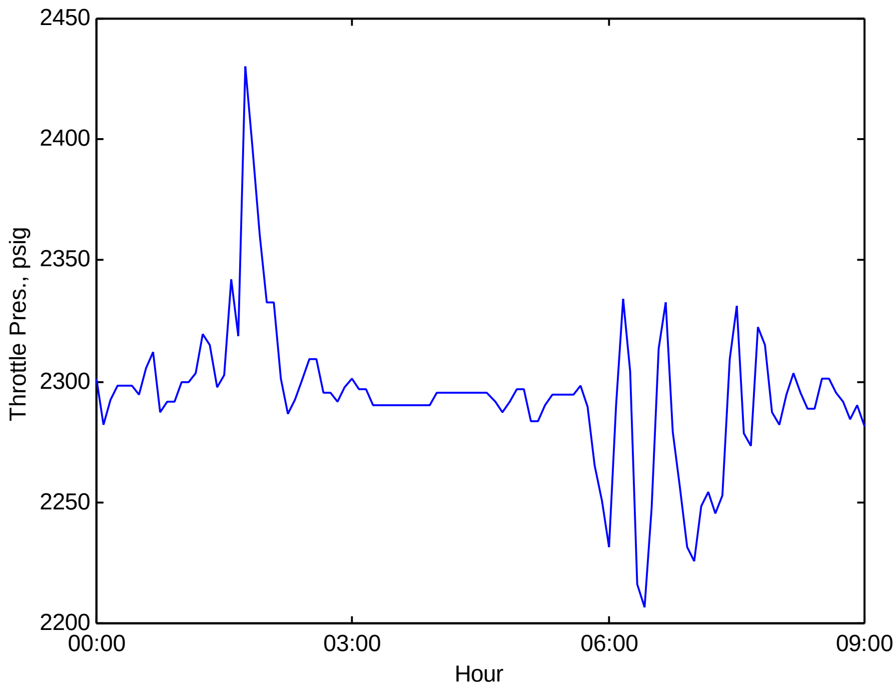


Figure 3-27 Throttle Pressure Response (Baseline)

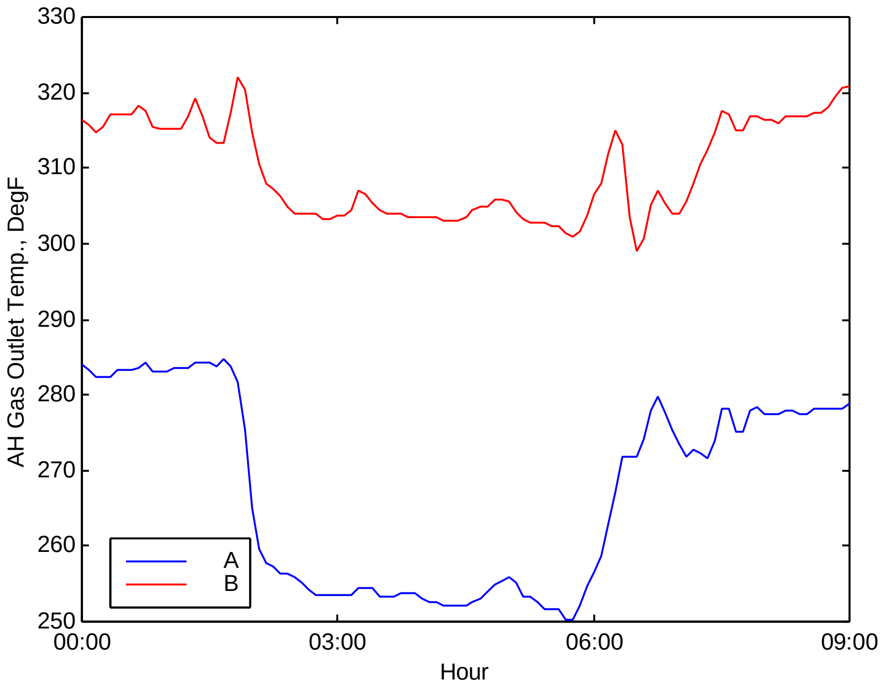


Figure 3-28 Air Heater Outlet Temperature Response (Baseline)

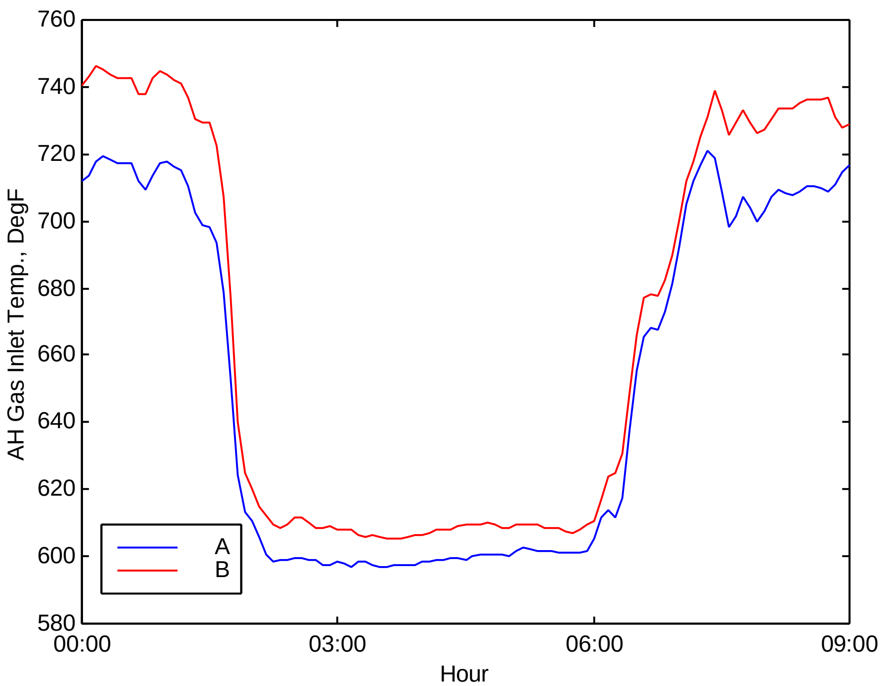


Figure 3-29 Economizer Outlet Temperature Response (Baseline)

4 PHASE 4A - DCS

The overall goal of Phase 4 of the project was to evaluate the impact of digital control systems and on-line optimization techniques to NOx emissions, boiler efficiency, and other unit operational aspects. As part of this overall effort, several distinct test efforts were conducted:

- Characterization of the combustion characteristics of the unit following an extended outage including diagnostic and performance testing.
- LOI testing for the purpose of (1) further characterizing the unit and (2) evaluation of several on-line carbon-in-ash analyzers.
- GNOCIS testing to evaluate the performance of the on-line, continuous optimization tool selected for demonstration for this phase of the project.

The findings from the testing of the DCS as it applies to emissions and performance characteristics of the unit are discussed in this section. Findings related to the evaluation of the on-line carbon-in-ash analyzers are reported elsewhere [SCS 1997].

Several aspects of the test program differed from the prior phases, the most important of which are that the determinations of flue gas SO_3 concentration, fly ash chemical composition, and fly ash particle size distribution were deleted from the test matrix. Other than the known impact of excess oxygen on the SO_2-to-SO_3 conversion rate, it was highly unlikely the unit modifications and operational changes would have any affect and therefore they were deleted for economic reasons.

On September 3, 1993, Hammond 4 began a major outage. Activities during this outage included (1) installation of a distributed digital control system, (2) installation of a new precipitator, (3) upgrades to the steam turbine, and (4) replacement of the two remaining FWEC Planetary and Table type mills (mills B and D) with Babcock and Wilcox MPS 75 mills. Following the nine-month outage, coal-fired operation resumed at Hammond Unit 4 on June 5, 1994.

Diagnostic testing took place during August 1994. Additional diagnostic testing and modified performance type testing was conducted during November 1994. The purpose of these tests was to determine the emissions and performance characteristics of the unit subsequent to the major modifications to the unit. Following the installation of two of the three on-line carbon-in-ash analyzers to be evaluated, a series of LOI tests was performed during August 1995. After the installation of the third analyzer, another LOI test series was conducted during February 1996.

4.1 Phase 4A Testing

4.1.1 Diagnostic Testing

Preliminary diagnostic testing was conducted from August 5, 1994 to August 8, 1994. Diagnostic testing continued on November 2, 1994 through November 18, 1994. In total, 51 tests were conducted at four nominal load conditions (300, 400, 480, and 520 MW). A summary of these tests can be found in Table 4-1 with further information provided in Appendix A.

<u>NOx Emissions</u>

The primary purpose of these tests was to determine the short-term NOx emissions characteristics particularly as a function of excess oxygen but also overfire air and mill biasing. As shown in Figure 4-1 and Figure 4-2, excess oxygen and overfire air levels were exercised well above and below "normal" levels yielding variations in NOx emissions (Figure 4-3) from approximately 0.35 to 0.55 lb/MBtu at full load (480 MW) and 0.35 to 0.45 lb/MBtu at the low intermediate load (300 MW). Based on these O_2 variations, the NOx vs. O_2 gradient was determined for each of the three loads tested. As can be seen in Figure 4-4, at 480 MW, NOx emissions were highly dependent on excess O_2 and, apparently, to a great extent, a linear function of excess O_2 over the range tested ($R^2 > 0.97$). Also, it is apparent from this figure that the emission characteristics of the unit during the August 1994 testing were considerably different than that observed during the November testing with the latter being approximately 0.1 lb/MBtu less at the same oxygen levels. Also, the November data is more representative of that seen earlier from this unit. The cause of this discrepancy is unknown; however, potential reasons include:

- Change in Burner Tuning - During October 1994, the unit was off-line for approximately one month. During this period, it is conceivable that the burner registers (particularly the inner and outer registers) were adjusted. This is difficult to confirm or rebut since the actual positions of the registers is not accurately portrayed by the indicator at the boiler front and inspection from the windbox is required.

- Increase in Backpass Leakage - If furnace backpass leakage increased as a percentage of total combustion air between the August and November tests, for a given economizer exit oxygen level, the amount of combustion air in the combustion zone would be reduced. The reduced combustion air would lead to decreased NOx emission levels.

- Change in Sampling Line Leakage - Air infiltration into the ECEM sampling lines or bubbler would affect the excess oxygen level measured. Since the leakage would have no impact on O_2 corrected NOx measurements, it would shift the NOx vs. Excess Oxygen curve to the right. This hypothesis is somewhat supported by other process data

Similar results were found at 400 MW and 300 MW load levels (Figure 4-5 and Figure 4-6). Comparisons of the sensitivities at the three loads tested are shown in Figure 4-5. As shown, NOx emissions sensitivity to excess O_2 decreased with decreasing load (Figure 4-7). For comparison, the sensitivities determined from prior phases of the project are shown in Table 4-2.

As can be seen, sensitivities varied greatly from phase-to-phase for a given load. The explanation for the variation is unknown at this time, however, a contributing factor is likely the relative (as compared to the latest testing) non-repeatability of the short-term tests during prior phases (Phases 1, 2, 3A, and 3B) and the resultant influence of this non-repeatability on sensitivity determination. For the testing conducted during August 1994, NOx emission characteristics were more repeatable than what had been observed in prior phases.

As can be seen in Figure 4-7, short-term, full load NOx emission levels were near 0.49 lb/MBtu at design excess O_2 levels. This NOx emission level is above that experienced during the prior LNB plus AOFA test phase (Phase 3B) for which full load, normal excess O_2 emission levels were approximately 0.40 lb/MBtu. This increase in NOx emissions was also evident at the lower test loads (400 MW and 300 MW). The reduction could be the result of several factors including:

- AOFA Flow Rates - Indicated AOFA flow rates were below those used in the previous phase. Design AOFA flow rate is 800 klb/h at full load whereas during the August 1994 tests, AOFA rates were approximately 640 klb/h.

- Mill Biasing - The inadvertent mill bias existing during Phase 3B which led to reduced NOx emissions may have no longer existed.

- Coal Properties - The coal used during the August 1994 testing could have been more favorable to NOx production.

- Selection of short-term test conditions which were not representative of long-term operation.

<u>CO Emissions</u>

As experienced during prior phases, CO emissions were relatively low -- generally below 50 ppm -- at recommended excess O_2 levels. At full load, as excess O_2 levels were reduced, CO emission levels rose producing the familiar “knee” in emissions (Figure 4-8). A similar CO vs. excess O_2 characteristic was evident in the 400 MW tests. At the 300 MW load, excess O_2 was not reduced sufficiently to generate increased CO emissions.

<u>Response Plots</u>

The response plots (Figure 4-9) show the tradeoffs in combustion optimization. As previously shown, NOx emissions generally decrease with increased excess O_2 whereas CO emissions and LOI generally increase, thereby producing a conflict of goals; i.e. to reduce both NOx, CO, and LOI to a minimum. As can be seen, using excess O_2 alone, NOx emissions could be reduced to below 0.40 lb/MBtu while maintaining CO emissions below 50 ppm and LOI below 8 percent. Similarly, overfire flow affects NOx, CO, and LOI whereas mill bias appears to only affect LOI (at least at full load). Using these variables (excess O_2, OFA flow, and mill biasing) in combination could be used to optimize a combination of output variables (i.e. NOx, CO, and LOI).

Table 4-1 P4A / Diagnostic Tests Conducted

TEST NO.	DATE	TEST CONDITIONS	LOAD MW	MOOS PATRN	OFA FLOW KPPH	Econ. O2 DRY (%)
129-1	08/05/94	HI-LOAD NORMAL O2	486	AMIS	NA	3.0
129-2	08/05/94	HI-LOAD LOW O2	483	AMIS	NA	2.7
129-3	08/05/94	HI-LOAD HIGH O2	483	AMIS	NA	3.9
130-1	08/06/94	MID-LOAD LOW O2	398	B		2.8
130-2	08/06/94	MID-LOAD NORM O2	400	B	297	3.6
130-3	08/06/94	MID-LOAD HIGH O2	398	B	318	4.7
130-4	08/06/94	MID-LOAD NORM O2, DECR OFA	399	B	211	4.0
130-5	08/06/94	MID-LOAD NORM O2	399	E	294	3.7
131-1	08/07/94	MD/LO LOAD LOW O2	300	B,E	119	4.4
131-2	08/07/94	MD/LO LOAD NORM O2	300	B,E	134	4.8
131-3	08/07/94	MD/LO LOAD HIGH O2	302	B,E	143	5.5
131-4	08/07/94	MD/LO LOAD HIGHER O2	301	B,E	133	6.4
132-1	08/08/94	HI-LOAD LOW O2	482	AMIS	650	2.9
132-2	08/08/94	HI-LOAD NORM O2	484	AMIS	658	3.5
132-3	08/08/94	HI-LOAD HIGH O2	479	AMIS	666	4.1
132-4	08/08/94	HI-LOAD FUEL BIASED TO UPPER MILLS	476	AMIS	613	4.1
132-5	08/08/94	HI-LOAD FUEL BIASED TO UPPER MILLS	479	AMIS	596	3.4
133-1	11/02/94	MID-LOAD NORMAL O2	401	B	278	4.0
133-2	11/02/94	MID-LOAD HIGH O2	401	B	276	4.8
133-3	11/02/94	MID-LOAD NORMAL O2	400	B	284	3.6
133-4	11/02/94	MID-LOAD LOW O2	401	B	278	2.8
133-5	11/02/94	MID-LOAD LOW O2	400	E	289	3.2
133-6	11/02/94	MID-LOAD NORMAL O2	401	E	306	4.2
134-1	11/03/94	MID-LOAD NORMAL O2 BAL MILLS	400	B	285	3.6
134-2	11/03/94	MID-LOAD FUEL BIASED TO LOWER MILLS	400	B	287	3.5
134-3	11/03/94	MID-LOAD FUEL BIASED TO UPPER MILLS	400	B	276	3.7
134-4	11/03/94	MID-LOAD NORMAL O2 BAL MILLS	400	B	276	3.5
135-1	11/09/94	HIGH LOAD, AMIS, NOMINAL O2	481	AMIS	606	3.4
135-2	11/09/94	HIGH LOAD, AMIS, LOW O2	482	AMIS	653	2.9
135-3	11/09/94	HIGH LOAD, AMIS, HIGH O2	479	AMIS	675	3.9
136-1	11/10/94	HIGH LOAD, NOM O2, BALANCED MILLS	478	AMIS	582	4.0
136-2	11/10/94	HIGH LOAD, NOM O2, COAL BIASED HIGH	478	AMIS	595	4.1
136-3	11/10/94	HIGH LOAD, NOM O2, COAL BIASED LOW	479	AMIS	597	4.0
136-4	11/10/94	HIGH LOAD, NOM O2, BALANCED MILLS	480	AMIS	606	4.1
137-1	11/11/94	HIGH LOAD, NOM O2, BAL MILLS, NOM OFA	478	AMIS	636	3.9
137-2	11/11/94	HIGH LOAD, NOM O2, BAL MILLS, HIGH OFA	481	AMIS	872	4.1
137-3	11/11/94	HIGH LOAD, NOM O2, BAL MILLS, MID OFA	480	AMIS	515	3.8
137-4	11/11/94	HIGH LOAD, NOM O2, BAL MILLS, LOW OFA	480	AMIS	268	4.1
143-1	11/17/94	MAX LOAD, HIGH O2, BAL MILLS, NOM OFA	519	AMIS	780	4.0
143-2	11/17/94	MAX LOAD, NOM O2, BAL MILLS, NOM OFA	520	AMIS	774	3.3
143-3	11/17/94	MAX LOAD, LOW O2, BAL MILLS, NOM OFA	521	AMIS	747	3.0
143-4	11/17/94	HIGH LOAD, NOM O2, BAL MILLS, HIGH OFA	480	AMIS	823	3.8
143-5	11/17/94	HIGH LOAD, NOM O2, BAL MILLS, MID OFA	479	AMIS	490	3.7
143-6	11/17/94	HIGH LOAD, NOM O2, BAL MILLS, MIN OFA	479	AMIS	280	3.7
144-1	11/18/94	LOW LOAD, HIGH O2, BAL MILLS, NOM OFA	300	B,E	117	6.7
144-2	11/18/94	LOW LOAD, NOM O2, BAL MILLS, NOM OFA	301	B,E	126	6.0
144-3	11/18/94	LOW LOAD, LOW 2, BAL MILLS, NOM OFA	301	B,E	100	5.0
144-4	11/18/94	MID LOAD, HIGH O2, BAL MILLS, NOM OFA	399	E	306	4.7
144-5	11/18/94	MID LOAD, LOW O2, BAL MILLS, NOM OFA	400	E	266	3.5
144-6	11/18/94	MID LOAD, NOM O2, BAL MILLS, NOM OFA	399	E	307	3.9
144-7	11/18/94	MID LOAD, NOM O2, BAL MILLS, HIGH OFA	399	E	492	4.0

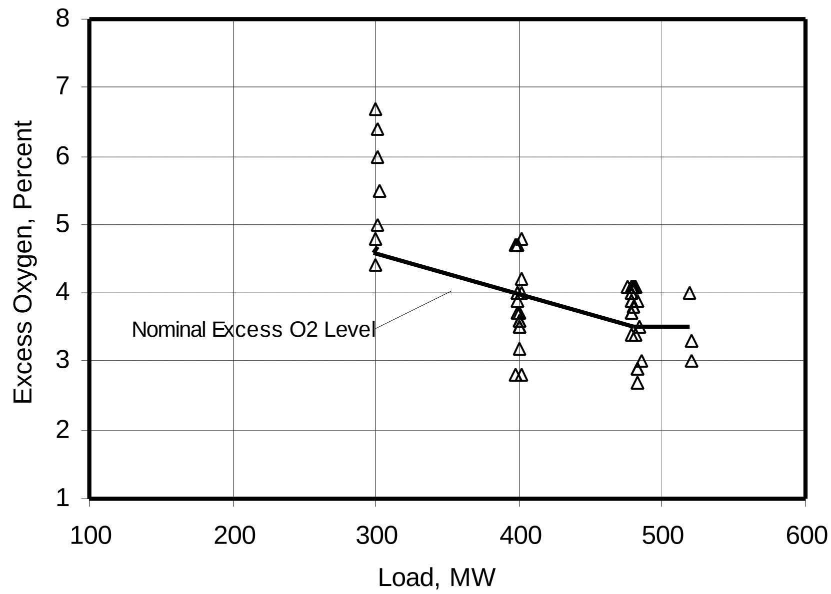


Figure 4-1 P4A / Diagnostic Tests / Oxygen Levels Tested

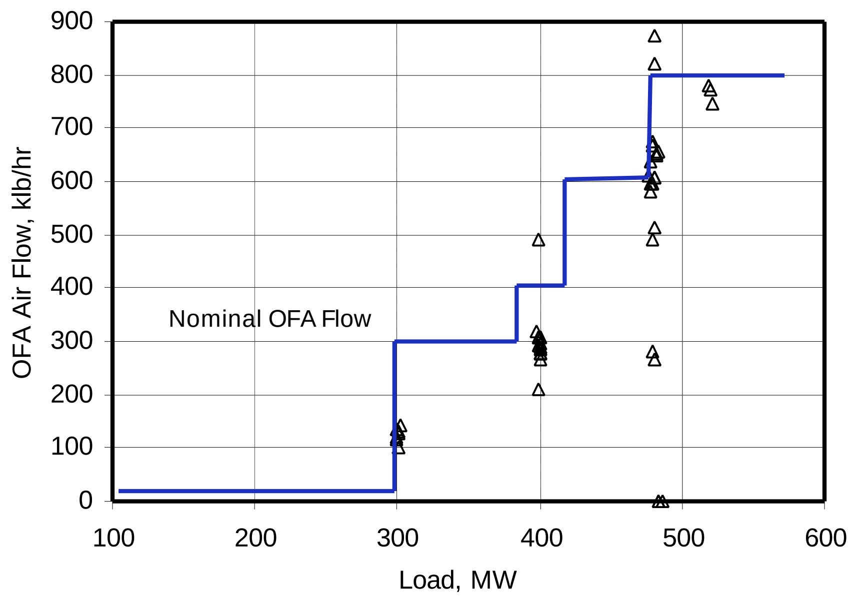


Figure 4-2 P4A / Diagnostic Tests / OFA Air Levels Tested

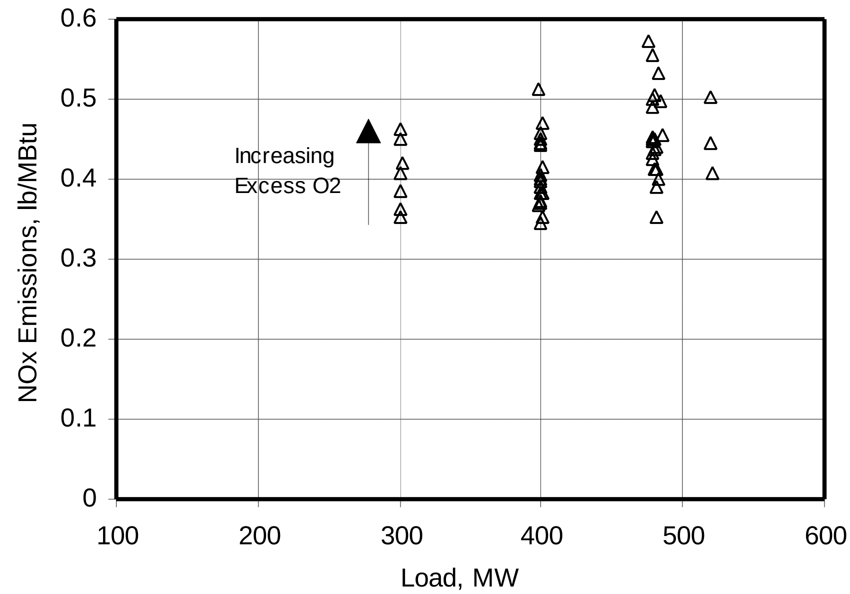


Figure 4-3 P4A /Diagnostic Tests / NOx Emissions

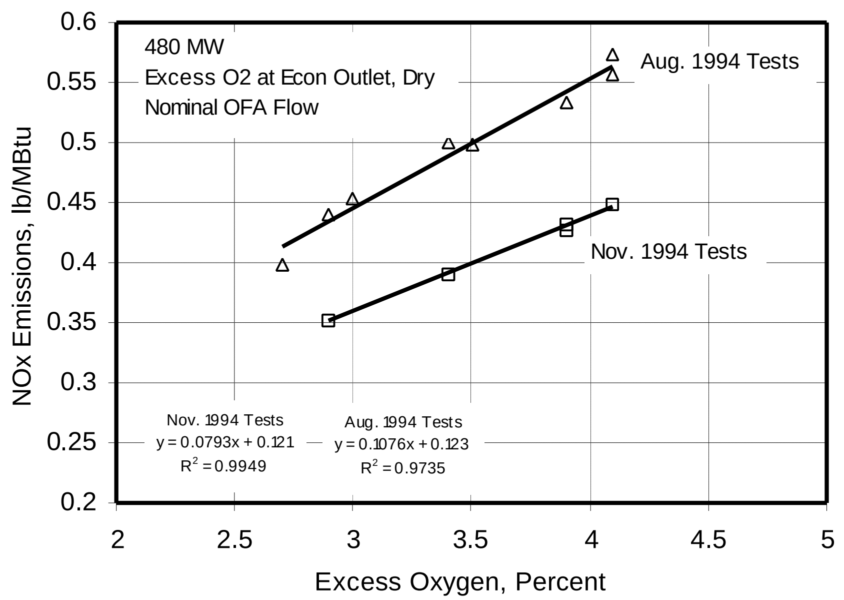


Figure 4-4 P4A / Diagnostic Tests / NOx vs. O_2 at 480 MW

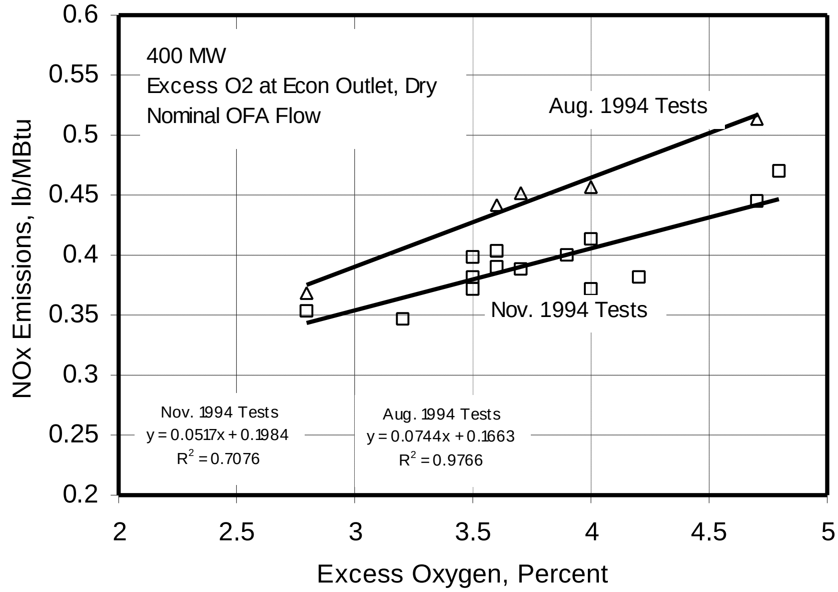


Figure 4-5 P4A / Diagnostic Tests / NOx vs. O_2 at 400 MW

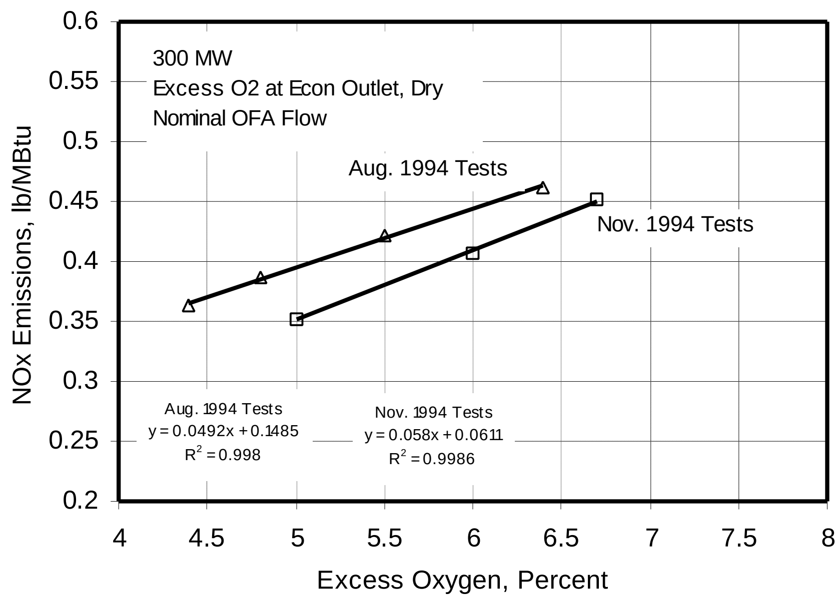


Figure 4-6 P4A / Diagnostic Tests / NOx vs. O_2 at 400 MW

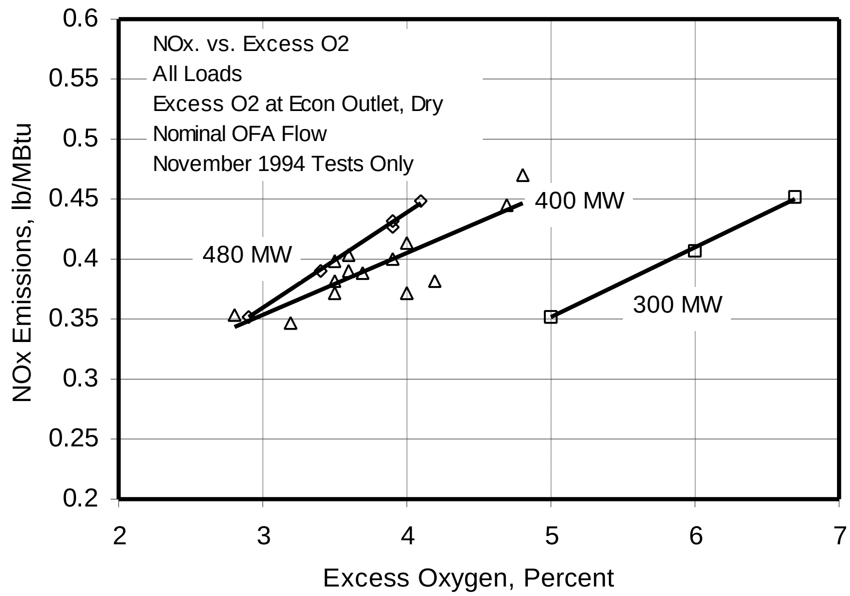


Figure 4-7 P4A / Diagnostic Tests / NOx vs. O_2 / All Loads

Table 4-2 P4A / NOx Sensitivity to Excess O_2

Phase 4A Diagnostic Tests November 1994			Prior Phases NOx Sensitivity#,* (lb/MBtu)/(% O_2)			
Nominal Load	NOx Sensitivity*	R^2	Phase			
MW	(lb/MBtu)/(% O_2)		1	2	3A	3B
480	0.0834	0.98	~0.10	~0.09	~0.06	~0.05
400	0.0613^	0.78	~0.10	~0.11	~0.05	~0.08
300	0.058	0.99	~0.08	~0.14	~0.04	~0.06

*Based on short-term diagnostic tests.
#See previous text for a discussion on the uncertainty of these results.
^E Mill out of service.

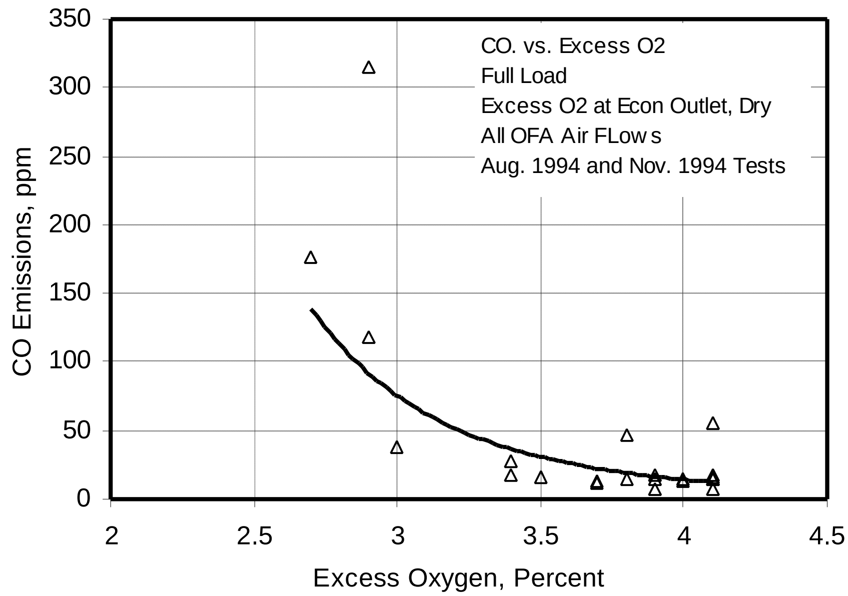


Figure 4-8 P4A / Diagnostic Tests / CO vs. O_2 at 480 MW

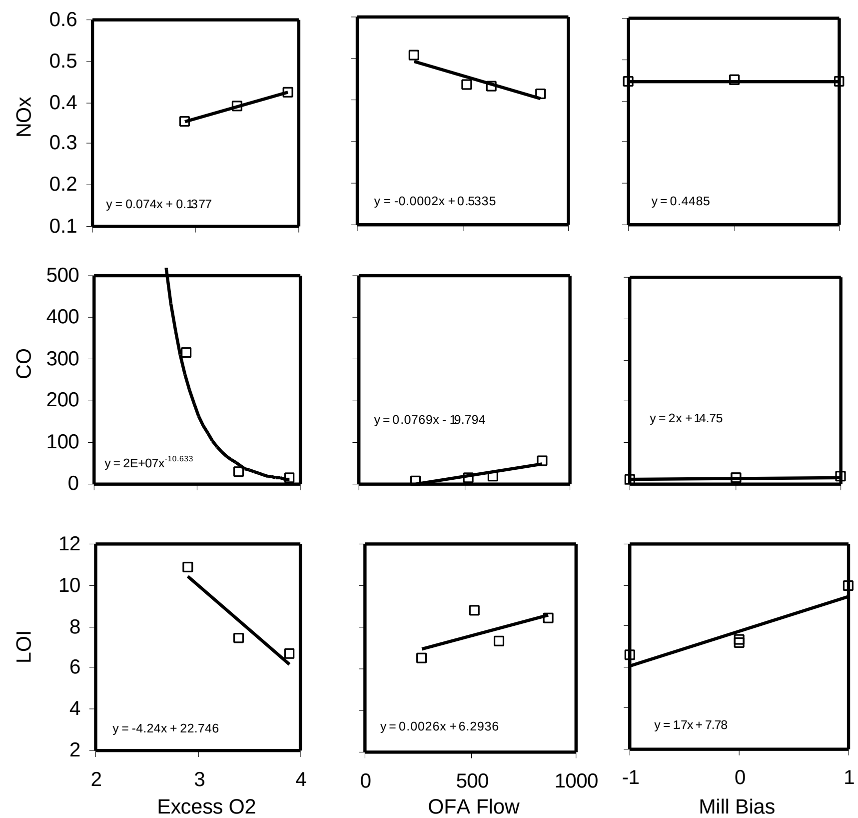


Figure 4-9 P4A / Diagnostic Tests / Response Plots at 480 MW

4.1.2 Performance Testing

Performance testing was conducted from November 12 through November 16, 1994. As in prior phases of the project, performance tests were used (1) to establish baseline evaluation criteria for retrofits, (2) to quantify boiler characteristics for comparison with other phases of the program, and (3) for comparison with the results of the diagnostic trends. For each performance configuration (10- to 12- hour test day), the following types of data were obtained:

- Gaseous emission measurements of NO_x, O_2, and CO, each composed of at least 10 one-minute sample distribution manifold composite flue gas measurements.
- Two ASME PTC 4.1 boiler efficiency determinations.
- Isokinetic fly ash collection at the ESP inlet.
- Inlet fuel and air measurements (primary air distribution, secondary air distribution, coal particle size, and coal flow in each coal pipe).

The performance tests conducted during this period differed from those previously conducted for this project in that (1) fly ash resistivity, (2) flue gas SO_3, and (3) furnace temperature profiles were not evaluated and coal pipe measurements were only conducted at full-load.

Five performance tests were conducted at nominal loads of 520, 400, 300, and 180 MW. At each nominal load, the coal firing rate was kept as constant as possible and generation allowed to swing slightly as affected by coal, boiler ash deposits, turbine cycle, and ambient variations. The coal feed rate to all in-service mills was kept as nearly equal as possible based upon digital control system readings. For each performance test, the desired test conditions were established and allowed to stabilize at least one hour prior to commencement of testing. Normal primary air/fuel ratios and mill outlet temperatures were maintained to the extent possible. A summary of the performance tests can be found in Table 4-3.

4.1.2.1 Pulverizer Performance

The airflow to each mill and the particle size and mass flow distributions of coal to each burner were measured. Specific determinations were:

- Coal fineness as percentage passing 50, 100, and 200 U.S. Standard Sieve designations,
- Dirty air flow and distribution between burner lines as observed by dirty air traverse,
- Fuel flow and distribution between burner lines as observed by isokinetic sample,
- Pulverizer air to fuel ratios,
- Primary air flow, as measured at the pulverizer inlet, and
- Temperature and static pressure of the fuel and air mixture in each burner line.

Coal samples for coal fineness, fuel flow, and fuel distribution were collected utilizing an isokinetic coal sampler. Plant Hammond laboratory personnel performed coal sieving for fineness analysis. Coal fineness was ascertained during Tests 141 and 142 conducted at 520 MW. Isokinetic coal samples were not collected for fineness analysis during tests at 180, 300, or 400 MW since mill performance is generally poorest at higher mill loadings. Coal fineness was observed to be at or above typical levels (Table 4-4) ranging from 73 percent to 80 percent passing 200 mesh with 0.1 percent or less remaining on 50 mesh.

Generally, air and fuel balance between each pulverizer's burner lines was very good by industry standards. As shown in Figure 4-10 for Test 141, dirty air velocities were near 6000 fps with the minimum being approximately 5700 fps. Resultant airflow imbalance is shown in Figure 4-11. Fuel imbalance between the burners exceeded 10 percent of the mean during both tests on pulverizer A and during one of the two tests on pulverizers C and F. Dirty air velocities were within 5 percent of the mean on all pulverizers except for pulverizer F, which was only slightly beyond 5 percent. Coal flows and coal flow deviations are shown in Figure 4-12 and Figure 4-13, respectively.

Air and fuel flows on a per mill basis are shown in Figure 4-14 and Figure 4-15, respectively. For the tests (141 and 142), the mills were nominally balanced per control room instrumentation with a flow rate near 65 klb/hr. Measured coal flow showed some imbalance with a difference of approximately 8 klb/hr between maximum and minimum flows (approximately 10 percent of nominal levels). Pulverizer air to fuel ratios were calculated by two methods. The first method calculates air to fuel ratio utilizing the fuel flow observed by the isokinetic sampler and measured dirty airflow. The second method utilizes readings obtained from the digital control system and primary airflow observed at the pulverizer inlet. Pulverizer air to fuel ratio observed by isokinetic sample ranged from 1.86 to 2.31 pounds of air per pound of coal (Figure 4-16). Pulverizer air to fuel ratio using primary air measured at the pulverizer inlet and feeder fuel flow ranged from 2.14 to 2.6 pounds of air per pound of coal. The design air/fuel ratio for these mills (all B&W MPS 75) is 1.75 at full load, however, air flow was increased to help prevent coal layout and potential plugging in the burners.

4.1.2.2 Air Flow Measurement

Unit airflow was measured at the following locations:

Secondary air at east(A) and west (B) side main air venturi.

Total airflow leaving each of the air heaters was measured at this location. Airflow measured at this location includes airflow to the burners and to the advanced overfire air ports. Each venturi was traversed on an equal area measurement grid consisting of (48) traverse points (4 ports–12 points per port) by a three-hole Fecheimer probe. Secondary airflow was measured on all performance tests (Tests 138, 139, 140, 141 and 142).

Primary air at the pulverizer inlets.

Primary airflow entering the pulverizer inlet (under the pulverizer's grinding table) was measured at this location. Airflow measured at this location includes combined tempering air from the forced draft fans and hot primary air from the primary air preheater. The point of measurement for primary air is prior to introduction of seal airflow. Due to this fact, primary airflow measured at this location will be lower than total airflow observed in the fuel lines. Inlet ducting of each pulverizer was traversed on an equal grid of (40) traverse points (10 ports – 4 points per port) by a standard 90° Pitot Tube. Primary airflow to each operating pulverizer was measured during all performance tests.

Dirty airflow at the fuel lines

Dirty airflow was measured in each of the pulverizer's four fuel lines. The total dirty airflow measured includes primary airflow (tempering and hot) and seal airflow to the pulverizer and coal feeders. Dirty airflow was measured on an equal area grid of (24) points (2 ports – 12 points per port) by a dirty air probe. Dirty air traverses were conducted to quantify pulverizer airflow and to establish isokinetic sampling rate for collection of coal samples. Dirty airflow was measured during performance tests at 520 MW (Tests 141 and 142) and Test 138 at 400 MW. The dirty air probe was also utilized to quantify airflow through each pulverizer that was off-line during performance tests at 300 MW and 180 MW.

Overfire airflow

Overfire airflow was measured in each of the four corners of the advanced overfire air windbox downstream of each louver damper assembly. Overfire airflow in each corner was traversed on an equal grid of (24) points (4 ports–6 points per port) by a three-hole Fecheimer probe. Overfire airflow was measured on all performance tests except for the test at 180 MW (Test 140). During test 140 at 180 MW, duct velocities were between 0 and 80 fpm and airflow at these velocities cannot be accurately measured using typical instrumentation. Very low duct velocities were also observed on other performance tests making repeatable and accurate test data difficult to obtain. Due to low duct velocities, a Microtector with 1/1000" w.c. resolution was required to measure the lower than typical velocities.

Overfire air flow measured by traverse was lower than that indicated by control room instrumentation. For all four windbox quadrants, actual overfire air flow was less than that indicated by plant instrumentation (Figures 4-17 through 4-20). In most instances, overfire air flow was 15 to 30 percent below that indicated by plant instrumentation. Higher absolute deviations between traverse measurements and plant instrumentation were observed at higher overfire airflows. The differences between the two measurements were not as pronounced in prior phases of the project in which this comparison was made. Although significant errors exist between the two measurements, these errors appear to be partly correctable using a linear calibration (Figure 4-21). Figure 4-22 shows the design and actual overfire flow rate as a function of load if these errors were not taken into consideration. Whether this simple correction factor would be sufficient for long-term operation is unknown.

Total unit airflow was calculated by addition of air flow measured at the main air venturi(s), total primary air flow, seal air to the pulverizers and air flow to off-line pulverizers when applicable. Seal air to the pulverizer was ascertained by inference between dirty air flow measured in the fuel lines (which is inclusive of seal air flow) and primary air flow measured at the pulverizer inlet. Dirty airflow from the pulverizers was not measured during tests conducted at 300 MW and 180 MW. Seal air to the pulverizers is not accounted for in total unit airflow during these tests. Table 4-5 summarizes the total unit airflow and the distribution of unit airflow during each performance test. Two or more traverses of overfire air and secondary air were conducted during each test.

Total unit airflow at full load was 6 to 10 percent higher than that observed during pervious phases. At low loads there was also increased airflow requirements. A summary of the partitioning of the combustion air between primary, secondary, and OFA airflows is shown in Figure 4-23 and Figure 4-24. This data indicates that the overfire airflow represented approximately 15 percent of the total combustion air flow at full load, decreasing to approximately 5 percent at 300 MW. Below 300 MW, the AOFA control dampers were in the closed position per FWEC recommendations.

As a result of the errors discussed above, overfire air flow, with respect to total unit air flow, was lower than observed during the Phase 3B testing phase conducted in June 1993. During Phase 3B, overfire air flow was observed to be 10 percent of total unit air flow at 300 MW and 21 percent of total unit air flow at 480 MW. During this test, overfire air was 5 percent of total unit airflow at 300 MW and 12 percent of total unit air flow at 520 MW. No performance tests were conducted at 480 MW (520 MW tests were run) during this testing phase. The lower overfire air flows resulted in an increase of 13 percent to 21 percent of the total unit air flow delivered to the burners, as compared to the Phase 3B tests. Based on the perceived relatively large potential for measurement errors in the OFA measurement system but more so on equipment reliability problems, it was decided to forego the use of the OFA measurement in favor of the OFA control damper position for use in the on-line optimization strategies.

Table 4-3 P4A / Performance Tests Conducted

Test	Date	Load MW	MOOS Pattern	OFA Flow (KPPH)	Econ O_2 Dry %	Stack O_2 Dry %	NOx lb/MBtu	CO ppm	Fly Ash LOI %	Fly Ash Carbon %
138	11/12/94	400	B	293	3.9	5.5	0.38	49	8.4	7.7
139	11/13/94	300	B,E	90	4.8	6.9	0.34	51	8.1	7.1
140	11/13/94	180	B,D,E	0	5.3	7.2	0.33	9	3.6	3.3
141	11/15/94	520	None	791	3.6	5.4	0.43	61	8.2	7.2
142	11/16/94	520	None	786	3.5	5.4	0.45	46	8.1	6.9

Table 4-4 P4A / Performance Tests / Mill Grinding Performance

Pulverizer	Test 141		Test 142	
	%Passing 200 Mesh	% Rem. on 50 Mesh	%Passing 200 Mesh	% Rem. on 50 Mesh
A	74.48%	0.10%	73.69%	0.10%
B	77.38%	0.04%	80.03%	0.09%
C	73.30%	0.11%	76.49%	0.07%
D	76.76%	0.03%	76.73%	0.02%
E	73.48%	0.05%	75.41%	0.05%
F	74.87%	0.12%	76.58%	0.11%
Average	*75.05%*	*0.08%*	*76.49%*	*0.07%*

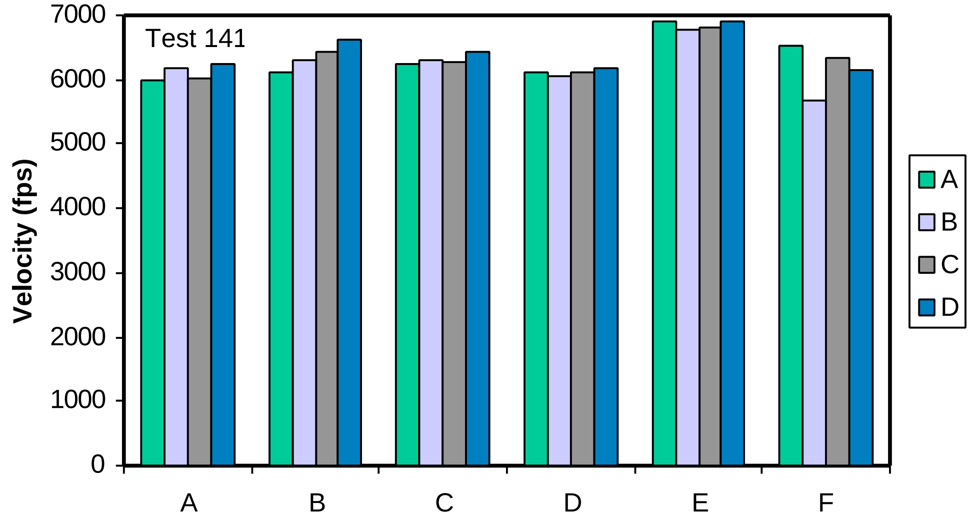


Figure 4-10 P4A / Measured Dirty Air Velocity by Mill and Coal Pipe

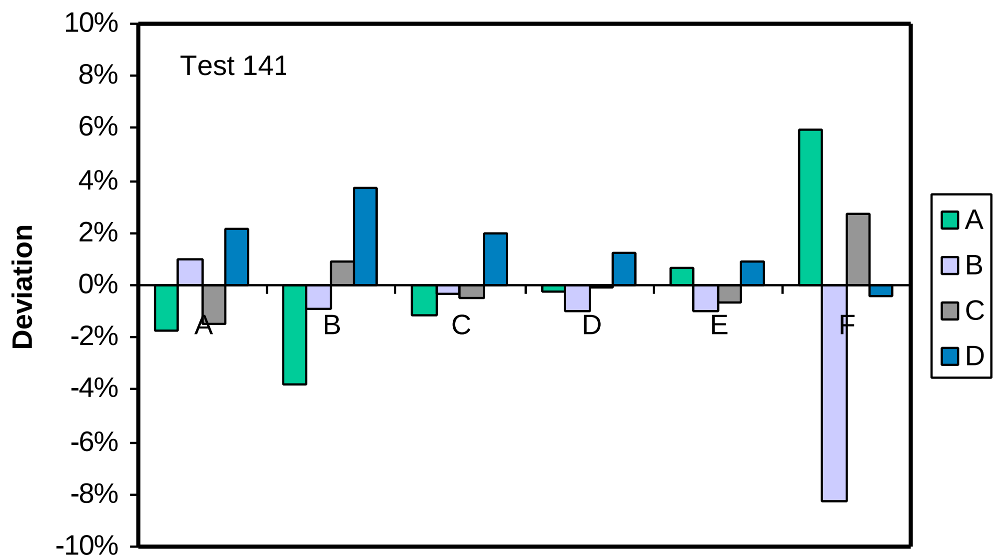


Figure 4-11 P4A / Deviation of Coal Pipe Dirty Air Velocity from Mill Average

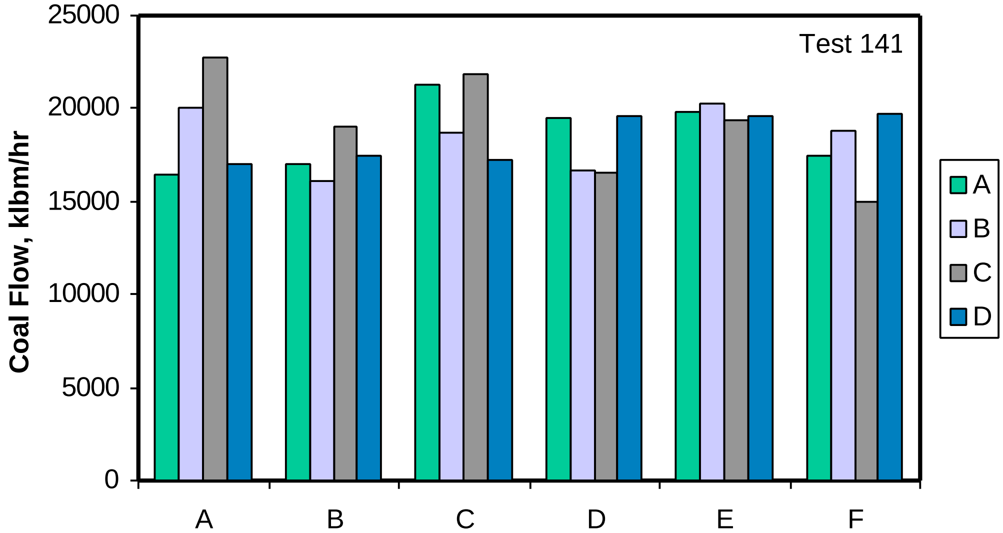


Figure 4-12 P4A / Measured Coal Flows by Mill and Coal Flow

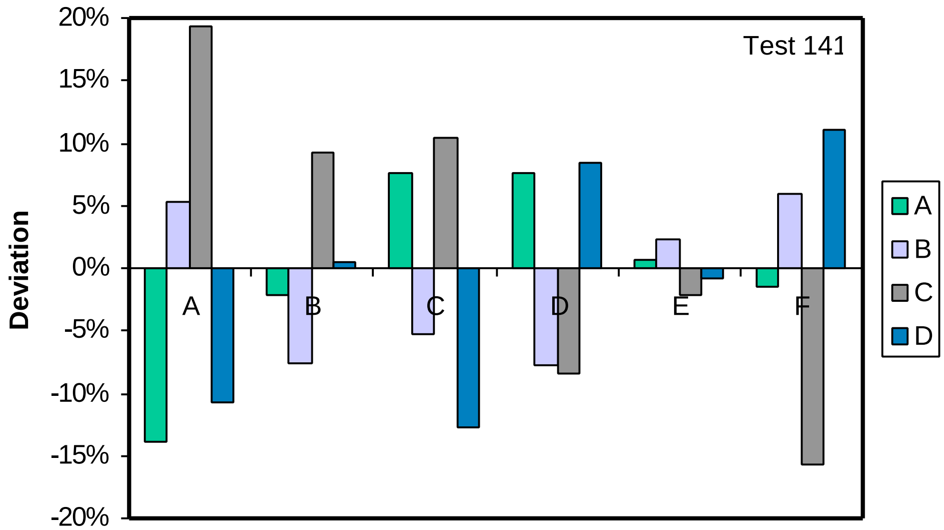


Figure 4-13 P4A / Deviation of Coal Pipe Flow from Mill Average Flow

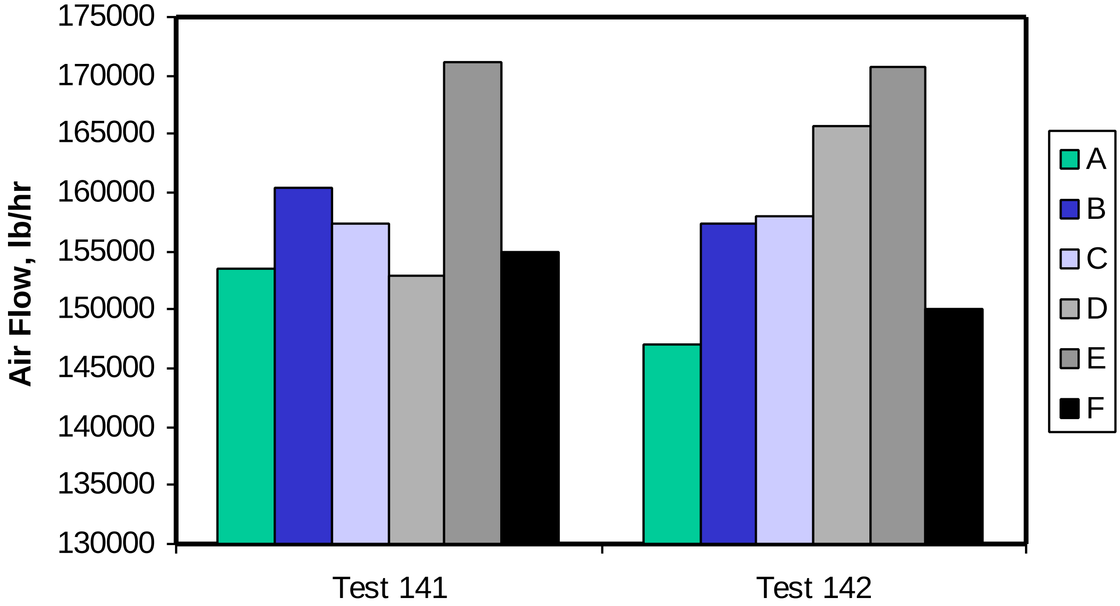


Figure 4-14 P4A / Primary Air Distribution

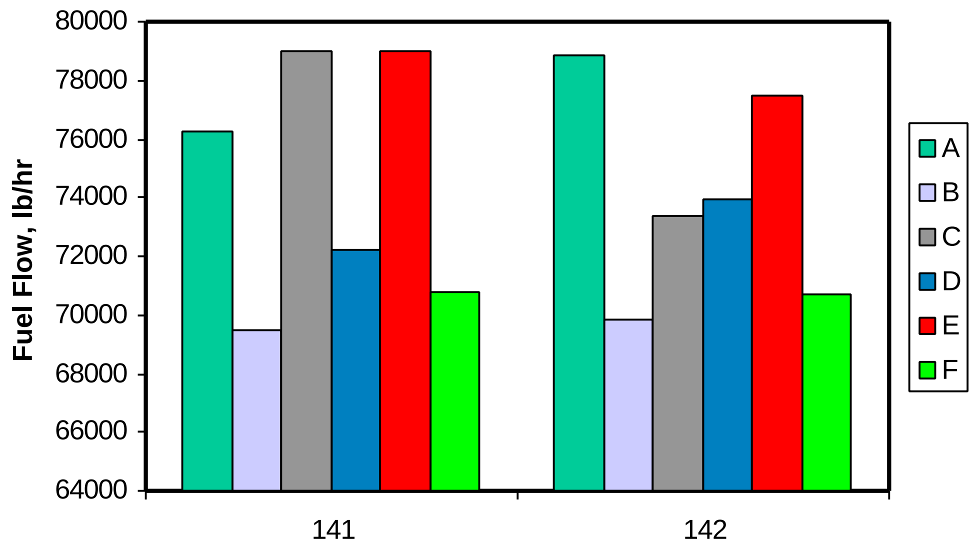


Figure 4-15 P4A / Pulverizer Fuel Distribution

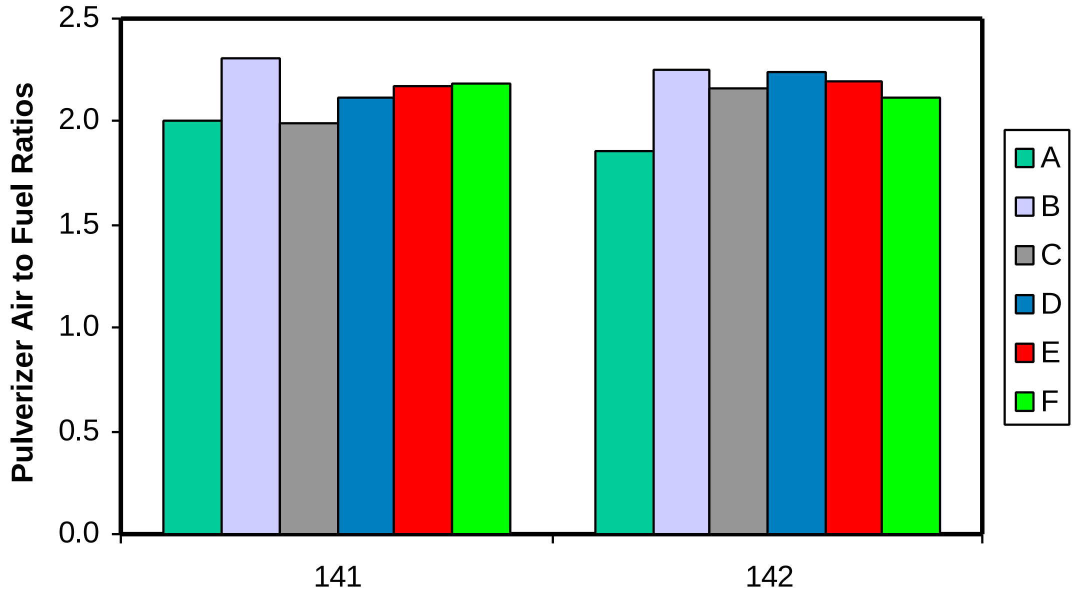


Figure 4-16 P4A / Pulverizer Air to Fuel Ratio

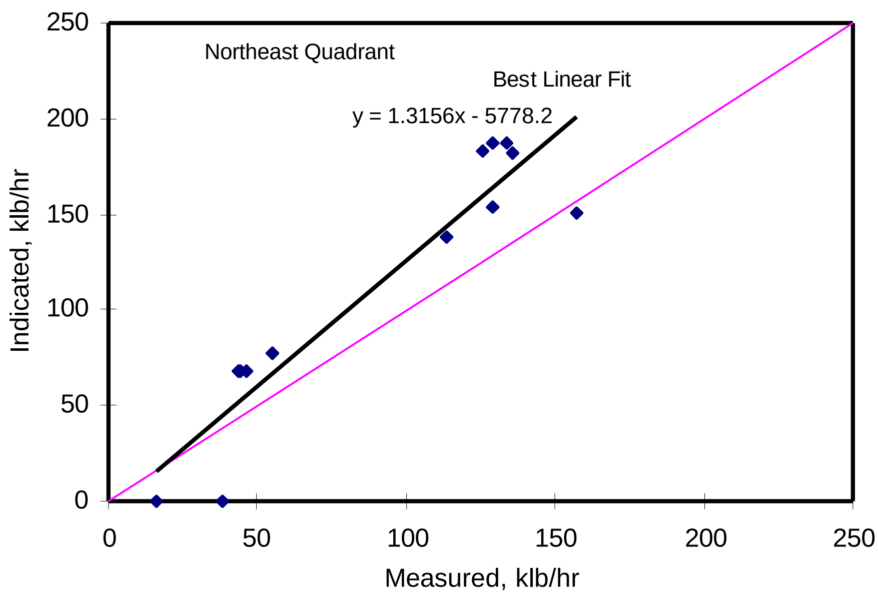


Figure 4-17 P4A / Indicated vs. Measured OFA Flow - Northeast Quadrant

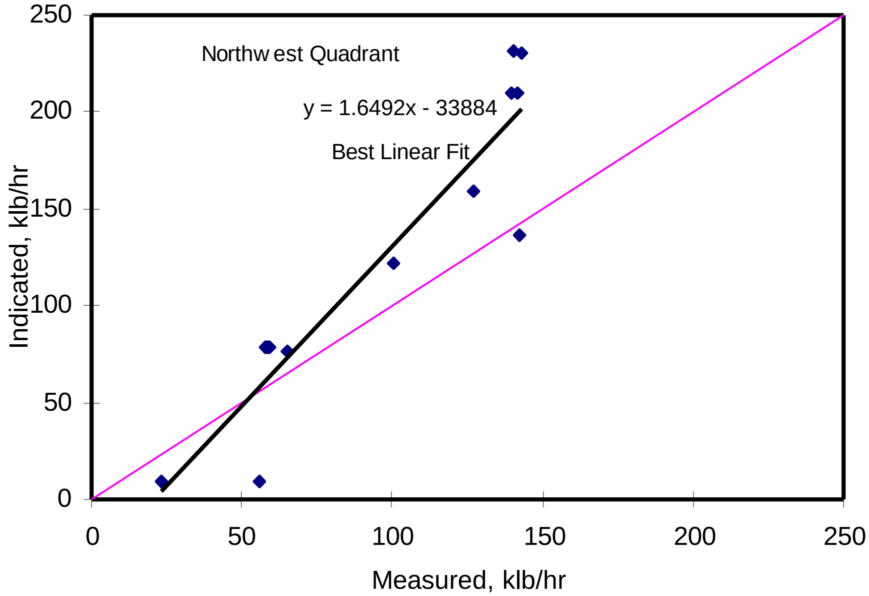


Figure 4-18 P4A / Indicated vs. Measured OFA Flow - Northwest Quadrant

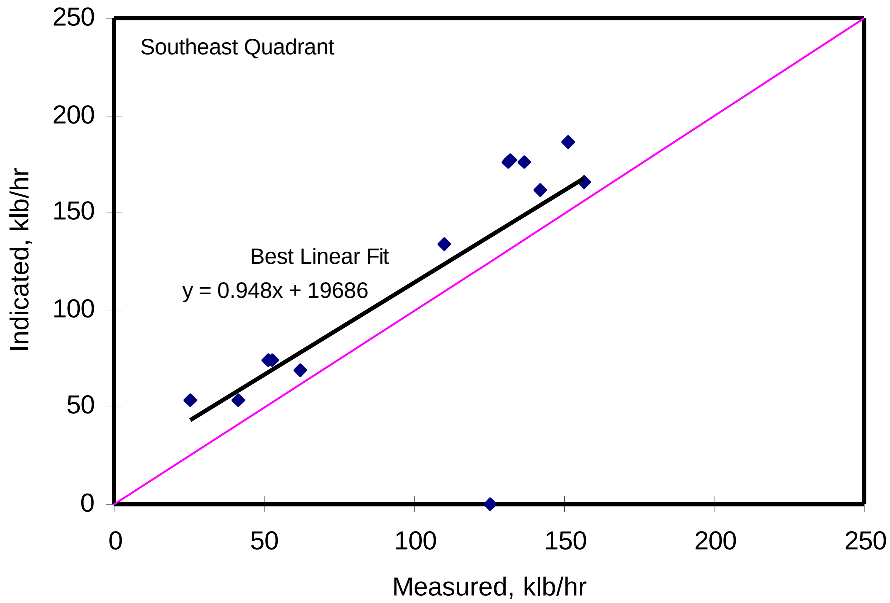


Figure 4-19 P4A / Indicated vs. Measured OFA Flow - Southeast Quadrant

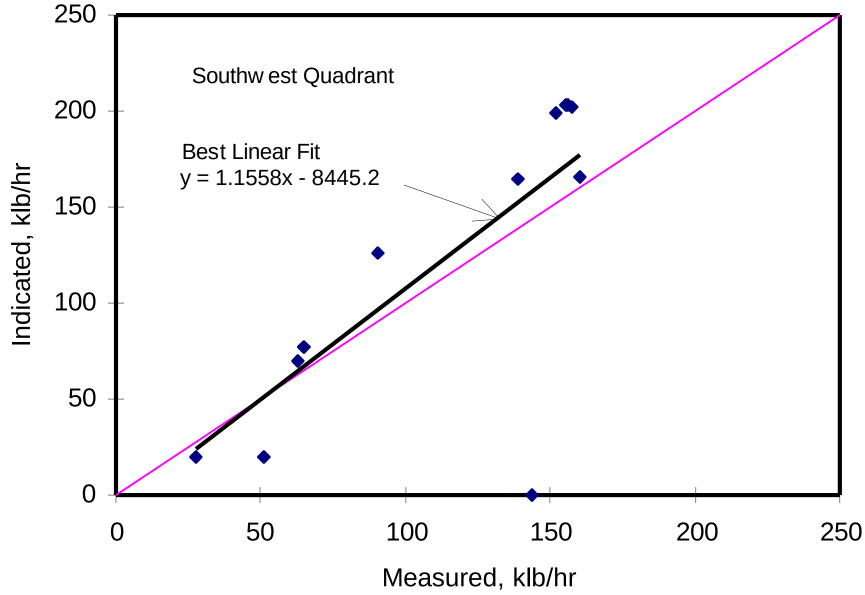


Figure 4-20 P4A / Indicated vs. Measured OFA Flow - Southwest Quadrant

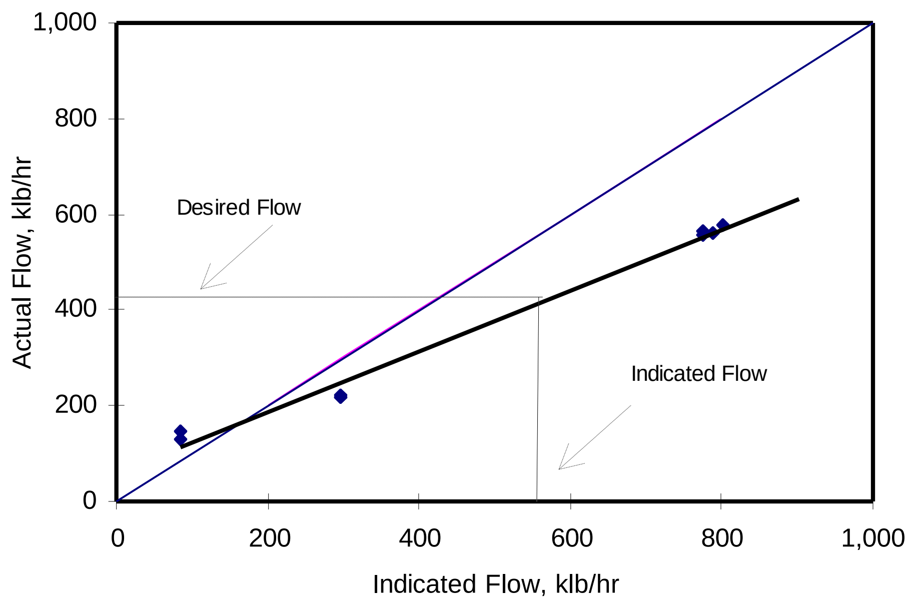


Figure 4-21 P4A / Actual vs. Indicated Overfire Air Flow

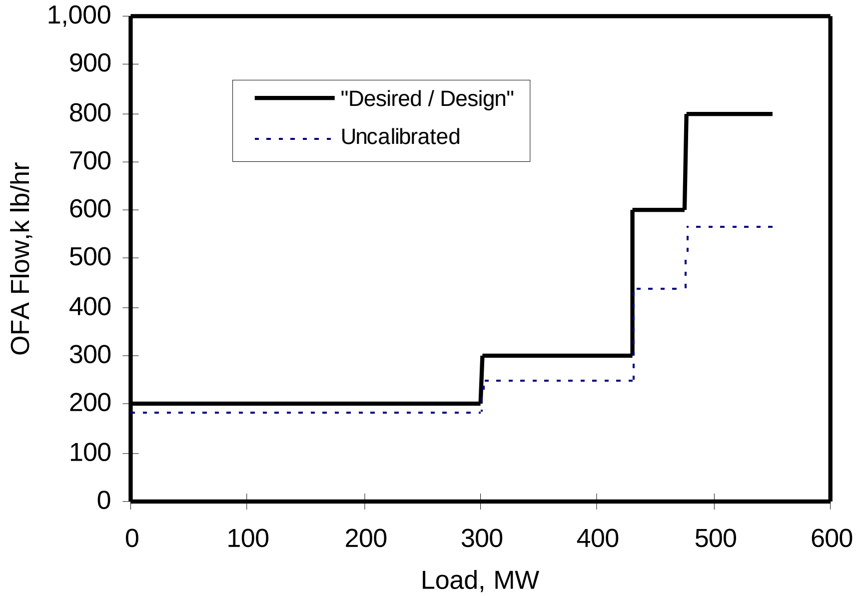


Figure 4-22 P4A / Error in OFA Flow

Table 4-5 P4A / Performance Tests / Combustion Air Flow

Test Number	→	138	139	140	141	142
Unit Load (MW)	→	400 MW	300 MW	180 MW	520 MW	520 MW
Pulverizer Primary Air (lb/hr)		734,888	556,118	383,764	902,090	899,812
Pulverizer Seal Air (lb/hr)		72,734	Na	Na	47,990	49,208
Secondary Air @ Venturi(s)* (lb/hr)		2,595,371	2,073,794	1,169,547	3,648,928	3,553,601
Overfire Air * (lb/hr)		220,179	139,312	Na	569,025	561,753
Secondary Air to Burners (lb/hr)		2,375,192	1,934,482	Na	3,079,903	2,991,848
Air to Off-line Mills (lb/hr)		Na	204,432	377,199	0	0
Total Unit Air (TUA) (lb/hr)		3,402,993	2,834,344	1,930,510	4,599,008	4,502,621

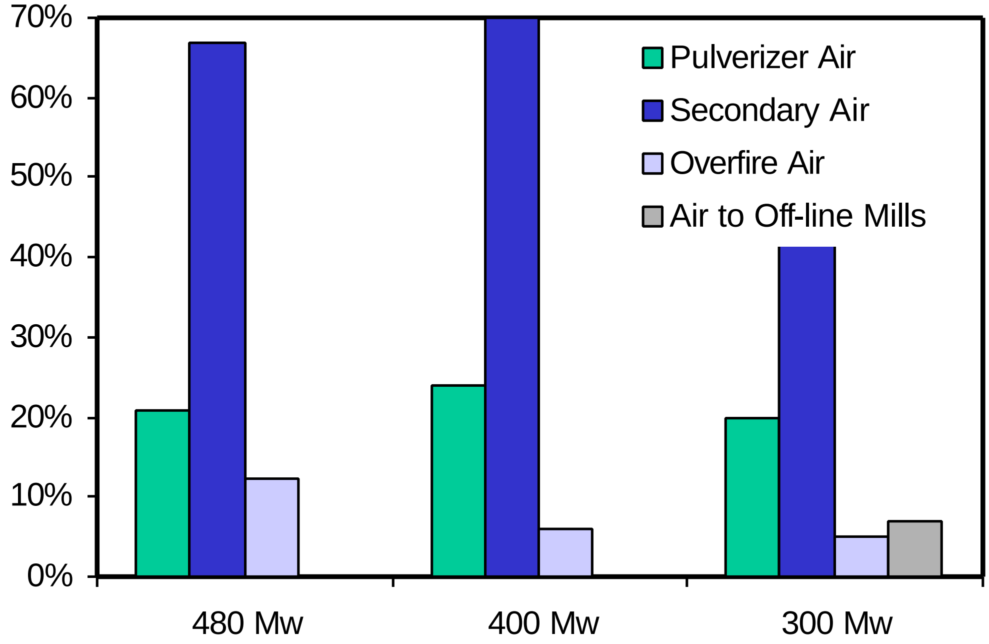


Figure 4-23 P4A / Distribution of Unit Air Flow by Load

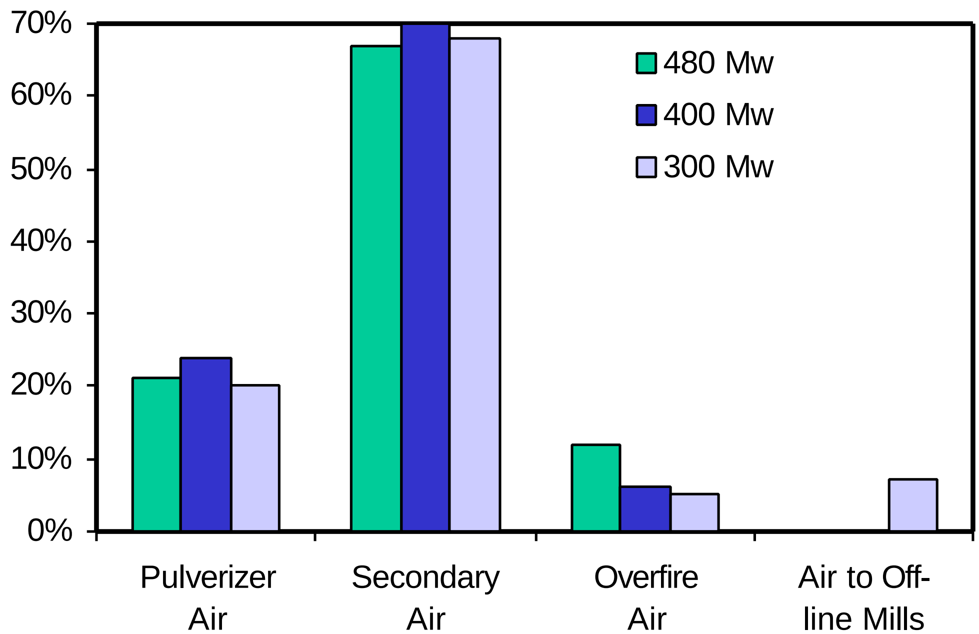


Figure 4-24 P4A / Distribution of Unit Air Flow by Component

4.1.2.3 NOx Emissions

NO_x emissions observed during the performance tests were comparable to those obtained during Phase 3B for all load levels (Figure 4-25). At 520 MW, NO_x emissions were near 0.44 lb/Btu, reducing to 0.33 lb/MBtu at the 180 MW level. At full-load, NO_x emission levels are between 30 to 35 percent of baseline levels.

4.1.2.4 Fly Ash Loss-on-Ignition

Fly ash loss-on-ignition levels were also similar to those observed during Phase 3B with full-load values of near 8 percent (Figure 4-26). Some decrease in LOI might have been expected since Phase 3B overall mill performance has improved as a result of the installation of two mills during the outage between Phases 3B and 4A. The cause for this lack of improvement in LOI is at this time unknown. Potential factors include:

- The mills that were replaced were not major contributors to LOI during Phase 3B,
- Changes in combustion air distribution, or
- Measurement error.

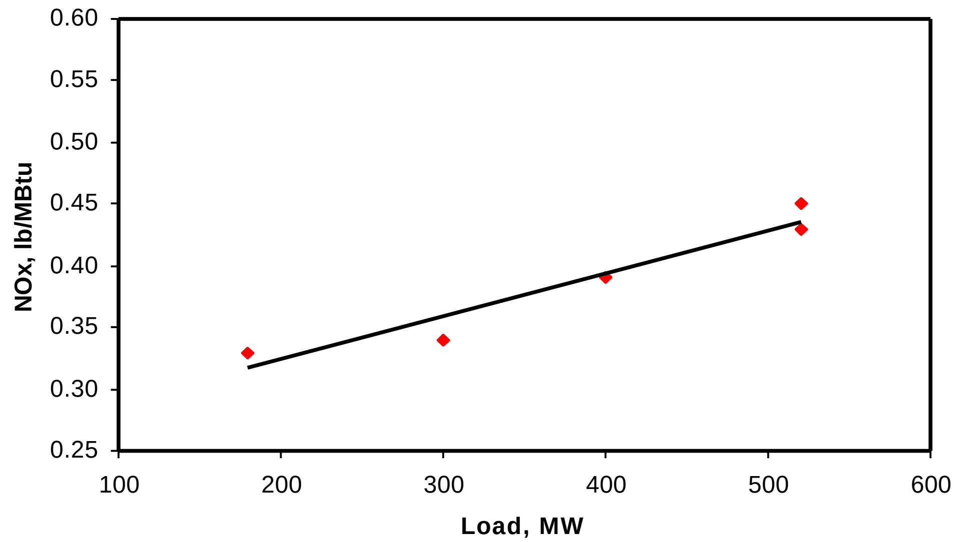


Figure 4-25 P4A / Performance Tests / NOx Emissions

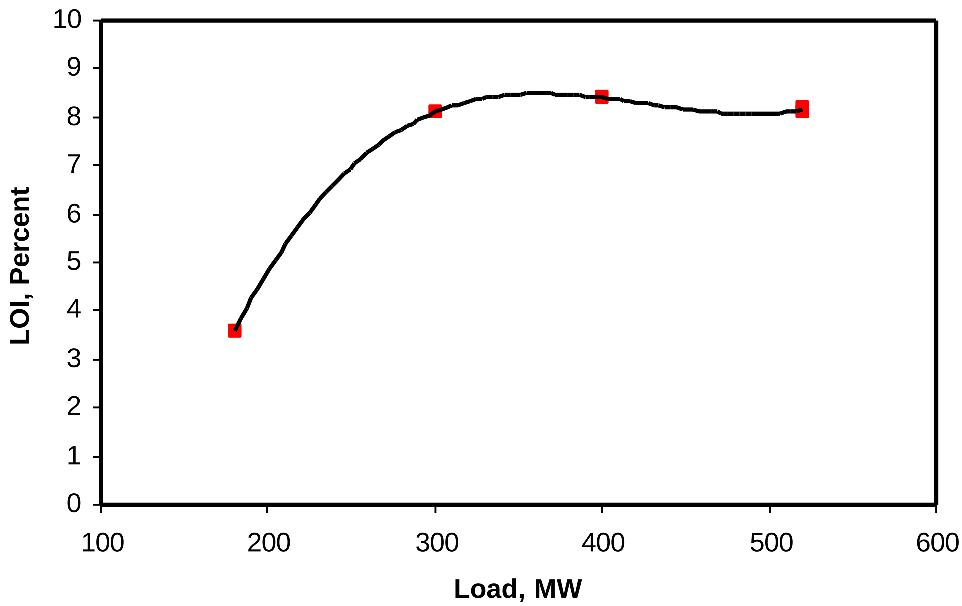


Figure 4-26 P4A / Performance Tests / Fly Ash LOI

4.1.2.5 Coal Properties

As can be seen from Table 4-6, the coal utilized during the Phase 4A performance tests had similar characteristics to that used during Phase 3B and prior phases. The individual analysis can be found in Appendix A.

Table 4-6 P4A / Performance Tests / Coal Properties

		Phase							
						4A			
Characteristic	Units	1	2	3A	3B	Mean	Max	Min	Std.Dev.
Moisture	% by Wt.	4.3	5.6	5.7	6.4	6.0	6.8	4.7	0.70
Carbon	% by Wt.	72.4	73.2	72.5	70.8	71.8	73.3	70.4	0.85
Hydrogen	% by Wt.	4.7	4.7	4.7	4.7	4.7	4.7	4.6	0.05
Nitrogen	% by Wt.	1.4	1.4	1.4	1.4	1.3	1.4	1.3	0.02
Chlorine	% by Wt.	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.01
Sulfur	% by Wt.	1.7	1.6	1.5	1.7	1.3	1.4	1.3	0.04
Ash	% by Wt.	9.8	8.9	9.4	9.5	10.1	10.7	9.5	0.31
Oxygen	% by Wt.	5.7	4.6	4.7	5.6	4.8	5.4	4.4	0.30
	TOTAL	100.0	100.0	100.0	100.1	100.0	100.1	100.0	0.01
HHV	BTU/lb	12921	13000	12869	12494	12599	12855	12416	137
Volatile	% by Wt.	33.5	33.27	32.56	33.6	32.0	32.5	31.4	0.4
Fixed C	% by Wt.	52.7	52.22	52.29	50.4	51.9	52.9	51.1	0.4
Fixed C/Volatile		1.57	1.57	1.61	1.50	1.62	1.65	1.60	0.0
Oxygen/Nitrogen		3.95	3.20	3.41	4.01	3.65	4.11	3.27	0.3

4.1.3 Long-Term Testing

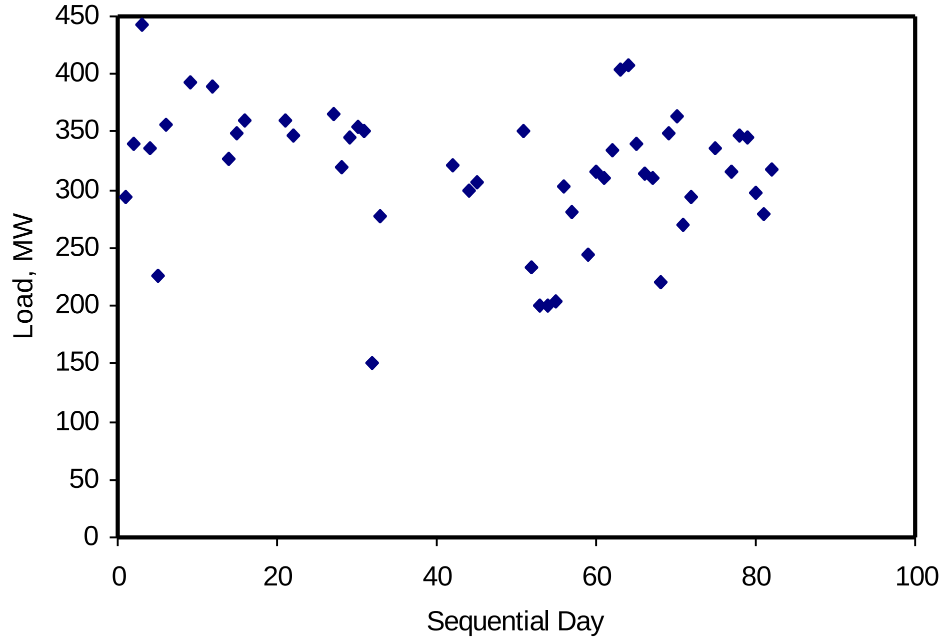
As in prior phases, the long-term-testing consisted of continuous measurement of operating parameters while the unit operated under normal load dispatch. Long-term data was collected from July 12, 1994 through November 17, 1994. During this period, fifty-one (51) days of valid long-term data were collected composed of 1360 hourly averages and 16,572 five-minute averages. As before, the focus of the analysis was:

- Characterization of the daily load and NOx emissions.
- Characterization of the NOx emissions as a function of the O_2 and mill patterns.
- Determination of the thirty-day rolling average NOx emissions.
- Determination of the achievable NOx emission level based upon valid days of CEMS data.
- Comparison of long-term results to short-term results.

The following paragraphs describe the major results of these analyses.

From this long-term data, the daily average load and NOx were determined (Figure 4-27). As shown, daily average load varied considerably during this test period, ranging from approximately 150 MW to 450 MW. Daily average NOx emissions ranged from approximately 0.35 lb/MBtu to 0.53 lb/MBtu, showing a general downward trend over this period. Diurnal characteristics for load and NOx are shown in Figure 4-28. For this period, the unit operated above 300 MW approximately 13 hours. NOx emissions generally followed the load characteristic with maximum emissions corresponding to maximum load.

For the parametric analysis, all of the valid five-minute data were used. The five-minute data were analyzed to determine the overall relationship between NOx and load. Since the data was obtained while the unit was under normal dispatch, the data represents the long-term characteristics. The NOx versus load relationship was determined by first segregating the five minute average load data into 20 MW wide load ranges. The population for each load range, as well as the lower five percentile and upper ninety-five percentile are shown for both load and NOx emission values. Figure 4-29 through Figure 4-32 illustrates the excess oxygen, NOx, CO, and SOx versus load trend for these data. The excess oxygen downstream of the air heater shows the same trend as that for the other phases of the program -- increasing excess oxygen with decreasing load. Contrary to what has been seen in prior phases, NOx, in general, increased with increasing load. CO emissions remained on average low during this period with maximum mean emissions of near 15 ppm. As would be expected, SOx emissions were independent of load.



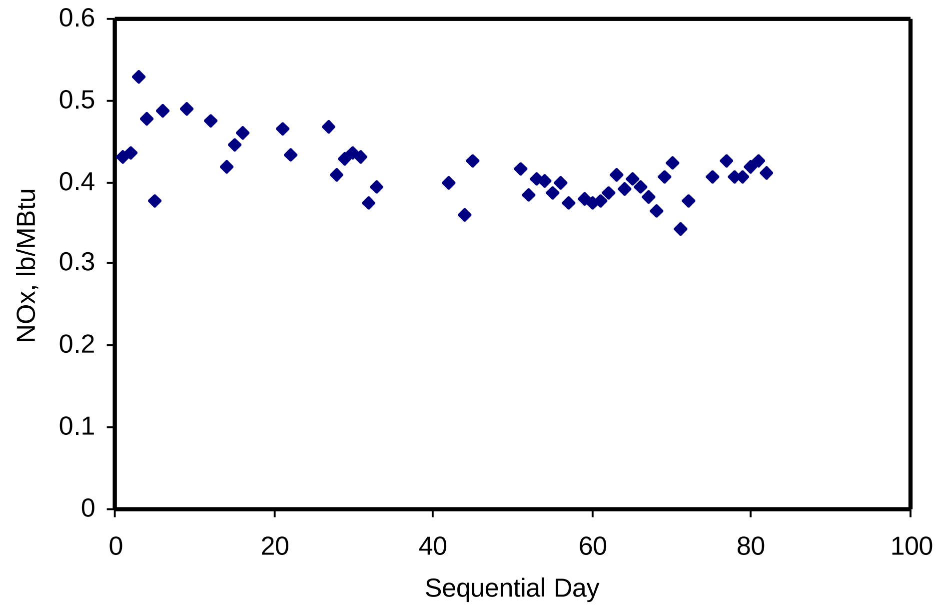


Figure 4-27 P4A / Long-Term Daily Average Characteristics

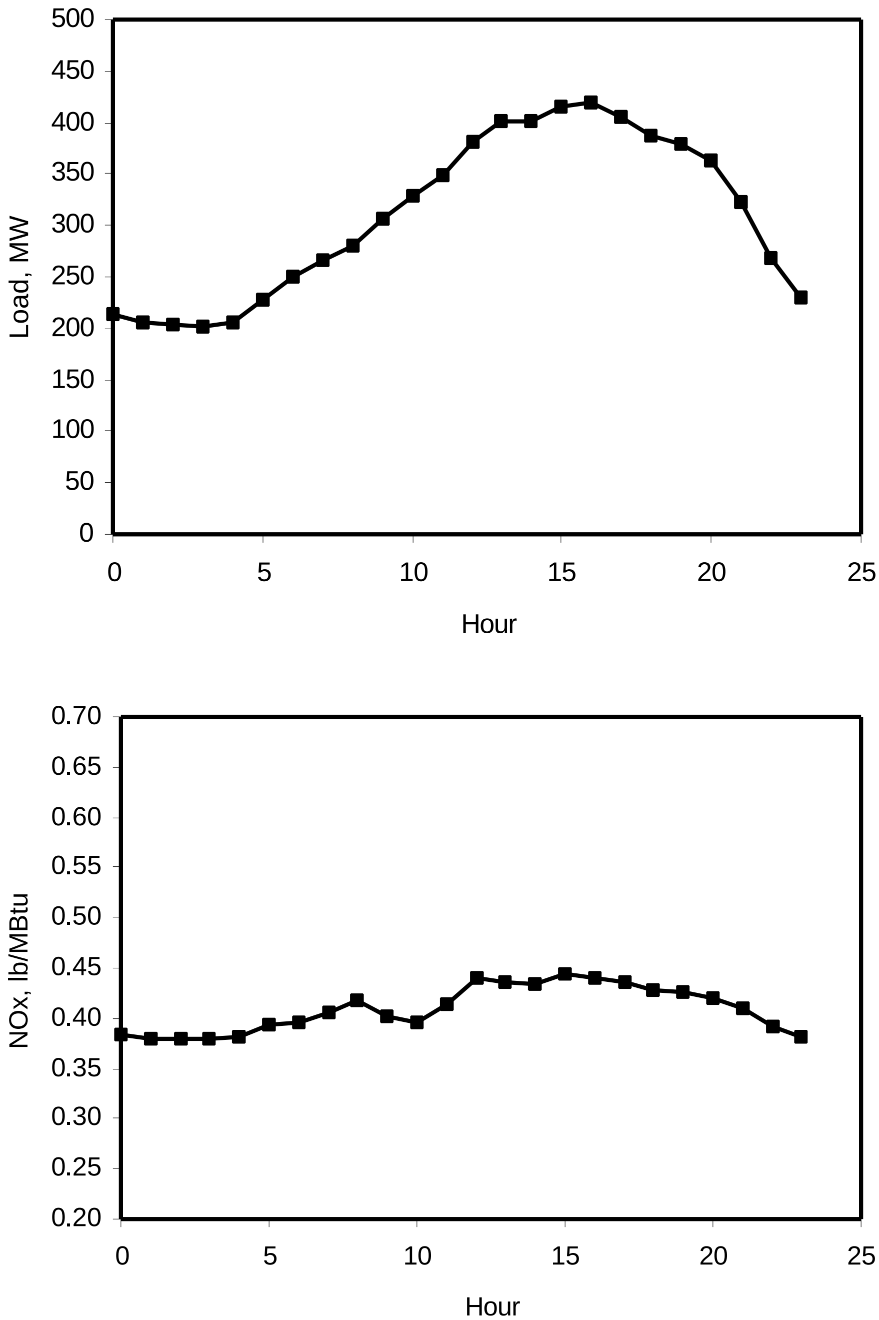


Figure 4-28 P4A / Long-Term Diurnal Characteristics

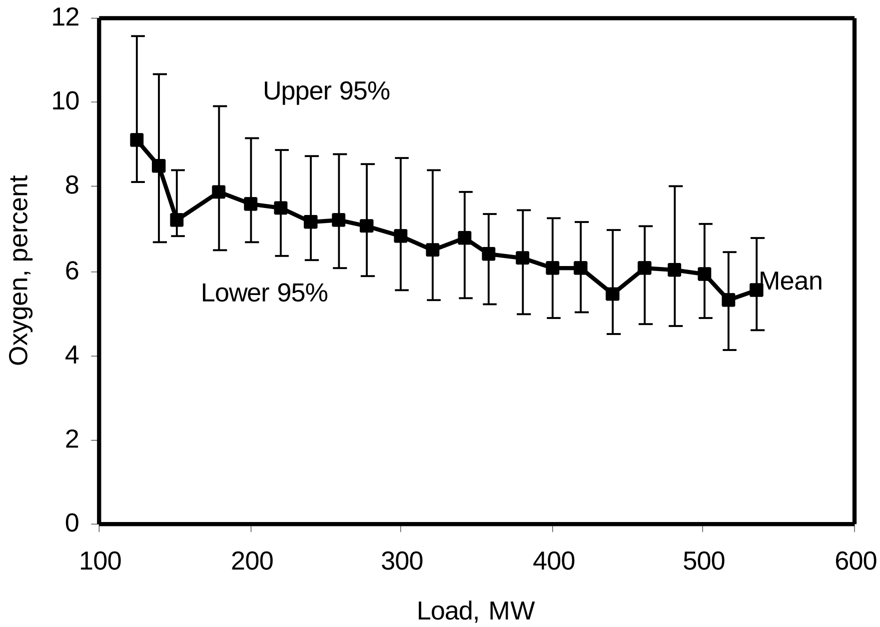


Figure 4-29 P4A / Long-Term Stack O_2 vs. Load

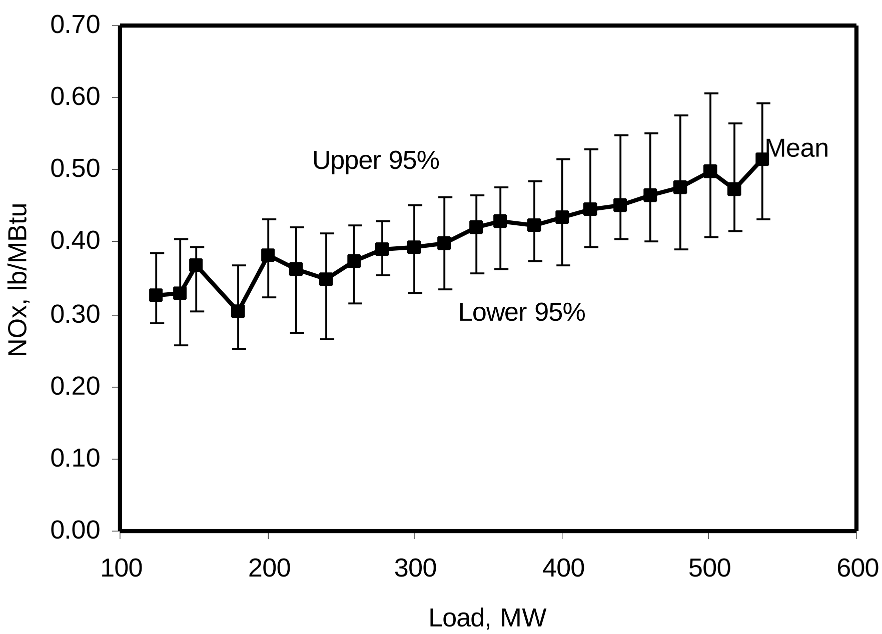


Figure 4-30 P4A / Long-Term NOx vs. Load

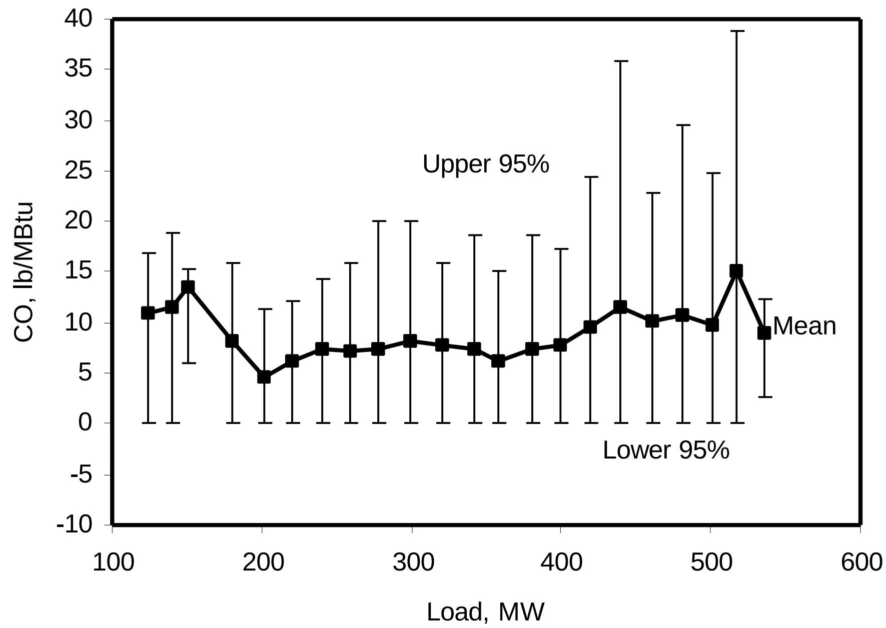


Figure 4-31 P4A / Long-Term CO vs. Load

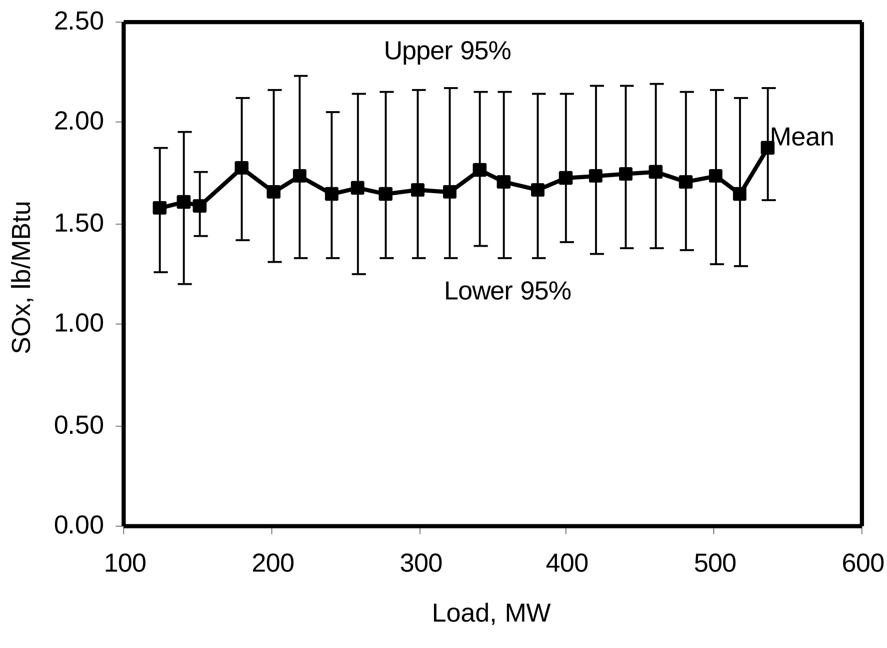


Figure 4-32 P4A / Long-Term SOx vs. Load

The achievable NOx emission limit on a 30-day rolling average basis is determined using the descriptive statistics for 24-hour average NOx emissions. The descriptive statistics for the 24-hour average NOx emissions data are shown in Table 4-7. As shown, fifty-one days of valid NOx emission data were collected during this time frame (June 1994 through November 1994). Average NOx emissions were 0.41 lb/MBtu -- for comparison, the long-term NOx emissions during Phase 3B were also 0.41 lb/MBtu. The achievable emission depends on the long-term mean, variability, and autocorrelation level. Based on the daily values given, the 30-day achievable NOx emissions limit was found to be 0.45 lb/MBtu. This limit should be exceeded, on average, once per ten years. The assumption related to these achievable emission levels is that the Hammond unit will be operated in the future under similar load dispatching and operating conditions (such as AOFA utilization). Other load scenarios, the thirty-day rolling averages would be different and therefore the achievable emission level would also be different.

Table 4-7 P4A / Descriptive Statistics for Daily Average NOx Emissions

Statistic	Value
Number of Daily Values	51
Average Emissions (lb/MBtu)	0.41
Standard Deviation (lb/MBtu)	0.037
First Order Autocorrelation (ρ)	0.38
AEL 30 Day (ρ = 0)	0.44
AEL 30 Day (ρ = 0.38)	0.45

4.1.4 Process Data for 1st Quarter 1995

In addition to the long-term emissions data described earlier, process data was collected during all test phases to provide insight to changes in the boiler performance and turbine cycle heat rate. During Phases 1 through 3, this data was collected with the project's data acquisition system (DAS) [SCS, 1998]. For Phase 4, a large majority of the existing field inputs to the DAS were terminated at the just installed DCS. The plan was to have the archiving procedures set up prior to the return of the unit to operation in May 1994, however, due to problems with the DCS, data was not archived reliably until first quarter 1995.

Steam Temperatures

Main steam and reheat temperatures are shown in Figure 4-33 and Figure 4-34, respectively. Main steam temperature averaged approximately 990°F at full load. The design steam temperature for the unit is 1000°F. In general, a 10°F decrease in main steam temperature results in a 0.15 percent increase in turbine cycle heat rate for subcritical, drum units. There was some improvement in temperature at intermediate loads before decreasing at loads below 200 MW. Hot reheat temperature averaged near 997°F at the upper loads, again with the design being 1000°F. As with main steam temperatures, there is a 0.15 percent increase in turbine cycle heat rate for a 10°F decrease in reheat temperature. Mean reheat temperature remained above 980°F until about 200 MW.

Main Steam Pressure

Main steam pressure as a function of load is shown in Figure 4-35. As shown, the pressure remained near the design level of 2400 psig for most of the load range, only dropping significantly below 200 MW. There is 0.4% decrease in turbine cycle heat rate for every 100 psi deviation from design.

Secondary Air Heater Inlet and Outlet Gas Temperatures

The secondary air heater inlet and outlet gas temperatures are shown in Figure 4-36 through Figure 4-39. Full load air heater inlet temperatures (economizer outlet temperatures) averaged near 780°F. The design temperature for the unit is 710°F at full load. As expected, the temperature dropped with decreasing load, averaging near 650°F at 260 MW. The design temperature at this load is near 590°F. The secondary air heater outlet temperature averaged approximately 310°F at full load dropping to near 280°F at 260 MW. The full load design temperature is near 282°F.

Excess Oxygen

In addition to the ECEM excess oxygen measurement, excess oxygen was also measured at the economizer outlet using the plant's in situ instrumentation. Excess oxygen for the east and west economizer outlet is shown in Figure 4-40 and Figure 4-41, respectively. As shown in Figure 4-42, based on plant instrumentation, the east and west sides were relatively well balanced over the load range. The stack oxygen level is shown in Figure 4-43.

NOx Emissions

NOx emissions for first quarter 1995 are shown in Figure 4-44. As shown, NOx emissions averaged approximately 0.40 lb/Mbtu over the load range. The bars on this figure represent the 5^{th} and 95^{th} percentiles of NOx emissions data collected. Comparing these emissions characteristic with that seen from July to November 1994 (Figure 4-30) and during Phase 3B, it is evident that the NOx emissions had returned to levels seen during Phase 3B. The upward shift in NOx emissions in the July to November data set is likely related to the controllable operating parameters such as excess oxygen and mills in service.

Mill Coal Flows

Mill coal flows as functions of load are shown in Figure 4-45. As shown, the "C" and "D" mills tended to be utilized earlier than the other mills during this period. The "C" and "D" supply the front-top and front-middle burners, respectively. The choice of mills will generally affect all boiler performance measures including NOx emissions, LOI, and efficiency. The mill patterns by load are provided in Appendix A. The most common mill patterns along with NOx emissions for several load ranges are shown in Table 4-8. As shown, mill pattern selection appeared to affect NOx emissions by approximately 10 percent.

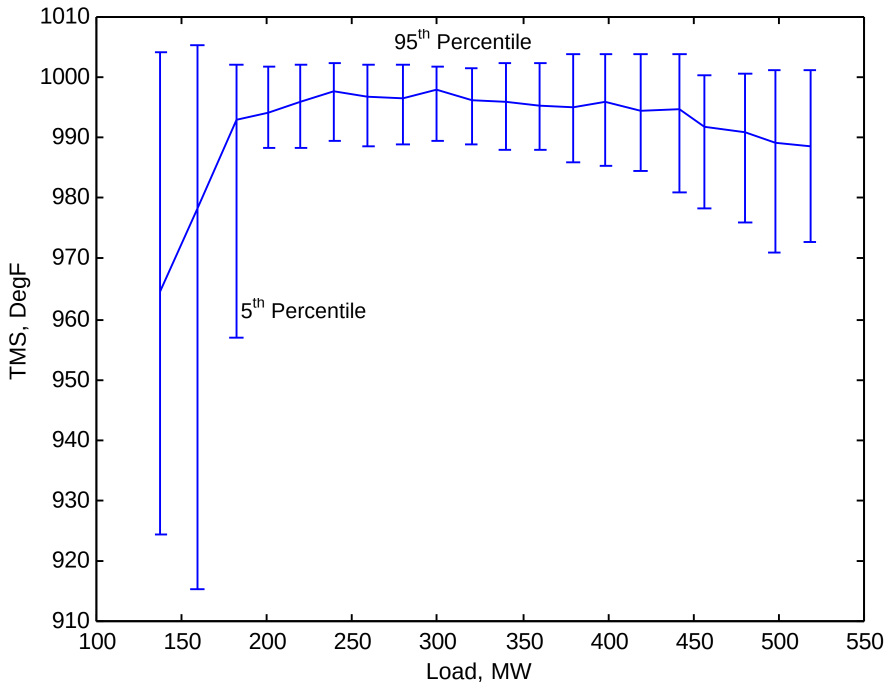


Figure 4-33 P4A – Main Steam Temperature vs. Load (1Q95)

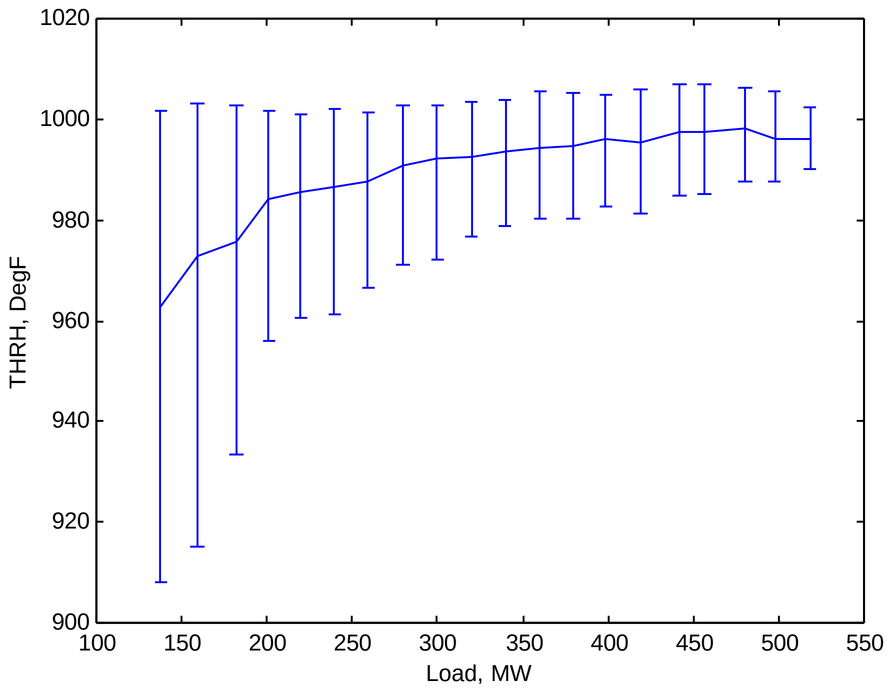


Figure 4-34 P4A – Hot Reheat Temperature vs. Load (1Q95)

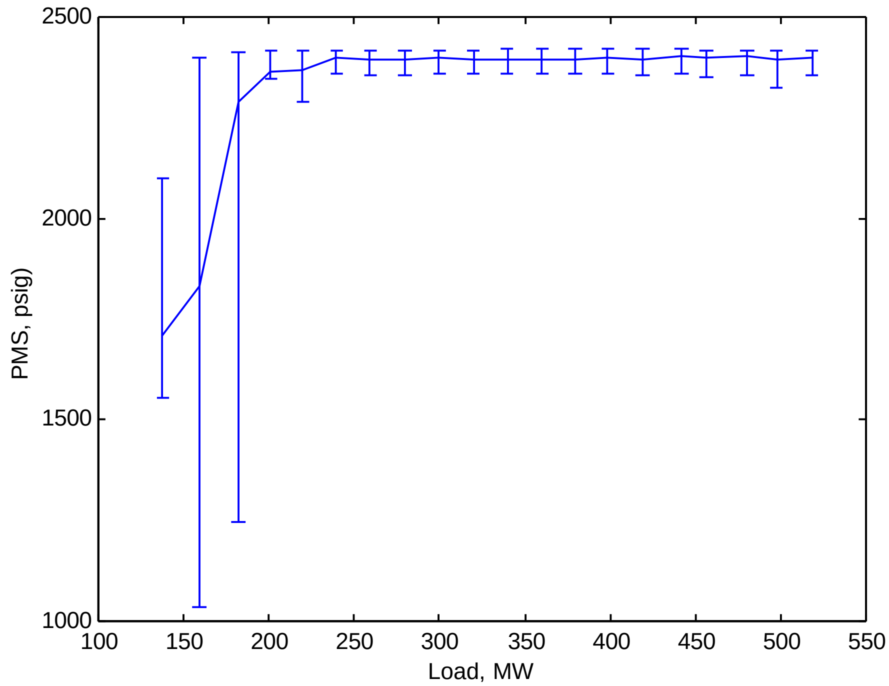


Figure 4-35 P4A – Main Steam Pressure vs. Load (1Q95)

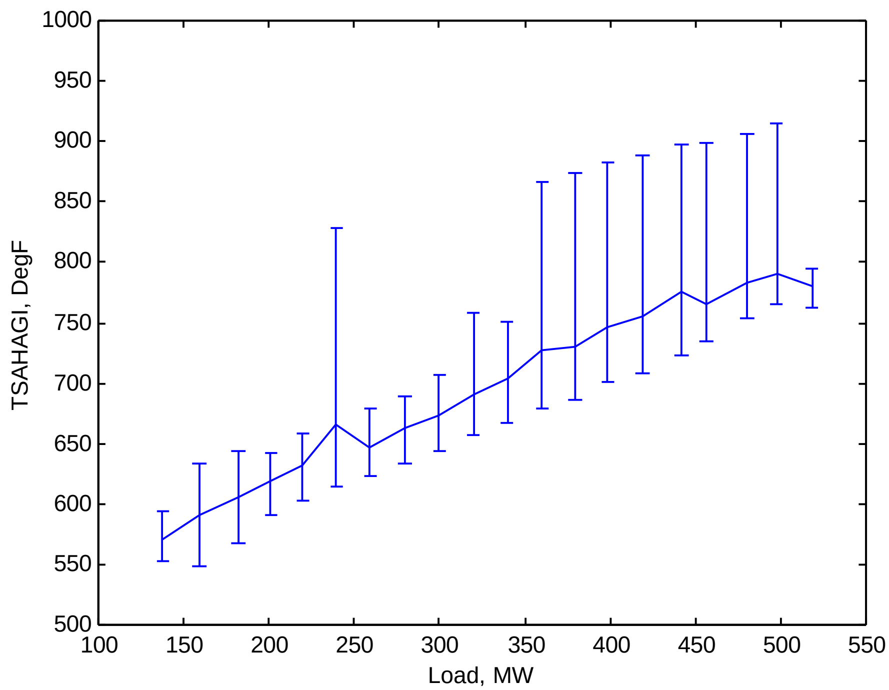


Figure 4-36 P4A – Secondary Air Heater A Gas Inlet Temperature vs. Load (1Q95)

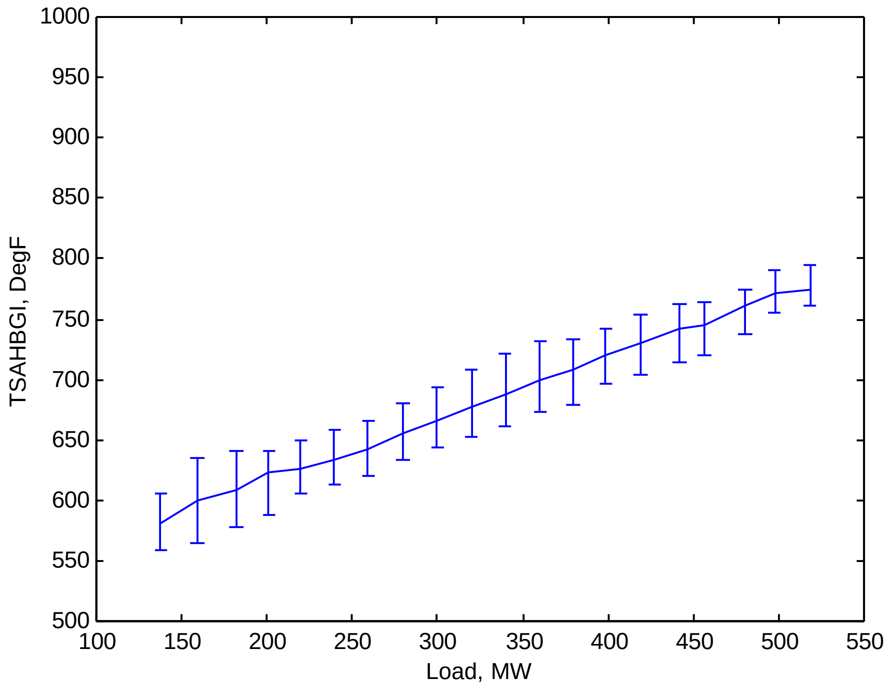


Figure 4-37 P4A – Secondary Air Heater B Gas Inlet Temperature vs. Load (1Q95)

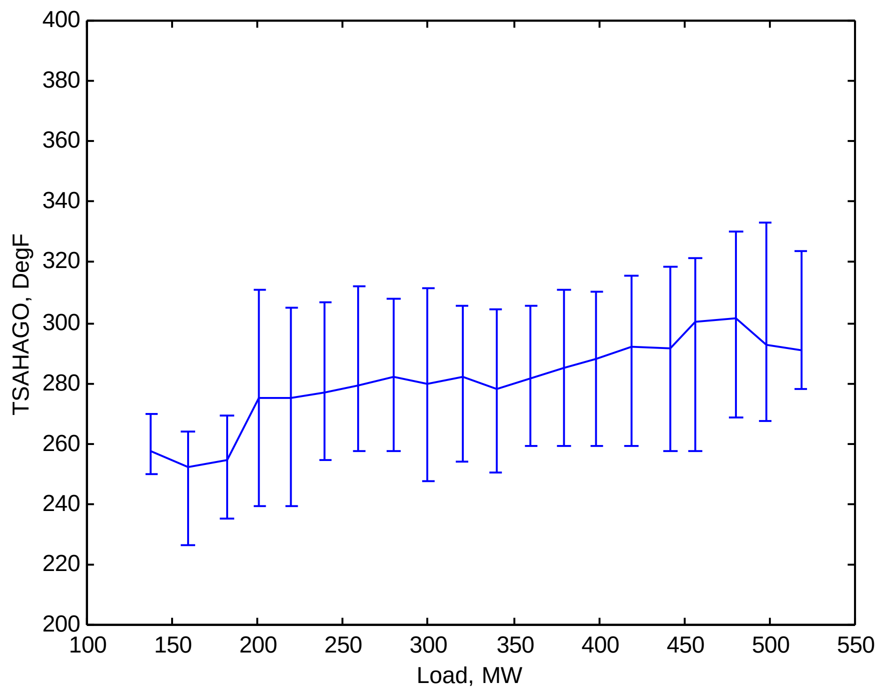


Figure 4-38 P4A – Secondary Air Heater A Gas Outlet Temperature vs. Load (1Q95)

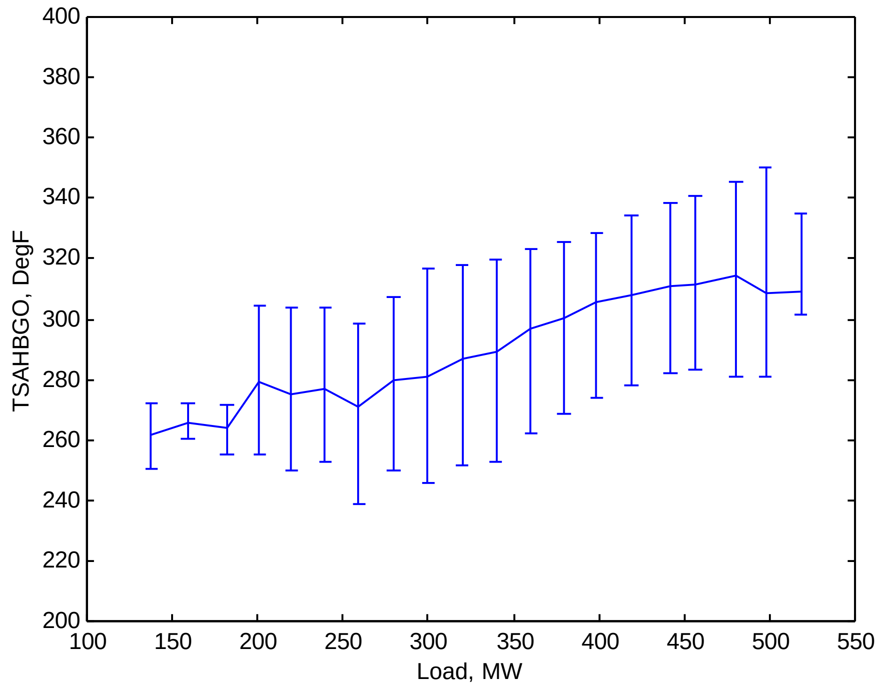


Figure 4-39 P4A – Secondary Air Heater B Gas Outlet Temperature vs. Load (1Q95)

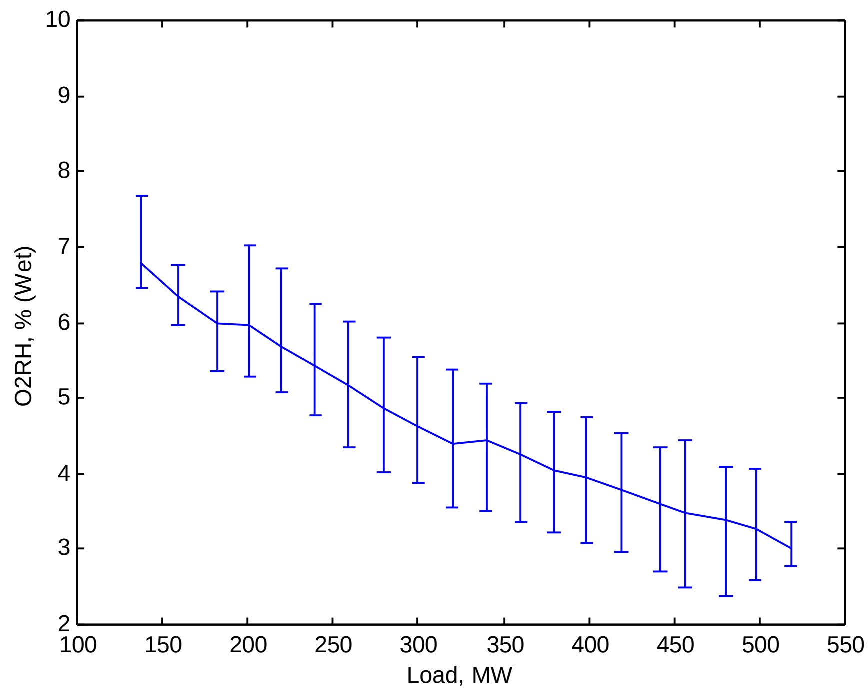


Figure 4-40 P4A – Excess Oxygen East Duct vs. Load (1Q95)

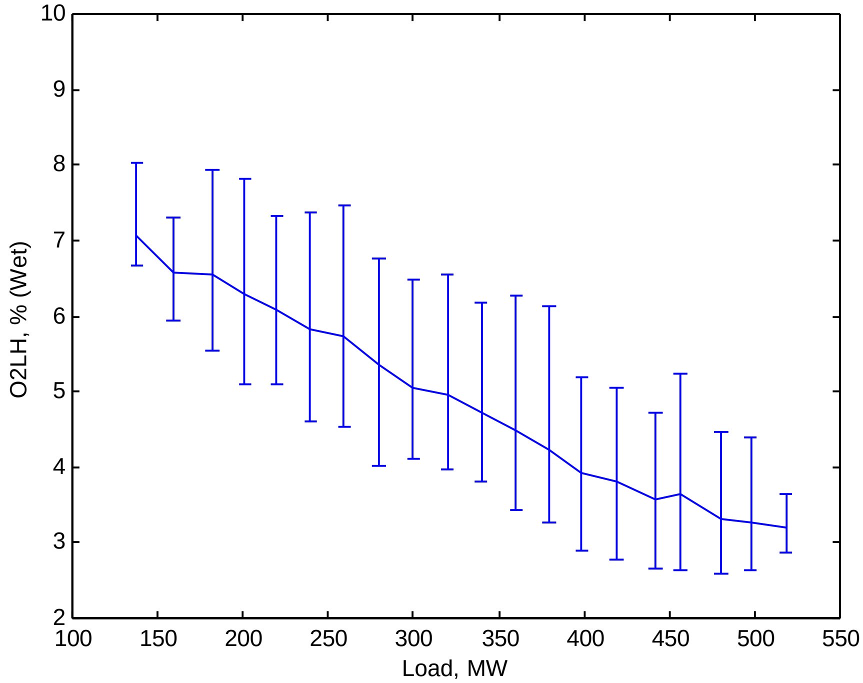


Figure 4-41 P4A – Excess Oxygen West Duct vs. Load (1Q95)

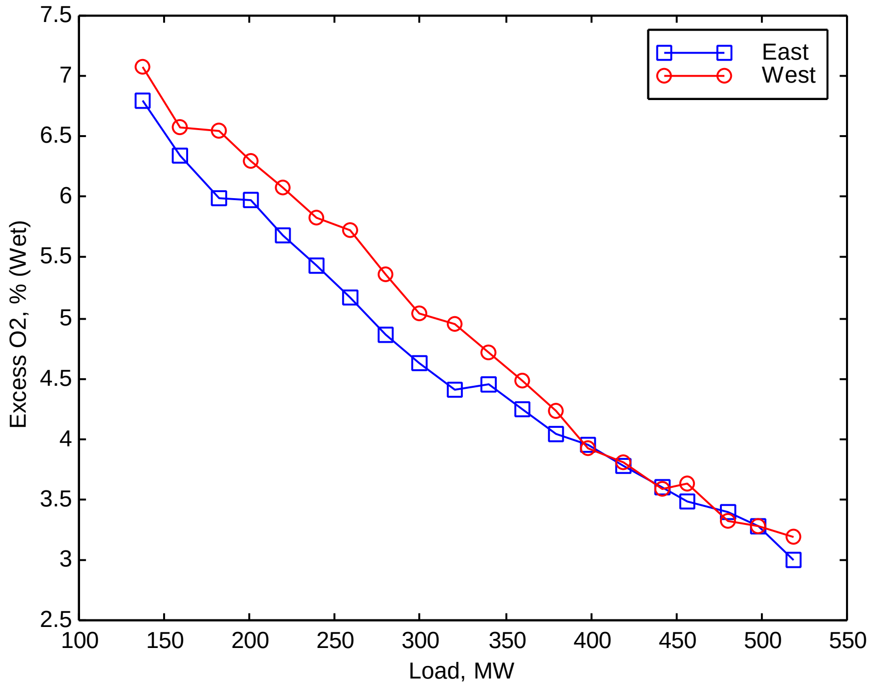


Figure 4-42 P4A – Excess Oxygen vs. Load (1Q95)

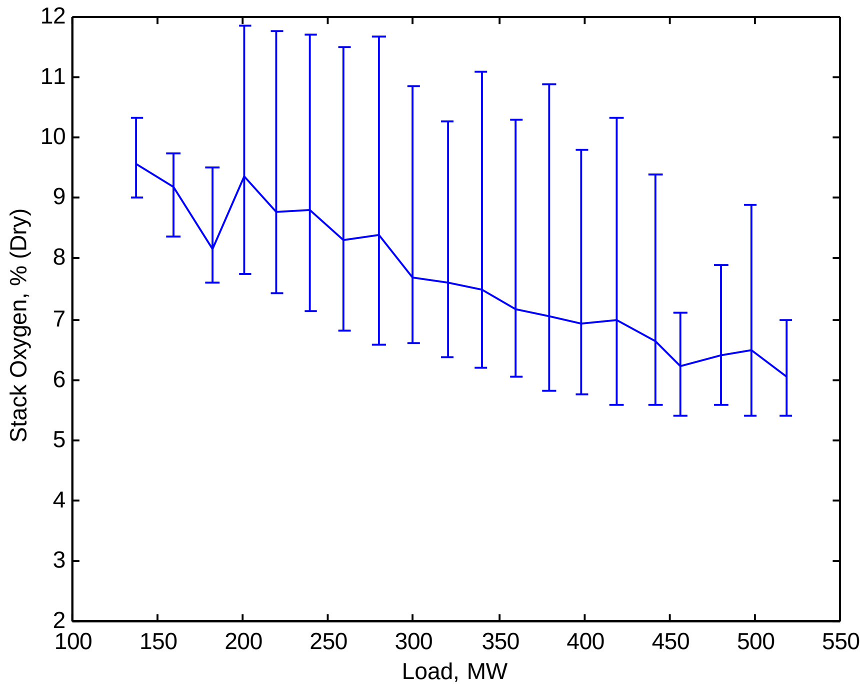


Figure 4-43 P4A – Stack Oxygen vs. Load (1Q95)

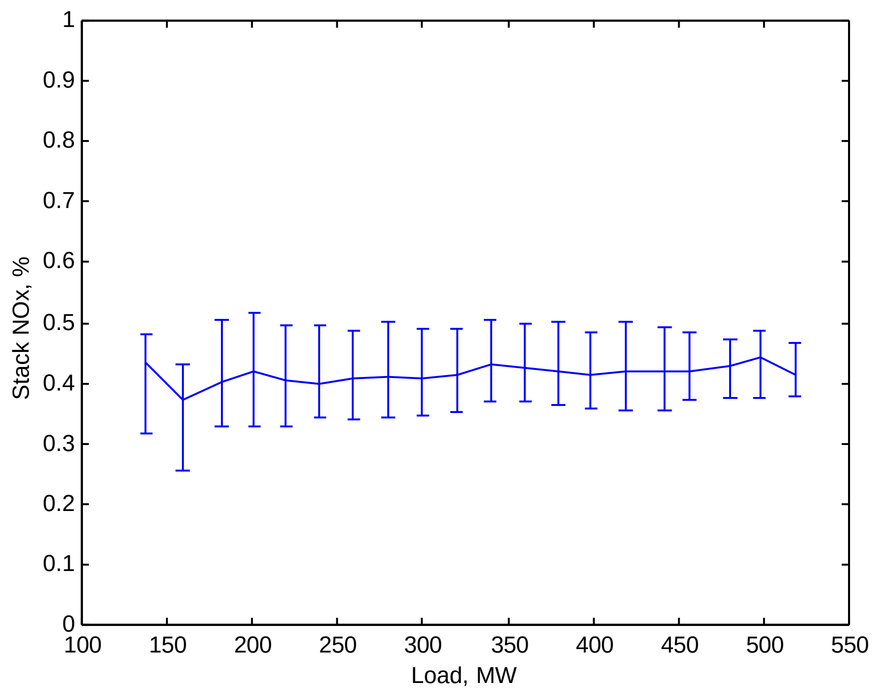


Figure 4-44 P4A – Stack NOx vs. Load (1Q95)

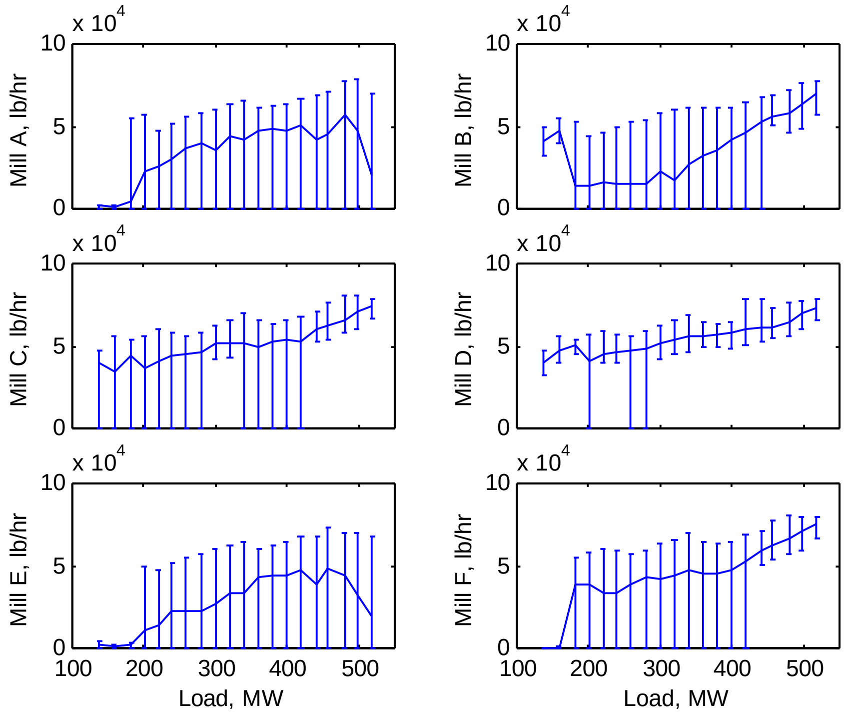


Figure 4-45 P4A – Mill Coal Flows vs. Load (1Q95)

Table 4-8 P4A - NOx Emissions vs. Mill Pattern (1Q95)

Load Range	Mill Pattern A-B-C-D-E-F	NOx Emissions lb/MBtu
190-210	0-0-1-1-0-1	0.387
	0-1-1-1-0-1	0.418
	1-0-1-1-0-1	0.440
290 - 310	0-1-1-1-0-1	0.421
	1-0-1-1-0-1	0.418
	1-0-1-1-1-1	0.429
380 - 400	1-0-1-1-1-1	0.419
	1-1-1-1-1-0	0.395
	1-1-1-1-1-1	0.430
490 - 510	1-1-1-1-0-1	0.426
	1-1-1-1-1-1	0.447

4.1.5 Process Data for 1st Quarter 1996

For purposes of comparison with earlier data, process data collected during first quarter 1996 is presented.

Steam Temperatures

Main steam and reheat temperatures are shown in Figure 4-46 and Figure 4-47, respectively. Main steam temperature averaged approximately 998°F from approximately 200 MW up to full load (500 MW). The design steam temperature for the unit is 1000°F. In general, a 10°F decrease in main steam temperature results in an 0.15 percent increase in turbine cycle heat rate for subcritical, drum units. Hot reheat temperature averaged near 997°F at the upper loads but dropped below 990°F at approximately 200 MW. As with main steam temperatures, the design temperature is 1000°F and there is an 0.15 percent increase in turbine cycle heat rate for a 10°F decrease in reheat temperature.

Main Steam Pressure

Main steam pressure as a function of load is shown in Figure 4-48. As shown, the pressure remained near the design level of 2400 psig for most of the load range, only dropping significantly below 200 MW. There is 0.4% decrease in turbine cycle heat rate for every 100 psi deviation from design.

Secondary Air Heater Inlet and Outlet Gas Temperatures

The secondary air heater inlet and outlet gas temperatures are shown in Figure 4-49 through Figure 4-52. Full load air heater inlet temperatures (economizer outlet temperatures) averaged near 730°F with the east side being nearly 80°F hotter than the west. The design temperature for the unit is 710°F at full load. However at lower loads, the east side temperatures were less than the corresponding west side temperatures. This large difference in temperatures was not evident in earlier datasets and the cause is unknown. As expected, the temperature dropped with decreasing load, averaging near 650°F at 260 MW. The design temperature at this load is near 590°F. The secondary air heater outlet temperature averaged approximately 310°F at full load dropping to near 280°F at 260 MW. The full load design temperature is near 282°F.

Excess Oxygen

In addition to the ECEM excess oxygen measurement, excess oxygen was also measured at the economizer outlet using the plant's in situ instrumentation. Excess oxygen for the east and west economizer outlet is shown in Figure 4-54 and Figure 4-53, respectively. As shown in Figure 4-55, based on plant instrumentation, the east and west sides were relatively well balanced over the load range. The stack oxygen level is shown in Figure 4-56.

NOx Emissions

NOx emissions for first quarter 1996 are shown in Figure 4-57. As shown, NOx emissions averaged approximately 0.40 lb/Mbtu over the load range. The bars on this figure represent the 5^{th} and 95^{th} percentiles of NOx emissions data collected. As with first quarter 1995 data (Figure 4-44), NOx emissions compared more similar to the Phase 3B data than that collected from July to November 1994 (Figure 4-30).

Mill Coal Flows

Mill coal flows as functions of load are shown in Figure 4-58. As shown, the "A" and "D" mills tended to be utilized earlier than the other mills during this period. The "A" and "D" supply the front and rear middle elevation burners, respectively. The choice of mills will generally affect all boiler performance measures including NOx emissions, LOI, and efficiency. The mill patterns by load are provided in Appendix A. The most common mill patterns along with NOx emissions for several load ranges are shown in Table 4-9. As shown, mill pattern selection appeared to affect NOx emissions by approximately 10 percent.

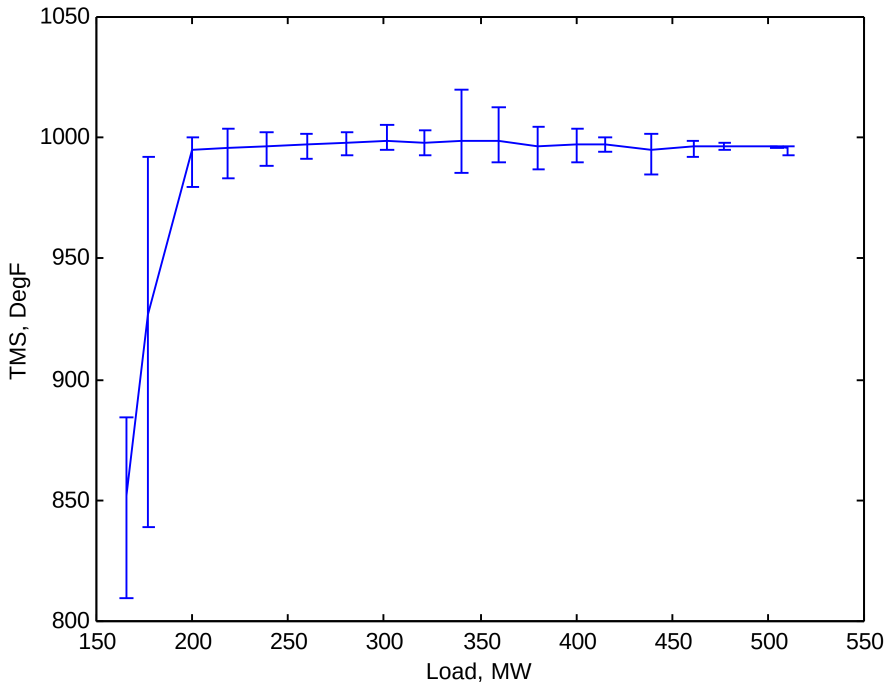


Figure 4-46 P4A – Main Steam Temperature vs. Load (1Q96)

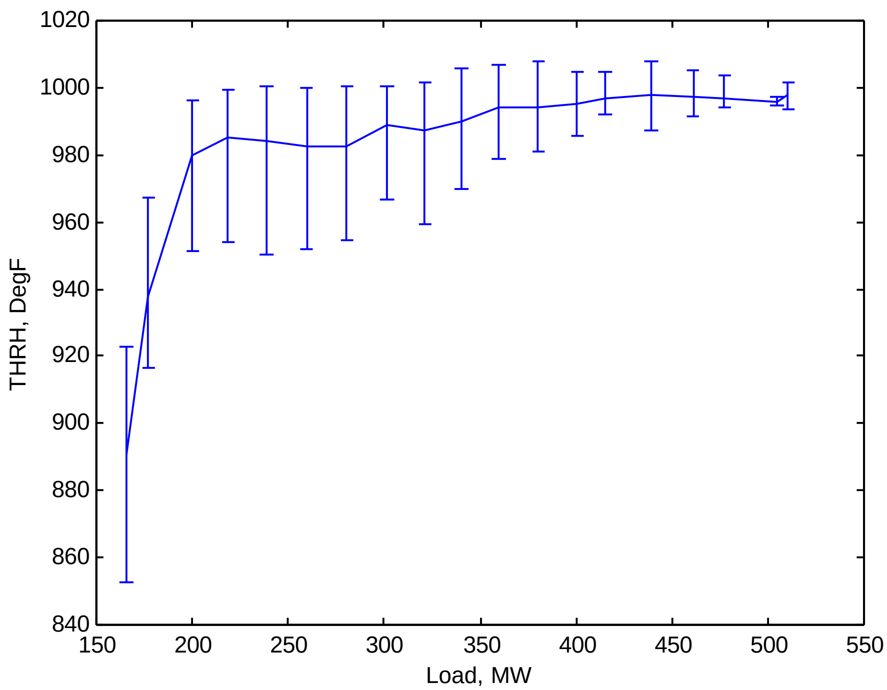


Figure 4-47 P4A – Hot Reheat Temperature vs. Load (1Q96)

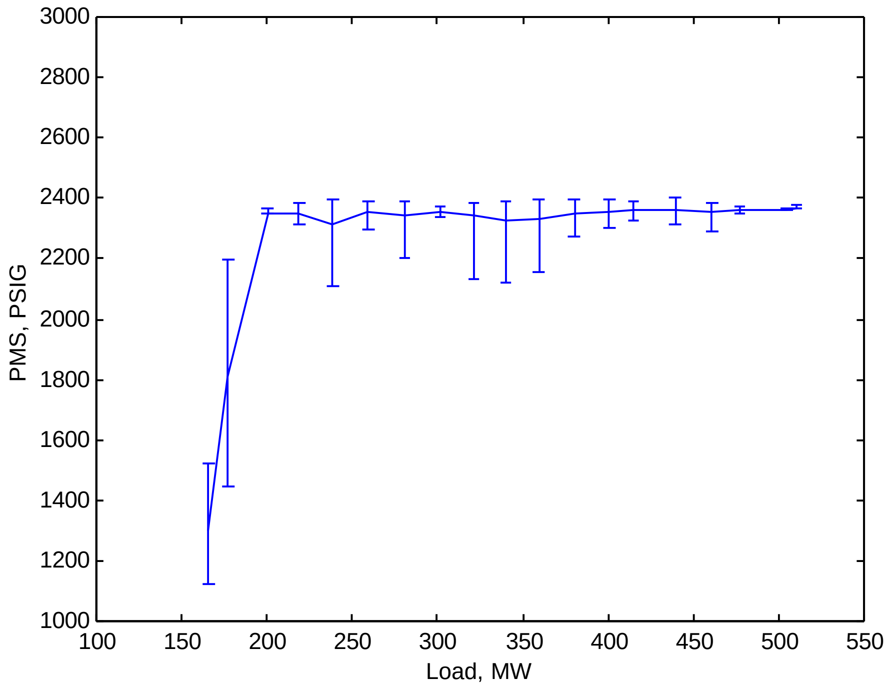


Figure 4-48 P4A – Main Steam Pressure vs. Load (1Q96)

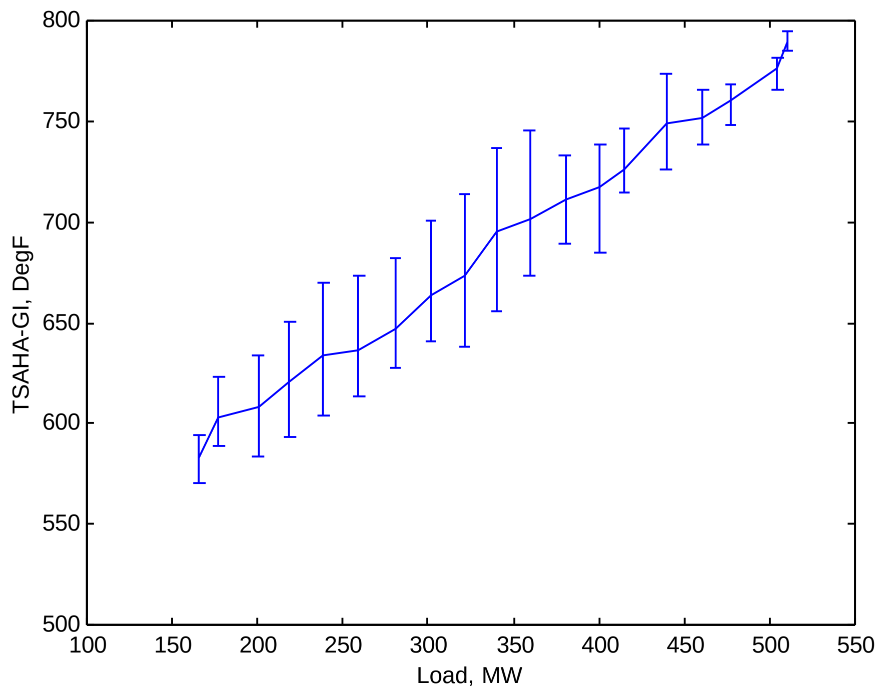


Figure 4-49 P4A – Secondary Air Heater A Gas Inlet Temperature vs. Load (1Q96)

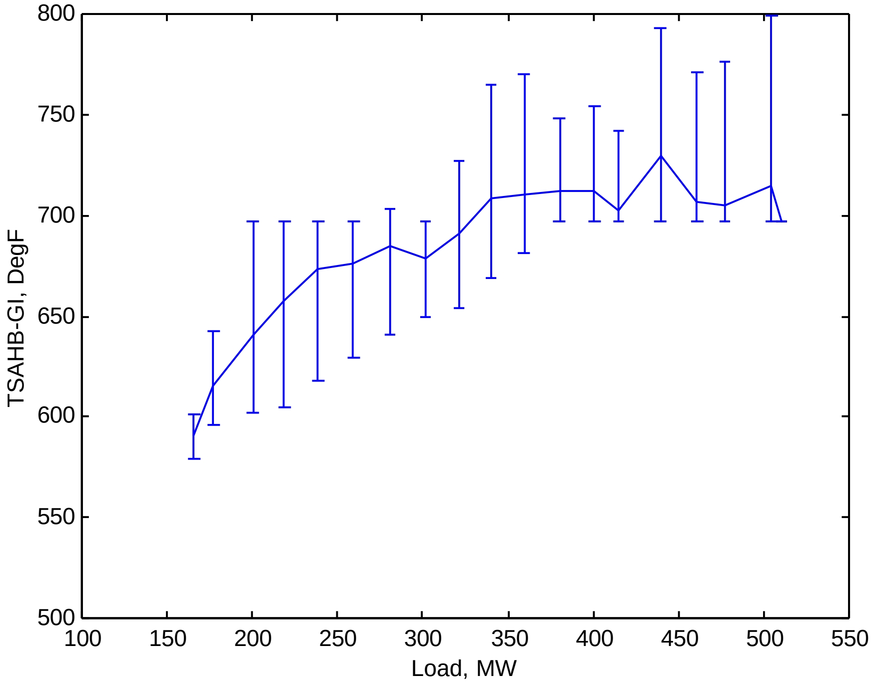


Figure 4-50 P4A – Secondary Air Heater B Gas Inlet Temperature vs. Load (1Q96)

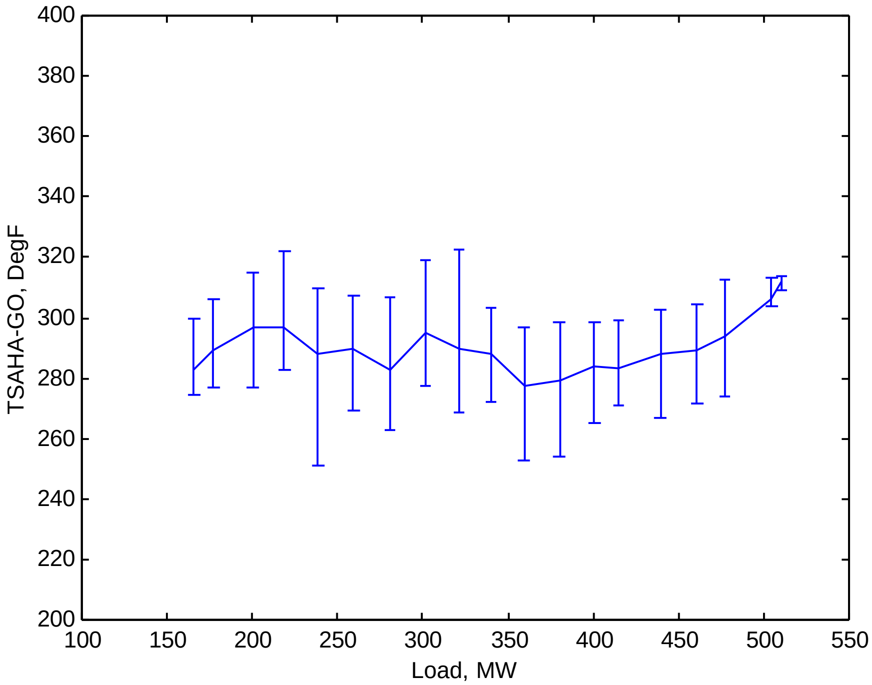


Figure 4-51 P4A – Secondary Air Heater A Gas Outlet Temperature vs. Load (1Q96)

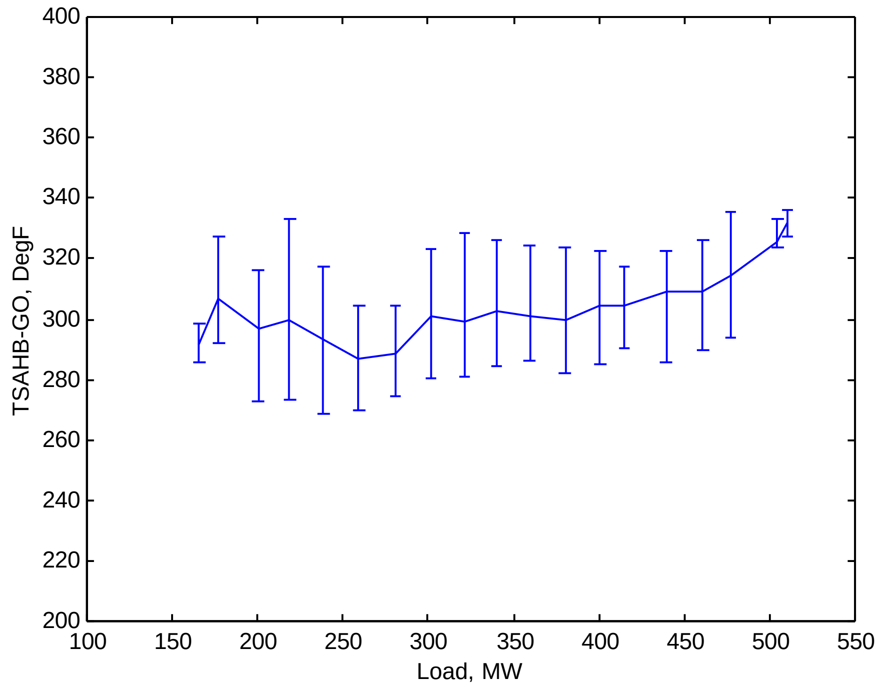


Figure 4-52 P4A – Secondary Air Heater B Gas Outlet Temperature vs. Load (1Q96)

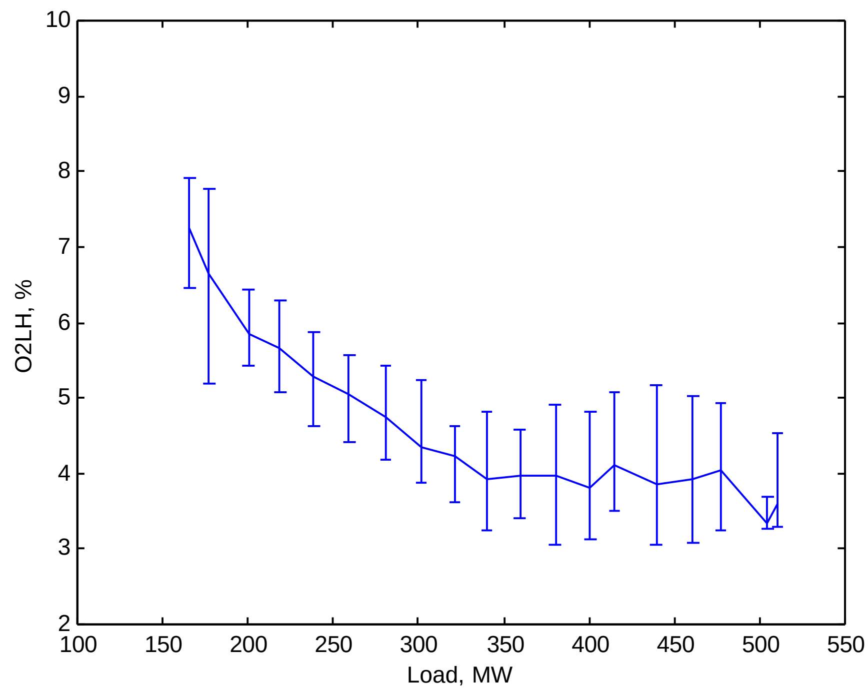


Figure 4-53 P4A – Excess Oxygen Left (West) vs. Load (1Q96)

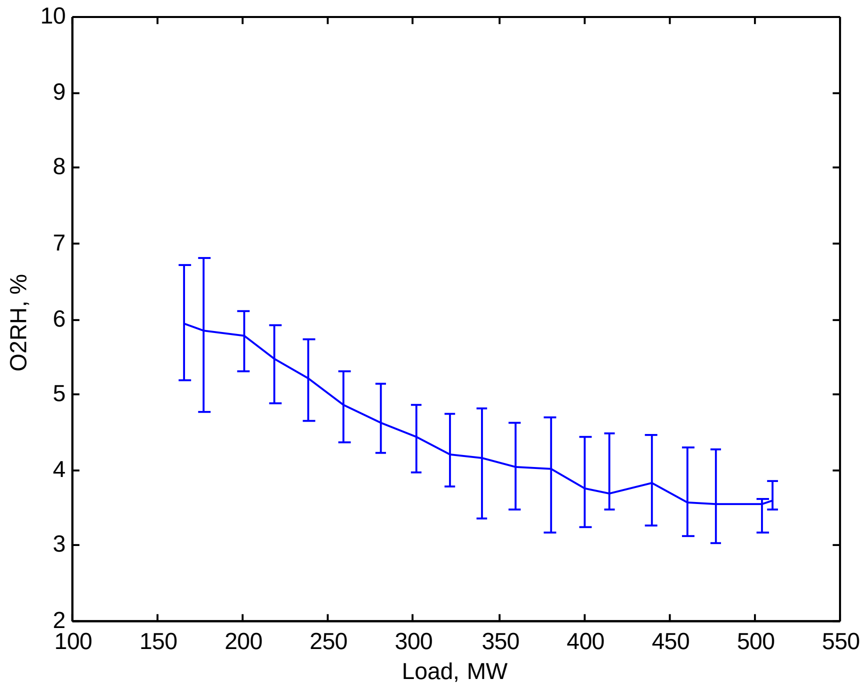


Figure 4-54 P4A – Excess Oxygen Right (East) vs. Load (1Q96)

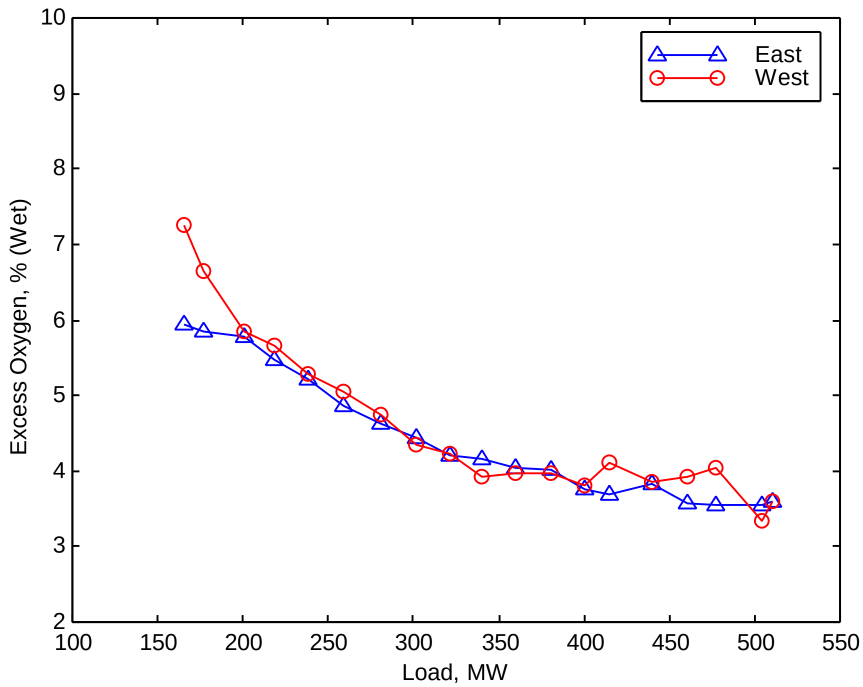


Figure 4-55 P4A – Excess Oxygen vs. Load (1Q96)

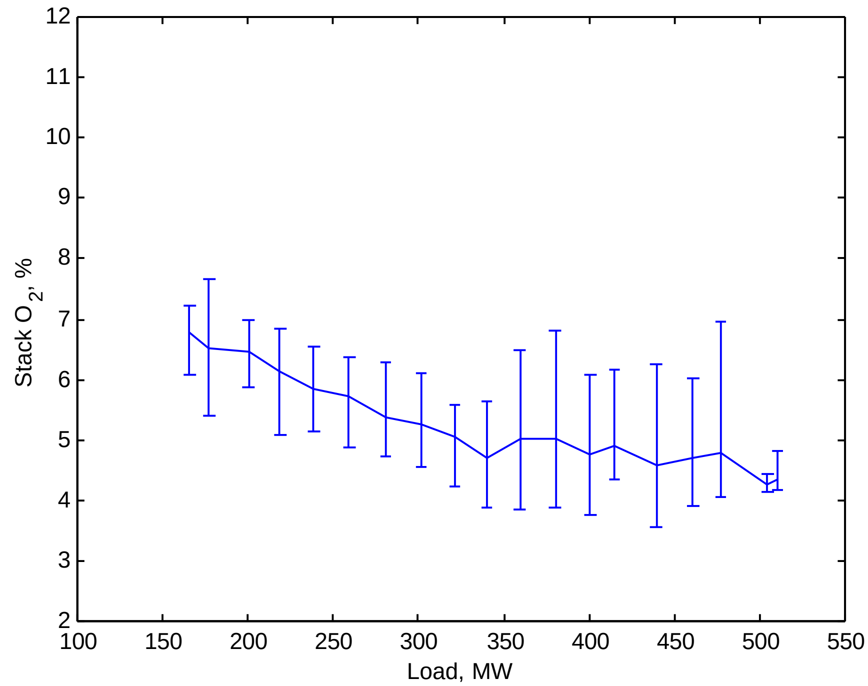


Figure 4-56 P4A – Stack Oxygen (Dry) vs. Load (1Q96)

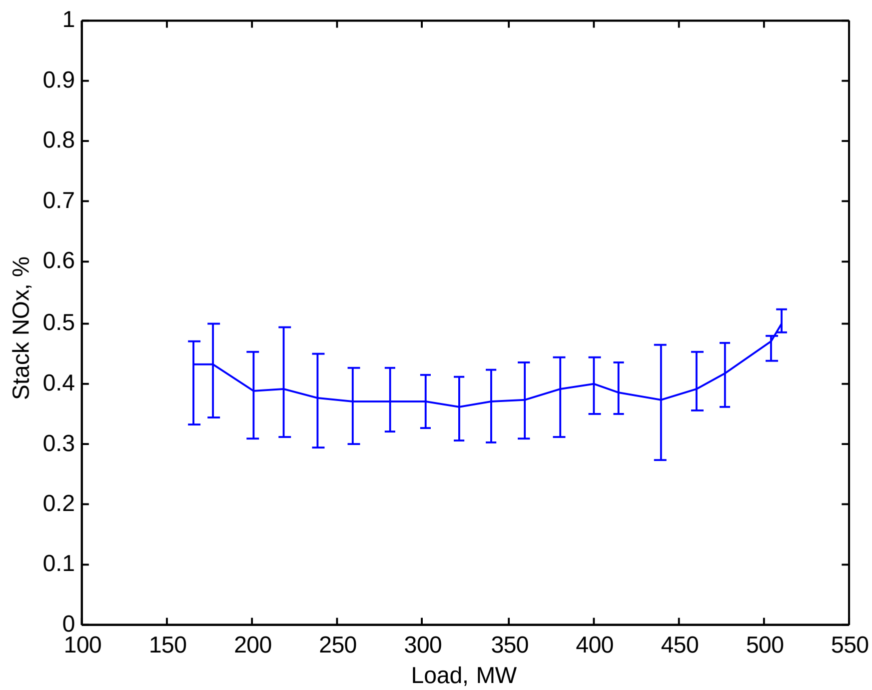


Figure 4-57 P4A – Stack NOx vs. Load (1Q96)

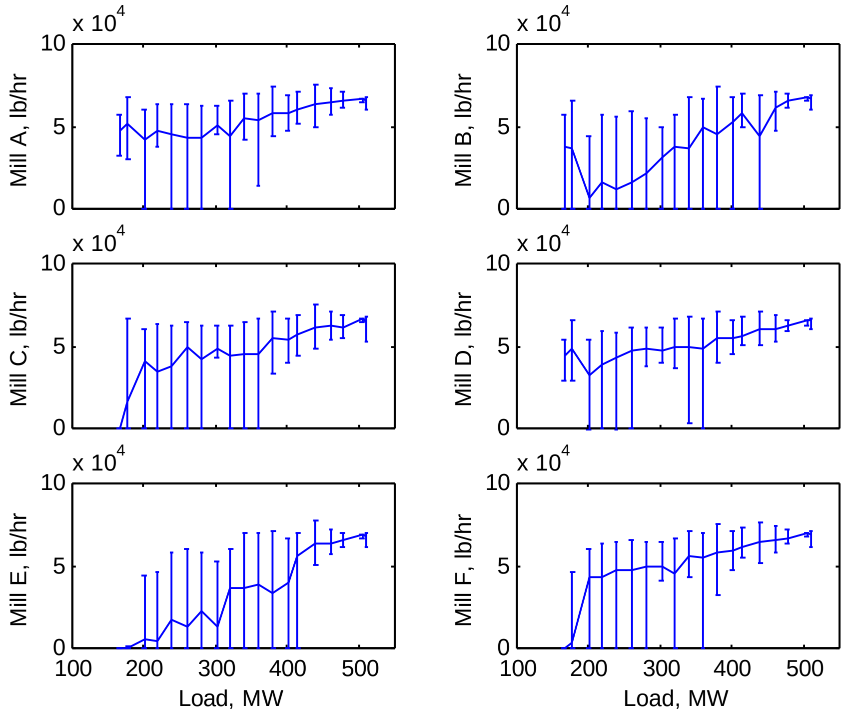


Figure 4-58 P4A – Mill Coal Flow vs. Load (1Q96)

Table 4-9 P4A - NOx Emissions vs. Mill Pattern (1Q96)

Load Range	Mill Pattern A-B-C-D-E-F	NOx Emissions lb/MBtu
190 - 210	1-0-1-0-0-1	0.378
	1-0-1-1-0-1	0.399
	1-1-1-0-1-0	0.348
290 - 310	1-0-1-1-0-1	0.349
	1-0-1-1-1-1	0.375
	1-1-1-1-0-1	0.378
390 - 410	1-0-1-1-1-1	0.366
	1-1-1-1-0-1	0.412
	1-1-1-1-1-1	0.400
490 - 510	1-1-1-1-1-1	0.469

4.2 Performance Comparison

This section provides a comparison of the performance of the unit after the addition of the DCS to other phases. Factors compared include NOx emissions, fly ash unburned carbon levels, CO emissions, excess oxygen and combustion air, air heater and economizer outlet gas temperatures, steam temperatures, drum and throttle pressure, boiler efficiency, and unit heat rate. When available, both short- and long-term data are used in the comparison. It should be noted that this data reflects how the technologies performed on Hammond Unit 4 and although extrapolation to other units is reasonable, consideration must be given to how close other units are to Hammond 4 in terms of boiler design, coal characteristics, and operating conditions.

4.2.1 NOx Emissions

A comparison of the long-term, mean NOx emissions observed during Phase 4A to that observed previously is shown in Figure 4-59. As shown, the Phase 4 NOx emissions were similar to those observed during Phase 3B and considerably below the baseline levels (Phase 1). However from this figure it is also evident that NOx emissions did not generally improve from Phase 3B to Phase 4A (Figure 4-60).

NOx emissions for the performance tests during each phase are shown in Figure 4-61. As shown, full-load NOx reductions for these tests were greater than those obtained during long-term, normal operation. The principal cause of the increase was the higher NOx emissions during the baseline performance test (1.44 lb/Mbtu vs. 1.23 lb/Mbtu). When the performance test NOx values are corrected to stack O_2 levels (Table 4-10) observed during long-term testing, the emission reductions obtained for the performance and long-term tests are very similar. Also, the full-load NOx emissions during Phase 4A were slightly greater than that observed in prior phases. This increase may have been the result of the selection of overall lower operating combustion air levels.

4.2.2 Fly Ash LOI

A comparison of the LOI levels for the four phases as determined during the performance tests for Phases 1 through 4A is shown in Figure 4-62. These values are the average of the performance test conducted during the test period. Full-load LOI levels for Phase 3B (LNB+AOFA) and Phase 4A (LNB+AOFA+DCS) were similar, however, at lower load levels, the Phase 4A LOI levels were greater than the Phase 3B tests. This increase occurred despite the replacement of two pulverizes during the intervening outage and the resultant improvement of coal fineness between the phases (Baseline – Pass 200 Mesh = 63% / Remain 50 Mesh = 2.7%, AOFA = 67% / 2.3%, LNB = 66% / 1.6 %, LNB+AOFA = 74% / 0.6%; LNB+AOFA+DCS = 76% / 0.1).

As stated previously, the performance test conditions were selected based on predicted long-term operating factors including excess oxygen and mill patterns. Because the unit was not necessarily operated at these selected conditions, short-term performance tests do not necessarily match that obtained during long-term tests. To partially compensate for differences in the long-term and short-term operating conditions, the LOI can be adjusted to the stack oxygen levels observed during the long-term data collection. The full-load estimate for Phase 4A is shown in Table 4-11 with that for all loads in Figure 4-63. A comparison of the Phase 3B and Phase 4A LOI levels are shown in Figure 4-64.

4.2.3 Excess Oxygen

As shown in Figure 4-65, measured stack oxygen levels were generally less during Phase 4A than Phase 3B. The differences between the two phases could be the result of several factors including: (1) shift in combustion air, (2) changes in the amount of air in-leakage in the furnace backpass and precipitator (the stack probe is located downstream of the precipitator), and (3) air in-leakage in the sampling system to the stack probe (since the NOx is compensated to 3% excess O_2, this reading would not be affected by the leakage). The first two hypothesis are supported by a reduction in economizer outlet O_2 levels (Figure 4-66).

4.2.4 Economizer Exit and Air Heater Exit Temperatures

The economizer exit and air heater exit gas temperatures are shown in Figure 4-67 and Figure 4-68, respectively. As shown, economizer outlet temperatures during Phase 3B were in general slightly lower than that observed during Phase 4A. However, air heater gas outlet temperatures during Phase 4A were improved over the Phase 3B temperatures.

4.2.5 Main Steam and Hot Reheat Temperatures

There was a general decline in main steam temperatures from Phase 3B to Phase 4A (Figure 4-69). As shown, there was some improvement in temperatures for 1st quarter 1996 when compared to 1st quarter 1995. Hot reheat temperature, shown in Figure 4-70, was similar from about 400 MW upwards but exhibited a degradation below this load level. The cause of the steep decline in steam temperatures below 200 MW is unknown.

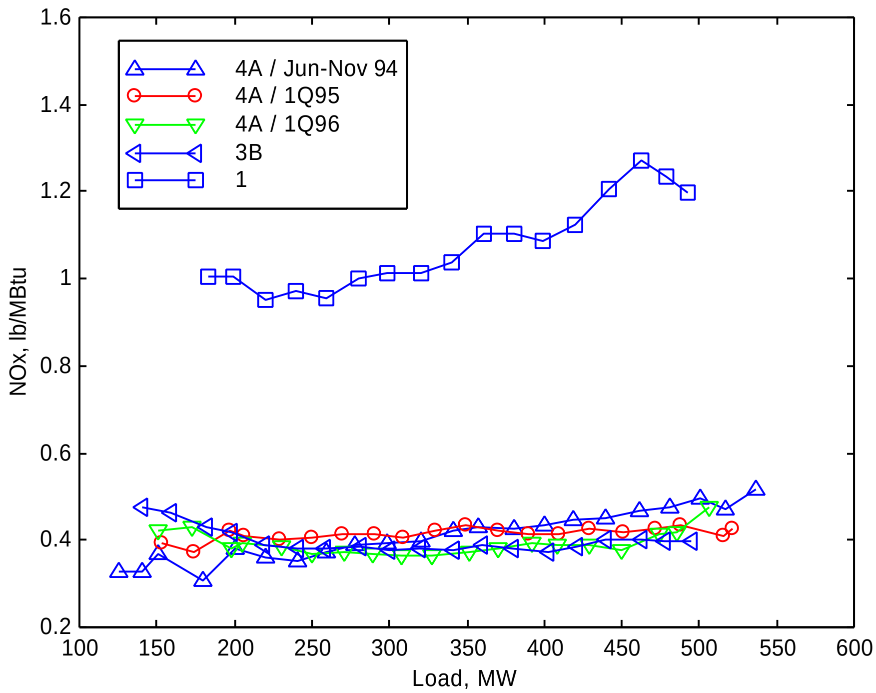


Figure 4-59 Comparison of Long-Term NOx Emissions

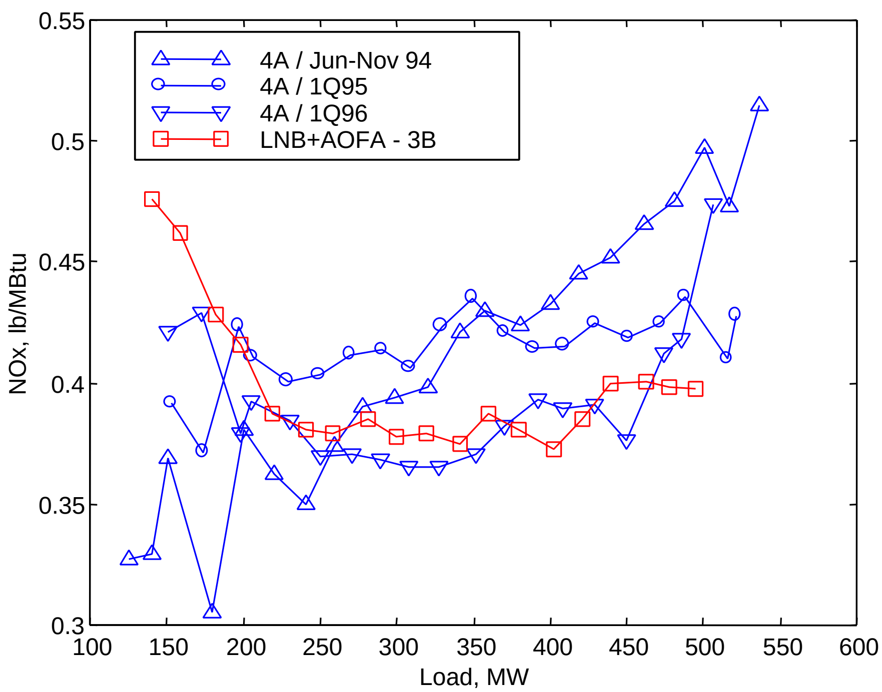


Figure 4-60 Comparison of Long-Term NOx Emissions (Reduced Range)

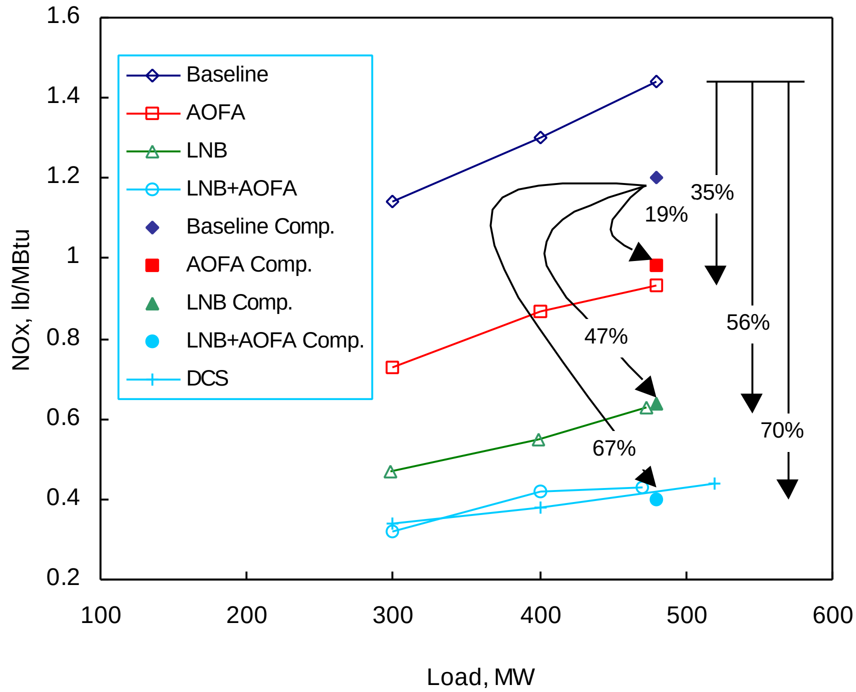


Figure 4-61 P4A – Comparison of Performance Tests NOx Levels

Table 4-10 NOx Emissions Obtained During Long-Term and Performance Tests

	Long-Term NOx Emissions Lb/MBtu	Long-Term Stack O_2 Percent	Perf. Test NOx Emissions Lb/Mbtu	Perf. Test Stack O_2 Percent	Compensated[2] Perf. Test NOx Emissions Lb/Mbtu
Baseline	1.24	5.0	1.44	7.5	1.19
AOFA	0.94	6.5	0.93	6.3	0.94
LNB	0.65	6.6	0.63	6.4	0.64
LNB+AOFA	0.40	6.1	0.43	6.6	0.40
+DCS	0.47	5.3	0.44	5.4	0.43

[1]Full-load (480 MW for baseline, AOFA, LNB, LNB+AOFA, 520 MW for DCS)
[2]NOx emissions compensated to stack O_2 levels observed during the corresponding long-term test period.

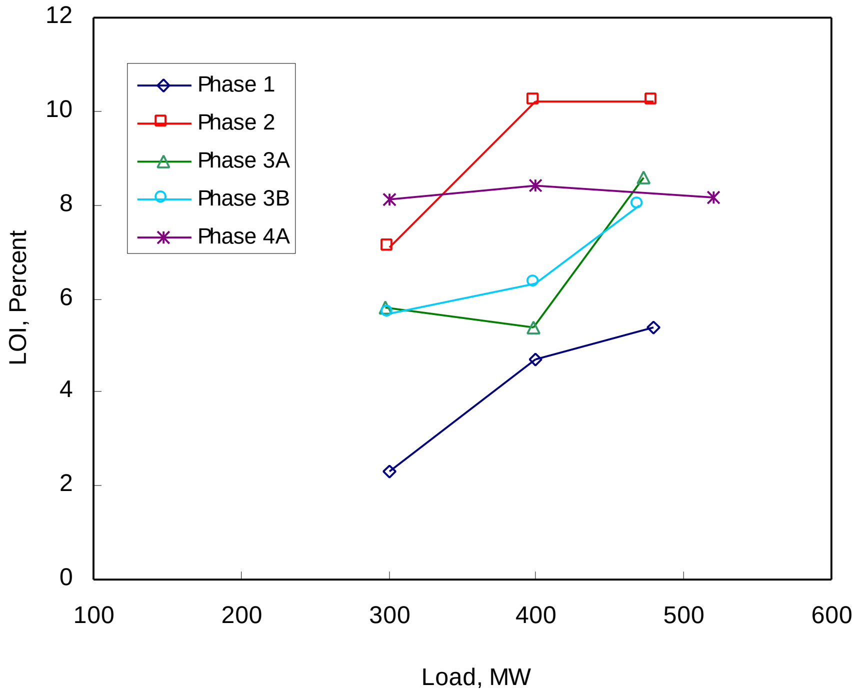


Figure 4-62 P4A – Comparison of Performance Tests LOI Levels

Table 4-11 Full-Load LOI Levels

	Perf. Test Stack O_2 Percent	Perf. Test LOI Percent	Perf. Test Percent Increase	Long-Term Stack O_2 Percent	Long-Term LOI Percent[1]	Long-Term Percent Increase[2]
Baseline	7.5	5.2	na	5.0	7.1	na
AOFA	6.3	10.2	96	6.5	10.1	42
LNB	6.4	8.6	65	6.6	8.2	16
LNB+AOFA	6.6	8	54	6.1	8.4	18
Phase 4A	5.4	8.2	58	5.3	8.3	17

[1]LOI compensated to stack O_2 levels obtained during long-term test using a sensitivity of 0.75 LOI percent per percent change in excess O_2.
[2]Relative to baseline.

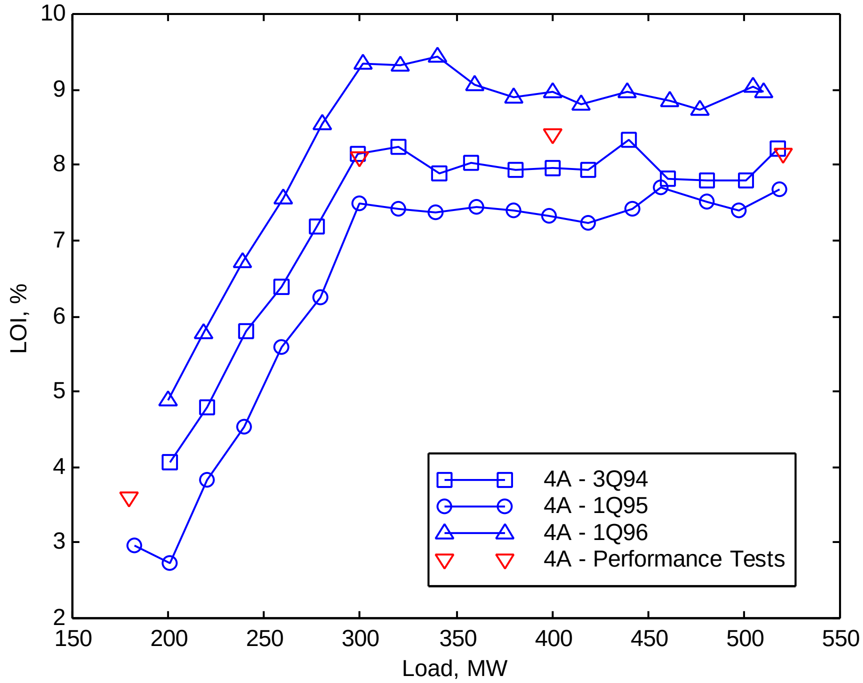


Figure 4-63 P4A – Comparison of Performance Tests to Predicted Long-Term LOI Levels

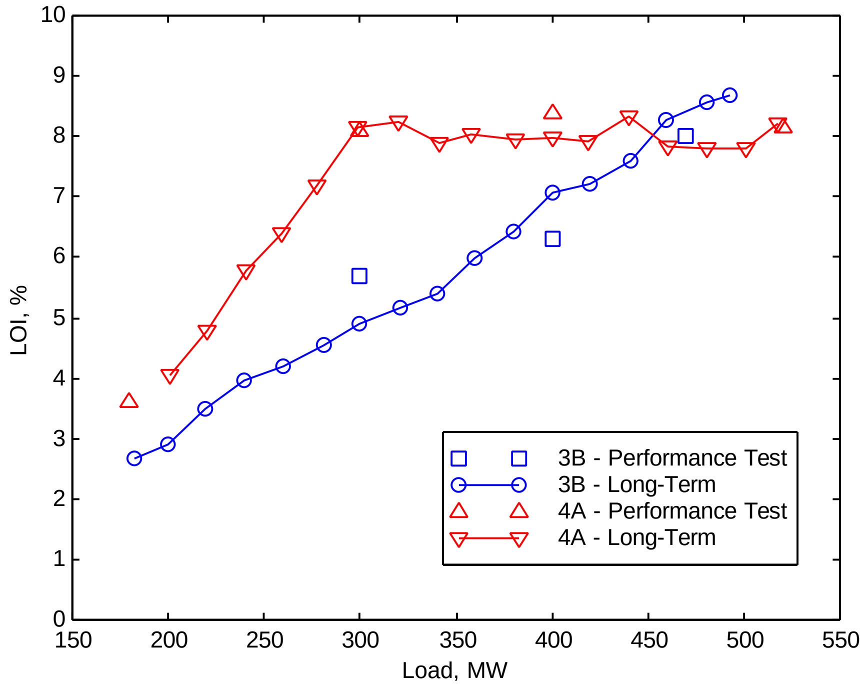


Figure 4-64 P4A – Comparison of LOI Levels

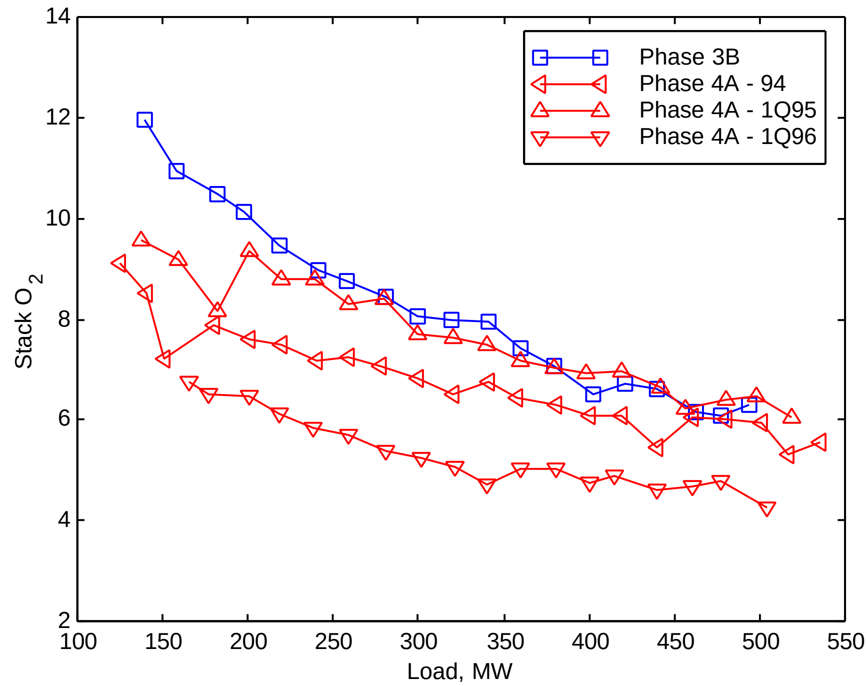


Figure 4-65 P4A – Comparison of Stack O_2 Levels

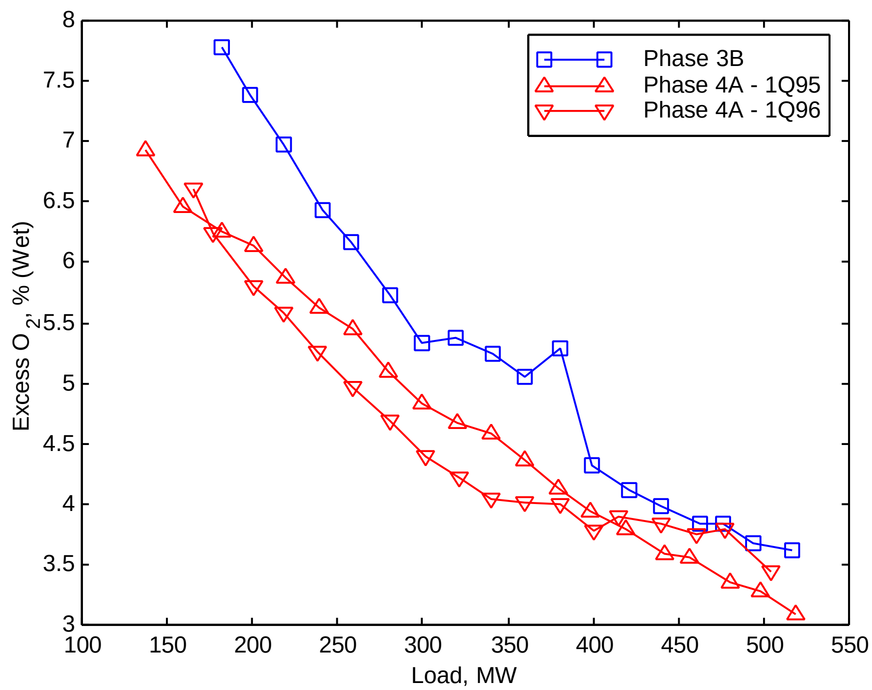


Figure 4-66 P4A – Comparison of Economizer Outlet O_2 Levels

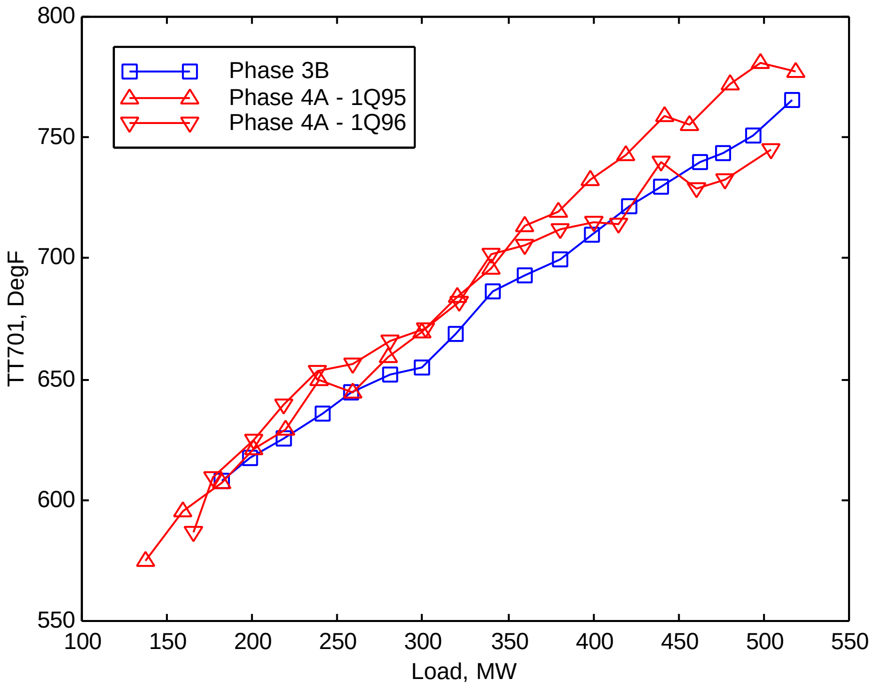


Figure 4-67 P4A – Comparison of Economizer Gas Inlet Temperatures

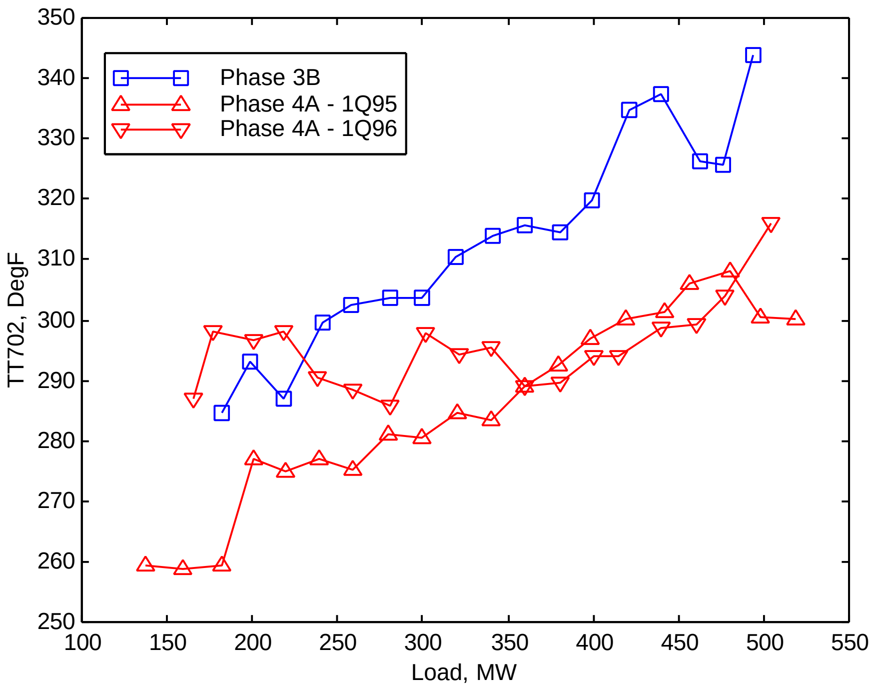


Figure 4-68 P4A – Comparison of Economizer Gas Outlet Temperatures

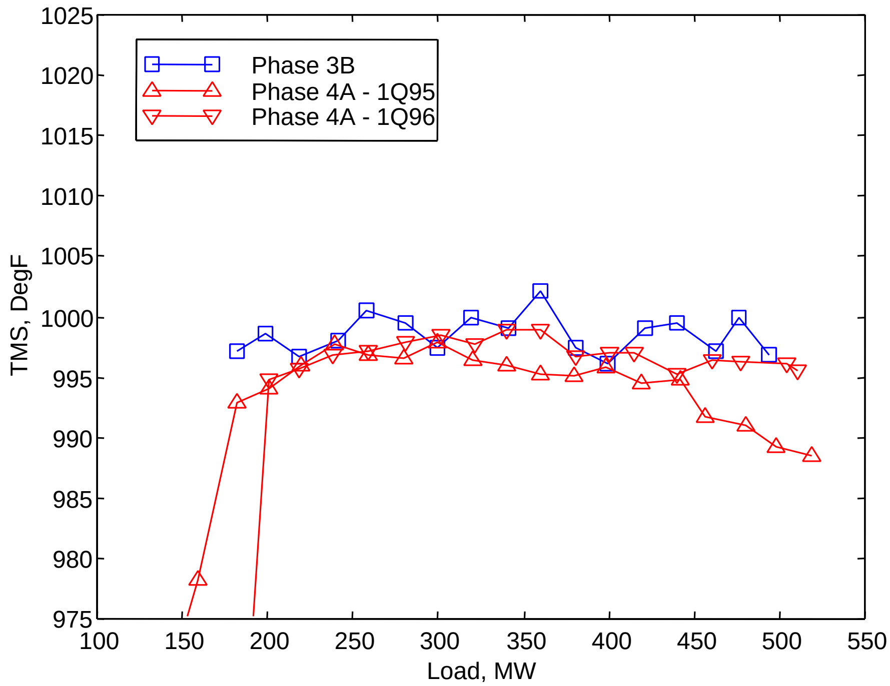


Figure 4-69 P4A – Comparison of Main Steam Temperatures

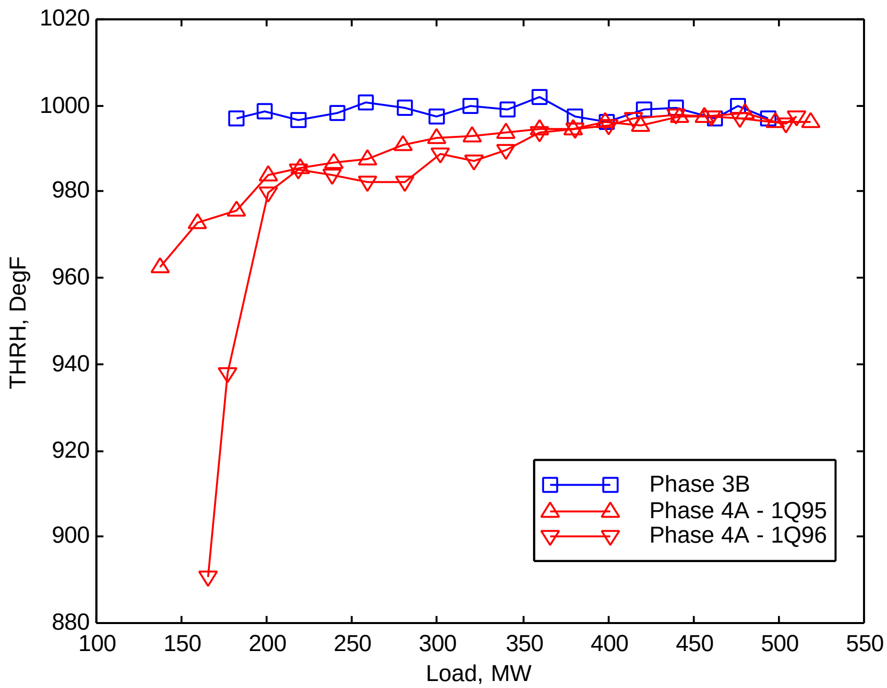


Figure 4-70 P4A – Comparison of Hot Reheat Temperatures

5 OPTIMIZATION

5.1 Introduction

As discussed in Section 3, results from Hammond and other sites indicated that there was potential for the use of on-line combustion techniques to improve combustion performance both for NOx emissions and efficiency. During 1991, SCS, along with the other project participants, began initial discussions on extensions to the project that would explore and evaluate these techniques. The following studies grew out of these discussions.

- During 1992, SCS contracted with Tennessee Technological University's Center for Electric Power to perform a feasibility study for advanced controls and optimization which eventually led to a demonstration of ULTRAMAX at Hammond 4.
- As a follow up to this work, the project participants looked at applying neural networks to modeling the combustion process including NOx emissions and boiler performance parameters.
- Following installation of the DCS and testing of this unit, the on-line optimization package GNOCIS (Generic NOx Control Intelligent System) was installed on the unit. GNOCIS became operational on the unit in open-loop mode during first quarter 1996 with closed-loop operation during second quarter 1996.

The major findings of these studies are discussed in the following paragraphs.

5.2 Feasibility Study

On January 6, 1992, Southern Company Services proposed to the project participants an initial feasibility study to investigate on-line combustion optimization. This proposal was based on evidence from this and other combustion demonstration projects that control strategies can affect NOx reduction potential. Tennessee Technological University's Center for Electric Power was selected to perform this study.

The broad activities of this study were:

- Literature search to identify existing art and promising technologies.
- Plant testing as necessary to validate promising technologies.
- Computer modeling as necessary to evaluate the effects of the advanced control strategies on NOx emissions.
- Preliminary control development and conceptual design.

Based on these initial investigations, ULTRAMAX®, was selected to perform preliminary optimization. ULTRAMAX is a software product from Ultramax Corporation. This selection was based on several factors:

- It was commercially available
- Does not require a digital control system, data acquisition system, or great computing resources.
- Only a moderate learning curve required to become competent in its use.

<u>Description of ULTRAMAX</u>

ULTRAMAX is an optimization package by which the improvements to the process are achieved by making adjustments to the process inputs, monitoring the output response, and using the response from prior perturbations to make performance predictions. This commercial package has been available for a number of years and is used extensively in the process industries. This package traverses the multi-dimensional process space in it's search for the optimum operating condition and in doing so develops a regression model of the process. The software uses a goal-oriented, locally accurate model to make predictions and operating recommendations.

Commonly known constrained optimization techniques being used are Simplex and EVOP (Evolutionary Operation). Simplex is used to solve linear programming problems delimited by an objective function where constraint functions may be included [Ragsdell, 1983]. EVOP is a statistical method for process improvement that is best suited for 2^k and 3^k factorial design of experiments [Box, 1969]. These methods are not very well suited for on-line combustion optimization. Aside from the fact that both of them are not easily applied to ongoing processes and require too much time and attention; Simplex sensitivity to noise and variability makes it an even poorer candidate, and the large number of variables to consider would make the factorial design of experiments a costly technique. "The difficulty of operating an EVOP scheme increases greatly as the number of factors (variables) is increased, because of the number of process conditions involved and the number of changes that must be made" [Box, 1969].

Sequential optimization is based on the principle of EVOP "that a process should be operated so as to produce not only a product but also *information on how to improve the product*" [Box, 1969]. In addition, a fundamental principle of sequential statistical analysis is that proper and timely use of existing information is more effective than not using it [Wald, 1947]. These principles underline the advantages of sequential optimization over other methods since process data is used cognitively and immediately, instead of being reserved for later analysis. As a result, process models developed using sequential optimization may be able to quickly learn to avoid settings that produce poor performance and tend to move rapidly in the direction of improvement.

A more recent technique is based on a statistical approach to create quadratic models of the measurements in a system and, integrating these models, recommend adjustments to the control settings [Moreno, 1989]. In this technique, the system's variables are categorized in three groups: (1) controlled inputs, (2) external inputs, and (3) results. A problem formulation is then devised where the variables take roles as "controlled" (that can be adjusted by the user), "external" (measurable but not influenced by the user), "ruled" (governed by user-defined rules), "results" (of interest only), "important results" (constrained or used for computational purposes), and "measure of performance" (the objective of the optimization). These roles are interchangeable during the process making this technique flexible.

In constrained sequential optimization, linear regression is the tool used to determine the relationship between the independent variable (X) and the dependent variable (Y) so that the expected value of Y, let's call it Y', can be calculated from any given input value X. Based on the principle that continuous functions can be locally approximated with a quadratic expression, this relationship is defined with the formula:

$$Y' = a + bX + cX^2$$

Linear regression uses the technique of least squares to calculate the coefficients a, b and c [Neter, 1990]. The criterion used is, as the name indicates, the minimization of the sum of the squares; that is, the difference between a measured value of Y and the theoretical value Y' is the least. For *n* pairs of values, the relation between X and Y becomes:

$$Y_{kx1} = a_{kx1} + b_{kx1} X_{1xk} + c_{kx1} \; X^2_{1xk} \; + \varepsilon_{kx1}$$

This quadratic model can be extended to multiple input variables X_1, X_2, X_3,…, X_n creating a multidimensional surface in which sequential optimization can be applied. Two parameters that determine the goodness of a regression model are (1) the *coefficient of determination* (R^2), which measures the proportionate reduction of total variation in the dependent variable (Y) associated with the use of the set of independent variables (X_i), and (2) the *Standard Distance* (σ) is a parameter representing a standard (dimensionless) measure of the distance from the current independent variables to the region defined by the run data selected to generate the current local models.

In addition to constructing a multidimensional surface, Moreno's method weights the latest data points collected to create *locally accurate* or *goal-oriented* models, avoiding the creation of descriptive (global) models for all the data that may override smaller details. These models are used to predict results and provide sequential *advice* on how to run the process, that is, how to adjust the input variables for the next cycles. This advice is called sequential since every time it is followed, new data is generated that is used to calculate a new regression function which in turn is used to generate new advice. The advice is not always an optimum prediction because perturbations can be added about the estimated optimum to obtain more information about the process and potentially increase the accuracy of the models. This technique has been integrated into ULTRAMAX [Moreno, 1989].

<u>Testing at Hammond</u>

Preliminary *on-line* testing of this software package was conducted at Plant Hammond Unit 4 on July 28-29, 1992 [Catasus-Servia, 1993]. The objective of this experiment was to determine the validity of the data used with the optimization package and the statistical process model (for NOx, CO, opacity, etc.) created by this package. The accuracy of the model represents the software's ability to predict the process outputs given the optimization objective function and constraints (both physical and those defined in the software). Experiment 1 was done using instantaneous data as provided by direct readings of the five second scan rate of the DAS with the purpose of investigating the application and performance of the sequential optimization software as a controller. Until now, this methodology has not been applied to an emissions control problem and therefore, this experiment was designed as a limited feasibility study to determine whether this approach had potential for boiler control. The experiment consisted of six independent variables (Total Air, OFA West Front, OFA East Front, OFA West Rear, and OFA East Rear), three constraints (opacity, O_2, and CO) and NOx as the measure of performance. The model formulation used is listed in Table 5-1. Opacity, O_2, and CO constraints were set to meet the safety and environmental operational requirements of the boiler as prescribed by plant operations personnel. A CO constraint of 30 ppm was required to consistently maintain CO emissions below 100 ppm. The recommendations provided by the software were implemented manually by the operator. The results of these changes on NOx, CO, and opacity were fed back into the optimization package manually.

Table 5-1 Feasibility Study - Problem Formulation Experiment 1

Variable	Units	Variable Type
Total Air	MPPH	1 - Controlled
OFA West Front	KPPH	1 - Controlled
OFA East Front	KPPH	1 - Controlled
OFA West Rear	KPPH	1 - Controlled
OFA East Rear	KPPH	1 - Controlled
Total Coal	KPPH	2 - External
CO	PPM	5 - Important Result - Constraint < 30 ppm
Economizer O_2	PCT	5 - Important Result - Constraint > 3.0%
Opacity	PCT	5 - Important Result - Constraint < 30.0%
NOx	lb/MBtu	6 - Measure of performance

The test was run at approximately 450 MW with five mills in service (mill D out of service). During the test, a "snapshot" reading of the process data was taken from the wall-fired project's data acquisition system following a change in one of the controlled variables and settling of the boiler. A total of 45 data points were collected during the two days of testing of which 42 were considered suitable for the software's use. These snapshot readings were used in real time to generate the advice for the settings of the control variables. In addition to this data, five-minute averages were also collected for later analysis. An evaluation of the data gathered during the test showed that instantaneous data contained too much noise to produce significant improvements on the measure of performance since the models built lacked a satisfactory coefficient of multiple determination, R^2. Nevertheless, NOx emissions were reduced from 0.58 lb/MBtu to about 0.49 lb/MBtu, a reduction of approximately 15%. Later analysis of the data, comparing instantaneous and five-minute averages, showed that five-minute averages should have been used as the input because of the significant reduction of noise. For the variable configuration used in Experiment 1, the adjusted R^2 (adjusted for the degrees of freedom) increased from 59.8% to 76.6% when using the five-minute averages. Unburned carbon losses included a loss-on-ignition (LOI) term that was calculated from a linear model developed from prior LOI data since on-line measurements for LOI were not available. Although the model was not as accurate as would be desired, it was still applied to determine the software behavior to a change in the measure of performance.

With the predefined models created from the data of the first experiment and using the first two runs to duplicate the conditions at the end of the first experiment, 26 more runs were conducted before an apparent optimum had been achieved. The improvement in NOx emissions during the second experiment was on the order of 16%, reducing the NOx emissions level from 0.52 lb/MBtu to 0.42 lb/MBtu. At this point, the measure of performance was changed to minimize losses, constraining NOx emissions to 0.45 lb/MBtu. Only five additional points were taken after the measure of performance was changed, but these seemed sufficient to show that changing the objective function did not reduce the ability of the software to maintain the NOx emissions at the level indicated by the constraint. As mentioned earlier, the constraint setpoint for CO in the software had to be set to 30 ppm to ensure a level below 100 ppm due to the extremely steep, highly non-linear, dependency of CO emissions on local combustion conditions.

Table 5-2 Feasibity Study - Problem Formulation Experiment 2

Variable	Units	Variable Type
Air East	MPPH	1 - Controlled
Air West	MPPH	1 - Controlled
OFA West Front	KPPH	1 - Controlled
OFA East Front	KPHH	1 - Controlled
OFA West Rear	KPPH	1 - Controlled
OFA East Rear	KPPH	1 - Controlled
Total Coal Flow	KPPH	2 - External
Fluegas Temperature	^oF	5 - Used in Subroutine
CO	PPM	5 - Important Result - Constraint < 40 ppm
Economizer O2	PCT	5 - Important Result - Constraint > 2.8 %
Opacity	PCT	5 - Important Result - Constraint < 30.0 %
NOx	PPM	6 - Measure of Performance
LOI East	PCT	5 - Calculated
LOI West	PCT	5 - Calculated
Losses	PCT	5 - Calculated

During the course of both optimization sequences (Experiments 1 and 2), NOx was reduced from approximately 0.58 to 0.44 lb/MBtu (Figure 5-1). It must be noted that the transition from Experiment 1 to Experiment 2 was done with two initial runs to simulate the last point of Experiment 1 which are not represented in the figure. The oscillation of the scatter plot with respect to the moving average can in part be explained by the constrained sequential optimization process. As mentioned before, the advice generated is not always an optimum estimate because exploration runs are made to increase the accuracy of the models being created. During these experiments, the optimum settings were requested every third run. Point “A” corresponds to the change in measure of performance done once it was thought an optimum had been reached. It can be seen that in the five runs conducted, the NOx level remained below the constraint imposed.

To produce an estimate of the performance of the sequential optimization applied to Unit 4, a historical plot corresponding to Experiment 2 was generated (Figure 5-2) using five-minute averages and showing the rated load and the NOx emissions throughout the two days of testing. Figure 5-2 has been divided in 8 sections, “A” through “H”, that are significant to illustrate the performance of the unit with the actual control system and the performance using constrained sequential optimization for the NOx emissions control. Table 5-3 shows the time period corresponding to each section and provides a brief description. Section “A” shows that for constant load, 420 MW, it was possible to reduce the NOx emissions from 0.45 lb/MBtu to about 0.37 lb/MBtu. The spike in the load curve was caused by a mill going out of service. Section B corresponds to a period of time where, maintaining the load, the plant returns to its normal operation. The significance of this section is the increase of NOx levels to approximately 0.5 lb/MBtu. In section “E” constrained sequential optimization was again used for the air flow distribution, and doing so halted the ascending trend of NOx from the load increase. Sections “F” and “G” show that the NOx level remained below the constraint imposed. Section “H”, as it happened the previous day (section “B”), shows that the return to normal operation produced an increase in NOx emissions.

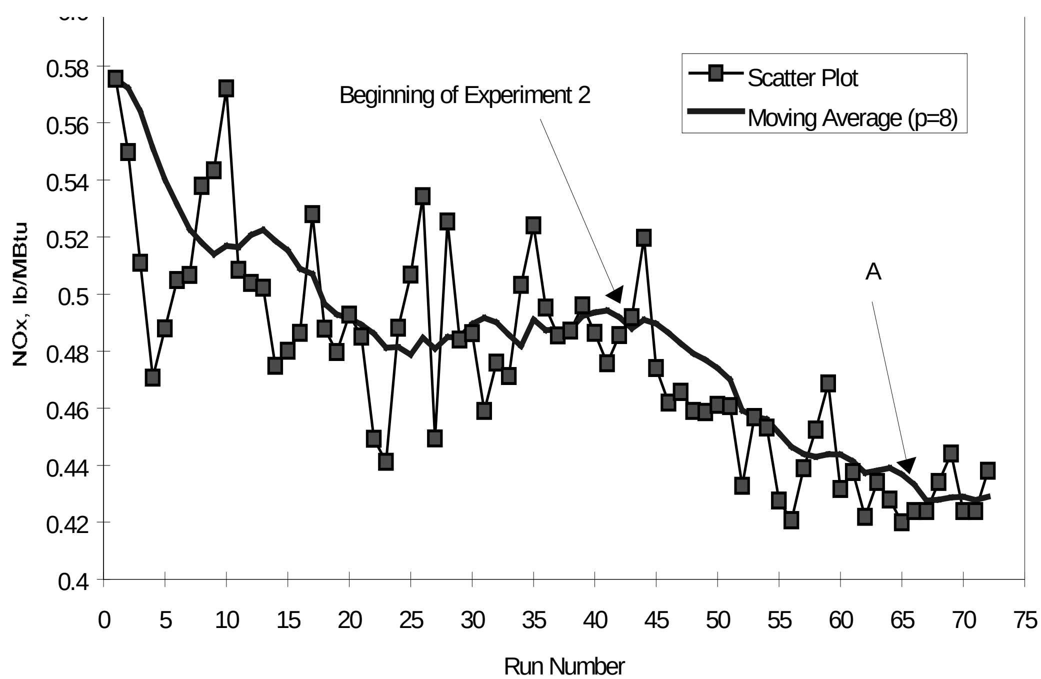


Figure 5-1 Feasibility Study - NOx Reduction for the Two Experiments

Table 5-3 Feasibility Study - Sequence of Experiment 2

Section	Time Period	Remarks
	September 26	
A	11:00 - 18:00	Following CSO* advice to minimize NOx
B	18:00 - 20:00	Return to actual control system
C	20:00 - 04:50	Reduction of load to night operation
	September 27	
D	04:50 - 08:00	Raising load to resume testing
E	08:00 - 13:05	Following CSO* advice to minimize NOx
F	13:05 - 14:25	Change the measure of performance
G	14:25 - 16:00	Manual operation with settings provided by CSO*
H	16:00 - 21:25	Return to actual control system

* CSO - Constrained Sequential Optimization.

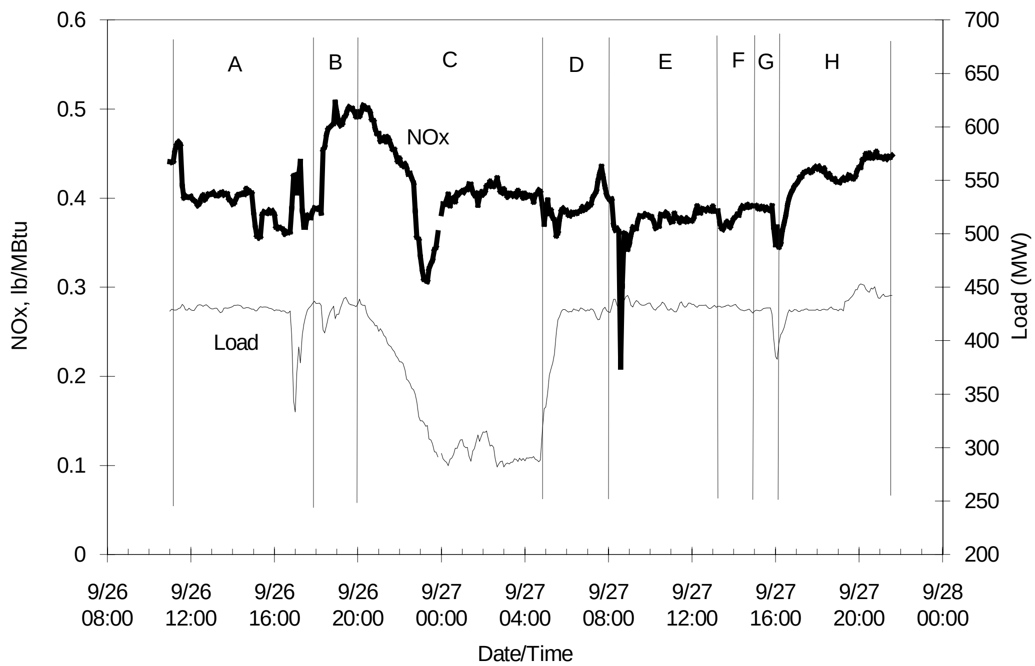


Figure 5-2 Feasibility Study - Plot of the NOx and Load Behavior for Experiment 2

<u>Summary</u>

Overall, this study was successful in that it provided further indication that on-line optimization techniques could be used to improve boiler performance. With this success, the project participants felt it warranted to pursue the additional stages: installation of a digital control system and closed-loop optimization.

5.3 Preliminary Modeling

Modeling of the furnace is a critical element of combustion optimization. Since all optimization techniques make use of models (either local or global) of the process in developing recommendations, the veracity of the process model is highly important for the success of the optimization. There are several broad categories of modeling that are available including those based on (1) statistical / regression methods, (2) neural networks, (3) expert systems, (4) fuzzy logic, and (5) first-principles. No one method is categorically superior to any of the other methods and therefore the selection of a technique is dependent on the problem to be solved. Due to the complexity of the combustion process, techniques which depend on a first principles model are not appropriate for control system design in this case, whereas, an approach which uses a model generated from on-line measurements can be effective.

This type of modeling is known as input-output modeling and there are three types of such modeling:

- Type 1 - Models that are linear in their inputs and their coefficients;
- Type 2 - Models that are non-linear in their inputs but linear in their coefficients; and
- Type 3 - Models that are non-linear in their inputs and in their coefficients.

Type 1 models are the simplest and consist of linear regression using the measured input variables, possibly suitably scaled. Type 2 models are also based on linear regression but they use extra inputs. These extra inputs are non-linear functions of the original variables; for example, powers of the input data. This modeling approach still has the calculational simplicity and uniqueness of linear regression but allows non-linear input-output behaviour. The disadvantages are (i) the modeler has to decide which forms of non-linearity to use and (ii) the effective number of inputs can be quite large. Type 3 modeling used to be a restricted option but the advent of neural network technology has simplified the implementation of this type of modeling, although the time taken for the parameter estimation can be large, and there is no guarantee of unique solutions.

A neural network is a computer code which models the system responses at its' boundaries and as such can be considered a sophisticated curve fitting routine tool. This technique can recognize patterns in a series of inputs and 'learn' to ascribe a particular pattern to a particular plant state. The training phase in which the network learns can be very time consuming. However, once a network has been trained on historical data, it can respond very rapidly to new inputs. Also, in the event any inputs to the model are faulty, neural networks prediction capabilities degrade only gradually as compared to other modeling techniques. To explore the use of the neural network modeling technique to predicting coal fired boiler emission and performance parameters, preliminary modeling studies were performed on data from Phase 3B of the project.

Table 5-4 Preliminary Modeling Data Set

Tag	Description	Type	Tag	Description	Type
AT000RH	RELATIVE HUMIDITY	I	PT201	TURBINE 1st STAGE PRESSURE	D
AT7920	OPACITY	D	PT300	FEEDWATER PRESSURE	D
CO	CO EMISSIONS	D	SOX	SOx EMISSIONS (ppm)	D
FT103A	SH SPRAY FLOW(DP) LOWER	D	TT000	AMBIENT TEMPERATURE	I
FT103B	SH SPRAY FLOW(DP) UPPER	D	TT200	MAIN STEAM TEMP	D
FT300	FEEDWATER FLOW(DP)	D	TT202	COLD REHEAT TEMP	D
FT510	"A" MILL COAL FLOW	I	TT300	FEEDWATER TEMP	D
FT520	"B" MILL COAL FLOW	I	TT510	MILL "A" TEMP	D
FT530	"C" MILL COAL FLOW	I	TT520	MILL "B" TEMP	D
FT540	"D" MILL COAL FLOW	I	TT530	MILL "C" TEMP	D
FT550	"E" MILL COAL FLOW	I	TT540	MILL "D" TEMP	D
FT560	"F" MILL COAL FLOW	I	TT550	MILL "E" TEMP	D
FT605A	AOFA-F1 WEST FRONT	I	TT560	MILL "F" TEMP	D
FT605B	AOFA-F2 EAST FRONT	I	TT611	SEC AIR "A" INLET TEMP	D
FT605C	AOFA-R1 WEST REAR	I	TT612	SEC AIR "A" OUT TEMP	D
FT605D	AOFA-R2 EAST REAR	I	TT621	SEC AIR "B" INLET TEMP	D
FT611	SEC AIR "A" FLOW (DP)	D	TT622	SEC AIR "B" OUT TEMP	D
FT621	SEC AIR "B" FLOW (DP)	D	TT631	PRI AIR "A" INLET TEMP	D
FT631	PRI AIR "A" FLOW (DP)	D	TT632	PRI AIR "A" OUT TEMP	D
FT641	PRI AIR "B" FLOW (DP)	D	TT641	PRI AIR "B" INLET TEMP	D
FT750A	TEMP AIR "A" FLOW (DP)	D	TT642	PRI AIR "B" OUT TEMP	D
FT750B	TEMP AIR "B" FLOW (DP)	D	TT711	SEC "A" GAS IN TEMP	D
JT001	LOAD	D	TT712	SEC "A" GAS OUT TEMP	D
NOX	NOx EMISSIONS	D	TT721	SEC "B" GAS IN TEMP	D
OT711	ECON OUT "A" O2	I	TT722	SEC "B" GAS OUT TEMP	D
OT712	SAH OUT "A" O2	D	TT731	PRI "A" GAS IN TEMP	D
OT721	ECON OUT "B" O2	I	TT741	PRI "B" GAS IN TEMP	D
OT722	SAH OUT "B" O2	D	WT103A	SH SPRAY FLOW LOWER	D
PT000	BAROMETRIC PRESSURE	I	WT103B	SH SPRAY FLOW UPPER	D
PT100	DRUM PRESSURE	D	WT300	FEEDWATER FLOW	D
PT200	MAIN STEAM PRESSURE	D			

The data set used for this preliminary modeling covered from May 5, 1993 through June 16, 1993 during which time the unit was in the LNB+AOFA configuration. For most of this period, the unit operated under economic dispatch but there were periods during which the unit was not taken off dispatch so that test could be performed under steady-state conditions. The data set included nearly 12,000 records of 5-minute data collected from the DCS with approximately 65 variables per record (Table 5-4). Details on the data acquisition and archiving methodology can be found in the project final report [SCS, 1998]. No special precautions were taken other than those described in that report to obtain data and the unit was not deliberated “exercised” to obtain operating data out of the normal operating range.

Load, NOx, CO, and SOx for this period are shown in Figure 5-3. As can be seen, the unit operated over the entire load range. Since minimum load during the LNB+AOFA test phase (Phase 3B) was approximately 170 MW, periods when loads were below this level were excluded from the data set. NOx and CO emissions also exhibited considerable variability during this period reflecting numerous operating scenarios. SOx emission variation was much less as may be expected since it is largely a function of coal properties and independent of combustion conditions.

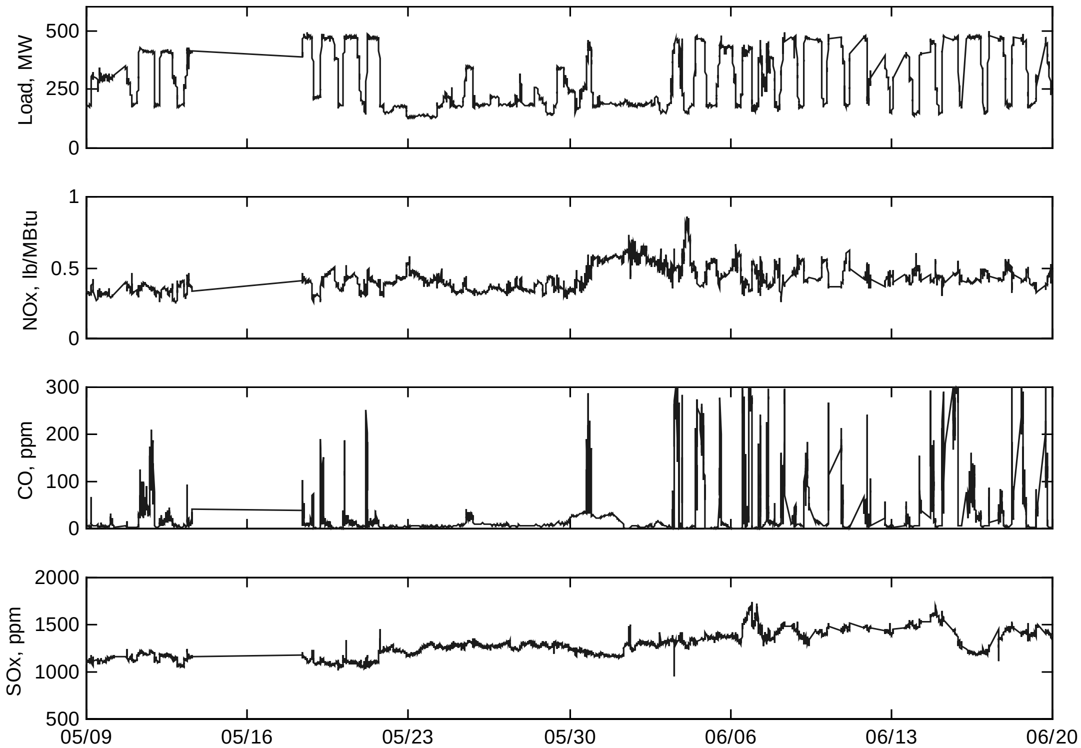


Figure 5-3 Load, NOx, CO, and SOx Profiles During Preliminary Modeling

Many potential strategies could be taken to develop a model suitable for on-line optimization. These include but are not necessarily limited to:

- Input / Output Methods
  - Statistical
  - Neural network
- Descriptive Methods
  - First principles
  - Expert systems
  - Fuzzy logic

Due to the complexity of the combustion process and uncertainty about combustion parameters, descriptive models are not particularly well suited for combustion modeling, especially when the models are intended for use in on-line, continuous optimization.

To exemplify the modeling difficulties, NOx as a function of load and excess oxygen is shown in Figure 5-4. As shown, there was considerable scatter when viewed from this perspective highlighting the little correlation (low R^2) between load or excess oxygen with NOx and CO (Table 5-1). Air heater gas outlet temperature (TT702) showed moderate correlation with excess oxygen and load. This temperature is important in that it is a major factor in boiler efficiency determination.

Examples of the results obtained with a linear model are shown in Figure 5-5 through Figure 5-8 with the model inputs/outputs shown in Table 5-5. As shown, a linear model was only moderately successful in predicting the outputs. A scatter diagram is shown in the top half of the figure. The prediction mean as a function of the actual mean is shown in the lower half of the figure. Also shown in the lower half are error bars representing the standard deviation of the error (standard deviation ($y_{predicted}$ - y_{actual})). A nonlinear neural network approach created much better models (Figure 5-9 to Figure 5-12). Further indication of the performance of the neural network model in predicting NOx and CO is shown in Figure 5-13 and Figure 5-14. Both the linear and nonlinear models were developed using approximately 67 percent of the May to June 1993 data set. The data shown is a validation set (the remaining 33 percent) which was not used in the development of the models.

As may be imagined, there are almost an infinite variety of input/output models that may be used, with some performing better that others. The variations include both input selection and model structure. Using the same inputs as described in the previous paragraph, a different type of neural network structure was tested, one based on radial basis functions. A histogram comparison of the performance between the radial basis network and the backpropagation network is shown in Figure 5-15 and Figure 5-16. The radial basis network appeared to be a better prediction tool for this data, however this may not hold true for other data presented to the networks. Also, the radial basis network has approximately five times as many neurons as the backpropagation network. This is not untypical since the radial basis functions have only local influence while the activation functions used in backpropagation networks (typically hyperbolic tangent sigmoid or log sigmoid) [NeuralWare, 1993][MathWorks, 1997][Tsoukalis, 1996]. These investigations into model structure were only cursory but they provide sufficient evidence that backpropagation, radial basis, and potentially other network structures would be suitable to use for combustion modeling and provide roughly equivalent results.

Table 5-5 Model Inputs and Outputs

Inputs		Outputs	
FT510	"A" MILL COAL FLOW	NOx	NOx EMISSIONS
FT520	"B" MILL COAL FLOW	CO	CO EMISSIONS
FT530	"C" MILL COAL FLOW	SOx	SOx EMISSIONS
FT540	"D" MILL COAL FLOW	TT702	AIR HEATER GAS OUTLET TEMP
FT550	"E" MILL COAL FLOW		
FT560	"F" MILL COAL FLOW		
FT605A	AOFA-F1 WEST FRONT		
FT605B	AOFA-F2 EAST FRONT		
FT605C	AOFA-R1 WEST REAR		
FT605D	AOFA-R2 EAST REAR		
OT711	ECON OUT "A" O2		
OT721	ECON OUT "B" O2		

Since in addition to the parameters shown in Table 5-5 other variables potentially affect NOx and the other performance parameters; models that include these additional parameters may improve the predictions. The results from one model with many more (approximately 50 total) input parameters is shown in Figure 5-17 and Figure 5-18. This model includes as inputs not only parameters which are directly controllable, but also ambient conditions, steam temperatures, and other boiler operating parameters. At least for the data presented, this model performs much better that the twelve input model. As before, the data presented is validation data only. Although increasing the number of input variables may likely improve the prediction performance of a model, these models are not necessarily well suited for on-line optimization. First, increasing the number of variables increases the likelihood of using a bad reading in the model. The overall impact of a faulty reading on the model prediction is model dependent. Also, the input variables may not be independent which leads to problems in determining a set of inputs for a desired set of outputs -- i.e., running the model in reverse.

Using the twelve-input, back propagation network described earlier, the inputs minimizing NOx emissions for the validation data set were determined. Constraints were added to the inputs to limit the recommendations to that which might be implemented on the unit (Table 5-7). Although they could have easily been, CO, SOx, and furnace exit gas temperature were not included in the objective or constraint functions. As shown, the projected NOx levels when running at the recommended setpoints were considerably below that which the unit actually operated, averaging 0.07 lb/Mbtu or 16 percent below non-optimized levels (Figure 5-19 and Figure 5-20).

In summary, these studies provided credence that neural network methods could be used to develop combustion models sufficiently robust to perform on-line combustion optimization.

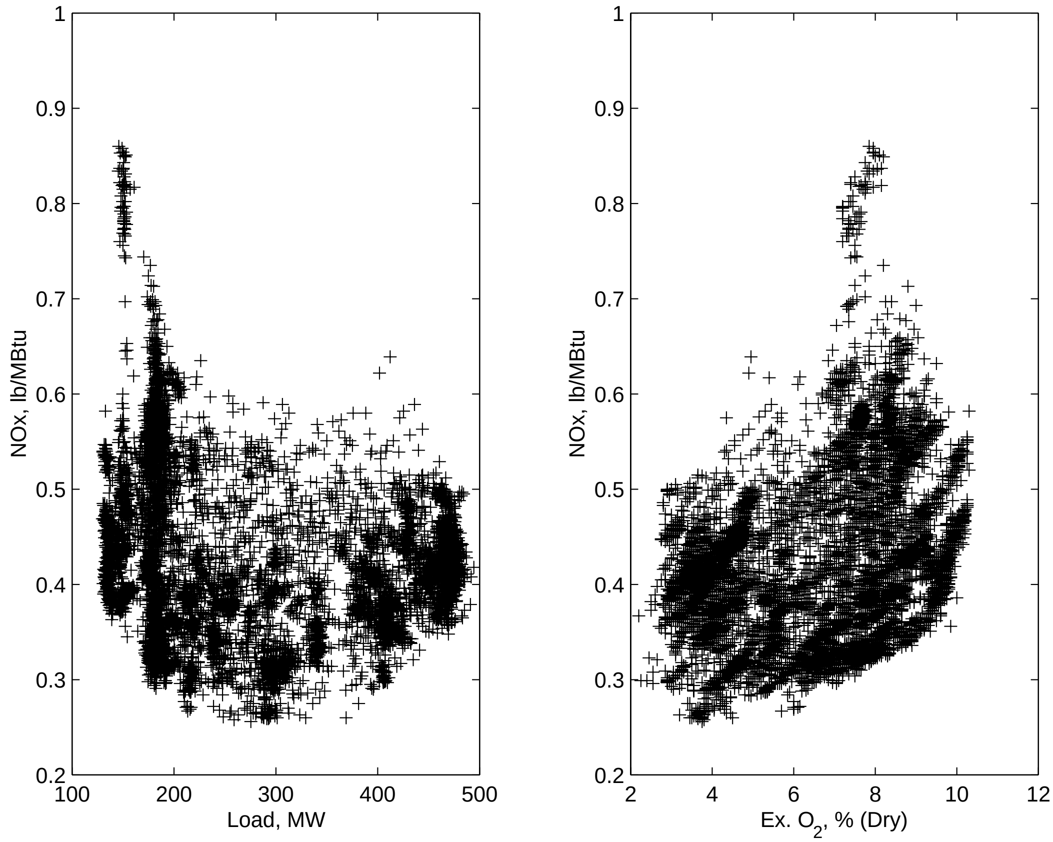


Figure 5-4 NOx vs. Load and Excess Oxygen

Table 5-6 Correlation of Important Process Parameters with Load and O_2

	Load	O2	NOx	CO	SOx	TT702
Load	1	-0.9064	-0.1779	0.4526	0.0228	0.8272
O2	-0.9064	1	0.3207	-0.4688	0.0445	-0.7625
NOx	-0.1779	0.3207	1	-0.0795	0.1898	0.0243
CO	0.4526	-0.4688	-0.0795	1	0.2172	0.4321
SOx	0.0228	0.0445	0.1898	0.2172	1	0.1717
TT702	0.8272	-0.7625	0.0243	0.4321	0.1717	1

TT702 - Average air heater gas outlet temperature
O_2 - Excess oxygen (wet) measured at economizer outlet
NOx - Measured at the stack.
SOx - Measured at the stack (wet), corrected to 3% excess O_2
CO - Measured at the stack (wet),

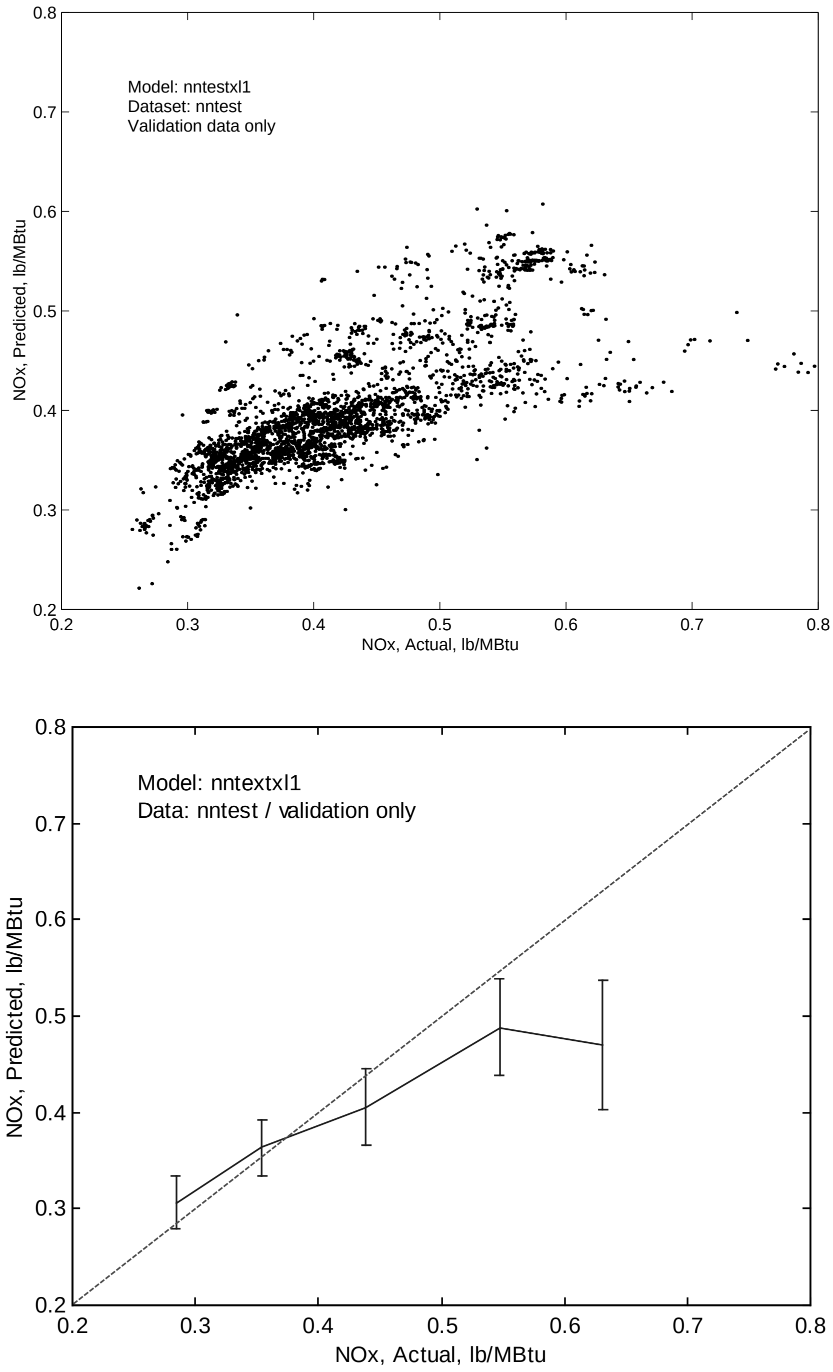
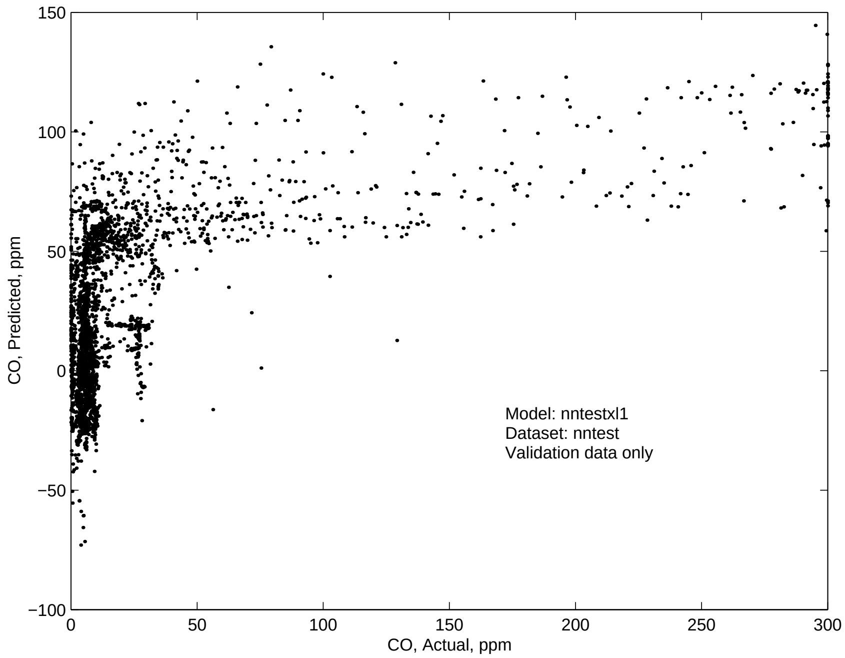


Figure 5-5 Predicted NOx vs. Actual NOx Linear Model (R^2 = 0.492)



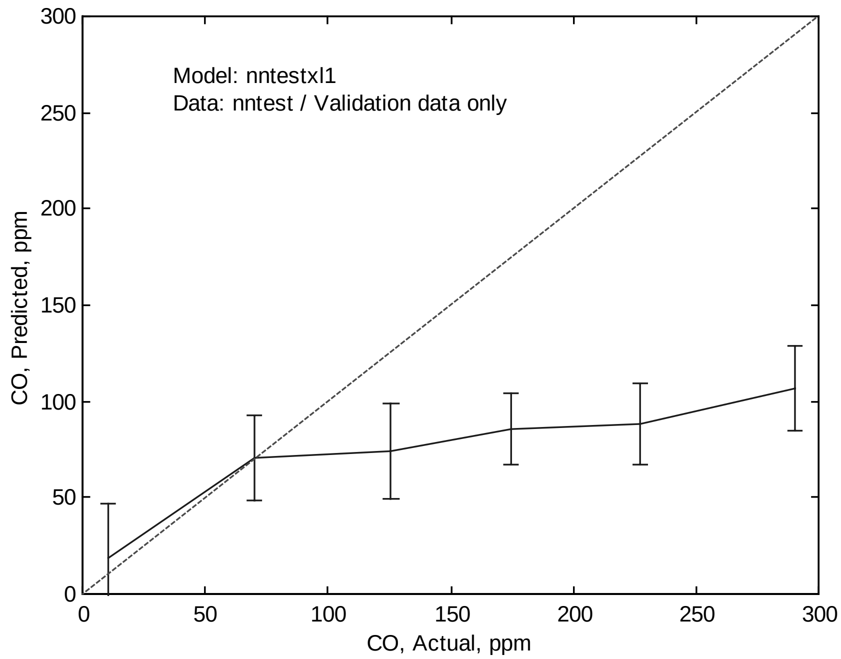


Figure 5-6 Predicted CO vs. Actual CO Linear Model (R2= 0.343)

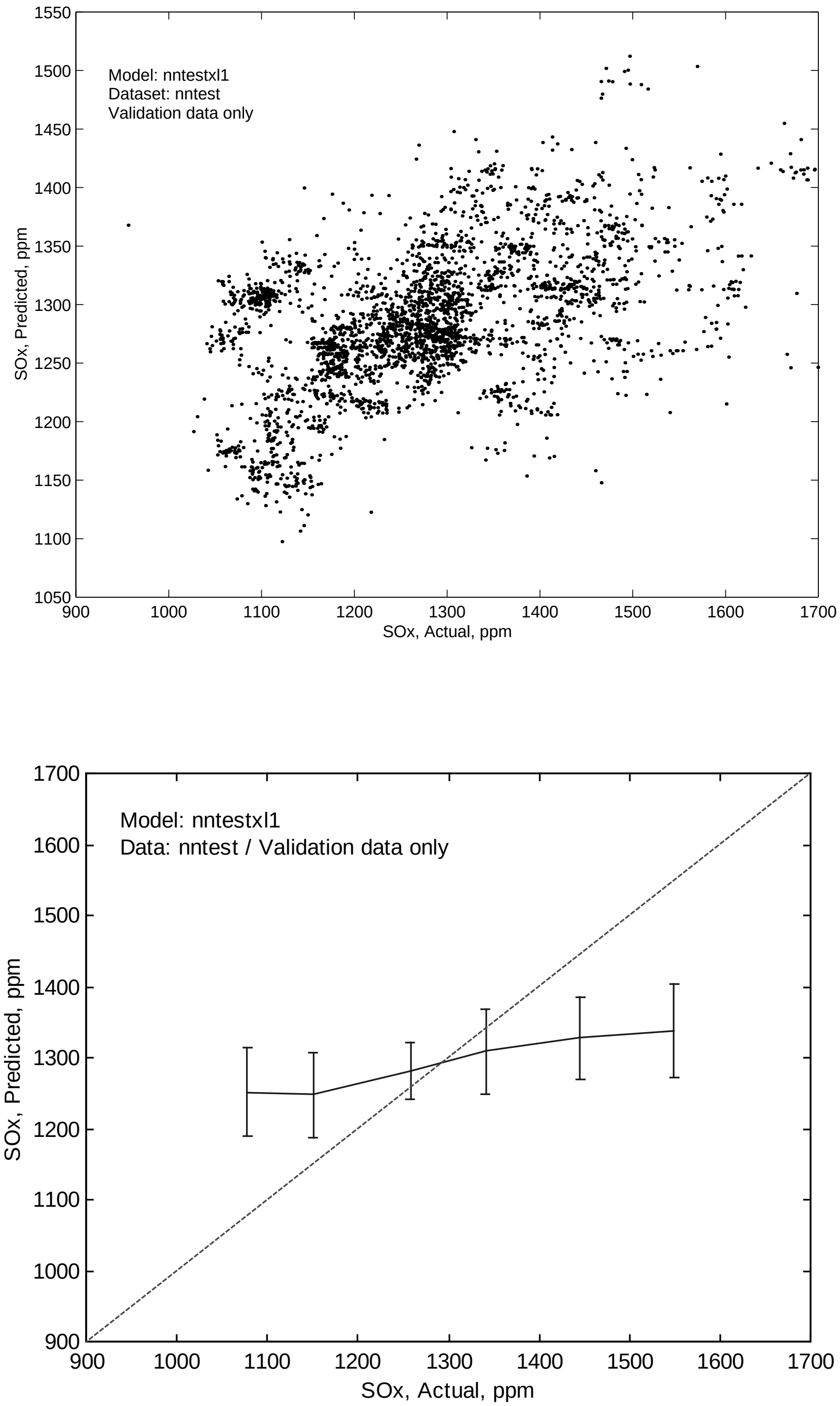
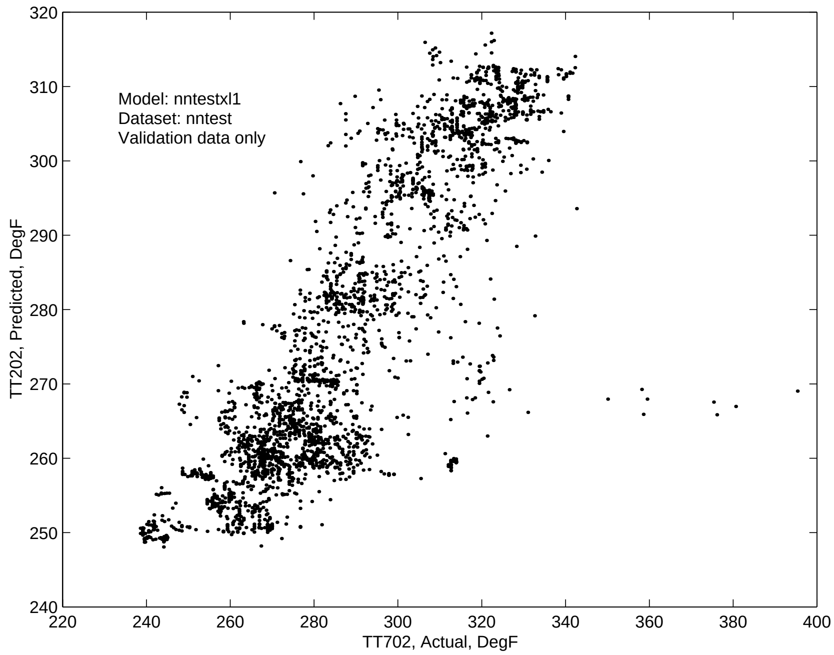


Figure 5-7 Predicted SOx vs. Actual SOx Linear Model (R^2= 0.26)



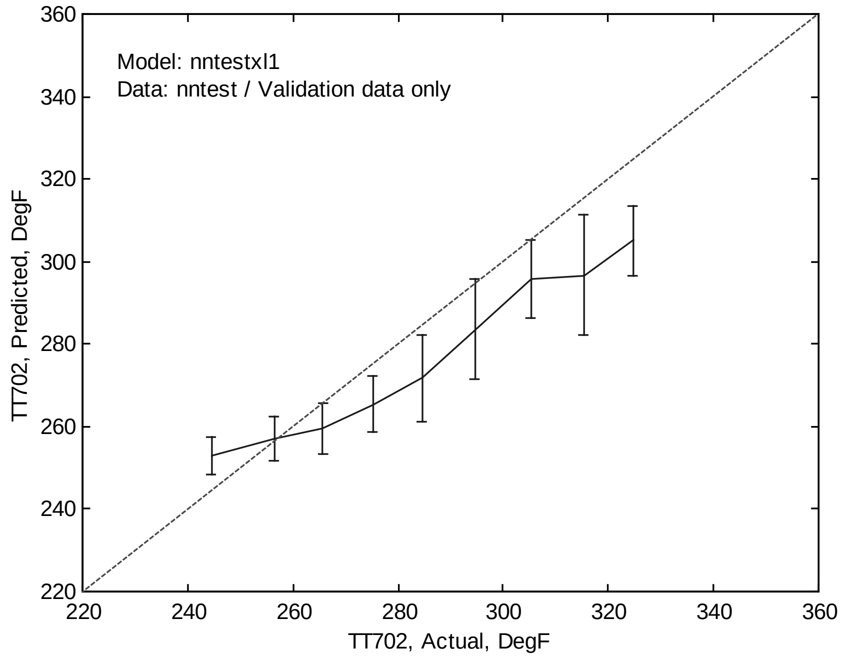
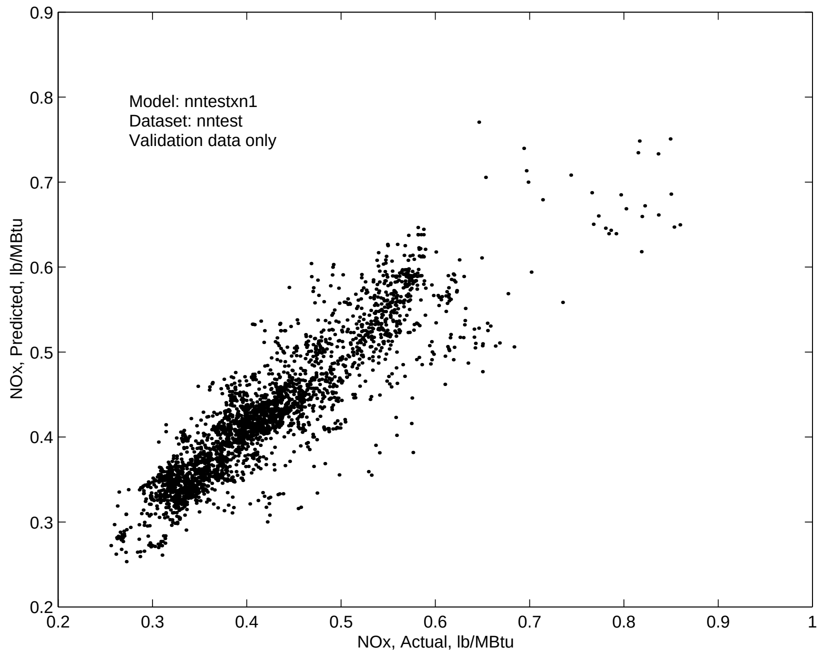


Figure 5-8 Predicted TT702 vs. Actual TT702 Linear Model (R^2= 0.51)



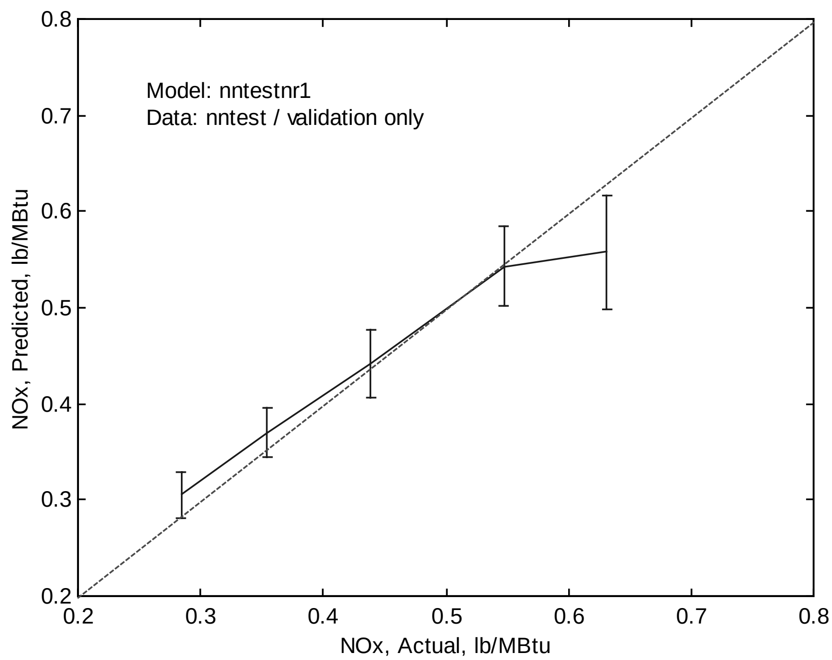


Figure 5-9 Predicted NOx vs. Actual NOx Nonlinear Model (R^2 = 0.81)

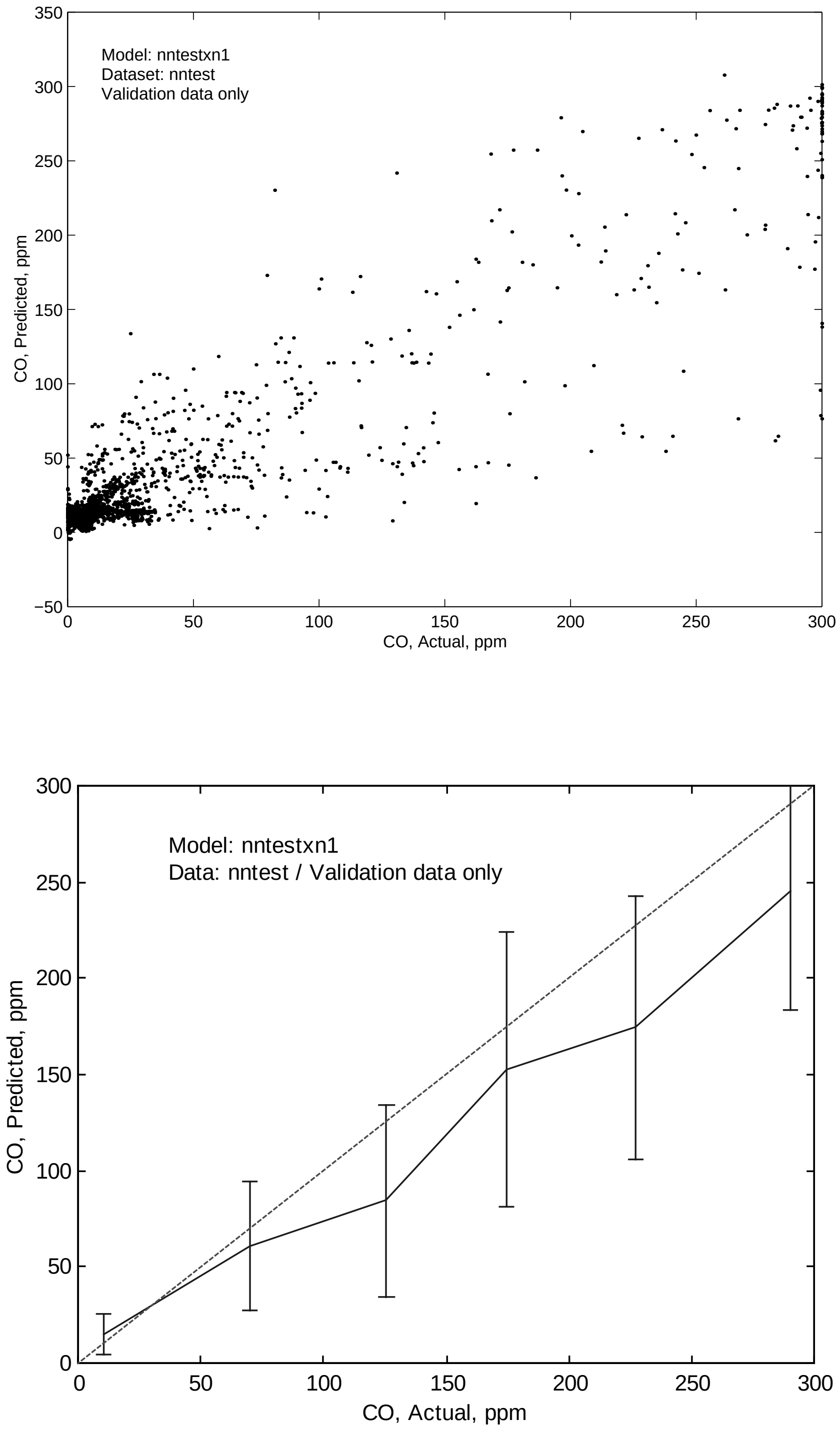
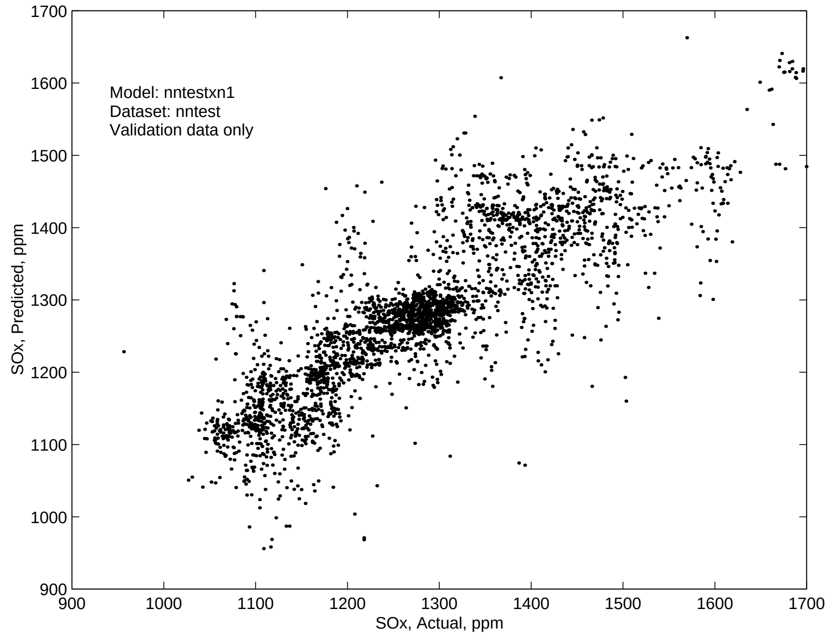


Figure 5-10 Predicted CO vs. Actual CO Nonlinear Model (R^2 = 0.81)



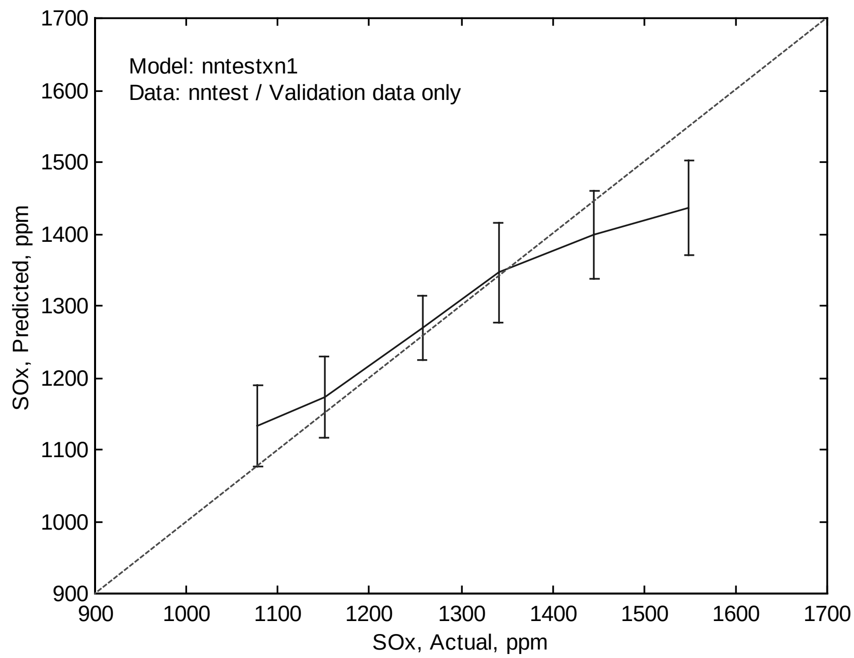
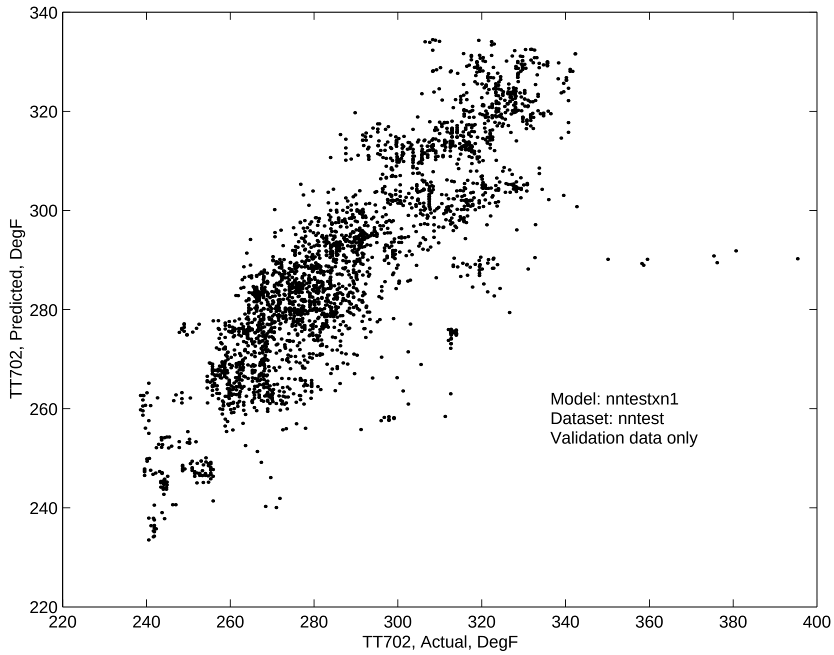


Figure 5-11 Predicted SOx vs. Actual SOx Nonlinear Model (R^2= 0.72)



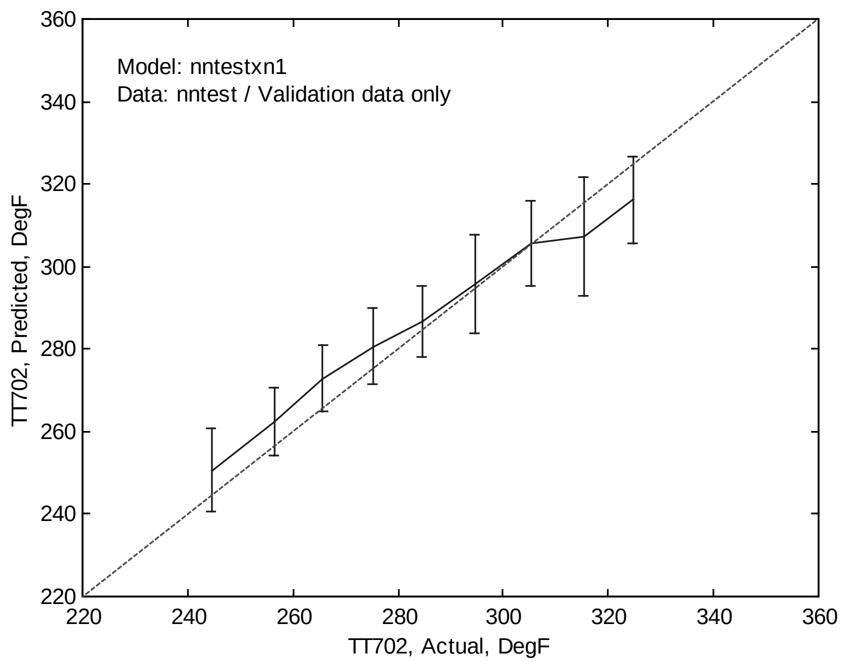


Figure 5-12 Predicted TT702 vs. Actual TT702 Nonlinear Model (R^2= 0.73)

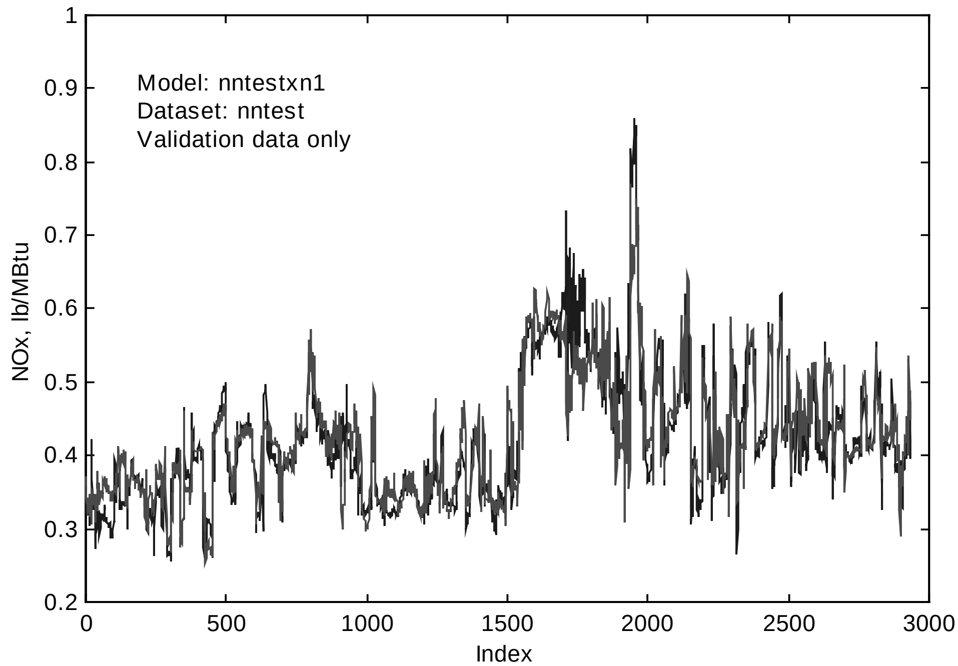


Figure 5-13 Predicted NOx vs. Actual NOx Nonlinear Model

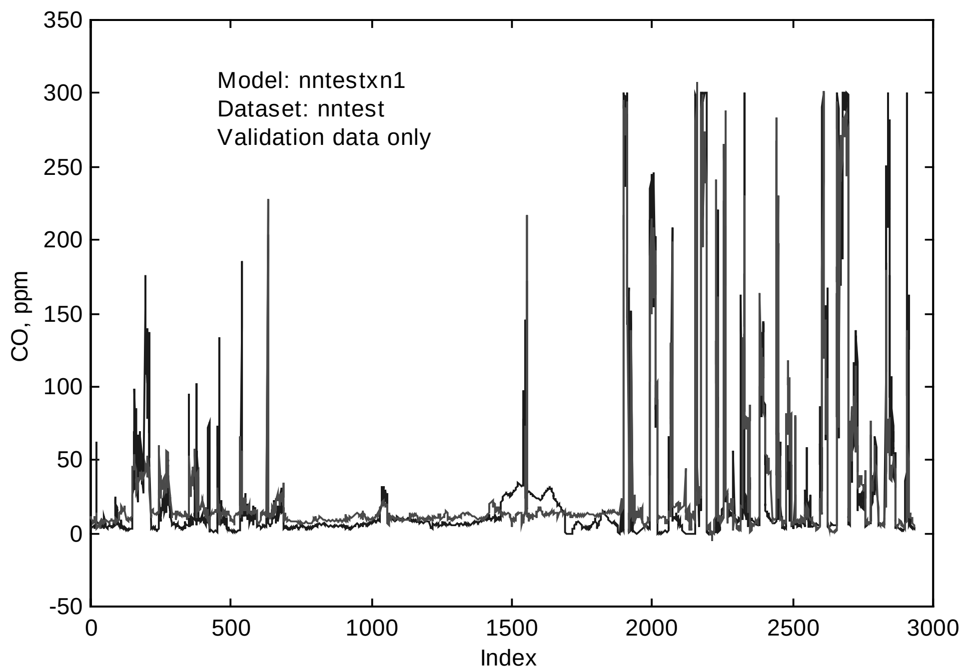


Figure 5-14 Predicted CO vs. Actual CO Nonlinear Model

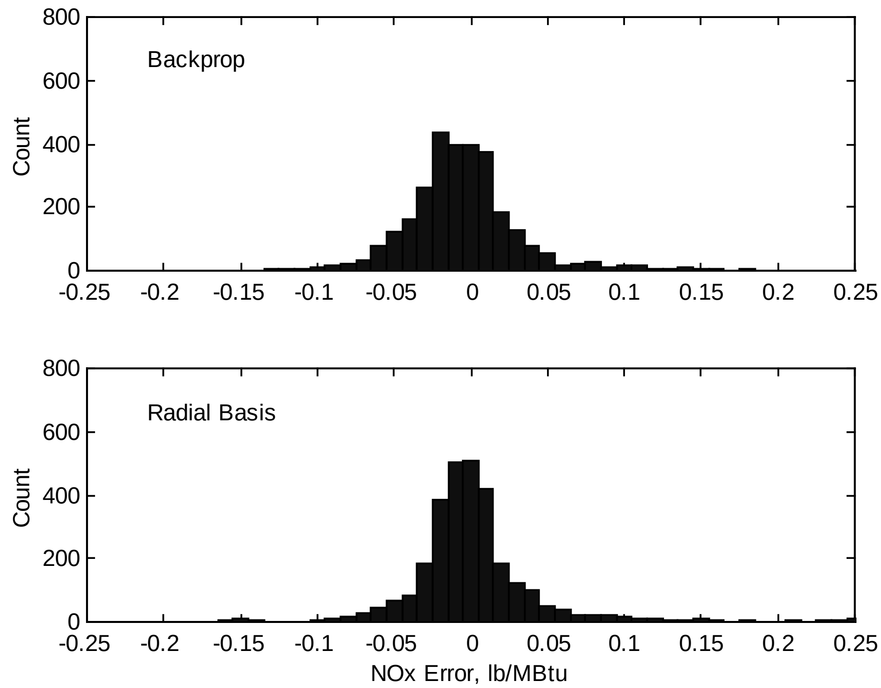


Figure 5-15 Back Propagation Network vs. Radial Basis Network Approximation (NOx)

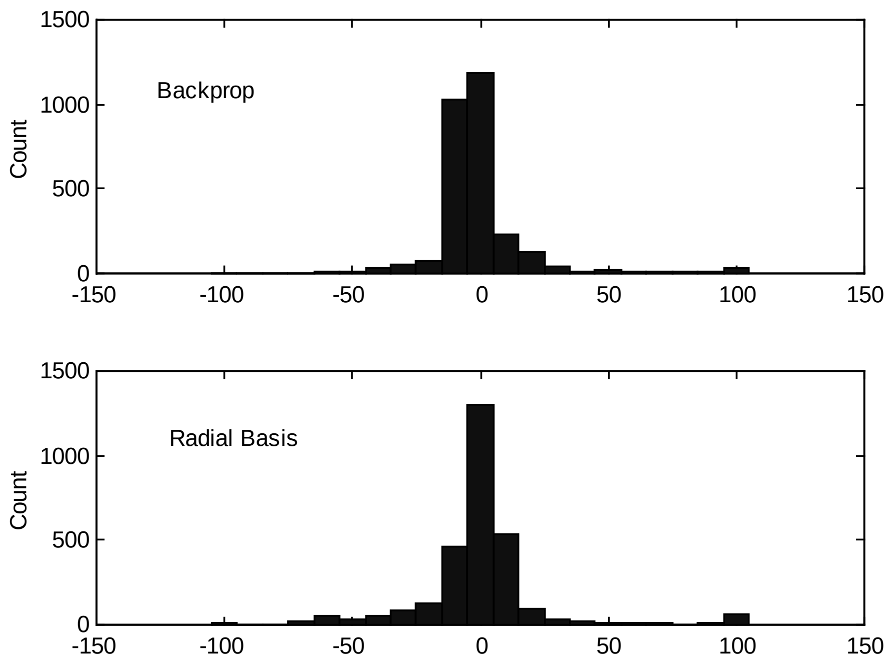
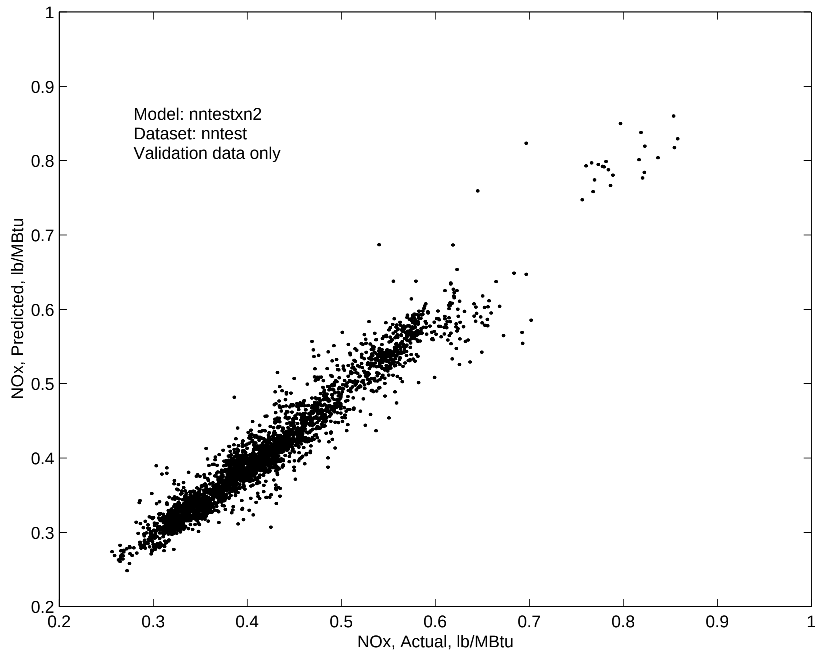


Figure 5-16 Backpropagation Network vs. Radial Basis Network Approximation (CO)



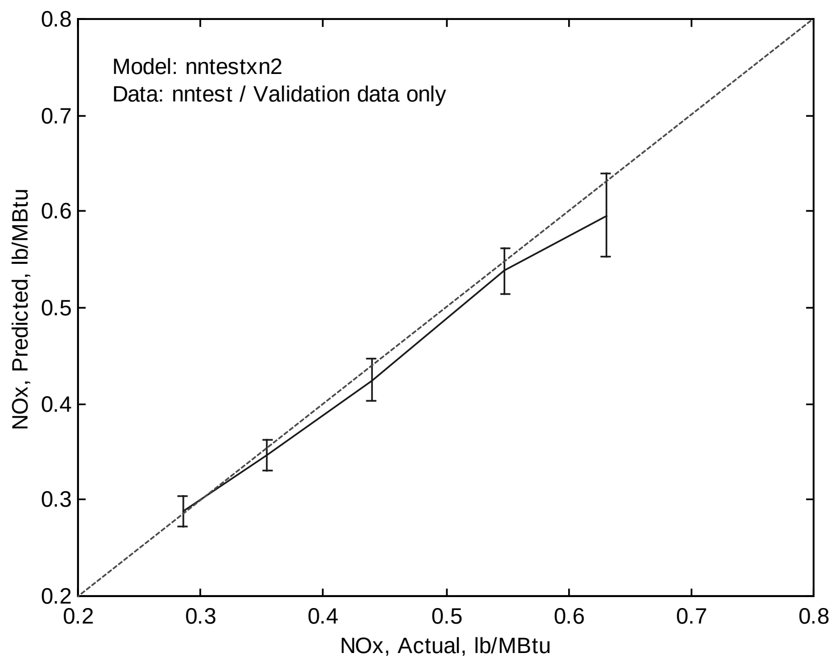


Figure 5-17 Predicted NOx vs. Actual NOx Nonlinear Model (R^2 = 0.93)

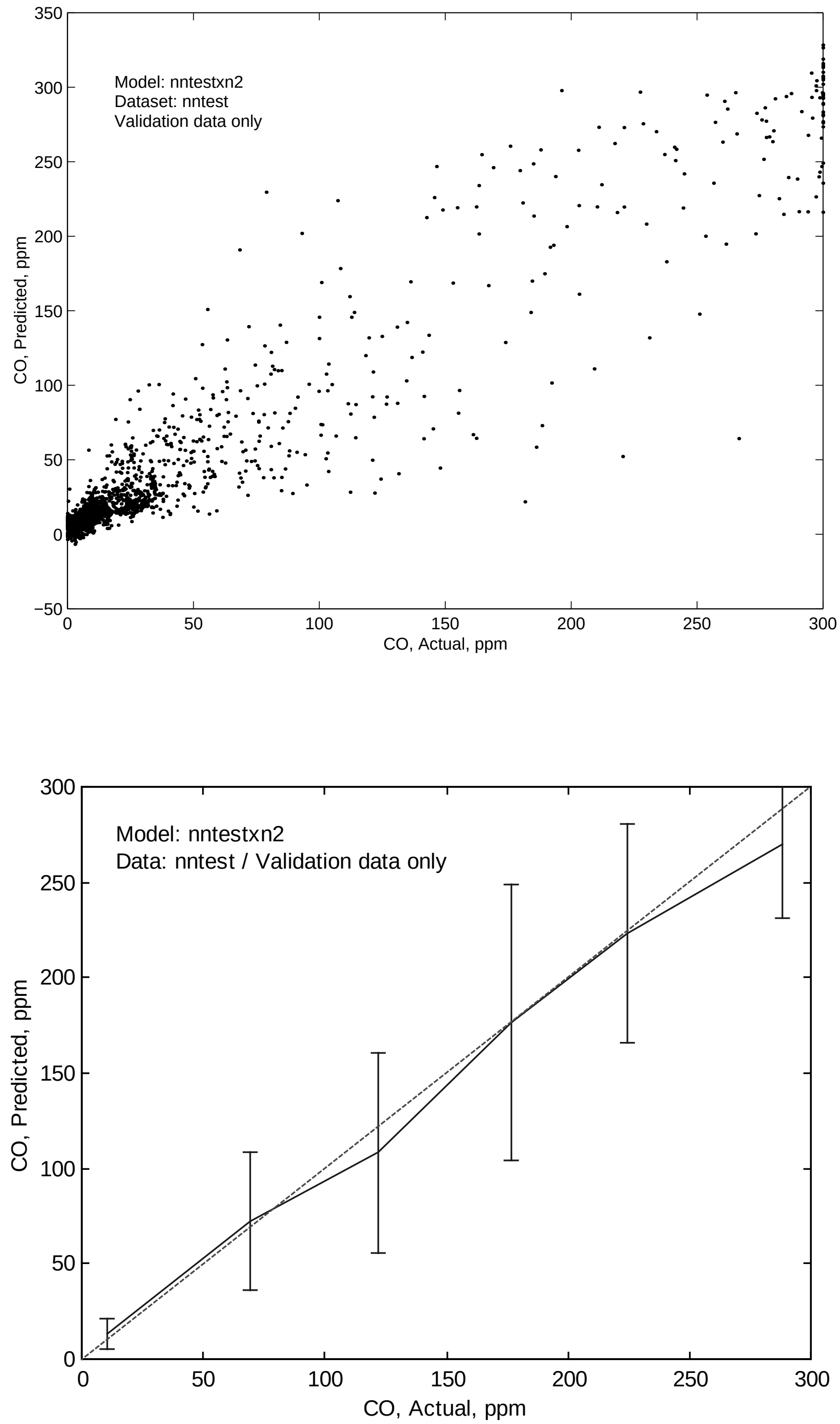


Figure 5-18 Predicted CO vs. Actual CO Nonlinear Model (R^2 = 0.90)

Table 5-7 Constraints Applied to Optimization

Constraints	Description
$-5 < FT510_f - FT510_i < 5$	Don't change fuel to mill by more than 5 klb/h amount
$-5 < FT520_f - FT520_i < 5$	"
$-5 < FT530_f - FT530_i < 5$	"
$-5 < FT540_f - FT540_i < 5$	"
$-5 < FT550_f - FT550_i < 5$	"
$-5 < FT560_f - FT560_i < 5$	"
$-0.5 < OT711_f - OT711_i < 0.5$	Don't change excess O_2 by more than 0.5 percent
$-0.5 < OT711_f - OT711_i < 0.5$	"
$-20 < FT605A_f - FT605A_i < 20$	Don't change OFA flow by more than 20 klb/h
$-20 < FT605B_f - FT605B_i < 20$	"
$-20 < FT605C_f - FT605C_i < 20$	"
$-20 < FT605D_f - FT605D_i < 20$	"
$0 < \Sigma FT5X0_f - \quad < \Sigma FT5X0_i < 0$	Total coal flow to remain constant

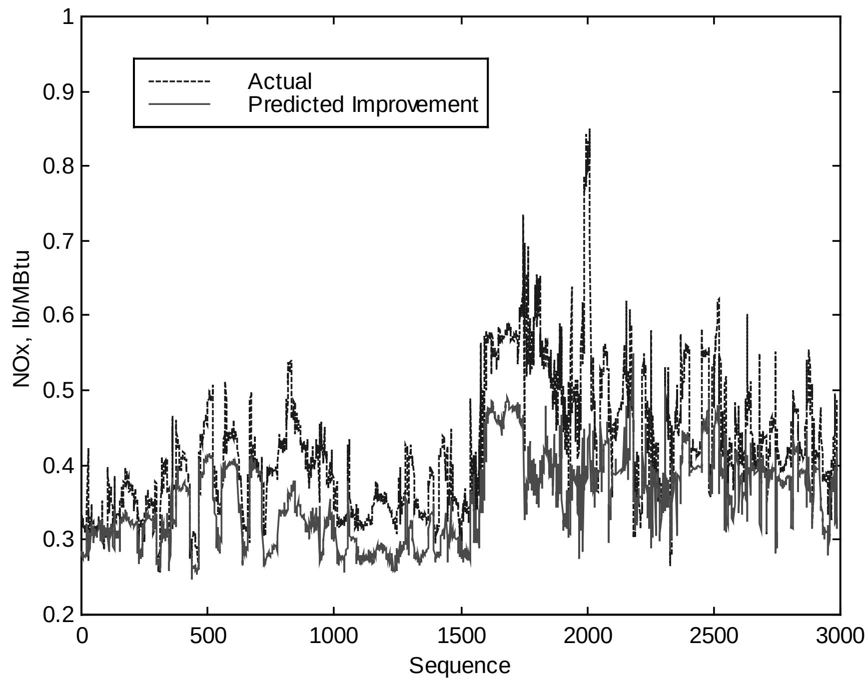


Figure 5-19 Optimizing NOx Emissions

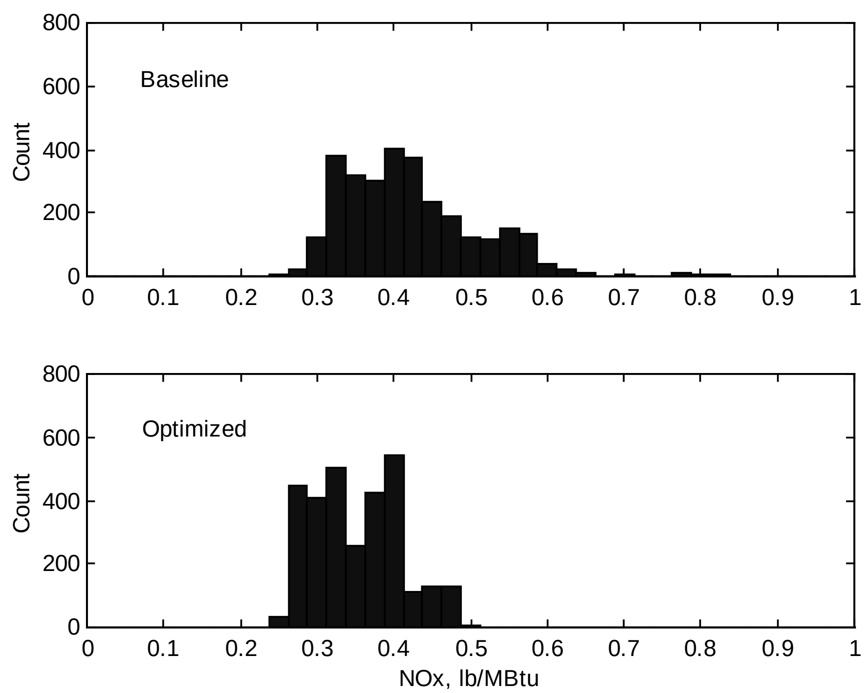


Figure 5-20 Optimizing NOx Emissions

5.4 GNOCIS Testing

5.4.1 Testing at Developmental Sites

Prior to testing at Hammond, GNOCIS underwent development and testing at Alabama Power Company's Gaston Unit 4 and PowerGen's Kingsnorth Unit 1. A brief overview of this testing is provided below [PowerGen, 1997].

5.4.1.1 Gaston Unit 4

The objective of the Gaston trial was to develop and demonstrate GNOCIS on a wall-fired unit. Gaston Unit 4 is a 270 MW pulverized coal unit. The Babcock and Wilcox (B&W) opposed-wall-fired boiler is arranged with nine burners (3W x 3H) on two opposing walls such that no burner has another burner directly across from it. Combustion air is supplied to the burners via common wind boxes on each side of the boiler. The unit is equipped with B&W XCL low NO_x burners and six B&W EL-76 ball and race mills. Fuel is delivered to the mills by two-speed table feeders. The unit has two forced-draft fans, six primary air fans, and two flue gas recirculation fans. Combustion air is heated with Ljungstrom air heaters. The boiler control system for Gaston Unit 4 is a Leeds and Northrup Max 1000 distributed digital control system. The control system is designed such that the unit is controlled through the CRTs -- there are no bench board mounted controls.

<u>GNOCIS Implementation</u>

The original objective at Gaston was to implement an open-loop, advisory system with no immediate plans to migrate to closed-loop operation. This objective influenced the original design philosophy in a number of respects, primarily selection and quantity of control variables, increased demand for flexible and informative operator displays, and reduced necessity for stringent recommendation checking and incorporation of safeguards. However, during the course of the project, it was determined that there were significant benefits, both in performance and ease of use of the system, if upgrades were made to GNOCIS to enable closed-loop operation. These enhancements also give the operator an easier way to implement open-loop recommendations.

Figure 5-21 shows the informational flow for the GNOCIS implementation at Gaston. All process data is collected through the DCS and passed on to the GNOCIS host (a PC running Windows NT) for calculation of the recommendations. This system interfaces to the DCS using local area network connection and TCP/IP. These recommendations are then conveyed to the operator via the DCS operator displays. If acceptable, the operator can then implement these changes through the DCS operator displays. Also, the operator has the option of running GNOCIS closed-loop in which the recommendations are automatically implemented. The primary operator display, which resides on the DCS, is shown in Figure 5-22.

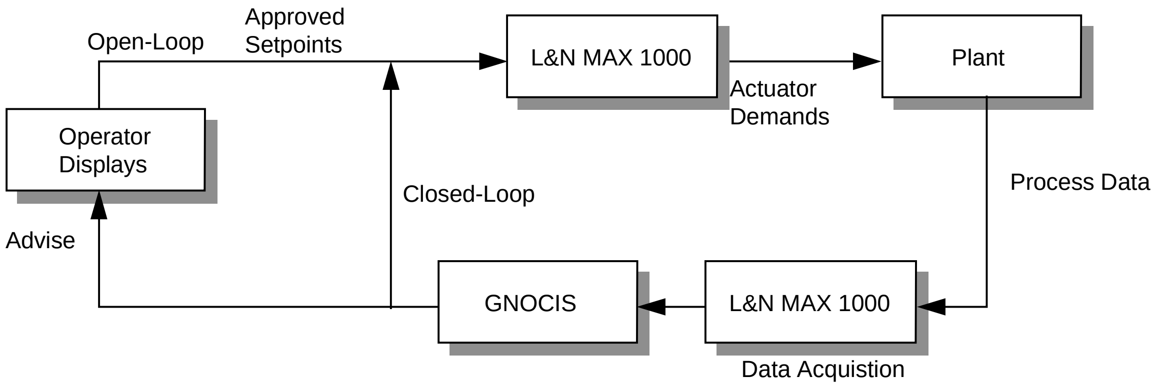


Figure 5-21Gaston GNOCIS Installation

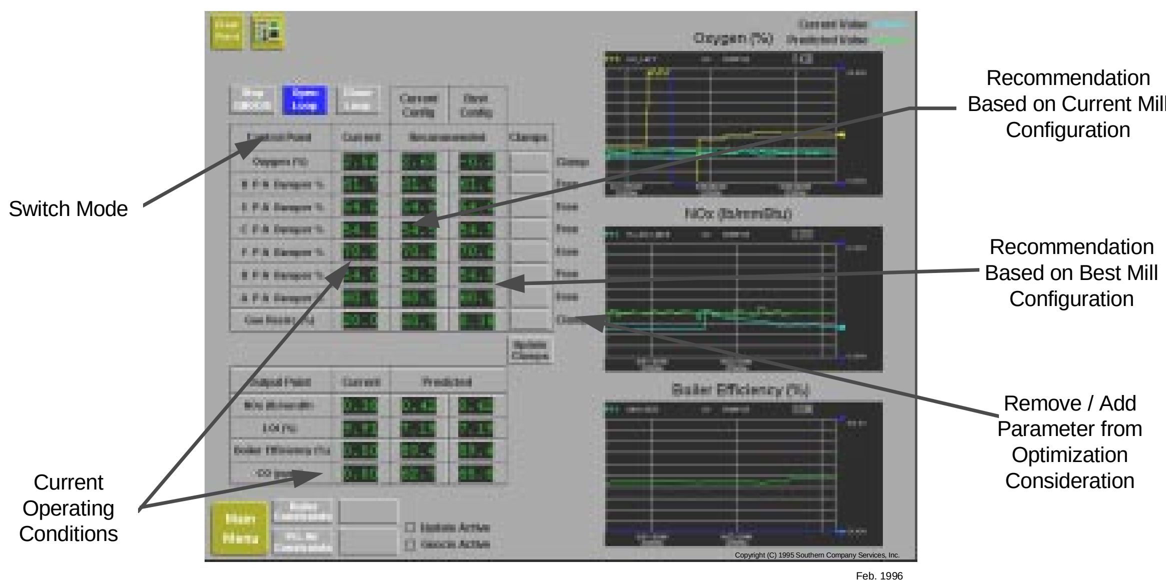


Figure 5-22 Gaston / GNOCIS Operator Interface

<u>Model Development</u>

Data collected through the DCS was used to create the combustion models. Although in excess of 1000 points are being archived in the DCS, early in the project, a subset of approximately 100 parameters were identified as being possibly important for combustion modeling purposes. Modeling efforts have concentrated on the most recent three to four months of long-term data. Short-term tests were periodically run during which the unit was run at off-design conditions to augment data available from normal operation and thereby expand the range over which the combustion model could make estimates. Also, results from testing GNOCIS were generally included in the training data for future models. The collected data was preprocessed to remove invalid data and to some extent, data collected during transients. In general, the existing control system and instrumentation provided an excellent platform for the collection of real-time process data in a format usable by GNOCIS.

Trial Results

Preliminary open-loop testing of GNOCIS was conducted during second quarter 1995. The combustion model used during these tests was based on training data collected during October and November 1994 and February 1995. Based on these tests, it was evident that the models needed to be retrained using more recent data. Although the actual reason for model inaccuracies still are unknown, possible factors include the result in ongoing mill maintenance or an undetected change in coal characteristics. In September 1995, further open-loop testing was conducted. In general, predictions and recommendations made by GNOCIS were robust and beneficial. The results of two tests are shown in Figure 5-23 and Figure 5-24. In the first, GNOCIS was directed to maximize efficiency with no limitations placed on LOI, NOx, and CO and an approximate 0.5 percent improvement in efficiency was obtained. In the latter, the reduction of NOx emissions was the objective with the improvement being approximately 15 percent. In both these tests, relatively narrow limits were placed on the recommendations GNOCIS was allowed to provide.

Since these initial tests, GNOCIS has been converted to closed-loop operation. Example results are shown in Figure 5-25. Data shown in this figure are from when the unit is under economic dispatch and between 250 and 270 MW. Also, excess O_2 was excluded from the optimization determinations (i.e. no recommendations were made for O_2). As shown, LOI was reduced by approximately 2.5 percent and boiler efficiency improved by 0.4 percent.

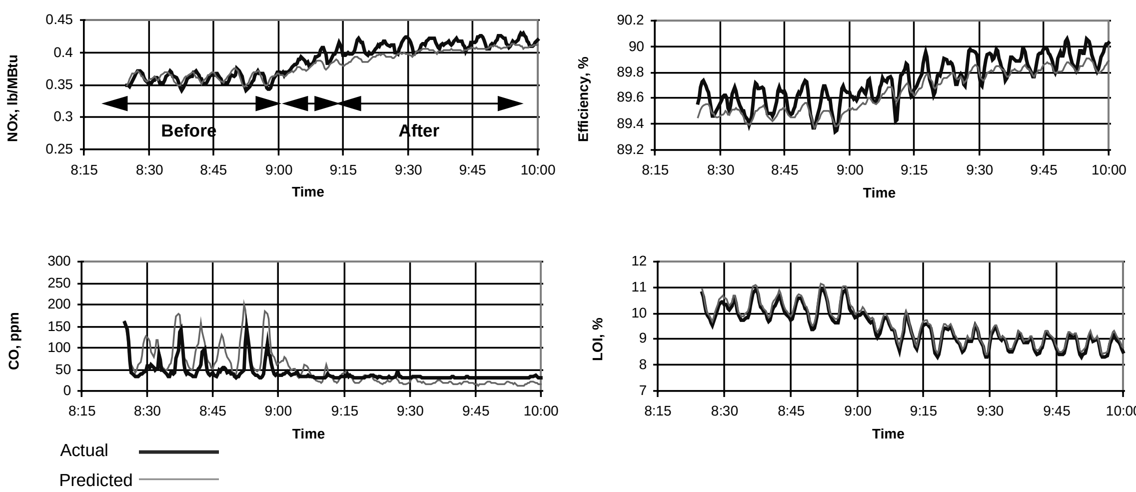


Figure 5-23 Gaston / Maximize Efficiency Objective

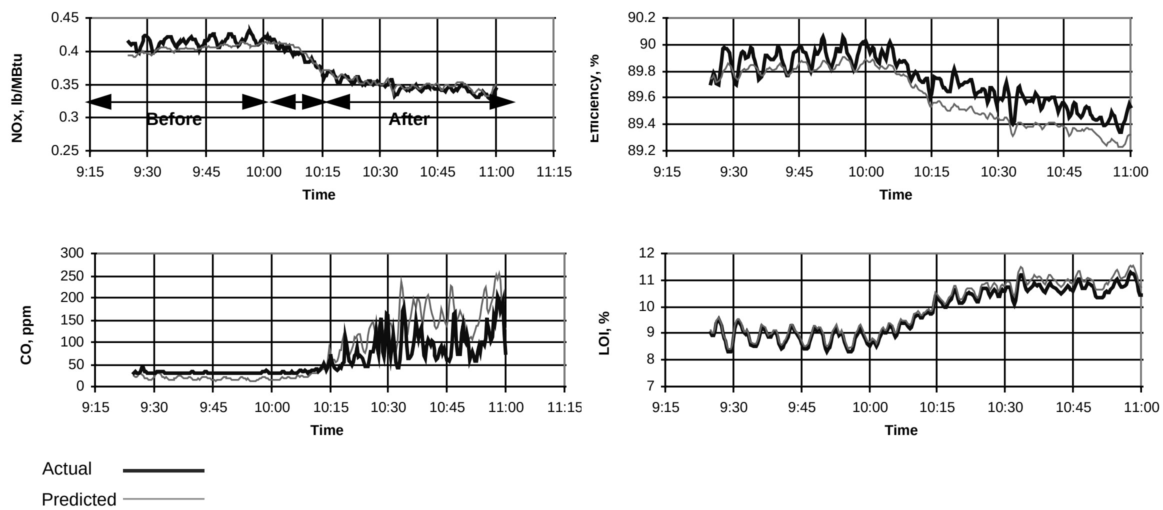


Figure 5-24 Gaston / Minimize NO_x Objective

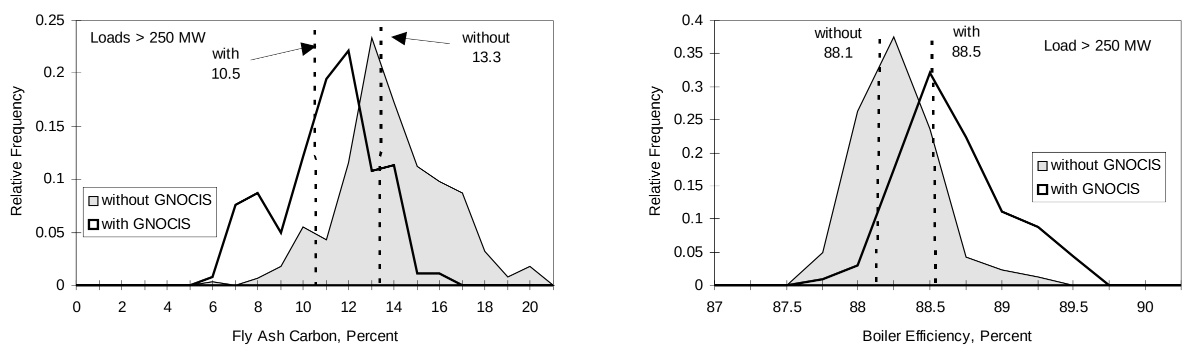


Figure 5-25 Gaston / Maximize Efficiency / Closed-Loop

5.4.1.2 Kingsnorth Unit 1

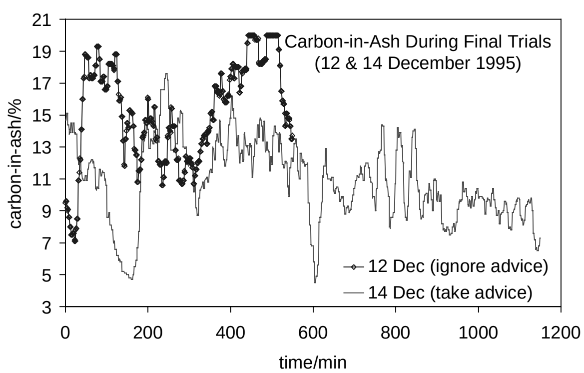
Kingsnorth Power Station is located near London. Unit 1 is a 500 MW tangential-fired unit equipped with an NEI International Combustion boiler and is capable of meeting full load on either pulverized coal or residual fuel oil. The furnace has a central vertical dividing wall which forms two identical combustion chambers. The four burner boxes in each chamber have independent tilt control that can be moved nominally between +20 and -20° from the horizontal. Each mill fires a single level within the furnace. The furnace is fitted with a low NO_x firing system with separated and close-coupled overfire air. The digital control system at Kingsnorth uses an in-house system known as CUTLASS that is based on DEC PDP 11 hardware and Instem I/O equipment. The primary objective at Kingsnorth is to minimize CIA in the fly ash while maintaining NO_x below the current level of 390 ppm. With the current DCS configuration, only seven parameters are adjustable by the operators - burner tilts (ganged together as one setting), excess air, and five mill settings; therefore these parameters were selected for use in GNOCIS.

Model Development

The data acquisition system was receiving and storing data twenty-four hours a day throughout the Kingsnorth trials. However, not all data was suitable for use in the models; in its raw form the data covered periods when the instrumentation was faulty and when the plant was operating in a regime outside of the GNOCIS specification (zero and low load). Data was therefore preprocessed to remove invalid data and data not corresponding to GNOCIS operating regimes. Predictive models were constructed, as a first step, to give an indication for the overall accuracy of the modeling and to highlight potential difficulties. The performance of the model was evaluated by selecting up to four periods of operation, omitting these from the input data and then running the model on this data. Similar to the predictive model evaluation, four periods of operation were chosen against which the model performance would be assessed. This was done for the control models by taking expert advice on what information should have been given to an operator to prompt any desired control action. The experts were the Kingsnorth efficiency engineer and a PowerGen combustion expert. This advice was then compared with control advice suggested by the model.

Trial Results

Testing of GNOCIS at Kingsnorth began November 1994 and was completed in January 1996. During these tests, the primary interest was to evaluate the performance of GNOCIS especially in regard to its ability to produce recommendations that would result in reduced carbon-in-ash. The final tests of GNOCIS were conducted during four days of testing in December 1995 and February 1996 (Figure 5-26 and Figure 5-27).



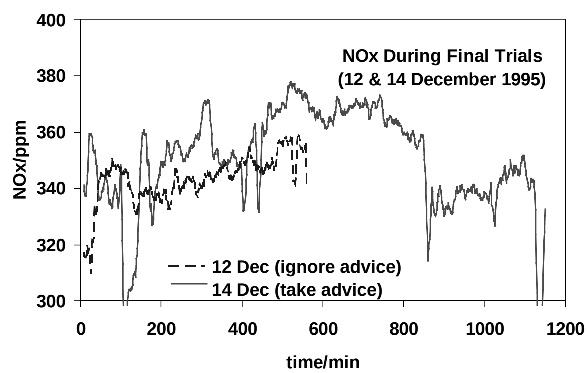


Figure 5-26 Kingsnorth / GNOCIS Minimize Carbon-in-Ash

In the December test, GNOCIS was set to give advice so that carbon-in-ash would be minimized and NOx would remain below 390 ppm (the NOx limit for the unit). During one day of trials, the advice would be taken and during the next it would be ignored and the unit operated at the non-optimized, normal settings. GNOCIS recommended significant changes in “A” and “E” feeder, excess oxygen, and burner tilt. As shown, carbon-in-ash was reduced from 15 percent to near 11 percent with minimal impact on NOx emissions. In the February tests, the objective was modified to minimize NOx emissions. NOx emissions were reduced by near 10 percent with little effect on carbon-in-ash.

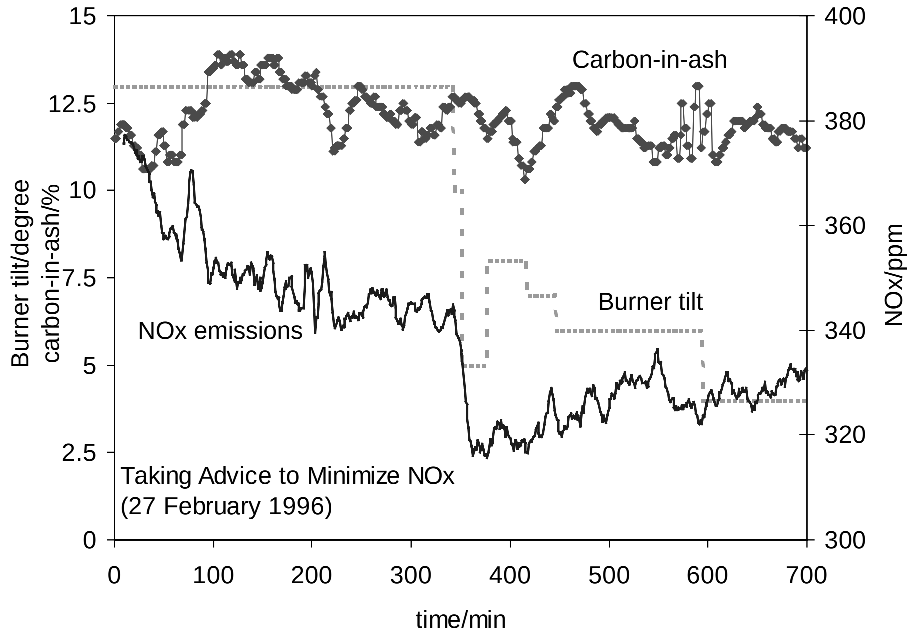


Figure 5-27 Kingsnorth / GNOCIS Minimize NOx

5.4.2 GNOCIS Testing at Hammond

Following the completion of installation, GNOCIS was available for testing at this site first quarter 1996. The results of many of the tests conducted are discussed in the following paragraphs.

5.4.2.1 GNOCIS Testing Conducted First Quarter 1996

Preliminary testing of GNOCIS at Hammond 4 began during February 1996 with tests being conducted at loads of 500 MW, 400 MW, and 300 MW. The control model (*hamconfc*) used for these tests had the structure shown in Table 5-8. This model was trained on data collected from January 10 to February 7, 1996 and consisted of approximately 40,000 one-minute records. The results of the training are shown in Figure 5-28.

Various combinations of objectives were tested including minimizing NOx emissions, minimizing carbon-in-ash, and maximizing efficiency in both open- and closed-loop modes. Implementation of the GNOCIS recommendations were greatly facilitated as a result of enhancements made to the DCS. The primary purpose of these initial tests was to better help identify implementation and model issues. For these tests, recommendations were provided by GNOCIS for excess oxygen, individual mill coal flows, and overfire airflow to each corner of the windbox. GNOCIS operated in both open- and closed-loop modes. Most of the tests were conducted in open-loop mode, however, some of the latter were in closed-loop.

Table 5-8 Control Model Structure for February 1996 Testing

Control Model: hamconfc	
Control Variables	State Variables
Average Excess Oxygen	Mill Temperatures (A - F)
Mill Coal Flow A	Mill Primary Air Flows (A - F)
Mill Coal Flow B	Main Steam Temperature
Mill Coal Flow C	Main Steam Pressure
Mill Coal Flow D	Hot Reheat Temperature
Mill Coal Flow E	Cold Reheat Pressure
Mill Coal Flow F	Excess Oxygen Side A
AOFA Airflow R1	Excess Oxygen Side B
AOFA Airflow R2	Feedwater Flow
AOFA Airflow F1	Drum Pressure
AOFA Airflow F2	First Stage Pressure
	Superheat Spray Flows
	Feedwater Temperature
	Total Secondary Air
	Air Heater Gas Inlet and Outlet Temp.
	Superheat Inlet Temperatures
Output Variables	External Variables
NOx Emissions	<None>
LOI	
Boiler Efficiency	

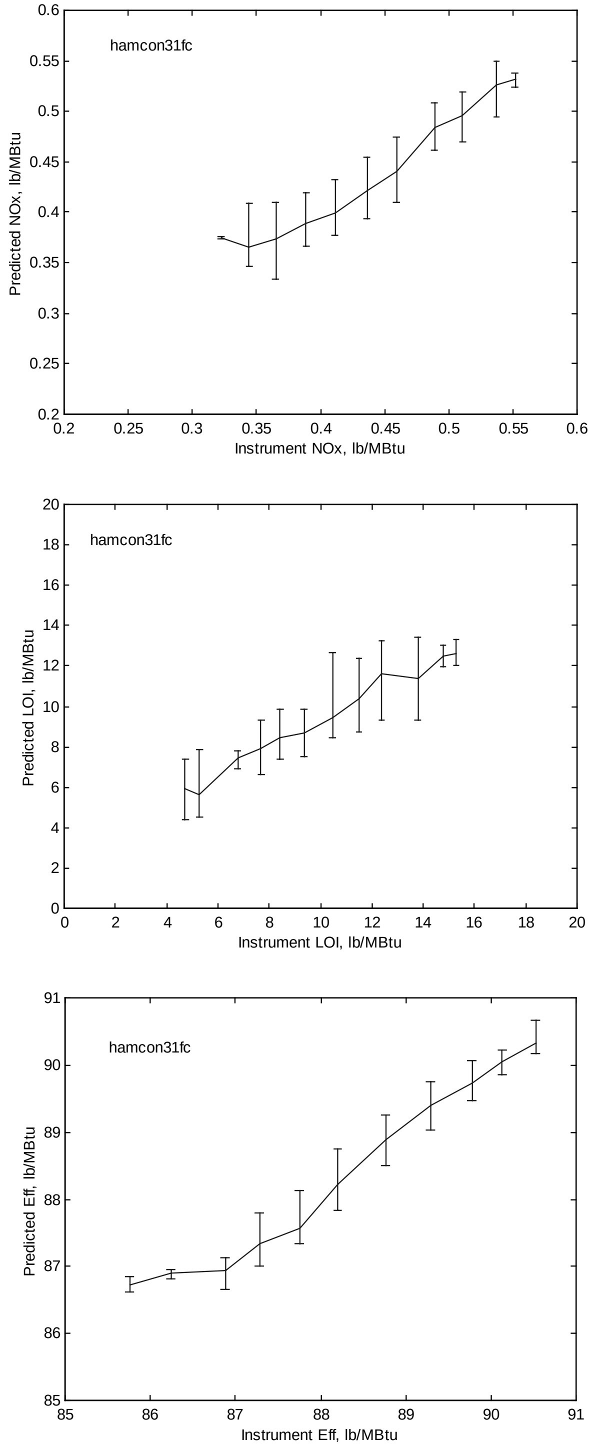


Figure 5-28 GNOCIS / Predicted vs. Actual / Hamcon31fc

Table 5-9 GNOCIS Testing Conducted First Quarter 1996

Test	Date Appr. Start Time Appr. Stop Time	Mode	Goals	Constraints	Notes
154-1	13-Feb-96 12:30 13:30	Open-Loop Min NOx	0.2 < NOx < 0.2 0<LOI<20 0<Eff<100	-0.2 < ΔO2 < 0.2 Mills clamped AOFA clamped	
154-2	13-Feb-96 13:00 14:30	Open-Loop Min LOI	0.2 < NOx < 1.0 0<LOI<0 0<Eff<100	-0.2 < ΔO2 < 0.2 Mills clamped AOFA clamped	
154-3	13-Feb-96 14:00 15:30	Open-Loop Min NOx	0.2 < NOx < 0.2 0<LOI<20 0<Eff<100	-0.2 < ΔO2 < 0.2 Mills clamped -5 < AOFA < 5	
155-1	15-Feb-96 9:40 11:40	Open-Loop Min NOx	0.2 < NOx < 0.2 0<LOI<20 0<Eff<100	-0.2 < ΔO2 < 0.2 Mills clamped AOFA clamped	
155-2	15-Feb-96 10:30 12:50	Open-Loop Min LOI	0.2 < NOx < 1.0 0<LOI<0 0<Eff<100	-0.2 < ΔO2 < 0.2 Mills clamped AOFA clamped	
155-3	15-Feb-96 12:10 14:30	Open-Loop Min LOI	0.2 < NOx < 1.0 0<LOI<0 0<Eff<100	-0.2 < ΔO2 < 0.2 -5.2 < Mills < 5.2 AOFA clamped	• O_2 recommendation flip flops.
155-4	15-Feb-96 14:00 15:20	Open-Loop Min NOx	0.2 < NOx < 0.2 0<LOI<20 0<Eff<100	0.2 < ΔO2 < 0.2 -5.2 < Mills < 5.2 B Mill clamped AOFA clamped	
156-1	16-Feb-96 11:30 13:30	Open-Loop Min NOx	0.2 < NOx < 0.2 0<LOI<20 0<Eff<100	0.2 < ΔO2 < 0.2 Mills clamped AOFA clamped	
156-2	16-Feb-96 12:50 14:00	Open-Loop Min LOI	0.2 < NOx < 0.2 0<LOI<20 0<Eff<100	0.2 < ΔO2 < 0.2 Mills clamped AOFA clamped	
156-3	16-Feb-96 13:45 15:00	Open-Loop Max Eff	0.2 < NOx < 1.0 0<LOI<20 100<Eff<100	0.2 < ΔO2 < 0.2 -5.2 < Mills < 5.2 -5 < AOFA < 5	
157-1	22-Feb-96 14:30 16:00	Open-Loop Min NOx	0.2 < NOx < 0.2 0<LOI<20 0<Eff<100	0.2 < ΔO2 < 0.2 Mills clamped AOFA clamped	
157-2	22-Feb-96 15:30 17:30	Closed-Loop Min LOI	0.2 < NOx < 1.0 0<LOI<0 0<Eff<100	0.2 < ΔO2 < 0.2 Mills clamped AOFA clamped	• First closed-loop test. • Test aborted when operator changed mills in service.
157-3	22-Feb-96 17:30 19:00	Closed-Loop Min LOI	0.2 < NOx < 1.0 0<LOI<0 0<Eff<100	0.2 < ΔO2 < 0.2 Mills clamped AOFA clamped	• Move suppression on O_2 zero.
157-4	22-Feb-96 19:00 19:30	Closed-Loop Min NOx	0.2 < NOx < 0.2 0<LOI<20 0<Eff<100	0.2 < ΔO2 < 0.2 Mills clamped AOFA clamped	• Move suppression on O_2 zero.
157-5	22-Feb-96 19:30 20:00	Closed-Loop Min NOx, Max Eff LOI < 10	0.2 < NOx < 0.2 0<LOI<10 100<Eff<100		• Optimizer failure due to starting point being outside feasible region.
157-6	22-Feb-96 20:00 21:00	Closed-Loop Min LOI	0.2 < NOx < 1.0 0<LOI<0 0<Eff<100		• Optimizer failure due to starting point being outside feasible region.

Tests 154

Results of the first day of testing during which three tests were conducted are shown in Figure 5-29 and Figure 5-30. The unit was operating at full load (500 MW) with all mills in service, overfire in operation, and otherwise normal operating conditions.

For the first test (Test 154-1), the goal was to minimize NOx with excess oxygen, with the other control variables (AOFA airflow and mill coal flow) being clamped to the current operating condition. GNOCIS was allowed to make recommendations for excess oxygen of ±0.2% about the current operating condition. As may be expected, the recommendation was to decrease excess oxygen to the lower bound of the operating limit. This resulted in an approximate 0.02 lb/MBtu reduction in NOx emissions. This sensitivity (0.1 lb/MBtu per 1% change in excess oxygen) is similar to what had been observed in prior phases. Note that fly ash carbon-in-ash, as measured by the FOCUS system, increased in response to the decrease in excess oxygen with a sensitivity of 5% change in CIA per 1% change in excess oxygen.[1] This increase was also evident on the SEKAM monitor, but delayed due to the relatively slow response of this instrument.

The objective of the second test (Test 154-2) was to minimize LOI. As before, all control variables other than excess oxygen was clamped with the limits for the latter again being ±0.2%. The recommendation for excess oxygen was to increase it to the upper limit (3.6%). As shown in Figure 5-29, LOI decreased by about 2 percentage points while NOx increased to around 0.60 lb/MBtu.

For the final test of the day (Test 154-3), the objective was again to minimize NOx emission, however, in addition to excess oxygen, the AOFA airflow to the four corners of the windbox were included in the optimization mix. As shown, NOx emission levels were not obviously lower than that achieved with excess oxygen alone (~0.55 lb/MBtu). Potential reasons that the inclusion of AOFA did not improve performance include:

- Relatively small limits placed on AOFA movement (±5000 lb/h or approximate ±2% of full range).
- Relative low sensitivity of NOx to changes in OFA when LNBs are installed (1.25e-7 lb/MBtu per lb/h OFA flow). Based on prior testing, for the given constraints placed on the movement of the OFA, this would result in a change in NOx of about 0.003 lb/MBtu.
- There is considerable noise on the OFA flow measurements, in particular the “F2” flow. This makes the process difficult to control to setpoint.

[1] The CAM, FOCUS, and SEKAM are on-line LOI monitors; detailed descriptions can be found in the topical report *On-Line Carbon-in-Ash Monitors* [SCS, 1997].

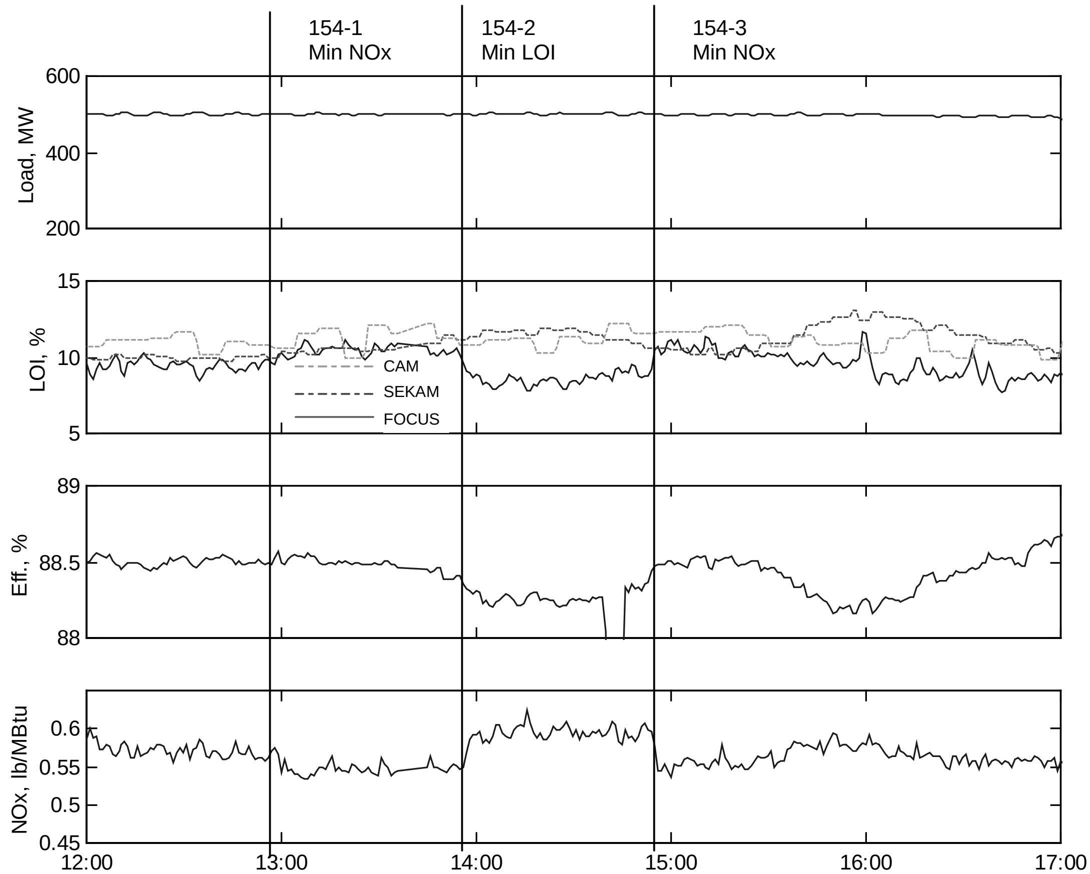


Figure 5-29 GNOCIS / Test 154 / Optimized Variables

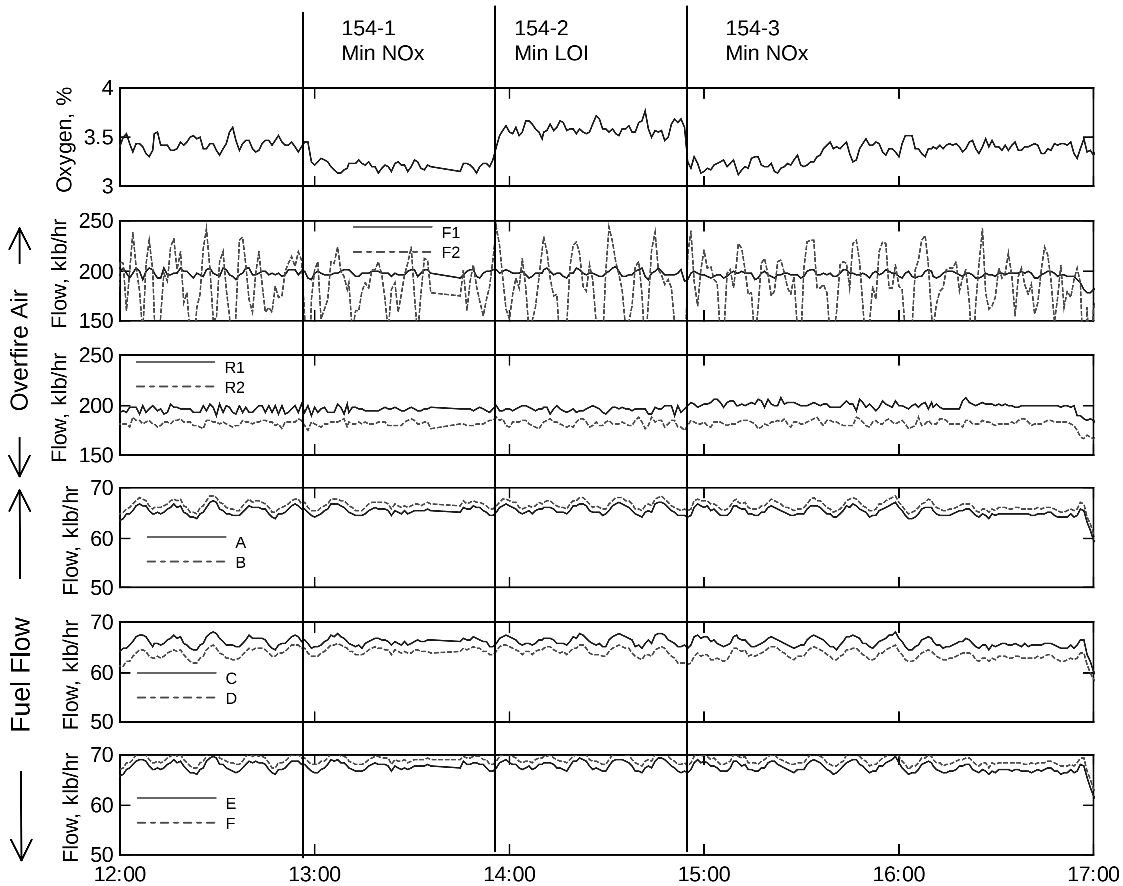


Figure 5-30 GNOCIS / Test 154 / Manipulated Variables

Tests 155

Test day 155 occurred on February 15, 1996 during which four tests were conducted (Figure 5-31 and Figure 5-32). The tests were conducted at 300 MW with “B” mill out of service and no overfire airflow. As shown, load was relatively constant during the test period. During the entire test period, the combustion side of the process was oscillating at a period of approximately 15 minutes that sometimes made the interpretation of results difficult. Note that this oscillation was independent of whether GNOCIS was operating. Again starting with only excess oxygen in the optimizing mix, recommendations were made to NOx emissions (Test 155-1). Excess oxygen was reduced from the nominal 4.4% to approximately 4.2% with the NOx emissions going from 0.52 to 0.49 lb/MBtu. As before, the limits on the excess oxygen bias were set to ±0.2% around the nominal operating point. As may be expected with the reduction in excess oxygen, LOI increased as a result of the recommendation (Figure 5-31). As shown, the SEKAM, CAM, and FOCUS systems all indicated an increase, however, due to the slow response of the SEKAM, it did not reach its maximum until the beginning of the next test. Also, although the CAM has a relatively response time (about 10 minutes at this load level), it generally increased during the entire time from the beginning of Test 155-1 to the beginning of Test 155-2 (Figure 5-33). Changing coal conditions or otherwise uncontrolled inputs to the furnace may have caused this increase.

In Test 155-2, the objective was to minimize LOI with the result being it reduced by approximately 1 to 2%, using the CAM as reference. However, as shown, LOI began to increase during the test period even though, to our knowledge, no controllable parameters were changed. Again, changing coal conditions or otherwise uncontrolled inputs to the furnace may have caused this increase.

In the Test 155-3, the mills were included in the optimization mix to reduce LOI. The biasing of the mills appeared to, at least temporarily, forestall the increase in LOI. To minimize LOI, the “A” mill (middle elevation, rear wall) was reduced in flow while the “D” mill (middle elevation, front wall) was increased.

The objective of the last test of the day was to minimize NOx emissions using excess oxygen and mill biasing. As shown, the NOx emissions reduced by about 0.03 lb/MBtu, similar to what was achieved with excess oxygen alone. The recommendation was to reduce excess oxygen from the nominal limit to the lower limit allowed. Although included in the optimization mix, the recommendation was to leave the mills in the current operating configuration. Unless disabled, GNOCIS has move suppression that prevents excessive movement in a control variable if only marginal improvement is obtained. This suppression is the likely reason the mills were left in the current configuration.

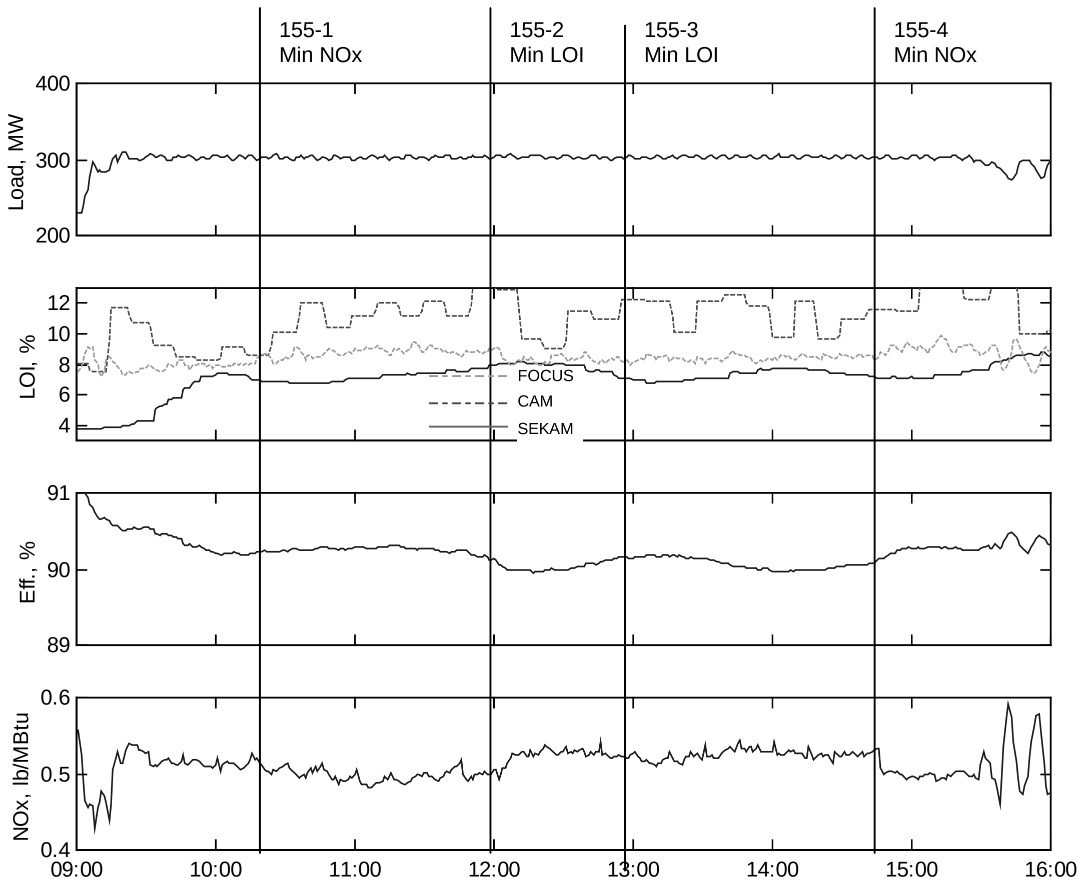


Figure 5-31 GNOCIS / Test 155 / Optimized Variables

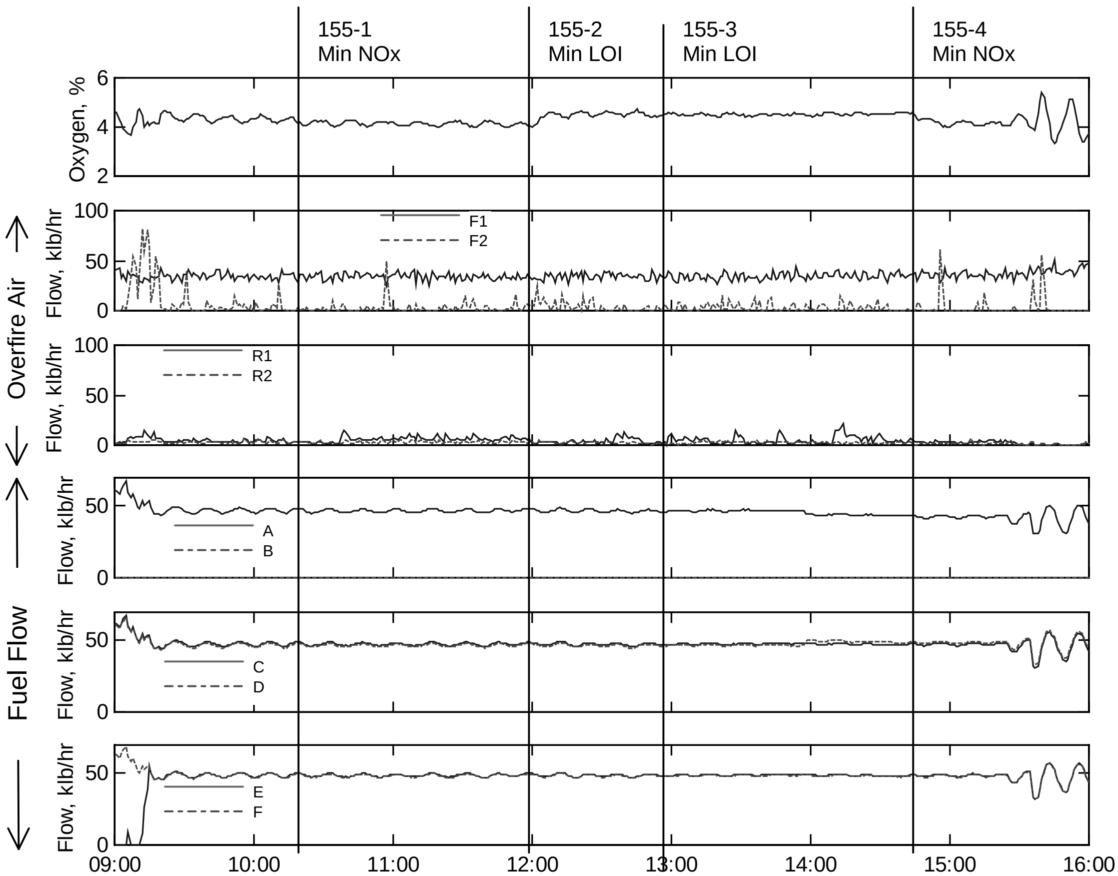


Figure 5-32 GNOCIS / Test 155 / Manipulated Variables

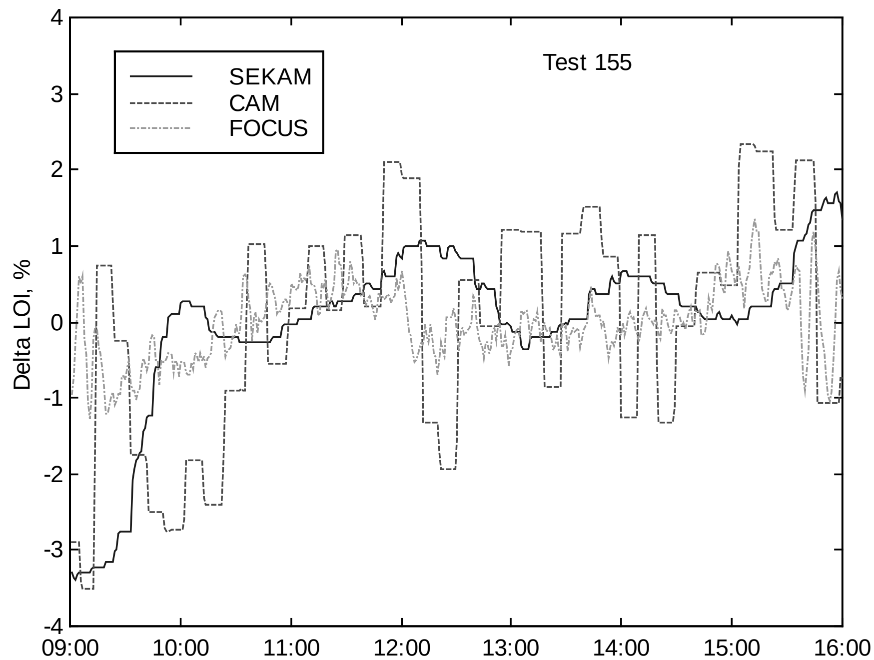


Figure 5-33 GNOCIS / Test 155 / Delta LOI

Tests 156

Three tests were conducted on February 16, 1996. The unit was operating at 400 MW with all mills in service and overfire air at nominal operating conditions. The unit was off economic dispatch and generation remained relatively constant during the test period (Figure 5-34).

The objective of Test 156-1 was to minimize NOx emissions with excess oxygen only, all other control variables being clamped. Excess oxygen, which was allowed to deviate from nominal by ±0.2%, decreased to the lower limit (Figure 5-35). As shown, NOx decreased by approximately 0.02 lb/MBtu. This sensitivity (0.1 lb/MBtu per percent change in excess oxygen) is similar to what has been observed in prior tests. Fly ash LOI (as measured by the SEKAM unit) increased by about 1% from this action (Figure 5-34 and Figure 5-36). This LOI increase would reduce boiler efficiency by approximately 0.13%. A decrease in excess oxygen typically reduces dry flue gas losses (by about 0.4 percentage points per percent change in excess oxygen).

The goal of Test 156-2 was to reduce LOI using excess oxygen alone. As shown, LOI decreased by about 1% to the original level.

For Test 156-3, with all control variables unclamped, boiler efficiency was optimized. The recommendation was to lower excess oxygen to the lower limit, increase mills “D” and “F”, and decrease mills “A” and “B”. Overfire air and mill “C” and “E” coal flows were left unchanged. As shown, there appeared to be some improvement in efficiency (about 0.25%) (Figure 5-37).

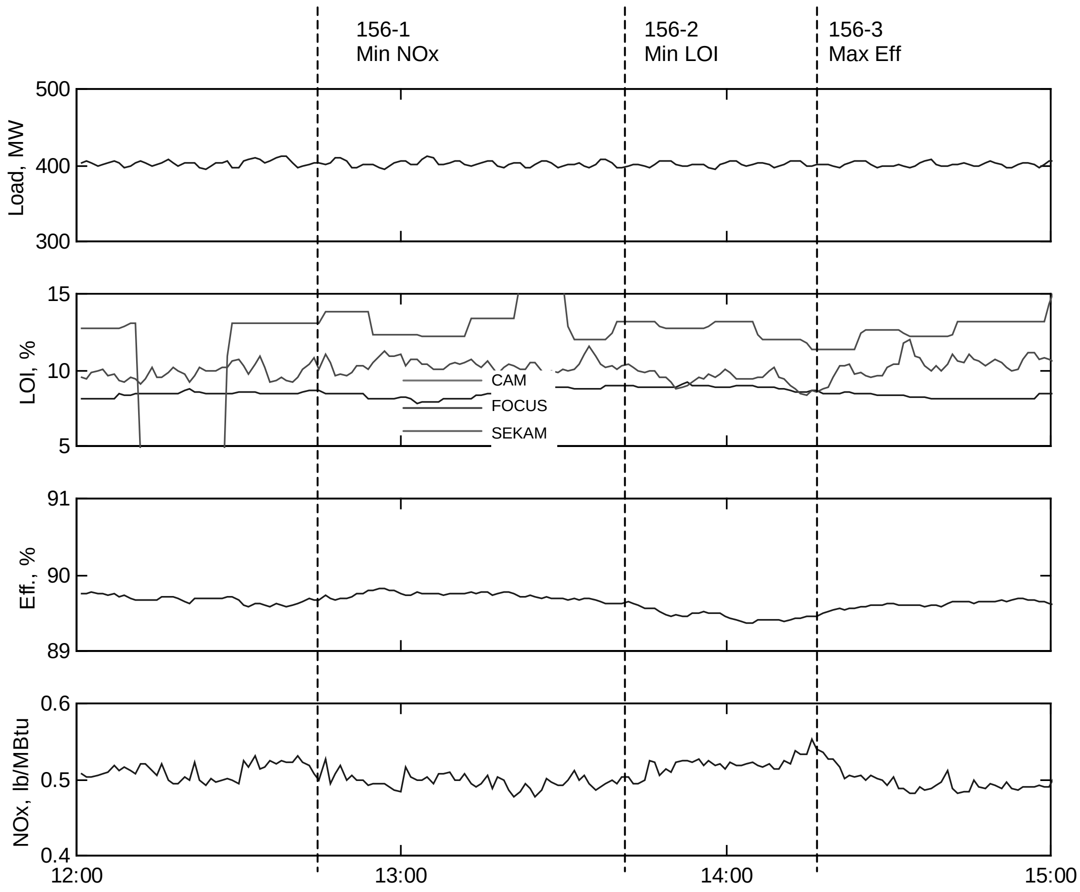


Figure 5-34 GNOCIS / Test 156 / Optimized Variables

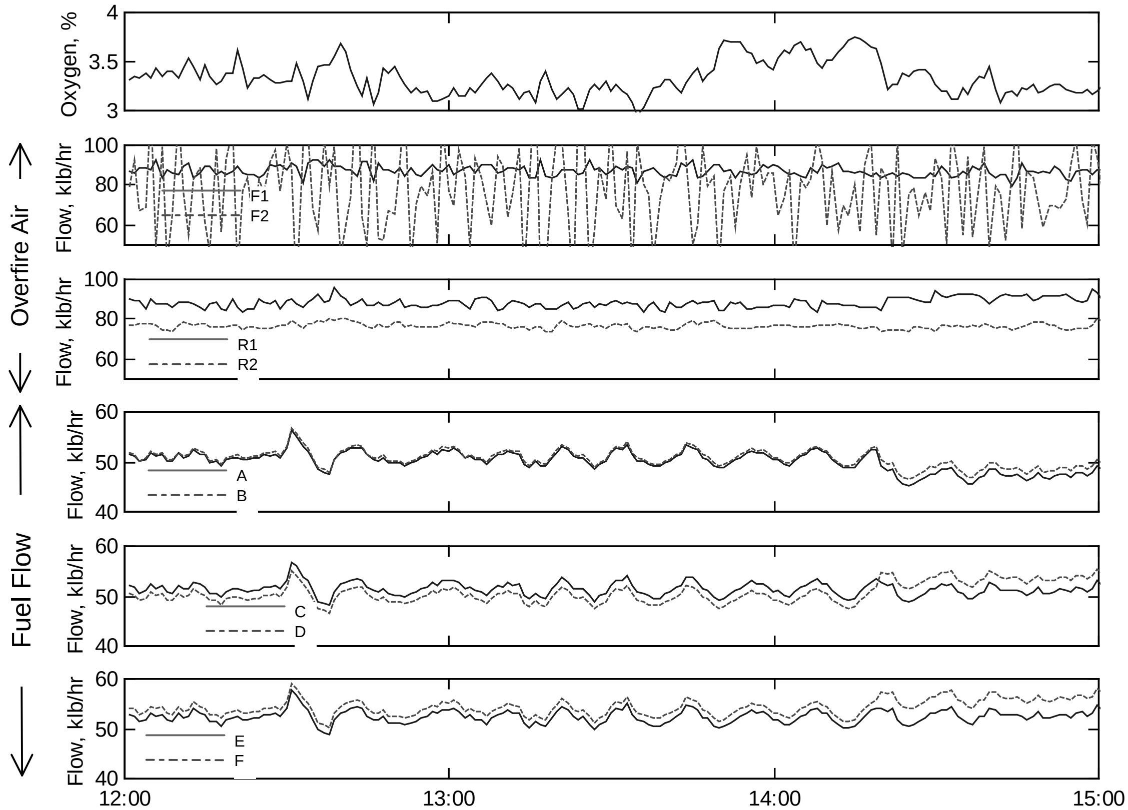


Figure 5-35 GNOCIS / Test 156 / Manipulated Variables

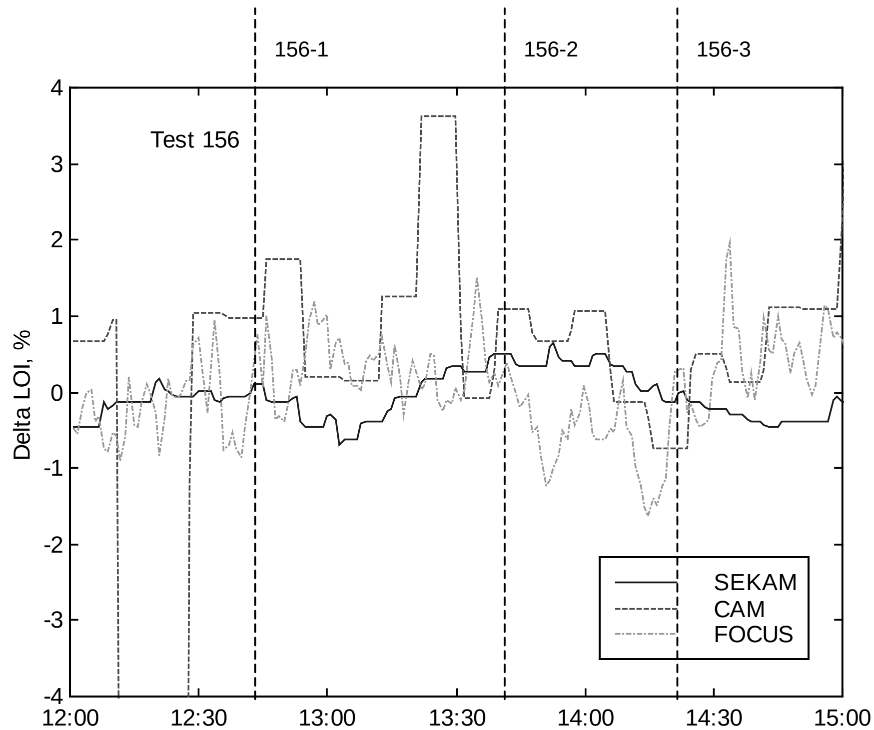


Figure 5-36 GNOCIS / Test 156 / Delta LOI

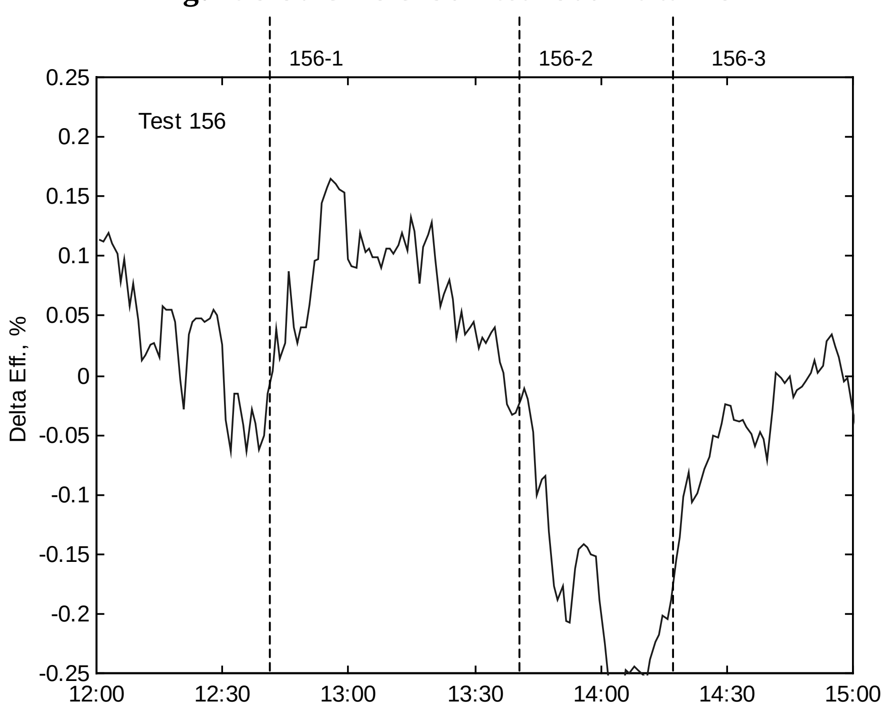


Figure 5-37 GNOCIS / Test 156 / Delta Efficiency

Tests 157

Five tests were conducted on February 22, 1996. The unit was operating at 250 MW and was under economic dispatch, resulting in load variations of about 50 MW during the test period. This load variation hinders the interpretation of test results. Per design operating procedures, overfire air was at minimum and was not available to be used in the optimization mix. The unit was in a normal operating mode for this load. Midway during the test day, "C" mill was removed from service and "F" mill brought online. Excluding Test 157-1, all tests were conducted in closed-loop mode.

The objective of Test 157-1 was to minimize NOx emissions with excess oxygen only, all other control variables (the mills) being clamped (Figure 5-38). Excess oxygen was allowed to deviate from nominal by ±0.2% and the resulting recommendation was to decease it to the lower limit (Figure 5-39). A comparison of the actual, design from the control system excess oxygen curve, and recommended levels are shown in Figure 5-40. As shown, NOx decreased by approximately 0.02 lb/MBtu or about 5% of baseline. Fly ash LOI (as measured by all the SEKAM, CAM, and FOCUS) showed very little movement and, in fact, moved little during the entire test day (Figure 5-41). This relative lack of movement may be more reflective of the performance of the online LOI monitors than of the process itself.

The goal of Test 157-2 was to minimize LOI, however, this test was aborted when the operator changed the mills in service. As a result, in Test 157-3, GNOCIS was again set to minimize LOI with excess oxygen being increased, the other control variables being clamped. Also, move suppression on excess oxygen was removed. As before, there was very little change in the LOI monitors, with the changes shown being within the accuracy limits of the instruments. The predicted change in LOI (based on the then existing GNOCIS models) was about 0.5%.

The goal for Test 157-4 was to minimize NOx with only excess oxygen. Move suppression for excess oxygen was again turned off. As shown, the recommendation was to increase excess oxygen to the upper limit. Due to load demand variations, the change in excess oxygen as a result of the GNOCIS recommendations is masked.

For Test 157-5, the goal was to minimize NOx emissions while maximizing efficiency and maintaining LOI below 10%. However, due to a failure in the optimizer, the results were not implemented. This failure was the result of the initial starting conditions given to the optimizer being outside the range of model training data. This also occurred on Test 157-6.

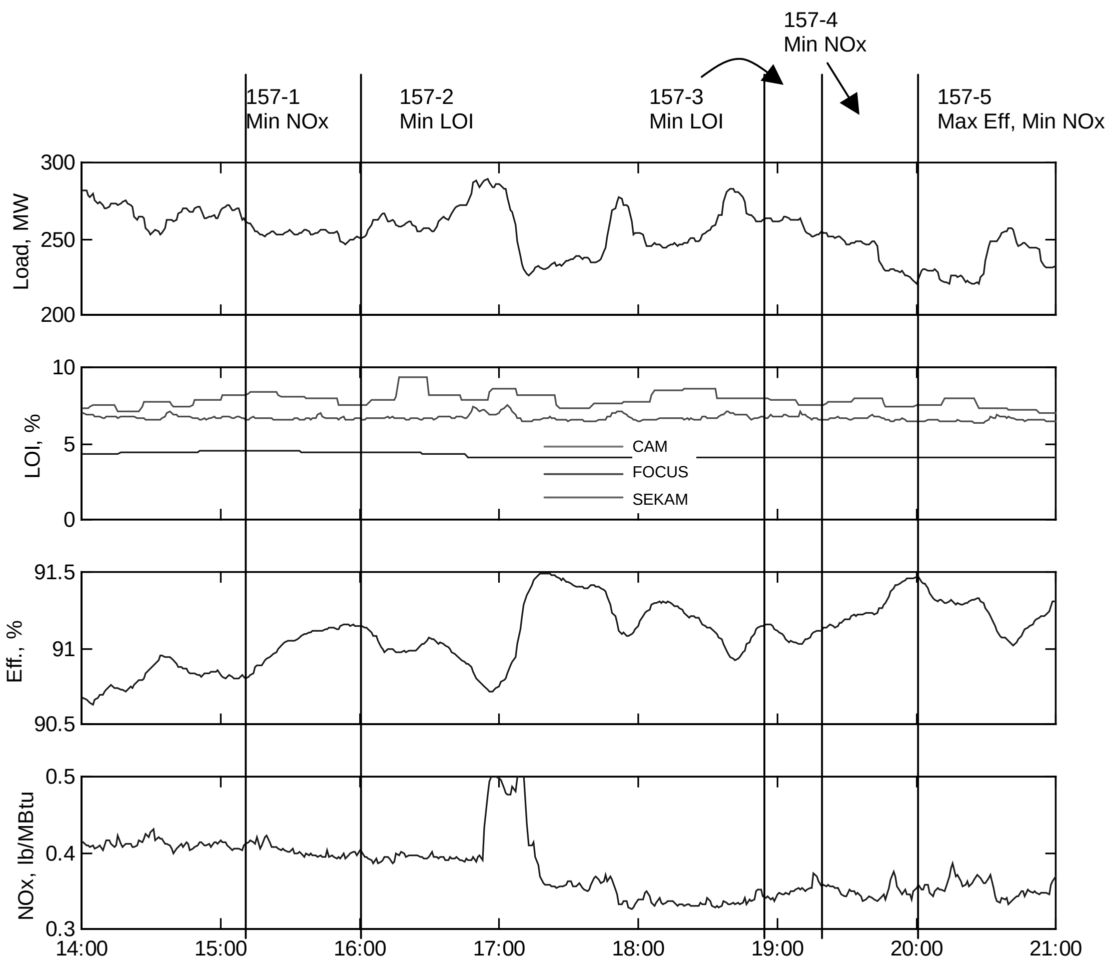


Figure 5-38 GNOCIS / Test 157 / Optimized Variables

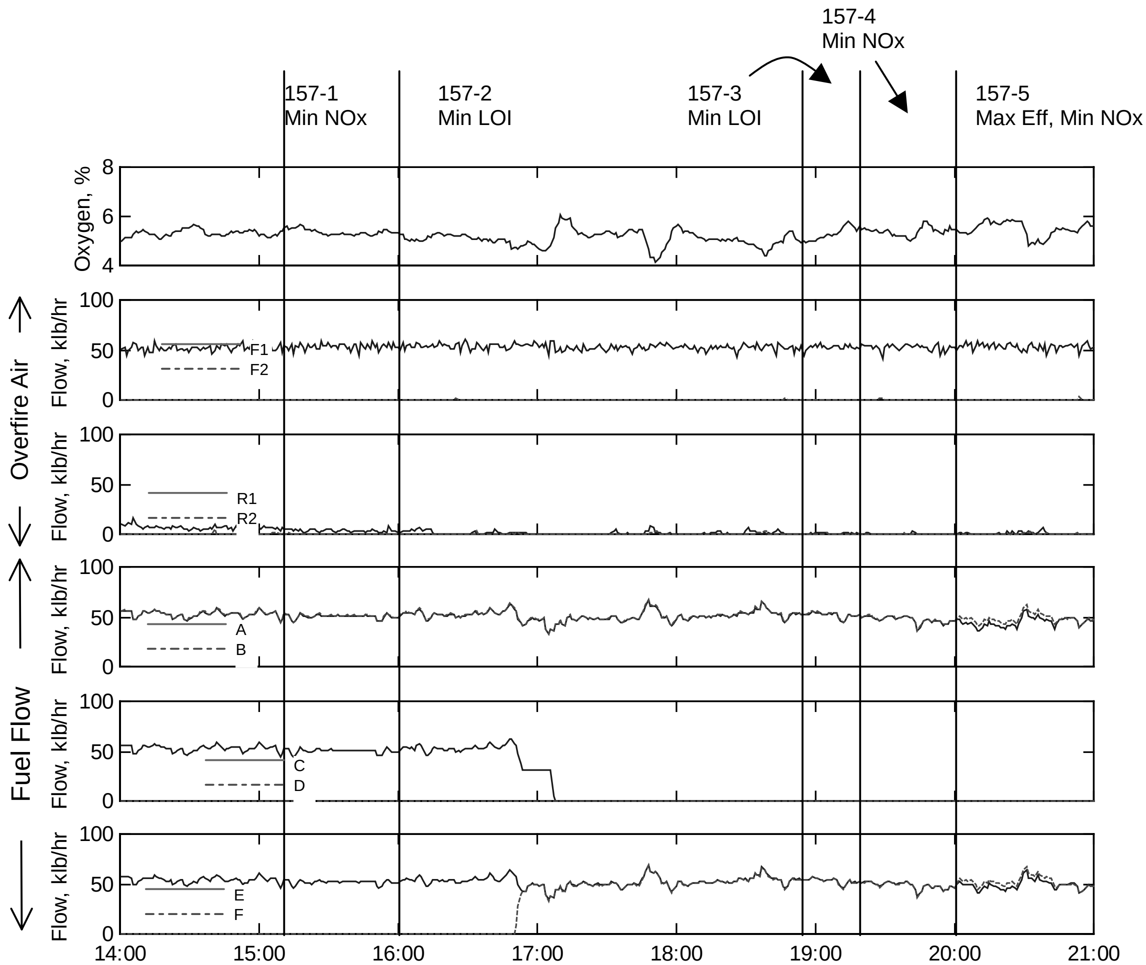


Figure 5-39 GNOCIS / Test 157 / Manipulated Variables

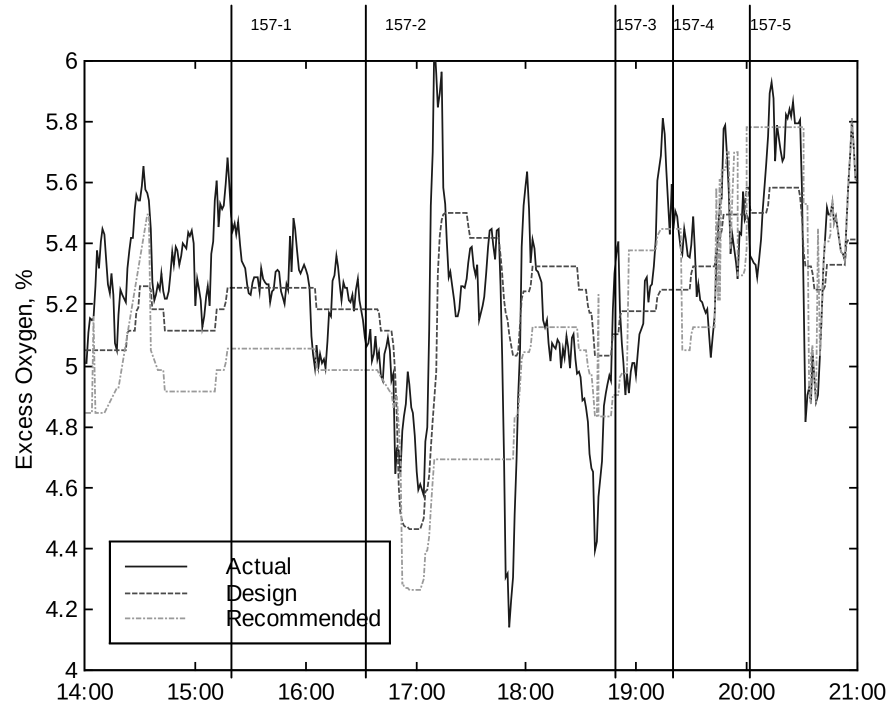


Figure 5-40 GNOCIS / Test 157 / Excess Oxygen Comparison

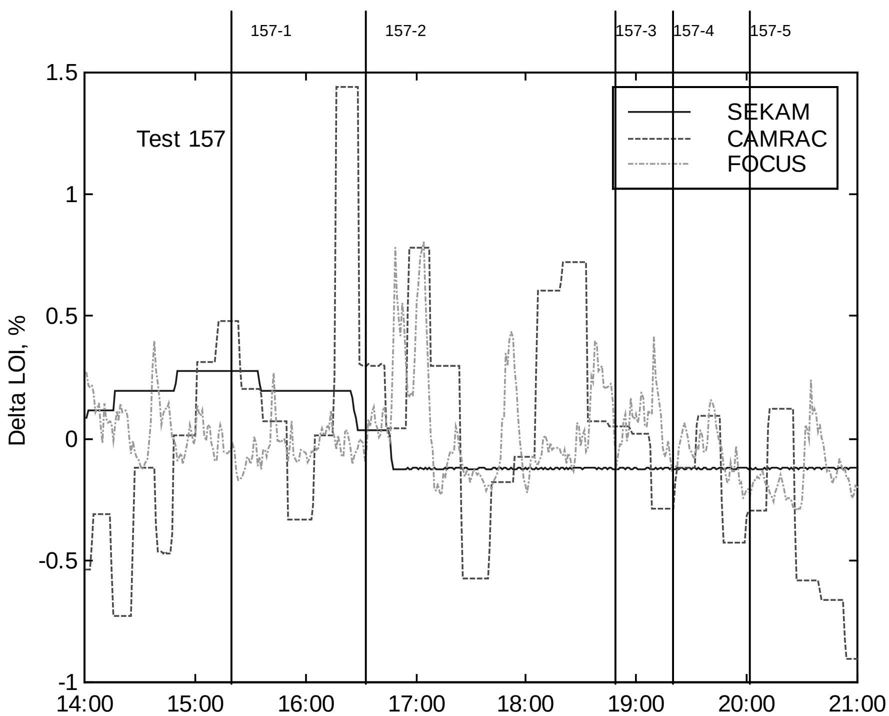


Figure 5-41 GNOCIS / Test 157 / Delta LOI

Summary of Findings from First Quarter 1996 Testing

In view of the goals, these tests were successful. The following is a summary of the findings from these tests.

- GNOCIS could be run in a closed-loop mode without adversely influencing unit stability, safety, or reliability.

- Due to instability and unreliability, the AOFA flow monitors were not suitable for inclusion in GNOCIS. As a result, the AOFA flow dampers were substituted for AOFA flows in subsequent models.

- The online LOI monitors, although providing some information, are problematic. Problems include slow response time for the extractive systems, particularly at lower loads. Although not affected by sampling considerations, the non-extractive system suffered from insensitivity to process changes, again during low load conditions (SCS 1997).

- Coding changes must be made to prevent the optimizer from returning an error when the initial starting conditions are not in the feasible region.

5.4.2.2 GNOCIS Testing Conducted Second Quarter 1996

During second quarter, testing of GNOCIS in both open- and closed-loop modes resumed with 22 tests being conducted. The control model used for these tests (hamcon31h1) was modified from that used previously with the most significant changes being:

- Substitution of AOFA damper position for AOFA flow rates. This change was prompted by the high frequency of problems with the flow monitors and high noise in the signal.
- Reduction in the number of state variables. This modification was made to reduce the complexity.

The structure of the model is shown in Table 5-10. The model was trained on data collected from January 23 to March 21, 1996 and consisted of approximately 39,000 records. Graphs showing predicted versus actual for this data set and model are provided in Figure 5-42. As might be conjectured due to the reduced number of inputs, this model did not have as good predictive qualities as the model used in the first quarter testing (*hamcon31fc*), particularly for LOI. Additional details on LOI and efficiency for several days of operation are shown in Figure 5-43 and Figure 5-44 and they indicate that the predicted LOI and efficiency trended fairly well with instrument provided values. Although not as accurate as some earlier models, it was judged that the models were sufficiently accurate to use. Also, since the testing was to be conducted following the spring outage, whereas the model was trained on data collected before the outage, there was some curiosity as to how the models would bridge this outage.

Test were conducted at several load levels, both with and without overfire air. All major boiler components, as well as ancillary equipment, were in the normal "as-found" operating conditions. The fuel supply burned was from the normal supply and handled according to common plant practice. As before, various objectives were tested (Table 5-11). The tests conducted during this period are discussed below.

Table 5-10 Control Model Structure for 2nd Quarter 1996 Testing

Control Model: hamcon31h	
Control Variables	State Variables
Average Excess Oxygen	Total Secondary Air Flow
Mill Coal Flow A	Excess Oxygen Left Side
Mill Coal Flow B	Excess Oxygen Right Side
Mill Coal Flow C	
Mill Coal Flow D	
Mill Coal Flow E	
Mill Coal Flow F	
AOFA Damper R1	
AOFA Damper R2	
AOFA Damper F1	
AOFA Damper F2	
Output Variables	External Variables
NOx Emissions	<None>
LOI	
Boiler Efficiency	

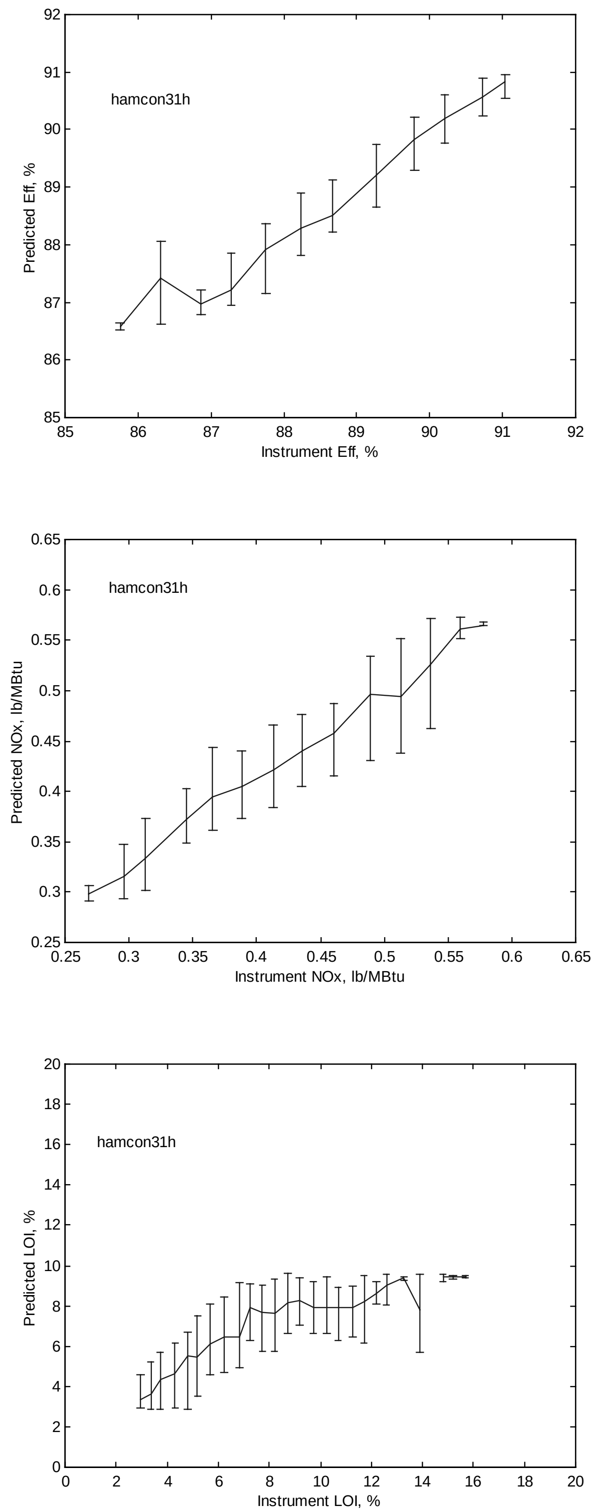


Figure 5-42 GNOCIS / Predicted vs. Actual / Hamcon31h

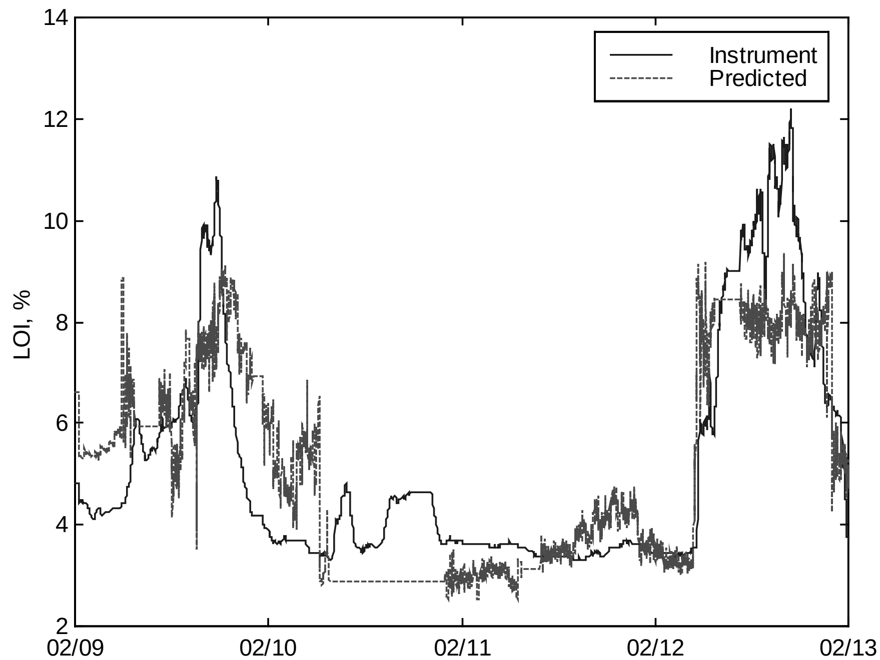


Figure 5-43 GNOCIS / Predicted vs. Actual / Hamcon31h / LOI

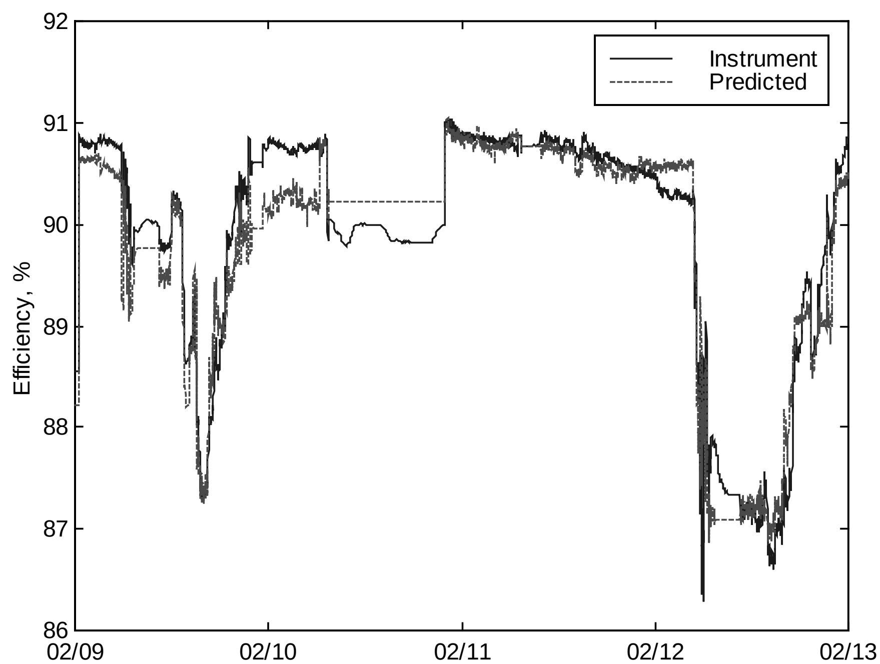


Figure 5-44 GNOCIS / Predicted vs. Actual / Hamcon31h / Efficiency

Table 5-11 GNOCIS Testing Conducted Second Quarter 1996

			Goals			Limits		
Test	Date	Mode	NO_x	LOI	Efficiency	Excess O_2	AOFA Dmpr.	Mill Flows
158-1	5/7/96	OL	-	-	Max	±0.2	Clamped	Clamped
158-2	5/8/96	OL	-	-	Max	±0.2	±5	Clamped
158-3	5/8/96	OL	-	-	Max	±0.2	±5	±5k
158-4	5/8/96	OL	-	-	Max	±0.2	±5	±5k
159-1	5/9/96	OL	-	-	Max	±0.2	±5	±5k
159-2	5/9/96	OL	-	-	Max	±0.2	±5	±5k
159-3	5/9/96	OL	-	Min	-	±0.2	±5	±5k
159-4	5/9/96	OL	-	-	Max	±0.2	±5	±5k
159-5	5/9/96	OL	-	Min	-	±0.2	±5	±5k
159-6	5/9/96	OL	-	-	Max	±0.2	±5	±5k
160-1	5/14/96	OL	-	-	Max	±0.2	±5	±5k
160-2	5/14/96	CL	-	Min	-	±0.2	±5	±5k
160-3	5/14/96	CL	Min	-	-	±0.2	±5	±5k
161-1	5/15/96	CL	Min	-	-	±0.2	±5	±5k
161-2	5/15/96	CL	-	-	Max	±0.2	±5	±5k
161-3	5/15/96	CL	-	Min	-	±0.2	±5	±5k
161-4	5/15/96	OL	Min	-	-	±0.2	±5	±5k
161-5	5/15/96	OL	-	-	Max	±0.2	±5	±5k
162-1	5/16/96	CL	-	Min	-	±0.4	±5	±5k
162-2	5/16/96	CL	Min	-	-	Clamped	±5	±5k
162-3	5/16/96	CL	Min	-	-	±0.4	±5	±5k

Test158

Test 158 was conducted on May 7, 1996 with the unit off economic dispatch and at 480 MW. The purpose of the test was to evaluate the performance of GNOCIS in regards to boiler efficiency improvements as GNOCIS was made sequentially less constrained. The tests were conducted in open-loop mode. The testing was compromised since the LOI and NOx monitors were not operational for the test period and the predicted values were used as surrogates. Boiler efficiency and a subset of the independent control variables during the course of the test period are shown in Figure 5-45 and Figure 5-46. As shown, nominal boiler efficiency was near 87.5 percent at the beginning of the testing and with sequential application of the GNOCIS recommendations, an efficiency of approximately 88.3 percent was attained. Recommendations for excess oxygen, AOFA damper, and mill loading were implemented at approximately 11:15, 12:10, and 12:45, respectively. Also note that the recommended damper position is dependent on whether the mills are included in the optimization mix. The final recommendation tended to move fuel from the front of the furnace to the rear and also decreased overfire air flow to the east side while decreasing that to the west.

The dry flue gas losses as measured for the test period are shown in Figure 5-47. These values are determined using the air heater inlet and outlet temperatures and excess oxygen. Using the predicted LOI and these measured losses, boiler efficiency can be estimated and compared to the predicted result (Figure 5-48). As shown, the predicted change was greater than calculated using the measured dry flue gas losses and predicted LOI. The reason for this difference is unknown, however, it may be due to the air/gas temperatures never reaching equilibrium during the test period.

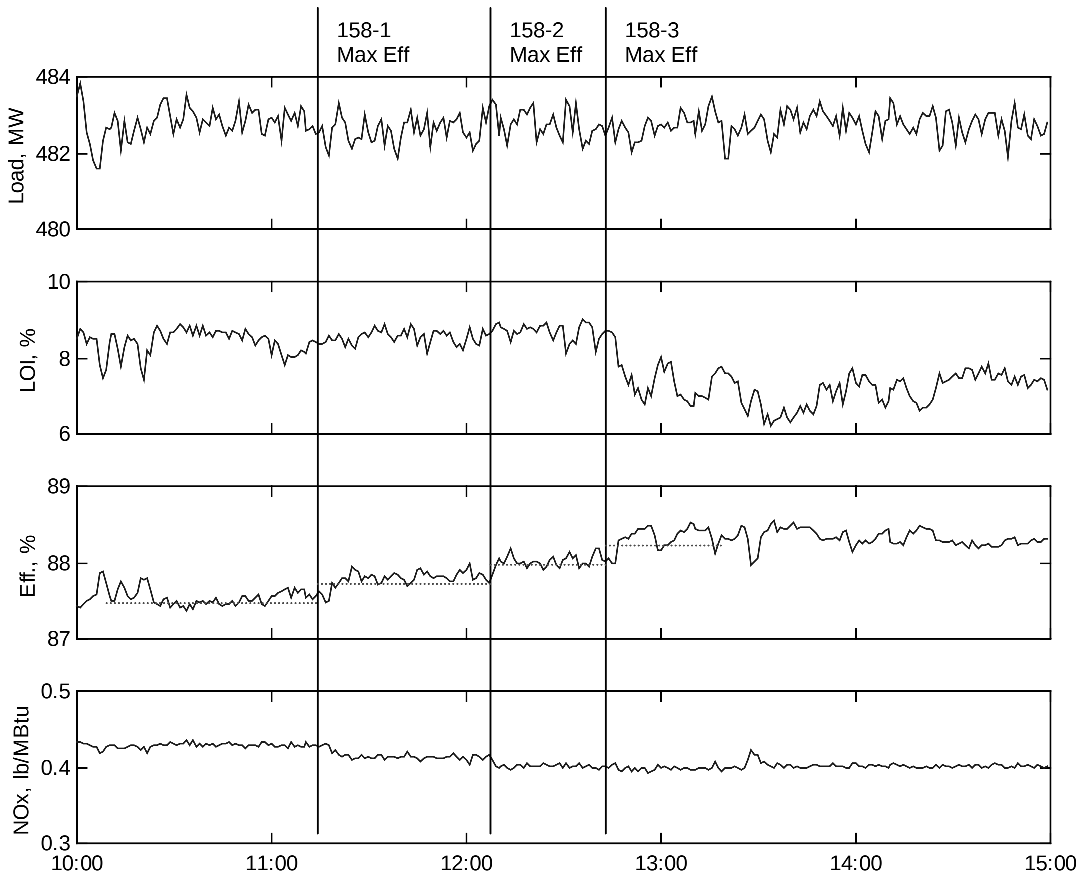
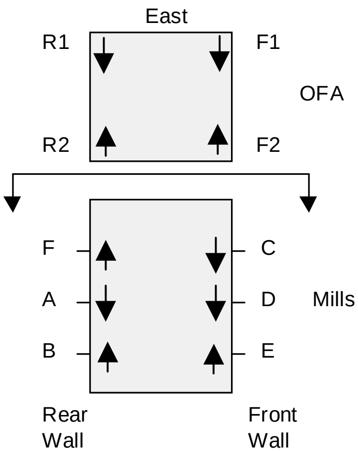


Figure 5-45 GNOCIS / Test 158 / Optimized Variables

Table 5-12 Recommendations for Test 158

Control Variable	Max. Eff.	Max Eff	Max Eff
Excess Oxygen	⇩	⇩	⇩
OFA F1	-	⇧	⇩
OFA F2	-	⇧	⇧
OFA R1	-	⇩	⇩
OFA R2	-	⇧	⇧
Mill A	-	-	⇩
Mill B	-	-	⇧
Mill C	-	-	⇩
Mill D	-	-	⇩
Mill E	-	-	⇧
Mill F	-	-	⇧



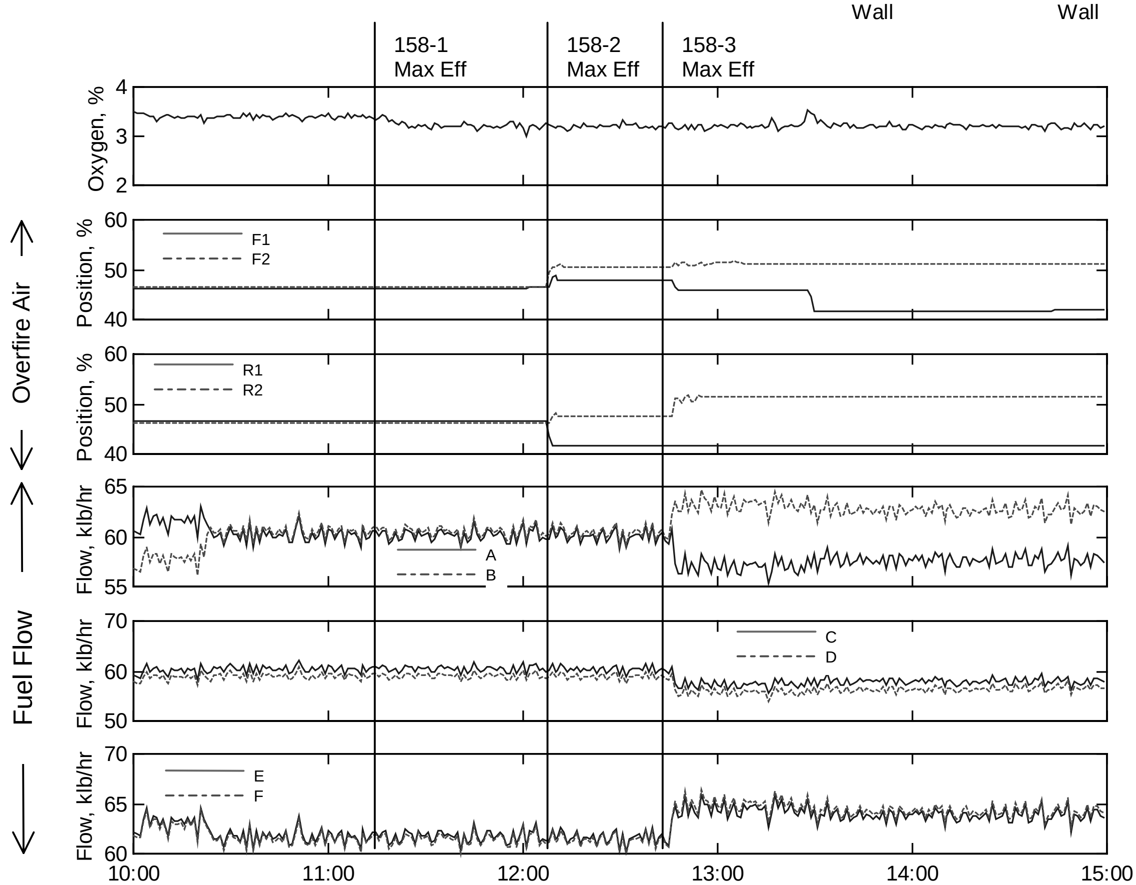


Figure 5-46 GNOCIS / Test 158 / Manipulated Variables

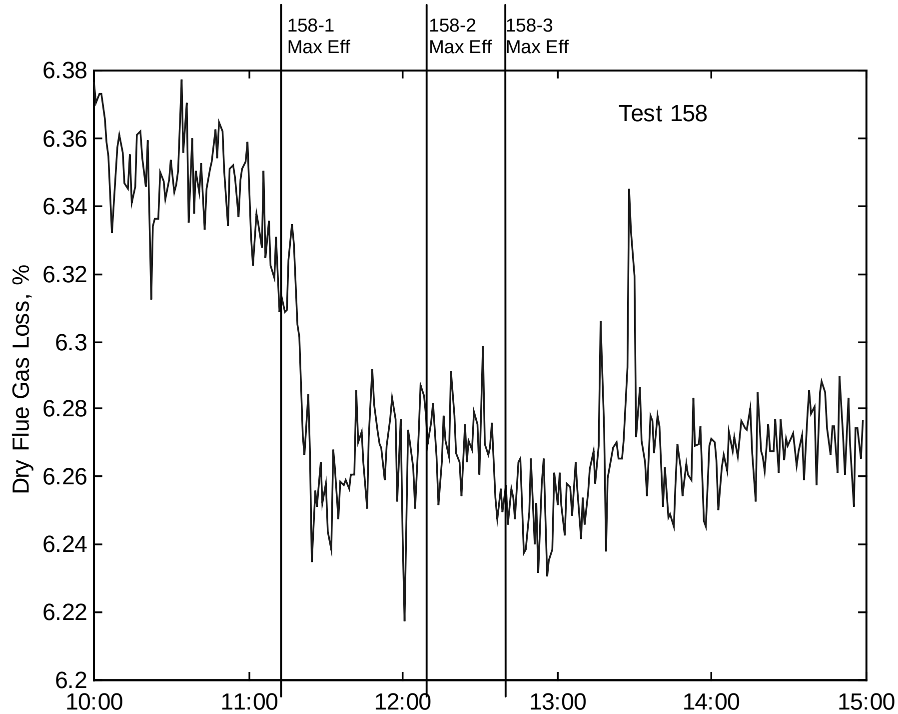


Figure 5-47 GNOCIS / Test 158 / Dry Flue Gas Loss

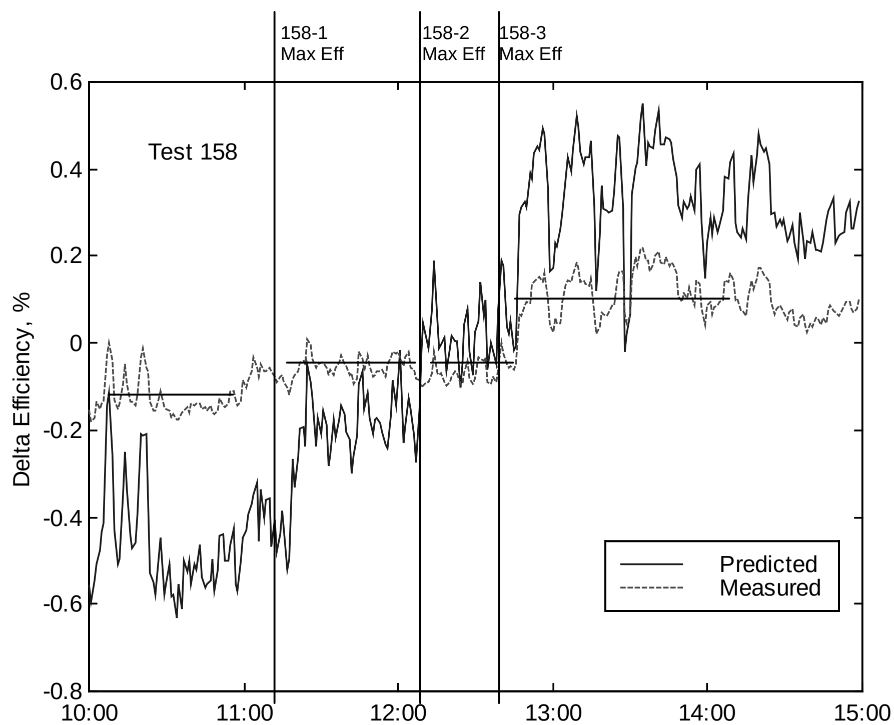


Figure 5-48 GNOCIS / Test 158 / Boiler Efficiency

Test 159

Test 159 occurred on May 9, 1996 with the unit off economic dispatch and at a load of approximately 480 MW. The tests were conducted in open-loop mode. As in Test 158, the LOI and NOx monitors were not operational for the test period and the predicted values were used as surrogates. Six tests were conducted during the test day.

As shown in Figure 5-49, efficiency exhibited a variation of 0.5% between the maximize efficiency and minimize LOI modes whereas LOI varied approximately 1% between the two operating modes. The recommendations for the tests are shown in Figure 5-50. As had been previously observed, in all cases, the recommendation was to increase excess oxygen to improve efficiency (Table 5-13). As for the other manipulated variables, for maximizing efficiency, the recommendations tended to move fuel from the rear of the furnace to the front and decreased overfire airflow to the rear of the furnace while increasing that to the front.

The dry flue gas losses as measured for the test period are shown in Figure 5-51. These values are determined using the air heater inlet and outlet temperatures and excess oxygen. Using the predicted LOI and these measured losses, boiler efficiency can be estimated and compared to the predicted result (Figure 5-52). As shown, the predicted change was greater than calculated using the measured dry flue gas losses and predicted LOI. The reason for this difference is unknown, however, it may be due to the air/gas temperatures never reaching equilibrium during the test period.

Note that these recommendations were somewhat different than those for maximize efficiency mode during Test 158. Possible reasons for the different recommendations include:

- Although excess oxygen level was essentially equal for the two days, the excess oxygen split between the left and right side of the furnace was considerably greater for Test 158 (averaging 0.34%) than Test 159 (averaging 0.68%). The left and right oxygen levels are brought individually into the combustion model and therefore have the potential to affect the recommendations.

- Move suppression on the manipulated variables could have inadvertently been enabled. Move suppression limits the movements of the manipulated variables when only marginal benefits will be obtained. Since the test had different initial conditions, this could have been a factor.

- The constraints are applied around the current operating point, therefore if starting operating points are different, the recommendations can be different.

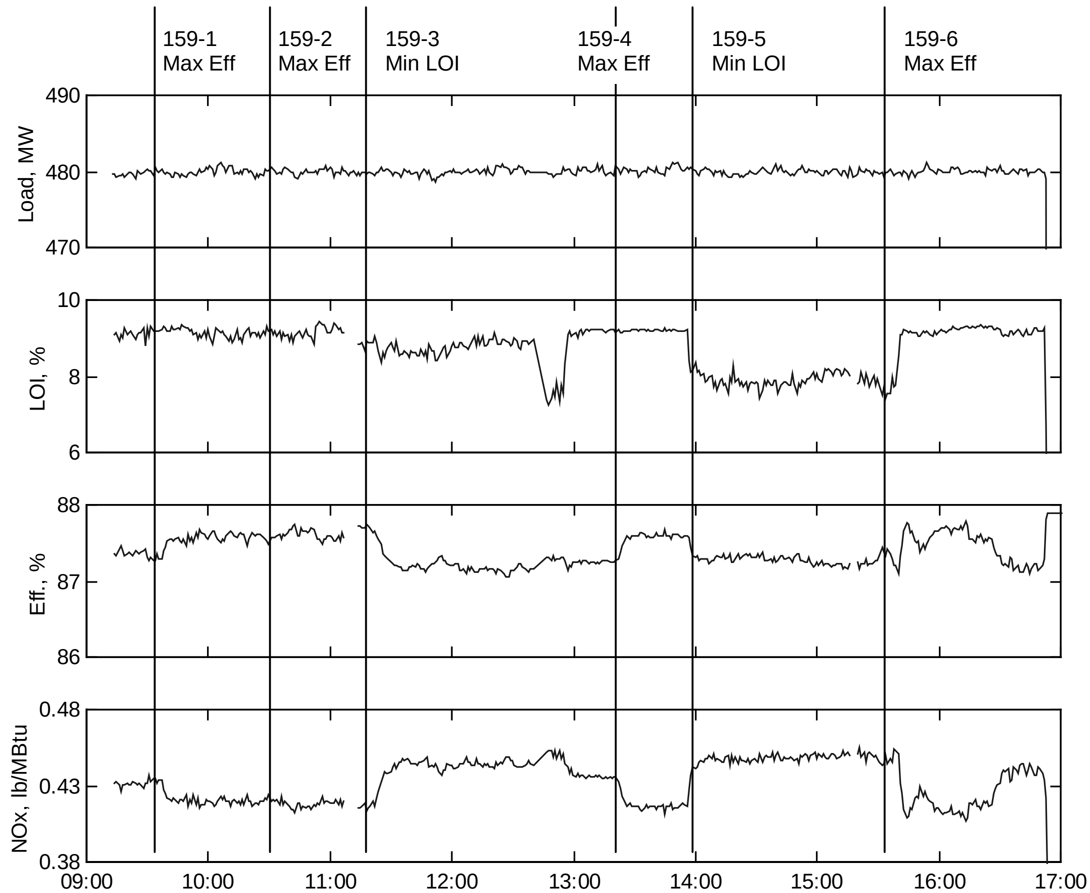
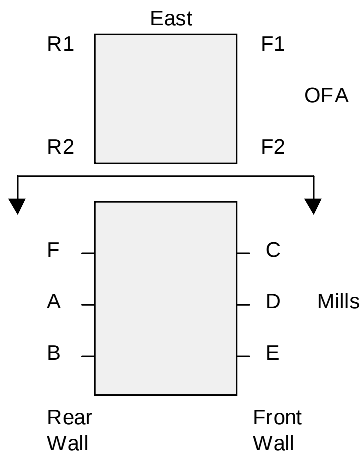


Figure 5-49 GNOCIS / Test 159 / Optimized Variables

Table 5-13 Recommendations for Test 159

Control Variable	Max. Efficiency	Min LOI
Excess Oxygen	⇩	⇧
OFA F1	⇧	⇩
OFA F2	⇧	⇩
OFA R1	⇩	⇧
OFA R2	⇩	⇧
Mill A	⇩	⇩
Mill B	⇧	⇧
Mill C	⇧	⇩
Mill D	⇧	⇩
Mill E	⇩	⇧
Mill F	⇩	⇧



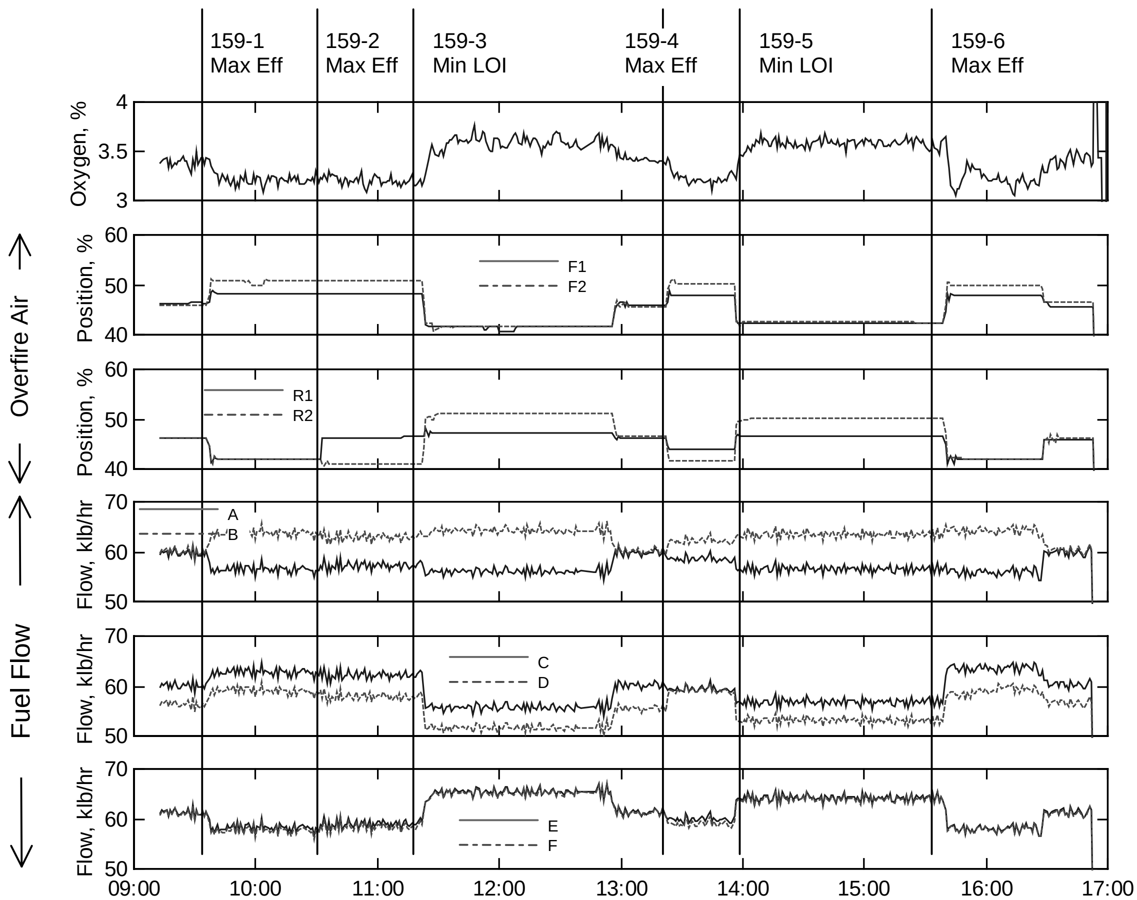


Figure 5-50 GNOCIS / Test 159 / Manipulated Variables

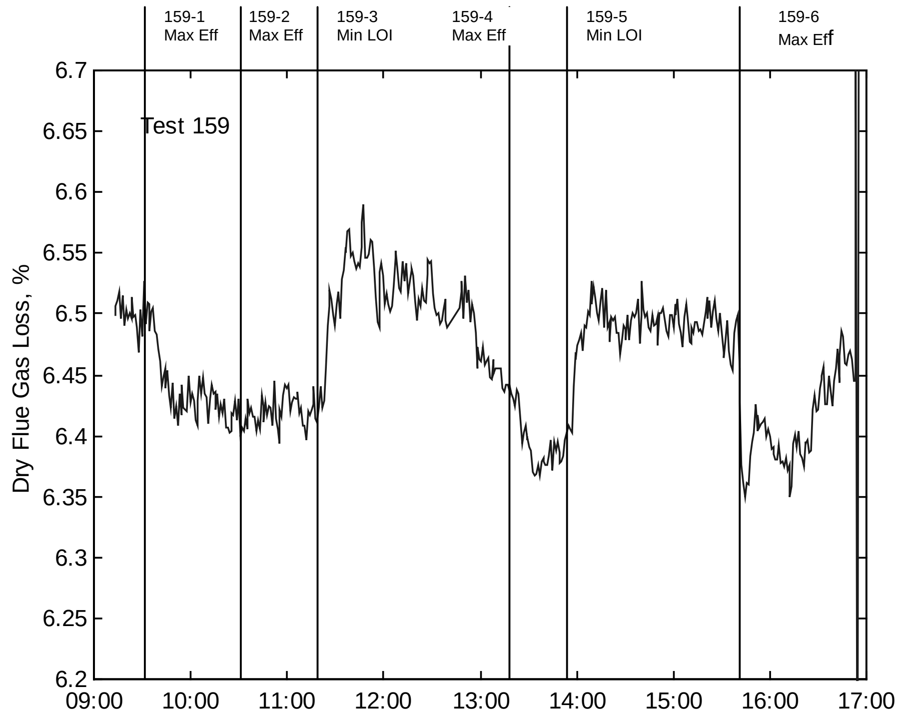


Figure 5-51 GNOCIS / Test 159 / Dry Flue Gas Loss

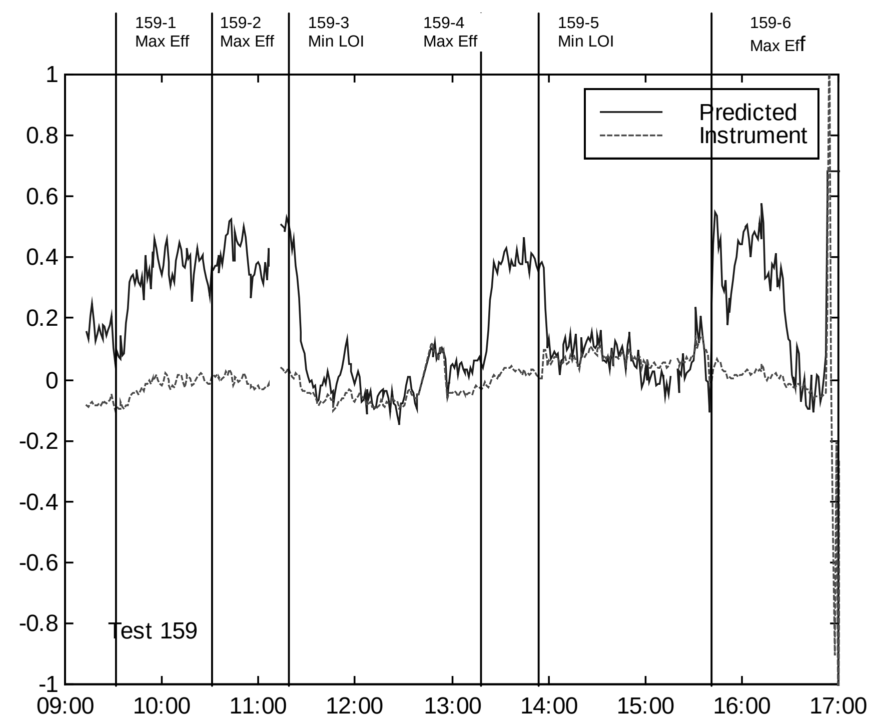


Figure 5-52 GNOCIS / Test 159 / Boiler Efficiency

Test 160

Test 160 was conducted on May 14 with the unit off economic dispatch and at 480 MW. The tests were conducted in open- and closed-loop mode. The variables being optimized and the independent control variables during the course of the test period are shown in Figure 5-53 and Figure 5-54.

The first test of the day (Test 160-1) was to maximize efficiency using all control variables. As shown, the recommendation was to reduce excess oxygen from 3.4% to 3.2%, the lower constraint. The recommendations for AOFA damper position and coal flow are shown in Table 5-14. As shown, nominal boiler efficiency was near 88 percent at the beginning of the testing. Following implementation of the recommendations, fly ash LOI (as measured by the SEKAM) increased greatly, going from near 12% to 19%. This large increase was unexpected based on prior testing [SCS, 1998]. For example, during Phase 3B NOx vs. LOI testing, the sensitivity of LOI to excess oxygen variations was found to be approximately 2.5% change in LOI for every 1% change in excess oxygen. Since excess oxygen was allowed to move only 0.2% for this test, one would expect a change in LOI of about 0.5%, far less than what the SEKAM indicated. A comparison of all LOI readings and the predicted value are shown in Figure 5-55. As shown, there was wide discrepancy between the readings (the CAMRAC system was not functional on this day). These tests highlight the importance of obtaining a reliable LOI reading on units with relatively high LOI.

Since the efficiency shown in Figure 5-53 is partly comprised of this LOI reading, the 7% increase in LOI accounted for an approximate 0.7% decrease in boiler efficiency. Dry flue gas losses decreased for this test due to the small decrease in excess oxygen (0.2%) and air heater gas inlet temperatures (~2ºF) (Figure 5-56). The predicted efficiency improvement was about 0.2%, what might be expected for only moving excess oxygen by 0.2%. The objective of Test 160-2 was to minimize LOI. As shown, SEKAM indicated a reduction in LOI of about 8% whereas the FOCUS and predicted reductions were both around 1.5%. For Test 160-3, the goal was to minimize NOx emissions and they were reduced by about 0.03 lb/MBtu.

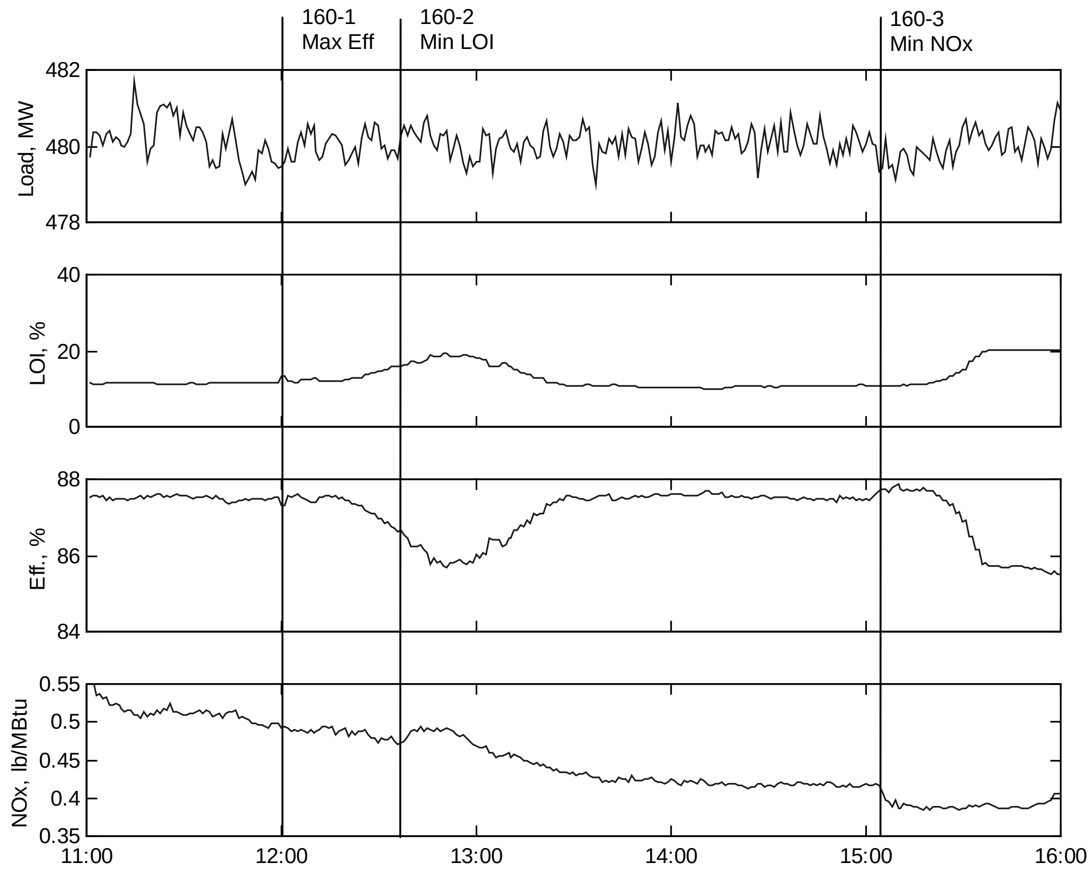
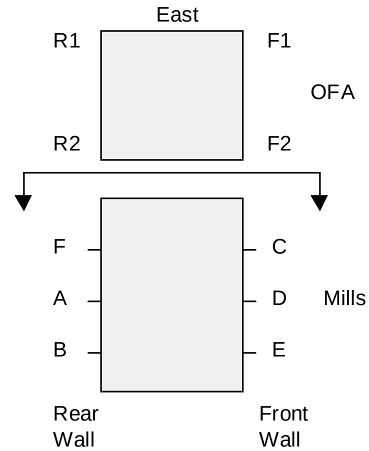


Figure 5-53 GNOCIS / Test 160 / Optimized Variables

Table 5-14 Recommendations for Test 160

Control Variable	Max. Efficiency	Min LOI	Min NOx
Excess Oxygen	⇩	⇧	⇩
OFA F1	⇧	⇩	⇩
OFA F2	⇧	⇩	⇩
OFA R1	⇩	⇧	⇧
OFA R2	⇩	⇧	⇩
Mill A	⇩	⇩	⇩
Mill B	⇧	⇧	⇩
Mill C	⇧	⇩	⇩
Mill D	⇧	⇩	⇧
Mill E	⇩	⇧	⇧
Mill F	⇩	⇧	⇧



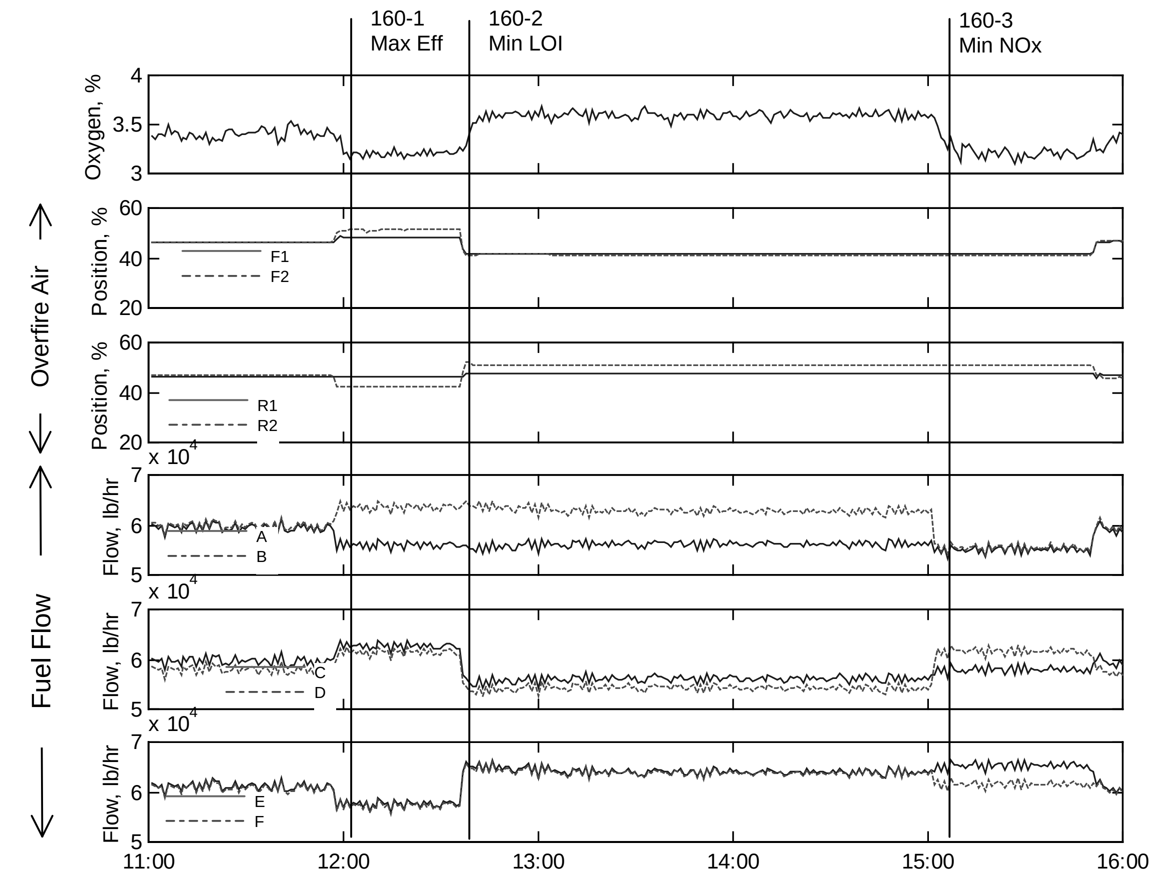


Figure 5-54 GNOCIS / Test 160 / Manipulated Variables

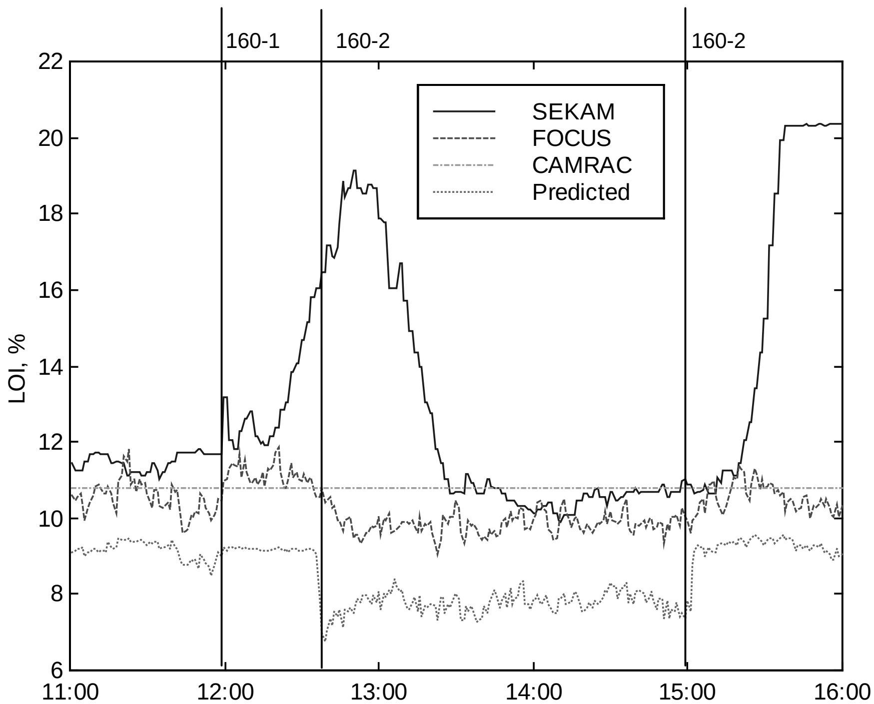


Figure 5-55 GNOCIS / Test 160 / Comparison of LOI Signals

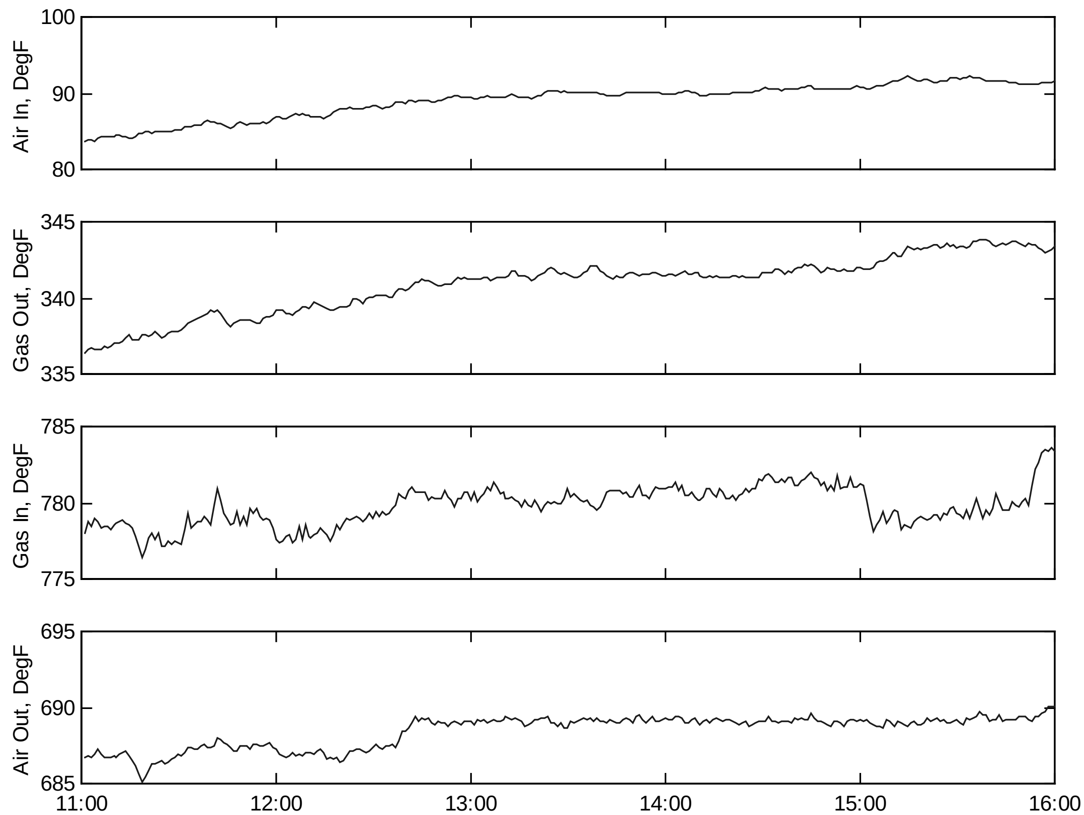


Figure 5-56 GNOCIS / Test 160 / Air Heater Temperatures

Test 161

Test 161 was conducted on May 15 at full load in both closed- and open-loop modes. During the test period, the unit was off economic dispatch and was at stable conditions. Overfire air was in operation and at nominal conditions. The fuel for the test was the normal coal supply.

Results and control actions taken are shown in Figure 5-57 and Figure 5-58, respectively. During the course of the testing several objectives were tested including minimizing NOx and LOI and maximizing boiler efficiency. As with previous closed-loop tests at this site, recommendations were intentionally made narrow until further confidence was gained in the stability of GNOCIS recommendations (Table 5-11). When NOx minimization was the goal (Test 161-1), NOx emissions were reduced by approximately 10% from baseline. Similarly, when efficiency and LOI were goals (161-2 and 161-3), improvements of near 0.7% and 2%, respectively, were obtained. Also, in Test 161-2, simultaneous improvements in NOx, LOI, and efficiency were obtained.

It is interesting to compare the recommendations and outcomes of the min NOx emissions, max efficiency, and min LOI test modes (Table 5-15). For the first two tests, the recommendation was to reduce excess oxygen to the lower constraint. However, the recommendations for the AOFA and mill coal flows were different. It appears that these changes in recommendations produced slightly lower NOx emissions than the min NOx test. However, the boiler efficiency for the maximize efficiency test was approximately 0.25% above that observed for the min NOx test. For the min LOI test (161-3), the mill configuration was not changed from that recommended for the max efficiency mode, whereas the excess oxygen and OFA damper position recommendations were changed. Note that the change in LOI from the minimize NOx to the minimize LOI mode is approximately 5%. This change is much higher than the change in LOI that a similar change in excess oxygen alone produced in the past (about 2%).

A comparison of the LOI signals for the test day is shown in Figure 5-59. As shown, the SEKAM analyzer was more influenced by operating conditions than the other instruments as well as the predicted value. The LOI swing of the SEKAM for this day was less than the 10% observed during Test 160 and more inline with earlier experience.

As can be seen, the two minimize NOx tests (161-1 and 161-4) as well as the two maximize efficiency tests (161-2 and 161-5) conducted during the day did not produce the same recommendations. Possible reasons for the different recommendations include:

- Unit changes during the intervening periods creating a different optimum.
- Since the starting points were different for the tests, move suppression could have influenced the recommendation.

A comparison of the calculated (based on current readings of excess oxygen, furnace gas temperatures and LOI via the SEKAM) and predicted efficiency (from the combustion model) changes are shown in Figure 5-60. The predicted changes were greater than that calculated, however time lags and delays in furnace gas temperatures and LOI affect the latter. Both of these measurements are determined using a control volume which excludes the air heaters.

Alternate calculations that include the air heater are shown also. The trend with the legend *Calc/AHO* uses the SEKAM reading whereas the one labeled *Calc/AHO/pred. LOI* uses the predicted LOI.

As can be seen, GNOCIS did not adversely affect the stability of the control actions and the recommendations were very stable. This characteristic is partly due to the inclusion of recommendation move suppression in GNOCIS.

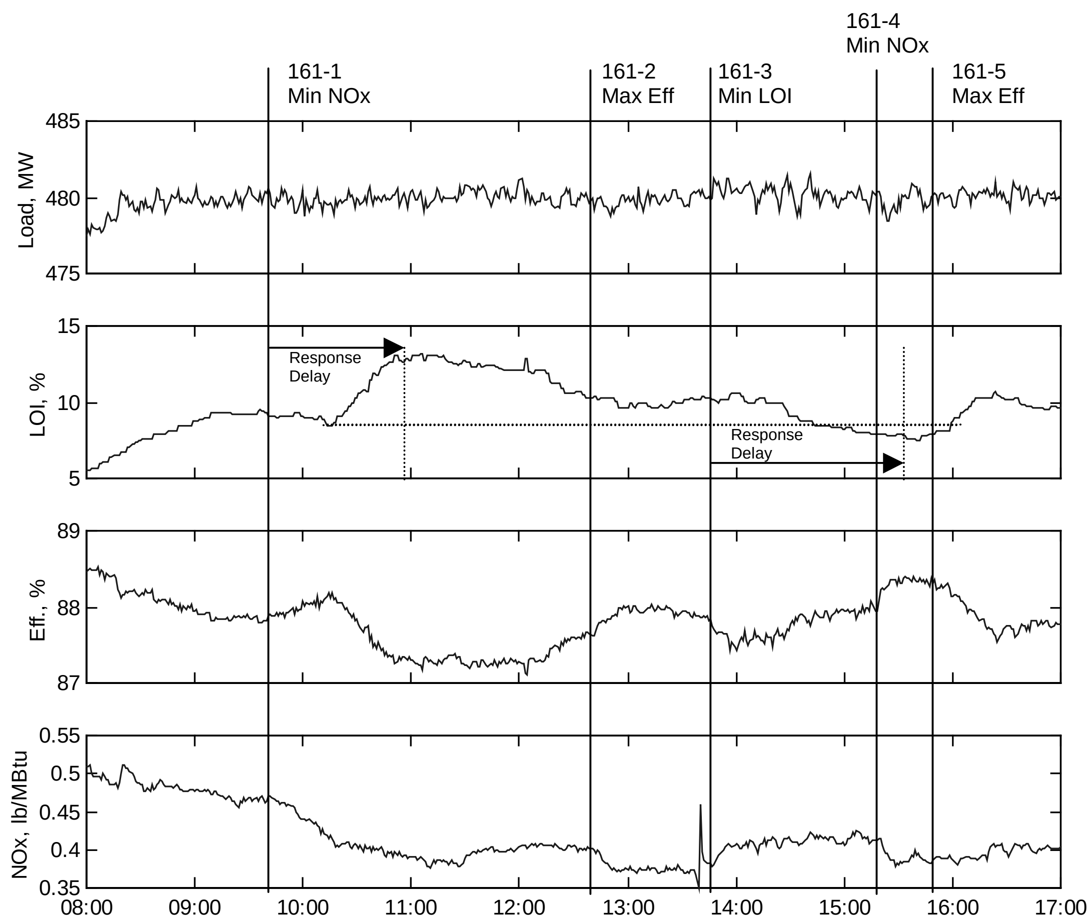
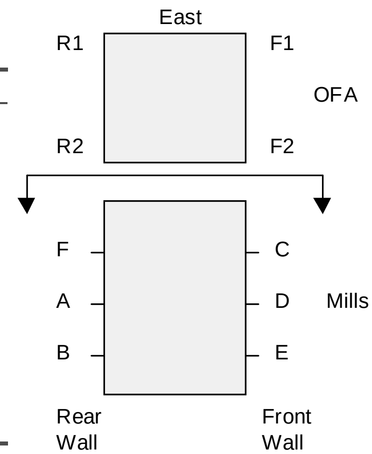


Figure 5-57 GNOCIS / Test 161 / Optimized Variables

Table 5-15 Recommendations for Test 161

Control Variable	Min NOx	Max Eff.	Min LOI	Min NOx	Max Eff
Excess Oxygen	⇩	⇩	⇧	⇩	⇩
OFA F1	⇧	⇧	⇩	⇩	⇩
OFA F2	⇧	⇧	⇩	⇩	⇩
OFA R1	⇩	⇩	⇧	⇧	⇧
OFA R2	⇩	⇧	⇧	⇧	⇧
Mill A	⇩	⇩	⇩	⇩	⇩
Mill B	⇧	⇧	⇧	⇩	⇧
Mill C	⇧	⇩	⇩	-	-
Mill D	⇧	⇩	⇩	⇧	⇩
Mill E	⇩	⇧	⇧	⇧	⇧
Mill F	⇩	⇧	⇧	⇧	⇧



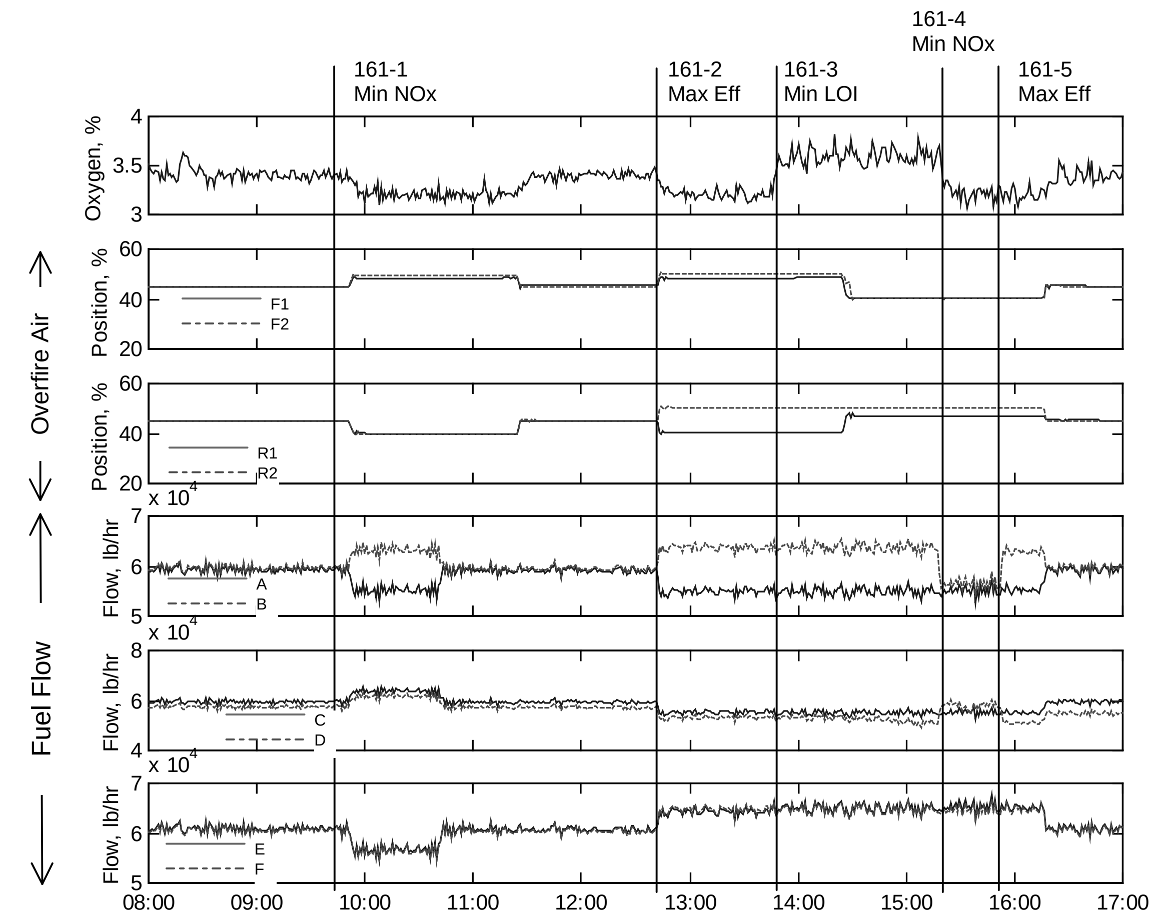


Figure 5-58 GNOCIS / Test 161 / Manipulated Variables

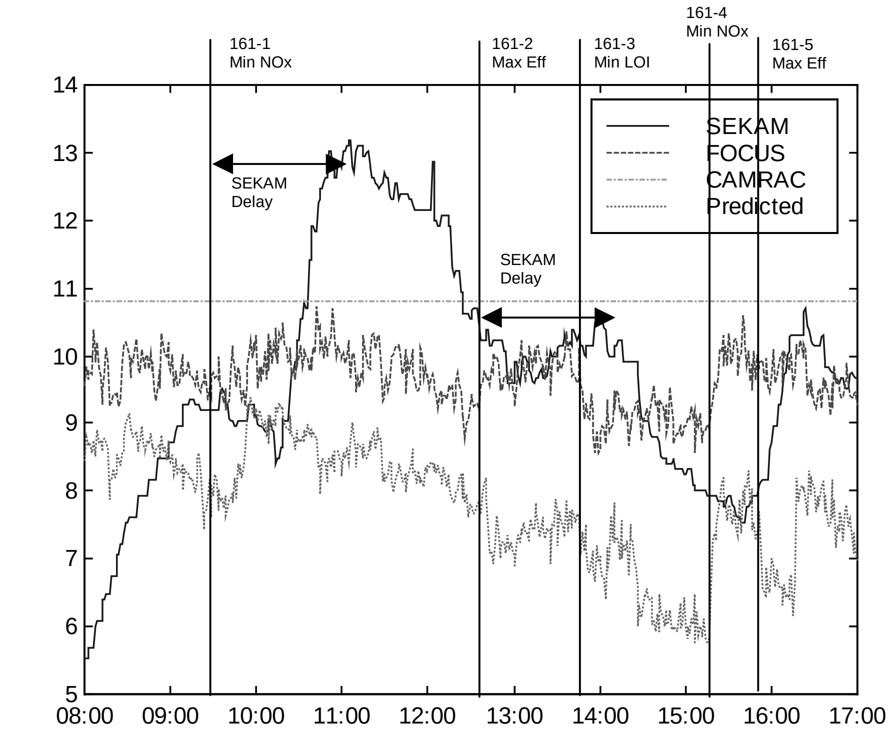


Figure 5-59 GNOCIS / Test 161 / Comparison of LOI Signals

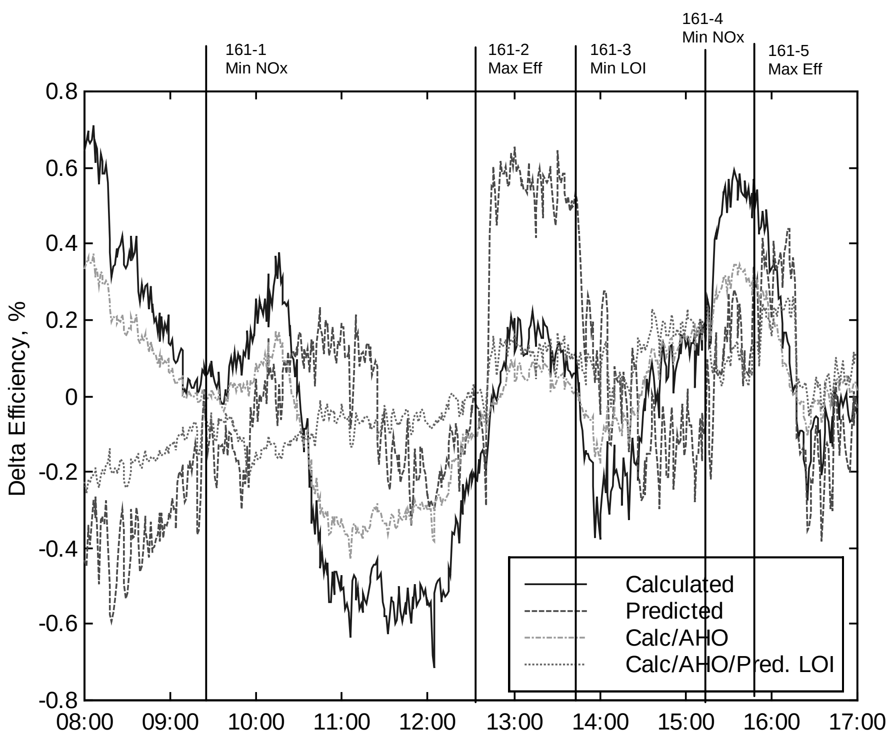


Figure 5-60 GNOCIS / Test 161 / Delta Efficiency

Test 162

Test 162 (Figure 5-61 and Figure 5-62), conducted on May 16, was also at full load and GNOCIS was operating in closed-loop mode. During the test period, the unit was off economic dispatch and was at stable conditions. Overfire air was in operation and at nominal conditions. The fuel for the test was the normal coal supply. A summary of the control actions for these tests is shown in Table 5-16.

In Test 162-1, minimize LOI was the goal and as shown, a reduction of approximately 2.2 percent was obtained. As expected due to the increased oxygen levels, NOx emissions were increased. The goal was then changed to minimize NOx with oxygen clamped to the current levels. As shown, at least for the conditions present for this test, GNOCIS estimated that the other independent control variables (AOFA dampers and mill loadings) would have minimal impact on NOx emissions and therefore no control action was implemented. The final test (162-3) freed up excess oxygen and the control action was taken resulting in a NOx reduction of approximately 10 percent. As with the prior days testing, there was no apparent adverse impact on the stability of the unit.

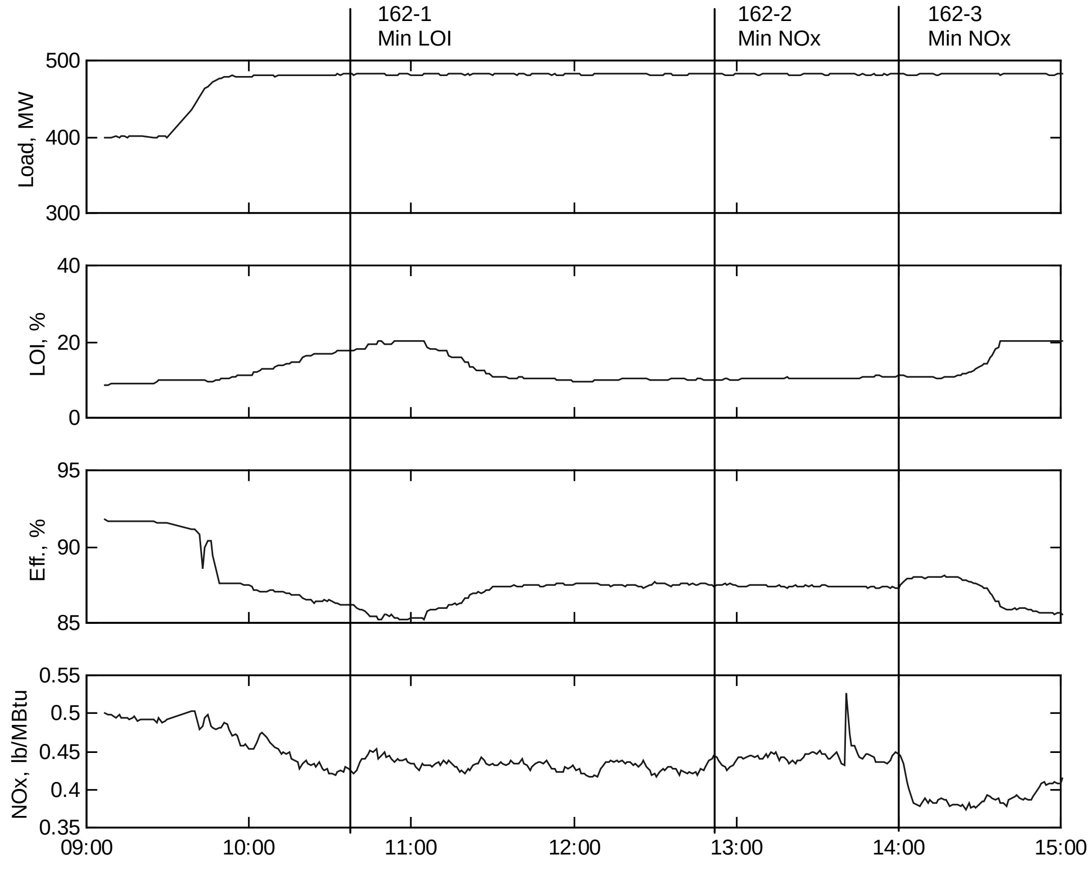
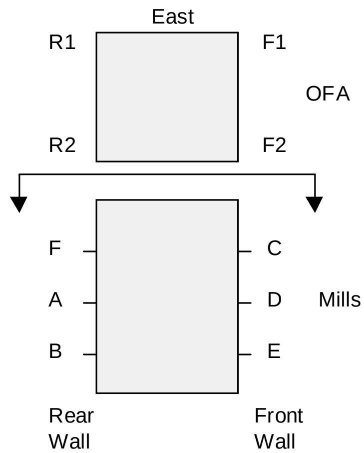


Figure 5-61 GNOCIS / Test 162 / Optimized Variables

Table 5-16 Recommendations for Test 162

Control Variable	Min LOI	Min NOx	Min NOx
Excess Oxygen	⇧	-	⇩
OFA F1	⇩	-	-
OFA F2	⇩	-	-
OFA R1	⇧	-	-
OFA R2	⇧	-	-
Mill A	⇩	-	-
Mill B	⇧	⇩	⇩
Mill C	⇩	-	-
Mill D	⇩	⇧	-
Mill E	⇧	⇩	⇧
Mill F	⇧	⇩	⇧



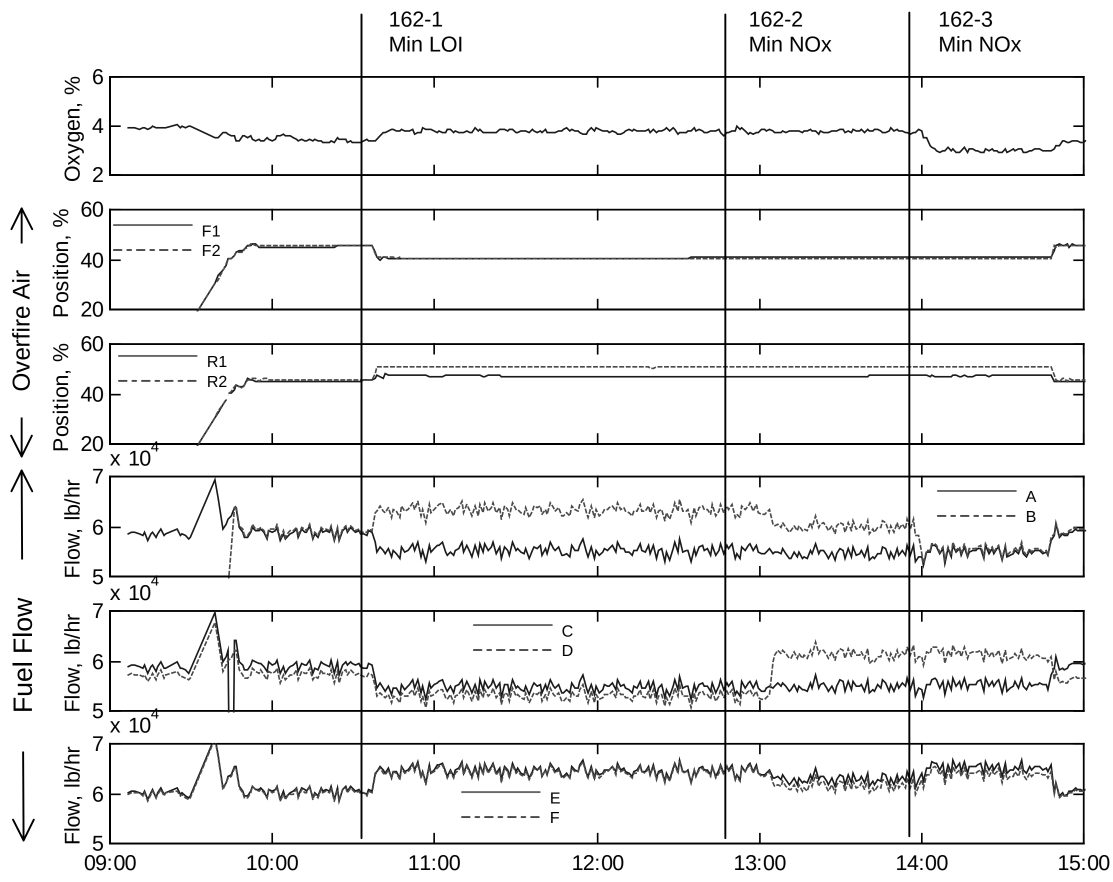


Figure 5-62 GNOCIS / Test 162 / Manipulated Variables

Summary of Findings from Second Quarter 1996 Testing

The following is a summary of the findings from these tests.

- GNOCIS could be run in a closed-loop mode without adversely influencing unit stability, safety, or reliability.
- With reasonable constraint limits, GNOCIS could be expected to achieve NOx reductions approximately 10 to 15% over the load range with a positive impact on boiler efficiency.
- Efficiency improvements of around 0.5 percentage points are achievable within the constraints tested.
- The performance of the online LOI monitors still pose a problem to the implementation of GNOCIS.

5.4.3 GNOCIS Performance Estimate

Based on the actual test data from Hammond and other sites and GNOCIS model studies conducted, estimates can be made as to the impacts of GNOCIS on important unit parameters such as boiler efficiency, NOx emissions, and fly ash LOI. Since GNOCIS can be operated in numerous configurations (minimize NOx, minimize LOI, maximize efficiency, etc.), a decision must be made as to what mode GNOCIS is configured. Also, a decision must be made as to the flexibility GNOCIS is allowed in achieving this goal. With this in mind, the three scenarios considered include: (1) minimize NOx emissions, (2) maximize boiler efficiency, and (3) minimize LOI, all subject to the following constraints on the controllable parameters:

- Fuel change to each mill limited to ±5000 lb/hr of current operating level.
- Excess oxygen change limited to ±0.5% from current operating level over the entire load range.
- OFA damper positions restricted to ±5% from current operating position.
- Total change in fuel to furnace is zero.
- Recommendations given for current mill configuration. Greater benefits may be achieved if the recommendations for mills in service are followed, however, this recommendation is only advisory.

These constraints are in line with those tested at Hammond and other sites.

Using these constraints, the combustion models were run to determine the performance gains that could be expected if the recommendations were followed continuously and over the load range, much as would occur if GNOCIS were operating in closed-loop mode.

Results from these studies are shown in Figure 5-63 through Figure 5-65 in which a comparison of NOx emissions, boiler efficiency, and LOI for the various operating modes are compared. The corresponding recommendations for excess oxygen, mill flows, and overfire air (as biases from baseline) for the various operating modes are shown in Figure 5-66 through Figure 5-72.

As shown, full load NOx emissions were reduced by about 14% and averaged 11% below baseline over the entire load range. The maximum efficiency mode reduced NOx emissions by approximately 12% at full load, however at lower loads (below 340 MW), the recommendations increased NOx emissions so that the average for the entire load range was near zero. As may be expected, the minimize LOI mode produced the highest emissions averaging 6% over baseline. The predictions for NOx reduction are consistent with that observed from plant testing.

Boiler efficiency is shown in Figure 5-64. Efficiency improvements of about 1.0 percentage points are predicted with improvements of around 0.7 percentage points indicated over the load range. Even given the broader range allowed of the recommendations, these values are somewhat though not extremely higher than has been observed at Hammond and other sites.

The LOI characteristic is shown in Figure 5-65. At full load, there was a maximum difference of around 4 percentage points between the LOI in the various operating modes, with the minimize NOx emissions mode having the greatest LOI and the minimize LOI mode having the lowest. At low loads, the differential between the lowest and highest LOI was much less (around 1 percentage point). It is interesting to note that below approximately 370 MW, the model predicts that the three optimum modes (Max Efficiency, Min LOI, and Min NOx) all produce lower LOI than the baseline case (though only slightly for the Min NOx case). This result is somewhat curious in that:

- Given all else being equal, a decrease in excess oxygen is expected to increase LOI.
- The excess recommended oxygen level for the minimize NOx scenario for all load levels is, as expected, lower than the baseline case.

Possible explanations for this counter intuitive result are:

- Other manipulated variables (mill biasing and overfire air damper positions) affected the combustion process sufficiently to offset the excess oxygen effect.
- Combustion model inaccuracies with respect to LOI.

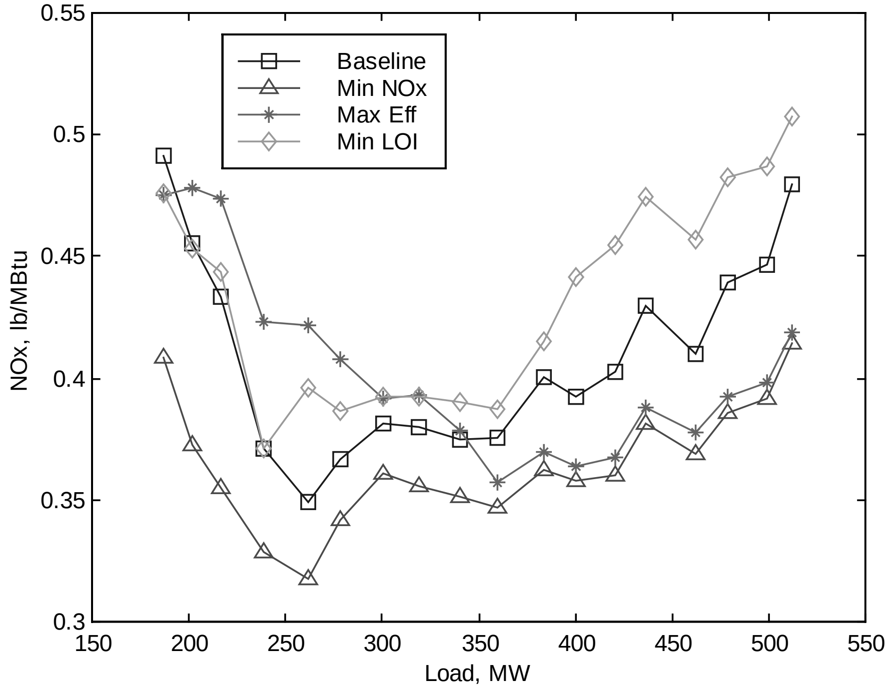


Figure 5-63 GNOCIS / NOx Emissions

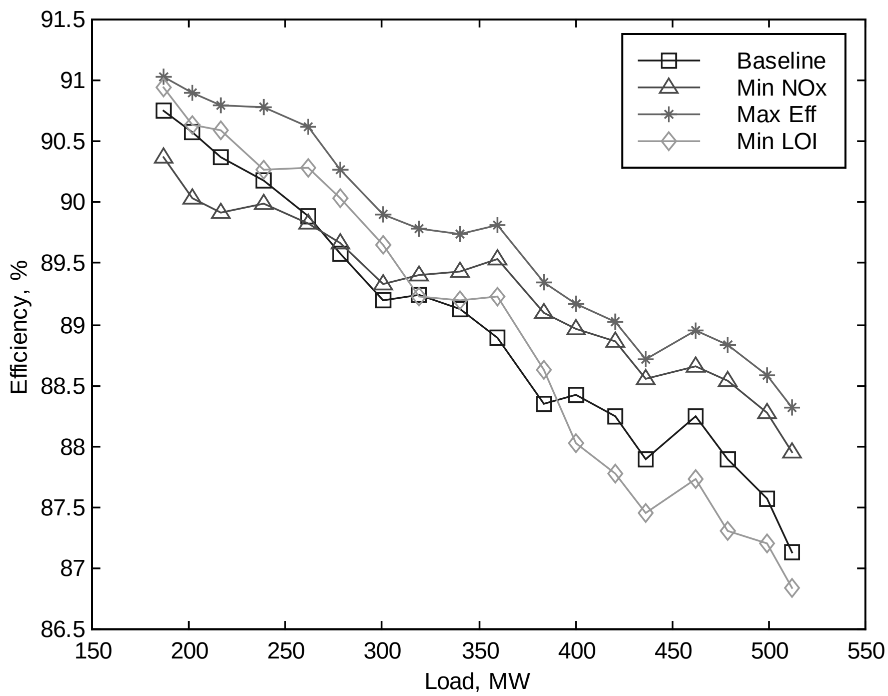


Figure 5-64 GNOCIS / Boiler Efficiency

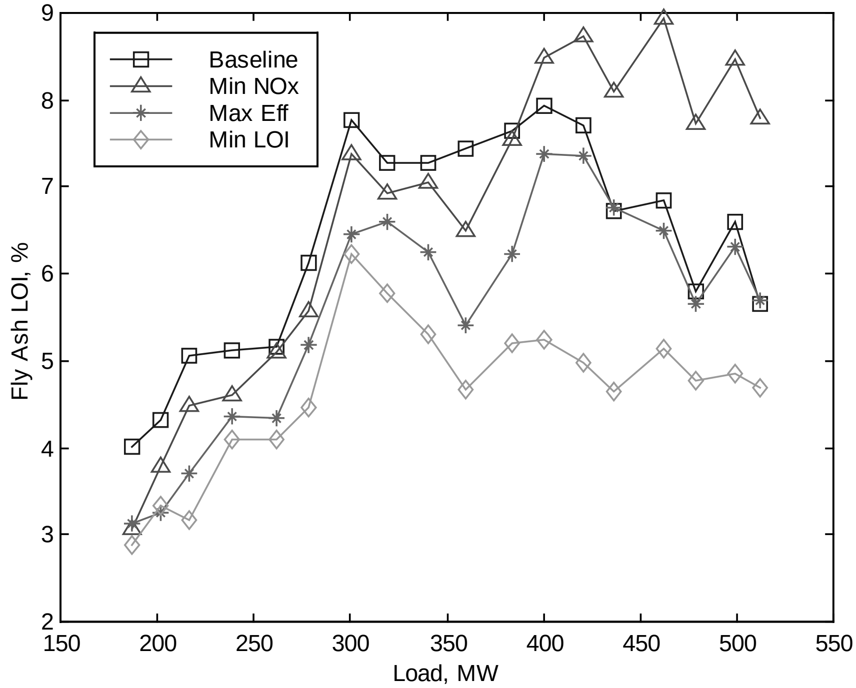


Figure 5-65 GNOCIS / Fly Ash LOI

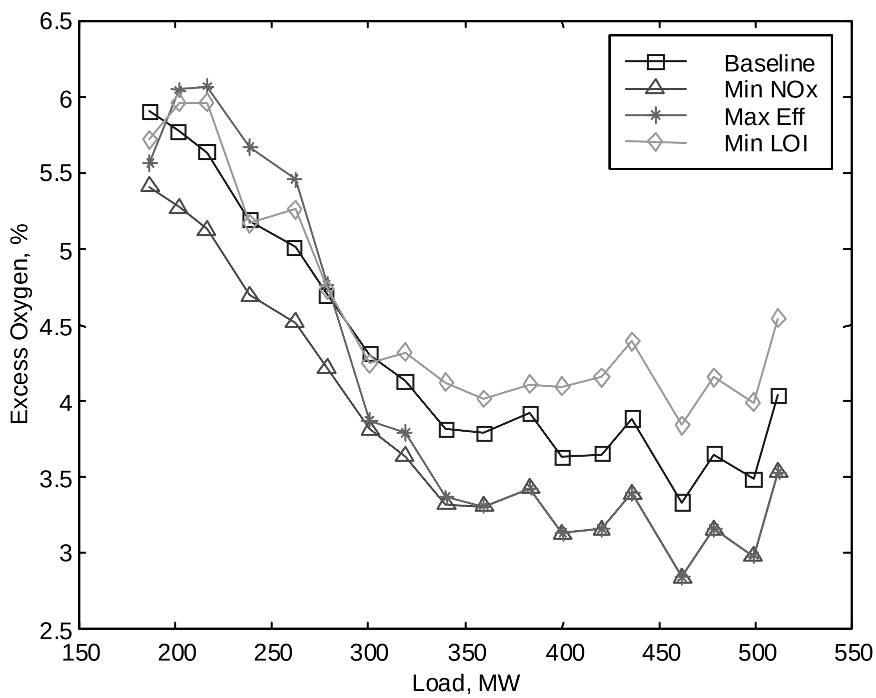


Figure 5-66 GNOCIS / Excess Oxygen

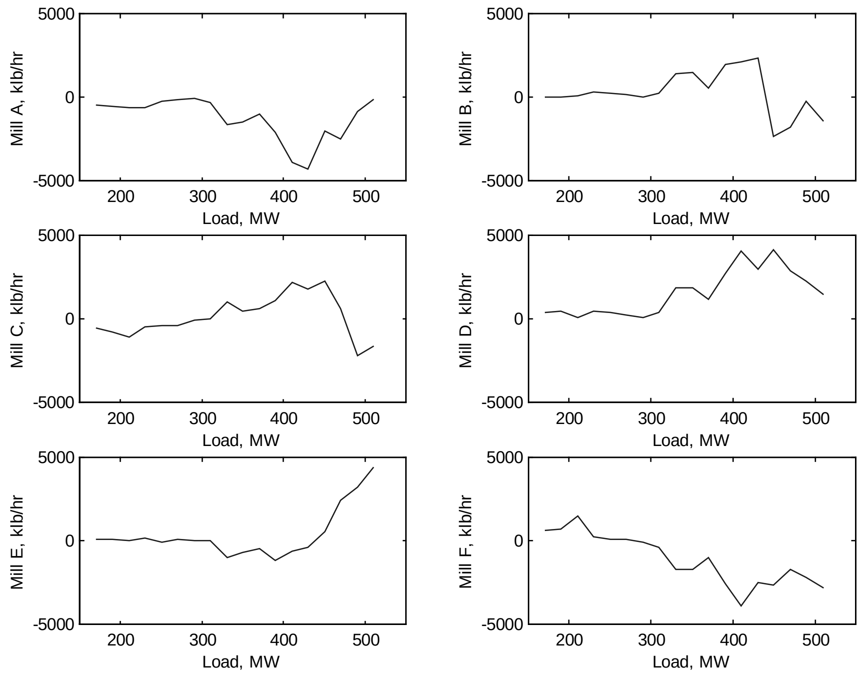


Figure 5-67 GNOCIS / Minimize NOx Emissions / Mill Bias

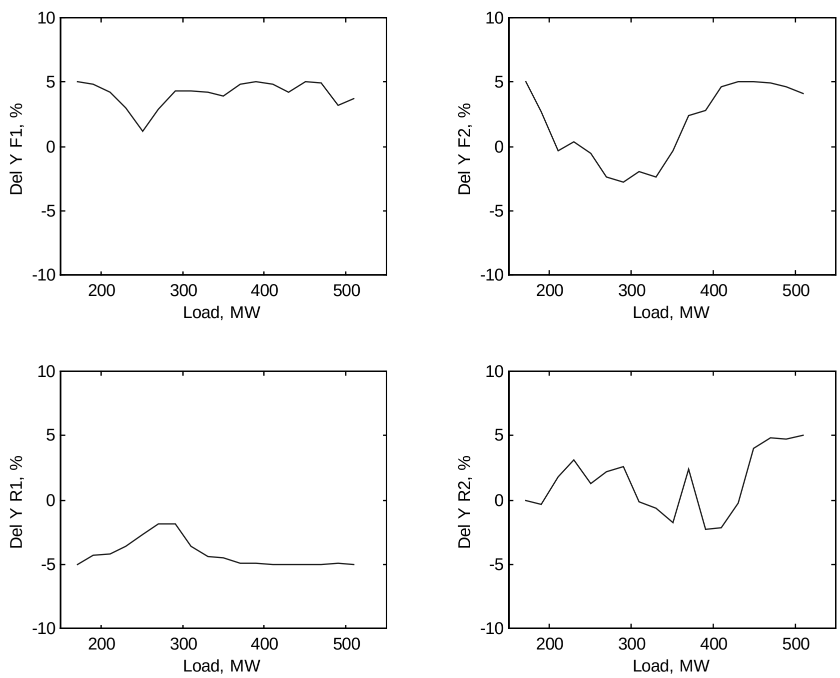


Figure 5-68 GNOCIS / Minimize NOx Emissions / Overfire Air Bias

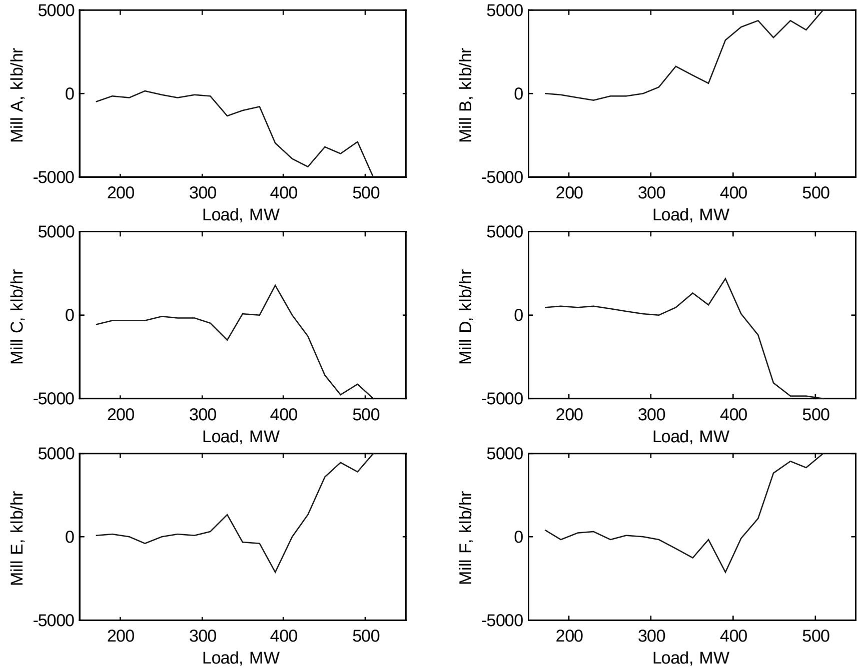


Figure 5-69 GNOCIS / Maximize Efficiency / Mill Bias

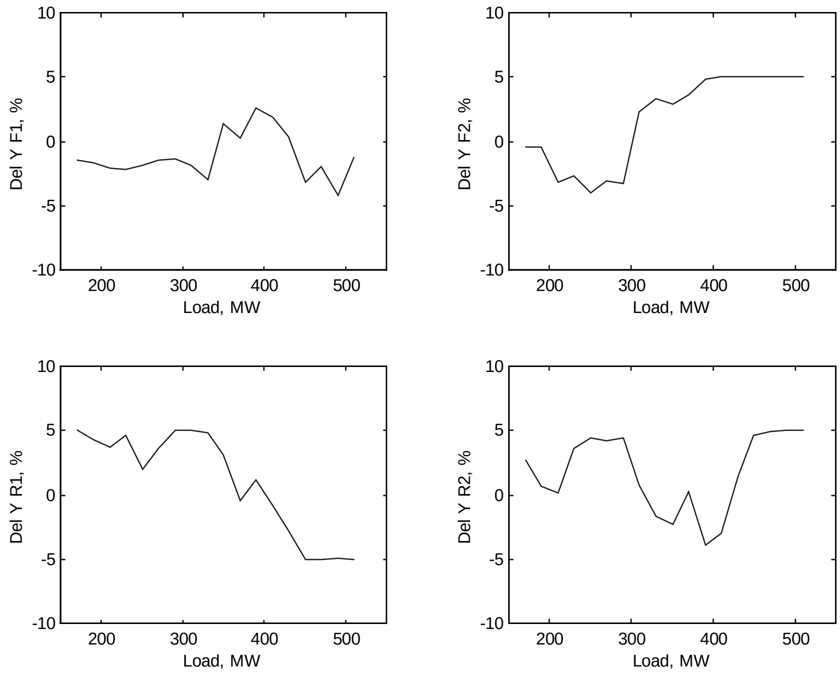


Figure 5-70 GNOCIS / Maximize Efficiency / Overfire Air Bias

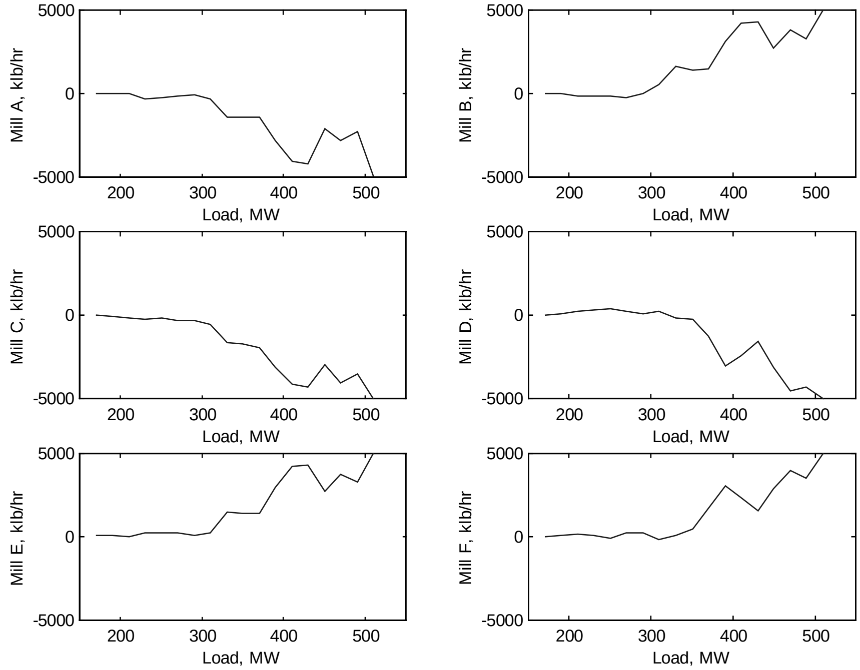


Figure 5-71 GNOCIS / Minimize LOI / Mill Bias

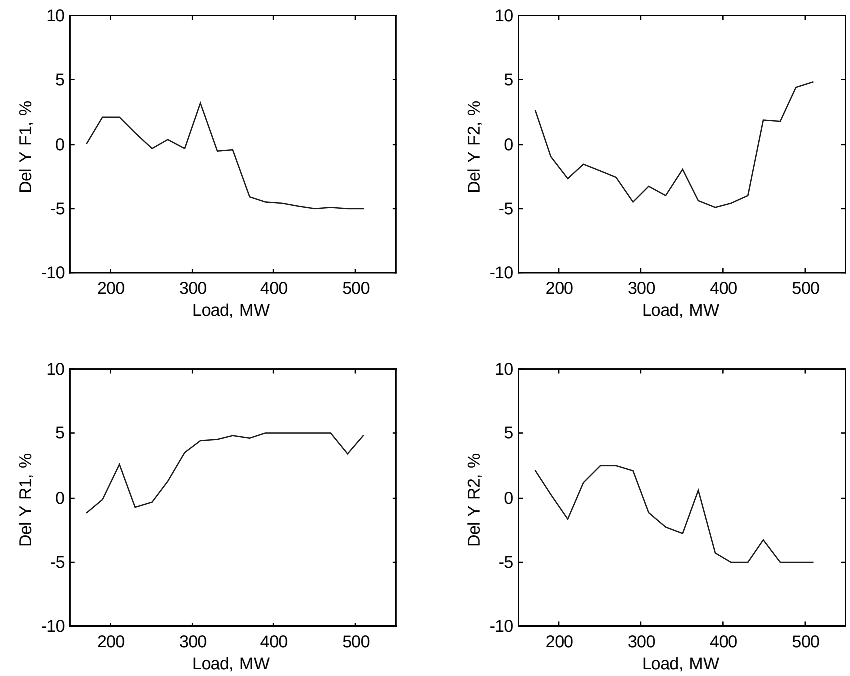


Figure 5-72 GNOCIS / Minimize LOI / Overfire Air Bias

6 ECONOMIC EVALUATION

The economic impacts of the combustion techniques for NOx reduction consist of capital costs for the retrofits, lost revenue as a result of unit outages, and changes in operating and maintenance costs, both fuel and non-fuel related. For the purposes of this report, it is assumed that the non-fuel related costs and the lost revenue due to the outages are similar for the considered NOx reduction technologies. Therefore, the main economic impacts are attributed to the capital costs and fuel related (heat rate related) O&M costs.

The average cost effectiveness of each NOx reduction technology (expressed in $/ton of NOx removed) is estimated in this section by taking into account the capital cost, O&M impacts, and the NOx emission reduction on an annual basis.

6.1 Estimated Capital Costs

Although the demonstration nature of the Hammond retrofit had an impact on the total project costs, the capital costs are within the expected range for wall-fired installations (6 - 15 $/kW for the LNB and 10 - 20 $/kW for the LNB + AOFA).[1] For the purposes of this report, the following estimates of the actual Hammond capital costs were developed excluding the demonstration related cost adders (e.g., testing, data analysis, and reporting). However, the estimates do include a certain amount of cost sharing by project participants:

AOFA	$3.8 million or 7.6 $/kW
LNB	$4.5 million or 9.0 $/kW
LNB+AOFA	$8.3 million or 16.6 $/kW
GNOCIS	$250 thousand or 0.5 $/kW

For a 500 MW wall-fired commercial installation, with a scope of supply similar to the Hammond retrofit, it is anticipated that the following estimated costs could be utilized for planning purposes:

AOFA	$4.4 million or 8.8 $/kW
LNB	$5.0 million or 10.0 $/kW
LNB+AOFA	$9.4 million or 18.8 $/kW
GNOCIS	$250 thousand or 0.5 $/kW

These estimates are based upon the actual Hammond Unit 4 costs and other available cost data from EPRI and additional sources.

Specifics of the costing of AOFA, LNB, and LNB+AOFA technologies can be found in the final report of the project [SCS, 1998]. For GNOCIS, the following assumptions have been made:

[1] All costs are in 1995 dollars.

- The DCS was excluded from the cost of a GNOCIS project. The cost of a DCS is very unit specific and is an order of magnitude higher than the cost of the optimization software itself, varying from $2 to $8 million.

- DCS configuration modifications that are required to incorporate GNOCIS into the DCS are included.

- Additional instrumentation (such as on-line carbon-in-ash monitors) not strictly necessary for GNOCIS operation are excluded. On-line carbon-in-ash monitor pricing ranges from $50,000 to $100,000.

6.2 Cost Effectiveness at Full-Load

The annual O&M cost and NOx reductions for the installed technologies relative to baseline depend to a large degree on the load profile of the unit. However as a first step, it is informative to perform the analysis for full-load conditions. The annual fuel related O&M cost changes relative to baseline were estimated based on the changes of the unit net heat rate and the following assumptions:

- Base loaded unit (i.e., full-load operation)

- 65 percent capacity factor; and

- $1.2 per MBtu coal cost.

The capital and O&M cost impacts, along with the annual NOx emission reduction (based on long-term, full-load operation), were used for estimating the average cost-effectiveness of the low NOx technologies tested at Hammond Unit 4.

For GNOCIS, three scenarios were considered. In the first, the objective was to minimize NOx emissions without explicit consideration of boiler efficiency or LOI. In the second, the objective was to maximize boiler efficiency without consideration of NOx emissions and LOI. For the third, the objective was set to minimize LOI without consideration for NOx emissions and boiler efficiency. For these scenarios, the allowable ranges on the manipulated variables were set to that which were shown to be feasible by testing at Hammond.

Given the assumptions above and performance and cost of GNOCIS as described in Section 5 and shown in Table 6-1, the projected annual O & M costs of GNOCIS operated in the various modes ranged from approximately $231,000 (Min LOI) to -$340,000 (Max Efficiency). The NOx removal cost effectiveness ranged from -$299 (Min NOx) to -$463 (Max Efficiency) per ton of NOx removed. The NOx removal cost effectiveness in the minimize LOI mode is not shown since operating in this mode would produce a NOx emissions increase. When the assumption is made that there would be no efficiency improvements when operating in the maximize efficiency mode, the cost effectiveness of the technology would be approximately $29 per ton NOx removed (Table 6-2). Also shown in this table is the cost effectiveness of GNOCIS when it is operated in the maximize efficiency mode with the assumption of ½ the performance gain shown in Table 6-1 (0.45 vs. 0.9). In the last column of Table 6-2, the effectiveness is shown when the cost of the DCS is included in the capital cost. For comparison, corresponding numbers for the other technologies tested at Hammond are shown in Table 6-3.

Table 6-1 NOx Reduction Cost Effectiveness of GNOCIS

	Baseline	Min NOx	Max Eff	Min LOI
O&M				
Boiler Efficiency	87.9	88.5	88.8	87.3
Efficiency Change	Base	0.6	0.9	-0.6
Turbine Heat Rate - Btu/kWh	9,000	9,000	9,000	9,000
Unit Net Heat Rate - Btu/kWh	10,239	10,169	10,135	10,309
% NHR Change	Base	-0.68	-1.01	0.69
Annual O & M	Base	-$228,058	-$340,931	$231,192
Cost Effectiveness				
NOx Full Load	0.44	0.39	0.39	0.48
% NOx Reduction	Base	11	11	-9
Annual NOx Reduction - Tons/yr	Base	696	694	(564)
Capital Costs - $ millions	Base	0.25	0.25	0.25
Cost Effectiveness - $/ton removed	Base	-$299	-$463	n/a

n/a – There was a net NOx emission increase for this mode.

Table 6-2 NOx Reduction Cost Effectiveness of GNOCIS

	Baseline	Min NOx (1)	Max Eff (2)	Min NOx (3)
O&M				
Boiler Efficiency	87.9	87.9	88.45	88.5
Efficiency Change	Base	0	0.55	0.6
Turbine Heat Rate - Btu/kWh	9,000	9,000	9,000	9,000
Unit Net Heat Rate - Btu/kWh	10,239	10,239	10,175	10,169
% NHR Change	Base	0.00	-0.62	-0.68
Annual O & M	Base	$0	-$209,171	-$228,058
Cost Effectiveness				
NOx Full Load	0.44	0.39	0.39	0.39
% NOx Reduction	Base	11	11	11
Annual NOx Reduction - Tons/yr	Base	701	696	696
Capital Costs - $ millions	Base	0.25	0.25	3.6
Cost Effectiveness - $/ton removed	Base	$29	-$272	$86

(1) Assume no heat rate improvement.
(2) Assume 1/2 efficiency improvement as base case.
(3) Include DCS cost in cost of technology.

Table 6-3 NOx Reduction Cost Effectiveness of Low NOx Technologies

	Baseline	Baseline -> AOFA	Baseline -> LNB	Baseline -> LNB+AOFA	LNB -> LNB+AOFA	LNB (Adj.) -> LNB+AOFA
O&M						
Boiler Efficiency	90	89.2	89.3	88.7	88.7	88.7
Efficiency Change	Base	-0.8	-0.7	-1.3	-0.6	-0.6
Turbine Heat Rate - Btu/kWh	9,000	8,999	8,975	8,960	8,960	8,960
Unit Net Heat Rate - Btu/kWh	10,000	10,089	10,050	10,101	10,101	10,101
% NHR Change	Base	0.89	0.50	1.01	0.51	-0.51
Annual O & M	Base	$290,968	$165,556	$333,351	$167,795	$167,795
Cost Effectiveness						
NOx Full Load	1.24	0.94	0.65	0.4	0.4	0.4
% NOx Reduction	Base	24	48	68	38	22
Annual NOx Reduction - Tons/yr	Base	4,143	8,117	11,615	3,457	1,521
Capital Costs - $ millions	Base	3.8	4.5	8.3	3.8	3.8
Cost Effectiveness - $/ton removed	Base	$144	$65	$86	$136	$310

Levelization factor of 0.08 assumed.

6.3 Load Profile Impact on Cost Effectiveness

The previous analysis was based on NOx and heat rate performance at full load. Because both of these operating parameters are potentially dependent on load, it is important to consider the effect of load profiles on the cost effectiveness of the technologies. Four load scenarios, shown in Figure 6-1 were considered for this analysis. The *Phase 1* scenario was the actual load profile for Phase 1 test phase. The *base load*, *peaking*, *cycling*, and *flat* profiles are hypothetical load profiles. As shown in Table 6-4, for the Phase 1 load profile, NOx emission reductions of 11, 0, and –9% were obtained for Min NOx, Max Efficiency, and Min LOI operating modes, respectively. Similarly, for the base load profile, reductions of 12, 7, and –9% were obtained. For the peaking load profile, the Max Efficiency mode produced a net increase in NOx emissions. This is in part due to the recommendation for excess oxygen in this mode being greater than the baseline case for higher loads and less than the baseline case for lower loads. Also, it is interesting to note that although there was a 0% decrease in NOx emissions for the Flat Load / Max Efficiency combination, there was a net emissions reduction because of unit heat rate improvements.

The load average impact on heat rate is shown in Table 6-5. As shown, the Min NOx and Max Efficiency improved heat rate for all load scenarios except one (Peaking / Min NOx). However, the Min LOI mode increased heat rate for all except the Peaking load scenario. The fuel cost implications are shown in Table 6-6. For the Min NOx and Max Efficiency modes, there was actually a net fuel savings (except for the Peaking / Min NOx combination), therefore the cost effectiveness is negative, indicating net savings to the site. Also, for the profile/mode combinations where NOx emissions increased, the cost is not shown since the combination is not at all effective in removing NOx.

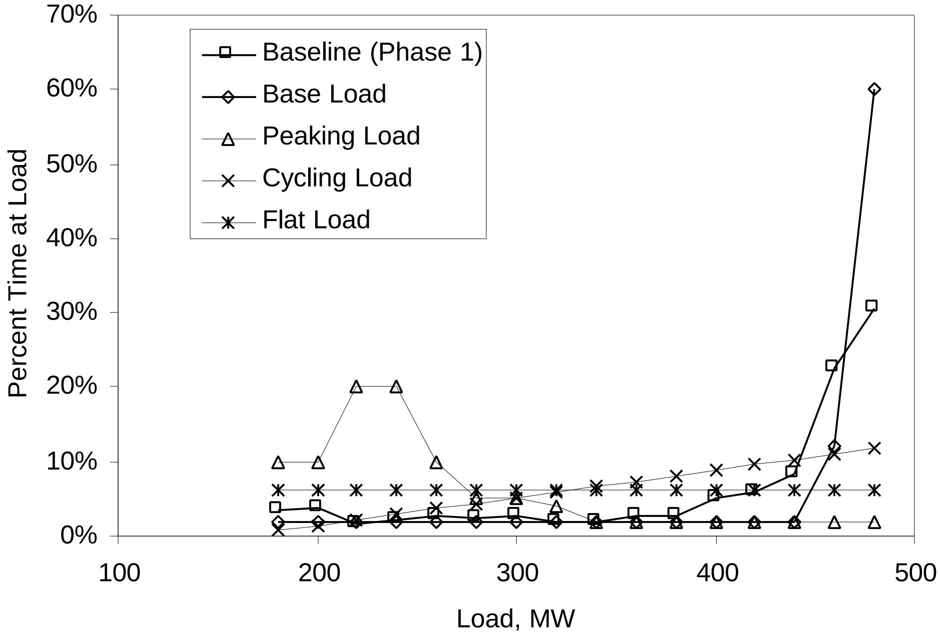


Figure 6-1 Load Profiles

Table 6-4 NOx and NOx Reduction vs. Load Profile and Operating Mode

	Operating Mode			
Load Profile	Baseline	Min NOx	Max Eff	Min LOI
Phase 1 (lb/Mbtu)	0.42	0.37	0.39	0.45
percent reduction	--	11%	6%	-9%
tons reduced/year	--	834	544	-717
Base Load (lb/Mbtu)	0.43	0.38	0.39	0.46
percent reduction	--	12%	7%	-9%
tons reduced/year	--	942	680	-766
Peaking Load (lb/Mbtu)	0.41	0.35	0.43	0.42
percent reduction	--	13%	-6%	-3%
tons reduced/year	--	572	-226	-192
Cycling Load (lb/Mbtu)	0.40	0.36	0.39	0.43
percent reduction	--	10%	4%	-8%
tons reduced/year	--	671	346	-576
Flat Load (lb/Mbtu)	0.40	0.36	0.40	0.43
percent reduction	--	11%	0%	-6%
tons reduced/year	--	604	110	-397

Table 6-5 Average Heat Rate Deviation vs. Load Profile and Operating Mode

		Operating Mode		
Load Profile	Baseline	Min NOx	Max Eff	Min LOI
Phase 1	--	-47	-78	38
Base Load	--	-56	-88	47
Peaking Load	--	1	-37	-6
Cycling Load	--	-43	-71	18
Flat Load	--	-25	-56	5

Table 6-6 Fuel Cost Deviation vs. Load Profile and Operating Mode

		Operating Mode		
Load Profile	Baseline	Min NOx	Max Eff	Min LOI
Phase 1	--	-$237,610	-$391,804	$190,685
Base Load	--	-$280,727	-$446,273	$237,479
Peaking Load	--	$4,483	-$187,014	-$28,909
Cycling Load	--	-$216,281	-$356,717	$90,939
Flat Load	--	-$127,076	-$283,833	$26,589

Positive number is an expenditure.
Negative number is a savings.

Table 6-7 NOx Reduction Cost Effectiveness vs. Load Profile and Operating Mode

		Operating Mode		
Load Profile	Baseline	Min NOx	Max Eff	Min LOI
Phase 1	--	-$261	-$684	n/a
Base Load	--	-$277	-$627	n/a
Peaking Load	--	$43	n/a	n/a
Cycling Load	--	-$293	-$975	n/a
Flat Load	--	-$177	-$2,403	n/a

n/a – There was a net NOx emission increase for these load/mode combinations.

7 SUMMARY AND CONCLUSIONS

The primary objective of the demonstration at Hammond Unit 4 was to determine the long-term effects of commercially available wall-fired low NOx combustion technologies on NOx emissions and boiler performance. Short-term tests of each technology were also performed to provide engineering information about emissions and performance trends. A target of achieving fifty percent NOx reduction using combustion modifications was established for the project.

Specifically, the original objectives of the project were:

- Demonstrate in a logical stepwise fashion the short-term NOx reduction capabilities of the following advanced low NOx combustion technologies:

  ◊ FWEC's Advanced Overfire Air (AOFA)

  ◊ FWEC's Controlled Flow / Split Flame Low NOx burners (LNB)

  ◊ LNB with AOFA

- Determine the dynamic, long-term emissions characteristics of each of these combustion NOx reduction methods using statistical techniques.

- Evaluate the progressive cost effectiveness (i.e., dollars per ton NOx removed) of the low NOx combustion techniques tested.

- Determine the effects on other combustion parameters (e.g., CO production, carbon carryover, particulate characteristics) of applying the NOx reduction methods listed above.

Based on observations during the first three phases of the project, Phase 4 of the project was conceived and added to the scope of the project -- the installation and demonstration of a digital control system and advanced on-line optimization system. For the optimization effort, the principal effort was placed on the application of GNOCIS (Generic NOx Control Intelligent System).

GNOCIS is an enhancement to digital control systems (DCS) targeted at improving utility boiler efficiency and reducing emissions. GNOCIS is designed to operate on units burning gas, oil, or coal and is available for all combustion firing geometries. GNOCIS utilizes a neural-network model of the combustion characteristics of the boiler that reflects both short-term and longer-term trends in boiler characteristics. A constrained-nonlinear optimizing procedure is applied to identify the best set points for the plant. These recommended set points can be implemented automatically without operator intervention (closed-loop), or, at the plant's discretion, conveyed to the plant operators for implementation (open-loop). The software is designed for continuous on-line use. GNOCIS development was funded by a consortium consisting of the Electric Power Research Institute, PowerGen, Southern Company, Radian International, U.K. Department of Trade and Industry, and U.S. Department of Energy.

Based on competitive bidding, a Foxboro I/A DCS was selected for installation at Hammond replacing the pneumatic control system. The DCS was installed at Hammond during a nine-month outage starting in September 1993 and continuing to June 1994. Since there had been major modifications to the unit during the outage (precipitator replacement, mill replacements, turbine upgrades), testing was conducted on the unit following this outage to reevaluate the performance of the unit in particular to regards to NOx emissions. This test was conducted over an extended period lasting from third quarter 1994 and continuing to first quarter 1996. The major findings were:

- NOx emissions did not change significantly from that observed during Phase 3B.
- LOI levels were similar to that observed during Phase 3B despite the installation of two new mills and a resultant improvement in coal fineness.
- Excess oxygen levels decreased slightly from that observed during Phase 3B.
- Air heater gas outlet temperatures were slightly improved over that observed during Phase 3B.
- There was a degradation in steam temperatures (main and reheat) when compared to Phase 3B.
- Dispatch speed of the unit improved dramatically following the installation of the DCS.
- Boiler/unit stability was much improved over that which had been observed during Phases 1-3B.
- The ability to gather data from the DCS greatly facilitated testing and data analysis.

Although the DCS provided many benefits, overall, it appears that the DCS did not improve the heat rate of the unit.

The second part of Phase 4 of the project was the installation and demonstration of GNOCIS. Prior to this, other work related to the optimization scope of work consisted of the demonstration of Ultramax (at the time, an off-line optimization tool) and modeling studies. Both of these efforts provided additional evidence that optimization was a viable tool for NOx emission abatement and heat rate improvement.

GNOCIS was under development at Alabama Power's Gaston Unit 4 and PowerGen's Kingsnorth Unit 1 from 1994 through 1996 (PowerGen, 1997). Results from these sites further indicated that specifically GNOCIS could provide useful recommendations for unit performance improvement.

Following the work at these two sites, GNOCIS was installed and became fully operational at Hammond during first quarter 1996. At Hammond, GNOCIS was designed to operate in either open-loop (advisory) or closed-loop (supervisory) modes, although more emphasis was placed on the latter. During first quarter and second quarter 1996, short-term testing on the unit was conducted. The results from this testing were similar to that observed at the other GNOCIS sites with NOx reductions of around 10 to 15% and efficiency improvements of about 0.5%. Additional GNOCIS testing at this site was hoped for including additional short-term and long-term testing. However, due in part to the relative unavailability of the unit for testing, this testing never materialized. Although testing was not as extensive as first hoped, numerous GNOCIS tests have been conducted at Hammond and other sites and it is felt that the results obtained at Hammond are representative of the true performance of the technology. With this in consideration and using the available short-term results, model studies further predict that GNOCIS could, at least for this unit, simultaneously reduce NOx emissions and improve unit heat rate.

The major conclusions from this part of the project are:

- GNOCIS has been successfully deployed at Hammond 4.
- GNOCIS provides advice that, if implemented, improves boiler performance, including NOx emissions and efficiency. NOx emissions reductions of around 10% with improvement in heat rate can be obtained.
- GNOCIS is flexible in that the goals can be modified by plant staff with immediate results. As a result of this flexibility, a utility can dynamically assign goals to a unit in designing a NOx emissions plan (i.e. minimize NOx emissions during the summer months).
- GNOCIS does not adversely impact unit dynamics in either open- or closed-loop mode. The unit can be dispatched at full speed with GNOCIS in closed-loop mode. Also, recommendations do not appear to "wander" at steady-state operation.
- GNOCIS is very cost effective as a NOx reduction strategy.
- The on-line carbon-in-ash monitors used as part of the test program have been both beneficial and detrimental. When working properly, the instruments provide important process information that is not available otherwise. However, the monitors, in general, require maintenance greatly above that of normal instrumentation and reliabilities have been much less than desired. This unreliability impacted the test program at times.

Based on GNOCIS testing at this site and others, at plant management's request, GNOCIS is being incorporated into the unit's standard operating procedures. Also, consideration is being given to applying GNOCIS to other plant processes.

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APPENDIX A
DCS CHARACTERIZATION

Table A-1 Diagnostic Test Summary

TEST NO.	DATE	TEST CONDITIONS	LOAD MW	MOOS PATRN	OFA FLOW KPPH	Econ. O2 DRY (%)	Econ. CO DRY (%)	NOx lb/MBtu
129-1	08/05/94	HI-LOAD NORMAL O2	486	AMIS	NA	3.0	38	0.454
129-2	08/05/94	HI-LOAD LOW O2	483	AMIS	NA	2.7	177	0.399
129-3	08/05/94	HI-LOAD HIGH O2	483	AMIS	NA	3.9	7	0.533
130-1	08/06/94	MID-LOAD LOW O2	398	B		2.8	128	0.368
130-2	08/06/94	MID-LOAD NORM O2	400	B	297	3.6	7	0.442
130-3	08/06/94	MID-LOAD HIGH O2	398	B	318	4.7	7	0.513
130-4	08/06/94	MID-LOAD NORM O2, DECR OFA	399	B	211	4.0	6	0.457
130-5	08/06/94	MID-LOAD NORM O2	399	E	294	3.7	6	0.451
131-1	08/07/94	MD/LO LOAD LOW O2	300	B,E	119	4.4	20	0.363
131-2	08/07/94	MD/LO LOAD NORM O2	300	B,E	134	4.8	13	0.386
131-3	08/07/94	MD/LO LOAD HIGH O2	302	B,E	143	5.5	10	0.421
131-4	08/07/94	MD/LO LOAD HIGHER O2	301	B,E	133	6.4	8	0.462
132-1	08/08/94	HI-LOAD LOW O2	482	AMIS	650	2.9	118	0.440
132-2	08/08/94	HI-LOAD NORM O2	484	AMIS	658	3.5	16	0.498
132-3	08/08/94	HI-LOAD HIGH O2	479	AMIS	666	4.1	15	0.556
132-4	08/08/94	HI-LOAD FUEL BIASED TO UPPER MILLS	476	AMIS	613	4.1	16	0.573
132-5	08/08/94	HI-LOAD FUEL BIASED TO UPPER MILLS	479	AMIS	596	3.4	18	0.500
133-1	11/02/94	MID-LOAD NORMAL O2	401	B	278	4.0	11	0.414
133-2	11/02/94	MID-LOAD HIGH O2	401	B	276	4.8	7	0.470
133-3	11/02/94	MID-LOAD NORMAL O2	400	B	284	3.6	21	0.390
133-4	11/02/94	MID-LOAD LOW O2	401	B	278	2.8	91	0.353
133-5	11/02/94	MID-LOAD LOW O2	400	E	289	3.2	168	0.346
133-6	11/02/94	MID-LOAD NORMAL O2	401	E	306	4.2	4	0.382
134-1	11/03/94	MID-LOAD NORMAL O2 BAL MILLS	400	B	285	3.6	18	0.404
134-2	11/03/94	MID-LOAD FUEL BIASED TO LOWER MILLS	400	B	287	3.5	30	0.398
134-3	11/03/94	MID-LOAD FUEL BIASED TO UPPER MILLS	400	B	276	3.7	15	0.389
134-4	11/03/94	MID-LOAD NORMAL O2 BAL MILLS	400	B	276	3.5	24	0.382
135-1	11/09/94	HIGH LOAD, AMIS, NOMINAL O2	481	AMIS	606	3.4	28	0.390
135-2	11/09/94	HIGH LOAD, AMIS, LOW O2	482	AMIS	653	2.9	315	0.352
135-3	11/09/94	HIGH LOAD, AMIS, HIGH O2	479	AMIS	675	3.9	14	0.426
136-1	11/10/94	HIGH LOAD, NOM O2, BALANCED MILLS	478	AMIS	582	4.0	14	0.449
136-2	11/10/94	HIGH LOAD, NOM O2, COAL BIASED HIGH	478	AMIS	595	4.1	17	0.448
136-3	11/10/94	HIGH LOAD, NOM O2, COAL BIASED LOW	479	AMIS	597	4.0	13	0.448
136-4	11/10/94	HIGH LOAD, NOM O2, BALANCED MILLS	480	AMIS	606	4.1	15	0.449
137-1	11/11/94	HIGH LOAD, NOM O2, BAL MILLS, NOM OFA	478	AMIS	636	3.9	18	0.432
137-2	11/11/94	HIGH LOAD, NOM O2, BAL MILLS, HIGH OFA	481	AMIS	872	4.1	56	0.413
137-3	11/11/94	HIGH LOAD, NOM O2, BAL MILLS, MID OFA	480	AMIS	515	3.8	15	0.438
137-4	11/11/94	HIGH LOAD, NOM O2, BAL MILLS, LOW OFA	480	AMIS	268	4.1	8	0.506
143-1	11/17/94	MAX LOAD, HIGH O2, BAL MILLS, NOM OFA	519	AMIS	780	4.0	12	0.503
143-2	11/17/94	MAX LOAD, NOM O2, BAL MILLS, NOM OFA	520	AMIS	774	3.3	31	0.445
143-3	11/17/94	MAX LOAD, LOW O2, BAL MILLS, NOM OFA	521	AMIS	747	3.0	169	0.408
143-4	11/17/94	HIGH LOAD, NOM O2, BAL MILLS, HIGH OFA	480	AMIS	823	3.8	46	0.412
143-5	11/17/94	HIGH LOAD, NOM O2, BAL MILLS, MID OFA	479	AMIS	490	3.7	12	0.453
143-6	11/17/94	HIGH LOAD, NOM O2, BAL MILLS, MIN OFA	479	AMIS	280	3.7	13	0.489
144-1	11/18/94	LOW LOAD, HIGH O2, BAL MILLS, NOM OFA	300	B,E	117	6.7	9	0.451
144-2	11/18/94	LOW LOAD, NOM O2, BAL MILLS, NOM OFA	301	B,E	126	6.0	27	0.407
144-3	11/18/94	LOW LOAD, LOW 2, BAL MILLS, NOM OFA	301	B,E	100	5.0	200	0.352
144-4	11/18/94	MID LOAD, HIGH O2, BAL MILLS, NOM OFA	399	E	306	4.7	17	0.445
144-5	11/18/94	MID LOAD, LOW O2, BAL MILLS, NOM OFA	400	E	266	3.5	110	0.372
144-6	11/18/94	MID LOAD, NOM O2, BAL MILLS, NOM OFA	399	E	307	3.9	40	0.400
144-7	11/18/94	MID LOAD, NOM O2, BAL MILLS, HIGH OFA	399	E	492	4.0	31	0.371

Table A-2 Performance Tests Summary

Test	Date	Load MW	MOOS Pattern	OFA Flow (KPPH)	DAS O_2 Dry %	NOx lb/MBtu	CO ppm	Fly Ash LOI %	Fly Ash Carbon %
138	11/12/94	400	B	293	3.9	0.38	49	8.4	7.7
139	11/13/94	300	B,E	90	4.8	0.34	51	8.1	7.1
140	11/13/94	180	B,D,E	0	5.3	0.33	9	3.6	3.3
141	11/15/94	520	None	791	3.6	0.43	61	8.2	7.2
142	11/16/94	520	None	786	3.5	0.45	46	8.1	6.9

Table A-3 Performance Tests / Combustion Air Flow Distribution

Test Number →		138	139	140	141	142
Unit Load (MW) →		400	300	180	520	520
Pulverizer Primary Air	Total Flow	734,888	556,118	383,764	902,090	899,812
	% of TUA	21.60%	19.62%	19.88%	19.61%	19.98%
Pulverizer Seal Air	Total Flow	72,734	Na	Na	47,990	49,208
(Difference between dirty and P.A. airflow)	% of TUA	2.14%	Na	Na	1.04%	1.09%
Secondary Air @ Venturi(s)*	Total Flow	2,595,371	2,073,794	1,169,547	3,648,928	3,553,601
(Combined secondary air to burners & OFA)	% of TUA	76.27%	73.17%	60.58%	79.34%	78.92%
Overfire Air *	Total Flow	220,179	139,312	Na	569,025	561,753
	% of TUA	6.47%	4.92%	Na	12.37%	12.48%
Secondary Air to Burners	Total Flow	2,375,192	1,934,482	Na	3,079,903	2,991,848
(by inference)	% of TUA	69.80%	68.25%	Na	66.97%	66.45%
Air to Off-line Mills	Total Flow	Na	204,432	377,199	0	0
	% of TUA	Na	7.21%	19.54%	0.00%	0.00%
Total Unit Air (TUA)	Total Flow	3,402,993	2,834,344	1,930,510	4,599,008	4,502,621

Note: * Air flow value represents average of individual runs

Table A-4 Performance Tests / Overfire Air Flow

	Left Front			Left Rear			Right Front			Right Rear			Total		
Test	Mea.	Ind.	Err.	Mea.	Ind.	Err.	Mea.	Ind.	Err.	Mea.	Ind.	Err.	Mea.	Ind.	Err.
136-4	143.3	Na		127.4	Na		125.5	Na		119.1	Na		515.4		
137-1	138.6	164.6	-19%	126.9	159.3	-25%	142.3	161.6	-14%	129.3	153.4	-19%	537.1	639.0	-19%
137-2	160.5	165.6	-3%	142.4	136.0	5%	156.5	165.2	-6%	157.4	150.7	4%	616.9	617.4	0%
137-3	90.6	125.6	-39%	100.7	122.2	-21%	110.1	134.0	-22%	113.6	138.2	-22%	415.1	519.9	-25%
137-4	62.9	70.2	-12%	65.5	76.6	-17%	62.2	69.4	-11%	55.2	77.6	-40%	245.9	293.8	-19%
138-1	64.7	76.8	-19%	58.7	78.6	-34%	52.4	73.7	-40%	46.5	68.2	-47%	222.3	297.2	-34%
138-2	64.9	76.8	-18%	59.5	78.6	-32%	51.1	73.7	-44%	43.5	68.2	-57%	219.0	297.2	-36%
138-3	65.2	76.8	-18%	58.0	78.6	-36%	51.4	73.7	-43%	44.7	68.2	-53%	219.2	297.2	-36%
139-2	51.0	20.3	60%	55.9	9.8	83%	25.0	53.9	-116%	16.2	-0.3	102%	148.1	83.7	43%
139-3	28.0	20.3	27%	23.3	9.8	58%	41.3	53.9	-31%	38.0	-0.3	101%	130.5	83.7	36%
141-1	151.9	199.0	-31%	142.6	230.0	-61%	132.3	176.9	-34%	135.8	181.8	-34%	562.7	787.6	-40%
141-2	157.7	202.0	-28%	140.3	231.2	-65%	151.4	186.4	-23%	126.0	182.7	-45%	575.4	802.3	-39%
142-1	156.3	203.6	-30%	141.6	209.4	-48%	131.4	175.7	-34%	129.3	187.2	-45%	558.5	775.9	-39%
142-2	155.5	203.6	-31%	139.7	209.4	-50%	136.4	175.7	-29%	133.5	187.2	-40%	565.0	775.9	-37%

Mea. - Measured (klbm/hr)
Ind. - Indicated (klbm/hr)
Err. - Percent Error

Table A-5 Performance Tests / Summary of Mill Performance

Test	Load MW	Parameter	Total	Mill A	Mill B	Mill C	Mill D	Mill E	Mill F
141-1	520	Indicated Fuel Flow, klb/hr	392.4	65.0	65.3	66.2	65.2	64.6	66.1
		Pulverizer Air Flow, klb/hr	902.1	145.1	150.4	145.5	149.6	168.1	143.4
		Measured Fuel Flow, klb/hr	446.7	76.3	69.5	79.0	72.2	79.0	70.8
		Dirty Air Flow, klb/hr	950.1	153.5	160.5	157.3	152.8	171.1	154.8
		A/F Ratio	2.13	2.01	2.31	1.99	2.12	2.17	2.19
		Passing 200 Mesh	75.05	74.48	77.38	73.3	76.76	73.48	74.87
		Remaining 50 Mesh	0.08	0.1	0.04	0.11	0.03	0.05	0.12
		Velocity, fpm	6,321	6,109	6,370	6,312	6,117	6,843	6,173
		High Pipe Flow, klb/hr	22.8	22.8	19.0	21.8	19.6	20.2	19.7
		Low Pipe Flow, klb/hr	14.9	16.4	16.1	17.2	16.5	19.3	14.9
142-1	520	Indicated Fuel Flow, klb/hr	389.5	63.2	67.6	67.3	63.5	63.6	64.2
		Pulverizer Air Flow, klb/hr	899.8	138.5	151.3	150.8	157.2	164.6	137.4
		Measured Fuel Flow, klb/hr	444.2	78.9	69.8	73.4	73.9	77.5	70.7
		Dirty Air Flow, klb/hr	949.0	146.9	157.4	158.2	165.6	170.8	150.0
		A/F Ratio	2.14	1.86	2.25	2.16	2.24	2.2	2.12
		Passing 200 Mesh	76.49	73.69	80.03	76.49	76.73	75.41	76.58
		Remaining 50 Mesh	0.07	0.1	0.09	0.07	0.02	0.05	0.11
		Velocity, fpm	6,352	5,906	6,290	6,370	6,666	6,872	6,007
		High Pipe Flow, klb/hr	23.2	23.2	18.9	18.9	20.4	20.5	19.5
		Low Pipe Flow, klb/hr	15.6	15.6	16.1	17.7	17.6	18.1	16.6

Table A-6 Performance Tests / CP Air Velocities and Fuel Flows

	Test 141				Test 142			
Burner Line	Dirty Air Velocity	%Deviation from Mean	Fuel Flow	%Deviation from Mean	Dirty Air Velocity	%Deviation from Mean	Fuel Flow	%Deviation from Mean
4A-A	6,005	-1.70%	16,415	-13.90%	5,689	-3.68%	20,821	+5.62%
4A-B	6,172	+1.03%	20,070	+5.27%	5,883	-0.39%	23,244	+17.91%
4A-C	6,016	-1.52%	22,753	+19.34%	5,925	+0.32%	19,165	-2.78%
4A-D	6,243	+2.19%	17,026	-10.70%	6,128	+3.75%	15,623	-20.75%
4B-A	6,129	-3.78%	16,995	-2.18%	6,108	-2.90%	18,892	+8.25%
4B-B	6,313	-0.89%	16,052	-7.61%	6,093	-3.14%	16,824	-3.60%
4B-C	6,430	+0.95%	18,991	+9.31%	6,358	+1.07%	16,073	-7.91%
4B-D	6,607	+3.72%	17,458	+0.48%	6,603	+4.97%	18,023	+3.27%
4C-A	6,239	-1.16%	21,243	+7.59%	6,381	+0.17%	18,000	-1.86%
4C-B	6,293	-0.30%	18,690	-5.34%	6,424	+0.85%	17,731	-3.33%
4C-C	6,279	-0.52%	21,815	+10.49%	6,249	-1.90%	18,751	+2.23%
4C-D	6,437	+1.98%	17,228	-12.74%	6,426	+0.88%	18,884	+2.96%
4D-A	6,103	-0.23%	19,431	+7.66%	6,586	-1.20%	17,831	-3.53%
4D-B	6,056	-1.00%	16,658	-7.70%	6,471	-2.92%	17,629	-4.63%
4D-C	6,114	-0.05%	16,533	-8.40%	6,786	+1.80%	18,028	-2.47%
4D-D	6,195	+1.28%	19,571	+8.44%	6,820	+2.31%	20,448	+10.63%
4E-A	6,891	+0.70%	19,875	+0.64%	6,844	-0.41%	18,138	-6.37%
4E-B	6,775	-1.00%	20,215	+2.36%	7,153	+4.09%	20,527	+5.96%
4E-C	6,800	-0.63%	19,331	-2.12%	6,632	-3.49%	19,183	-0.97%
4E-D	6,907	+0.93%	19,576	-0.88%	6,859	-0.19%	19,638	+1.38%
4F-A	6,542	+5.98%	17,445	-1.43%	6,394	+6.44%	17,340	-1.92%
4F-B	5,663	-8.26%	18,764	+6.02%	5,790	-3.62%	17,343	-1.90%
4F-C	6,340	+2.71%	14,925	-15.67%	6,053	+0.76%	16,566	-6.30%
4F-D	6,147	-0.42%	19,661	+11.09%	5,792	-3.58%	19,469	+10.12%

Table A-7 Performance Tests / Coal Analysis

Date	H20 %	C %	H %	N %	Cl %	S %	Ash %	O %	TOTAL	HHV BTU/lb	VM %.	FC %
11/09/94	6.07	71.33	4.6	1.32	0.03	1.32	10.59	4.78	100.04	12539	31.4	51.94
11/11/94	6.06	70.95	4.64	1.3	0.03	1.37	10.73	4.95	100.03	12461	31.74	51.47
11/12/94	6.78	70.35	4.57	1.29	0.03	1.35	10.52	5.15	100.04	12416	31.57	51.13
11/12/94	6.74	71.07	4.63	1.31	0.03	1.34	10.12	4.79	100.03	12464	31.6	51.54
11/13/94	5.74	72.53	4.7	1.33	0.03	1.38	9.87	4.45	100.03	12695	32.46	51.93
11/13/94	5.79	72.5	4.72	1.34	0.03	1.34	9.53	4.78	100.03	12748	32.47	52.2
11/14/94	4.7	72.27	4.73	1.35	0.03	1.26	10.72	4.97	100.03	12709	32.49	52.09
11/14/94	4.91	73.33	4.73	1.36	0.02	1.26	9.77	4.64	100.02	12855	32.42	52.91
11/15/94	6.16	71.2	4.65	1.31	0.03	1.36	9.95	5.38	100.04	12545	32	51.89
11/15/94	6.84	71.11	4.6	1.32	0.03	1.39	9.95	4.79	100.03	12438	31.39	51.82
11/15/94	6.62	70.94	4.61	1.31	0.04	1.37	10.03	5.12	100.04	12476	31.91	51.44
11/16/94	6.4	71.63	4.62	1.32	0.03	1.39	10.07	4.57	100.03	12580	31.74	51.79
11/16/94	5.91	72.24	4.69	1.34	0.06	1.35	10.1	4.38	100.07	12646	32.32	51.67
11/16/94	5.86	71.86	4.68	1.32	0.03	1.36	9.97	4.96	100.04	12613	32.18	51.99
11/17/94	4.66	73.34	4.74	1.40	0.03	1.25	10.56	4.05	100.03	12843	31.85	52.92
Average	5.95	71.78	4.66	1.33	0.03	1.34	10.17	4.78	100.04	12602	32.0	51.9
Std. Dev.	0.72	0.90	0.06	0.03	0.01	0.05	0.37	0.34	0.01	144	0.40	0.49
Var.	0.52	0.81	0.00	0.00	0.00	0.00	0.14	0.11	0.00	20683	0.16	0.24

Table A-8 P4A / Long-Term / Emissions by Load

		Pct	<---------Load--------->			<----------O_2--------->			<----------NOx--------->			<----------CO----------->			<----------SOx-------->			<---------THC-------->		
LoadCat	Count	Load	Mean	Per05	Per95	Mean	Per05	Per95	Mean	Per05	Per95	Mean	Per05	Per95	Mean	Per05	Per95	Mean	Per05	Per95
110-130	32	0%	125	121	129	9.12	8.12	11.57	0.327	0.288	0.384	11	0	17	1.582	1.257	1.875	1.4	0.0	4.0
130-150	35	0%	140	131	150	8.50	6.67	10.66	0.329	0.258	0.404	12	0	19	1.607	1.202	1.951	0.7	0.0	3.7
150-170	348	2%	151	150	156	7.20	6.81	8.40	0.369	0.305	0.394	14	6	15	1.587	1.439	1.753	0.2	0.0	1.0
170-190	57	0%	180	172	188	7.87	6.49	9.90	0.305	0.251	0.368	8	0	16	1.773	1.418	2.123	0.6	0.0	3.2
190-210	5741	35%	201	199	205	7.59	6.69	9.17	0.381	0.322	0.432	5	0	11	1.657	1.310	2.160	0.1	0.0	0.5
210-230	680	4%	220	211	229	7.50	6.36	8.86	0.362	0.275	0.421	6	0	12	1.739	1.325	2.237	0.1	0.0	0.2
230-250	804	5%	241	231	249	7.16	6.25	8.71	0.350	0.265	0.413	7	0	14	1.643	1.325	2.055	0.1	0.0	0.8
250-270	674	4%	259	250	269	7.23	6.05	8.77	0.374	0.316	0.424	7	0	16	1.680	1.246	2.146	0.3	0.0	1.0
270-290	691	4%	278	271	289	7.06	5.89	8.56	0.390	0.355	0.428	7	0	20	1.647	1.326	2.154	0.2	0.0	1.0
290-310	477	3%	299	291	308	6.81	5.55	8.67	0.394	0.329	0.451	8	0	20	1.667	1.325	2.159	0.1	0.0	0.9
310-330	287	2%	320	311	329	6.50	5.32	8.41	0.398	0.334	0.462	8	0	16	1.658	1.327	2.172	0.1	0.0	0.9
330-350	687	4%	341	332	349	6.76	5.36	7.87	0.421	0.356	0.464	7	0	19	1.766	1.386	2.151	0.1	0.0	0.7
350-370	484	3%	358	351	369	6.42	5.21	7.37	0.430	0.364	0.475	6	0	15	1.705	1.333	2.157	0.3	0.0	1.0
370-390	363	2%	381	371	389	6.31	5.00	7.43	0.424	0.373	0.484	7	0	19	1.668	1.328	2.144	0.1	0.0	1.0
390-410	379	2%	400	391	409	6.08	4.87	7.23	0.433	0.367	0.515	8	0	17	1.724	1.405	2.145	0.3	0.0	1.0
410-430	335	2%	419	412	428	6.06	5.01	7.17	0.445	0.393	0.529	10	0	24	1.739	1.352	2.180	0.2	0.0	1.0
430-450	423	3%	440	431	448	5.46	4.48	6.98	0.452	0.404	0.548	11	0	36	1.741	1.381	2.179	0.2	0.0	1.0
450-470	426	3%	461	450	470	6.05	4.75	7.08	0.466	0.401	0.549	10	0	23	1.760	1.382	2.195	0.5	0.0	1.0
470-490	541	3%	481	470	489	6.02	4.71	8.04	0.475	0.391	0.574	11	0	29	1.702	1.371	2.154	0.4	0.0	1.9
490-510	1582	10%	501	491	509	5.93	4.89	7.13	0.497	0.407	0.606	10	0	25	1.738	1.303	2.168	0.4	0.0	1.3
510-530	965	6%	517	511	522	5.31	4.14	6.45	0.473	0.414	0.563	15	0	39	1.651	1.294	2.125	0.2	0.0	1.0
530-550	161	1%	536	531	541	5.54	4.59	6.78	0.515	0.431	0.591	9	3	12	1.874	1.617	2.175	1.6	0.0	1.2
All Loads	16172	100%	311	200	515	6.85	4.97	8.69	0.411	0.321	0.537	8	0	18	1.685	1.322	2.161	0.2	0.0	1.0

ALL DATA
PROCESSING FOR LOAD CATEGORIES
COMMON ALL

Table A-9 P4A / Long-Term / Within-Day Averages

HOUR	LOAD	NOX	CO	THC	O2
0	214	0.383	4.6	0.1	7.54
1	206	0.379	4.4	0.1	7.63
2	203	0.380	4.4	0.1	7.64
3	202	0.380	4.3	0.1	7.67
4	206	0.382	4.3	0.1	7.62
5	227	0.393	4.9	0.0	7.49
6	249	0.396	5.9	0.0	7.37
7	266	0.405	5.9	0.0	7.29
8	281	0.418	8.6	0.2	7.06
9	306	0.401	12.6	0.5	6.79
10	328	0.396	10.0	0.1	6.80
11	349	0.414	9.0	0.2	6.57
12	381	0.440	9.2	0.3	6.32
13	401	0.437	13.8	0.3	6.19
14	402	0.434	13.1	0.3	6.34
15	415	0.444	11.8	0.4	6.27
16	420	0.440	9.7	0.4	6.30
17	406	0.437	8.5	0.3	6.25
18	388	0.429	7.9	0.3	6.29
19	379	0.425	7.3	0.2	6.33
20	362	0.420	6.8	0.2	6.47
21	323	0.409	6.1	0.2	6.63
22	268	0.391	6.3	0.2	7.05
23	230	0.381	5.9	0.2	7.45

Table A-10 P4A / Long-Term / Within-Day Averages

DID	ICOUNT	LOAD	O2	CO	THC	NOX	SOX
940712	3	230.592	7.475	0	0	0.342	1.992
940713	24	285.924	7.417	0.433	0	0.421	1.97
940714	24	306.792	7.55	1.778	0	0.429	2.057
940715	24	410.959	6.751	5.642	0	0.49	2.126
940716	24	356.735	7.216	0.713	0	0.474	2.147
940717	21	323.698	8.209	0	0	0.452	2.08
940718	24	259.57	9.144	0.018	0	0.444	2.071
940719	18	367.068	8.952	13.234	0.019	0.441	1.906
940720	11	424.955	7.848	15.531	1.654	0.515	1.392
940721	22	337.017	7.594	6.405	0.843	0.448	1.636
940722	24	401.308	7.116	1.561	0.851	0.485	1.724
940723	8	443.765	6.699	8.186	1.664	0.488	1.572
940724							
940725	1	123.246	9.343	14.168	4.041	0.298	1.453
940726	24	232.46	8.019	4.238	1.102	0.385	1.734
940727	24	358.479	7.503	4.188	0.035	0.436	1.997
940728	24	358.259	7.84	3.36	0.002	0.457	2.14
940729	21	328.968	7.722	4.72	0.156	0.444	2.217
940730							
940801							
940802							
940803	24	357.177	7.016	6.141	0.002	0.467	2.103
940804	24	350.085	6.89	5.85	0.558	0.453	2.015
940805	12	468.844	5.72	10.368	2.884	0.479	1.872
940806							
940807							
940808							
940809	12	235.781	6.807	11.398	0.062	0.387	1.581
940810	24	323.329	6.076	15.788	0.824	0.408	1.509
940811	24	350.609	5.911	12.093	0.825	0.431	1.735
940812	24	363.11	6.042	13.676	0.746	0.446	1.724
940813	24	288.462	6.166	14.342	0.559	0.406	1.665
940814	24	184.42	6.885	14.863	0.014	0.385	1.483
940815	18	295.31	5.967	12.916	0.446	0.392	1.427
940816	14	266.071	6.578	4.818	0.124	0.39	1.364
940817	9	394.334	5.703	10.025	0.111	0.401	1.666
940818							
940819							
940820							
940821							
940822							
940823							
940824	2	138.442	7.981	13.974	0	0.301	1.559
940825	23	225.368	6.627	8.098	0	0.281	1.51
940826	24	295.482	6.769	0	0	0.407	1.505
940827	14	353.469	6.036	0	0	0.428	1.765
940828							
940829							
940830							
940831	2	336.581	9.635	0	0	0.095	2.227

Table A-9 P4A / Long-Term / Within-Day Averages

DID	ICOUNT	LOAD	O2	CO	THC	NOX	SOX
940901	24	344.997	6.267	1.372	0.316	0.425	1.743
940902	24	353.343	6.098	3.529	0.815	0.417	1.552
940903	24	210.188	7.313	5.374	0.008	0.394	1.45
940904	24	200.81	7.46	5.462	0	0.408	1.352
940905	24	200.783	6.911	7.011	0	0.388	1.375
940906	24	212.688	6.943	7.896	0	0.393	1.486
940907	24	304.885	6.17	11.355	0	0.385	1.558
940908	15	310.303	5.835	9.209	0	0.376	1.468
940909	14	215.791	6.737	9.225	0	0.368	1.324
940910	24	252.762	6.68	7.438	0	0.374	1.371
940911	24	303.435	6.105	8.62	0	0.372	1.444
940912	24	338.758	6.004	7.454	0	0.395	1.533
940913	24	378.561	5.802	9.031	0	0.405	1.585
940914	23	412.817	5.512	10.297	0	0.38	1.56
940915	24	336.913	6.456	5.308	0	0.408	1.395
940916	24	354.3	6.262	9.595	0	0.399	1.19
940917	24	300.711	6.205	8.232	0	0.383	1.376
940918	24	297.939	6.243	4.215	0	0.383	1.738
940919	24	284.954	6.384	4.806	0	0.377	1.804
940920	24	353.691	6.005	14.797	0	0.437	1.776
940921	24	301.288	6.118	26.386	0	0.337	1.725
940922	24	265.086	7.149	7.02	0	0.369	1.954
940923	24	384.164	6.894	17.023	0	0.432	1.633
940924	10	265.643	7.124	11.069	0	0.353	1.394
940925							
940927	22	259.299	7.769	2.955	0	0.405	1.366
940928	24	328.368	6.761	11.648	0	0.403	1.58
940929	24	351.145	6.733	7.89	0	0.404	1.591
940930	24	334.823	7.149	17.113	0	0.423	1.429
941001	24	283.032	7.528	6.222	0	0.423	1.49
941002	24	266.886	7.72	3.019	0	0.41	1.602
941003	14	430.627	6.512	11.488	0	0.416	1.723
941004							
941005							
941006							
941007							
941008							
941009							
941010							
941010							
941011							
941012							
941013							
941014							
941015							
941016							
941017							
941018							
941019							
941020							
941021							
941022							
941023							
941024							
941025							
941026							
941027							
941028							
941029							
941030							
941031							

Table A-9 P4A / Long-Term / Within-Day Averages

DID	ICOUNT	LOAD	O2	CO	THC	NOX	SOX
941101	3	175.21	7.689	13.063	0	0.331	1.682
941102	17	215.16	7.998	6.017	0	0.371	1.931
941103							
941104							
941105							
941106							
941107							
941108							
941109	12	194.818	7.79	13.973	0	0.289	1.792
941110							
941111							
941112	5	201.749	8.078	7.254	0	0.378	2.014

Table A-11 LOI Test Summary

Test	Date	Load	Description	MOOS	Ex. O2.	AOFA	NOx	LOI
150-1	20-Jul-95	519	Full-Load / Low O2	AMIS		50	0.39	9.47
150-2	20-Jul-95	520	Full-Load / Med. O2	AMIS		50	0.45	6.37
150-3	20-Jul-95	500	Full-Load / Hi O2	AMIS		50	0.54	5.16
151-1	21-Jul-95	305	Low-Load / Low O2	E		0	0.36	8.64
151-2	21-Jul-95	305	Low-Load / Med. O2	E		0	0.43	4.23
151-3	21-Jul-95	305	Low-Load / Hi O2	E		0	0.49	2.59
151-4	21-Jul-95	400	Med-Load / Low O2	E		20	0.35	8.98
151-5	21-Jul-95	400	Med-Load / Med. O2	E		20	0.43	5.62
151-6	21-Jul-95	400	Med-Load / Hi O2	E		20	0.51	4.35
152-1	8-Feb-96	480	Full-Load / Low O2	AMIS		40	0.40	9.3
152-2	8-Feb-96	480	Full-Load / Mid O2	AMIS		40	0.44	8.2
152-3	8-Feb-96	480	Full-Load / High O2	AMIS		40	0.49	6.3
152-4	8-Feb-96	400	Mid-Load / Mid O2	E		20	0.44	9.5
152-5	8-Feb-96	400	Mid-Load / Low O2	E		20	0.38	11.1
153-1	9-Feb-96	300	Mid-Load / Mid O2	B		0	0.37	7.5
153-2	9-Feb-96	300	Mid-Load / Low O2	B		0	0.34	9.4
153-3	9-Feb-96	300	Mid-Load / High O2	B		0	0.42	5.7
153-4	9-Feb-96	390	Mid-Load / High O2	B		20	0.38	7.6

Table A-12 Process Data for 1st Quarter 1995

Load, MW

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	120	137.669	137.669	130.425	149.856	3.72083	131.694	147.23
150	170	86	159.078	159.078	150.041	169.969	5.31443	151.606	168.081
170	190	238	182.11	182.11	170.353	189.931	4.99533	174.476	189.554
190	210	2824	201.171	201.171	190.141	209.947	3.18294	197.556	207.998
210	230	1110	220.026	220.026	210.047	229.978	5.50638	211.353	229.034
230	250	1072	239.646	239.646	230.006	249.981	5.99319	230.974	249.068
250	270	1281	259.368	259.368	250.009	270	5.80464	250.563	268.683
270	290	1084	279.773	279.773	270.069	289.984	5.82234	270.972	289.087
290	310	1194	299.899	299.899	290.025	309.969	5.72843	290.903	308.641
310	330	1007	320.148	320.148	310.003	330	5.91449	310.719	328.945
330	350	857	339.69	339.69	330.009	349.997	5.75978	330.721	349.074
350	370	817	360.282	360.282	350.069	370	5.95176	350.682	369.129
370	390	798	379.563	379.563	370.016	390	5.83973	370.55	388.891
390	410	729	398.761	398.761	390.009	409.984	5.80076	390.578	408.287
410	430	605	418.97	418.97	410.006	429.991	5.67919	410.686	428.074
430	450	572	441.973	441.973	430.006	449.959	6.49924	430.934	449.632
450	470	668	456.323	456.323	450.025	469.963	5.73437	450.188	468.256
470	490	430	480.33	480.33	470.031	489.984	5.38917	471.144	489.641
490	510	242	497.522	497.522	490.025	509.966	6.55732	490.138	509.214
510	530	571	518.616	518.616	510.003	525.35	2.88668	511.874	522.262

Main Steam Temperature, °F

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	120	137.669	964.48	884.333	1009.69	23.9794	924.242	1004.2
150	170	86	159.078	978.261	913.183	1009.33	31.5398	915.186	1005.38
170	190	238	182.11	992.855	935.268	1007.62	14.8249	957.035	1002.14
190	210	2824	201.171	994.12	943.309	1004.27	7.272	988.419	1001.82
210	230	1110	220.026	995.927	943.309	1008.39	8.74645	988.218	1002
230	250	1072	239.646	997.755	974.19	1039.65	5.15352	989.526	1002.49
250	270	1281	259.368	996.787	963.017	1019.4	6.09937	988.498	1002.22
270	290	1084	279.773	996.582	955.921	1050.76	6.29332	988.739	1002.06
290	310	1194	299.899	997.883	955.821	1024.29	5.27878	989.332	1001.71
310	330	1007	320.148	996.35	964.257	1009.8	5.78822	988.889	1001.51
330	350	857	339.69	995.957	942.231	1008.38	6.22316	987.922	1002.35
350	370	817	360.282	995.209	951.304	1005.45	6.11202	987.915	1002.52
370	390	798	379.563	995.151	952.383	1013.58	6.38383	985.998	1003.7
390	410	729	398.761	995.825	965.166	1005.28	6.62601	985.327	1003.7
410	430	605	418.97	994.536	963.049	1004.49	6.28455	984.594	1003.7
430	450	572	441.973	994.848	967.356	1004.89	7.1247	981.001	1003.7
450	470	668	456.323	991.673	966.846	1007.91	7.20751	978.279	1000.38
470	490	430	480.33	990.91	953.19	1003.02	8.31134	975.953	1000.58
490	510	242	497.522	989.265	962.986	1001.11	9.53225	971.117	1001.11
510	530	571	518.616	988.478	965.349	1001.11	8.88287	972.89	1001.1

Hot Reheat Temperature, °F

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	120	137.669	962.659	888.989	1003.66	26.539	907.922	1001.74
150	170	86	159.078	972.978	915.274	1006.92	33.27	915.274	1003.07
170	190	238	182.11	975.811	917.887	1012.29	25.0288	933.485	1002.81
190	210	2824	201.171	984.053	906.311	1006.02	14.6157	956.106	1001.58
210	230	1110	220.026	985.436	942.012	1008.68	12.9598	960.354	1001.05
230	250	1072	239.646	986.572	949.061	1006.42	12.6732	961.344	1002.17
250	270	1281	259.368	987.738	951.241	1010.15	10.7238	966.522	1001.34
270	290	1084	279.773	990.858	954.664	1008.19	10.2194	970.93	1002.62
290	310	1194	299.899	992.33	947.474	1010.37	10.2321	972.311	1002.75
310	330	1007	320.148	992.703	950.331	1010.24	9.19696	976.563	1003.32
330	350	857	339.69	993.747	951.184	1011.1	8.90022	978.762	1003.95
350	370	817	360.282	994.363	956.866	1012.54	8.29917	980.353	1005.58
370	390	798	379.563	994.521	959.821	1011.97	8.5231	980.302	1005.19
390	410	729	398.761	995.996	962.662	1013.84	7.39954	982.6	1004.77
410	430	605	418.97	995.226	964.768	1012.17	7.79817	981.143	1005.92
430	450	572	441.973	997.439	966.091	1014.61	6.73199	984.862	1006.96
450	470	668	456.323	997.561	966.358	1011.73	6.42844	985.187	1006.93
470	490	430	480.33	998.183	976.348	1015.08	5.79424	987.602	1006.41
490	510	242	497.522	996.024	980.918	1014.79	5.82914	987.609	1005.72
510	530	571	518.616	995.991	985.262	1011.58	3.73174	989.995	1002.27

Excess O2 Left Hand, %

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	120	137.669	7.06996	6.15835	9.22035	0.47618	6.67023	8.02803
150	170	86	159.078	6.58039	4.06675	9.30478	0.58105	5.95158	7.30202
170	190	238	182.11	6.54002	5.26639	8.52375	0.81	5.54036	7.94409
190	210	2824	201.171	6.29503	4.11886	8.12534	0.79343	5.08946	7.81373
210	230	1110	220.026	6.0722	4.35246	7.97128	0.63776	5.10378	7.32796
230	250	1072	239.646	5.82814	3.85311	7.82574	0.7248	4.61369	7.37915
250	270	1281	259.368	5.72995	3.52137	8.30507	0.90004	4.52997	7.47532
270	290	1084	279.773	5.35278	3.3405	7.67151	0.76936	4.02318	6.75169
290	310	1194	299.899	5.0421	3.08207	7.46712	0.66957	4.11922	6.48174
310	330	1007	320.148	4.94753	2.90298	7.29754	0.7115	3.97111	6.55723
330	350	857	339.69	4.71355	2.5182	7.2225	0.68828	3.80613	6.17249
350	370	817	360.282	4.4787	2.36996	7.03945	0.81326	3.43452	6.26489
370	390	798	379.563	4.23047	2.30139	6.68774	0.81482	3.26276	6.13554
390	410	729	398.761	3.91697	2.27198	6.16085	0.66257	2.8847	5.18161
410	430	605	418.97	3.79792	1.90751	5.92257	0.65377	2.77445	5.04102
430	450	572	441.973	3.5784	1.30876	6.01612	0.65538	2.66738	4.72894
450	470	668	456.323	3.63598	1.44957	5.59206	0.72536	2.63019	5.24723
470	490	430	480.33	3.31669	1.97125	5.59302	0.59967	2.59421	4.46315
490	510	242	497.522	3.2702	1.72922	4.92533	0.54137	2.64404	4.39595
510	530	571	518.616	3.18607	2.7081	4.26435	0.25716	2.878	3.63487

Excess O2, Right Hand, %

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	120	137.669	6.79295	6.26245	9.03593	0.41623	6.46107	7.67042
150	170	86	159.078	6.3484	3.70395	7.85667	0.42888	5.9555	6.76204
170	190	238	182.11	5.98261	5.23919	6.59914	0.3583	5.34656	6.4034
190	210	2824	201.171	5.96794	4.64792	7.95109	0.49803	5.28066	7.01764
210	230	1110	220.026	5.68512	4.4425	7.55495	0.47778	5.07251	6.71314
230	250	1072	239.646	5.43225	4.04461	6.95904	0.45711	4.76702	6.23921
250	270	1281	259.368	5.16239	3.80702	6.58551	0.49676	4.34869	6.00994
270	290	1084	279.773	4.85374	3.11426	6.406	0.54545	4.01965	5.80832
290	310	1194	299.899	4.62471	3.56303	5.99237	0.50035	3.87129	5.5322
310	330	1007	320.148	4.39944	3.29984	5.87956	0.52816	3.55015	5.36727
330	350	857	339.69	4.45005	2.91832	5.71426	0.50159	3.50134	5.19157
350	370	817	360.282	4.24396	2.52837	5.7901	0.49545	3.35245	4.92137
370	390	798	379.563	4.04215	2.76714	5.49658	0.51159	3.21956	4.80556
390	410	729	398.761	3.9492	2.59811	5.49145	0.51557	3.08925	4.73424
410	430	605	418.97	3.7713	2.53711	4.86411	0.50619	2.96681	4.5359
430	450	572	441.973	3.59927	1.4562	4.71649	0.47991	2.70245	4.3359
450	470	668	456.323	3.48839	1.26072	4.69703	0.56038	2.48512	4.44238
470	490	430	480.33	3.39439	1.83543	4.56292	0.50575	2.37861	4.08233
490	510	242	497.522	3.27408	1.82659	4.43596	0.42144	2.58561	4.06914
510	530	571	518.616	2.99719	2.49305	4.25366	0.24261	2.77487	3.36263

Main Steam Pressure, PSIG

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	120	137.669	1709.85	1054.99	2426.46	223.514	1554.67	2100.02
150	170	86	159.078	1832.37	1034.94	2531.26	515.178	1034.94	2398.54
170	190	238	182.11	2288.7	1095	2422.35	311.615	1247.98	2410.25
190	210	2824	201.171	2363.44	1179.34	2454.7	125.299	2347.92	2415.53
210	230	1110	220.026	2369.39	1602.02	2550.16	114.137	2287.64	2415.53
230	250	1072	239.646	2397.53	2248.55	2480.4	24.539	2357.44	2415.53
250	270	1281	259.368	2393.42	2327.54	2446.71	25.3622	2356.69	2415.53
270	290	1084	279.773	2393.12	2314.65	2482.07	25.7526	2356.55	2415.53
290	310	1194	299.899	2400.03	2333.12	2430.22	21.4315	2359.34	2415.52
310	330	1007	320.148	2393.23	2343.87	2472.65	24.796	2358.36	2415.53
330	350	857	339.69	2393.02	2334.89	2429.47	24.7267	2357.28	2421.56
350	370	817	360.282	2392.88	2336.36	2456.82	25.066	2358.84	2421.74
370	390	798	379.563	2395.61	2243.64	2458.32	26.0045	2358.38	2421.74
390	410	729	398.761	2400.14	2310.14	2442.13	24.6346	2359.49	2421.74
410	430	605	418.97	2394.71	2233.59	2438.02	27.0047	2354.96	2421.74
430	450	572	441.973	2403.59	2257.77	2457.57	24.0609	2357.86	2421.74
450	470	668	456.323	2399.44	2234.12	2434.9	27.1558	2351.83	2415.53
470	490	430	480.33	2402.18	2263.1	2431.41	24.2279	2354.31	2416.89
490	510	242	497.522	2392.5	2216.98	2435.6	37.3012	2322.72	2415.53
510	530	571	518.616	2398.36	2287.92	2424.36	26.5153	2354.59	2415.53

Secondary Air Heater A Gas Outlet Temperature, °F

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	120	137.669	257.73	228.286	284.541	7.5709	249.861	270.011
150	170	86	159.078	252.085	218.961	276.344	12.4483	226.544	263.658
170	190	238	182.11	254.636	233.094	281.233	8.80402	235.002	269.094
190	210	2824	201.171	275.028	155.062	314.73	25.7784	239.05	310.678
210	230	1110	220.026	274.952	232.875	325.979	21.6311	239.05	304.888
230	250	1072	239.646	277.075	234.141	325.93	19.1568	254.442	306.845
250	270	1281	259.368	279.397	239.05	324.604	18.2344	257.235	312.082
270	290	1084	279.773	282.298	239.05	321.184	18.2668	257.403	308.176
290	310	1194	299.899	279.881	237.393	320.529	21.5695	247.752	311.511
310	330	1007	320.148	282.251	235.861	316.873	17.4981	254.15	305.79
330	350	857	339.69	277.878	239.05	312.823	17.2173	250.613	304.178
350	370	817	360.282	281.576	239.05	313.906	15.9081	259.107	305.38
370	390	798	379.563	284.842	243.062	316.627	16.5372	259.114	310.752
390	410	729	398.761	288.148	245.049	322.471	17.7341	259.114	310.542
410	430	605	418.97	292.094	253.795	323.744	17.7938	259.114	315.473
430	450	572	441.973	291.649	255.054	326.572	22.7083	257.702	318.554
450	470	668	456.323	300.32	257.702	329.241	20.2029	257.702	321.126
470	490	430	480.33	301.709	257.702	336.152	22.2142	268.873	329.924
490	510	242	497.522	292.528	257.785	341.045	22.7252	267.636	333.045
510	530	571	518.616	291.143	257.785	342.826	14.3064	277.804	323.718

Secondary Air Heater B Gas Outlet Temperature, °F

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	120	137.669	261.299	241.211	287.136	7.83188	250.539	272.377
150	170	86	159.078	265.488	243.383	286.478	4.98619	260.184	272.098
170	190	238	182.11	263.99	246.581	293.07	5.38636	255.247	271.696
190	210	2824	201.171	279.052	233.51	478.768	32.0532	255.136	304.664
210	230	1110	220.026	275.118	232.441	316.094	16.9282	249.911	303.64
230	250	1072	239.646	276.607	234.415	308.962	16.2241	252.63	303.635
250	270	1281	259.368	270.901	218.605	309.067	18.2945	238.759	298.63
270	290	1084	279.773	279.805	225.71	315.593	17.0882	250.112	307.069
290	310	1194	299.899	280.863	232.645	329.903	21.9569	245.826	316.46
310	330	1007	320.148	287.08	237.788	333.265	20.2937	251.623	317.832
330	350	857	339.69	288.989	242.905	333.391	20.4736	252.922	319.529
350	370	817	360.282	296.52	245.015	334.944	18.6181	262.1	323.029
370	390	798	379.563	300.264	253.348	337.869	18.0748	268.486	325.668
390	410	729	398.761	305.7	259.057	340.47	17.3454	274.148	328.234
410	430	605	418.97	308.115	261.448	340.704	17.5865	277.915	334.461
430	450	572	441.973	311.006	261.448	345.021	17.4079	282.32	338.564
450	470	668	456.323	311.66	270.957	348.358	17.449	283.452	340.782
470	490	430	480.33	314.437	276.354	353.438	22.3807	280.71	345.37
490	510	242	497.522	308.314	280.183	354.299	21.4497	281.079	350.378
510	530	571	518.616	308.9	281.48	356.908	11.4397	301.527	334.718

Secondary Air Heater A Gas Inlet Temperature, °F

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	120	137.669	569.945	529.187	597.836	14.2611	552.485	594.186
150	170	86	159.078	590.601	544.338	635.579	24.3437	548.36	632.952
170	190	238	182.11	606.016	557.391	648.698	27.0821	567.403	643.935
190	210	2824	201.171	619.233	562.762	818.081	30.4923	590.381	641.569
210	230	1110	220.026	631.532	586.646	827.599	38.3451	602.366	657.653
230	250	1072	239.646	665.549	599.718	837.788	71.031	613.981	828.85
250	270	1281	259.368	647.27	604.525	845.445	37.3032	623.25	679.588
270	290	1084	279.773	662.463	616.533	842.595	30.0391	632.998	689.84
290	310	1194	299.899	673.656	618.447	856.953	33.7326	644.105	707.034
310	330	1007	320.148	690.348	630.902	865.397	39.9367	657.235	758.259
330	350	857	339.69	704.21	645.781	870.393	38.59	667.484	750.733
350	370	817	360.282	727.207	654.773	876.277	57.1912	678.553	866.598
370	390	798	379.563	729.696	657.936	883.419	50.4866	686.633	874.157
390	410	729	398.761	745.933	670.871	887.109	56.4707	700.618	882.542
410	430	605	418.97	755.291	676.747	897.381	52.882	707.712	887.975
430	450	572	441.973	775.77	686.312	903.635	57.8336	722.322	897.817
450	470	668	456.323	765.352	709.107	909.698	41.4852	734.532	898.802
470	490	430	480.33	782.557	708.687	913.261	42.3767	753.101	906.772
490	510	242	497.522	790.468	759.958	923.757	44.4161	765.786	914.521
510	530	571	518.616	779.381	761.768	925.44	21.1743	761.768	793.992

Secondary Air Heater A Gas Inlet Temperature, °F

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	120	137.669	579.968	537.59	610.856	15.6271	558.616	605.158
150	170	86	159.078	599.863	565.217	639.45	24.2671	565.217	635.043
170	190	238	182.11	608.264	565.065	647.473	23.1888	577.364	641.458
190	210	2824	201.171	622.938	569.594	813.993	37.4805	587.704	640.098
210	230	1110	220.026	626.468	591.084	815.921	18.4724	605.409	649.134
230	250	1072	239.646	634.084	602.002	820.014	17.9587	612.914	657.732
250	270	1281	259.368	641.658	605.493	838.683	24.3404	619.841	665.748
270	290	1084	279.773	655.942	617.218	843.856	19.9579	632.853	679.858
290	310	1194	299.899	666.049	620.372	849.048	20.7201	643.289	693.817
310	330	1007	320.148	677.648	613.837	855.142	21.6763	652.62	708.036
330	350	857	339.69	687.47	375.035	858.337	41.384	661.026	721.081
350	370	817	360.282	699.894	655.336	844.216	18.4771	672.44	731.365
370	390	798	379.563	708.584	659.891	851.048	18.1142	679.589	732.407
390	410	729	398.761	719.855	669.737	849.894	17.8946	696.555	742.621
410	430	605	418.97	730.246	676.321	834.701	16.5503	703.398	753.425
430	450	572	441.973	742.319	686.826	784.853	13.3456	714.139	761.78
450	470	668	456.323	744.732	698.741	800.551	12.9756	719.977	763.281
470	490	430	480.33	761.082	277.623	805.419	26.1163	737.927	774.774
490	510	242	497.522	771.706	747.126	800.688	10.4555	754.417	790.333
510	530	571	518.616	774.521	754.573	805.795	11.2627	760.972	794.911

Stack O2, % (Dry)

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	120	137.669	9.55185	8.8165	11.1613	0.44792	9.00269	10.3263
150	170	86	159.078	9.17885	7.31201	9.92559	0.40912	8.35268	9.73531
170	190	238	182.11	8.1505	7.38574	9.70254	0.5631	7.60908	9.49414
190	210	2824	201.171	9.37226	3.84209	11.9997	1.39371	7.7417	11.8628
210	230	1110	220.026	8.78639	2.00176	11.9982	1.32931	7.43359	11.7656
230	250	1072	239.646	8.80363	3.50205	11.9981	1.42654	7.14209	11.693
250	270	1281	259.368	8.3104	2.04287	11.9976	1.34172	6.81628	11.4959
270	290	1084	279.773	8.4003	3.5832	11.9887	1.64032	6.57022	11.6912
290	310	1194	299.899	7.69515	4.36406	11.9607	1.19753	6.60498	10.8605
310	330	1007	320.148	7.61385	4.45918	11.9923	1.2015	6.36182	10.2592
330	350	857	339.69	7.47573	3.64766	11.9995	1.34753	6.19358	11.0851
350	370	817	360.282	7.17325	4.64766	11.9987	1.24873	6.0604	10.2957
370	390	798	379.563	7.02968	2.06543	11.9703	1.36766	5.81049	10.8857
390	410	729	398.761	6.9389	5.14248	11.9458	1.18138	5.76532	9.80063
410	430	605	418.97	6.97807	3.68115	11.9634	1.44174	5.59033	10.3201
430	450	572	441.973	6.64241	3.94727	11.8345	1.08069	5.57627	9.37878
450	470	668	456.323	6.215	2.77002	11.6539	0.73461	5.38916	7.09561
470	490	430	480.33	6.40135	4.69063	11.6869	0.8902	5.57959	7.89746
490	510	242	497.522	6.48363	2.65859	11.7107	1.11214	5.39088	8.88666
510	530	571	518.616	6.03488	4.7959	10.0775	0.49224	5.40772	6.99463

Stack NOx, lb/MBtu

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	120	137.669	0.43389	0.28282	0.52066	0.04377	0.31746	0.48061
150	170	86	159.078	0.37187	0.25294	0.50001	0.0656	0.25566	0.43072
170	190	238	182.11	0.40316	0.26589	0.53447	0.05897	0.32701	0.50577
190	210	2824	201.171	0.41802	0.2631	0.70432	0.05747	0.32961	0.51721
210	230	1110	220.026	0.40452	0.26829	0.66673	0.05288	0.32762	0.49605
230	250	1072	239.646	0.40018	0.26851	0.62132	0.04889	0.34191	0.4962
250	270	1281	259.368	0.40688	0.27271	0.62114	0.04758	0.34048	0.48615
270	290	1084	279.773	0.41155	0.29181	0.6252	0.04847	0.34362	0.50169
290	310	1194	299.899	0.40881	0.3012	0.56768	0.04646	0.3469	0.48868
310	330	1007	320.148	0.41431	0.29688	0.54403	0.04218	0.35196	0.48851
330	350	857	339.69	0.43238	0.17927	0.58883	0.0432	0.36988	0.50522
350	370	817	360.282	0.42642	0.29329	0.57418	0.04058	0.37016	0.49729
370	390	798	379.563	0.41851	0.17325	0.55466	0.04381	0.36374	0.50077
390	410	724	398.78	0.41315	0.23929	0.76575	0.04209	0.35805	0.48477
410	430	599	419.005	0.41901	0.2422	0.57154	0.04375	0.35345	0.50069
430	450	571	441.989	0.42002	0.29404	0.56059	0.04582	0.35522	0.4928
450	470	666	456.311	0.42029	0.28058	0.54058	0.03413	0.37388	0.48278
470	490	425	480.253	0.42693	0.34267	0.54619	0.02942	0.37574	0.47085
490	510	233	497.675	0.4417	0.23366	0.95977	0.0962	0.37596	0.48826
510	530	570	518.627	0.41314	0.30337	0.4938	0.02897	0.37691	0.46648

Stack CO, ppm (not corrected to 3% O2) (Dry)

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	119	137.667	17.7724	0	35.0859	11.5827	0.12129	31.6172
150	170	86	159.078	4.99536	-0.9375	12.0586	3.62313	-0.9375	12.0586
170	190	219	182.378	1.97793	-4.97227	45.8414	5.8301	-4.68305	9.90486
190	210	2824	201.171	38.816	-4.63008	90.8438	33.0688	-2.29688	86.2597
210	230	1098	220.03	26.4077	-4.98926	88.4895	29.6276	-1.1543	85.6474
230	250	1071	239.652	25.8261	-4.58496	108.205	28.9923	-2.54268	83.0162
250	270	1280	259.361	25.6585	-4.7915	159.851	29.9398	0	86.4955
270	290	1081	279.785	36.0752	-4.93945	198.052	35.5961	-2.95529	90.0227
290	310	1186	299.908	26.8744	-4.98047	269.027	38.8228	-3.59004	113.111
310	330	1004	320.139	35.1771	-4.93242	175.289	40.8179	0	113.61
330	350	843	339.663	26.0184	-4.99414	215.351	36.0591	-1.35023	90.7717
350	370	816	360.281	22.7526	-4.83398	253.606	33.762	-1.2668	87.3471
370	390	797	379.551	26.9018	-4.95996	216.056	36.5263	-1.76115	104.815
390	410	727	398.733	29.1881	-4.9248	265.119	47.4892	-2.90443	130.981
410	430	604	418.968	33.0523	-4.84375	304.066	56.376	-2.58351	149.943
430	450	567	441.908	20.6288	-4.97266	273.526	38.507	-3.78862	94.3912
450	470	664	456.36	55.3165	-4.88438	276.158	58.5749	-0.0457	179.153
470	490	430	480.33	68.1448	-1.89258	304.02	76.8394	0	236.555
490	510	242	497.522	99.2433	-2.42285	294.404	88.825	0	251.632
510	530	571	518.616	79.9254	-3.04834	300.047	54.619	9.7957	211.35

Mill A Coal Flow, lb/hr

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	120	137.669	1978.46	1.71875	58930.1	9530.83	1.71875	1808.13
150	170	86	159.078	1205.22	0	52071.9	7847.49	0	1.71875
170	190	238	182.11	4417.66	0	67802.6	15056.1	0	54412
190	210	2824	201.171	23067.7	-39.5313	77431.4	22006.7	0	56576.5
210	230	1110	220.026	25378.7	-39.5313	69069.7	21846.4	0	47400
230	250	1072	239.646	29656.1	-39.5313	78053.6	23349.3	0	51214.6
250	270	1281	259.368	36480.3	0	73273.4	22809.1	0	55428.3
270	290	1084	279.773	39444.3	-39.5313	73469	21315.8	0	57831.7
290	310	1194	299.899	35620.7	-39.5313	74878.4	24580.2	0	60505.3
310	330	1007	320.148	44442.9	-39.5313	74792.1	20737.1	0	63729
330	350	857	339.69	42381.8	-39.5313	79921.2	23291.9	0	65787.4
350	370	817	360.282	47073.7	0	73615.4	20058.4	0	60863.1
370	390	798	379.563	47869.2	0	75862.9	21552	0	62164.8
390	410	729	398.761	46870.5	0	72178.9	23457.9	0	63720
410	430	605	418.97	50446.6	0	82417.8	22003.1	0	67063.8
430	450	572	441.973	42021.7	0	83420.6	26605	0	68943.2
450	470	668	456.323	45432	0	82322.3	24837.7	0	71270.3
470	490	430	480.33	57208.5	0	83899.8	21417.2	0	77928.1
490	510	242	497.522	47272.9	0	82913.9	32260.9	0	78238.4
510	530	571	518.616	20071.9	0	82313	31049.6	0	69953.9

Mill B Coal Flow, lb/hr

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	120	137.669	41048.7	30.9375	66107.6	8079.17	32521.2	49133.1
150	170	86	159.078	46954.8	30.9375	64053.7	7253.19	39622.3	55141.6
170	190	238	182.11	13949.5	30.9375	64954.7	22354.8	37.8125	52249
190	210	2824	201.171	14448	27.5	66321.8	19773.7	32.6563	43738.1
210	230	1110	220.026	15970.8	27.5	65402.2	20959.4	30.9375	46207.9
230	250	1072	239.646	14851.6	30.9375	59886.4	21664.5	32.6563	49705.9
250	270	1281	259.368	15305.7	30.9375	70047	22743.5	34.5469	52996
270	290	1084	279.773	15329.7	30.9375	67709.5	22610.7	32.6563	53995.1
290	310	1194	299.899	22338.7	30.9375	71784.6	24794.5	32.6563	58417.6
310	330	1007	320.148	17282.8	30.9375	71576.3	24040.4	32.6563	60660.1
330	350	857	339.69	26348	30.9375	72464.2	25836.7	32.6563	60874.7
350	370	817	360.282	32093.1	30.9375	75955.7	25887.9	32.6563	60871.6
370	390	798	379.563	35461.1	32.6563	78639	25711	32.6563	61007.4
390	410	729	398.761	41568.3	32.6563	71354.9	23856.8	32.6563	61612.5
410	430	605	418.97	46041.7	32.6563	82656.4	22049.5	36.0938	64375.3
430	450	572	441.973	52181.2	36.0938	79863.8	18561.1	37.8125	67982.7
450	470	668	456.323	55826.8	36.0938	79669.9	10658.5	50892.4	68796.1
470	490	430	480.33	57707.6	36.0938	75674.5	11789.1	46218.2	71920.4
490	510	242	497.522	63633.2	36.0938	83113.9	10124.2	48687.8	76564.3
510	530	571	518.616	70340.1	36.0938	80600.4	11254.4	56814.4	77721.9

Mill C Coal Flow, lb/hr

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	120	137.669	39615.4	-8.59375	61815.2	12472.6	-6.875	47549.4
150	170	86	159.078	34939.9	-8.59375	65164.7	22405.6	-5.15625	56208.9
170	190	238	182.11	44620.4	-8.59375	61181.3	18646.7	-5.15625	54215.2
190	210	2824	201.171	36653.8	-8.59375	77306.3	17559.1	-5.15625	55687.1
210	230	1110	220.026	40885.2	-8.59375	75311.2	16408.9	-5.15625	59709
230	250	1072	239.646	44347.7	-8.59375	78372.3	14284.7	6.875	57736.8
250	270	1281	259.368	45388.9	-8.59375	74823	16224.4	0	56395.5
270	290	1084	279.773	46691.2	-8.59375	73819.6	14512.9	0	58589.2
290	310	1194	299.899	51165.7	-8.59375	78358.8	11959.4	42286.5	62886.5
310	330	1007	320.148	51949.8	-8.59375	75686.9	12937.9	42895.4	65713.6
330	350	857	339.69	51961	-6.875	86210.4	16922	0	69729.1
350	370	817	360.282	49134.4	-6.875	76542.5	18870.7	0	65187.6
370	390	798	379.563	52820.9	-6.875	76046.1	16123	0	63126.2
390	410	729	398.761	54042.2	-6.875	73752.3	16443.8	-6.875	65631.9
410	430	605	418.97	52473.3	-6.875	80562.6	20326.1	-6.875	68263.9
430	450	572	441.973	60717.4	10792.4	83631.3	6796.35	52883.6	71388.1
450	470	668	456.323	62064	-6.875	84586.9	7761.35	53771.6	75843.6
470	490	430	480.33	65768.5	-6.875	85363.1	8936.59	57801.2	80393.5
490	510	242	497.522	70988.7	53135.2	83081.3	6966.22	60502.8	80730
510	530	571	518.616	74677.7	55329	83569.8	4568.47	66188.2	78667.3

Mill D Coal Flow, lb/hr

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	120	137.669	40251.5	-134.063	60496.2	7953.52	31766.6	47071.1
150	170	86	159.078	47196.9	30709.8	64556.9	5408.6	39905.6	55588.4
170	190	238	182.11	51021.1	33004.1	66248.2	3221.01	45259.7	53563.1
190	210	2824	201.171	40608.9	-986.563	71262.8	13750	-440	56803.1
210	230	1110	220.026	45274.4	-823.281	73502	8516.28	39518.5	59153.9
230	250	1072	239.646	46353.8	-962.5	76322.5	10338.1	40024.2	57447.1
250	270	1281	259.368	47045.2	-965.938	77734.6	13195.5	-80.7813	55890.2
270	290	1084	279.773	47898.1	-965.938	79698.8	12825.9	0	58811.2
290	310	1194	299.899	51405.3	-720.156	75859.8	11431.9	41865.7	62725.4
310	330	1007	320.148	53407.3	-699.531	79616.6	9785.92	44763.7	65299.3
330	350	857	339.69	55452.1	-699.531	83478	9969.53	46588.4	69230.3
350	370	817	360.282	55586.2	-699.531	79572.3	6204.66	49508.4	64447
370	390	798	379.563	56801.1	-699.531	79321.3	7042.1	49092.7	63225.7
390	410	729	398.761	57899	-699.531	79584.7	7589.88	48721.9	64518.5
410	430	605	418.97	60577	-80.7813	80768.9	7682.01	50188.9	78368.8
430	450	572	441.973	61083.7	-658.281	82783.6	8966.82	52644.7	78108.1
450	470	668	456.323	61287.1	-658.281	81163.8	7017.13	55042.9	73418.4
470	490	430	480.33	64227.3	5667.41	84589.3	8927.07	56268.4	76550
490	510	242	497.522	70056.7	52922.4	84142.8	6083.36	60063.3	77385.3
510	530	571	518.616	73655.3	56209.7	82624.1	4268.22	65591.5	78465.8

Mill E Coal Flow, lb/hr

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	120	137.669	2234.46	-110	69266	11034.1	0	0
150	170	86	159.078	1158.64	0	53079.5	7569.41	0	0
170	190	238	182.11	1760.7	-110	62180.3	9630.97	-110	0
190	210	2824	201.171	10226	-110	78948.7	19318.4	-103.125	49049.4
210	230	1110	220.026	13814.6	-110	76321.8	21092.6	-103.125	47101
230	250	1072	239.646	22431	-110	68783.3	24334.3	-99.6875	51511.8
250	270	1281	259.368	22556.8	-110	75887.6	25229.4	-103.125	54627.5
270	290	1084	279.773	22728.5	-110	71064.8	24930.9	-99.6875	56743.5
290	310	1194	299.899	26405.1	-110	76193.6	25939.5	-99.6875	60292.8
310	330	1007	320.148	33044.1	-110	71654.7	25511.7	-99.6875	62629.1
330	350	857	339.69	33637.8	-115.156	72178.6	26159.5	-94.5313	64103.2
350	370	817	360.282	43047.8	-110	80855.8	23431.2	-89.375	60049.2
370	390	798	379.563	44156.2	-110	77280.2	24771	0	62651.9
390	410	729	398.761	44396.2	-104.844	73491.3	25572	0	64337.4
410	430	605	418.97	46880	-104.844	83712.8	25055.6	0	67479
430	450	572	441.973	39020.5	-104.844	77968.3	27803.4	0	67284.8
450	470	668	456.323	47950.3	-104.844	81483.2	23783.5	0	73217.5
470	490	430	480.33	44598	-104.844	82820.4	28392.3	0	70352.9
490	510	242	497.522	31856.4	0	83811.8	32866.6	0	69834.3
510	530	571	518.616	19733.5	0	81864.1	30514.1	0	67954.2

Mill F Coal Flow, lb/hr

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	120	137.669	-21.8282	-22.3438	-10.3125	2.08549	-22.3438	-17.1875
150	170	86	159.078	345.958	-24.0625	31668.8	3417.37	-24.0625	-22
170	190	238	182.11	38894.2	-22.3438	60773.6	22616.5	-22.3438	54394.9
190	210	2824	201.171	38654	-20.625	71902.2	17161.1	-18.9063	58244.3
210	230	1110	220.026	33790.9	-20.625	76084.9	22475	-18.9063	60145.6
230	250	1072	239.646	33234.4	-20.625	79111	23765.6	-18.9063	59429.6
250	270	1281	259.368	38488.5	-20.625	75620.9	22813.4	-18.9063	57208.1
270	290	1084	279.773	43513.9	-20.625	74285.4	18849.1	-18.9063	59261.5
290	310	1194	299.899	41475.4	-20.625	79496.3	23341	-18.9063	63429.3
310	330	1007	320.148	43937.6	-20.625	75113.8	22731	-18.9063	66097.1
330	350	857	339.69	47651.9	-18.9063	86412.6	21906.5	-18.9063	69910.9
350	370	817	360.282	45242.8	-18.9063	80817.7	22647	-18.9063	64097.7
370	390	798	379.563	45256.6	-18.9063	79918.4	23775.9	-18.9063	63661.7
390	410	729	398.761	47042.2	-18.9063	74397.8	23465	-18.9063	65028.1
410	430	605	418.97	52516.9	-18.9063	83548.4	20498.6	-10.3125	69005.2
430	450	572	441.973	58712.9	-18.9063	84704.8	11749.7	50052.5	70578.1
450	470	668	456.323	62271.8	5227.41	85432.9	8580.59	53414	76919.5
470	490	430	480.33	66355.1	45731.5	86295.3	8517.25	56672.7	80342.3
490	510	242	497.522	71479.3	51881.5	84033.5	7189.85	58938.2	80048.2
510	530	571	518.616	75204.5	56130.6	85095	4336.81	67092.2	79130.9

Table A-13 P4A – Mill Pattern Frequency by Load (1Q95)

Mill A-B-C-D-E-F	Load, MW 130	150	170	190	210	230	250	270	290	310	330	350	370	390	410	430	450	470	490	510
0-0-0-0-0-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-0-0-1-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-0-0-1-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-0-1-0-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-0-1-0-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-0-1-1-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-0-1-1-1	0	0	0	21	9	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-1-0-0-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-1-0-0-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-1-0-1-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-1-0-1-1	0	0	0	13	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-1-1-0-0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-1-1-0-1	0	0	170	454	120	48	10	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-1-1-1-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-1-1-1-1	0	0	0	3	31	54	50	19	1	0	0	0	0	0	0	0	0	0	0	0
0-1-0-0-0-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-0-0-0-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-0-0-1-0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-0-0-1-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-0-1-0-0	1	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-0-1-0-1	0	0	9	121	78	3	0	0	0	0	0	0	1	1	0	0	0	0	0	0
0-1-0-1-1-0	1	1	7	19	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-0-1-1-1	0	0	0	7	13	36	4	6	5	2	2	0	0	0	0	0	0	0	0	0
0-1-1-0-0-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-1-0-0-1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
0-1-1-0-1-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-1-0-1-1	0	0	0	87	16	9	6	2	0	0	0	0	0	0	0	0	0	0	0	0
0-1-1-1-0-0	110	61	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-1-1-0-1	0	1	0	573	198	251	277	200	357	150	145	65	86	111	63	155	80	37	75	402
0-1-1-1-1-0	0	0	0	15	1	0	0	2	3	2	0	0	0	0	0	0	0	0	0	0
0-1-1-1-1-1	0	0	0	0	0	0	6	4	6	14	43	56	43	29	28	4	69	11	0	0
1-0-0-0-0-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-0-0-0-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-0-0-1-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-0-0-1-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-0-1-0-0	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-0-1-0-1	0	0	0	74	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-0-1-1-0	1	1	1	35	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-0-1-1-1	0	0	0	141	23	25	98	50	27	26	5	0	0	0	0	0	0	0	0	0
1-0-1-0-0-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-1-0-0-1	0	0	0	27	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-1-0-1-0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-1-0-1-1	0	0	0	7	0	12	34	36	28	5	0	0	0	0	0	0	0	0	0	0
1-0-1-1-0-0	0	0	0	17	1	4	0	2	0	0	0	0	0	0	0	0	0	0	0	0
1-0-1-1-0-1	0	0	0	872	278	238	376	314	177	163	88	16	3	0	0	0	0	0	0	0
1-0-1-1-1-0	0	0	0	168	235	324	252	100	144	89	44	8	2	0	0	1	0	0	0	0
1-0-1-1-1-1	0	0	0	0	0	11	58	217	273	373	277	294	267	176	106	56	18	14	3	8
1-1-0-0-0-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-1-0-0-0-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-1-0-0-1-0	0	0	0	37	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-1-0-0-1-1	0	0	0	0	0	16	6	6	4	3	0	0	0	0	0	0	0	0	0	0
1-1-0-1-0-0	2	1	18	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-1-0-1-0-1	0	0	0	4	12	5	27	8	0	0	0	0	0	0	0	0	0	0	0	0
1-1-0-1-1-0	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-1-0-1-1-1	0	0	0	0	0	0	4	11	5	11	60	100	63	55	73	1	1	1	0	0
1-1-1-0-0-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-1-1-0-0-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-1-1-0-1-0	0	0	0	55	5	2	38	10	0	0	0	0	0	0	0	0	0	0	0	0
1-1-1-0-1-1	0	0	0	0	0	0	0	2	4	9	13	5	7	7	1	4	1	1	0	0
1-1-1-1-0-0	0	0	0	40	83	22	16	10	3	2	0	1	0	0	0	0	0	0	0	0
1-1-1-1-0-1	0	0	0	0	0	0	1	50	39	53	86	101	97	65	66	34	44	85	49	0
1-1-1-1-1-0	0	0	0	0	0	0	18	35	118	105	92	149	166	139	72	14	3	0	0	0
1-1-1-1-1-1	0	0	0	0	0	0	0	0	0	0	2	22	62	146	196	303	452	281	115	161

[1]Number of occurrances of mill combination
[2]Mill on = 1, Mill off = 0 (assumed off if flow < 20000 lb/hr)

Table A-14 P4A – NOx Emissions by Load and Mill Pattern (1Q95)

	Load, MW																			
Mill A-B-C-D-E-F	130	150	170	190	210	230	250	270	290	310	330	350	370	390	410	430	450	470	490	510
0-0-0-0-0-1	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-0-0-1-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-0-0-1-1	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-0-1-0-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-0-1-0-1	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-0-1-1-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-0-1-1-1	na	na	na	0.427	0.361	0.329	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-1-0-0-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-1-0-0-1	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-1-0-1-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-1-0-1-1	na	na	na	0.563	0.596	0.462	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-1-1-0-0	na	na	na	0.367	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-1-1-0-1	na	na	0.421	0.387	0.378	0.378	0.383	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-1-1-1-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-1-1-1-1	na	na	na	0.544	0.435	0.421	0.473	0.460	0.392	na	na	na	na	na	na	na	na	na	na	na
0-1-0-0-0-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-1-0-0-0-1	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-1-0-0-1-0	0.294	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-1-0-0-1-1	na	na	na	0.505	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-1-0-1-0-0	0.331	0.267	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-1-0-1-0-1	na	na	0.309	0.334	0.327	0.328	na	na	na	na	na	na	0.324	0.338	na	na	na	na	na	na
0-1-0-1-1-0	0.283	0.332	0.318	0.326	0.397	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-1-0-1-1-1	na	na	na	0.490	0.409	0.369	0.363	0.401	0.363	0.393	0.397	na	na	na	na	na	na	na	na	na
0-1-1-0-0-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-1-1-0-0-1	na	na	na	na	na	na	na	na	na	na	na	na	0.382	na	na	na	na	na	na	na
0-1-1-0-1-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-1-1-0-1-1	na	na	na	0.513	0.516	0.488	0.470	0.454	na	na	na	na	na	na	na	na	na	na	na	na
0-1-1-1-0-0	0.445	0.409	0.389	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-1-1-1-0-1	na	0.415	na	0.418	0.412	0.421	0.423	0.403	0.421	0.425	0.442	0.401	0.376	0.368	0.373	0.379	0.386	0.392	0.449	0.399
0-1-1-1-1-0	na	na	na	0.513	0.522	na	na	0.393	0.438	0.413	na	na	na	na	na	na	na	na	na	na
0-1-1-1-1-1	na	na	na	na	na	na	0.542	0.494	0.472	0.465	0.462	0.460	0.431	0.436	0.437	0.463	0.408	0.428	na	na
1-0-0-0-0-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-0-0-0-1	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-0-0-1-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-0-0-1-1	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-0-1-0-0	0.323	na	na	na	0.384	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-0-1-0-1	na	na	na	0.400	0.411	0.434	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-0-1-1-0	0.320	0.387	0.346	0.283	0.268	0.307	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-0-1-1-1	na	na	na	0.429	0.380	0.362	0.349	0.371	0.353	0.352	0.355	na	na	na	na	na	na	na	na	na
1-0-1-0-0-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-1-0-0-1	na	na	na	0.482	na	0.501	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-1-0-1-0	na	na	na	0.522	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-1-0-1-1	na	na	na	0.558	na	0.511	0.449	0.432	0.410	0.394	na	na	na	na	na	na	na	na	na	na
1-0-1-1-0-0	na	na	na	0.438	0.424	0.431	na	0.374	na	na	na	na	na	na	na	na	na	na	na	na
1-0-1-1-0-1	na	na	na	0.440	0.435	0.425	0.425	0.418	0.418	0.417	0.441	0.447	0.465	na	na	na	na	na	na	na
1-0-1-1-1-0	na	na	na	0.379	0.365	0.359	0.357	0.353	0.355	0.367	0.383	0.400	0.383	na	na	0.451	na	na	na	na
1-0-1-1-1-1	na	na	na	na	na	0.467	0.412	0.415	0.429	0.425	0.434	0.431	0.428	0.419	0.414	0.417	0.421	0.397	0.411	0.426
1-1-0-0-0-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-1-0-0-0-1	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-1-0-0-1-0	na	na	na	0.300	0.328	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-1-0-0-1-1	na	na	na	na	na	0.428	0.451	0.392	0.365	0.371	na	na	na	na	na	na	na	na	na	na
1-1-0-1-0-0	0.314	0.272	0.343	0.363	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-1-0-1-0-1	na	na	na	0.512	0.527	0.470	0.441	0.499	na	na	na	na	na	na	na	na	na	na	na	na
1-1-0-1-1-0	na	na	na	0.439	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-1-0-1-1-1	na	na	na	na	na	na	0.414	0.431	0.400	0.415	0.393	0.397	0.394	0.390	0.387	0.496	0.388	0.391	na	na
1-1-1-0-0-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-1-1-0-0-1	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-1-1-0-1-0	na	na	na	0.493	0.436	0.403	0.406	0.401	na	na	na	na	na	na	na	na	na	na	na	na
1-1-1-0-1-1	na	na	na	na	na	na	na	0.449	0.453	0.446	0.437	0.450	0.418	0.419	0.455	0.420	0.385	0.380	na	na
1-1-1-1-0-0	na	na	na	0.436	0.462	0.447	0.430	0.433	0.452	0.433	na	0.456	na	na	na	na	na	na	na	na
1-1-1-1-0-1	na	na	na	na	na	na	0.503	0.511	0.495	0.488	0.499	0.488	0.484	0.481	0.481	0.463	0.453	0.445	0.445	na
1-1-1-1-1-0	na	na	na	na	na	na	0.374	0.386	0.360	0.369	0.385	0.391	0.391	0.395	0.412	0.404	0.407	na	na	na
1-1-1-1-1-1	na	na	na	na	na	na	na	na	na	na	0.465	0.442	0.428	0.430	0.428	0.437	0.425	0.427	0.437	0.447

[1] Mill on = 1, Mill off = 0 (assumed off if flow < 20000 lb/hr)
[2] NOx filtered for invalid data points

Table A-15 P4A – Stack O2 by Load and Mill Pattern (1Q95)

Mill A-B-C-D-E-F	Load, MW 130	150	170	190	210	230	250	270	290	310	330	350	370	390	410	430	450	470	490	510
0-0-0-0-0-1	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-0-0-1-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-0-0-1-1	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-0-1-0-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-0-1-0-1	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-0-1-1-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-0-1-1-1	na	na	na	9.940	8.898	8.296	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-1-0-0-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-1-0-0-1	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-1-0-1-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-1-0-1-1	na	na	na	11.454	11.827	11.087	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-1-1-0-0	na	na	na	9.372	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-1-1-0-1	na	na	7.859	10.486	9.069	11.534	11.479	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-1-1-1-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-0-1-1-1-1	na	na	na	11.200	9.222	9.147	10.289	10.326	8.416	na	na	na	na	na	na	na	na	na	na	na
0-1-0-0-0-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-1-0-0-0-1	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-1-0-0-1-0	9.281	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-1-0-0-1-1	na	na	na	11.156	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-1-0-1-0-0	10.332	9.282	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-1-0-1-0-1	na	na	8.815	8.839	8.691	8.707	na	na	na	na	na	na	6.140	6.147	na	na	na	na	na	na
0-1-0-1-1-0	9.180	8.842	8.608	8.576	7.869	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-1-0-1-1-1	na	na	na	10.885	7.223	8.780	7.929	7.888	8.541	7.628	7.206	na	na	na	na	na	na	na	na	na
0-1-1-0-0-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-1-1-0-0-1	na	na	na	na	na	na	na	na	na	na	na	na	6.063	na	na	na	na	na	na	na
0-1-1-0-1-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-1-1-0-1-1	na	na	na	11.113	11.267	11.182	10.929	10.630	na	na	na	na	na	na	na	na	na	na	na	na
0-1-1-1-0-0	9.527	9.188	9.267	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
0-1-1-1-0-1	na	7.312	na	8.750	8.463	8.743	8.280	7.887	7.549	7.355	7.120	7.014	6.426	6.836	6.543	6.701	6.475	6.563	6.373	6.083
0-1-1-1-1-0	na	na	na	11.000	11.415	na	na	9.941	10.479	10.927	na	na	na	na	na	na	na	na	na	na
0-1-1-1-1-1	na	na	na	na	na	na	10.546	10.321	9.837	8.048	8.275	7.805	8.348	8.430	7.849	8.077	6.231	6.648	na	na
1-0-0-0-0-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-0-0-0-1	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-0-0-1-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-0-0-1-1	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-0-1-0-0	10.231	na	na	na	7.658	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-0-1-0-1	na	na	na	11.266	11.198	10.286	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-0-1-1-0	9.929	9.926	9.087	7.765	7.549	7.042	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-0-1-1-1	na	na	na	8.906	8.396	7.773	7.274	8.524	7.261	6.434	6.213	na	na	na	na	na	na	na	na	na
1-0-1-0-0-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-1-0-0-1	na	na	na	11.630	na	11.431	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-1-0-1-0	na	na	na	11.495	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-0-1-0-1-1	na	na	na	11.011	na	11.321	10.040	9.821	8.651	8.142	na	na	na	na	na	na	na	na	na	na
1-0-1-1-0-0	na	na	na	10.142	7.132	9.489	na	8.750	na	na	na	na	na	na	na	na	na	na	na	na
1-0-1-1-0-1	na	na	na	9.002	9.088	9.314	8.783	9.528	9.130	8.992	9.327	7.628	9.043	na	na	na	na	na	na	na
1-0-1-1-1-0	na	na	na	8.041	7.767	7.679	7.331	7.139	7.273	7.224	7.176	7.754	6.451	na	na	6.851	na	na	na	na
1-0-1-1-1-1	na	na	na	na	na	8.301	7.026	7.070	7.176	7.262	7.091	6.756	6.683	6.472	7.524	7.711	6.885	7.827	7.055	7.289
1-1-0-0-0-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-1-0-0-0-1	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-1-0-0-1-0	na	na	na	9.098	8.116	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-1-0-0-1-1	na	na	na	na	na	11.309	10.124	9.881	8.055	8.001	na	na	na	na	na	na	na	na	na	na
1-1-0-1-0-0	10.249	7.927	8.291	10.374	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-1-0-1-0-1	na	na	na	11.602	11.221	10.857	8.803	10.060	na	na	na	na	na	na	na	na	na	na	na	na
1-1-0-1-1-0	na	na	na	11.225	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-1-0-1-1-1	na	na	na	na	na	na	9.408	8.604	7.782	8.243	6.634	7.131	6.629	6.515	6.673	9.955	6.120	5.553	na	na
1-1-1-0-0-0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-1-1-0-0-1	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
1-1-1-0-1-0	na	na	na	10.838	8.895	8.407	8.546	7.984	na	na	na	na	na	na	na	na	na	na	na	na
1-1-1-0-1-1	na	na	na	na	na	na	na	8.061	7.166	7.496	7.537	8.550	6.936	6.728	6.406	7.475	7.639	6.937	na	na
1-1-1-1-0-0	na	na	na	9.497	10.396	10.273	9.227	8.878	9.087	8.582	na	8.227	na	na	na	na	na	na	na	na
1-1-1-1-0-1	na	na	na	na	na	na	8.366	9.060	8.550	8.282	8.118	7.863	7.850	7.778	7.543	6.837	6.296	6.292	6.317	na
1-1-1-1-1-0	na	na	na	na	na	na	7.458	8.374	7.037	7.146	7.234	7.246	7.244	7.191	7.286	6.957	6.266	na	na	na
1-1-1-1-1-1	na	na	na	na	na	na	na	na	na	na	6.253	7.242	6.959	6.844	6.512	6.337	6.129	6.334	6.612	5.853

[1] Mill on = 1, Mill off = 0 (assumed off if flow < 20000 lb/hr)
[2] Stack O_2 filtered for invalid data points

Table A-16 Process Data for 1st Quarter 1996

Load, MW

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.00	65535.00	65535.00	65535.00	65535.00	65535.00
150	170	8	165.87	165.87	154.87	169.19	4.72	154.87	169.19
170	190	28	177.21	177.21	171.24	189.78	5.95	171.35	189.66
190	210	2710	200.35	200.35	190.43	209.85	3.16	195.52	206.56
210	230	522	218.82	218.82	210.03	229.98	6.32	210.88	228.89
230	250	363	238.61	238.61	230.02	249.96	5.52	230.69	248.91
250	270	268	259.51	259.51	250.09	269.98	6.04	250.85	269.21
270	290	413	280.65	280.65	270.00	290.00	5.33	271.95	288.44
290	310	557	301.52	301.52	290.05	309.96	5.45	291.32	308.18
310	330	288	321.22	321.22	310.12	330.00	5.55	311.30	328.80
330	350	112	340.14	340.14	330.19	349.80	5.97	331.65	349.23
350	370	165	359.59	359.59	350.15	369.94	5.69	351.30	368.83
370	390	152	380.28	380.28	370.19	389.97	5.98	371.35	389.30
390	410	292	400.56	400.56	390.04	409.98	4.95	390.85	408.82
410	430	276	414.98	414.98	410.04	429.95	6.33	410.32	427.26
430	450	106	439.34	439.34	430.09	449.67	5.67	430.69	448.80
450	470	141	460.92	460.92	450.29	469.95	5.81	451.55	469.34
470	490	352	477.40	477.40	470.04	489.12	3.40	471.26	482.11
490	510	231	504.77	504.77	490.72	509.90	3.53	497.06	509.33
510	530	6	510.64	510.64	510.13	512.59	0.97	510.13	512.59

Main Steam Temperature,°F

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.00	65535.00	65535.00	65535.00	65535.00	65535.00
150	170	8	165.87	852.31	809.21	884.07	24.04	809.21	884.07
170	190	28	177.21	926.74	824.66	993.93	44.79	839.18	992.34
190	210	2710	200.35	994.81	849.68	1015.70	12.65	979.56	999.99
210	230	522	218.82	995.74	876.47	1010.75	10.32	983.04	1003.52
230	250	363	238.61	996.81	945.25	1008.14	7.18	988.60	1002.70
250	270	268	259.51	997.19	947.24	1052.81	7.14	991.46	1001.62
270	290	413	280.65	997.82	960.72	1054.26	5.47	993.04	1002.25
290	310	557	301.52	998.44	960.29	1026.10	4.35	995.09	1005.28
310	330	288	321.22	997.67	973.29	1024.77	4.39	992.83	1002.76
330	350	112	340.14	998.88	963.55	1040.51	10.34	985.61	1019.66
350	370	165	359.59	998.97	958.32	1051.99	8.74	990.14	1012.85
370	390	152	380.28	996.68	975.20	1036.41	6.47	987.03	1004.64
390	410	292	400.56	997.05	970.22	1036.85	5.43	989.54	1003.84
410	430	276	414.98	996.97	980.85	1028.64	3.36	994.19	1000.22
430	450	106	439.34	995.21	976.62	1009.28	4.99	985.06	1001.25
450	470	141	460.92	996.34	987.60	1006.60	2.19	992.14	998.99
470	490	352	477.40	996.29	990.01	1001.92	1.08	995.05	998.10
490	510	231	504.77	996.16	992.10	999.40	0.55	995.52	996.43
510	530	6	510.64	995.50	993.17	996.23	1.18	993.17	996.23

Hot Reheat Temperature, °f

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.00	65535.00	65535.00	65535.00	65535.00	65535.00
150	170	8	165.87	890.67	852.65	922.85	25.18	852.65	922.85
170	190	28	177.21	937.83	913.12	979.16	19.49	916.44	966.97
190	210	2710	200.35	979.81	850.58	1005.48	17.63	951.31	996.49
210	230	522	218.82	984.92	936.38	1009.50	14.25	953.79	999.21
230	250	363	238.61	983.91	937.57	1007.25	15.15	950.34	1000.64
250	270	268	259.51	982.28	934.20	1006.82	15.54	952.05	999.70
270	290	413	280.65	982.37	938.43	1009.57	15.37	954.30	1000.30
290	310	557	301.52	988.69	948.85	1013.40	9.33	966.91	1000.37
310	330	288	321.22	987.13	950.11	1008.93	13.02	959.25	1001.67
330	350	112	340.14	989.80	961.04	1009.52	10.93	970.08	1005.63
350	370	165	359.59	993.87	965.00	1011.78	8.98	978.70	1006.86
370	390	152	380.28	994.39	973.24	1015.36	7.33	980.86	1007.65
390	410	292	400.56	995.34	974.44	1015.78	5.49	985.47	1004.48
410	430	276	414.98	996.85	979.77	1013.81	3.88	991.82	1004.66
430	450	106	439.34	997.92	981.56	1012.69	6.02	987.25	1007.72
450	470	141	460.92	997.49	981.07	1009.61	4.48	991.70	1005.46
470	490	352	477.40	996.81	988.21	1008.49	2.78	994.31	1003.42
490	510	231	504.77	995.76	989.11	1007.32	1.58	994.86	997.29
510	530	6	510.64	997.60	993.61	1001.51	3.11	993.61	1001.51

Excess Oxygen, Left Hand, %

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.00	65535.00	65535.00	65535.00	65535.00	65535.00
150	170	8	165.87	7.26	6.47	7.91	0.54	6.47	7.91
170	190	28	177.21	6.64	4.70	7.94	0.87	5.19	7.77
190	210	2710	200.35	5.84	4.94	7.16	0.31	5.42	6.44
210	230	522	218.82	5.67	4.44	6.82	0.36	5.08	6.30
230	250	363	238.61	5.29	3.71	6.49	0.39	4.62	5.88
250	270	268	259.51	5.06	3.36	5.96	0.38	4.42	5.56
270	290	413	280.65	4.74	3.64	6.39	0.39	4.18	5.41
290	310	557	301.52	4.35	3.41	5.76	0.37	3.87	5.24
310	330	288	321.22	4.22	2.93	5.47	0.33	3.62	4.62
330	350	112	340.14	3.93	2.55	5.48	0.50	3.23	4.82
350	370	165	359.59	3.97	2.76	4.81	0.39	3.40	4.58
370	390	152	380.28	3.98	2.41	5.68	0.57	3.06	4.92
390	410	292	400.56	3.81	2.97	5.54	0.54	3.12	4.81
410	430	276	414.98	4.10	2.99	5.28	0.40	3.50	5.06
430	450	106	439.34	3.85	2.73	5.63	0.66	3.06	5.16
450	470	141	460.92	3.93	2.78	5.19	0.59	3.09	5.03
470	490	352	477.40	4.05	2.79	5.14	0.57	3.24	4.94
490	510	231	504.77	3.34	3.16	4.39	0.19	3.26	3.70
510	530	6	510.64	3.59	3.30	4.54	0.48	3.30	4.54

Excess Oxygen Right Hand, %

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.00	65535.00	65535.00	65535.00	65535.00	65535.00
150	170	8	165.87	5.95	5.20	6.72	0.51	5.20	6.72
170	190	28	177.21	5.85	4.66	7.10	0.56	4.78	6.82
190	210	2710	200.35	5.77	4.40	6.53	0.24	5.31	6.10
210	230	522	218.82	5.48	4.55	6.79	0.32	4.89	5.91
230	250	363	238.61	5.21	4.16	6.21	0.32	4.65	5.73
250	270	268	259.51	4.86	4.12	5.84	0.31	4.37	5.31
270	290	413	280.65	4.62	3.37	5.82	0.32	4.23	5.15
290	310	557	301.52	4.44	3.18	5.36	0.32	3.97	4.85
310	330	288	321.22	4.20	3.28	5.62	0.32	3.78	4.75
330	350	112	340.14	4.16	3.12	5.07	0.46	3.35	4.81
350	370	165	359.59	4.04	2.77	4.76	0.37	3.48	4.62
370	390	152	380.28	4.02	2.72	5.26	0.46	3.17	4.70
390	410	292	400.56	3.76	2.99	4.79	0.41	3.25	4.44
410	430	276	414.98	3.69	3.07	4.82	0.34	3.47	4.48
430	450	106	439.34	3.82	2.91	5.49	0.40	3.28	4.46
450	470	141	460.92	3.58	2.91	4.58	0.39	3.12	4.29
470	490	352	477.40	3.55	2.78	4.42	0.42	3.04	4.27
490	510	231	504.77	3.54	2.77	3.76	0.15	3.16	3.61
510	530	6	510.64	3.59	3.47	3.86	0.15	3.47	3.86

Main Steam Pressure, PSIG

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.00	65535.00	65535.00	65535.00	65535.00	65535.00
150	170	8	165.87	1300.08	1124.30	1523.50	134.53	1124.30	1523.50
170	190	28	177.21	1807.98	1310.75	2332.23	239.89	1445.88	2197.77
190	210	2710	200.35	2350.64	1502.34	2452.66	71.45	2347.24	2367.93
210	230	522	218.82	2349.87	2016.90	2449.21	53.48	2313.57	2383.80
230	250	363	238.61	2316.41	2081.30	2455.60	96.27	2108.92	2393.16
250	270	268	259.51	2352.98	2095.42	2444.13	44.66	2293.79	2391.55
270	290	413	280.65	2345.83	2097.40	2450.10	58.88	2204.55	2390.38
290	310	557	301.52	2355.92	2075.79	2427.11	38.34	2337.58	2373.35
310	330	288	321.22	2345.70	2082.03	2452.15	60.67	2131.13	2382.44
330	350	112	340.14	2324.76	2046.08	2458.69	85.51	2121.56	2390.48
350	370	165	359.59	2333.77	2066.21	2439.43	74.04	2152.58	2398.25
370	390	152	380.28	2349.73	2081.42	2474.94	53.25	2274.42	2396.84
390	410	292	400.56	2354.33	2070.23	2428.98	50.31	2304.38	2394.01
410	430	276	414.98	2359.68	2107.55	2437.07	26.23	2325.56	2392.41
430	450	106	439.34	2361.08	2167.05	2450.91	32.34	2312.40	2400.21
450	470	141	460.92	2355.11	2169.19	2411.36	33.26	2292.74	2385.87
470	490	352	477.40	2359.80	2122.43	2412.32	27.04	2347.80	2371.43
490	510	231	504.77	2362.99	2318.76	2387.83	6.29	2360.39	2366.93
510	530	6	510.64	2367.06	2363.86	2378.24	5.58	2363.86	2378.24

Secondary Air Heater A Gas Outlet Temperature, °F

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.00	65535.00	65535.00	65535.00	65535.00	65535.00
150	170	8	165.87	282.44	274.69	299.91	7.78	274.69	299.91
170	190	28	177.21	289.34	275.78	319.26	11.31	276.90	305.99
190	210	2710	200.35	296.49	257.17	327.55	13.04	277.07	315.10
210	230	522	218.82	296.52	257.93	338.12	14.17	282.69	321.80
230	250	363	238.61	287.90	247.18	336.24	18.16	250.87	309.61
250	270	268	259.51	289.89	257.50	327.96	11.70	269.26	307.13
270	290	413	280.65	282.80	258.24	333.15	13.76	262.93	306.82
290	310	557	301.52	295.19	260.55	336.74	11.54	277.35	319.25
310	330	288	321.22	289.65	261.45	333.92	18.26	268.36	322.77
330	350	112	340.14	288.01	256.71	328.86	11.69	272.37	303.13
350	370	165	359.59	277.61	248.76	302.88	13.77	253.02	297.00
370	390	152	380.28	279.29	251.65	303.47	12.28	253.76	298.58
390	410	292	400.56	283.79	252.21	304.22	9.56	265.01	298.44
410	430	276	414.98	283.54	259.33	307.77	7.25	270.94	299.00
430	450	106	439.34	288.23	263.42	307.21	10.53	266.76	302.84
450	470	141	460.92	289.44	266.02	311.56	9.68	271.27	304.50
470	490	352	477.40	293.64	270.20	314.09	12.31	274.19	312.36
490	510	231	504.77	306.05	304.05	314.24	3.39	304.05	313.28
510	530	6	510.64	311.95	308.83	313.67	1.69	308.83	313.67

Secondary Air Heater B Gas Outlet Temperature, °F

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.00	65535.00	65535.00	65535.00	65535.00	65535.00
150	170	8	165.87	291.66	285.88	298.50	4.28	285.88	298.50
170	190	28	177.21	306.80	291.63	329.32	13.12	292.34	327.26
190	210	2710	200.35	296.58	255.23	347.70	13.45	272.47	316.02
210	230	522	218.82	299.45	261.10	338.48	17.50	273.05	333.19
230	250	363	238.61	293.04	247.54	329.85	14.42	268.82	317.17
250	270	268	259.51	287.01	247.72	320.35	12.64	269.73	304.16
270	290	413	280.65	288.74	264.31	333.26	9.48	274.73	304.47
290	310	557	301.52	300.59	269.32	336.10	11.63	280.35	323.38
310	330	288	321.22	299.02	276.64	337.08	16.52	281.10	328.48
330	350	112	340.14	302.82	275.80	335.71	14.50	284.36	326.38
350	370	165	359.59	300.61	280.62	330.95	11.42	286.33	324.30
370	390	152	380.28	299.62	273.71	328.81	13.65	282.22	323.49
390	410	292	400.56	304.16	273.24	329.12	10.82	285.23	322.36
410	430	276	414.98	304.37	281.34	328.75	7.03	290.16	317.23
430	450	106	439.34	309.15	283.86	329.47	11.44	285.51	322.56
450	470	141	460.92	308.90	285.60	334.42	10.28	289.53	326.10
470	490	352	477.40	314.21	287.27	337.11	13.21	293.60	335.37
490	510	231	504.77	325.62	323.60	337.87	3.60	323.60	333.21
510	530	6	510.64	332.00	327.19	335.79	2.92	327.19	335.79

Secondary Air Heater A Gas Inlet Temperature, °F

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.00	65535.00	65535.00	65535.00	65535.00	65535.00
150	170	8	165.87	582.98	570.09	594.43	7.91	570.09	594.43
170	190	28	177.21	603.07	588.60	627.94	10.87	589.09	623.06
190	210	2710	200.35	607.93	574.32	652.53	15.96	583.65	633.29
210	230	522	218.82	620.74	585.21	663.73	20.22	593.60	650.62
230	250	363	238.61	633.76	591.07	678.57	22.13	603.98	669.53
250	270	268	259.51	636.37	605.66	690.95	16.66	613.17	673.42
270	290	413	280.65	647.06	617.60	703.60	18.99	627.25	682.22
290	310	557	301.52	663.99	626.61	719.55	16.16	640.47	700.82
310	330	288	321.22	673.19	635.59	733.94	25.43	638.49	714.20
330	350	112	340.14	695.11	653.87	743.92	26.76	655.49	736.43
350	370	165	359.59	701.32	662.13	755.17	21.50	673.58	745.33
370	390	152	380.28	711.51	682.24	760.35	14.86	688.74	733.10
390	410	292	400.56	717.58	680.80	771.86	15.55	684.35	738.20
410	430	276	414.98	726.44	710.27	767.23	9.11	714.85	746.73
430	450	106	439.34	749.38	721.93	777.08	15.84	726.36	773.37
450	470	141	460.92	751.25	726.36	779.10	9.12	738.19	765.77
470	490	352	477.40	760.56	743.19	780.44	6.29	748.18	768.48
490	510	231	504.77	776.15	759.31	794.89	4.92	765.49	781.30
510	530	6	510.64	789.36	784.63	795.01	4.27	784.63	795.01

Secondary Air Heater B Gas Inlet Temperature, °F

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.00	65535.00	65535.00	65535.00	65535.00	65535.00
150	170	8	165.87	590.99	579.30	600.98	6.95	579.30	600.98
170	190	28	177.21	615.14	593.93	697.51	19.64	595.87	642.94
190	210	2710	200.35	641.02	587.02	697.51	34.77	601.65	697.51
210	230	522	218.82	657.62	588.15	697.51	33.35	604.98	697.51
230	250	363	238.61	673.26	606.81	697.51	27.19	617.51	697.51
250	270	268	259.51	676.13	615.43	706.39	26.84	629.58	697.51
270	290	413	280.65	684.60	630.01	728.62	20.64	641.08	703.47
290	310	557	301.52	678.41	640.86	733.51	17.40	649.55	697.51
310	330	288	321.22	690.90	647.52	764.67	19.61	653.68	727.39
330	350	112	340.14	708.51	661.51	771.94	31.95	668.80	764.85
350	370	165	359.59	709.91	672.19	785.28	27.74	681.36	770.09
370	390	152	380.28	711.90	688.07	788.20	19.50	697.51	747.74
390	410	292	400.56	712.29	694.49	806.21	21.25	697.51	754.60
410	430	276	414.98	702.29	697.51	787.51	15.79	697.51	742.15
430	450	106	439.34	729.98	697.51	796.59	40.60	697.51	793.32
450	470	141	460.92	706.84	697.51	799.10	25.16	697.51	770.98
470	490	352	477.40	705.17	697.51	793.24	24.41	697.51	776.35
490	510	231	504.77	714.24	697.51	801.50	37.25	697.51	799.28
510	530	6	510.64	697.51	697.51	697.51	0.00	697.51	697.51

Stack O2, %

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.00	65535.00	65535.00	65535.00	65535.00	65535.00
150	170	8	165.87	6.77	6.08	7.23	0.41	6.08	7.23
170	190	28	177.21	6.51	4.68	8.05	0.72	5.41	7.65
190	210	2710	200.35	6.46	4.31	7.75	0.33	5.86	6.99
210	230	522	218.82	6.13	4.66	7.51	0.51	5.09	6.85
230	250	363	238.61	5.83	4.78	7.35	0.45	5.15	6.56
250	270	268	259.51	5.71	4.52	6.80	0.41	4.88	6.37
270	290	413	280.65	5.38	4.35	7.06	0.49	4.74	6.28
290	310	557	301.52	5.24	4.07	6.79	0.41	4.55	6.10
310	330	288	321.22	5.05	3.58	8.97	0.53	4.22	5.58
330	350	112	340.14	4.71	3.76	6.90	0.58	3.89	5.63
350	370	165	359.59	5.03	3.63	8.37	0.83	3.84	6.49
370	390	152	380.28	5.02	3.61	10.62	0.85	3.89	6.81
390	410	292	400.56	4.75	3.59	10.24	0.86	3.77	6.09
410	430	276	414.98	4.90	3.62	10.39	0.83	4.33	6.16
430	450	106	439.34	4.59	3.24	7.75	0.86	3.57	6.24
450	470	141	460.92	4.69	3.54	9.50	0.82	3.89	6.03
470	490	352	477.40	4.79	3.73	10.14	0.91	4.04	6.95
490	510	231	504.77	4.26	3.65	4.73	0.09	4.14	4.42
510	530	6	510.64	4.35	4.16	4.81	0.24	4.16	4.81

Stack NOx, lb/MBtu

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.000	65535.000	65535.000	65535.000	65535.000	65535.000
150	170	8	165.87	0.431	0.331	0.469	0.047	0.331	0.469
170	190	28	177.21	0.430	0.336	0.540	0.049	0.344	0.500
190	210	2710	200.35	0.386	0.282	0.834	0.042	0.307	0.451
210	230	522	218.82	0.390	0.278	0.582	0.052	0.311	0.492
230	250	363	238.61	0.374	0.245	0.523	0.047	0.293	0.447
250	270	268	259.51	0.369	0.278	0.519	0.040	0.299	0.425
270	290	413	280.65	0.371	0.261	0.510	0.037	0.321	0.424
290	310	557	301.52	0.368	0.292	0.508	0.028	0.326	0.414
310	330	288	321.22	0.361	0.287	0.481	0.035	0.305	0.410
330	350	112	340.14	0.368	0.243	0.463	0.040	0.302	0.423
350	370	165	359.59	0.373	0.285	0.507	0.037	0.307	0.433
370	390	152	380.28	0.390	0.263	0.485	0.037	0.310	0.443
390	410	292	400.56	0.399	0.275	0.492	0.033	0.350	0.443
410	430	276	414.98	0.385	0.270	0.465	0.027	0.350	0.435
430	450	106	439.34	0.374	0.254	0.529	0.066	0.273	0.463
450	470	141	460.92	0.390	0.227	0.469	0.041	0.354	0.452
470	490	352	477.40	0.415	0.227	0.498	0.035	0.362	0.468
490	510	231	504.77	0.469	0.401	0.516	0.014	0.436	0.478
510	530	6	510.64	0.500	0.485	0.522	0.014	0.485	0.522

Stack CO, ppm (Uncorrected)

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.00	65535.00	65535.00	65535.00	65535.00	65535.00
150	170	2	165.77	10.53	-4.91	25.96	21.83	-4.91	25.96
170	190	11	177.86	6.41	-4.96	56.18	19.39	-4.96	54.94
190	210	2154	200.38	28.09	-5.00	88.50	23.64	-3.97	62.32
210	230	433	218.26	24.55	-4.99	78.44	22.40	-3.42	68.30
230	250	318	238.92	22.57	-4.92	78.52	19.53	-3.13	61.40
250	270	245	259.27	28.42	-4.91	195.61	23.40	-3.80	65.61
270	290	389	280.76	42.29	-4.98	280.99	46.25	-3.06	126.04
290	310	546	301.51	63.01	-4.78	298.71	47.19	7.64	129.31
310	330	286	321.23	61.77	-4.96	298.32	58.47	0.00	157.88
330	350	112	340.14	89.51	-3.41	289.49	76.48	1.87	252.42
350	370	165	359.59	94.12	-1.95	294.39	79.22	12.34	266.22
370	390	150	380.22	69.91	-4.96	296.99	65.95	3.31	221.39
390	410	290	400.52	74.57	-5.00	295.68	67.15	0.26	245.02
410	430	273	414.91	75.60	-4.80	300.37	51.78	-2.62	165.38
430	450	105	439.38	97.75	-4.85	296.34	86.05	-3.04	279.37
450	470	141	460.92	101.16	-4.69	305.07	78.67	-1.22	270.43
470	490	352	477.40	105.20	-3.86	300.77	87.92	-0.38	276.51
490	510	231	504.77	43.87	12.96	294.22	28.36	22.64	66.90
510	530	6	510.64	41.41	23.28	55.23	11.23	23.28	55.23

NOx, Compliance CEM, lb/Mbtu

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.000	65535.000	65535.000	65535.000	65535.000	65535.000
150	170	8	165.87	0.4394	0.3730	0.4650	0.0290	0.3730	0.4650
170	190	28	177.21	0.5557	0.3840	1.3130	0.2565	0.4056	1.1915
190	210	2710	200.35	0.5183	0.2620	1.3290	0.2152	0.3630	1.2720
210	230	522	218.82	0.4386	0.2510	0.7260	0.0586	0.3402	0.5150
230	250	363	238.61	0.4249	0.2700	1.0100	0.0812	0.3267	0.5254
250	270	268	259.51	0.4146	0.2850	0.9730	0.0823	0.3270	0.5099
270	290	413	280.65	0.4070	0.2360	0.7020	0.0578	0.3380	0.5379
290	310	557	301.52	0.3918	0.2410	0.7230	0.0626	0.3214	0.5243
310	330	288	321.22	0.3696	0.2030	0.6160	0.0476	0.3069	0.4371
330	350	112	340.14	0.3834	0.2500	0.6580	0.0653	0.3100	0.5062
350	370	165	359.59	0.4047	0.2370	1.4490	0.1465	0.2785	0.6480
370	390	152	380.28	0.4239	0.2380	0.8230	0.0888	0.3545	0.5934
390	410	292	400.56	0.3991	0.2420	0.7980	0.0606	0.3440	0.5039
410	430	276	414.98	0.4070	0.3390	0.8320	0.0548	0.3708	0.5100
430	450	106	439.34	0.4190	0.2470	0.5670	0.0681	0.3426	0.5514
450	470	141	460.92	0.4257	0.2780	0.6450	0.0692	0.3580	0.5282
470	490	352	477.40	0.4422	0.2700	0.7340	0.0675	0.3630	0.5479
490	510	231	504.77	0.4777	0.3170	0.6880	0.0562	0.4160	0.6230
510	530	6	510.64	0.4822	0.4300	0.6650	0.0913	0.4300	0.6650

Mill A Coal Flow, lb/hr

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.00	65535.00	65535.00	65535.00	65535.00	65535.00
150	170	8	165.87	47324.00	32360.97	56774.84	8831.89	32360.97	56774.84
170	190	28	177.21	51307.44	13.64	69303.56	14364.56	30034.30	67549.81
190	210	2710	200.35	42317.10	11.69	73375.67	13975.05	14.78	59783.80
210	230	522	218.82	47846.17	11.52	76869.55	11154.45	37319.28	63853.02
230	250	363	238.61	45679.48	11.52	71537.81	17924.37	12.38	62946.08
250	270	268	259.51	42995.39	12.03	76811.91	21049.09	12.38	63831.39
270	290	413	280.65	43158.20	11.34	77781.28	21086.94	13.18	62780.78
290	310	557	301.52	50265.05	15.13	79195.48	6843.75	44707.22	62817.31
310	330	288	321.22	44123.96	12.83	79000.06	20415.79	13.98	65108.82
330	350	112	340.14	54766.64	13.64	76511.48	9695.72	42061.78	69577.61
350	370	165	359.59	53910.29	11.52	78342.23	14930.48	13526.51	69362.43
370	390	152	380.28	58570.35	20008.77	80782.06	8520.22	43742.92	73901.97
390	410	292	400.56	57567.79	13.29	80498.23	9024.26	47012.68	68590.93
410	430	276	414.98	60579.54	12.55	80648.39	8948.79	51749.29	70891.87
430	450	106	439.34	63130.83	13.23	81920.90	10671.40	49479.61	75167.92
450	470	141	460.92	64955.80	11427.00	77245.09	6489.94	56773.30	73011.69
470	490	352	477.40	65992.57	50762.94	73406.56	3343.61	60962.85	71334.62
490	510	231	504.77	66219.61	57295.11	71513.29	1181.51	64589.43	66474.09
510	530	6	510.64	65696.81	60134.65	67228.05	2747.15	60134.65	67228.05

Mill B Coal Flow, lb/hr

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.00	65535.00	65535.00	65535.00	65535.00	65535.00
150	170	8	165.87	37175.04	7.73	57127.70	23550.46	7.73	57127.70
170	190	28	177.21	36587.57	12.03	66145.92	25063.52	12.19	66063.01
190	210	2710	200.35	6473.24	3.27	73799.29	16028.74	12.20	43613.17
210	230	522	218.82	15594.42	3.44	64415.83	23090.41	11.86	57294.40
230	250	363	238.61	12050.94	3.32	70303.92	21673.97	12.94	55378.49
250	270	268	259.51	16086.02	3.32	69792.25	24311.09	12.36	58994.23
270	290	413	280.65	21808.20	3.09	66152.22	22744.45	11.88	54504.76
290	310	557	301.52	31229.44	3.09	72141.04	21923.30	12.72	49995.10
310	330	288	321.22	37848.57	12.72	76848.35	22010.23	17.53	57159.18
330	350	112	340.14	36797.58	11.00	76943.11	24899.65	13.45	67365.21
350	370	165	359.59	49049.76	10.48	78786.24	19766.52	16.37	66765.20
370	390	152	380.28	45376.03	13.75	80727.28	23832.96	16.84	73721.79
390	410	292	400.56	53077.30	13.06	79420.34	17304.64	17.88	68242.02
410	430	276	414.98	58427.53	14.95	79780.82	10411.53	49076.26	69486.64
430	450	106	439.34	44017.74	15.30	82189.08	27641.24	15.64	69056.26
450	470	141	460.92	61507.26	15.70	78385.60	12004.02	47213.66	70649.05
470	490	352	477.40	65368.77	51088.01	73018.52	2652.15	61426.23	69378.41
490	510	231	504.77	67308.87	57746.79	72043.81	1197.02	65739.69	67580.37
510	530	6	510.64	66708.26	60571.61	68341.06	3025.38	60571.61	68341.06

Mill C Coal Flow, lb/hr

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.00	65535.00	65535.00	65535.00	65535.00	65535.00
150	170	8	165.87	0.24	-6.02	1.55	2.54	-6.02	1.55
170	190	28	177.21	16578.28	1.20	68685.03	27058.78	1.20	66922.78
190	210	2710	200.35	40635.33	-7.22	72409.56	15622.81	3.61	59713.44
210	230	522	218.82	34932.70	-5.50	76851.38	21721.70	-2.27	63140.64
230	250	363	238.61	37363.32	-6.70	73137.80	23172.21	-2.64	62882.57
250	270	268	259.51	49071.35	-5.61	74008.00	13942.22	1.82	63992.72
270	290	413	280.65	41989.48	-3.78	75445.10	20095.78	2.39	62311.20
290	310	557	301.52	48008.33	-3.44	79155.66	9042.90	42754.35	62401.46
310	330	288	321.22	44225.98	0.17	78508.89	17528.62	1.72	62423.90
330	350	112	340.14	44954.42	0.52	73342.45	20254.34	1.22	65019.14
350	370	165	359.59	45202.71	0.52	76049.99	22879.12	1.20	67138.80
370	390	152	380.28	55022.66	-0.34	77103.47	12736.78	33568.54	70481.12
390	410	292	400.56	53747.76	-0.17	78316.68	10715.44	40152.81	66395.41
410	430	276	414.98	57422.35	-41.82	77138.99	9694.87	44471.62	68966.72
430	450	106	439.34	61695.01	9.63	81708.34	10954.17	48182.23	75405.75
450	470	141	460.92	62238.82	7.33	77795.78	7238.18	53827.81	71037.99
470	490	352	477.40	61569.26	22780.89	71766.18	5741.77	54379.16	68667.20
490	510	231	504.77	66393.78	49778.04	68001.54	2207.38	64030.20	67122.88
510	530	6	510.64	65017.34	52641.25	67950.04	6074.66	52641.25	67950.04

Mill D Coal Flow, lb/hr

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.00	65535.00	65535.00	65535.00	65535.00	65535.00
150	170	8	165.87	44539.72	28594.62	53898.68	8958.84	28594.62	53898.68
170	190	28	177.21	48798.49	-924.12	67238.70	14003.79	28501.52	65517.75
190	210	2710	200.35	31850.78	-996.65	69423.92	20102.97	-591.59	53827.47
210	230	522	218.82	38906.79	-938.09	69654.23	17672.21	-487.51	59241.46
230	250	363	238.61	42607.92	-993.21	68611.87	16380.53	-546.65	58099.71
250	270	268	259.51	46786.86	-799.79	69182.27	13477.75	-377.90	60957.89
270	290	413	280.65	48844.13	-790.57	77670.59	9622.64	37409.60	61242.59
290	310	557	301.52	47044.03	-738.72	75720.91	11472.15	39302.27	61789.73
310	330	288	321.22	49939.66	-778.65	75311.96	11078.63	36351.26	66949.07
330	350	112	340.14	49983.69	-758.54	74429.84	14380.62	2992.76	67807.46
350	370	165	359.59	48253.09	-376.64	76420.84	18391.02	-374.86	66370.51
370	390	152	380.28	55255.49	-518.38	75337.63	12236.81	40002.14	70936.38
390	410	292	400.56	54943.17	-521.47	74343.04	9106.60	45428.43	65201.05
410	430	276	414.98	55629.13	-488.30	74630.88	5872.41	50916.05	67266.74
430	450	106	439.34	60319.34	41616.50	76765.10	6687.83	50170.60	70827.82
450	470	141	460.92	60060.67	50461.07	73219.73	4565.23	52982.56	68852.23
470	490	352	477.40	61967.55	50451.44	72117.77	2409.72	58687.69	65673.56
490	510	231	504.77	65381.86	56995.81	71129.15	1367.45	62888.69	65835.97
510	530	6	510.64	65178.66	59831.75	66703.95	2647.73	59831.75	66703.95

Mill E Coal Flow, lb/hr

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.00	65535.00	65535.00	65535.00	65535.00	65535.00
150	170	8	165.87	-97.88	-99.00	-92.98	2.00	-99.00	-92.98
170	190	28	177.21	4.78	-105.53	2227.67	449.60	-103.98	663.01
190	210	2710	200.35	5737.45	-105.53	60756.38	15066.50	-103.81	44053.00
210	230	522	218.82	4123.76	-105.36	69969.97	14489.69	-103.64	46752.27
230	250	363	238.61	17526.91	-106.05	74973.13	25007.87	-102.78	57619.78
250	270	268	259.51	12942.95	-104.50	75872.27	23289.26	-103.64	60611.66
270	290	413	280.65	22389.24	-104.50	73393.43	25477.28	-102.83	58446.07
290	310	557	301.52	12536.42	-104.39	65506.61	22165.21	-103.98	52573.07
310	330	288	321.22	36135.71	-103.93	71703.45	25582.85	-101.41	60207.96
330	350	112	340.14	36891.08	-104.04	78331.12	27527.37	-101.57	69824.78
350	370	165	359.59	38520.76	-103.81	80236.23	28066.96	-100.98	69674.89
370	390	152	380.28	32971.15	-103.01	78466.27	30063.25	-102.08	71309.83
390	410	292	400.56	39415.50	-104.50	80193.61	25986.24	-103.93	67160.83
410	430	276	414.98	55564.65	-104.16	81101.97	16741.21	-95.39	69588.71
430	450	106	439.34	63027.31	-95.39	82664.31	10809.64	50823.71	77006.04
450	470	141	460.92	63942.83	16731.98	79080.03	6182.04	56913.28	72413.12
470	490	352	477.40	65236.50	48579.90	74182.91	2966.05	61151.79	70219.48
490	510	231	504.77	68489.90	58697.95	73167.93	1237.97	66816.98	68786.09
510	530	6	510.64	67902.81	61553.65	69667.24	3137.30	61553.65	69667.24

Mill F Coal Flow, lb/hr

Bin Low	Bin High	Samples	Load Mean	PV Mean	PV Min	PV Max	PV Std	PV 5thP	PV 95thP
130	150	0	147.50	65535.00	65535.00	65535.00	65535.00	65535.00	65535.00
150	170	8	165.87	0.54	-0.80	7.22	2.71	-0.80	7.22
170	190	28	177.21	3471.94	-6.36	51428.61	12774.75	-5.59	46374.87
190	210	2710	200.35	42862.81	-425.96	73756.72	15910.75	1.72	59724.16
210	230	522	218.82	42755.71	-1.89	78128.07	17914.95	2.89	62935.96
230	250	363	238.61	47648.19	-3.09	74504.38	16769.75	1.18	64091.31
250	270	268	259.51	47785.46	-0.69	75382.66	17948.02	0.17	65260.73
270	290	413	280.65	49804.53	-0.69	79236.49	15299.93	0.59	64584.28
290	310	557	301.52	49492.51	0.23	80557.30	12437.42	40466.96	64748.59
310	330	288	321.22	45025.61	-0.17	80444.32	21761.08	4.30	66572.65
330	350	112	340.14	55418.54	-0.69	77909.79	12122.98	42605.52	70865.65
350	370	165	359.59	54311.84	-3.44	79807.41	16433.80	-0.99	69748.99
370	390	152	380.28	57727.84	-4.81	83173.46	15002.81	32151.85	75673.05
390	410	292	400.56	59022.64	3150.81	80403.30	9652.12	47137.57	70860.03
410	430	276	414.98	61343.70	36768.30	83086.78	5404.38	54340.98	72608.77
430	450	106	439.34	64452.35	-3.27	82183.29	9933.99	52011.99	76591.68
450	470	141	460.92	65624.65	26548.10	79206.31	5709.95	58217.59	74670.58
470	490	352	477.40	67055.26	51679.55	76525.97	3259.45	63332.21	72293.68
490	510	231	504.77	69727.38	58386.74	72769.07	1362.03	68169.16	70112.54
510	530	6	510.64	68948.81	61233.85	70945.76	3797.71	61233.85	70945.76

Table A-17 P4A – Mill Pattern Frequency by Load (1Q96)

Mill A-B-C-D-E-F	Load, MW 130	150	170	190	210	230	250	270	290	310	330	350	370	390	410	430	450	470	490	510
0-0-0-0-0-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-0-0-1-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-0-0-1-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-0-1-0-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-0-1-0-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-0-1-1-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-0-1-1-1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
0-0-1-0-0-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-1-0-0-1	1	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-1-0-1-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-1-0-1-1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-1-1-0-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-1-1-0-1	0	0	0	107	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-1-1-1-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-0-1-1-1-1	0	0	0	0	0	1	2	17	0	0	0	0	0	0	0	0	0	0	0	0
0-1-0-0-0-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-0-0-0-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-0-0-1-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-0-0-1-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-0-1-0-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-0-1-0-1	0	0	0	62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-0-1-1-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-0-1-1-1	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
0-1-1-0-0-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-1-0-0-1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-1-0-1-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-1-0-1-1	0	0	0	15	3	4	3	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-1-1-0-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0-1-1-1-0-1	0	0	0	5	8	33	29	12	2	1	0	0	0	0	0	0	0	0	0	0
0-1-1-1-1-0	0	0	0	27	3	3	14	0	0	0	0	1	0	0	0	0	0	0	0	0
0-1-1-1-1-1	0	0	0	0	0	1	0	44	0	44	1	8	0	2	4	1	1	0	0	0
1-0-0-0-0-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-0-0-0-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-0-0-1-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-0-0-1-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-0-1-0-0	0	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-0-1-0-1	0	0	0	143	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-0-1-1-0	0	0	0	11	15	4	0	1	0	0	0	0	0	0	0	0	0	0	0	0
1-0-0-1-1-1	0	0	0	0	3	59	1	9	2	0	0	0	0	0	0	0	0	0	0	0
1-0-1-0-0-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-1-0-0-1	0	0	0	397	43	8	1	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-1-0-1-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-1-0-1-1	0	0	0	113	6	16	5	2	1	2	0	0	0	0	0	0	0	0	0	0
1-0-1-1-0-0	0	0	6	43	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-0-1-1-0-1	0	0	1	1510	270	176	153	152	94	5	0	0	0	0	0	0	0	0	0	0
1-0-1-1-1-0	0	0	0	0	2	4	3	3	0	1	0	0	0	0	0	0	0	0	0	0
1-0-1-1-1-1	0	0	0	0	0	6	20	30	82	59	32	21	30	23	7	29	4	0	0	0
1-1-0-0-0-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-1-0-0-0-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-1-0-0-1-0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-1-0-0-1-1	0	0	0	0	0	7	3	0	0	0	0	0	0	0	0	0	0	0	0	0
1-1-0-1-0-0	0	6	20	13	16	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-1-0-1-0-1	0	0	0	65	94	10	2	11	3	3	0	0	0	0	0	0	0	0	0	0
1-1-0-1-1-0	0	0	0	0	0	13	8	1	0	0	0	0	0	0	0	0	0	0	0	0
1-1-0-1-1-1	0	0	0	0	0	0	1	49	6	30	17	30	5	7	5	1	1	0	0	0
1-1-1-0-0-0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-1-1-0-0-1	0	0	0	7	21	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-1-1-0-1-0	0	0	0	189	10	1	3	2	1	1	0	0	0	0	0	0	0	0	0	0
1-1-1-0-1-1	0	0	0	0	0	0	1	2	21	5	6	19	5	3	1	0	0	0	0	0
1-1-1-1-0-0	0	0	0	0	10	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-1-1-1-0-1	0	0	0	0	2	3	18	54	321	85	38	54	66	85	21	1	1	0	0	0
1-1-1-1-1-0	0	0	0	0	0	0	1	22	24	49	3	11	7	3	0	1	0	0	0	0
1-1-1-1-1-1	0	0	0	0	0	0	0	1	0	1	15	21	39	169	238	73	134	352	231	6

[1]Number of occurrances of mill combination
[2]Mill on = 1, Mill off = 0 (assumed off if flow < 20000 lb/hr)

Table A-18 P4A – NOx Emissions by Load and Mill Pattern (1Q96)

	Load, MW																			
Mill A-B-C-D-E-F	130	150	170	190	210	230	250	270	290	310	330	350	370	390	410	430	450	470	490	510
0-0-0-0-0-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-0-0-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-0-0-1-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-0-1-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-0-1-0-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-0-1-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-0-1-1-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.313	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-1-0-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-1-0-0-1	0.386	n/a	0.336	0.348	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-1-0-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-1-0-1-1	n/a	n/a	n/a	n/a	n/a	0.392	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-1-1-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-1-1-0-1	n/a	n/a	n/a	0.342	0.351	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-1-1-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-1-1-1-1	n/a	n/a	n/a	n/a	n/a	0.329	0.356	0.348	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-0-0-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-0-0-0-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-0-0-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-0-0-1-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-0-1-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-0-1-0-1	n/a	n/a	n/a	0.364	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-0-1-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-0-1-1-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.370	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-1-0-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-1-0-0-1	n/a	n/a	n/a	n/a	n/a	0.413	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-1-0-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-1-0-1-1	n/a	n/a	n/a	0.431	0.410	0.415	0.400	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-1-1-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-1-1-0-1	n/a	n/a	n/a	0.473	0.426	0.424	0.395	0.374	0.394	0.365	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-1-1-1-0	n/a	n/a	n/a	0.398	0.342	0.339	0.302	n/a	n/a	n/a	n/a	0.332	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-1-1-1-1	n/a	n/a	n/a	n/a	n/a	0.501	n/a	0.406	n/a	0.372	0.372	0.370	n/a	0.397	0.341	0.373	0.399	n/a	n/a	n/a
1-0-0-0-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-0-0-0-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-0-0-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-0-0-1-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-0-1-0-0	n/a	0.394	n/a	0.321	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-0-1-0-1	n/a	n/a	n/a	0.298	0.341	0.346	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-0-1-1-0	n/a	n/a	n/a	0.298	0.303	0.300	n/a	0.333	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-0-1-1-1	n/a	n/a	n/a	n/a	0.455	0.395	0.364	0.351	0.338	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-1-0-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-1-0-0-1	n/a	n/a	n/a	0.378	0.375	0.359	0.387	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-1-0-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-1-0-1-1	n/a	n/a	n/a	0.451	0.407	0.398	0.428	0.371	0.417	0.372	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-1-1-0-0	n/a	n/a	0.478	0.411	0.417	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-1-1-0-1	n/a	n/a	0.540	0.399	0.381	0.362	0.367	0.370	0.349	0.353	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-1-1-1-0	n/a	n/a	n/a	n/a	0.382	0.387	0.387	0.352	n/a	0.338	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-1-1-1-1	n/a	n/a	n/a	n/a	n/a	0.447	0.383	0.364	0.375	0.367	0.349	0.360	0.368	0.366	0.302	0.282	0.276	n/a	n/a	n/a
1-1-0-0-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-0-0-0-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-0-0-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-0-0-1-1	n/a	n/a	n/a	n/a	n/a	0.366	0.340	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-0-1-0-0	n/a	0.444	0.415	0.348	0.322	0.283	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-0-1-0-1	n/a	n/a	n/a	0.393	0.435	0.350	0.346	0.356	0.363	0.395	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-0-1-1-0	n/a	n/a	n/a	n/a	n/a	0.285	0.280	0.324	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-0-1-1-1	n/a	n/a	n/a	n/a	n/a	n/a	0.369	0.339	0.345	0.322	0.355	0.352	0.417	0.358	0.355	0.348	0.447	n/a	n/a	n/a
1-1-1-0-0-0	n/a	n/a	n/a	n/a	n/a	0.386	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-1-0-0-1	n/a	n/a	n/a	0.444	0.427	0.414	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-1-0-1-0	n/a	n/a	n/a	0.348	0.340	0.370	0.304	0.308	0.325	0.301	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-1-0-1-1	n/a	n/a	n/a	n/a	n/a	n/a	0.387	0.361	0.335	0.330	0.336	0.353	0.363	0.361	0.361	n/a	n/a	n/a	n/a	n/a
1-1-1-1-0-0	n/a	n/a	n/a	n/a	0.388	0.390	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-1-1-0-1	n/a	n/a	n/a	n/a	0.487	0.439	0.408	0.404	0.378	0.389	0.392	0.397	0.401	0.412	0.399	0.381	0.448	n/a	n/a	n/a
1-1-1-1-1-0	n/a	n/a	n/a	n/a	n/a	n/a	0.387	0.344	0.323	0.321	0.321	0.337	0.354	0.368	n/a	0.423	n/a	n/a	n/a	n/a
1-1-1-1-1-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.368	n/a	0.381	0.385	0.397	0.395	0.400	0.387	0.410	0.393	0.415	0.469	0.500

[1] Mill on = 1, Mill off = 0 (assumed off if flow < 20000 lb/hr)
[2] NOx filtered for invalid data points

Table A-19 P4A – Stack O2 by Load and Mill Pattern (1Q96)

	Load, MW																			
Mill A-B-C-D-E-F	130	150	170	190	210	230	250	270	290	310	330	350	370	390	410	430	450	470	490	510
0-0-0-0-0-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-0-0-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-0-0-1-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-0-1-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-0-1-0-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-0-1-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-0-1-1-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5.226	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-1-0-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-1-0-0-1	9.423	n/a	8.051	7.041	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-1-0-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-1-0-1-1	n/a	n/a	n/a	n/a	n/a	5.574	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-1-1-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-1-1-0-1	n/a	n/a	n/a	6.221	6.548	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-1-1-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-0-1-1-1-1	n/a	n/a	n/a	n/a	n/a	5.751	5.662	5.175	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-0-0-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-0-0-0-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-0-0-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-0-0-1-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-0-1-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-0-1-0-1	n/a	n/a	n/a	6.382	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-0-1-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-0-1-1-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4.838	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-1-0-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-1-0-0-1	n/a	n/a	n/a	n/a	n/a	5.962	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-1-0-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-1-0-1-1	n/a	n/a	n/a	6.377	6.253	5.868	5.415	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-1-1-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-1-1-0-1	n/a	n/a	n/a	6.810	6.504	5.879	5.596	5.360	5.284	5.331	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-1-1-1-0	n/a	n/a	n/a	6.218	5.952	5.723	5.531	n/a	n/a	n/a	n/a	6.615	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
0-1-1-1-1-1	n/a	n/a	n/a	n/a	n/a	6.012	n/a	4.916	n/a	4.849	4.870	5.872	n/a	6.342	4.690	5.874	5.054	n/a	n/a	n/a
1-0-0-0-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-0-0-0-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-0-0-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-0-0-1-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-0-1-0-0	n/a	7.140	n/a	6.431	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-0-1-0-1	n/a	n/a	n/a	6.099	6.071	6.034	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-0-1-1-0	n/a	n/a	n/a	6.068	5.836	5.375	n/a	5.058	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-0-1-1-1	n/a	n/a	n/a	n/a	6.091	5.384	4.682	4.948	4.626	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-1-0-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-1-0-0-1	n/a	n/a	n/a	6.771	6.727	6.452	6.155	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-1-0-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-1-0-1-1	n/a	n/a	n/a	6.546	6.300	5.999	5.533	5.296	5.572	8.965	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-1-1-0-0	n/a	n/a	5.778	6.272	5.826	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-1-1-0-1	n/a	n/a	7.106	6.410	6.199	5.906	5.857	5.812	5.713	5.370	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-1-1-1-0	n/a	n/a	n/a	n/a	5.778	5.936	5.502	5.130	n/a	4.707	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-0-1-1-1-1	n/a	n/a	n/a	n/a	n/a	5.541	5.262	5.132	5.149	5.011	4.576	4.806	4.934	4.706	3.919	3.696	3.634	n/a	n/a	n/a
1-1-0-0-0-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-0-0-0-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-0-0-1-0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-0-0-1-1	n/a	n/a	n/a	n/a	n/a	5.377	4.869	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-0-1-0-0	n/a	6.644	6.616	6.069	6.399	6.386	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-0-1-0-1	n/a	n/a	n/a	6.433	5.502	5.792	5.531	5.308	5.036	4.012	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-0-1-1-0	n/a	n/a	n/a	n/a	n/a	6.147	6.061	5.689	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-0-1-1-1	n/a	n/a	n/a	n/a	n/a	n/a	4.607	4.853	4.331	4.507	4.253	4.301	5.865	5.926	5.984	4.493	5.487	n/a	n/a	n/a
1-1-1-0-0-0	n/a	n/a	n/a	n/a	n/a	6.484	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-1-0-0-1	n/a	n/a	n/a	6.951	6.616	6.331	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-1-0-1-0	n/a	n/a	n/a	6.642	6.191	5.505	5.726	5.856	5.556	4.990	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-1-0-1-1	n/a	n/a	n/a	n/a	n/a	n/a	5.460	5.442	5.153	4.999	5.083	5.479	6.601	4.834	4.446	n/a	n/a	n/a	n/a	n/a
1-1-1-1-0-0	n/a	n/a	n/a	n/a	6.608	6.407	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-1-1-1-0-1	n/a	n/a	n/a	n/a	5.429	5.726	5.570	5.350	5.155	5.150	5.085	5.221	5.026	5.156	4.688	4.522	7.742	n/a	n/a	n/a
1-1-1-1-1-0	n/a	n/a	n/a	n/a	n/a	n/a	5.021	5.363	5.245	5.326	5.317	5.910	5.956	5.846	n/a	5.897	n/a	n/a	n/a	n/a
1-1-1-1-1-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5.220	n/a	4.357	4.291	4.577	4.594	4.465	4.931	4.913	4.686	4.790	4.259	4.354

[1] Mill on = 1, Mill off = 0 (assumed off if flow < 20000 lb/hr)
[2] Stack O_2 filtered for invalid data points