INNOVATIVE CLEAN COAL TECHNOLOGY (ICCT)

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

Phase 3A Low NOx Burner Tests
Topical Report

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Legal Notice

Executive Summary

This Phase 3A test report summarizes the testing activities and results for the third testing phase of an Innovative Clean Coal Technology (ICCT) demonstration of advanced wall-fired combustion techniques for the reduction of nitrogen oxide (NOx) emissions from coal-fired boilers. The project is being conducted at Georgia Power Company's Plant Hammond Unit 4 located near Rome, Georgia. The primary goal of this project is the characterization of the low NOx combustion equipment through the collection and analysis of long-term emissions data.

This demonstration project is divided into the following phases:

Phase 0	-	Pre-award activities,
Phase 1	-	Baseline "as-found" testing,
Phase 2	-	AOFA installation and testing,
Phase 3A	-	LNB installation and testing,
Phase 3B	-	LNB plus AOFA testing,
Phase 4	-	Advanced digital controls installation and testing, and
Phase 5	-	Final reporting.

Described in this report arc the test plans, data measurements, and data analyses performed during the Phase 3A effort. The present report also contains sufficient background material to provide an understanding of the overall program scope, the relationship of Phase 3A to the overall program, the testing methodologies. testing procedures, and unit configuration.

Results from 66 short-term tests indicate increasing NOx emissions over the load range ranging from 0.5 lb/MBtu at 300 MW to around 0.65 lb/MBtu at 480 MW. Fly ash loss-on-ignition (LOI) for these loads ranged from 5.4 to 8.6 percent. Long-term test results indicated high load (480 MW) NOx emissions of approximately 0.6S lb/MBtu. At the 300 MW mid load point, the emissions dropped to 0.47 lb/MBtu which is slightly lower than the 0.50 lb/MBtu shown for the short-term data. The annual and 30-day average achievable NOx emissions were determined to be 0.55 and 0.64 lb/MBtu, respectively, for the load scenario experienced during the Phase 3A long-term test period. Based on the long-term test results for Phase 3A, at full-load the LNB retrofit resulted in a NOx reduction of 48 percent from baseline, while at 300 MW the reduction was approximately 50 percent.

A special series of tests was conducted during Phase 3A to evaluate the effects of various burner equipment settings and mill coal flow biasing on both NOx and LOI emissions. The results of these tests are included in this report.

Table of Contents

List of Figures

List of Tables

Table of Abbreviations

AOFA	Advanced Overfire Air
ASME	American Society of Mechanical Engineers
AMIS	All mills in service
B&W	Babcock and Wilcox
C	carbon
CAA(A)	Clean Air Act (Amendments)
CEM	continuous emissions monitor
CFSF	Controlled Flow/Split Flame
Cl	chlorine
CO	carbon monoxide
DAS	data acquisition system
DCS	digital control system
DOE	United States Department of Energy
ECEM	extractive continuous emissions monitor
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ESP	Electrostatic precipitator
ETEC	Energy Technology Consultants
F	Fahrenheit
FC	fixed carbon
FWEC	Foster Wheeler Energy Corporation
GPC	Georgia Power Company
H	hydrogen
HHV	higher heating value
ICCT	Innovative Clean Coal Technology
KPPH	Kilo pounds per hour
lb(s)	pound(s)
LNB	low NOx burner
LOI	loss on ignition
(M)BtU	(million) British thermal unit
MOOS	Mill out of service
MW	megawatt
N	nitrogen
NOx	nitrogen oxides
NSPS	New Source Performance Standards
O, O_2	oxygen
PA	Primary air
psig	pounds per square inch gauge
PTC	Performance Test Codes

Table of Abbreviations (continued)

RSD	relative standard deviation
S	sulfur
SCS	Southern Company Services
SO_2	sulfur dioxide
SoRI	Southern Research Institute
THC	Total hydrocarbons
UARG	Utility Air Regulatory Group
VM	volatile matter

1. Introduction

This document discusses the technical progress of a U. S. Department of Energy (DOE) Innovative Clean Coal Technology (ICCT) project demonstrating advanced wall-fired combustion techniques for the reduction of nitrogen oxide (NOx) emissions from coal-fired boilers. The project is being conducted at Georgia Power Company's Plant Hammond Unit 4 (500 MW) near Rome, Georgia.

The project is being managed by Southern Company Services, Inc. (SCS) on behalf of the project co-funders: The Southern Company, the U. S. Department of Energy (DOE), and the Electric Power Research Institute (EPRI). In addition to SCS, The Southern Company includes five electric operating companies: Alabama Power, Georgia Power, Gulf Power, Mississippi Power, and Savannah Electric and Power. SCS provides engineering, research, and financial services to The 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 which 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 which 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.

This report is provided to document the testing performed and results achieved during Phase 3A -Low NOx Burner. This effort began in July 1991 following completion of Phase 2 - Advanced Overfire Air testing and installation of the retrofit LNB equipment. The Phase I baseline effort and results were documented in the Southern Company Services report titled *500 MW Demonstration of Advanced Wall-Fired Combustion Techniques for the Reduction of Nitrogen Oxides (NOx) Emissions from Coal-Fired Boilers - Phase 1 Baseline Tests.* The Phase 2 effort and results are documented in *500 MW Demonstration of Advanced Wall-Fired Combustion Techniques for the Reduction of Nitrogen Oxides (NOx) Emissions from Coal-Fired Boilers - Phase 2 Overfire Air Tests.* Those reports contain detailed descriptions of the program, test plans, and testing procedures.

1.1 Project Description

On December 20, 1989, Southern Company Services was awarded a DOE Innovative Clean Coal Technology Round II (ICCT) contract for the project, "500 MW Demonstration of Advanced, Wall-Fired Combustion Techniques for the Reduction of Nitrogen Oxide (NOx) Emissions from Coal-Fired Boilers". The primary objective of this demonstration is 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 are also being performed to provide engineering information about emissions and performance trends. A target of achieving *fifty* percent NOx reduction using combustion modification has been established for the project. Specifically, the objectives of the project are:

1. 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
    - Advanced digital control methodologies

2. Determine the dynamic, long-term emissions characteristics of each of these combustion NOx
reduction methods using sophisticated statistical techniques.
3. Evaluate the progressive cost effectiveness (i.e., dollars per ton NOx removed) of the low NOx combustion techniques tested.
4. 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 this evaluations. the project is partitioned into the following test phases:

- Phase I - Baseline
- Phase 2 - Advanced Overfire Air
- Phase 3A - Low NOx Burners
- Phase 3B - Low NOx Burners plus Advanced Overfire Air
- Phase 4 - Advanced Low NOx Digital Control System

Each of the phases of the project involves three distinct testing periods - short-term characterization, long-term characterization, and short-term verification. The short-term characterization testing establishes 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) establishes the dynamic response of the NOx emissions to all of the influencing parameters encountered. The short-term verification testing documents any fundamental changes in NOx emissions characteristics that may have occurred during the long-term test period.

1.2 Project Organization

Southern Company Services is the prime contractor to the funders on this project. SCS directs in-house and Georgia Power Company personnel to perform various duties related to site coordination, design engineering, environmental matters and cost coordination, and has overall responsibility for the execution of this project. SCS also directs subcontracted efforts of the burner manufacturer, installation contractors and test coordination contractor, supplying the NOx emissions control systems as described below.

Energy Technology Consultants Inc. ETEC has responsibility for the on-site testing and analysis of the data, serving as the test coordinator and results engineer under Southern Company Services direction. ETEC is responsible for overall management of the test efforts, including preparation of test plans and coordination of other test contractors.

Spectrum Systems. Inc. Spectrum provides a full-time, on-site instrument technician who is responsible for operation and maintenance of the data acquisition system (DAS) housed within the instrument control room. For the full duration of the program (short-term characterization, long-term characterization, and short-term verification), Spectrum; maintains and repairs, as necessary, the instrumentation system and monitors the function of the data acquisition system on a daily basis.

Southern Research Institute (SoRI) SoRI is responsible for testing related to flue gas particulate measurements during the performance testing portion of the short-term characterization. In addition to the testing activities, SoRI is responsible for ESP modeling efforts for each of the four phases.

Flame Refractories Inc. (Flame) Flame is responsible for activities related to fuel/air input parameters and furnace output temperature measurements during the performance testing portion of the short-term characterization.

W. S. Pitts Consulting. Inc. (WSPC) WSPC is responsible for the statistical analysis of the long-term emissions data.

1.3 Hammond Unit 4 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. The unit 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, 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. The burners are arranged in a matrix of 12 burners (4W x 3H) on opposing walls with each mill supplying coal to 4 burners per elevation. As part of this demonstration project, the unit was retrofit with an advanced overfire air system. The unit is equipped with a coldside ESP and utilizes two regenerative secondary air preheaters and two regenerative primary air heaters. The unit was designed for pressurized furnace operation but was converted to balanced draft operation in 1977.

1.4 Report Organization

The remainder of this report is organized into six sections. Section 2 provides background material for the project and describes the program methodology. Section 3 provides details on the instrumentation and the data collection methods. The data analyses methods for both short-term and long-term data are described in Section 4.0. The results for the short-term characterization portion of the Phase 3A effort are presented in Section 5. Section 6 provides a description of the statistical approach used to analyze the continuous emission monitor (CEM) data. Section 7 provides a summary of conclusions for the analyses of both the short-term and long-term data. A final report will summarize the testing results for all phases.

2. Test Program Description

In the past, there have been a number of demonstration programs by various burner manufacturers for the purpose of evaluating the NOx reduction potential of their equipment. These demonstrations have provided only minimal amounts of information that could be used to extrapolate to the general population of utility boilers. All of these demonstrations provided only small amounts of short-term data (generally less than one day for each data point) in both pre- and post-retrofit configurations. Very few of these demonstrations have provided long-term data (on the order of months of continuous data) in the post-retrofit configuration, and none have provided long-term data in the pre-retrofit configuration. The purpose of this program is to provide detailed short- and long-term pre- and post-retrofit emission data on a number of low NOx combustion technologies applied to a wall-fired utility boiler.

The following paragraphs describe the technologies that are to be investigated during the four phases of this program, the general methodology used to obtain data, and the general outline of Phase 3A.

2.1 Technology Background

At the completion of the DOE ICCT II program, the following NOx control technologies will nave been demonstrated and compared to the baseline configuration:

1. Advanced Overfire Air (AOFA),

2. Low NOx Burner (LNB),

3. Combined LNB and AOFA operation, and

4. Advanced digital control methodologies.

Each of the technologies (or combination of technologies) will eventually be compared to the baseline configuration to ascertain the NOx reduction effectiveness. Southern Company Services contracted with Foster Wheeler Energy Corporation to provide the low NOx burner and AOFA hardware which have been retrofit to Hammond Unit 4.

The baseline configuration is defined as the "as found" configuration of the unit. The "as found" configuration is further defined as the configuration under which the unit has operated in the recent past prior to the retrofit activities. In the case of Hammond Unit 4, this consisted of operation with some existing burner-related problems. The results of this baseline effort will be compared to the results for subsequent phases of the overall program. The following paragraphs provide an overview of AOFA and LNB retrofits as they have been incorporated into Unit 4.

2.1.1 Advance Overfire Air System

The standard offering of overfire air ports incorporates combustion air bypass from the main burner windbox through ports above the burners. This secondary combustion air is obtained from an extension of the burner windbox and is generally integral to the main burner windbox. The portion of the combustion air diverted away from the burners drives the primary combustion stoichiometry toward a fuel rich condition which facilitates reduction of NOx. The secondary combustion air diverted above the burners to the overfire air ports provides sufficient air to complete combustion before the products reach the convective pass.

Studies by EPRI and boiler manufacturers have shown that the standard overfire air (OFA) offerings do not result in optimum NOx reduction due to inadequate mixing of the secondary air with the partially combusted products from the fuel rich burner zone. This inadequate mixing limits the effectiveness of the OFA technique. The advanced overfire air system (AOFA) provided by FWEC incorporates separate (from the windbox) injection port and duct configurations that are designed to provide increased secondary air penetration. Typical standard offerings provide penetration velocities approximately two times the furnace flow velocity. AOFA systems provide increased penetration velocities by supplying secondary air from completely separate aerodynamically designed ducts located above the existing burner windbox. The ports themselves are also designed to provide increased penetration velocities.

For Phase 2, an advanced overfire air system was retrofit to the unit. This retrofit consisted of additional of ductwork, dampers, various instrumentation and controls, and AOFA ports above the top row of burners on the front and rear walls of the furnace. The overfire air is extracted from the two main secondary air ducts between the air flow venturis and the entrance to the combustion air windbox (east and west sides of the boiler). Figure 2-l depicts the major components of the AOFA system.

2.1.2 Low NOx Burners

For Phases 3A and 3B, FWEC supplied their Controlled Flow/Split Flame (CF/SF) burner for retrofit into the existing wall penetrations of the 24 Intervane burners. The CF/SF burner was originally developed for use on the San Juan Unit 1 of the Public Service Company of New Mexico in the mid-1970s. Subsequent to that development, modifications of the burner have been incorporated into new boilers and more recently into older boilers to comply with the Clean Air Act Amendments of l 990. Figure 2-2 schematically illustrates the CF/SF burner.

As with all of the manufacturers of new low NOx burners, FWEC's burners utilize the principle of separating the fuel and air streams in the primary combustion zone. Unique design features of the CF/SF burner allow low NOx operation with shorter flames than may result from other wall-fired burner manufacturers' concepts. These "internally" staged burners accomplish NOx reduction in a manner similar to that accomplished with overfire air, but much more efficiently. Internally staged burners result in significantly better-mixed final products of combustion than do overfire air ports. This low NOx burner concept was evaluated during Phase 3A of the project. Due to the unique design features of the burner, it can be operated with or without the AOFA system described above. The combination of the CF/SF burner operation used in conjunction with the AOFA system will be evaluated during Phase 3B of the project.

2.1.3 Advanced Low NOx Digital Controls

This scope addition to the original project is designed to evaluate and demonstrate the effectiveness of advanced digital control and optimization strategies use in conjunction with above NOx abatement technologies. The testing and utilized during the evaluation of this technology will be similar to that used in prior phases. The technology utilized and results obtained will be described in future reports.

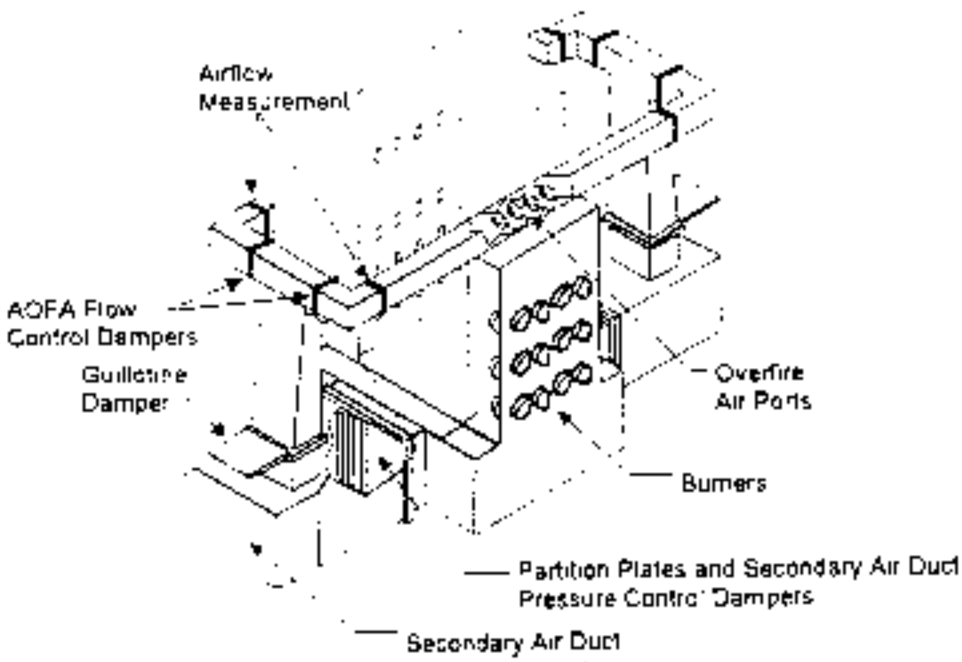


Figure 2-1 Hammond Advanced Overfire Air System

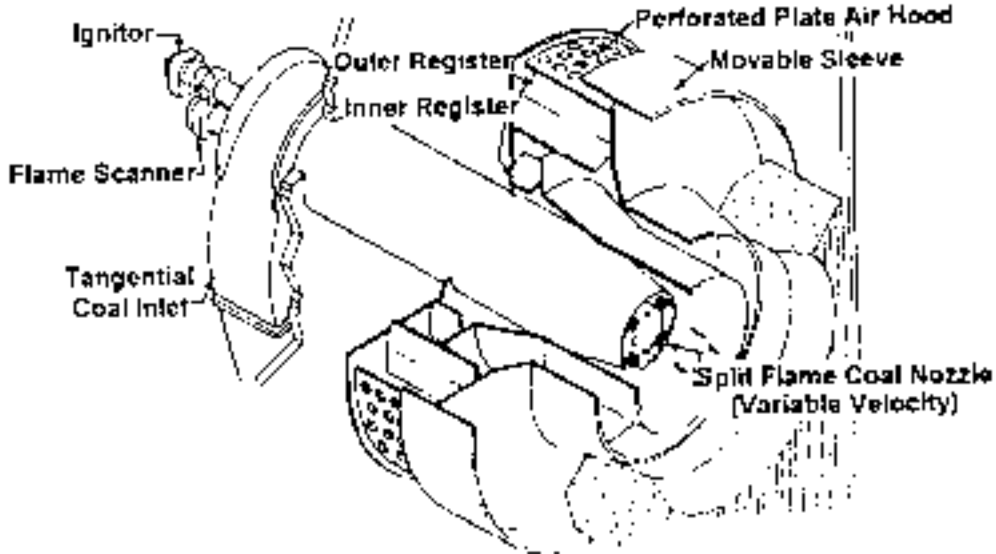


Figure 2-2 Controlled Flow/Split Flame Burner

2.2 Program Test Elements

One of the underlying premises for the structure of the testing efforts in all of the phases of this project is that short-term tests cannot adequately characterize the true emissions of a utility boiler. As a consequence of this, the focal point of the test efforts during all phases of this project is long-term testing. Short-term testing is used only to establish trends that may be used to extrapolate the results of this project to other similar boilers. During this program, the short-term test results are not intended to be used to determine the relative effectiveness of the retrofitted NOx control technologies. This will be accomplished by performing statistical analyses of the long-term data. A description of the purpose and sequence for each of the three types of testing involved in all phases of the project follows.

2.2.1 Short-Term Characterization

Initial short-term testing is generally performed to establish the trends of NOx emissions under the most commonly used configurations. While NOx is comprised of NO and NO_2, only a small fraction of NOx is NO_2 (generally <5%). During this program NO was measured since the NO_2 represents a small, actual incremental contribution. To account for this small contribution significant instrumentation costs would have to be incurred. Aside from NOx measurements, short-term testing is also used to assess the performance of the boiler in the normal modes of operation. The characterization testing is divided into three elements - diagnostic, performance, and verification tests.

Diagnostic testing involves characterizing the gaseous emissions under three to four load conditions over the range of operating parameters that might normally be encountered on Unit 4 as well as excursions about these normal conditions. The primary parameters that were used for characterization were excess oxygen, mill pattern, and mill bias. Testing at each of the selected conditions is accomplished during a one- to three-hour period with the unit in a fixed configuration while it is off system load dispatch to ensure steady boiler operation.

Performance testing is accomplished at specified loads in configurations recommended by plant engineering and the vendor and which have been tested during the diagnostic testing. Each of these configurations represents one of the normal modes of operation for each load condition. The 'nominal" burner settings was based upon initial testing by FWEC. Performance data were recorded during ten- to twelve-hour test periods with the unit off of system load dispatch to provide steady operating conditions.

Over the 70- to 80-day test period, changes in the unit condition and coal can occur. Verification testing is normally conducted at the end of each of the four test phases for the purpose of quantifying some of the impacts of these potential changes on the long-term emission characterization. Results of this verification testing can assist in explaining potential anomalies in the long-term data statistical analysis by comparing diagnostic and verification operating conditions and fuels. The verification tests are conducted in a similar manner to that of the diagnostic testing described above.

Results from each of these tests in Phase 3A (LNB) are used for comparison with results from similar testing of the various NOx control technologies undertaken in other project phases.

2.2.2 Long-Term Characterization

Long-term testing for each phase is conducted under normal system load dispatch control conditions with the burners adjusted to the settings established by FWEC. Generally, no intervention with respect to specifying the other operating configurations or conditions is imposed by test personnel!. The long-term testing provides emission and operational results that include most if not all of the possible influencing parameters that can affect NOx emissions for a boiler ever the long run. These parameters include coal variability, mill in-service patterns, mill bias ranges, excess oxygen excursions, and equipment conditions as well as many as-yet undetermined influencing parameters. Results from this long-term testing provide a true representation of the emissions from the unit. Data for the parameters of interest are recorded continuously (~-minute averages) for periods greater than 51 days.

2.3 Phase 3A Test Plan

The Hammond Unit 4 Phase 3A testing effort was begun on July 9, 1991, and completed on October 28, 1992, and included five months of long-term testing. The testing was interrupted periodically for various burner repairs and other boiler maintenance work. The following briefly describes the test sequence during this period.

2.3.1 Short-Term Characterization Testing

The test plan for Phase 3A short-term characterization incorporated four load points ranging from 180 to 480 MW which duplicated the testing range of Phases 1 and 2.

The Phase 3A diagnostic test matrix for Unit 4 was performed over the period from July 9, 1991 to January 15, 1992. This diagnostic test matrix included the basic test conditions shown in Table 2-1. Each of these tests was performed over a duration of from one to three hours.

Table 2-1 Diagnostic Test Matrix

Load, MW	Mill pattern	Number of Tests
480	All Mills in Service	28
400	All Mills in Service	10
300	3 MOOS Patterns	19
180	2 MOOS Patterns	7

The performance portion of the short-term characterization tests included tests at 300, 400 and 480 MW load levels, and was performed from July 16 through July 28, 1991, with some interruption for LOI testing. Based on those brief LOI tests, the subsequent performance tests were conducted at lower mill primary air/fuel ratios than were previously employed.

Subsequent to the completion of the short-term diagnostic and performance testing, a short program was initiated to investigate the impact of burner and boiler related variables on the LOI and NOx emissions. To ascertain the relationship between specific boiler operating parameters (i.e. excess O_2, mill bias and burner settings) under the Phase 3A configuration (LNB alone), parametric tests were performed at 450 MW with variations in the listed operating parameters, while measuring the loss-on-ignition (LOI) and carbon content of the ash entering the ESP. Forty tests were conducted between October 20 and 28, l 992. For each test condition ash samples were obtained from both economizer exit ducts and analyzed on-site for LOI. Each ash sample was subsequently analyzed for elemental carbon content. Southern Research Institute obtained the ash samples and performed the analyses. Each day of testing Flame Refractories set the mills to the desired operating point (coal and primary air flows) and determined the particle size distribution within each burner coal pipe.

2.3.2 Long-Term Characterization Testing

Long-term characterization testing began in August 1991 and was completed in December 1991. During this period a substantial amount of continuous emission data was collected. During this period, 94 days of valid long-term data were collected.

2.3.3 Verification Testing

A portion of the diagnostic testing was conducted near the conclusion of the Phase 3A test effort and served as the verification test. Based upon the verification testing results from Phases 1 and 2, it was expected that no significant shift in NOx emissions characteristics were likely to have occurred during the Phase 3A long-term characterization period. This was confirmed by the diagnostic testing.

3. Test Procedures And Measurements

A wide variety of measurement apparatus and procedures were employed during the test program described in Section 2. The acquisition of data can be conveniently grouped into four broad data categories relating to the equipment and procedures used. These are: manual boiler data collection, automated boiler data collection, combustion systems tests, and solid/sulfur emissions tests. A brief description of each data category follows.

<u>Manual Boiler Data Collection</u>

Data were recorded manually onto data forms based on readings from plant instruments and controls. The data were subsequently entered manually into a computer data management program. Coal, bottom ash, and ESP hopper ash (which was taken separately from inlet and outlet hoppers on both east and west sides of the ESP) samples were collected regularly for subsequent laboratory analysis. In addition to the data readings taken during Phase 1, readings of burner damper settings were recorded during Phase 3A.

<u>Automated Boiler Data Collection</u>

Two scanning data loggers were installed to record the signals both from pre-existing plant instrumentation and from instruments installed specifically for this test program. The data loggers were monitored by a central computer that maintained permanent records of the data and also allowed instantaneous, real-time interface with the data acquisition equipment. In addition to the measurements provided in Phase 1, signals were recorded from four OFA flow meters, one in each OFA windbox quadrant during Phase 3A. This was done to document the low OFA flow rate due to leakage through the nominally closed OFA flow control dampers.

Specialized instrumentation was also installed to measure some specific parameters related to the combustion and thermal performance of the boiler, as well as selected gaseous pollutant emissions. These included combustion gas analyzers, pollutant emissions analyzers, an acoustic pyrometer system to measure furnace temperature contours across a plane in the upper furnace, fluxdomes to measure heat flux at selected points on the boiler wall, and continuous ash samplers. The combustion gas and emissions analyzers and the acoustic pyrometer system were linked to the central computer for automated data recording.

<u>Combustion System Tests</u>

At several specific operating conditions tests were performed by a team of engineers from Flame Refractories, Inc. using specialized apparatus and procedures to measure parameters related to the combustion and thermal performance of the boiler. The measurements included the following:

Primary Air/Fuel Supply

- Primary air flow rate to each mill
- Primary air velocity to each burner
- Coal flow rate to each burner
- Coal particle size distribution to each burner

Secondary Air Supply

Secondary air flow and temperatures, east/west
Secondary air flow and temperatures, front/rear windboxes

Overfire Air Supply

OFA flow to each quadrant of OFA (Front and rear/east and west)

Furnace Combustion Gases

Gas temperatures near furnace exit
Gas species near furnace exit

Boiler Efficiency

Exit gas temperatures
Exit gas excess O_2
Unburned carbon losses

Solid/Sulfur Emissions Tests

During the performance tests, a team of scientists and technicians from SoRI made measurements of particulate and gaseous emissions exiting the boiler, using specialized equipment and procedures. These measurements included:

- Total particulate emissions and particle sizes
- Fly ash resistivity at the ESP inlet
- SO_2 and $S0_3$ concentrations

The results of the solid/sulfur emissions tests are to be used in calculations to estimate the effect of NOx controls on the performance of a generic ESP representative of large utility installations.

Special LOI Tests

Because of the interest in identifying the major parameters that affect the fly ash LOI and the NOx emissions related to burner settings and excess oxygen levels, a special set of LOI tests were performed. The principal objective of this effort was to determine whether the carbon content of the fly ash could be reduced by simple adjustments to the boiler operation without substantially increasing NOx emissions or any other adverse condition. Flame first evaluated the existing primary air and coal flows to each mill and the resulting effects on coal particle size. From these initial tests Flame recommended that revised primary air/fuel ratios be used. With these revised ratios, ETEC conducted a series of tests with variations in several boiler operating parameters, one at a time. The parameters varied were:

- Bias of coal flow to selected mills
- Burner inner and outer vane positions and coal nozzle insertion depth
- Overall boiler excess O_2

At each of the first two parameter variations (mill bias or burner setting) at least three excess O_2 levels were tested. At each test condition, SoRI personnel obtained ash samples using two identical EPA Method 17 particulate probes and sample trains. SoRI analyzed each sample for LOI on-site, within 24 hours. Subsequently, each sample was analyzed for elemental carbon content at the SoRI laboratory in Birmingham, Alabama. For each day of testing, Flame measured the primary air flow to each mill and the coal flow rate and particle size distribution within each coal pipe. During a single day's testing, the mill coal and air flow controls were maintained constant. A single coal sample was obtained each day for composition analysis at the Alabama Power Company fuel laboratory in Birmingham. All testing was done at a nominal load of 450 MW with the AOFA flow control dampers barely cracked open to admit a minimum of cooling air flow to the AOFA ports, as recommended by FWEC. Simultaneously with the particulate and coal/air measurements, NOx, excess O_2. and CO were measured in the economizer exhaust ducts, along with the large array of boiler operating parameters recorded on the DAS and by control room readings.

4. Data Analysis Methodology

Two distinctly different types of data analyses are utilized to characterize the data: discrete analyses for short-term data, and statistical analysis for long-term data. The short-term data are used to establish emission trends, provide information for engineering assessments' and provide data for evaluating guarantees or goals established with the equipment vendors. Long-term data are used to statistically establish the long-term emission trends and regulatory assessments when the unit is operated in a normal system load dispatch mode.

4.1 Short-Term Characterization Data Analysis

The short-term data collection portion of the project is divided into diagnostic, performance, and verification test efforts. The diagnostic data collection effort is used to establish the trends of NOx versus load, mill patterns, and excess oxygen. The performance data collection effort is used to establish input/output characterizations of fuel, air, flue gas emissions, and boiler efficiency. The diagnostic, performance, and verification efforts are performed under well controlled conditions with the unit off of system load dispatch. Each data point is for a single operating condition. Unlike the data collected in the long-term effort, the data collected during the short-term effort is generally not of sufficient quantity to apply sophisticated mathematical analysis. Most of the analysis of the short-term data is graphical.

4.1.1 Diagnostic Data

Although much more information is obtained, the primary emphasis of the diagnostic testing is to determine the NOx emission characteristics of the unit. The NOx, O_2 and CO are automatically recorded every five seconds and stored as 5-minute averages in the historic files on a computer. The NOx measurements of interest during this element of the short-term testing are those obtained from the sample flow distribution manifold. The manifold allows sampling from individual probes or combinations of probes located in the economizer exit upstream of the primary and secondary air preheaters. The composite emission measurement over the entire economizer exit (average of 28 probes) for the period of a diagnostic test represents a single data point for one configuration.

A single data point is obtained by selecting a probe group and obtaining numerous one-minute averages of the five-second data over the one- to three-hour period of the test. Sampling of one of the groupings is made for a sufficient time to insure that the readings are steady. The DAS is then prompted to gather data for one minute (12 five-second readings) and to calculate the statistics for that period (e.g. average and standard deviation). The average of all of the one-minute average measurements over the test duration constitutes a single data point for NOx for the condition under which the test was performed.

Early diagnostic test efforts showed that the variability of the NOx emissions was significant for seemingly identical conditions, i.e., load, O_2. and mill pattern. Since only a limited amount of short-term data were to be collected in the diagnostic effort. the high variability jeopardized the ability to trend the emissions data adequately. If the diagnostic test effort had included many more data points (requiring significant more test days), the approach may have provided sufficient information to perform experimental design regression analyses. As a result of the NOx variability, the test plan reverted to a more or less sequential approach to collecting emission data, i.e., one load and mill pattern per day with a range of excess oxygen levels measured during steady-state conditions.

During the Phase 3A diagnostic testing, attempts were made to gather three sequential data points (either increasing or decreasing excess oxygen level) at each load level (or mill pattern). With three data points on one day with a minimum variation of the other influencing parameters, the general trend of NOx versus load (or mill pattern) could be determined. Test points that were not sequential (different loads or mill patterns on the same day) were used to indicate the potential variability about the trend lines. It is assumed that the trends for these single, non-sequential data points is similar to that determined for sequential data and that families of curves exist. This assumption was tested during Phase 1 and found to be true.

4.1.2 Performance Data

Performance data are used to: (1) to establish baseline evaluation criteria for retrofits, (2) to quantify the boiler characteristics for comparison with other phases of the program and (3) for comparison with the results of the diagnostic trends. The emphasis for the performance tests was on the analysis of the flows, solids capture, and boiler efficiency rather than on the NOx trends. As with the diagnostic test data, insufficient data samples were available to perform meaningful advanced statistics.

For each performance configuration (10- to l 2-hour test day) the following types of data were obtained:

1. Two gaseous emission measurements of NOx, O_2 and CO, each composed of at least l 0 one-minute sample distribution manifold composite flue gas measurements,

2. Two ASME PTC 4.1 boiler efficiency determinations and two air preheater leakage determinations,

3. A minimum of three repetitions of specific flue gas solids emission parameters (total particulate emissions, $S0_3$, resistivity, LOI, or particle size), and

4. A minimum of one repetition of inlet fuel and air measurements (primary air distribution, secondary air distribution, coal particle size, or coal mill pipe distribution), or furnace combustion gas temperature and species.

4.2 Long-Term Characterization Data Analysis

During this portion of the test program, the emission and plant operating data input was automatically recorded on the DAS and archived. The emission input was handled automatically by the CEM. A single emission measurement point in the duct following the ESP was monitored 24 hours per day during the entire long-term effort. The emission sample was brought to the CEM through heated lines to preclude condensation of SO_2 in the lines. Prior to the start of the Phase 2 long-term test effort, the CEM was certified by Spectrum Systems, Inc.

The primary focus of the long-term test effort was to monitor the natural variation of the data in the normal mode of operation. During the entire long-term effort, no intervention by the SCS test team members (SCS or ETEC) occurred or was for that matter allowed.

This was to insure that the long-term data would not be biased by this type of input. For all practice. purposes, the boiler was operating in its normal day-to-day configuration under control of the load dispatcher. The only added constraint was that the new LNBs would be operated as determined by FWEC personnel.

The thrust of the analysis of the long-term data is its interpretation primarily by statistical methods. The specific types of analysis used are related to regulatory issues and the engineering interpretation of long-term results compared to short-term diagnostics results. The analyses related to the regulatory issues were associated with the determination of the 30-day rolling average and annual average emissions and the estimation of an achievable emission level. The analyses related to the engineering interpretations were associated with the determination of the best statistical estimates of the operating characteristics, i.e., NOx versus load, mill pattern, etc.

The following two subsections provide information on (1) the processing of the long-term data to produce a valid emission data set and (2) the fundamentals of the data-specific analytic techniques.

4.2.1 Data Set Construction

4.2.2 Five-minute Average Emission Data .

The data collected during the long-term test program consisted of 5-minute averages of parameters related to boiler operating conditions and emissions. Since the intent of all analyses of the long-term test periods is to depict normal operating conditions, data collected during startup, shutdown, and unit trips were excluded from the analyses.

The 5--minute average data are also used to compute hourly averages that are in turn used to compute daily average NOx emissions. The daily average emissions are used to estimate the achievable NOx emission limit.

The loss of 5-minute data due to CEM failure was treated based on an adaptation of EPA NSPS guidelines for determining how much data is sufficient to compute an hourly average for emissions monitoring purposes. Also, in the case of daily average emissions, EPA NSPS guidelines (at least 18 hours of valid hourly data per day) were used to define a valid daily average.

4.2.3 Data Analysis Procedures

Five-minute Average Emission Data

The edited 5-minute average data from the long-term tests were used to determine (I) the NOx versus load relationship and (2) the NOx versus O_2 response for various load levels.

Hourly Average Emission Data

The purpose of the hourly average emission analyses was to assess the hour-to-hour variation in NOx, O_2. and load for these periods. The within-day data analyses are performed by sorting the hourly averages by hour of the day and computing the average NOx, O_2. and load for these periods. The statistical properties for these hourly periods and the upper 95 and lower 5 percentile band was determined for each hourly data subset. These data will be used to compare the effectiveness of each technology against the baseline load scenario.

Daily Average Emission Data

The daily average emission data are used primarily to establish the trends in NOx O_2, and load, and to calculate the 30-day rolling NOx emission levels for the entire long-term period. The daily average emissions data were analyzed both graphically and statistically. The graphical analyses consist of a series of plots to depict the daily variations in NOx, O_2 and load to establish trends. The purpose of the statistical analyses was to determine the population mean, variability (standard deviation), distribution form (normal, lognormal), and time series (autocorrelation) properties of the 24-hour average NOx emissions. The SAS Institute statistical analysis packages UNIVARIATE and AUTOREG were used to perform the statistical analyses.

Achievable Emission Kate

The results of the UNIVARIATE and AUTOREG analyses were used to determine the achievable emission limit on a 30-day rolling average and an annual (block 365 day) basis. The achievable emission limit on a 30-day rolling average basis is defined as the value that will be exceeded, on average, no more than one time per ten years. This compliance level is consistent with the level used by EPA in the NSPS Subpart Da and Db rulemakings. The achievable emission limitation for an annual average NOx emission limitation was also determined to reflect the requirements of the 1990 amendments to the CAAA. A compliance level of 95 percent was chosen for this case.

The achievable emission limit can be computed analytically using the following relationship if the emissions data are normally distributed:

$$Z = (L - X) / (S_{AVG})$$

where: Z = the standard normal deviate
L = the emission limit
X = the long-term mean, and
S_{AVG} = the standard deviation of the 30-day averages. S_{AVG} is computed using the estimated standard deviation (SDay) and autocorrelation (r) level for daily averages.

For 30-day averages:

$$S30 = \frac{SDay}{\sqrt{30}} \left(\frac{1 + \rho}{1 - \rho} - \frac{(2)(\rho)(1 - \rho^{30})}{30\,(1 - \rho)^2} \right)^{1/2}$$

For 365-day averages

$$S365 = \frac{SDay}{\sqrt{365}} \left(\frac{1 - \rho}{1 - \rho} - \frac{(2)(\rho)(1 - \rho^{365})}{365\,(1 - \rho)^2} \right)^{1/2}$$

Since there are 3,650 thirty-day rolling averages in ten years, one exceedance per ten years is equivalent to a compliance level of (3649/3650), or 0.999726. For a compliance level of one violation in ten years, Z is determined to be 3.46 (based upon the cumulative area under the normal curve). The calculation of the annual average emission limitation is performed in a manner similar to that for the 30-day limitation. For annual averages, a 9S percent compliance level was arbitrarily chosen. The Z value for 95 percent compliance is 1.645.

5. Short-Term Test Results

The short-term testing consisted of first performing diagnostic testing to establish the general NOx and operating trends followed by performance testing to establish the characteristics of the fuel/air feed systems and the solid and gaseous emissions for the most representative configuration. All tests during both the diagnostic and performance portions of the short-term test effort were conducted within the normal limits of operating parameters for the unit, with the exception of excess oxygen. Excess oxygen was exercised well above and below the plant specified range to the potential levels that might be encountered during transient in the long-term test phase. All major boiler components, as well as ancillary equipment, were in the normal "as found" operating condition. The fuel burned throughout the Phase 3A short-term program was from the normal supply source and was handled according to common plant practice. For all Phase 3A testing (LNB without AOFA), the main AOFA guillotine dampers and AOFA porn dampers were left open but the AOFA flow control dampers were nominally "closed", with only sufficient AOFA Bow permitted to provide some cooling for the AOFA ports and dampers to prevent heat damage.

The initial Phase 3A short-term characterization testing was begun on July 9, 1991 and was completed on January 15, 1992. A total of 52 diagnostic tests were performed during this period. An additional 40 tests were performed during a special series of LOI tests performed from October 20 through 28, 1992. The following paragraphs describe the diagnostic, performance, and LOI testing performed during the Phase 3A effort.

5.1 Diagnostic Tests

The Phase 3A diagnostic effort consisted of characterizing emissions under normal operating conditions with the LNBs installed and the AOFA flow control dampers nominally closed. Fifty-two tests were performed at nominal loads of 180,300,400, and 480 MW. The diagnostic test efforts were interrupted to accomplish the performance testing due to scheduling conflicts. Diagnostic testing was then completed after the performance testing and long-term evaluation were completed. The initial diagnostic testing began shortly after FWEC conducted LNB start-up testing was completed. Each test condition (load, excess oxygen, and mill configuration) was held steady for a period of from one to three hours depending upon the type of test performed. During this period, data were collected manually from the control room, automated boiler operational data were recorded on the DAS, and economizer exit and preheater exit species and temperatures were recorded utilizing the sample distribution manifold and were recorded on the DAS. When sufficient time permitted, furnace backpass ash grab samples were collected from the CEGRIT ash samplers and coal samples were collected from the individual mills.

5.1.1 Unit Operating Condition

During the diagnostic test efforts no unusual operating conditions were encountered that placed restrictions on the test effort. Table 5- l presents the "as tested" conditions during the diagnostic portion of the testing. Sixteen days of testing were conducted comprising 52 various excess oxygen, mill pattern, and load conditions. Because historic load profiles indicated much greater operating times at 400 MW and above, most diagnostic testing was done in this load range.

5.1.2 Gaseous Emissions

During both the diagnostic and performance test efforts, flue gas data and boiler operating data were collected on the data acquisition system (DAS). The gas analysis system (GAS) allowed measurement of NOx, CO, O_2 and total hydrocarbons (THC) from 48 probe locations within the flue gas stream both upstream and downstream of the air preheater. Two basic types of tests were performed: (1) overall NOx characterization and (2) economizer exit plane species distribution characterization. The overall NOx characterization tests were performed over a period of approximately one hour and were used to obtain composite average specie concentrations from the individual probes in a duct sampled as a group. In general, the groups were: (1) A-side economizer outlet, (2) B-side economizer outlet, (3) A-side APH outlet and (4) B-side APH outlet composite concentrations. The economizer exit plane species distribution characterizations were performed over a period of approximately two to three hours. These tests used data from the individual probe species concentrations in the A- and B-side economizer exit planes to establish the extent of maldistribution of combustion products emanating from the boiler. These maldistributions, if present, indicate fuel and/or air non-uniformities.

Table 5-2 presents a summary of important emission and operating parameters recorded on the DAS during the diagnostic test effort. These operating parameters provide information on the steaming conditions and the fuel supply configuration. The range of excess oxygen and resulting NOx emissions for the four nominal load levels tested during the diagnostic portion of the Phase 3A effort are shown in Figures 5-l and 5-2. The conditions represented in these figures include excess oxygen variation, mill-out-of-service variation, mill biasing, etc. Figure 5-l illustrates that the testing was performed over a range of excess oxygen levels that were both below and above the levels recommended for this unit. The solid curve represents the recommended excess oxygen operating level. During system dispatch control of the unit, excursions to these levels are frequently experienced during transient load conditions. In order to properly compare the short-term and long-term characteristics, this O_2 excursion testing during the short-term diagnostic effort was required.

Figure 5-2 is a summary of all of the NOx data obtained for all test configurations. These configurations represented the range of normal configurations that were believed to be the predominant modes of operation that might be experienced during the normal load dispatch of the unit during long-term testing. The data scatter is partially due to the fact the different configurations are represented. The shaded area represents the range of NOx values experienced at excess O_2 levels within a ±0.5 percent O_2 variation about the recommended O_2 level It should be emphasized that analyses performed for data gathered during the long-term testing (Section 6.1) where virtually thousands of data points were used for the characterization provide a more statistically appropriate NOx band than that presented in Figure 5-2.

Table 5-1 Summary of Phase 3A Diagnostic Tests

Test NO.	Date	Test conditions	Load MW	MOOS	Stack O2 %	Econo O2 %	Econo Nox ppm	CO ppm	LOI E %
58-1	7/9/91	HIGH LOAD, AMIS, HIGH O2-LOI TEST	477	NONE	7.1	4.6	508	11	6.9
58-2	7/991	HIGH LOAD, AMIS, NORM OS-LOI TEST	475	NONE	6.5	4.1	480	11	8.1
58-3	7/9/91	HIGH LOAD, AMIS LOW O2-LOI TEST	473	NONE	5.5	2.9	426	67	11.0
59-1	7/10/91	HIGH LOAD, AMIS, HIGH O2-LOI TEST	471	NONE	7.3	5.0	483	12	4.9
59-2	7/10/91	HIGH LOAD, AMIS,NORM O2-LOI TEST	473	NONE	6.4	4.0	441	13	11.0
59-3	7/10/91	HIGH LOAD, AMIS,LOW O2-LOI TEST	475	NONE	5.8	3.1	418	26	12.3
59-4	7/10/91	HIGH LOAD, AMIS,MIN O2-LOI TEST	474	NONE	5.4	2.6	401	127	16.3
59-5	7/10/91	HIGH LOAD, AMIS,LO NORM O2-HVT TEST	474	NONE	6.3	3.7	448	31	
60-1	7/11/91	MID LOAD, AMIS, HIGH O2	393	NONE	7.1	4.6	408	11	
60-2	7/11/91	MID LOAD, AMIS, NORM O2	398	NONE	6.3	3.9	377	13	
60-3	7/11/91	MID LOAD, AMIS, LOW O2	397	NONE	6.0	3.5	360	119	
60-4	7/11/91	MAX LOAD, AMIS, NORM O2 GPC HEAT RATE	502	NONE	6.5	4.0	503	4	
61-1	7/12/91	MID LOAD, AMIS, REPEAT HIGH O2	392	NONE	7.1	4.7	401	6	
61-2	7/12/91	MID LOAD, AMIS, REPEAT NORM 02	392	NONE	6.4	4.1	377	6	
61-3	7/12/91	MID LOAD, AMIS, REPEAT LOW O2	390	NONE	5.7	3.2	340	81	
61-4	7/12/91	MAX LOAD, AMIS, NORM 02, GPC HEAT RATE	498	NONE	6.4	3.9	480	15	
62-1	7/13/91	MID/LOW LOAD, E MOOS, HIGH O2	289	E	9.2	7.1	458	7	
62-2	7/13/91	MID/LOW LOAD, E MOOS, MEDIUM O2	291	E	8.1	5.9	424	7	
62-3	7/13/91	MID/LOW LOAD, E MOOS, NORM O2	290	E	7.3	4.8	398	9	
62-4	7/13/91	MID/LOW LOAD, E MOOS, LOW O2-ABBREV.	289	E	-	4.0	375	14	
62-5	7/13/91	HIGH LOAD, AMIS, NORM O2	474	NONE	6.9	4.3	471	18	
63-1	7/14/91	MID/LOW LOAD, BE MOOS, HIGH O2	302	B&E	8.1	5.8	366	13	
63-2	7/14/91	MID/LOW LOAD, BE MOOS, HIGH O2	305	E	8.0	5.7	425	10	
63-3	7/14/91	MID/LOW LOAD, BE MOOS, NORM 02	303	E	7.3	4.8	402	26	
64-1	7/15/91	HI LOAD, HI/MID O2, AMIS, BALANCED MILLS	467	NONE	7.0	4.6	487	13	
64-2	7/15/91	HI LOAD, LOW 02, AMIS BALANCED MILLS	470	NONE	5.9	3.3	426	56	
67-1	7/18/91	HI LOAD, AMIS, HI O2-LOI TEST, OPEN INNER REG	472	NONE	6.7	4.3	443	16	12.7
67-2	7/18/91	HI LOAD, AMIS, MID O2-LOI TEST,	471	NONE	6.2	3.6	422	171	
67-3	7/18/91	HI LOAD, AMIS, LOW O2-LOI TEST, OPEN OUT REG	470	NONE	6.1	3.5	425	22	
67-4	7/18/91	HI LOAD, LOW O2, LOI TEST, UF AIR AT 25%	465	NONE	6.1	3.5	430	16	13.1
68-1	7/19/91	HI LOAD, AMIS-LOI TEST, LOWER PRIM AIR FLOW	460	NONE	6.2	3.5	442	37	8.7
69-1	7/20/91	HI LOAD, AMIS-LOI TEST, MILL FINENESS A-MILL	473	NONE	5.9	3.2	413	19	6.2
69-2	7/20/91	HI LOAD, AMIS-LOI TEST, MILL FINENESS F-MILL	469	NONE	5.9	3.3	448	15	
77-1	11/16/91	LOW LOAD, BC-MOOS, HI O2	180	BC	10.8	8.7	413	6	
77-2	11/16/91	LOW LOAD, BC-MOOS, HI O2, REPEAT TEST	180	BC	10.6	8.5	428	6	
77-3	11/16/91	LOW LOAD, BC-MOOS, MID O2	182	BC	9.9	7.4	416	6	
77-4	11/16/91	LOW LOAD, BC-MOOS, LOW O2	185	BC	8.9	6.4	444	5	
78-1	11/17/91	LOW LOAD, BE-MOOS, HI O2	181	BE	10.5	8.3	556	5	
78-2	11/17/91	LOW LOAD, BE-MOOS, MID O2	183	BE	9.6	7.2	543	5	
78-3	11/17/91	LOW LOAD, BE--MOOS, LOW O2	180	BBEE	8.5	5.8	507	5	
79-1	11/18/91	MID/LOW LOAD, BE-MOOS, HI O2	305	BE	9.1	7.1	476	9	
79-2	11/18/91	MID/LOW LOAD, BE-MOOS, MID O2	305	BE	8.4	6.1	487	9	
79-3	11/18/91	MID/LOW LOAD, BE-MOOS, LOW 02	305	BE	7.7	5.3	399	49	
80-1	11/18/91	MID/LOW LOAD, EF-MOOS, LOW O2	310	EF	7.3	4.8	333	101	
80-2	11/18/91	MID/LOW LOAD, EF-MOOS, MID O2	308	EF	8.5	6.3	405	11	
80-3	11/18/91	MID/LOW LOAD, EF-MOOS, MID O2, SLEEVES 50%	310	EF	8.3	6.2	342	14	
81-1	1/14/91	MID/LOW LOAD, BE-MOOS, LOW O2	302	BE	7.9	5.0	369	49	
81-2	1/14/91	MID/LOW LOAD, BE-MOOS, MID O2	299	BE	9.0	6.5	438	10	
81-3	1/14/91	MID/LOW LOAD, BE-MOOS, HI O2	301	BE	9.6	7.0	445	10	
82-1	1/15/91	MID LOAD, AMIS, LOW O2	395	NONE	6.8	3.8	395	74	
82-2	1/15/91	MID LOAD, AMIS, MID O2	395	NONE	7.4	4.5	427	5	
82-3	1/15/91	MID LOAD, AMIS, HI O2	395	NONE	8.1	5.4	464	4	

Table 5-2 Diagnostic Tests / Emissions and Operating Data

Test Number	Date	Gross Load MW	O2 Econ. East (Plant) %	O2 Econ. West (Plant) %	CEM O2 %	CEM NOx lb/MBtu	Opacity %	Mill A Flow klb/hr	Mill B Flow klb/hr	Mill C Flow klb/hr	Mill D Flow klb/hr
58-1	7/9/91	477	3.8	4.1	4.6	0.69	-	54	64	57	55
58-2	7/991	475	3.4	3.7	4.1	0.65	-	64	67	70	62
58-3	7/9/91	473	2.1	2.7	2.9	0.58	-	53	62	57	54
59-1	7/10/91	471	3.9	4.7	5.0	0.66	-	52	62	57	54
59-2	7/10/91	473	2.9	3.7	4.0	0.60	-	52	62	57	54
59-3	7/10/91	475	2.1	3.1	3.1	0.57	-	52	62	56	54
59-4	7/10/91	474	1.7	2.6	2.6	0.55	-	52	62	57	54
59-5	7/10/91	474	2.4	3.7	3.7	0.61	-	52	62	56	54
60-1	7/11/91	393	3.6	4.6	4.6	0.56	-	45	53	48	47
60-2	7/11/91	398	3.0	3.8	3.9	0.51	-	44	52	47	47
60-3	7/11/91	397	2.7	3.2	3.5	0.49	-	44	52	47	47
60-4	7/11/91	502	3.7	2.6	4.0	0.69	-	58	63	57	57
61-1	7/12/91	392	3.7	2.5	4.7	0.55	-	45	49	44	47
61-2	7/12/91	392	3.1	2.9	4.1	0.51	-	45	48	44	48
61-3	7/12/91	390	2.1	2.1	3.2	0.46	-	45	48	44	47
61-4	7/12/91	498	3.5	2.6	3.9	0.65	-	55	57	53	59
62-1	7/13/91	289	4.8	4.2	7.1	0.62	-	42	43	43	44
62-2	7/13/91	291	4.8	4.2	5.9	0.58	-	42	43	43	44
62-3	7/13/91	290	3.9	3.5	4.8	0.54	-	42	43	43	44
62-4	7/13/91	289	3.9	3.5	4.8	0.54	-	42	43	43	44
62-5	7/13/91	474	3.7	3.1	4.3	0.64	-	54	56	53	57
63-1	7/14/91	302	4.5	5.3	5.8	0.50	-	54	0	55	58
63-2	7/14/91	305	4.2	5.4	5.7	0.58	-	40	47	44	47
63-3	7/14/91	303	3.6	4.7	4.8	0.55	-	-	-	-	-
64-1	7/15/91	467	4.1	3.0	4.6	0.66	26.9	57	54	53	55
64-2	7/15/91	470	2.8	2.1	3.3	0.58	18.4	57	53	53	54
67-1	7/18/91	472	3.2	3.0	4.3	0.60	23.5	55	57	56	56
67-2	7/18/91	471	2.6	2.3	3.6	0.57	27.0	57	57	57	56
67-3	7/18/91	470	3.0	2.0	3.5	0.58	24.1	55	57	57	56
67-4	7/18/91	465	3.3	2.3	3.5	0.59	20.2	67	64	65	68
68-1	7/19/91	460	3.7	2.3	3.5	0.60	22.3	56	56	45	55
69-1	7/20/91	473	2.4	2.4	3.2	0.56	22.4	56	56	55	55
69-2	7/20/91	469	3.0	2.3	3.3	0.61	23.9	55	56	56	55
77-1	11/16/91	180	8.6	7.8	8.7	0.56	1.4	34	0	0	37
77-2	11/16/91	180	8.4	7.8	8.5	0.58	NA	33	0	0	36
77-3	11/16/91	182	7.2	7.1	7.4	0.57	1.2	35	0	0	32
77-4	11/16/91	185	5.7	7.2	6.4	0.61	1.0	34	0	0	36
78-1	11/17/91	181	7.7	8.3	8.3	0.76	2.2	35	0	33	39
78-2	11/17/91	183	6.6	7.7	7.2	0.74	1.5	35	0	35	39
78-3	11/17/91	180	5.8	6.1	5.8	0.69	1.7	35	0	35	39
79-1	11/18/91	305	6.4	6.7	7.1	0.65	4.7	59	0	55	57
79-2	11/18/91	305	4.8	6.5	6.1	0.66	3.7	58	0	55	57
79-3	11/18/91	305	4.0	5.2	5.3	0.54	3.7	58	0	55	57
80-1	11/18/91	310	3.3	5.7	4.8	0.45	4.6	59	57	53	57
80-2	11/18/91	308	4.8	6.5	6.3	0.55	6.2	59	57	53	57
80-3	11/18/91	310	4.2	6.5	6.2	0.47	6.0	59	57	53	57
81-1	1/14/91	302	3.4	3.2	5.0	0.50	16.6	57	0	57	58
81-2	1/14/91	299	4.8	4.8	6.5	0.60	22.6	56	0	57	58
81-3	1/14/91	301	5.3	5.1	7.0	0.61	25.5	56	0	57	58
82-1	1/15/91	395	3.2	2.2	3.8	0.54	16.9	45	49	45	50
82-2	1/15/91	395	3.7	3.1	4.5	0.58	21.3	45	49	44	50
82-3	1/15/91	395	4.3	3.9	5.4	0.63	24.8	45	49	45	50

Table 5-2 Diagnostic Tests / Emissions and Operating Data (Cont.)

Test Number	Date	Gross Load MW	SAPH A Outlet Temp. Deg. F	SAPH B Outlet Temp. Deg. F	Steam Flow Mlb/hr	SH Temp. Deg. F	SH Lower Spray klb/hr	SH Upper	Hot RH Temp. Deg. F
58-1	7/9/91	477	340	350	3.17	996	0.0	8.0	1022
58-2	7/9/91	475	340	350	3.15	983	0.0	8.0	997
58-3	7/9/91	473	320	350	3.15	1023	0.0	8.0	988
59-1	7/10/91	471	340	340	3.15	994	0.0	11.0	100
59-2	7/10/91	473	330	340	3.17	986	0.0	10.2	986
59-3	7/10/91	475	330	350	3.16	992	0.0	10.2	983
59-4	7/10/91	474	330	350	3.17	993	0.0	10.2	977
59-5	7/10/91	474	340	350	3.15	979	0.0	10.1	992
60-1	7/11/.91	393	300	330	2.60	1000	0.0	8.5	972
60-2	7/11/91	398	310	340	2.60	1007	0.0	8.8	969
60-3	7/11/91	397	300	360	2.60	991	0.1	10.5	967
60-4	7/11/91	502	350	360	3.32	969	0.1	10.2	1000
61-1	7/12/91	392	320	330	2.56	983	0.1	10.2	977
61-2	7/12/91	392	320	330	2.54	965	0.1	10.3	978
61-3	7/12/91	390	320	33 1	-	993	0.	10.8	973
61-4	7/12/91	498	350	350	-	965	0.1	11.3	1000
62-1	7/13/91	289	310	310	1.90	989	0.0	8.4	979
62-2	7/13/91	291	310	31 1	1.90	98	0.0	8.4	979
62-3	7/13/91	290	310	32 1	1.92	1009	0.0	7.8	978
62-4	7/13/91	289	310	320	1.92	1009	0.0	7.8	978
62-5	7/13/91	474	340	350	3.08	979	0.0	6.7	1008
63-1	7/14/91	302	290	320	2.00	1026	0.0	8.0	992
63 2	7/14/91	305	300	330	2.00	985	0.0	8.0	986
63-3	7/14/91	303	310	33 1	2.00	1000	0.0	8.0	886
64 1	7/15/91	467	336	349	3.1	962	0.0	13.2	997
64-2	7/15/91	470	335	351	3.16	985	0.0	11.3	985
67-1	7/18/91	472	325	331	3.17	987	0.0	0.1	986
67 2	7/18/91	471	325	333	3.19	1017	0.0	0.1	982
67-3	7/18/91	470	330	341	3.15	1012	0.0	0.1	98
67-4	7/18/91	465	330	340	3.10	983	0.0	0.1	981
68-1	7/19/91	460	320	333	3.07	101	0.1	0.1	999
69- 1	7/20/91	473	315	328	3.15	959	0.0	0.1	987
69-2	7/20/91	469	318	33 1	3.13	986	0.0	0.1	98
77-1	11/16/91	180	286	280	1.10	993	0.0	6.5	996
77-2	11/16/91	180	290	283	1.08	994	0.0	6.9	995
77-3	11/16/91	182	300	28 1	1.13	995	0.0	6.7	98
774	11/16/91	185	308	29 1	1.12	1000	0.0	7.0	979
78-1	11/17/91	181	290	29 1	1.11	993	0.0	8.0	98
78-2	11/17/91	18 1	300	302	1.10	992	0.0	0.1	978
78-3	11/17/91	18 1	305	320	1.10	999	0.0	0.1	968
79-1	11/18/91	30 1	281	304	1.92	997	0.0	0.0	987
79-2	11/18/91	30 1	281	30 1	1.90	996	0.0	0.0	981
79-3	11/18/91	30 1	280	299	1.90	992	0.0	15.0	974
80-1	11/18/91	31 1	280	303	1.94	1010	0.0	0.0	979
80-2	11/18/91	30	278	299	1.9 1	999	0.0	0.0	983
80-3	11/18/91	310	280	292	1.9 1	999	0.0	0.0	98
81-1	1/14/92	302	280	270	1.7 1	994	0.0	13.7	98
81 2	1/14/92	299	270	275	1.7 1	994	0.0	13.5	989
81-3	1/14/92	301	270	270	1.7 1	997	0.1	12.7	1006
82-1	1/15/92	395	300	300	2.4 1	1001	0.0	10.3	98
82-2	1/15/92	395	300	300	2.4 1	999	0.0	10.4	995
82-3	1/15/92	39S	300	300	2..41	1001	0.0	1 2.a	994

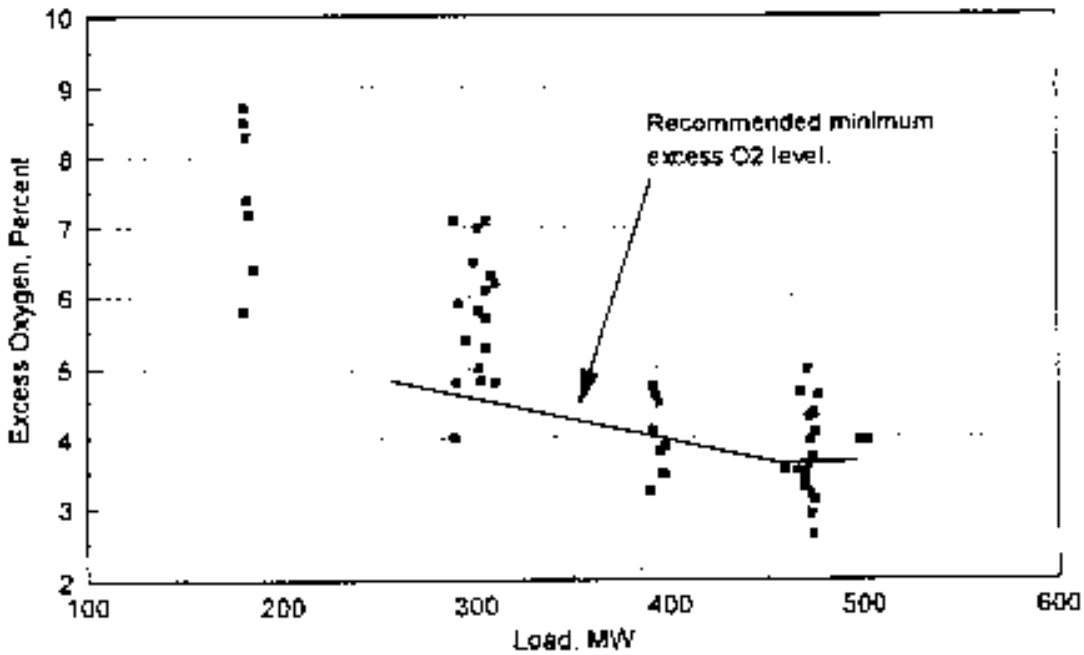


Figure 5-1 Short-Term Tests / Oxygen Levels Tested

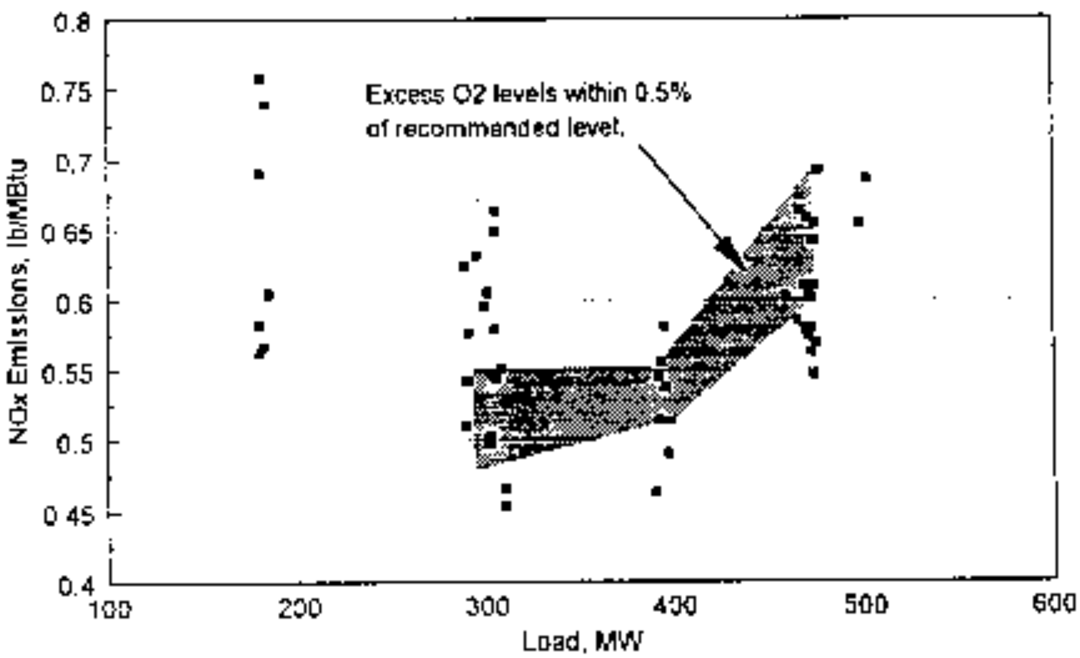


Figure 5-2 Short-Term Tests / NOx Emissions

Short-term characterization of the NOx emissions generally were made for trends determined on the same day of testing for a particular configuration to eliminate. to some extent, the influence of the uncontrollable parameters. Figures 5-3 through 5-6 show the diagnostic test results for the four nominal loads tested - 480, 400, 300, and 180 MW.

5.2 Performance Tests

Nine performance tests were conducted at nominal gross loads of 480, 400, and 300 MW. Testing at each load point required two consecutive days to complete sampling of all of the parameters included in the performance matrix. At each nominal load the coal firing rate was kept as constant as possible and the electric load allowed to swing slightly as affected by coal variations, boiler ash deposits, ambient temperature, etc.

Each performance test day covered a period from ten to twelve hours during which time manual and automated boiler operational data were recorded, fuel and ash samples acquired, gaseous and solid emissions measurements made, and fly ash resistivity measured in-situ.

The initial two performance tests (65 and 66) were performed with the mills set to the normal primary air/fuel (A/F) ratio as initially recommend by FWEC personnel. Based on previous LOI results and existing stack opacity readings, the FWEC representative on-site for these tests recommended that some additional diagnostic tests be performed at alternative primary air/fuel ratios and burner air register settings, while taking fly ash samples for LOI analysis. The performance testing was therefore interrupted for five days to plan and perform the desired diagnostic tests (days 67 through 69). Based upon the results of those tests the performance testing was resumed with reduced primary air/fuel ratios and minor burner adjustments. Table 5-3 summarizes the conditions of each of the nine performance tests.

5.2.1 Unit Operating Data

For each performance test, the desired test conditions were established and allowed to stabilize at least one hour prior to commencement of testing. To the extent possible the active coal mills were balanced with respect to coal feed rate. Normal primary air/coal ratios and mill outlet temperatures were maintained within the capabilities of the existing primary air system. When the desired operating conditions were established some controls were placed in manual mode to minimize fluctuations in fuel and air flows. This technique resulted in extremely stable operation over the test duration with only minor adjustments required to the air flow during the course of the test day.

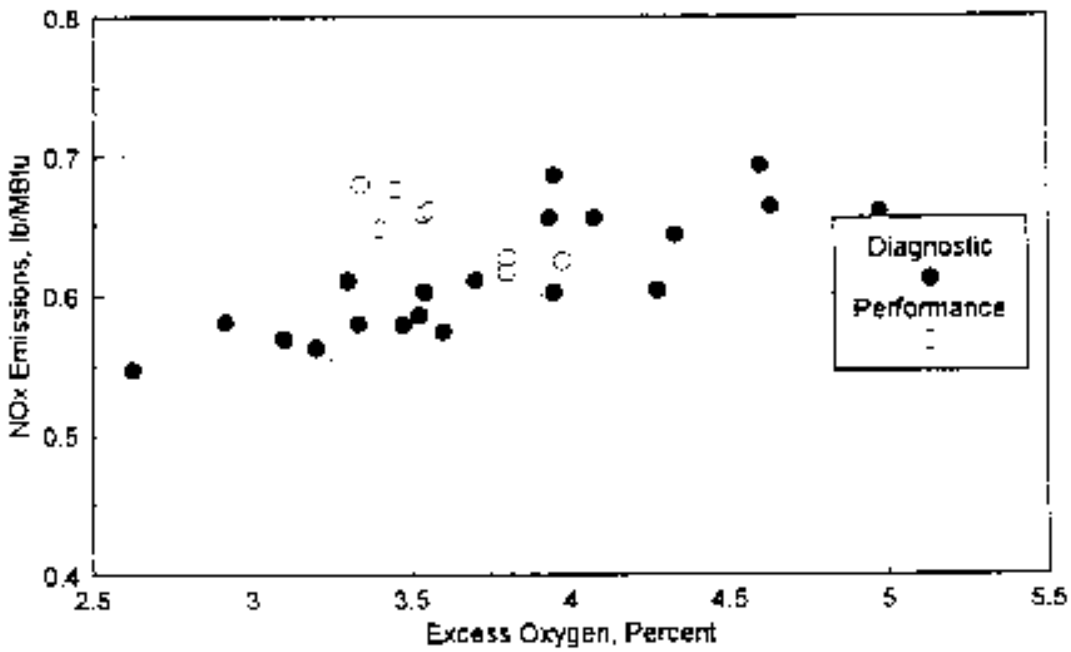


Figure 5-3 Short-Term Tests / NOx Characterization at 480 MW

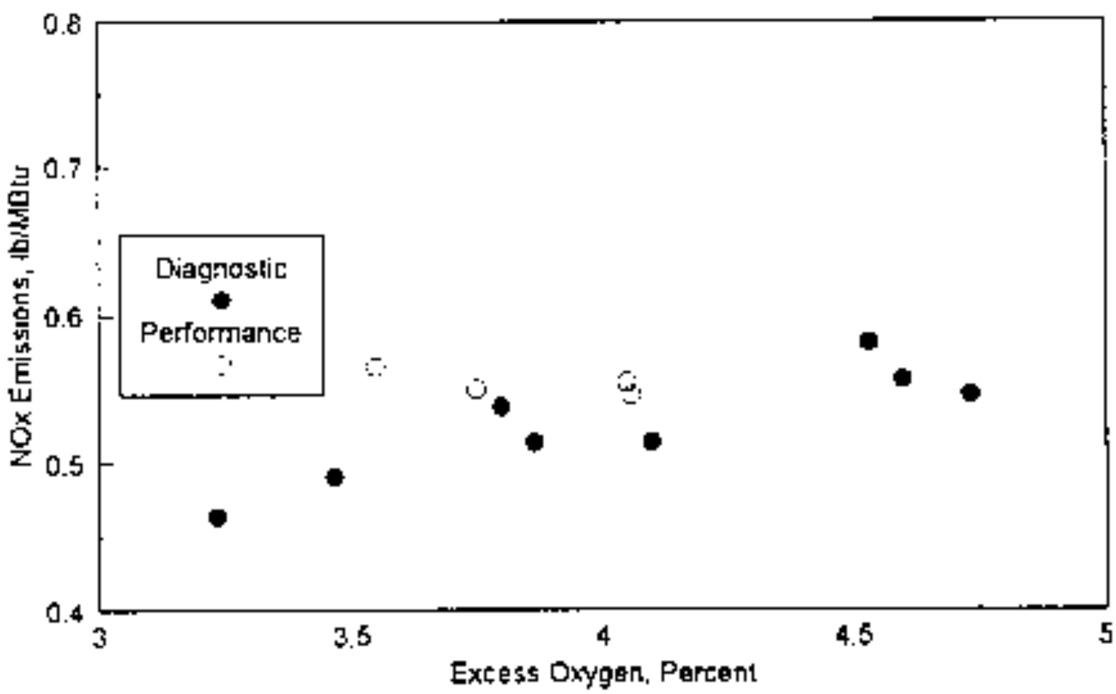


Figure 5-4 Short-Term Tests / NOx Characterization at 400 MW

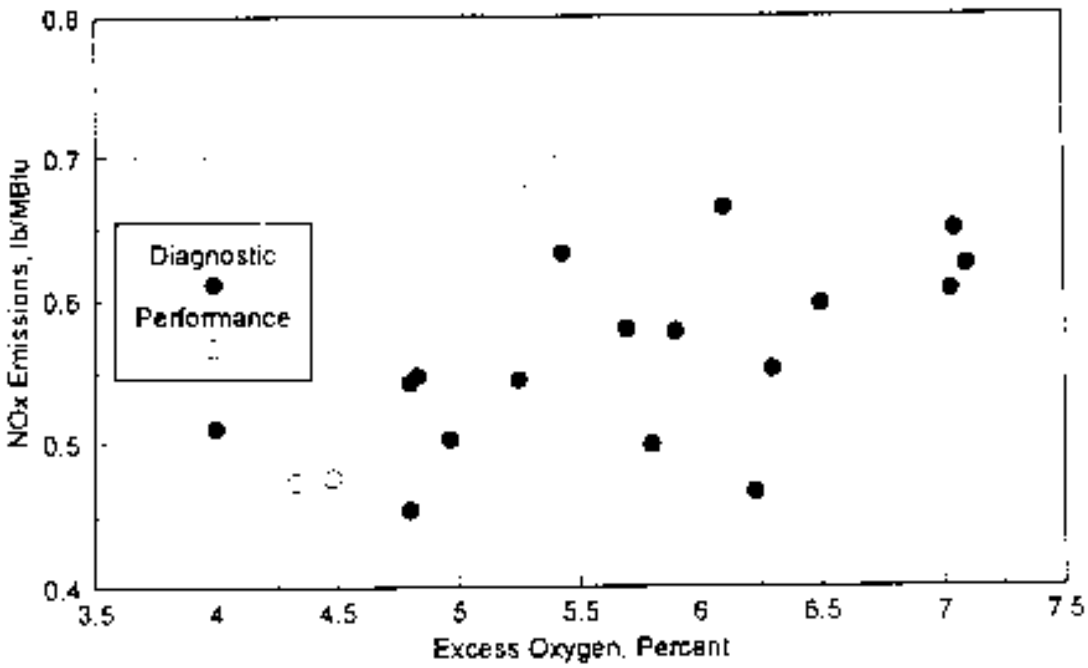


Figure 5-5 Short-Term Tests / NOx Characterization at 300 MW

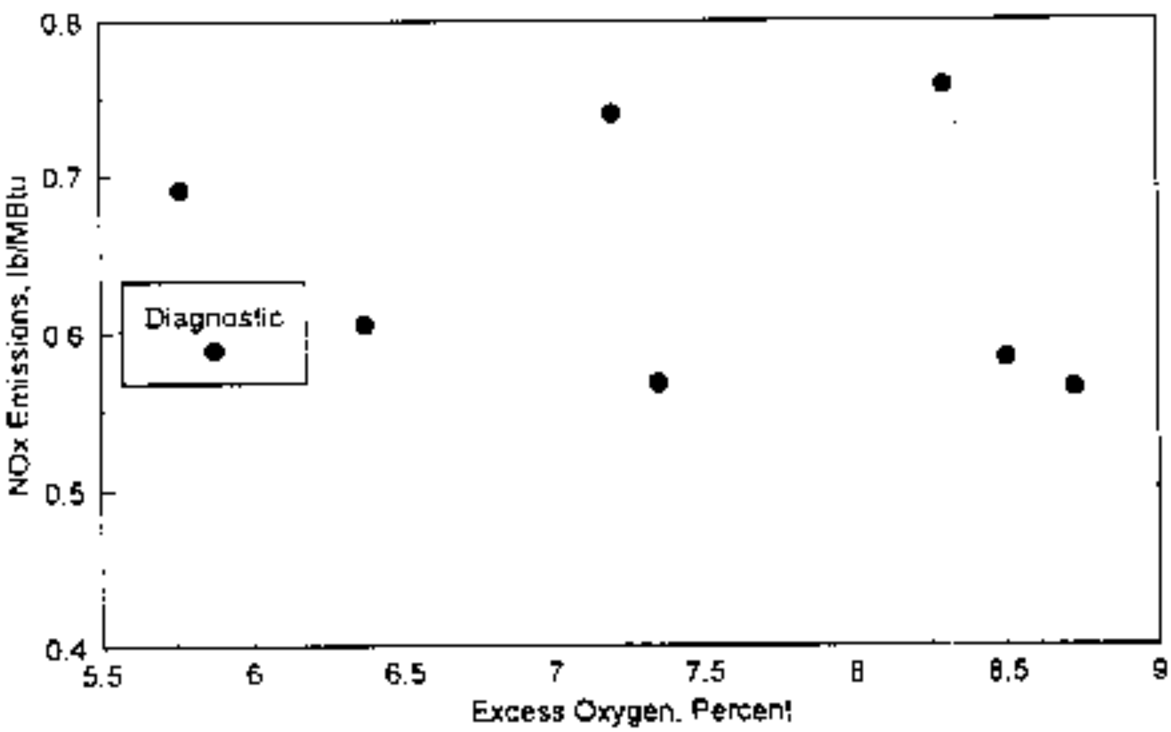


Figure 5-6 Short-Term Tests / NOx Characterization at 180 MW

Table 5-3 Summary of Phase 3A Performance Tests

Test No.	Date	Test Conditions	Load MW	MOOS	Stack O2 %	ECONO O2 %	ECONO NOx ppm	CO ppm	Comp LOI %	Com Carb %7
65-1	7/16/91	Hl LOAD, AMIS	470	NONE	6.4	4.0	458	13	7.6	
66-1	7/17/91	Hl LOAD, AMIS	475	NONE	6.3	3.8	452	13		
66-2	7117191	Hl LOAD. AMIS	474	NONE	6.5	3.8	460	15		
70-1	7/22/91	Hl LOAD. AMIS. REDUCED PRIM. AIR	479	NONE	5.9	3.3	498	19	7.8	7.3
70-2	7/22/91	Hl LOAD. AMIS. REDUCED PRIM. AIR	470	NONE	6.0	3.6	485	32		
71-1	7/23/91	Hl LOAD. AMIS, 50% 0UTER REG	473	NONE	6.0	3.5	483	15		
71-2	7/23/91	Hl LOAD. AMIS, REDUCED PRIM. AIR	465	NONE	5.9	3.5	496	15		
72-1	7124/91	HI LOAD AMIS, REDUCED PRIM. AIR	477	NONE	6.1	3.4	475	17	8.6	8.4
73-1	7/26/91	MID LOAD, AMIS. HI 02	388	NONE	6.5	4.1	400	11	5.4	5.1
73-2	7/26/91	MID LOAD, AMIS. HI 02	389	NONE	6.5	4.1	407	7		
74-1	7/27/91	MID LOAD. AMIS, HI 02	403	NONE	6.0	3.8	404	8		
74-2	7/27/91	MID L0AD, AMIS, HI 02	405	NONE	5.8	3.6	415	9		
75-1	7/28/91	MID/LOW LOAD, E MOOS	299	E	6.6	4.3	347	8	5.8	5.3
76-1	7/28791	MID/LOW LOAD, E MOOS	298	E	6.7	4.5	349	8		

Since a portion of the testing was concerned with measurement of various particulate emission characteristics, it was decided that soot blowing (both furnace and air preheaters) should be suspended during the particulate sampling periods so that the test measurements would include only particulate matter actually generated by the coal combustion at the time of testing (plus any normal attrition of wall or air preheater deposits) and not periodic portions of ash loosened by soot blowing. When necessary for proper unit operation, air preheaters were blown between repetitions in the solids emissions sampling.

Table 5-4 presents a summary of important operating parameters recorded during this test series. The values shown in this table represent averages over the duration of the test day.

5.2.2 Gaseous Emissions

During the performance tests, gaseous emissions were measured with the CEM operating in the manual mode. At various times during the performance tests, flue gas was sampled from selected probes or probe groups in the primary and secondary air preheater inlet and outlet ducts. These groupings consisted of composites of the individual east and west economizer exit ducts and individual measurements from each probe in these ducts. Composite grouping was performed to establish the overall emission characteristics while the individual probe measurements were made to establish spatial distributions of emission species.

5.2.3 Solid Emissions

Ash particulate emissions were measured both for total mass emission rate and for characteristic properties related to ash collection within an ESP. The specific measurements and analyses that were performed included: (1) total mass emissions, (2) particle size, (3) chemical composition, and (4) ash resistivity. These measurements were made immediately after the air preheater.

Total Mass Emissions Total mass emissions reflect both a fraction of the total coal ash injected into the furnace (100 percent minus the ash which drops into the furnace bottom hopper or the economizer hopper), plus most, if not all, of any unburned carbon leaving the flame zone. Table 5-5 presents the results of the Method 17 tests performed at each test condition. For all tests, the sampling rate was within four percent of isokinetic. The results shown for each test represent the average of three replicate samples.

As a measure of the degree of completeness of combustion, the ash collected in the cyclone portion of the Method I 7 train for each test was analyzed by two separate methods for carbon content and loss-on-ignition (LOI). The LOI is considered to represent carbon content along with volatile solids (sulfates, chlorides, etc) driven off the analysis procedure. The principal use of the performance test LOI analyses is as a reference for comparison with ash samples acquired during other phases of the program.

Table 5-4 Performance Tests / Operating and Emissions Data

Test Number	Date	Gross Load MW	Plant O2 Econ. East %	Plant O2 Econ. West %	CEM O2 %	CEM NOx PPM	CEM NOx lb/Mtbu	Opacity %	Mill A Flow klb/hr	Mill B Flow klb/hr	Mill C Flow klb/hr	Mill D Flow klb/hr	Mill E Flow klb/hr	M F kl
65-1	7/16/91	470	3.8	3.1	4.0	458	0.62	22.1	54	55	55	55	55	
66-1	7/17/91	475	3.6	2.7	3.8	452	0.62	2%.9	S4	55	56	55	55	
66-2	7/17/91	474	3.2	2.3	3.8	460	0.63	25.4	53	55	55	'5	55	
70-1	7/22/91	479	2.6	2.8	3.3	498	0.68	24.1	56	56	55	56	56	
70-2	7/22/91	470	2.3	2.8	3.6	485	0.66	16.7	65	58	67	62	60	
71-1	7/23/91	473	3.1	2.5	3.5	483	0.66	33.1	55	55	55	55	55	
71-2	7/23/91	465	3.0	2.6	3.5	496	0.68	22.3	54	54	53	54	54	
72-1	7/24/91	477	2.7	2.0	3.4	475	0.65	28.8	54	5S	55	55	55	
73-1	7/26/91	388	3.8	1.8	4.1	400	0.55	20.0	55	55	55	55	55	
73-2	7/26/91	389	4.0	1.7	4.1	407	0.55	17.3	55	55	55	55	55	
74~1	7/27/91	403	3.7	2.2	3.8	404	0.55	27.1	47	47	47	47	47	
74-2	7/27/91	405	3.7	1.S	3.6	415	0.57	19.2	47	47	47	47	47	
75- 1	7/28/91	299	5.0	2.4	4.3	347	0.47	16.7	44	41	43	43	0	
76-1	7/28/91	298	5.1	3.8	4.5	349	0.48	15.5	43	41	43	43	0	

Test Number	Date	Gross Load MW	SAPHA A Outlet Temp. Deg. F	SAPH B Outlet Temp. Deg. F	Steam Flow Mlb/hr	SH Temp. Deg. F	SH Lower Spray klb/hr	SH Upper Spray klb/hr	Hot R Temp Deg. I
65-1	7/16/91	470	330	335	3.13	994	0.0	0.1	
66-1	7/17/91	475	330	325	3.15	991	0.0	0.1	
66-2	7/17/91	474	338	335	3.15	1001	0.0	0.1	
70-1	7/22/91	479	320	330	3.20	1019	0.0	0.1	
70-2	7/22/91	470	328	338	3.14	986	0.0	0.1	
71-1	7/23/91	473	312	320	3.15	997	0.0	0.1	
71-2	7/23/91	465	325	340	3.11	991	0.0	0.1	
72-1	7/24/91	477	320	335	3.22	987	0.0	0.2	
73-1	7/26/91	388	310	320	2.53	1021	0.0	0.1	
73-2	7/26/91	389	310	325	2.51	1012	0.0	0.1	
74~1	7/27/91	403	310	322	2.60	991	0.0	0.1	
74-2	7/27/91	405	319	330	2.60	1008	0.0	0.1	
75- 1	7/28/91	299	289	303	1.87	1005	0.0	0.1	
76-1	7/28/91	298	291	312	1.87	988	0.0	0.1	

Table 5-5 Summary Of Solid Mass Emissions Tests

Test Number	Load MW	02 %, Dry	Loading gr/dscf	Gas Flow dscfm	Carbon %	LOI %
65	470	4.0	3.39	338,000	7.0	7.6
70	479	3.4	3.17	323,000	7.3	7.8
72	477	3.4	3.26	313,000	8.4	8.6
73	388	4.1	2.83	155,000	5.1	5.4
75	299	4 3	2.90	965 000	S.3	5.8

Particle Size The particle size distribution, of ash exiting the secondary air preheaters was determined using a cascade impactor Six samples were obtained for each test condition. Figure 5-7 shows the particle size distributions for all test loads as the total percentage of cumulative mass. Error bars representing the 90 percent confidence limits are plotted on this figure. For most of the data, the 90 percent confidence interval is smaller than the plotting

symbols. For large particle sizes the confidence band is exaggerated due to the exponential scale. The confidence interval for these points is still in the one percent range.

The very close agreement of all of the data indicates both excellent replication of testing under common conditions and also the relatively minor effect of load on the ash particle size distribution. The total particulate mass collected per unit gas volume sampled in the particle size tests was comparatively less than in the Method 17 tests. This is attributed to the inability to sample as close to the bottom of the flue gas duct with the impactor probe as can be done with the Method 17 probe, resulting in the potential failure to capture some larger particle sizes which may stratify near the duct bottom.

The derivative of cumulative mass with respect, to particle diameter is presented in Figure 5-8. This type of presentation emphasizes the particle size where mass is concentrated. This format facilitates comparison of the test data from various phases of the program and will highlight any significant changes in particle size distribution and potential effect on ESP performance due to the low NOx retrofits.

Analysis of the particle size data from an initial "high LOI" test (65) and a subsequent "low LOI" test (72) showed that the adjustment of the air/fuel ratios and burner registers had no effect on the fly ash particle size distribution.

Chemical Composition The ESP hopper samples (east and west composites separately) were analyzed for mineral composition and loss-on-ignition (LOI). Table 5-6 presents these data and allows a comparison of LOI between the air heater outlet (Method 17) and the ESP hopper chemical analysis.

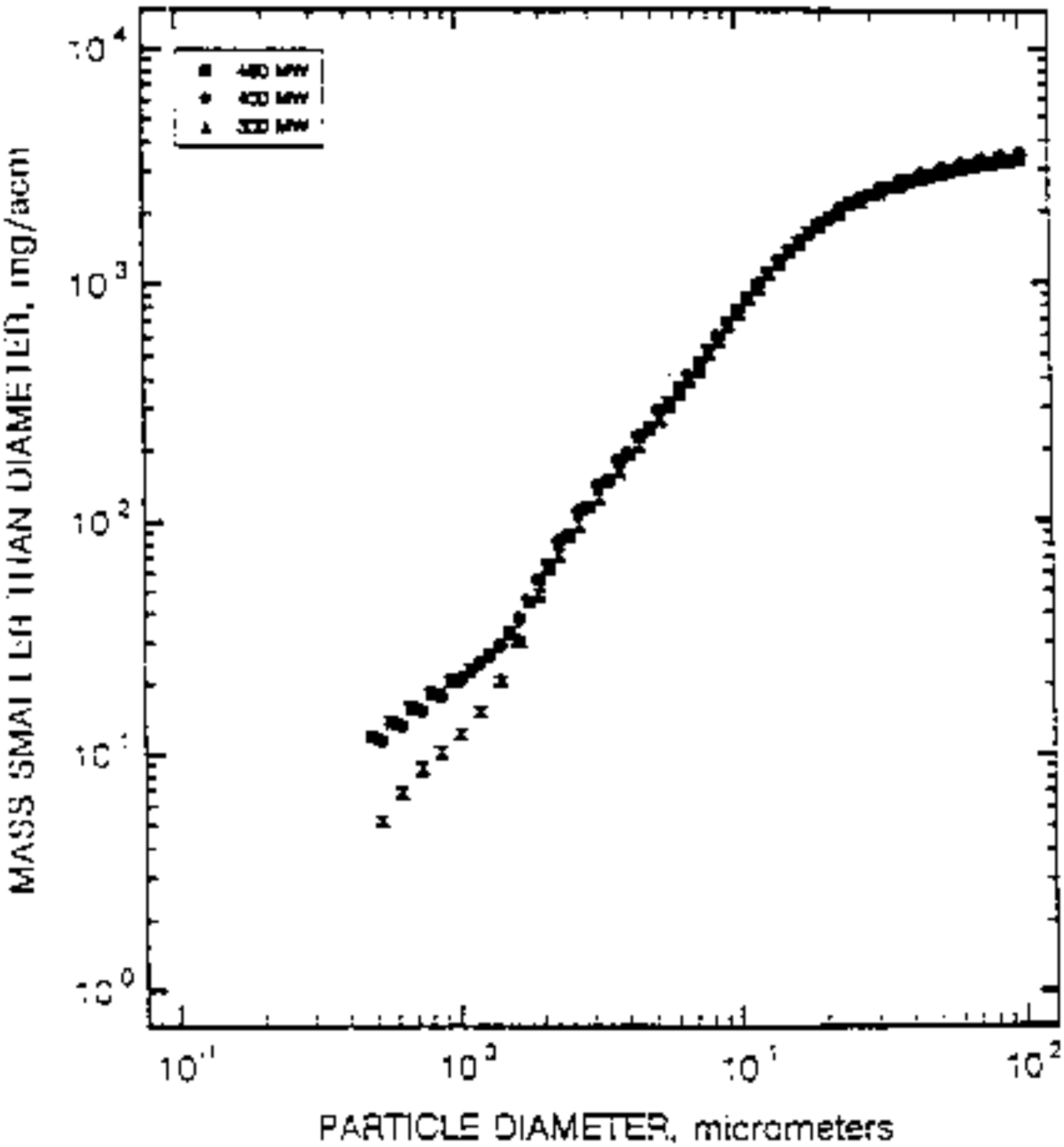


Figure 5-7   ESP Inlet Mass Distribution

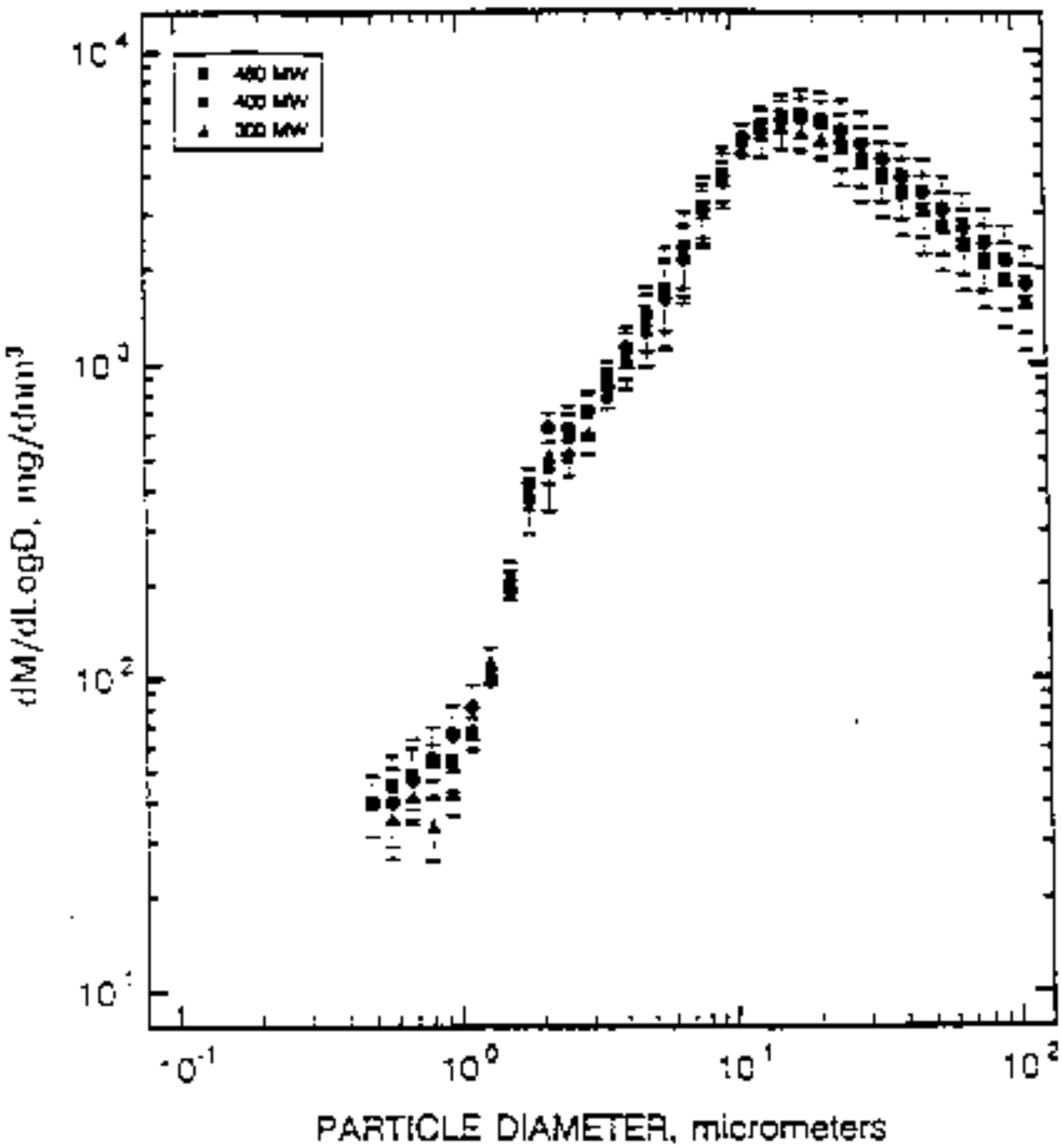


Figure 5-8   ESP Inlet Differential Mass Distribution

Table 5-6 Chemical Analysis of Hopper Samples

	Test 65 480 MW		Test 72 480 MW		Test 73 400 MW		Test 75 300 MW	
Oxide	East	West	East	West	East	West	East	West
Li_20	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.05
Na_2O	0.44	0.44	0.49	0.44	0.54	0.54	0.44	0.49
K_20	2.8	2.8	2.5	2.7	2.8	2.8	2.8	2.6
MgO	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
CaO	1.2	1.2	1.2	1.2	0.9	0.9	0.9	1.1
$Fe_2O,$	14.6	14.6	14.2	14.6	15.3	14.3	11.4	12.5
$Al_2O,$	26.4	27.1	26.9	27.6	26.4	27.0	27.2	27.3
SiO_2	51.2	50.6	50.8	49.8	51.6	52.1	54.5	53.1
TiO_2	1.5	1.5	1.5	1.5	1.4	1.5	1.4	1.5
P_2O_5	0.37	0.40	0.34	0.42	0.28	0.28	0.26	0.34
SO_3	0.16	0.20	0.18	0.19	0.14	0.13	0.20	0.24
LOI	3.9	10.5	6.9	4.1	7.7	4.9	14.9	6.5
Average LOI	*7.2*		*5.5*		*6.3*		*10. 7*	

The carbon / LOI data are useful primarily to establish a comparison between baseline and post retrofit results. The precise relation of carbon / LOI content of ash on ESP performance is not well understood and no current algorithms can confidently predict the effect of changes in their values on ESP performance. These data will be useful whenever an algorithm to correlate ash carbon content with ESP performance is developed.

Fly Ash Resistivity Measurements of in-situ resistivity were made during each LNB test condition. For each run, two values of resistivity are reported, one measured by the spark method and one measured by the V-I method. Considering the limitations of the two measurement techniques, relatively good agreement was observed. Because of the difficulty in measuring the voltage drop across the dust layer incrementally with the gas space voltage drop for low resistivities ($<1 \times 10^{10}$ ohm-cm), the spark data are considered a more reliable indicator of fly ash resistivity and will be used for analysis. The measured resistivity values correlate closely with values predicted theoretically from the ash mineral content, SO_3 concentration, flue gas temperature, and moisture content.

Table 5-7 provides the results of the in-situ ash resistivity measurements made during the tests. The data measured in-situ generally indicate that the resistivity was sufficiently low not to detrimentally affect ESP operation.

Table 5-7 In-Situ Ash Resisitivity Results

Date	Duct	Temp (°F)	Laser (mm)	Field (kV/cm)	Resistivity (ohm-cm)	Field (kV/cm)	Resis (ohm
480 MW Test							
7/16/91	West	281	0.73	12.3	8.4E+09	11.3	5.7
Test 65		283	0.24	6.3	1.0E+ 11	35.5	1.8
		284	0.11	1.6	1.6E+09	6.6	3.3
		328	0.41	6.1	5.8E+10	31.0	1.6
7/17/91	East	297	0.32	9.4	1.0E+11	8.6	4.3
Test 66		306	0.71	11.7	4.8E+10	8.4	4.2
		304	0.86	19.2	6.6E+09	10.6	5.3
7/22/91	East	289	1.31	15.9	9.5E+09	0.6	2.8
Test 70		296	0.91	21.2	2.8E+10	6.1	3.0
		296	1.24	15.7	2 2E+10	9.3	4.6
		297	1.11	17.1	1.5E+10	14.8	7.4
7/23/91	West	285	1.61	13.9	1.0E+10	8.9	4.5
Test 71		289	1.21	14.9	1.3E+10	13.2	6.6
		291	1.11	16.4	1.5E+10	14.9	7.5
7/24/91	East	289	2.51	8.3	8.6E+09	4.6	2.3
Test 72		295	2.00	8.3	1.5E+10	5.3	2.7
		294	1.39	13.0	4. lE+09	5.4	2.7
Average of 480 MW Data					*2. 7E+10*		*5.8*
400 MW Tests							
7/26/91	East	279	1.76	11.9	4.0E+09	5.8	2.9
Test 73		279	2.02	8.2	8.7E+09	1.9	9.5
		280	2.00	12.0	1.6E+01	5.0	2.5
7/27/91	West	280	1.57	12.4	2.8E+09	7.1	3.5
Test 74		282	1.31	13.7	3.6E+09	7.3	3.7
		283	1.31	13.0	7.0E+01	5.1	2.6
		285	1.24	14.5	3.4E+01	10.5	5.2
Average of 400 MW Data		281			*4.4 E+10*		*3.1*
300 MW Tests							
7/28/91	West	271	1.73	9.5	6.3E+09	5.9	2.9
Test 75		272	1.63	10.1	6.1E+09	7.1	3.5
		273	1.61	9.8	6.9E+09	1.8	9.1
		275	1.91	8.6	7.8E+09	4.2	2.1
Average of 300 MW Data		273			*6.8E+09*		*2.4*

Figures 5-9 and 5-10 show the variation of ash resistivity with temperature and SO_3 concentration based on calculations using the Bickelhaupt computer model and measured flue gas and fly ash chemical compositions, for the east and west ducts, respectively.

Laboratory resistivity measurements were also run on the ESP hopper samples obtained during the LNB test program. Figure 5-11 shows the results for the 480 MW tests, including the effect of the addition of $S0_3$. Figure 5-12 shows the results for the 400 and 300 MW tests, respectively. These data do not follow precisely the same trends observed in the in-situ resistivities. However, the data do indicate that all samples should respond to SO_3 in the flue gas environment and produce resistivity values which would not limit ESP performance. This result agrees with the baseline test data.

The LNB resistivity data are contrasted with the baseline data in Table 5-8. The average spark resistivity for the full load baseline test was somewhat higher than the average for the full load LNB test. This is probably due to the higher S03 concentrations in the LNB tests, which would tend to overcome the higher temperatures also experienced in the LNB tests. In the baseline case, the reduced SO_3 concentrations may be due to the loss of SO: from condensation in the air preheaters or to increased air infiltration around the air preheater seals.

5.2.4 Flue Gas $S0_3$ Concentration

Ash resistivity is strongly attenuated by surface films of sulfuric acid produced by the adsorption of SO_3 and water vapor from the flue gas. Thus, ash resistivity can be significant affected by changes in SO_3 and water vapor concentration in the flue gas. The concentrations of SO_3 measured at the ESP inlet during the LNB tests are given in Table 5-9. Since resistivity is affected by the actual concentration of SO_3 present, the values are not normalized to a constant oxygen level. However, since SO_3 is formed by the oxidation of SO_3, it is reasonable to expect the SO_3 concentration to vary with fluctuations in SO_2 and O_2 levels. As shown in Table 5-9, variations in S03 concentration do not necessarily track the variations in SO_2 level, i.e., the SO_3-to-SO_2 ratio is not constant. In fact, it varied from a low of 0.395 percent to a high of 0.778 percent. This could be explained by fluctuations in O_2 during these tests, or by other factors such as variations in temperature profiles or factors affecting catalytic conversion of SO_2 to SO_3.

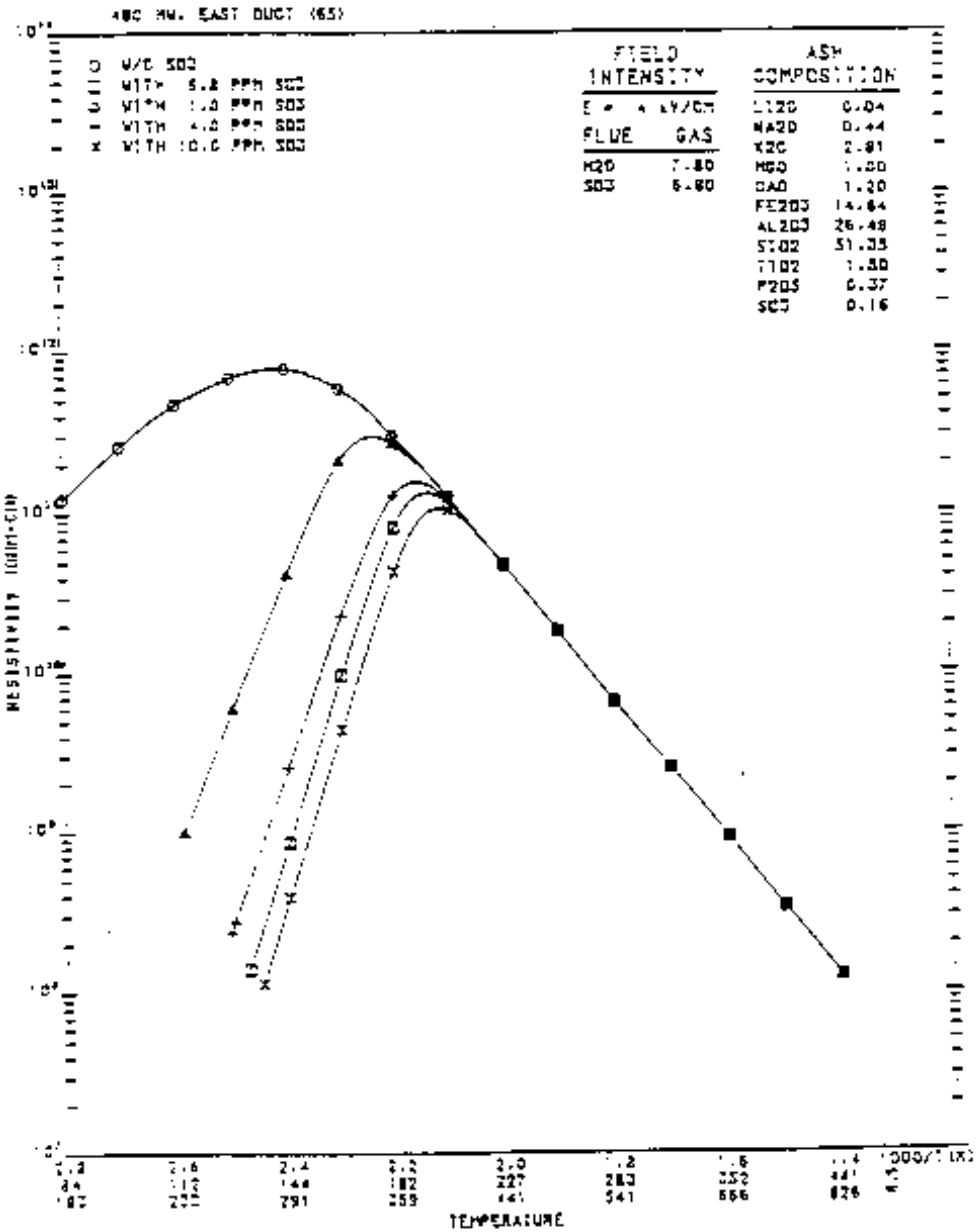


Figure 5-9 East Duct In-Situ Ash Resistivity

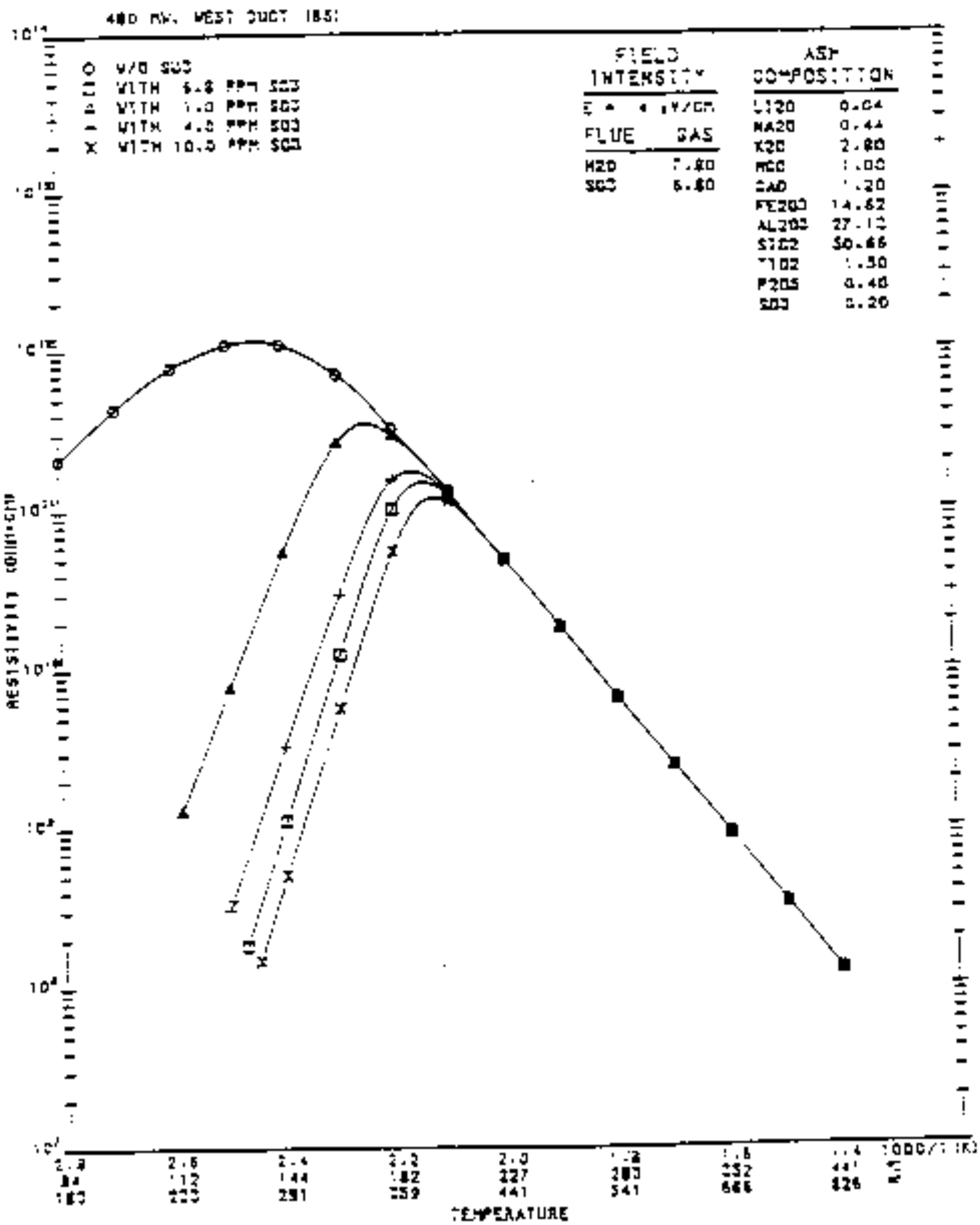


Figure 5-10   West Duct In-Situ Ash Resistivity

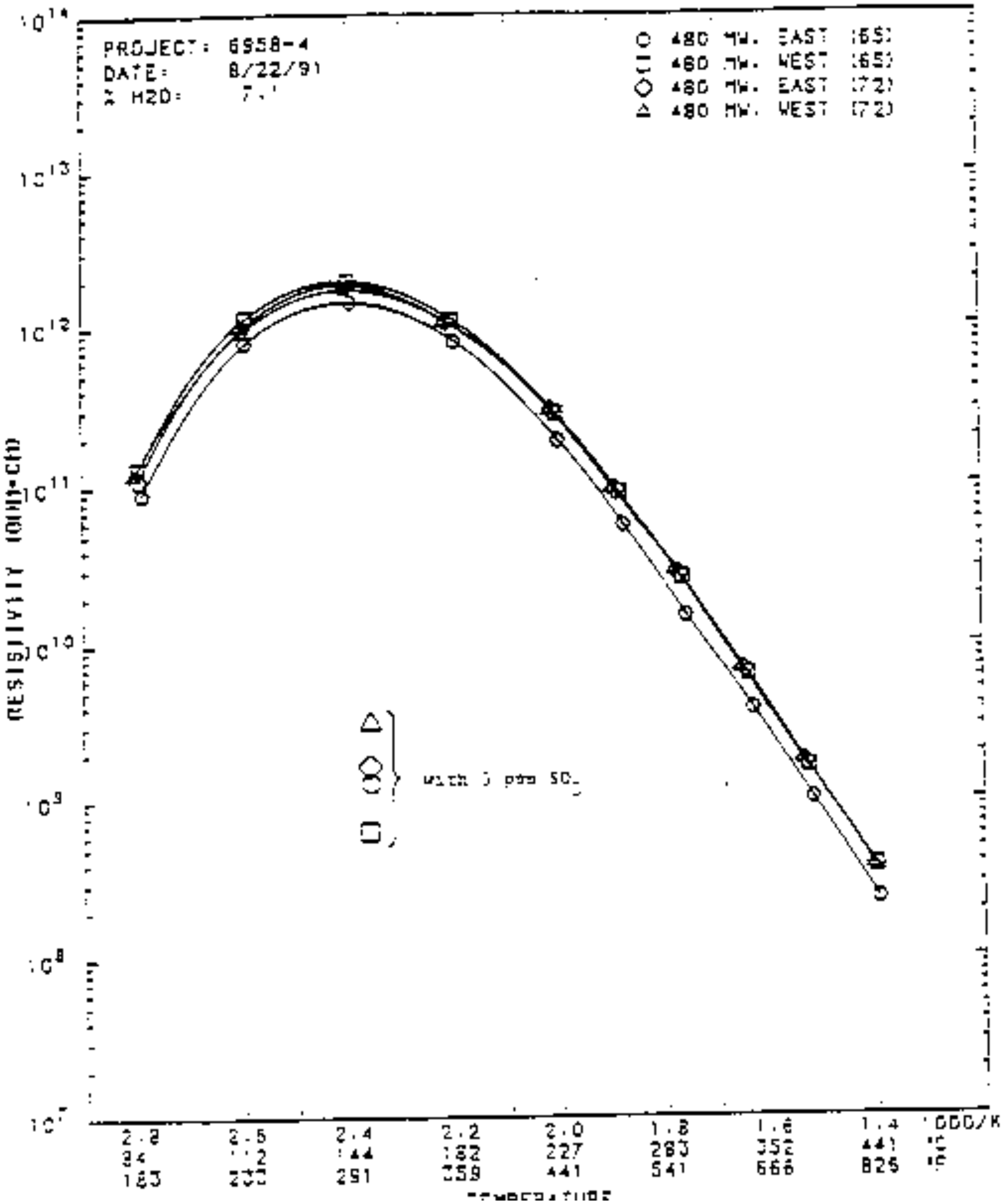


Figure 5-11 ESP Hopper Ash Resistivity / 480 MW

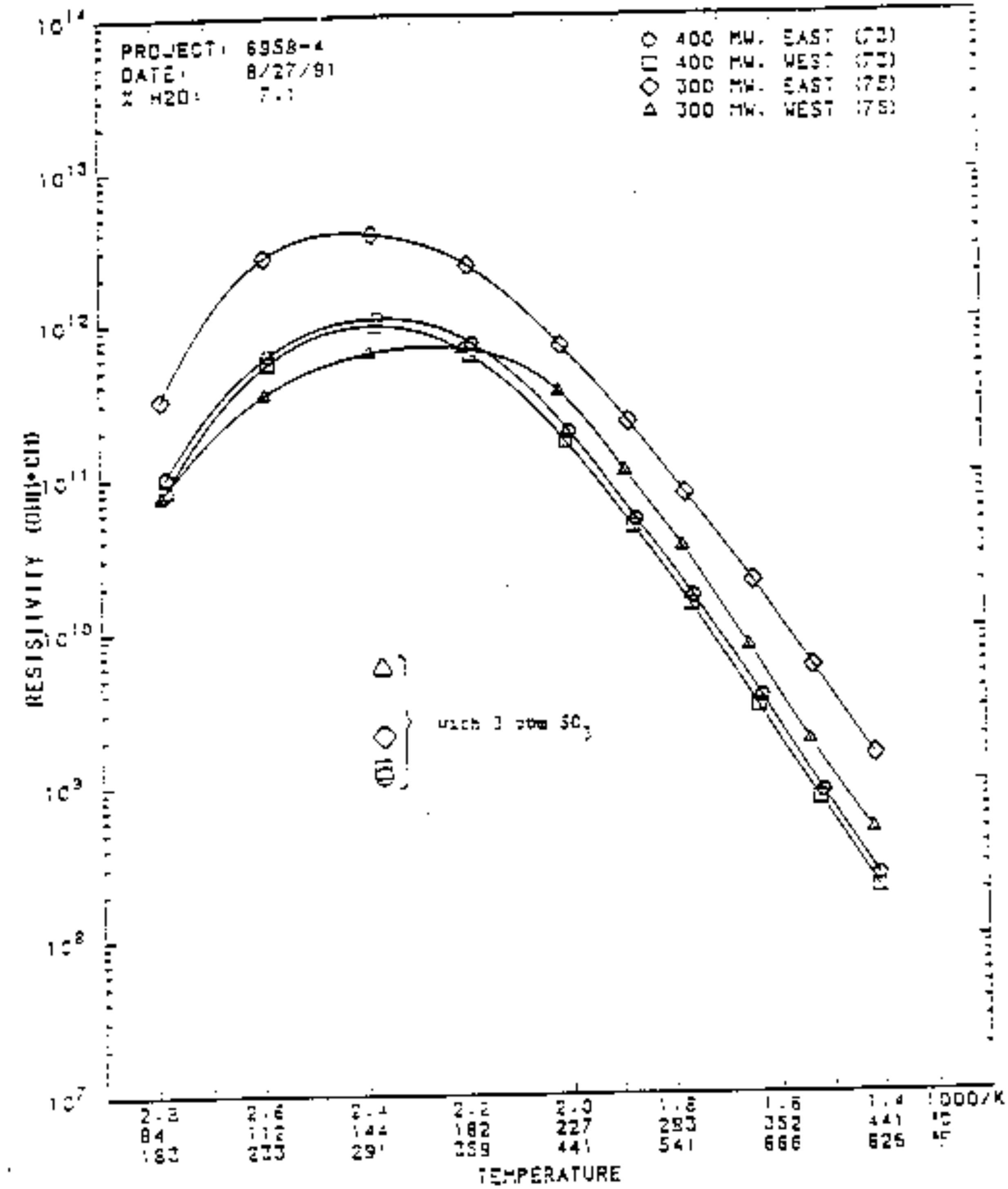


Figure 5-12   ESP Hopper Ash Resistivity / 400 MW and 300 MW

Table 5-8 Effect of Low NOx Burners on In-Situ Res

Load MW	Test Condition	Gas Temperature °F	SO_3 ppm	H_2O %	In-Situ Resistivity Spark Method	In-Situ Resistivity V-I Method
480	Baseline	284	2.3	6.6	4.0E+10	5.0 E+10
	LNB	294	6.8	7.8	2.7 E+10	5.8 E+10
400	Baseline	273	2.2	6.4	1.1 E+10	3.5 E+10
	LNB	281	6.3	7.9	4.4 E+09	3.1 E+10
300	Baseline	268	3.3	6.6	4.4 E+09	3.0 E+10
	LNB	273	4.8	7.5	6.8 E+09	2.4 E+10

Table 5-9 SO_x Results

Date	Duct	Gas Temperatur °F	Concentration (pp SO_2	SO_3	SO_3-to-SO Ratio (%)
480MW					
7/16/91	West	303		1049	0.58
Test 65		304			0.73
		305			0.75
		306			0.77
7/17/91	East	310			0.67
Test 66		312			0.71
		311			0.71
7/22/91	East	307			0.39
Test 70		310			
		315			0.52
		318			0.54
7/23/91	West	294			0.52
Test 71		295			0.62
		295			0.65
		297			0.67
7/24/91	East	299			0.50
Test 72		306			0.58
		308			0.60
		312			0.60
Avg. of 480 MW D		301			0.61
400MW					
7/26/91	East	288			0.51
Test 73		289			0.60
		288			0.65
7/27/91	West	288			0.50
Test 74		289			0.63
		290			0.68
		291			0.672
Avg. of 400 MW D		289			0.61
300 MW					
7/28/91	West	277			0.41
Test 75		277			0.51
		277			0.54
		278			0.55
Avg. of 300 MW D					0.50

5.2.5 Combustion System Tests

As in the Phase I baseline testing, combustion performance tests were performed at each of three load levels to document the specific performance parameters related to the fuel and air combustion systems. The results of the Phase 3A testing are summarized below.

Mill Performance The air flow to each mill and the particle size and mass flow distributions of coal to each burner were measured as described in Section 3. Duplicate tests were performed at two load levels (480 and 400 MW). Table 5-10 summarizes the results of these tests. From Table 5-10 it can be seen that despite the mills being set to approximately equal coal flows with the boiler controls, the measured coal flows varied considerably from mill to mill.

As discussed above, the initial performance tests (65 and 66) were conducted with high primary air/fuel (A/F) ratios, which were subsequently reduced for the remaining tests (70 through 76). From Table 5-10 it is seen that the initial full-load A/F ratios averaged around 2.5 (Test 66), whereas the reduced A/F ratios averaged about 2.2 (Tests 71 and 72). The A/F ratios increased somewhat as load was reduced to 300 MW in order to maintain a sufficiently high coal pipe velocity. As in previous tests, mill D required substantially higher primary air flows in order to avoid mill loading.

During these mill tests, coal fineness was found to be below 70 percent through 200 mesh on all mills except for D mill, with E mill achieving 70 percent only marginally at times. Mill performance was somewhat improved over baseline. As discussed below it was found that coal fineness has only a minor effect on NOx emissions but a substantial effect on fly ash LOI/carbon content.

Secondary Air Supply The secondary combustion air flow was measured at two locations. Table 5-11 presents the results of the flow measurements. The measurements made at the venturi throats in the secondary air supply ducts were very repeatable. The measurements taken at this location did not suffer from the inadequacies of the windbox flow locations used in previous phases of the program. Thus, there is a high level of confidence in the total air flow measurements based upon both the location and repeatability.

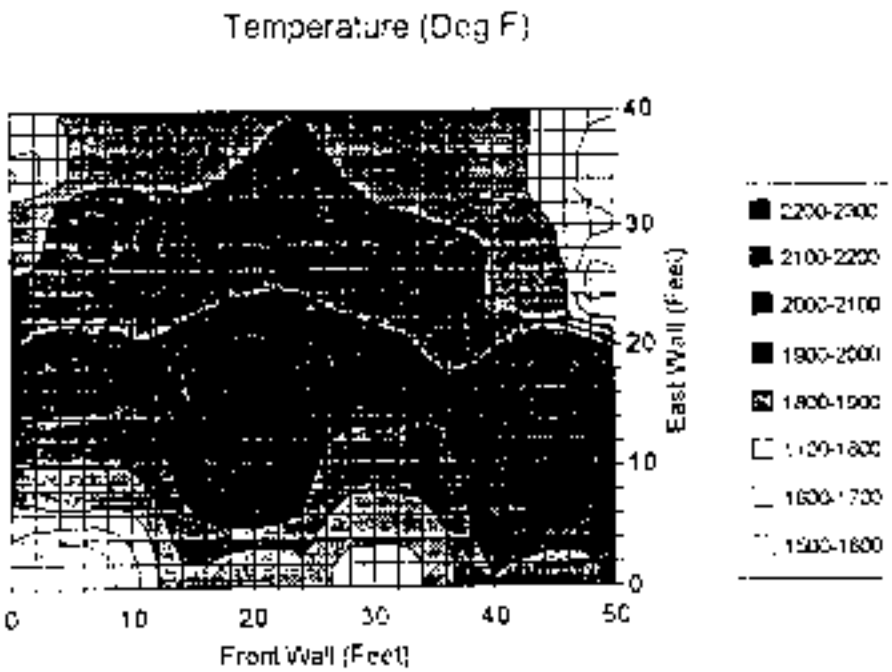
Furnace Measurements Measurements were made of combustion gas temperatures and 0: and CO species at eight locations within the boiler furnace furnace nose and convective pass entrance. Figure 5-13 shows the distribution of temperature and excess oxygen at the 480 MW nominal load point. Species concentrations of O_2 made simultaneously with the temperature measurements indicate a significant stoichiometry non-uniformity within the furnace, probably due to nonuniformity of coal and air flows to the individual burners, however, both the temperature and oxygen maldistributions are less severe than in either Phase 1 or 2. Generally speaking the excess O_2 level ranged from 2.5 to 5.0 percent. Figures 5-14 and 5-15 illustrate typical temperature and excess oxygen distributions for 400 and 300 MW load, respectively, and exhibit the same temperature and oxygen trends as at 480 MW. Again, the temperature and oxygen distributions are more uniform than in either Phase 1 or 2. In general, the furnace gas temperatures are roughly 200 to 400°F lower and the O_2 levels 2 to 4 percent higher than prior phases.

Table 5-10 Summary of Mill Performance Tests

Test No.	Unit Load MW	Pu~uneter	Mill A	B	C	D	E	F
65-1	480	Measured Coal Flow Klblhr	NA	NA	68639	49382	56150	NA
		Measured PA Flow. Klb/hr	142560	131991	NA	144275	135406	NA
		A/F Ratio	NA	NA	NA	2.92	2.41	NA
		Avg. Burner Pipe Velocity, FPM	7925	7502	7934	8137	7895	9072
		High Pipe Coal Flow, Klb/hr	NA	NA	20447	20170	14876	13511
		Low Pipe Coal Flow KJb/hr	NA	NA	13558	8219	12276	11207
		Avg. Passing 200 Mesh PCT	NA	NA	64.83	71.04	67.44	65.05
		Avg. Passing 50 Mesh PCT	NA	NA	99.92	97.44	97.84	99.92
66-1	480	Measured Coal Flow Klb/hr	61389	62273	73664	40523	56648	58082
		Measured PA Flow Klb/hr	142885	133733	141961	141025	134999	166921
		A/F Ratio	2.33	2.15	1.93	3.48	2.38	2.87
		Avg. Burner Pipe Velocity. FPM	7912	7638	8279	8307	7617	9450
		High Pipe Coal Flow, Klb/hr	18873	16242	22322	11256	14844	24061
		Low Pipe Coal Flow. Klb/hr	13056	14830	12874	8667	13806	9024
		Avg. Passing 200 Mesh PCT	60.06	63.68	61.95	74.03	68.34	68.81
		Avg. Passing 50 Mesh PCT	96.96	97.82	99.92	97.71	97.66	99.91
70-1	480	Measured Coal Flow Klb/br	55155	61315	64754	42182	60132	63585
		Measured PA Flow Klb/hr	121859	115962	124642	133426	113199	141513
		A/F Ratio	2.21	1.89	1.92	3.16	1.88	2.23
		Avg. Burner Pipe Velocity, FPM	7119	6663	7351	7692	6892	8183
		High Pipe Coal Flow, Klb/hr	15784	18089	2142 6	12388	15874	23144
		Low Pipe Coal Flow, Klb/hr	11249	13030	13324	8332	13374	12536
		Avg. Passing 200 Mesh PCT	64.69	65.79	66.32	73.63	70.97	66.35
		Ave. Passing 50 Mesh PCT	98.11	98.4	99.95	98.02	98.33	99.96
71-1	480	Measured Coal Flow,. Klb/hr	56236	61700	65901	48140	58666	67843
		Measured PA Flow, Klb/hr	130001	125450	132442	134923	120490	144364
		A/F Ratio	2.31	2.03	2.01	2.8	2.05	2.13
		Avg. Burnar Pipe Velocity, FPM	7248	7172	7616	7718	6998	8184
		High Pipe Coal Flow, Klb/hr	16873	16055	19224	19559	16220	22340
		Low Pipe Coal Flow, Klb/hr	8358	14847	13474	8105	13511	13688
		Avg. Passing 200 Mesh PCT	65.55	65.06	66.01	71.63	69.48	65.55
		Avg. Passing 50 Mesh PCT	97.88	98.31	99.96	97.92	98.43	99.94
72-1	480	Measured Coal Flow, Klb/hr	60460	63416	69987	50542	62803	72072
		Measured PA Flow. Klb/hr	140120	130193	132365	142962	116950	152660
		A/F Ralio	2.32	2.05	1.89	2.83	1.86	2.12
		Avg. Burner Pipe Velocity, FPM	7487	7579	7949	8040	7126	8377
		High Pipe Coal Flow, Klb/hr	17795	17473	19791	18907	18198	26410
		Low Pipe Coal Flow, Klb/hr	12054	13372	14901	8689	13358	13207
		Avg. Passing 200 Mesh, PCT	60.82	63.57	63.87	70.45	70.02	64.11
		Avg. Passing 50 Mesh, PCT	97.23	98.03	99.94	97.68	98.06	99.95
73- 1	400	Measure Coal Flow, Klb/hr	43903	47351	51869	38225	45376	58443
		Measured PA Flow, Klb/hr	139700	125822	127975	142814	122927	141809
		A/F Ralio	3.18	2.66	2.47	3.74	2.71	2.43
		Avg. Burner Pipe Velocity, FPM	7498	7074	7585	7999	7011	7791
		High Pipe Coal Flow, Klb/hr	12570	12850	14487	14526	12277	20911
		Low Pipe Coal Flow, Klb/hr	9498	10813	10874	8152	10258	11630
		Avg. Passing 200 Mech, PCT	66.81	68.08	67.59	74.29	70.48	66.98
		Avg Passing 50 Mesh, PCT	98.68	98.97	99.98	98.88	98.18	99.98
74-1	400	Measured Coal Flow, Klb/hr	49137	50405	64058	37902	49641	56793:
		Measured PA Flow, Klb/hr	142212	138009	131537	143376	123634	144847
		A/F Ralio	2.89	2.74	2.05	3.78	2.49	2.55
		Avg. Burner Pipe Velocity, FPM	7812	7425	7696	7792	6853	8023
		High Pipe Coal Flow, Klb/hr	13404	113326	19905	14949	13333	18670
		Low Pipe Coal Flow, Klb/hr	10866	11556	12357	6558	11715	10792
		Avg Passing 200 Mesh, PCT	65 0 5	65 49	65 44	73.45	68.75	67.67
		Avg. Passing 50 Mesh, PCT	98.2 2	98 64	99 96	98 65	97 77	99.98

Table 5-11 Combustion Air Flow Distribution

Test	Load	Secondary Air				Primary Air											
		Left		Right		Mill A		Mill B		Mill C		Mill D		Mill E		Mill F	
No.	MW	Mlb/hr	%	Mlb/hr	%	Mlb/hr	%	Mlb/hr	%	Mlb/hr	%	Mlb/hr	%	Mlb/hr	%	Mlb/hr	%
66-1	480	1 667	42	1.405	35.7	0.143	3.6	0.134	3.4	0.142	3.6	0.141	3.6	0.135	3.4	0.167	4.2
70-1	480	1 706	41	1.677	40.6	0.122	2.9	0.116	2.8	0.125	3.0	0.133	3.2	0.113	2.7	0.142	3.4
71 1	480	1.707	44	1.394	35.8	0.130	3.3	0.125	3.2	0.132	3.4	0.135	3.5	0.12 0	3.1	0.144	3.7
72-1	480	1.573	42	1.359	36.3	0.140	3.7	0.130	3.5	0.132	3.5	0.143	3.8	0.117	3.1	0.153	4.1
73-1	400	1.341	41	1.122	34.4	0.140	4.3	0.126	3.9	0.128	3.9	0.143	4.4	0.123	3.8	0.142	4.3
74-1	400	1.342	39	1.267	36.9	0.142	4.1	0.138	4.0	0.132	3.8	0.143	4.2	0.124	3.6	0 145	4.2
75 1	300	1.066	39	0.966	35.3	0.135	4.9	0.112	4.1	0.120	4.4	0.138	5.1	0.04 6	1.7	0.150	5.5
76.1	300	1.089	40	0.939	34.5	0.133	4.9	0.110	4.0	0.121	4.4	0.133	4.9	0.047	1.7	0.149	5.5



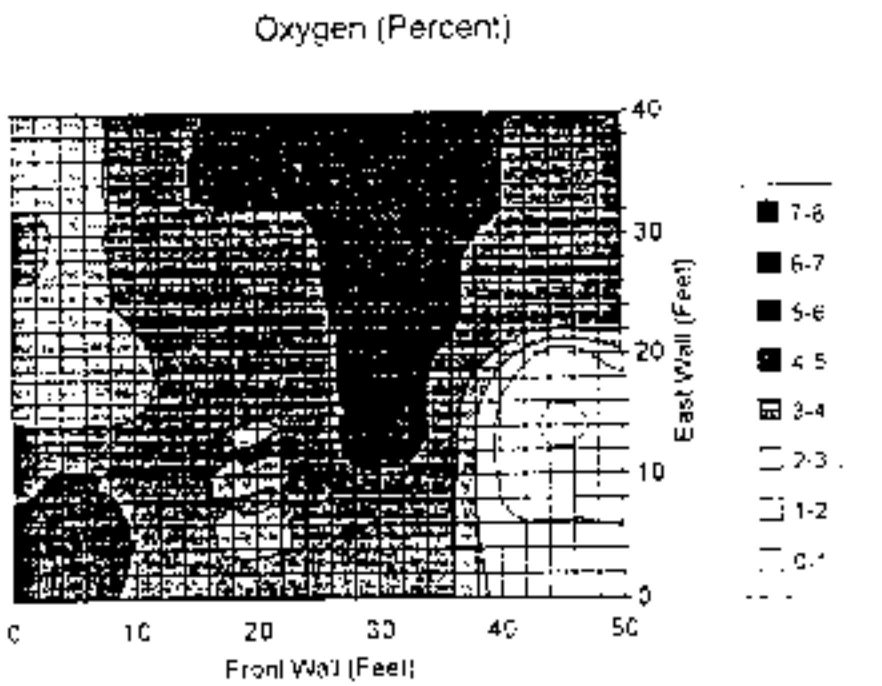
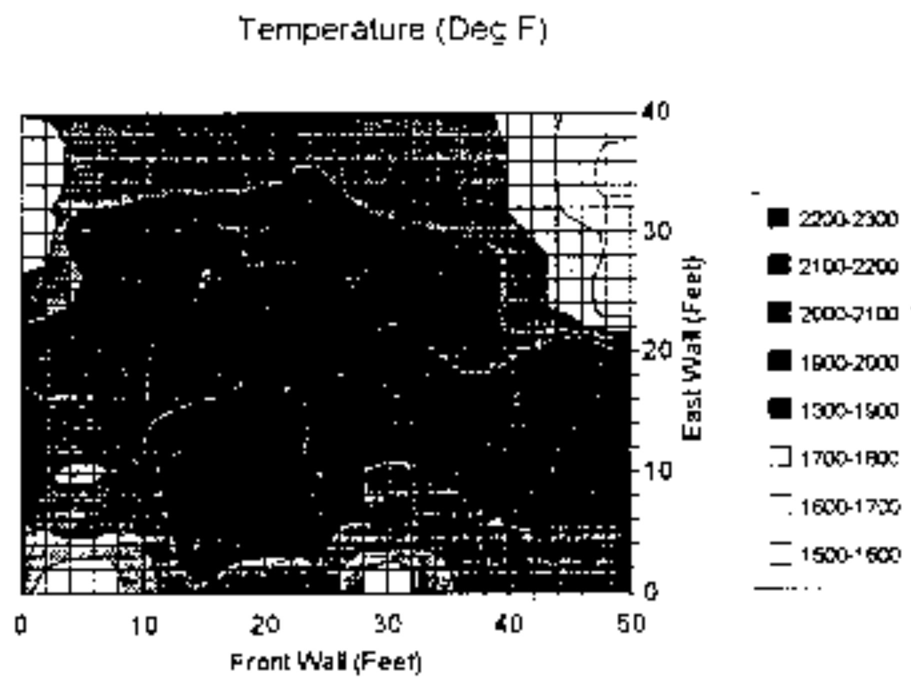


Figure 5-13 Furnace Exit Temperatures and Oxygen at 480 MW



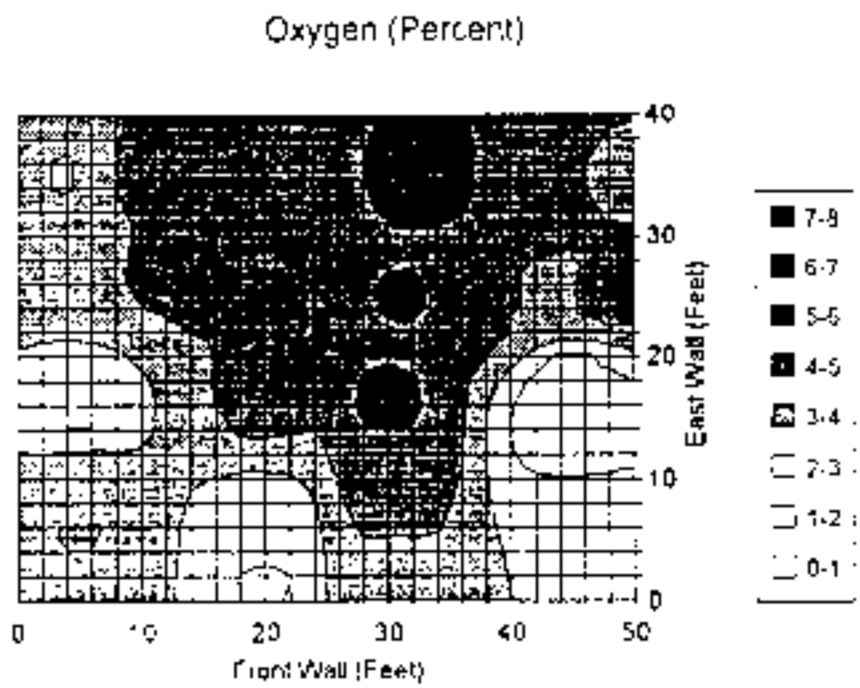


Figure 5-14 Furnace Exit Temperatures and Oxygen at 400 MW

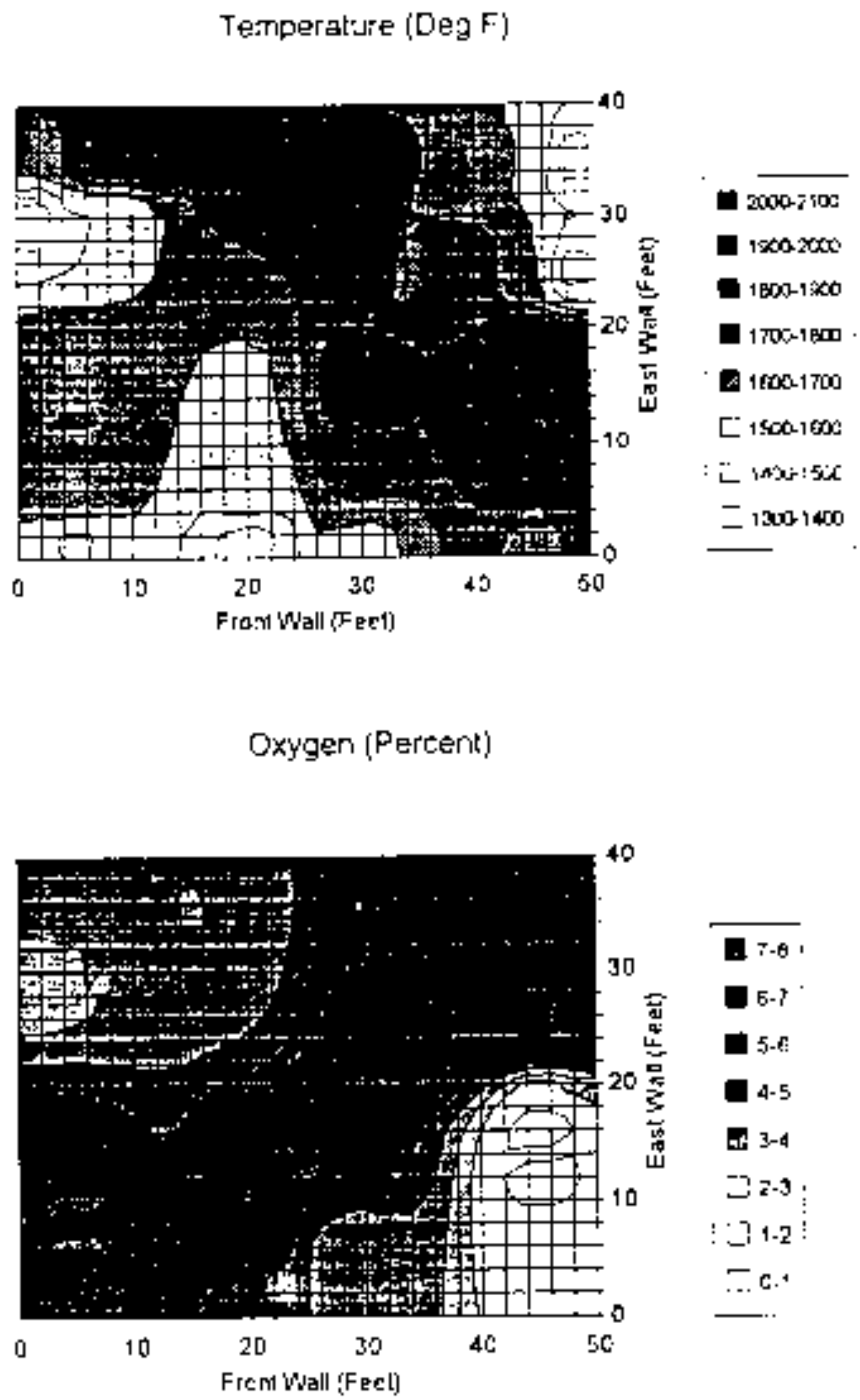


Figure 5-15 Furnace Exit Temperature and Oxygen at 300 MW

5.2.6 Coal and Ash Analyses

During each of the nine days of Phase 3A performance testing, samples were obtained of the coal entering the active mills, fly ash collected in the ESP (east and west sides), and bottom ash collected in the furnace ash pit

The coal samples were analyzed for proximate and ultimate composition, calorific value, grindability and ash fusion properties. Table 5-12 presents the results of these analyses. These analyses show that the coal properties remained consistent over the duration of the testing and are similar to the analyses obtained during the Phase 1 effort.

The results of the CEGRIT furnace ash and the furnace bottom ash analyses are shown in Table 5-13. As in the baseline testing (Phase 1), the CEGRIT LOI values were much higher than the bottom ash samples except for the 300 MW tests (75 and 76). The unusually high LOI content in the "A" hopper is believed to be due to dumping of the mill pyrite catch (including some spilled coal) into the bottom hopper during this test.

Table 5-12 Performance Tests Coal Analyses (Ultimate Analysis as Received)

Test Number	Date	H_2O %	C %	H %	N %	Cl %	S %	ASH %	O %	Total %	HHV Btu/lb	VOL %	FC %
65-1	7/17/91	6.85	71.18	4.62	1.34	0.01	1.41	9.67	4.93	100.02	12613	33.1	50.4
65-1	7/17/91	14.90	63.98	4.13	1.24	0.02	1.30	10.25	4.20	100.02	11364	29.5	45.4
65-1	7/17/91	4.55	73.11	4.72	1.45	0.02	1.66	9.95	4.55	100.01	12991	34.3	51.2
66-1	7/17/91	4.91	73 13	4.74	1.42	0.02	1.53	9.39	4.88	100.02	13015	32.8	52.9
66-1	7/17/91	4.62	73 54	4.74	1.38	0.02	1.66	9.31	4.75	100.02	13094	32.8	53.2
66-1	7/17/91	4.68	72.93	4.57	1.44	0.03	1.71	9.37	5.30	100.03	13058	32.6	53.4
66-1	7/17/91	3.59	74.71	4.79	1.47	0.02	1.69	9.28	4.47	100.02	13259	33.2	53.9
70-1	7/17/91	4.15	74.47	4.80	1.42	0.02	1.54	9.30	4.32	100.02	13220	32.8	53.7
70-1	7/22/91	4.94	73.88	4.71	1.40	0.02	1.56	9.11	4.40	100.02	13092	32.7	53.3
70-1	7/22/91	5.54	73.29	4.73	1.44	0.02	1.62	8.97	4.40	100.01	13041	32.8	52.7
71-1	7/23/91	4.76	73.71	4.70	1.36	0.02	1.67	9.28	4.52	100.02	13084	33.1	52.8
71-1	7/23/91	4.51	73.96	4.72	1.37	0.01	1.58	9.46	4.41	100.02	13105	33.5	52.5
71-2	7/23/91	4.53	73 94	4.77	1.42	0.01	1.77	9.07	4.50	100.01	13138	33.7	52.7
72-1	7/24/91	5.23	73.10	4.75	1.35	0.01	1.41	9.12	5.05	100.02	12928	33.7	52.0
72~2	7/24/91	6.25	71.41	4.59	1.28	0.01	1.43	9.76	5.28	100.01	12577	31.7	52.3
72~2	7/24/91	6.00	72.66	4.65	1.37	0.01	1.42	8.87	5.02	100.00	12833	32.6	52.5
72~2	7/24/91	6.36	71.64	4.39	1.35	0.01	1.42	9.48	5.36	100.01	12714	32.0	52.1
73-1	7/26/91	5.41	73.50	4.47	1.44	0.01	1.58	8.89	4.45	100.02	13042	32.7	53.0
73-1	7/26/91	5 79	71.72	4.67	1.37	0.01	1.59	9.72	4.96	99.83	12719	32.4	51.9
73-2	7/26/91	5.94	70.56	4.57	1 38	0.01	1.38	10.59	5.21	99.64	12517	31.9	51.3
74-1	7/27/91	4.93	72.76	4.74	1.45	0.01	1.64	10.03	4.45	100.01	12893	32.9	52.2
74-1	7/27/91	5.19	72.31	4.73	1.40	0.01	1.57	9.93	4.86	100.00	12892	32.6	52.3
74-2	7/27/91	5.96	72.29	4.68	1.36	0.01	1.48	9.7 1	4.49	100.01	12854	32.1	522
75-1	7/28/91	6.38	72.48	4.65	1.36	0.01	1.40	9.0 1	4.70	100.00	12775	31.7	52.9
75-1	7/28/91	6.34	72.36	4.65	1 44	0.01	1.47	9.1 5	4.59	100.01	12771	31.9	52.6
76-1	7/28/91	6.21	72.81	4.65	1.41	0.01	1.41	8.8 1	4.51	100.01	12819	32.0	52.8
76-1	7/28/91	5.74	72.99	4 73	1.43	0.01	1.51	9.1 1	4.44	100.00	12938	32.6	52.5
76-1	7/28/91	4.81	72.29	4 50	1a9	0 01	1.47	9.8 1	5.65	100.01	13035	33.1	52.2
76-1	7/28/91	5.71	72.58	4.96	1 46	0.01	1.41	9.21	4.81	100.28	12824	31.6	53.5
Average		5.61	72 53	4.67	1.39	0.01	1.53	9.4 1	4.74	100.00	12869	32.56	52.29
Std. Dev		1 91	1.87	0.14	0.05	0.01	0 11	0.43	0.36	0.09	339	0.87	1.50
Variance		3.63	3.50	0.02	0.00	0.00	0.01	0.18	0.13	0.0 1	114794	0.76	2.26

Table 5-13 Performance Tests CEGRIT Ash Analysis

Test	Date	Load MW	Excess Oxygen %	CEGRIT LOI %		Bottom Ash L01 %	
65-1	07/16/91	470	4.0	-	5.7	-	-
65-1	07/16/91			-	-	-	-
65-1	07/16/91			-	-	2.1	-
65-1	07/16/91			-	-	-	1.8
66-1	07/17/91	475	3.8	-	-	-	-
66-1	07/17/91	474	3.8	-	-	2.0	0.0
70-1	07/22/91	479	3.3	-	4.6	-	-
70-1	07/22/91	470	3.6	-	-	24.7	
70-1	07/23/91			-	-	-	-
71-1	07/23/91	473	3.5	-	-	-	-
71-1	07/23/91			-	-	1.7	2.3
71-1	07/23/91	465	3.5	-	4.8	-	-
71-1	07/23/91			-	4.1	-	-
72-1	07/24/91	477	3.4	-	-	2.1	2.7
72-1	07/24/91			3.0	5.2	-	-
72-1	07/24/91			-	6.4	-	-
72-1	07/24/91			-	,-	-	-
73-1	07/26/91	388	4.1	2.4	4.8	-	-
73-1	07/26/91			-	-	2.0	1.6
73-2	07/26/91	389	4.1	2.3	5.0	-	-
73-2	07/26/91			-	-	-	-
74-1	07/27/91	403	3.8	-	-	3.0	0.5
71-1	07/27/91			2.4	6.1	-	-
74-1	07/27/91			-	-	-	-
74-2	07/27/91	405	3.6	2.3	5.2	-	-
75-1	07/28/91	299	4.3	2.8	5.8	-	-
75-1	07/28/91			-	-	-	-
75-1	07/28/91			-	-	38.0	1.7
76-1	07/28/91	298	4.5	2.4	5.0	-	-
76-1	07/28/91			-	-	20.2	2.3
76-1 .	07/28/91			-	-	-	-

5.2.7 Boiler Efficiency

During selected performance tests at each load point, measurements were recorded for the flue gas temperatures and gaseous species, both upstream and downstream of the air preheaters, using the DAS and the CEM, for the purpose of calculating the heat loss efficiency. Over several hours of each test, the in-situ O_2 probes upstream and downstream of the air preheater were sampled continuously in sequence. In addition, the gas temperatures in each duct were measured continuously (every 5 seconds - compiled into 5-minute averages) over the entire test duration. Each efficiency test was .approximately 2 hours in duration. CO measurements were obtained from composite sampling of the CEM at discrete intervals over the test duration.

ASME PTC 4.1 type boiler efficiency calculations were made which included losses for dry flue gas, moisture in flue gas (humidity plus moisture in fuel plus hydrogen combustion product), combustibles in fly ash, combustibles in bottom ash (negligible), and radiation loss (standard

ASME curves). The purpose of the boiler efficiency calculations is to document the Phase 3A boiler efficiencies at specific operating conditions for comparison to the efficiencies determined in other test phases. Thus, the important parameter is any chance in efficiency attributable to the LNB and AOFA retrofits, rather than the absolute value of efficiency measured. For this reason, some efficiency loss components not related to combustion (e.g. blowdown, steam properties, etc.) were not considered. However, the heat loss calculations were done based upon the measured calorific value, moisture and chemical composition of the as-fired fuel samples taken during each test.

The results of the efficiency calculations are presented in Table 5- 14. The efficiencies are determined for "as measured" conditions and for "design" air preheater temperature conditions (normalized). In keeping with the desire to document efficiency at the operating conditions recommended by FWEC, only the reduced primary air/fuel ratio tests are included in Table 5-14.

Table 5-14 ASME PTC 4.1 Boiler Efficiency

Test Number	Date	Load MW	Measured Efficiency Percent	Normalized Efficiency Percent
72	7/24/91	479	88.6	88.4
73	7/26/91	388	88.7	88.7
75	7/28/91	298	88.8	88.8

5.3 Special LOl Tests

Testing to evaluate the effects of various burner and boiler operating settings on LOI and carbon content of ash particulate emissions from Plant Hammond Unit 4 was conducted between October 15 and 28, 1942. The testing consisted of two separate efforts. The first was performed by Flame to characterize the coal and primary air flow rates through each mill at a nominal load of 450 MW, as well as the coal and primary air distributions and particle size range in each individual coal pipe. The second test effort was conducted jointly by ETEC, SoRI, and Spectrum.

Test Methods The methods used in these LOI evaluation tests were identical to the methods used in the diagnostic and performance test efforts. Flame performed the mill coal and air flow and particle size analyses. SoRI utilized Method 17 procedures to obtain the ash samples for both LOI (performed on-site) and carbon (performed at the SoRI laboratories) analyses. In order to expedite the collection of ash samples, SoRI collected two separate Method 17 samples simultaneously, traversing the ESP inlet duct in opposite directions, but using the same test ports and probe insertion points. In this manner, duplicate samples could be obtained in about one hour for a single test condition. Spectrum operated the gas analysis system and data acquisition system to record gaseous emissions of oxygen, carbon monoxide, and nitrogen oxide from various points in the boiler exit gas stream, as well as numerous boiler operating parameters. ETEC established the boiler operating conditions for each test, recorded control room and burner front data and coordinated the efforts of SoRI and Spectrum during the LOI testing.

Test Results The following paragraphs present a summary of the most important findings of the test effort.

Mill Characterization Tests Flame performed tests to evaluate the condition of the coal and primary air supply systems with regard to coal and air flow distributions and coal particle size in each coal pipe. In addition, Flame also measured the secondary air flows in each duct (east and west) in an attempt to explain an apparent imbalance in those flows as indicated by plant instrumentation.

The results of the mill characterization testing are shown in Table 5- 15. Several important conclusions can be drawn from this data. First, it is apparent that the newer B&W MPS mills (A, C, E, F) provide excellent fineness, both at the small sizes (passing 200 mesh, all better than 70 percent) and the largest sizes (larger than 50 mesh, all less than 0.23 percent). The older FWEC MB mills (B & D) provided less than 70 percent passing 200 mesh, and approximately 2.0 percent remaining on 50 mesh. Second, there is a large variation in coal flow measured from pipe to pipe for all mills, varying from about +8 percent from the mean coal flow for the B mill, to over +30 percent for the D mill. Third, the D mill had substantially lower coal flow (and higher A/F ratio) than the other mills. This characteristic is consistent with the results observed during the previous Phase 3A performance test series (test days 66 through 73). For the current mill tests, the D mill feeder coal flow, as indicated by the feeder instrumentation, was approximately the same as the other mill feeders. The apparent conclusion is that either: (1) the D mill feeder calibration is not correct, or (2) the measurement of the D mill coal flow in the burner pipes is incorrect due to some abnormal flow condition such as roping or channeling which prevents the capture of a representative coal sample by the Flame technique. With the exception of the D mill, the A/F ratios were consistently between 2.0 and 2.3.

In addition to the mill testing, Flame also measured the total air flow rates through the east and west secondary air venturi ducts. Although the existing plant air flow instrumentation indicated a significant imbalance between the two venturi flow measurements (1,555,600 lb/hr - west, and 2,214,000 - east), the Flame measurements, made with type "S" pitot tube traverses across the ducts, indicated that the flows were equal within 0.5 percent (1,651,008 lb/hr-west / 1,642,427-east). Due to the apparent error in the east plant instrument reading, the plant instrumentation department has disconnected the east input to the plant air flow totalizer and is using the west venturi input only (doubled) to indicate total air flow for control and monitoring purposes.

LOI Testing The intent of the special LOI investigation was to determine the effects of various burner settings and mill operation on the carbon/LOI content of the fly ash leaving the boiler. In order to assess the effects of each selected parameter independently, a matrix of test conditions was devised such that a single parameter would be varied during each test day, and to the extent possible, other parameters held constant. The main parameters evaluated were, overall boiler excess O., mill coal flow bias, burner inner, and outer register settings, and coal pipe position (insertion depth). A summary of the parameters tested are shown in Table 5-16. Specifically excluded as a variable parameter was adjustment to the burner slide dampers, which control the total air flow to each burner. Since there are innumerable variations that could be made to the slide damper settings, which could affect the furnace combustion balance considerably, it was decided that any adjustment to these dampers should constitute a completely separate test series. As established by FWEC, the slide damper positions of the outer burners in each row (the A and D burners) were set at the 7 inch position, and the inner burners (B and C) at the 4 inch position.

The test series was conducted at a nominal load level of 450 MW, with all mills in service. This was the same condition that the mill coal/air flow and fineness tests were performed as described above.

The "baseline" condition for all tests was with equal coal flow to each mill and all burner mechanisms set to the "nominal" positions established by FWEC. Prior to the commencement of testing, ETEC obtained a listing of all pertinent burner and AOFA damper settings which constitute the "nominal" condition. FWEC also advised ETEC verbally as to proper procedures to be used in operating the burner mechanisms and the maximum degree of movement from "nominal" that should be made. This advice was followed in all subsequent testing. The principal cautions expressed by FWEC, were not to close the inner or outer swirl registers excessively and especially not to withdraw the burner inner coal pipe tips more than 2 inches from the current "nominal" setting of 4 inches insertion. The reason for the latter precaution was to prevent exposure of the burner ignitors to excessive radiant heat. Also, FWEC requested that the AOFA flow control dampers not be closed any more than would permit a minimal air flow of 50 klb/hr through each of the four dampers, so as to prevent excessive slagging or heating of the AOFA ports. Examination of the burners revealed that there were clear markings of the full-open, full-closed and "nominal" positions for the slide dampers, inner and outer registers and coal pipe positions on most burners. However, several of the indicated markings, especially for the inner registers, did not agree with the written listings supplied by FWEC. ETEC assumed that all of the burner markings were correct and recorded the various burner settings throughout the testing program. Since the inner and outer register position indicators were circumferential dials, with only the closed, open and "nominal" settings indicated by FWEC, ETEC had to estimate the degree of travel from the nominal position. This was done as a percentage of the total travel indicated between the closed and open indications. In all cases, the movement indicators responded properly to the operator actuation of the mechanism. Therefore, it is believed that the indicated positions recorded on the data sheets during the testing reflect a reasonably accurate account of the burner positions relative to the "nominal" positions marked on the burner housings. On each day of testing, coal samples were taken in accordance with normal plant procedures, a composite sample being obtained from equal samples from each mill feeder.

A total of 40 tests were conducted between October 20 and 28, 1992. Table 5-17 summarizes the results of those tests. Tests are numbered according to the format XX-Y, where XX represents the sequential test day since the program began at Plant Hammond, and Y represents the sequential test performed on that day.

Four tests were performed with the coal flow to all mills approximately equal, and with all burner settings at their "nominal" positions as established by FWEC. This was then the current "baseline" LNB case The boiler excess O_2 was varied from a "nominal" value ¢f about 4.0 percent (CEM composite economizer outlet average - the plant instrumentation indicated approximately 2.7 percent O_2). to a minimum of 2.8 percent (high CO readings) and a maximum of 4.6 percent (high opacity and ID fan control). Throughout the testing, the plant average O_2 reading was consistently 1.0 to 1.5 percent below the CEM composite economizer outlet reading. As shown in Figures 5-16 and 5-17, the excess O_2 level has a considerable effect on both ash LOI and NOx emissions The figures also include data from subsequent test days which reflect the "baseline" condition of all "nominal" burner settings, balanced coal flows to each mill and "minimal" air flow to the AOFA ports (flow control dampers virtually closed off). The lines shown in the figures depict linear, least-squares curve fits to the "baseline" data. These curve fits were used to normalize the subsequent parametric data to mitigate the effects of minor variations in excess O_2 on LOI and NOx emissions when comparing the effects of the other parameters being tested. Figures S-16 and 5-17 also show the results obtained when the AOFA dampers were set to their "nominal" open positions (providing approximately 600 klb/hr of total AOFA air flow) From Figure 5-16 ;t can be seen that the use of “nominal" AOFA produces a minor effect on LOI (slightly above the extended curve fit line). Figure 5-17 illustrates that, while the increased AOFA flow (from approximately 200 klb/hr minimum to 600 klb/hr nominal) does reduce NOx below the curve fit line substantially, the increased excess O_2 required to maintain CO emissions at a reasonable level results in little or no actual reduction in total NOx emissions compared to NOx emissions at the lower excess O_2 levels possible with reduced or no AOFA flow.

In all of the subsequent figures of LOI and NOx variation with burner settings, the results are normalized to a consistent excess O_2 level by using the slopes of the linear curve fits determined in Figures 5-16 and 5-17. Thus, the "normalized" values represent what the LOI or NOx "would have been" if the excess O_2 level had been maintained absolutely constant.

On two days, adjustments were made to the inner and outer air register positions. The inner registers were positioned to approximately 20 and 40 percent of their full travel from the "nominal" positions. Most of the "nominal" markings were very close to the zero position, so no further closed adjustments were attempted. The outer registers were adjusted approximately 20 percent more open and more closed than the "nominal" settings (60 percent open). The results of these tests showed that the inner and outer registers have only a minimal effect on either LOI or NOx within the range of adjustments made.

In one test series the coal flow to the mills was biased to provide first higher coal flow to the upper burner levels (mills C and F;) and lower coal flow to the lower burner levels (mills A and E), with the coal flow to the center burners (mills B and D) in between. All burner settings were normal. Another test was performed with the coal bias reversed, i.e. lower coal flow to the upper burners and higher to the bottom burners. Two tests were also conducted with balanced flow to all burners (according to the feeder coal flow indicators). Figures 5-18 and 5-19 show the results of these tests. Clearly, the mill bias affects the LOI substantially while it only affects the NOx emissions moderately.

In another series of tests, the positions of the inner coal pipe tips were adjusted (all burners equally) from the "nominal" position established by FWEC. The "nominal" position was 4 inches insertion from the "zero", or neutral position. In keeping with FWEC's request, the tips were withdrawn only to the 2 inch insertion position so as to prevent excessive thermal radiation exposure to the ignitors. As shown in Table 5-17, four tests were performed, two at the "nominal" setting and one each at the 2 inch and 3 inch positions. All other burner settings were at their “nominal" positions and the coal flow was equal to each mill. Figures 5-20 and 5-21 show that LOI was slightly decreased and NOx slightly increased as the coal pipes were withdrawn to the 2 inch position.

A summary of the sensitivities is shown in Figure 5-22. As can be seen, for excess O_2. 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 emission and LOI, it is likely that the positive NOx / LOI slope is primarily an artifact of process noise. It should be stressed that Figure 5-22 is a parametric plot and that neither NOx or LOI are the independent variables.

Table 5-15 NOx vs. LOI I Summary of Mill Performance Tests

Parameter	October 15,1992					
	A	B	C	D	E	F
MEASURED COAL FLOW, KLB/HR	65.1	65.8	71.6	43	72.1	65.3
EASURED PAI1JOW, KLB1HR	132.9	145.6	147.5	155.3	151	136.
A/F RATIO	2.04	2.21	2.06	3.61	2.09	2.
AVG BURNER PIPE VELOCITY, FPM	5288	7276	5836	7814	5993	532
HIGH PIPE COAL FLOW, KLB/HR	20.5	18.9	22.5	14.8	20.3	18.
LOW PIPE COAL FLOW, KLB/HR	13.1	15.1	14.4	7.3	15.5	12.
AVG PASSING 200 MESH.PCT	77.85	65.14	78.89	69.22	78.25	78.8
AVG PASSING 50 MESH,PCT	99.98	98.01	99.95	97.93	99.93	99.8
Parameter	October 15,1992					
	A	B	C	D	E	F
MEASURED COAL FLOW, KLB/HR	57.6	62.8	72.5	38.5	71.5	66.1
EASURED PAI1JOW, KLB1HR	127.9	146.1	145.1	152.8	149.1	136.8
A/F RATIO	2.22	2.33	2	3.97	2.09	2.07
AVG BURNER PIPE VELOCITY, FPM	5093	7326	5735	7680	5913	5323
HIGH PIPE COAL FLOW, KLB/HR	15.6	18.1	21.1	14	19.5	19.1
LOW PIPE COAL FLOW, KLB/HR	13.3	14.4	15.3	6.5	17	13.7
AVG PASSING 200 MESH.PCT	81.36	66.85	77.56	68.25	70.44	74.77
AVG PASSING 50 MESH,PCT	99.97	98.28	99.98	97.77	99.88	99.92

Table 5-16 NOx vs. LOI / Parameters Tested

Range Tested

Parametcr	Nominal Value	Range Tested	
		Low	High
Excess Air	4%	2.8%	5.0%
Inner Register	-I5%	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%

Table 5-17 NOx vs. LOI / Test Summary

Test	Date	Load MW	AOFA Setting	Burner Settings IR	OR	CPP	Mill Bias	Emissions O_2 %	NOx lb/MBtu	CO ppm	LOI %	Carbon %	Descr
92-1	10/20/92	452	MINIMUM	NORM	NORM	NORM	NONE	5.6	0.53	15	NA	NA	BASE
92-2	10/20/92	450	MINIMUM	NORM	NORM	NORM	BOTTOM	5.6	0.52	20	NA	NA	COA
92-3	10/20/92	450	MINIMUM	NORM	NORM	NORM	TOP	5.5	0.50	18	NA	NA	COA
93-1	10/21/92	448	MINIMUM	NORM	NORM	NORM	NONE	4.2	0.49	15	7.9	7.0	MED
93-2	10/21/92	447	MINIMUM	NORM	NORM	NORM	NONE	4.6	0.59	9	4.5	3.4	HIGH
93-3	10/21/92	442	MINIMUM	NORM	NORM	NORM	NONE	2.8	0.44	130	10.4	9.5	MIN (
93-4	10/22/92	442	MINIMUM	NORM	NORM	NORM	NONE	3.5	0.49	24	6.6	6.1	MED
94-1	10/22/92	443	MINIMUM	NORM	NORM	NORM	NONE	3.2	0.44	24	9.3	8.5	BASE
94-2	10/22/92	442	MINIMUM	+20%	NORM	NORM	NONE	3.5	0.45	69	9.6	8.4	INNE
94-3	10/22/92	441	MINIMUM	+40%	NORM	NORM	NONE	3.3	0.45	67	8.5	7.5	INNE
94-4	10/22/92	441	MINIMUM	+40%	NORM	NORM	NONE	3.4	0.45	61	7.5	6.7	INNE
94-5	10/22/92	442	MINIMUM	NORM	NORM	NORM	NONE	3.5	0.46	86	7.6	6.9	BASE
95-1	10/23/92	443	MINIMUM	NORM	-30%	NORM	NONE	4.1	0.53	23	5.4		OUTE
95-2	10/23/92	445	MINIMUM	NORM	NORM	NORM	NONE	4.0	0.52	80	5.7	4.7	BASE
95-3	10/23/92	443	MINIMUM	NORM	+30%	NORM	UPPER	3.3	0.46	93	6.9	5.0	OUTE
95-4	10/23/92	442	MINIMUM	NORM	NORM	NORM	NONE	3.9	0.55	32	4.6	6.2	BASE
96-1	10/24/92	445	MINIMUM	NORM	NORM	NORM	LOWER	4.4	0.50	31	7.7		COAI
96-2	10/24/92	441	MINIMUM	NORM	NORM	NORM	NONE	4.1	0.51	79	6.6		BASE
96-3	10/24/92	440	MINIMUM	NORM	NORM	NORM	LOWER	3.9	0.53	100	6.2	6.8	COAI
96-4	10/24/92	441	MINIMUM	NORM	NORM	NORM	NONE	4.2	0.53	71	6.2	6.0	BASE
96-5	10/24/92	440	NORMAL	NORM	NORM	NORM	NONE	5.5	0.53	44	4.8	5.5	BASE
97-1	10/25/92	447	MINIMUM	NORM	NORM	NORM	NONE	4.0	0.51	158	7.8	4.2	BASE
97-2	10/25/92	442	MINIMUM	NORM	NORM	3	NONE	4.0	0.52	113	7.4		COA
97-3	10/25/92	441	MINIMUM	NORM	NORM	2	NONE	4.1	0.55	35	6.3		COA
97-4	10/25/92	445	MINIMUM	NORM	NORM	NORM	UPPER	4.2	0.51	205	7.0	7.2	BASE
98-1	10/26/92	447	MINIMUM	NORM	NORM	NORM	NONE	4.2	0.52	14	6.5	5.7	BASE
98-2	10/26/92	441	MINIMUM	NORM	NORM	NORM	UPPER	4.4	0.51	25	7.8	6.2	COAI
98-3	10/26/92	441	MINIMUM	NORM	NORM	2	NONE	4.3	0.56	15	5.6		COA
98-4	10/26/92	440	MINIMUM	NORM	-20%	NORM	NONE	4.8	0.57	15	5.1		OUTE
98-5	10/26/92	441	MINIMUM	NORM	NORM	NORM	NONE	4.4	0.53	66	6.8	5.7	BASE
99-1	10/27/92	442	MINIMUM	NORM	NORM	NORM	NONE	4.2	0.51	36	5.4	4.9	BASE
99-2	10/27/92	445	MINIMUM	NORM	-20%	2	NONE	4.3	0.56	18	5.0	4.3	COAI
99-3	10/27/92	440	MINIMUM	NORM	-20%	2	NONE	3.6	0.52	153	6.3	6.1	SAMI
99-4	10/27/92	445	MINIMUM	NORM	-20%	2	NONE	5.9	0.74	19	2.1		SAM
99-5	10/27/92	445	MINIMUM	NORM	-20%	2	NONE	4.2	0.57	26	4.0		SAM
100-1	10/28/92	446	MINIMUM	NORM	NORM	NORM	NONE	4.2	0.51	36	4.2	4.4	BASI
100-2	10/28/92	442	MINIMUM	NORM	NORM	NORM	NONE	3.7	0.48	99	4.8	5.6	BASI
100-3	10/28/92	443	MINIMUM	NORM	NORM	NORM	NONE	5.0	0.59	17	2.8	1.6	BASI
100-4	10/28/92	442	MINIMUM	NORM	NORM	NORM	NONE	3.9	0.51	34	4.2	3.6	BASI
100-5	10/28/92	443	NORMAL	NORM	NORM	NORM	NONE	5.0	0.52	22	3.5		BASE

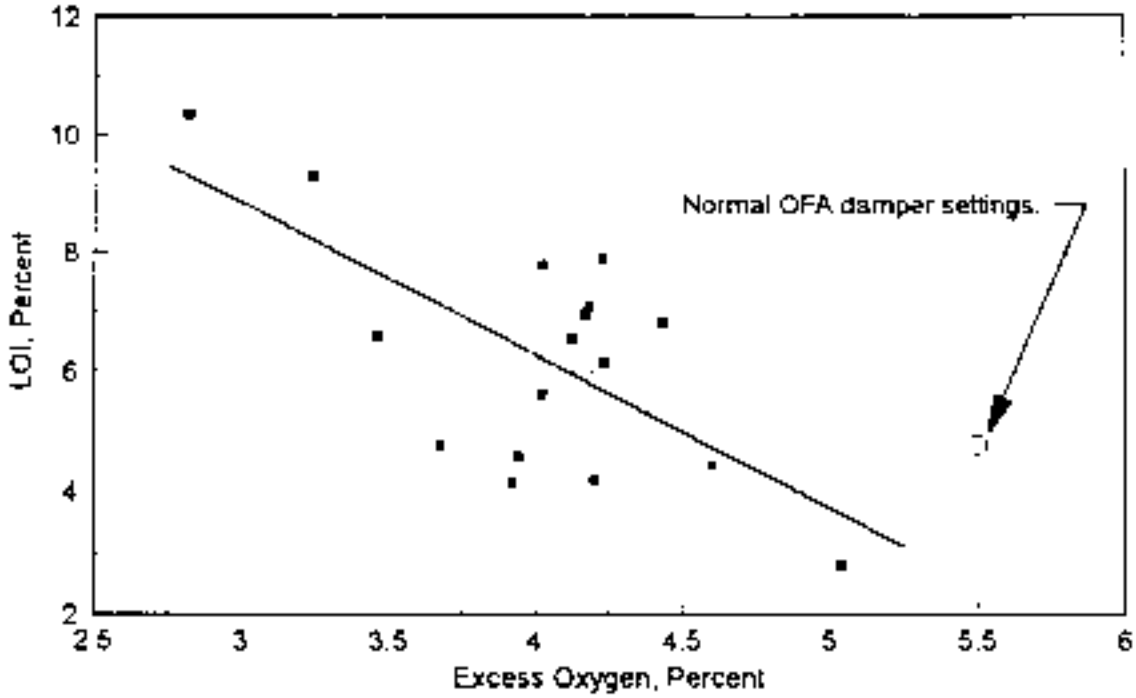


Figure 5-16 Nox vs. LOI Testing/LOI vs. O_2

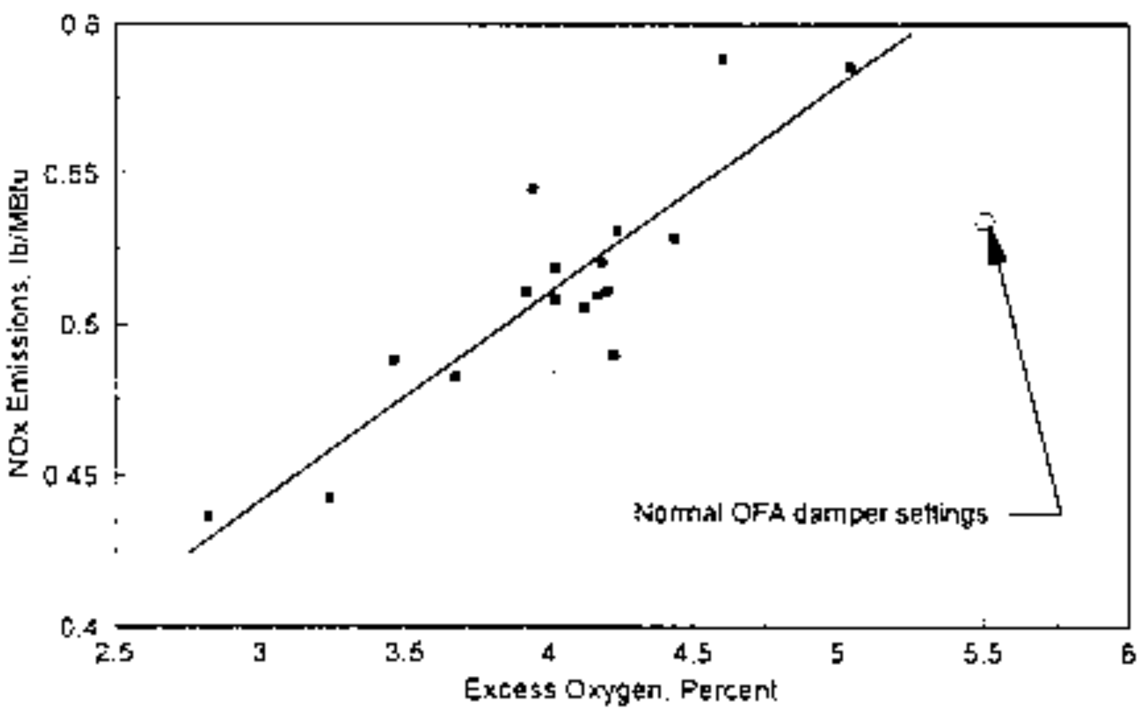


Figure 5-17 Nox vs. LOI Testing / Nox vs. O_2

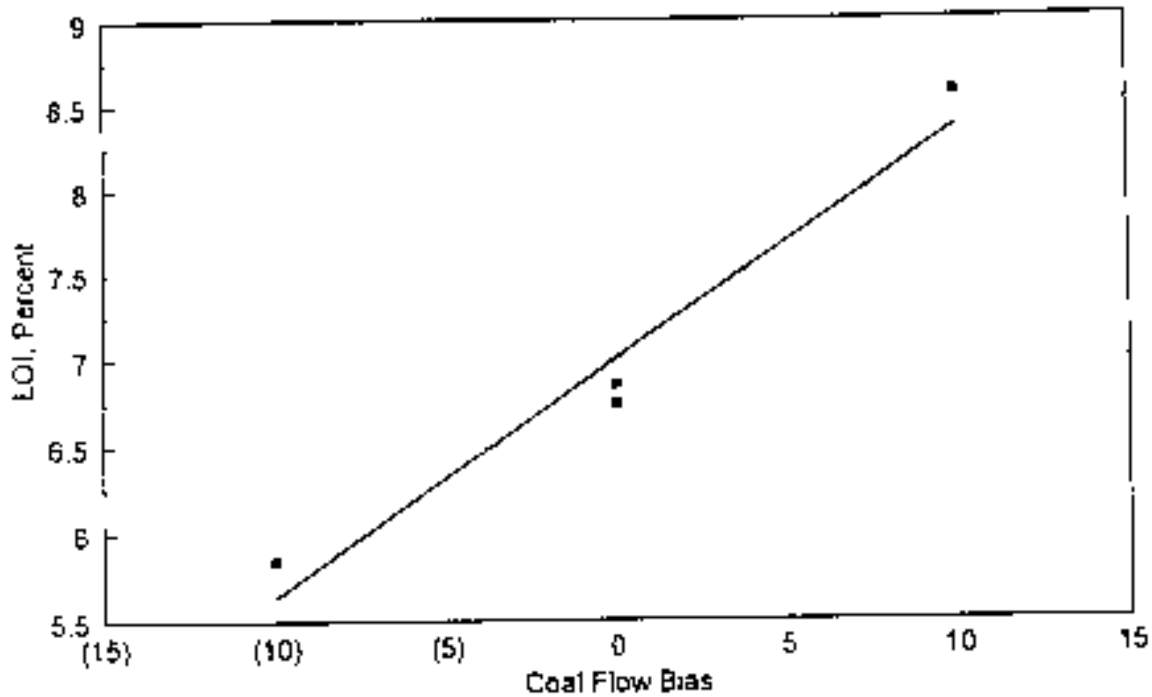


Figure 5-18 Nox vs. LOI Testing / LOI vs. Mill Bias

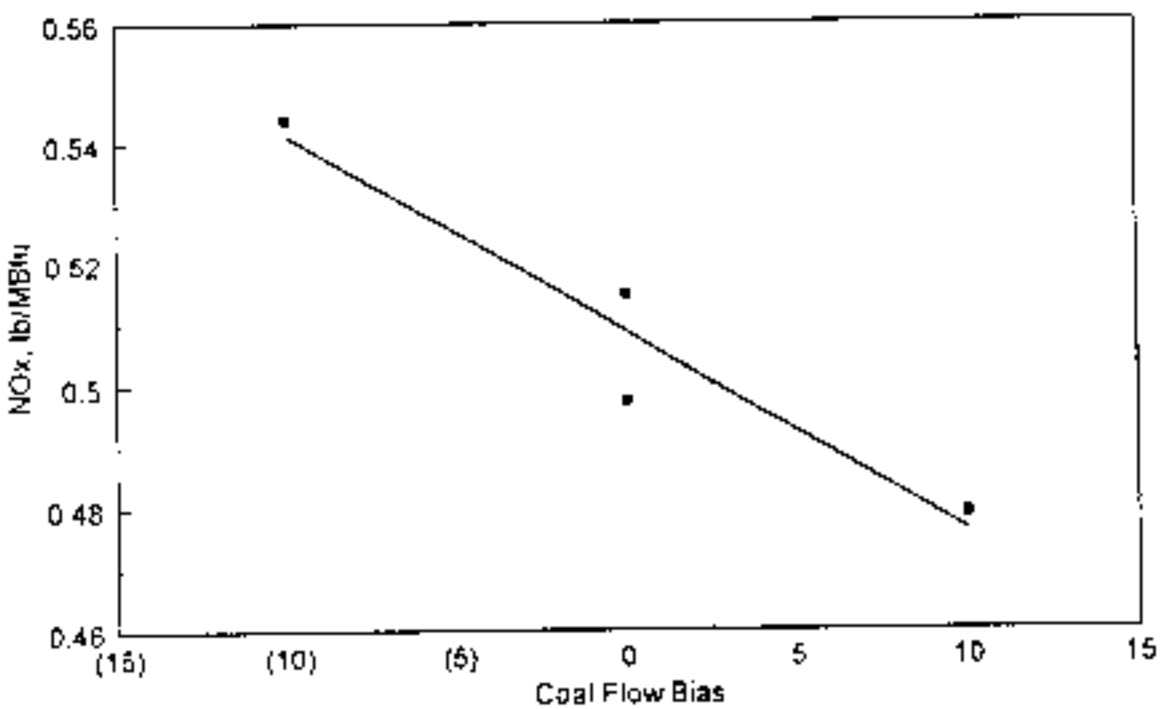


Figure 5-19 Nox vs. LOI Testing / Nox vs. Mill Bias

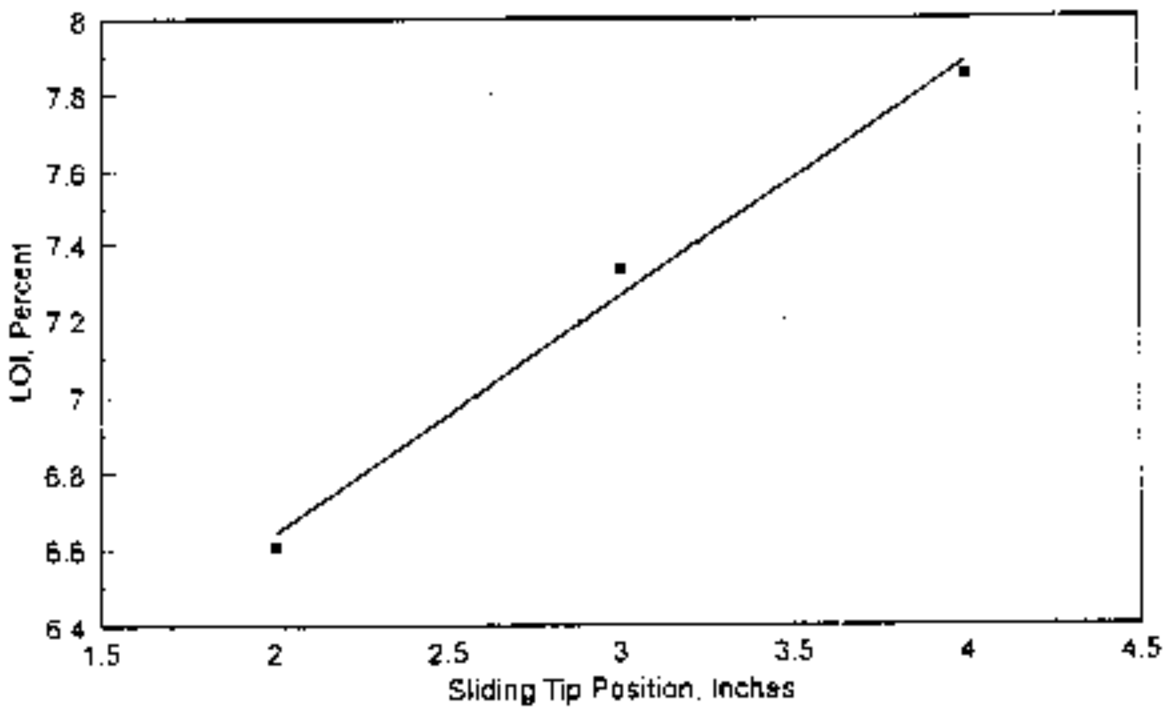


Figure 5-20 Nox vs. LOI Testing / LOI vs. Sliding Tip Position

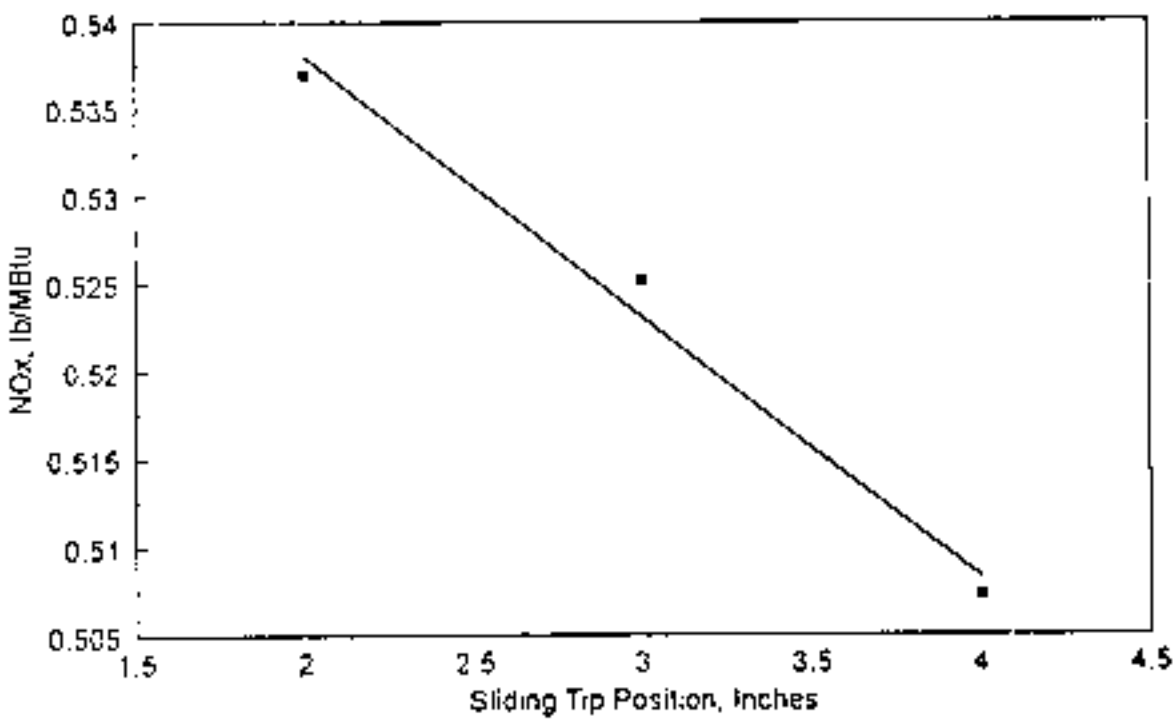


Figure 5-21   Nox vs. LOI Testing / Nox vs. Sliding Tip Position

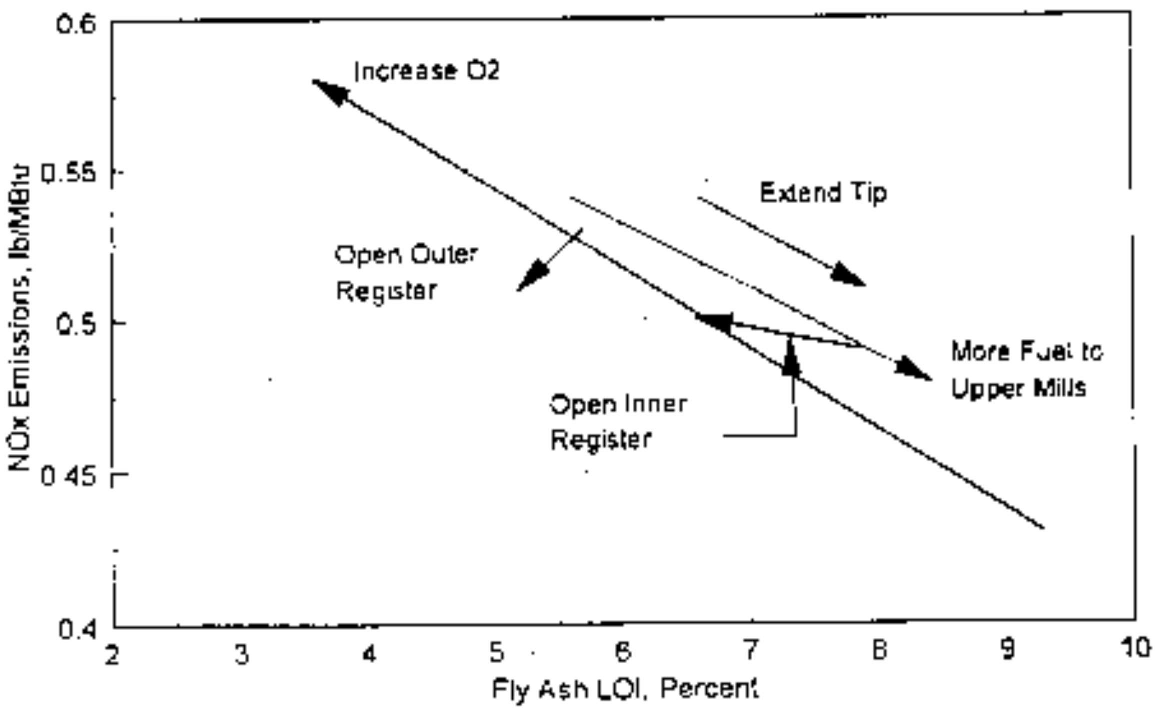


Figure 5-22 Nox vs. LOI Testing / All Sensitivities

6. Long-Term Data Analysis

The long-term testing consisted of continuous measurement of operating parameters while the unit was under normal load dispatch. This long-term testing was performed from August 7 through December 19, 1991. During this period, a number of unit outages were experienced that resulted in lost days of data capture. However, The data capture was sufficient to fully characterize the unit both from an engineering perspective as well as a regulatory point of view.

The focus of the analysis of this long-term data was:

- Characterization of the daily load and NOx emissions and the within day statistics,
- Characterization of the NOx emissions as a function of the O_2 and mill patterns for all five minute ECEM data,
- Determination of the thirty-day rolling average NOx emissions based upon valid days and hours of ECEM data,
- Determination of the achievable NOx emission level based upon valid days of ECEM data, and
- Comparison of long-term results to short-term results.

The following paragraphs describe the major results of these analyses.

6.1 Unit Operating Characteristics

Figures 6-1 and 6-2 illustrate the NOx emissions and the load for the load history experienced during the entire long-term test period. From Figure 6-1, it can be seen that the five-minute average NOx emissions varied from approximately 0.35 to 0.9 lb/MBtu. It is difficult to determine a trend using this type of data. The data does however illustrate that the unit experienced load changes from the minimum operating load (180 MW) to the maximum continuous operating load (500 MW) during the entire long-term test period. In addition, it is evident from this figure that there were prolonged periods of time that the unit did not operate over 300 MW. This is a significantly different load scenario than experienced during prior phases.

Based on the long-term emissions data, the daily averages of load and NOx were determined and are shown in Figure 6-3. These daily average data were determined using the EPA criteria for valid data explained in Section 4. Only days with at least 18 hours of data are presented in this figure. During the first half of the long-term testing, the average daily load was generally in excess of 400 MW. Midway in the long-term test effort, the load decreased to below 300 MW. This unit has been a base loaded unit in the past which was generally the first unit on and the last unit off of dispatch During the Phase 2 test effort, the unit was reclassified within the system and, while still a base loaded unit, was operated at lower load than in the past. This situation continued into the Phase 3A test period. For the Phase 3A long-term test period. the daily average emissions ranged from approximately 0.4 to 0.7 lb/MBTU.

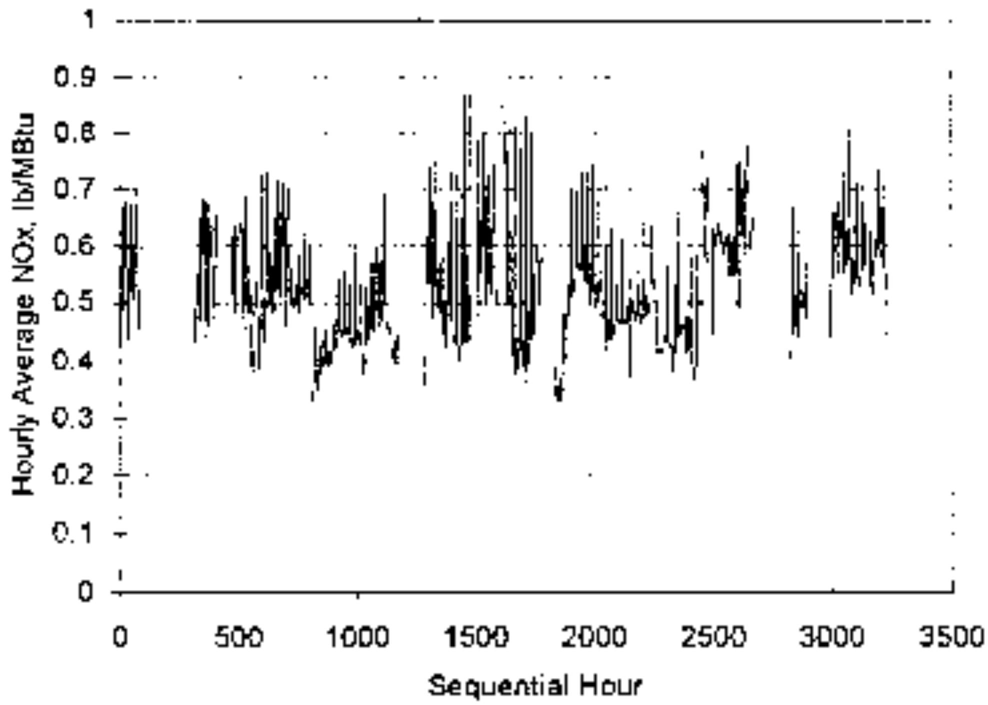


Figure 6-1 Hourly Average Nox Emissions

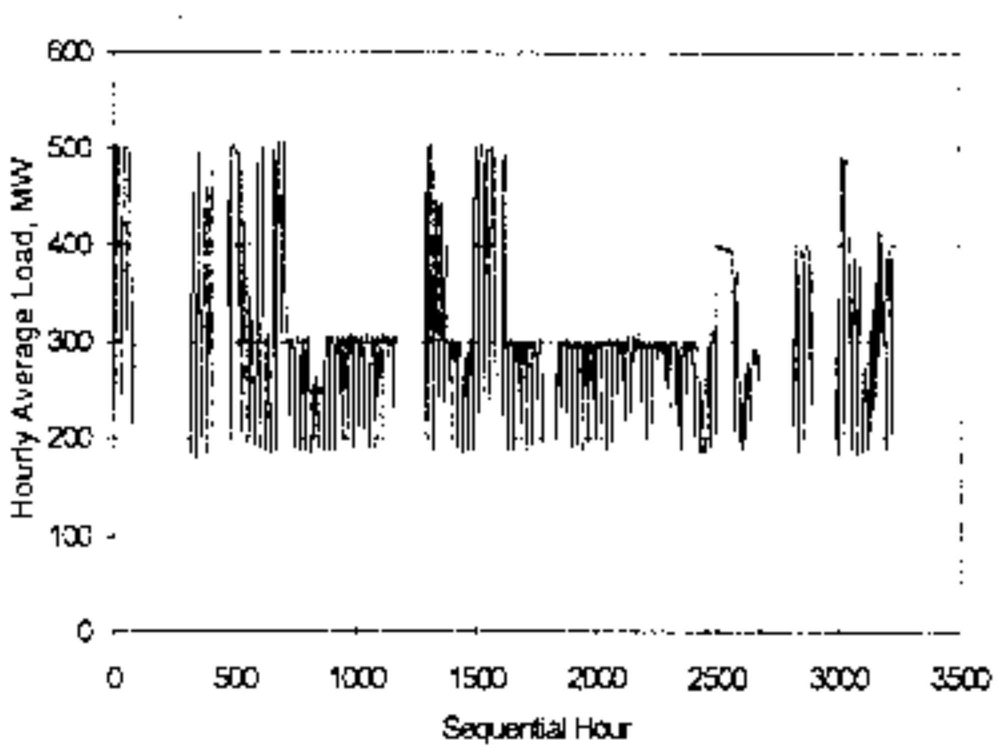


Figure 6-2 Hourly Average Load

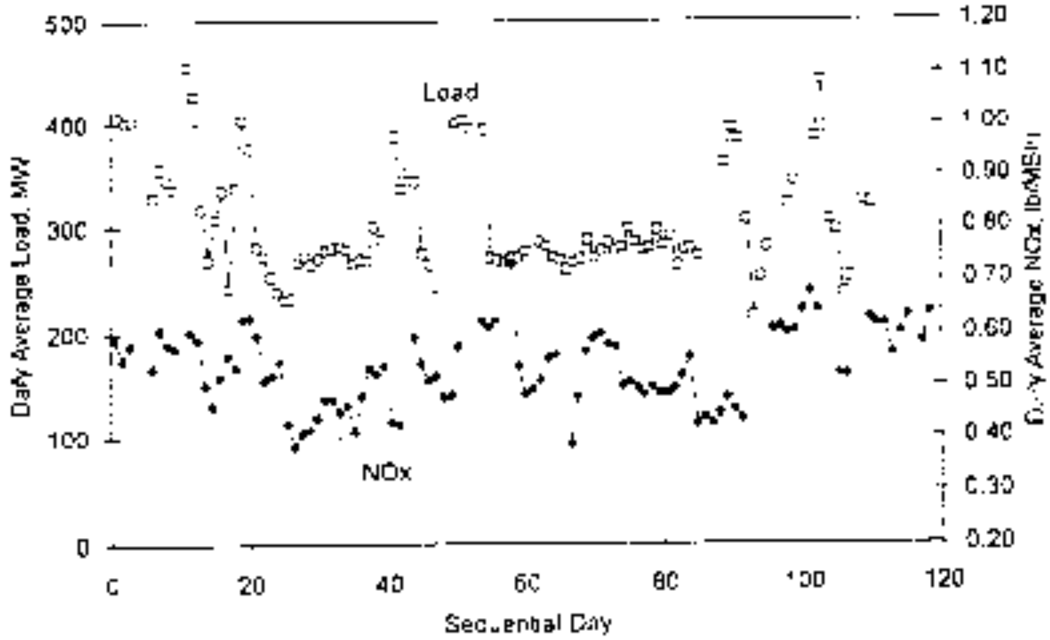
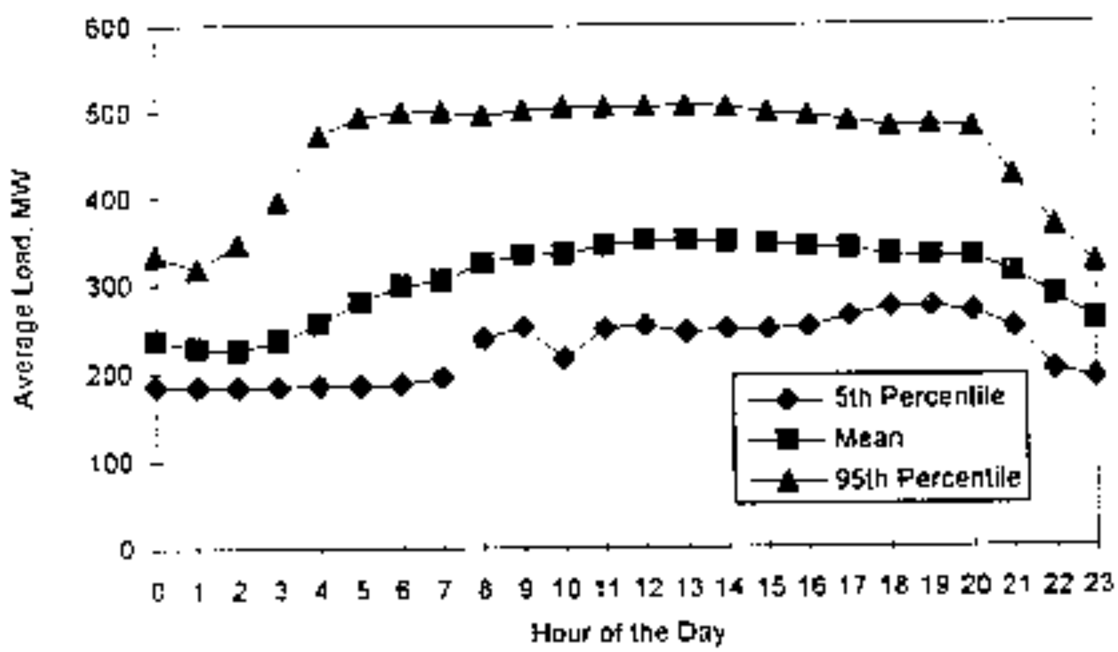


Figure 6-3 Daily Average Load and Nox Characteristics

One method of characterizing the boiler operating characteristics during the long-term testing is to examine the within-day variation of load and NOx. This was accomplished by segregating the data by hour of the day, i.e., 0100, 0200,...2400. For these segregated data, the mean load and NOx were computed. In addition, the hourly values representing the lower 5 percent and upper 95 percent of all values were determined. The results of this analysis are shown in Figure 6-4 which illustrates the daily trend for load and NOx emissions over the entire long-term test period. The figure illustrates that the unit was operated as a base loaded unit for most of the day (on average 16 hours were above 300 MW). This is a considerably lower base load than experienced during the previous two program phases. It is evident that the NOx versus load characteristic is very flat. The exact relationship will be illustrated in the following paragraphs.

6.2 Parametric Test Results

For the parametric analyses, all of the valid five-minute data were used. The 5-minute and hourly average emission data were analyzed to determine the overall relationship between NOx and load and the effect of boiler O_2 on NOx emissions for certain frequently used mill patterns. Since these data were obtained while the unit was under normal load dispatch, they represent the long-term NOx characteristics.



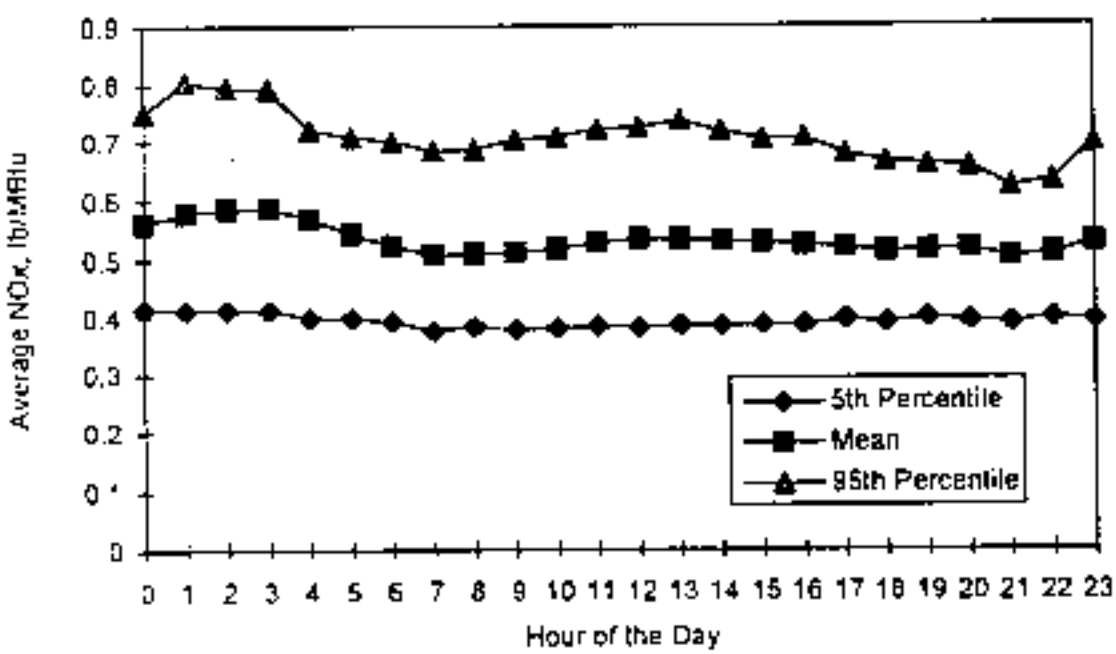


Figure 6-4 Diurnal Characteristics

The NOx versus load relationship was determined by first segregating the 5-minute average load data into 20 MW wide load ranges. Table 6-1 provides the results for this segregation of the data for the entire long-term data set. 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 6-5 illustrates the NOx versus load trend for these data.

Table 6-1 Long-Term Test Statistics / August 7 - December 19, 1991

Load Category	Sample Size	Load Lower 5% 5%	Load Average 5% 5%	Load Upper 5% 5%	Excess O_2 Lower 5% %	Excess O_2 Average 5% 5%	Excess O_2 Upper 5% 5%	NOx Average %	NOx Average %	NOx Upper 5%
170-190	2174	180	185	189	8.5	9.5	10.4	0.44	0.65	0
190-210	1582	191	199	209	8.5	9.6	10.9	0.40	0.58	0
210-Z30	1157	211	220	229	8.2	9.2	10.1	0.42	0.55	0
230-250	1382	231	241	241	8.0	9.0	9.9	0.38	0.50	0
250-270	2068	251	259	261	7.9	8.5	9.8	0.34	0.48	0
270-290	1954	271	281	291	7.7	8.7	10.0	0.38	0.50	0
290-310	8198	292	300	301	7.4	8.4	9.4	0.38	0.47	0
310-330	820	310	318	329	7.5	8.2	9.0	0.43	0.53	0
330-350	511	331	340	341	7 3	8.0	8.8	0.45	0.55	0
350-370	407	351	361	369	6.9	7 7	8.4	0.42	0.54	0
370-390	604	371	380	389	6.8	7.6	8.5	0.41	0.55	0
390-410	1502	391	396	402	6.8	7.3	8.0	0.45	0.57	0
410~430	283	412	422	429	6.3	7.1	8.1	0.46	0.56	0
430-S50	408	431	441	449	6.3	6.9	7.7	0.55	0.60	0
450-470	231	451	459	469	6.3	6.9	7.7	0.57	0.64	0
470~490	670	472	483	489	6.1	6.6	7.3	0.59	0.65	0
490-510	1486	492	501	50E	5.7	6.4	7.1	0.62	0.70	0

*Measurements at stack

The effect of operating O_2 on NOx emissions for certain mill patterns was examined for load ranges that corresponded to some of the loads tested during the short-term test portion of the Phase 2 test effort. These ranges were the 180-190, 290-300, 390-400 and 470-480 MW ranges. All of the valid five-minute data for these load ranges were used to assess the impact of excess oxygen level for the most commonly used mill patterns. In order to determine the most frequently used patterns, the frequency distribution of the mills-in-service pattern was determined. Table 6-2 presents the frequency distribution for the two most used mill patterns. It is apparent that there are certain preferred mill patterns for each load range. These patterns are dictated by the operational requirements of the unit (i.e., slag minimization, steam temperature control, etc.).

Prior to commencing the short-term testing effort, discussions with plant operations indicated that certain mill patterns were the preferred patterns. These patterns were then used during the diagnostic and performance testing with the intent of comparing the results with the same patterns during long-term testing. The mill patterns used during the short-term test effort were the E-, B&E, B&C and E&F-MOOS at loads below 400 M\~. Referring to Table 6-2 it is evident that these patterns were not the most prevalent during this long-term test effort. As a consequence

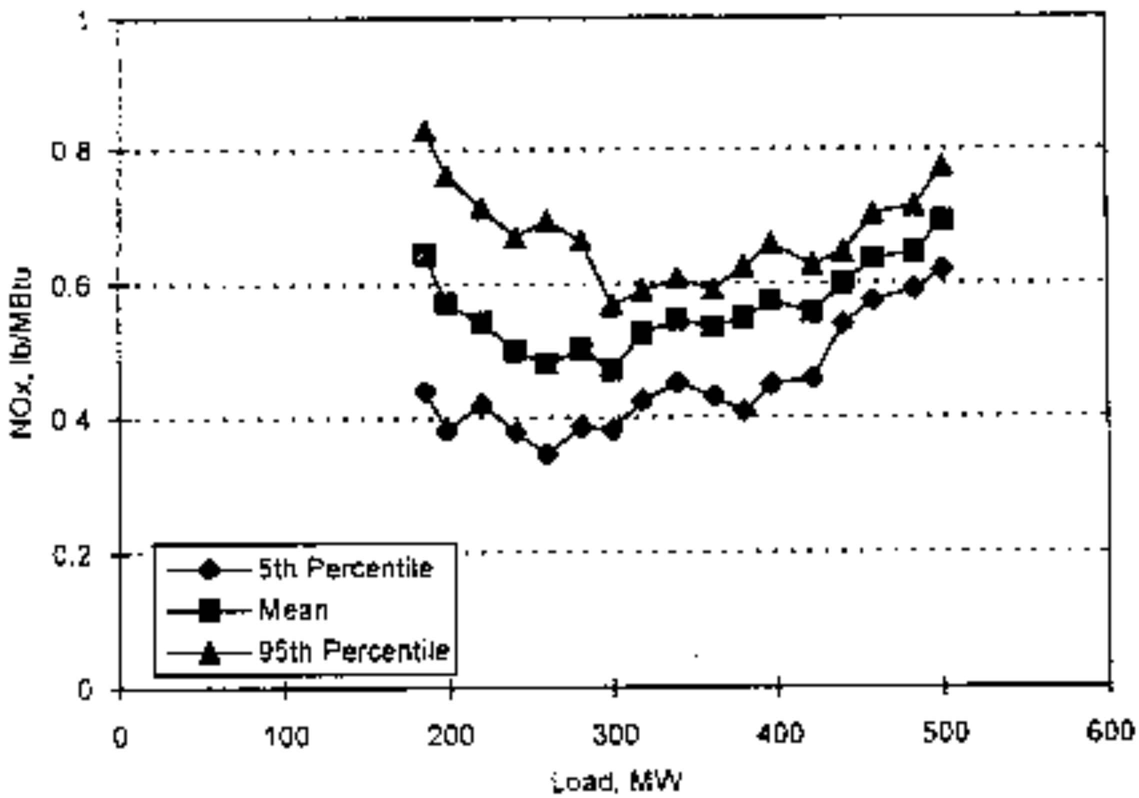


Figure 6-5 Nox vs. Load Characteristics

Table 6-2 Mill Pattern Use Frequency

Average Load MW	MOOS	Sample Size	Average O_2 Percent	Average Nox lb/MBtu
186	B,E	1070	9.6	0.69
186	C,F	379	9.2	0.63
296	B,E	1180	8.4	0.51
296	B,C	834	9.0	0.44
396	E	717	7.3	0.61
396	F	307	7.1	0.48
474	NONE	142	6.6	0.64

*Measurements at stack

of this, some comparisons will not be able to be made between the short- and long-term results discussed later.

All of the valid five-minute load data was analyzed for the most prevalent long-term MOOS patterns for each of the four load categories in order to establish the NOx versus O_2 characteristics. The NOx versus O_2 relationships for these patterns were evaluated using statistical regression techniques. The graphical analysis consists of two separate procedures. The data were characterized by first segregating the O_2 into cells that were one O_2 percentage point wide, i.e., 2.5-3.5, 3.5-4.5,...10.5-1 1.5 percent. The average NOx and O_2 for each O_2 cell were calculated and the best fit regression was then computed. For each of the average values the 5^{th} to 95^{th} percentile interval was computed. Some of the O_2 ranges contained only one value. For this condition, it is not possible to compute the lower 5^{th} and upper 95^{th} percentiles. Consequently, neither the average nor the percentiles for these data were included in the analysis.

The results of the above analyses are shown in Figures 6-6 through 6-9. In every instance, regardless of the MOOS patterns, the NOx emissions increased as the O_2 increased or remained relatively flat except at the 180 MW load level. At this load level, the NOx decreased slightly with increased in O_2. The NOx variation for each mill pattern was considerably less than that experienced during the previous two phases of the program.

6.3 Thirty-day Rolling Averages

The NSPS Subpart Da and Db standards are based upon compliance on a thirty-day rolling average. While this unit is not required to comply with these standards, it is of some value to evaluate the data for Phase 3A on a thirty-day rolling average basis and later compare it to the results from previous and subsequent phases of the program. Thirty-day rolling average load, NOx, and O_2 were computed using the valid hourly data as defined by the EPA criteria explained in Section 4. These thirty-day rolling averages are shown in Figure 6-10.

The thirty-day rolling average results shown in Figure 6-10 are only representative of the load scenario that was experienced by the unit during this long-term test period. During other periods when the load might be significantly different, the rolling averages would be expected to be somewhat different. For this particular period, it can be seen that the 30-day rolling average load was generally in the 300 MW range over the entire daily long-term effort. In the final report, thirty-day rolling average values will be computed for a consistent synthesized load scenario. These synthesized results will be used to illustrate the NOx emissions (and reductions) that would be reported on a unit if it were required to comply on a thirty-day rolling average basis standard.

6.4 Achievable Emission Characterization

EPA in their rulemaking process establishes an achievable emission level based upon daily average data samples obtained from CEMs. Most of this data is from NSPS Subpart Da units or units that used CEMs to obtain data during demonstration programs. The achievable NOx emission limit on a 30-day rolling average basis is determined using the descriptive statistics for 24-hour average NOx emissions As discussed in Section 4, the SAS UNIVARIATE and AUTOREG procedures

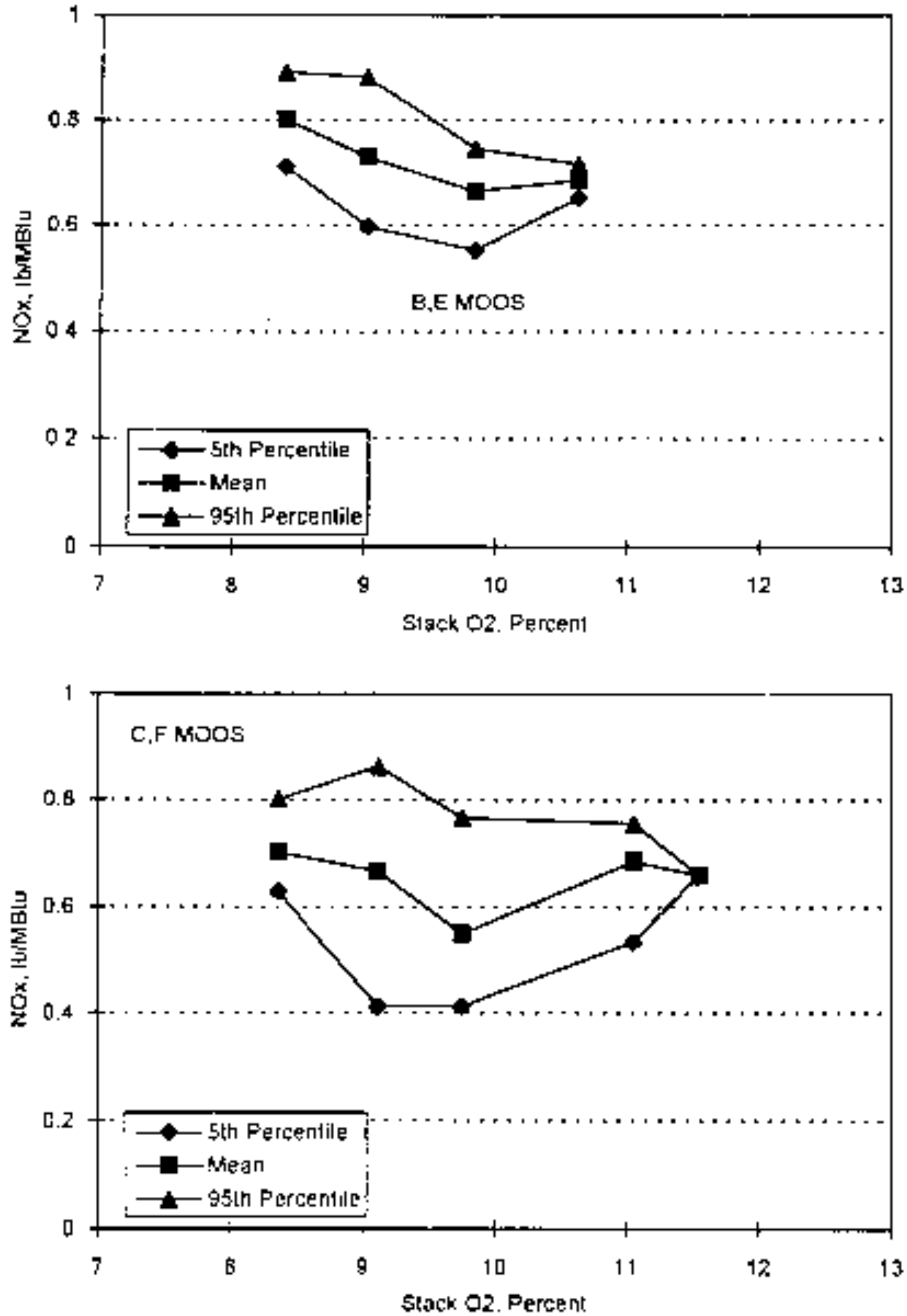


Figure 6-6 Nox vs. Excess Oxygen at 180 MW

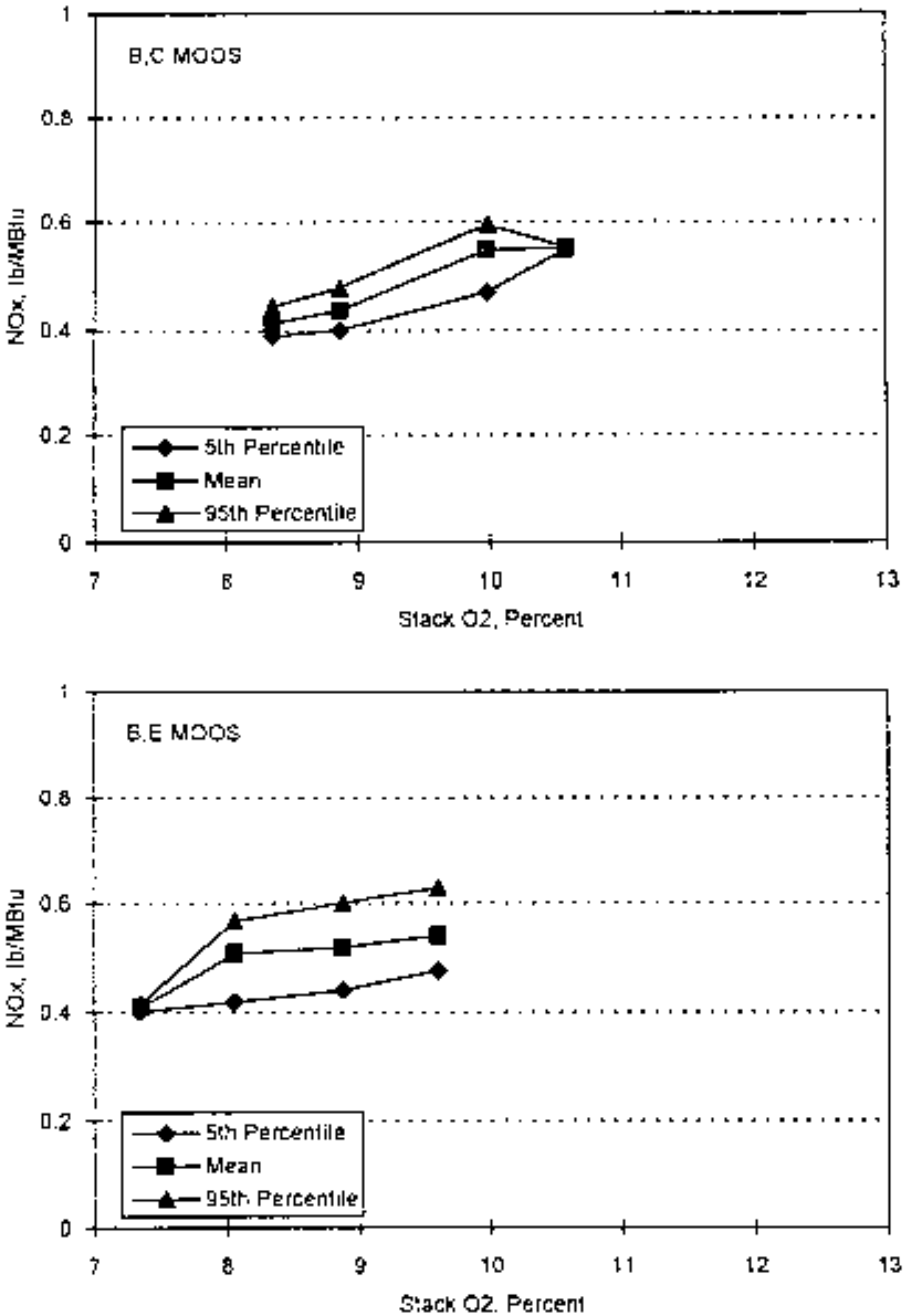


Figure 6-7 Nox vs. Excess Oxygen at 290 MW

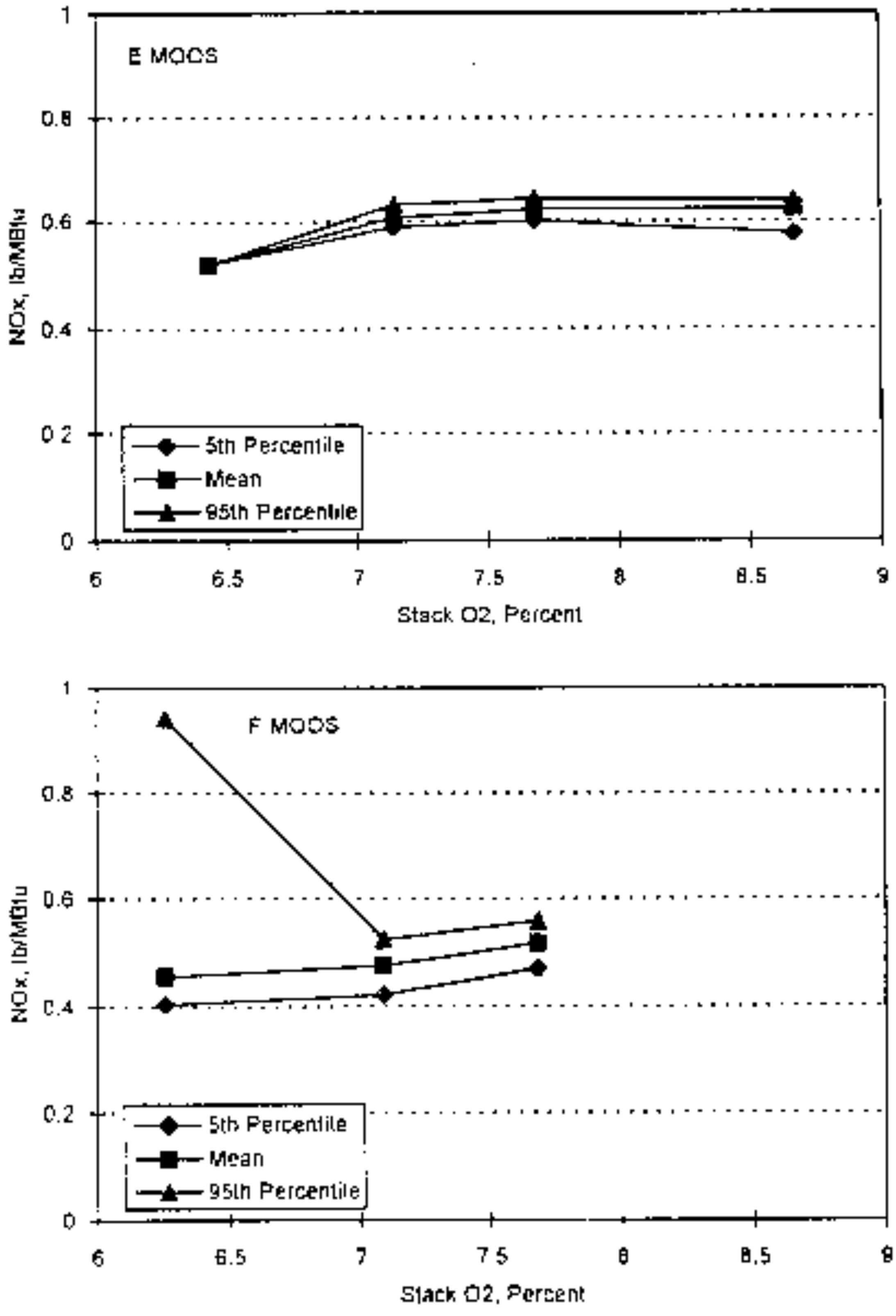


Figure 6-8 Nox vs. Excess Oxygen at 390 MW

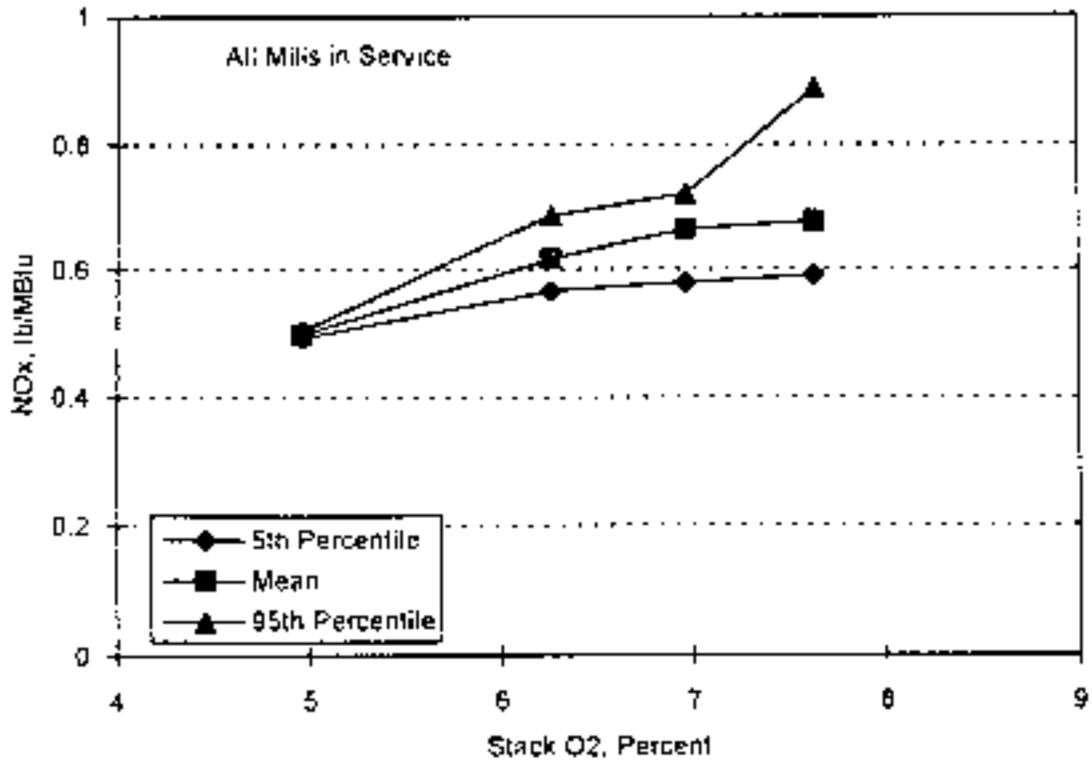


Figure 6-9 NOx vs. Excess Oxygen at 480 MW

are used to determine the descriptive statistics for the 24-hour average NOx emissions data. The results of the UNIVARIATE and AUTOREG analyses of the 24-hour average NOx emissions are presented in Table 6-3. The UNIVARIATE analysis indicated that the daily emissions were normally distributed. The AUTOREG analysis also indicated that the day-to-day fluctuations in NOx emissions followed a simple first order autoregressive model.

Based upon the EPA criteria, the achievable NOx emission limit should only be exceeded, on average, once per 10 years on a 30-day rolling average basis. The achievable emission depends on the long-term mean, variability, and autocorrelation level are shown in Table 6-3. The achievable emission limit is computed using these values as discussed in Section 4. Table 6-4 provides the achievable emission level, based on the daily values given in Table 6-3. The achievable NOx emission limits shown in this table, are computed for two conditions - no autocorrelation ($\rho = 0$) and the estimated value of 0.73 (which indicates highly time dependent data). The assumption in this table is that the Hammond unit will be operated in the future under similar load dispatching as that during the baseline test phase.

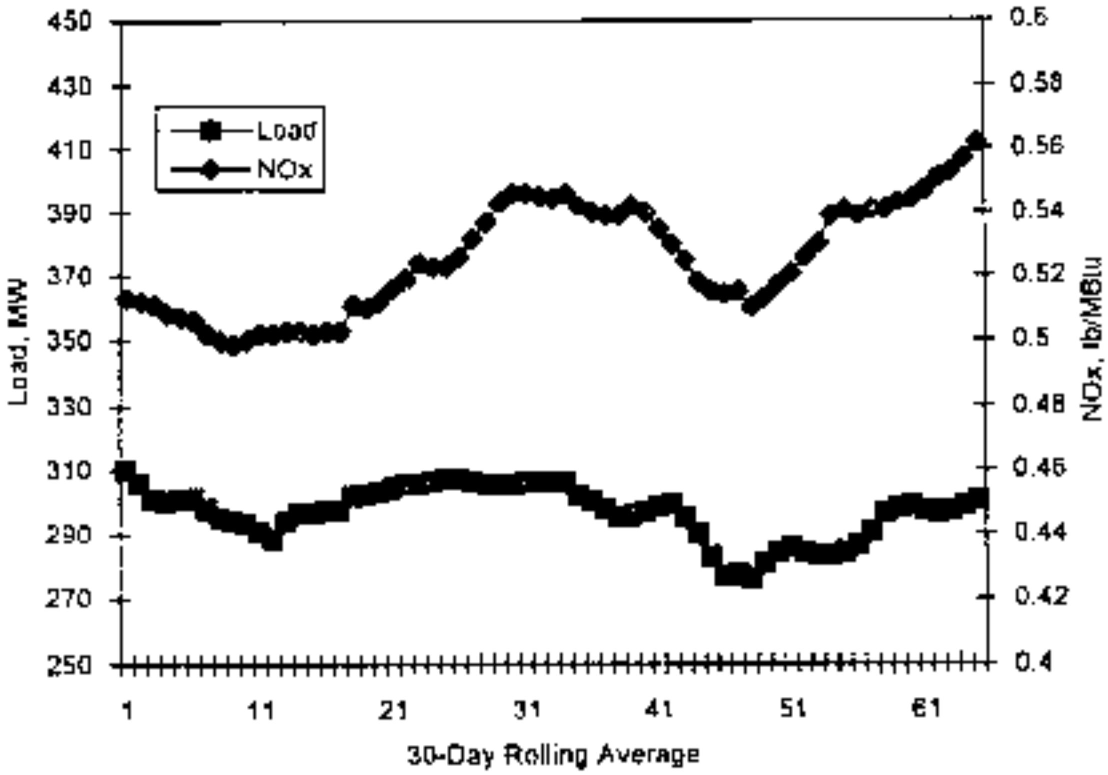


Figure 6-10 Thirty-Day Rolling Average

Table 6-3 Descriptive Statistics For Daily Average NOx Emissions

Number of Daily Values	94
Average Emissions (lb/MBtu)	0.53
Standard Deviation (lb/MBtu)	0.073
Distribution	Normal
First Order Autocorrelation (r)	0.73

Table 6-4 Achievable NOx Emission Limit

Autocorrelation (lb/MBtu)	Achievable Emission Limit 30-Day	Achievable Emission Limit Annual
$\rho = 0$	0.58	0.54
ρ =073	064	0.55

As explained above under other load scenarios, the thirty-day rolling averages would be different and therefore the achievable emission level would also be different.

It should be noted that the mean, variability, and autocorrelation levels given in Table 6-3 are only estimates. There is an uncertainty level implicit in the estimates of each of these statistical parameters. The uncertainty level in the mean is dependent on the variability. The estimated variability is, to some extent, dependent on the level of autocorrelation. Thus, uncertainty levels in the descriptive statistics are linked.

6.5 Comparison of Long- and Short-Term NOx Data

Section 5 presented data for the short-term load characteristics. This data included a number of mill configurations and a range of excess oxygen levels. Similar data was collected during the long-term effort and is shown in Figure 6-5. The data in Figure 6-5 includes all of the configurations normally experienced during the period from late August through December 1991. Figure 6-1 1 provides a comparison between these two sets of data showing the percentiles (upper 95 percent and lower 5 percent) for the long-term data. From the comparison it is evident that the data obtained during the short-term efforts was within the upper 95 and lower 5 percentile range. The agreement between short-term and long-term data is much better than prior phases.

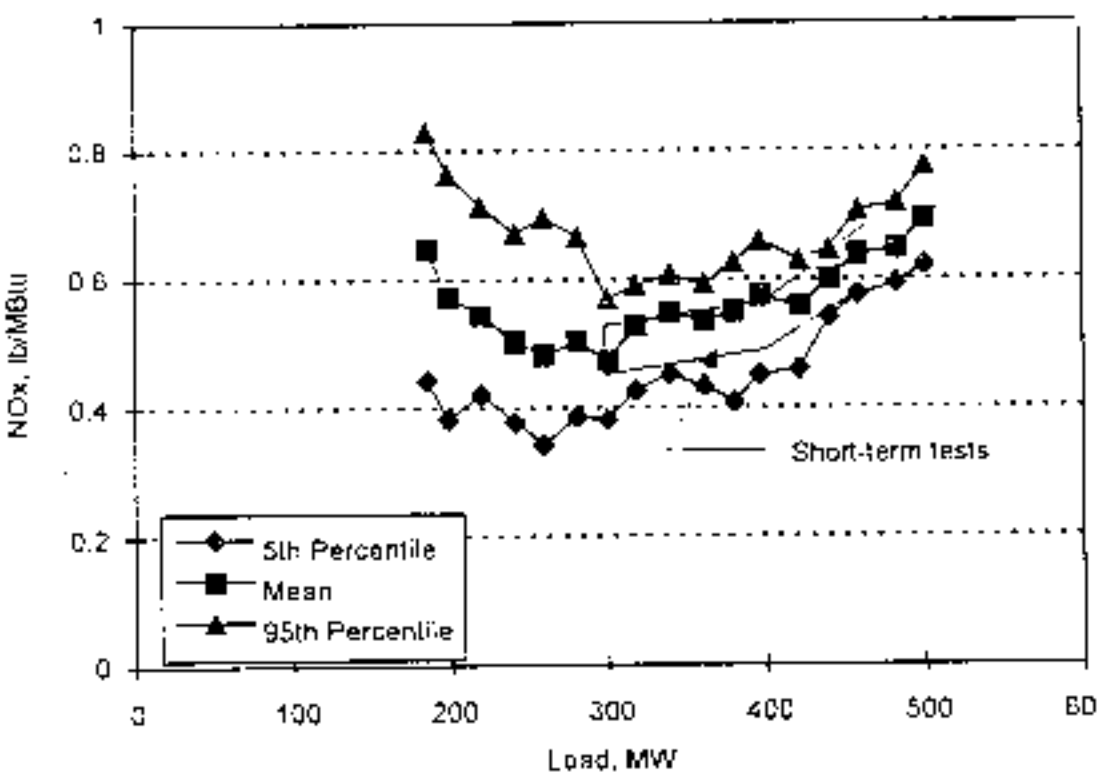


Figure 6-11 Comparison of Long- and Short-Term NOx Emissions

The true measure of the effectiveness of the particular NOx control technique is represented by the long-term load characteristics. A useful engineering comparison can be made by comparing the mean value of the baseline and the retrofit load characteristics. Figure 6-12 illustrates the load characteristics for both configurations. At the full load, the LNB retrofit resulted in an approximate 48 percent reduction in NOx. Figure 6-13 shows that the effectiveness was generally between 40 and 53 percent over the useful load range. In the high load range, the effectiveness was above 45 percent.

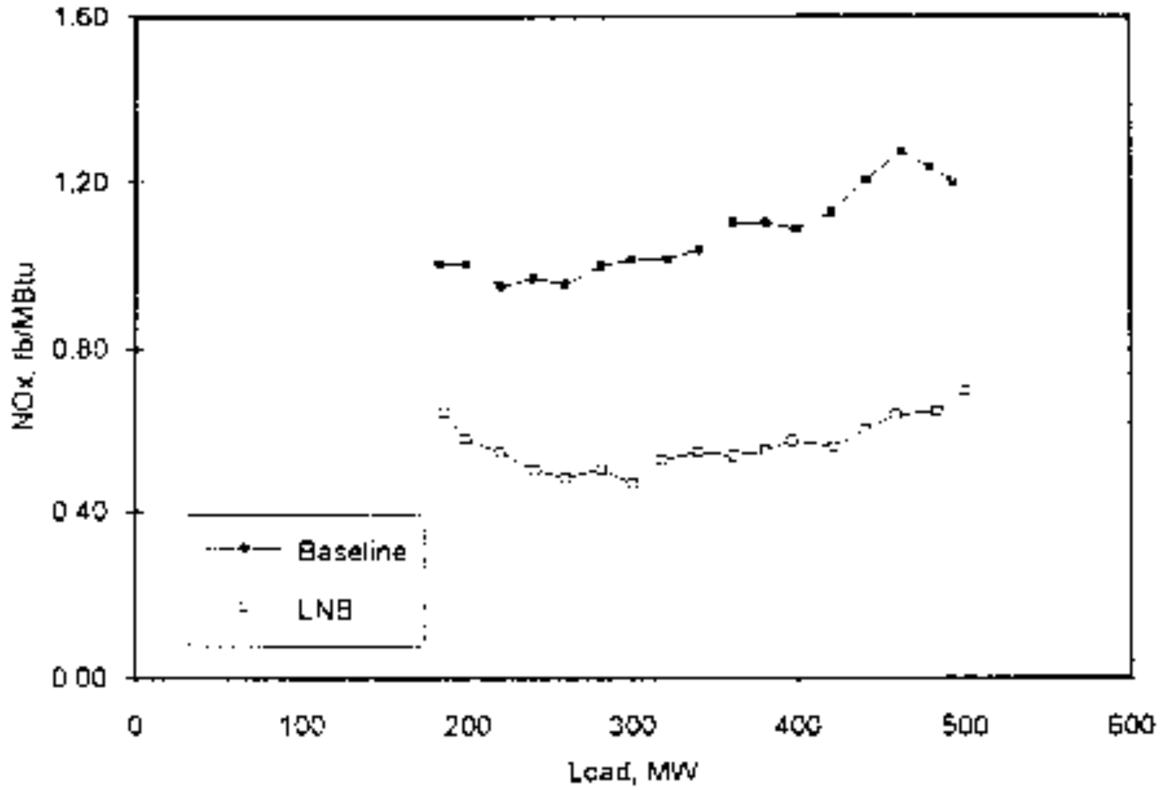


Figure 6-12 Comparison of Baseline and LNB NOx Emissions

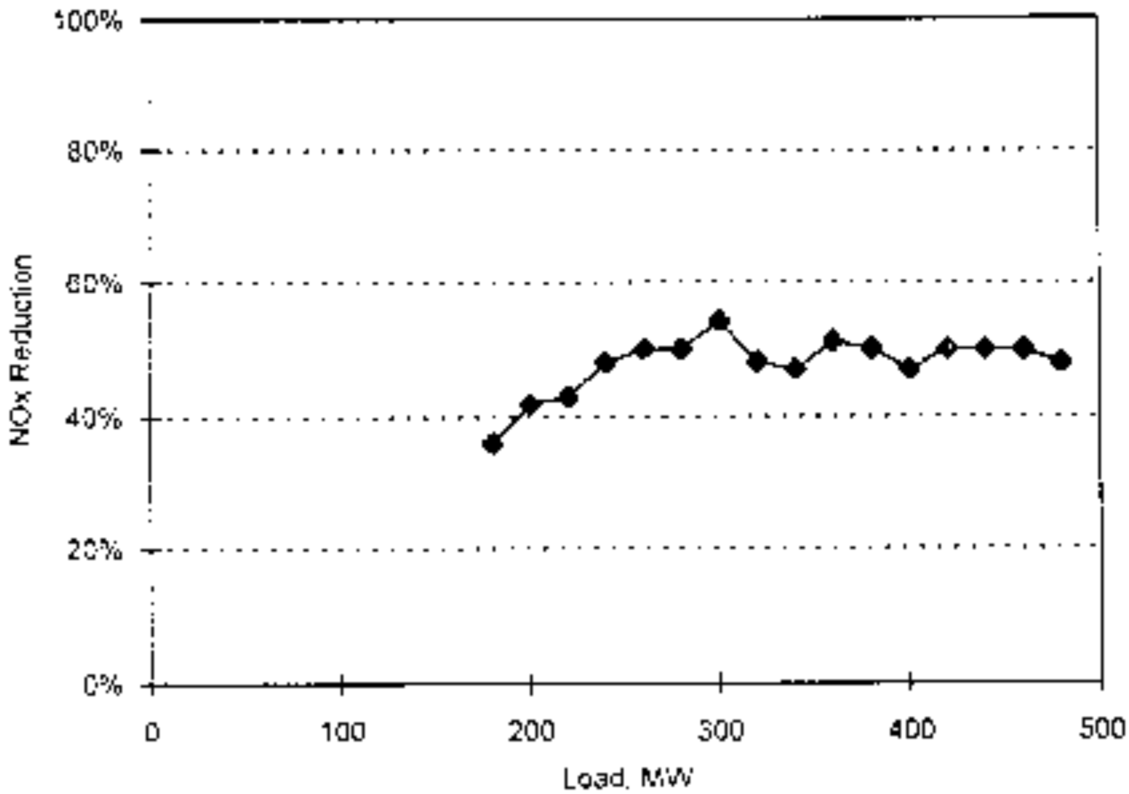


Figure 6-13 Baseline to LNB Nox Reduction

7. Conclusions

The primary objective of the Phase 3A test effort was to establish LNB retrofit NOx emission characteristics under short-term, well controlled conditions and under long-term, normal system load dispatch conditions. In addition, other important performance data related to the operation of the boiler in this retrofit configuration were documented for comparison to those measured during the Phase I baseline test effort. Protocols for data collection and instrumentation operation were established during Phase 1. In addition to this characterization, special LOI tests were performed to establish the impact of burner adjustment changes on NOx and LOI.

The following paragraphs provide brief discussions of the conclusions that can be drawn from the short-term and the long-term test results as well as from the special LOI tests. Conclusions related to the comparison of the short- and long-term results are also presented. A brief discussion related to the comparison between Phase I and Phase 3A data are included. More thorough comparisons will be presented in the final report after detailed analyses have been performed.

7.1 Short-term Characterization Tests

The following paragraphs provide a brief description of the major conclusions for the Phase 3A short-term testing.

7.1.1 Diagnostic Test Conclusions

The conclusions for the diagnostic portion of the testing are based primarily upon testing performed at 300, 400, and 480 MW. The major conclusions for the diagnostic testing are:

- NOx emissions were considerably less variable than for other previous phases of the program. The variation was, however, as much as 0.08 lb/MBtu.
- For one operating condition (mill pattern and load), NOx trends could be determined if O_2 excursions were performed on the same day and in a monotonic fashion. Trends at the same condition on different days exhibited like patterns which were biased by as much as 10 percent. All of the trends for all loads and mill patterns exhibited increasing NOx with increasing O_2 and the slopes were essentially the same.
- NOx emissions over the load range from 300 to 480 MW increase from approximately 0.50 to 0.65 lb/MBtu.
- Since the 185 MW load point was only tested for two days with two different mill patterns, the trend at this load could not readily be established.

7.1.2 Performance Test Conclusions

The performance tests documented the unit characteristics at nominal loads of 300, 400, and 480 MW. Over the 10 to 12 hour period of the individual performance test days, the unit

operated under extremely stable normal operating conditions. The major- conclusions for the performance tests are:

- The NOx scatter evidenced during the diagnostic tests was also present during the tests for nearly identical operating conditions (mill pattern and load).

- Nox and O_2 spatial distributions within the economizer exit ducts indicated significant maldistributions in flue gas temperature and O_2 levels.

- Primary air flow ranged from 22 to 32 percent at loads of 480 and 300 MW, respectively.

- Furnace exit gas temperatures were generally below 2300°F in the regions of low excess oxygen near the furnace nose. O_2 measurements at the furnace nose showed some regions with extremely low levels (well below one percent) in some regions at the furnace nose.

- Mill coal particle fineness was near the low end of the acceptable range. The coal fineness was determined to be 67 percent average through a 200 mesh screen at 480 MW. However, coal fineness during this phase was improved over baseline. Pipe-to-pipe coal flow were +23 to -41 percent from the mean at the full-load point. Primary air to coal ratio in the mills was +42 to -15 percent from the mean at the same load.

- ESP inlet ash resistivity was within the expected range for this coal. The resistivity remained unchanged from the baseline configuration.

- Fly ash LOI ranged from 5.4 to 8.6 percent over the load range. The LOI measurements indicated that LOI increased with the use of LNB over that of the original burners.

- At full load, mass loading and gas flow to the ESP increased by approximately 25 and 11 percent, respectively, when compared to baseline.

7.2 Long-Term Characterization Tests

Long-term testing took place from early August 1991 through mid December 1991. During this period the ECEM was operated 24 hours per day except during periods of repair and calibration. From time-to-time, the instrumentation experienced operational difficulties which resulted in lost data capture. These periods were minimal and did not affect the quality of the remainder of the data. Sufficient data was collected to perform meaningful statistical analyses for both engineering and regulatory purposes.

The following paragraphs provide the major conclusions that can be drawn from the long-term test results.

- In the past, the unit typically operated at high load for the majority of it's on-line time. The data taken during Phase 3A illustrated that the unit did not now operate at high loads for the majority of the time. Data show that the unit experienced significant periods of time where the average daily load was in the 300 MW range (60 percent load).

- Daily average NOx emission levels for the long-term test period ranged from approximately 0.4 to 0.7 lb/MBtu.

- The mean load characteristics showed that NOx exhibited a decreasing then increasing NOx relationship as load was increased. Low load (180 MW) and high load (480 MW) emissions were approximately equal. Ninety percent of the long-term NOx emission data collected was on the order of ± 0.2 lb/MBtu about the mean.

- Based upon 30-day rolling averages, the data showed that the average load was near 300 MW over the period of long-term testing. The 30-day rolling average NOx remained relatively constant at ranging from approximately 0.50 to 0.56 lb/Btu.

- Statistical analyses indicated that the data were autocorrelated with a correlation coefficient of p = 0.73. The data are more highly autocorrelated than the data collected in Phase 1 or Phase 2. The time dependent NOx emission characteristics resulted in a 30-day rolling average achievable emission limit of 0.64 lb/MBtu.

- Subsequent to Phase I testing, the Clean Air Act Amendments of 1990 passed requiring annual average emission rate limits. Based on data collected during the LND test phase, the average emission rate is 0.55 lb/MBtu.

7.3 Comparison of Phase 1 and Phase 3A Emission Data

The following briefly summarizes the conclusions that can be made with regard to the effectiveness of the LNB retrofit:

- NOx emissions decreased by 48 percent from the baseline configuration at 480 MW. The emission reduction increased as the load decreased to the 300 MW load point where the reduction was a maximum at approximately 54 percent. The effectiveness decreased to approximately 35 percent at the low load point of 180 MW.

- LOI emissions increased over the baseline configuration. At the 480 MW load point, the LOI increased by as much as approximately 60 percent to a level near 8 percent.

- Aside from LOI and NOx, all other solid and gaseous emission characteristics remained near the levels of those for the baseline configuration.

- Particulate mass loading and gas flow rates to the ESP increased as a result of the LNB retrofit.

7.4 Special LOI Test Conclusions

Based on analysis of the test results, the following conclusions were drawn with regard to the impact of operational and burner variations during the special LOI testing

- Excess oxygen is the principal variable influencing both LOI content in the fly ash and NOx emissions.

- NOx and LO1 in ash are inversely related; i.e. NOx increases and LOI decreases with increasing O_2.

- The "nominal" inner register settings established by FWEC (nearly at the "zero" position), results in the minimum LOI emissions and maximum NOx emissions for the configurations tested.

- Variations in outer register settings produced only slight changes in both LOI and NOx; LOI increased as the outer registers were closed from the FWEC "nominal" position. NOx was essentially unaffected by outer register position.

- Coal pipe position had a significant effect on both LOI and NOx. LOI decreased and NOx increased as the coal pipes were withdrawn from the FWEC "nominal" position.

- Biasing of the coal flow toward the lower burners resulted in a significant decrease in LOI and an increase in NOx emissions.

- LOI is a reliable indicator of carbon content in the fly ash for this coal, being consistently about 1.1 times the carbon level.

- There is considerable scatter in both LOI and NOx emissions for tests conducted under "identical" conditions on different days. Thus, it is important that any trends of LOI and NOx vs. variations in operating parameters be conducted on a single day.

These results are presented as the first indications of the impacts of the burner operating variables on LOI and NOx on the Hammond Unit 4. Additional analyses may be performed subsequently and included in the final project report.

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