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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

Technical Progress Report
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EXECUTIVE SUMMARY

This quarterly report discusses the technical progress 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. A target of achieving fifty percent NOx reduction using combustion modifications has been established for the project. The project provides a stepwise evaluation of the following NOx reduction technologies: Advanced overfire air (AOFA), Low NOx burners (LNB), LNB with AOFA, and Advanced Digital Controls and Optimization Strategies.

Baseline, AOFA, LNB, and LNB plus AOFA test segments have been completed. Analysis of the 94 days of LNB long-term data collected show the full-load NOx emission levels to be approximately 0.65 lb/MBtu with flyash LOI values of approximately 8 percent. Corresponding values for the AOFA configuration are 0.94 lb/MBtu and approximately 10 percent. For comparison, the long-term, full-load, baseline NOx emission level was approximately 1.24 lb/MBtu at 5.2 percent LOI. Comprehensive testing in the LNB+AOFA configuration indicate that at full-load, NOx emissions and flyash LOI are near 0.40 lb/MBtu and 8 percent, respectively. Based on a preliminary analysis, approximately 17 percent of the incremental change in NOx emissions between the LNB and LNB+AOFA configurations is the result of AOFA, the balance of the NOx reduction resulting from other operational adjustments.

Following a nine month outage, coal-fired operation resumed at Hammond Unit 4 on June 5. Installation of the digital control system (DCS) installed during this outage and as part of this project has been completed and the system is operational. Design of the advanced controls/optimization portion of the project is continuing. Following extensive evaluation, a final selection on the core optimization technology has been made. The version of the commercial software necessary for a successful demonstration will not be available until December 1994, however, an "Alpha" version of the software is now being tested at SCS and a "Beta" release will be made available to the project during October.

Preliminary diagnostic testing was conducted during August and September. The purpose of these tests was to determine the emissions and performance characteristics of the unit prior to activation of the advanced control/optimization strategies. Short-term, full load NOx emissions were near 0.47 lb/MBtu, slightly higher than that seen during the LNB+AOFA test phase. Long-term NO_x emissions for this quarter averaged near 0.41 lb/MBtu. Due to turbine problems, a four week outage has been planned for Hammond 4 starting October 1. Although testing has been rescheduled to accommodate this outage, overall project scheduled should not be impacted.

Two on-line carbon-in-ash monitors are being installed at Hammond Unit 4 as part of the Wall-Fired Project. These monitors will be evaluated as to their accuracy, repeatability, reliability, and serviceability.

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TABLE OF ABBREVIATIONS

acfm	actual cubic feet per minute
AMIS	All mills in service
AOFA	Advanced Overfire Air
ASME	American Society of Mechanical Engineers
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
ETEC	Energy Technology Consultants
F	Fahrenheit
FC	fixed carbon
FWEC	Foster Wheeler Energy Corporation
Flame	Flame Refractories
GPC	Georgia Power Company
H	hydrogen
HHV	higher heating value
HVT	High velocity thermocouple
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	Mills out of service
MW	megawatt
N	nitrogen
NOx	nitrogen oxides
NSPS	New Source Performance Standards
O, O_2	oxygen
OFA	overfire air
PA	primary air
psig	pounds per square inch gauge
PTC	Performance Test Codes

TABLE OF ABBREVIATIONS (continued)

RSD	relative standard deviation
S	sulfur
SCS	specific collection area
SCS	Southern Company Services
SO_2	sulfur dioxide
SoRI	Southern Research Institute
Spectrum	Spectrum Systems Inc.
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. 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 which are conducted as Cooperative Agreements in which the industrial participant contributes at least fifty percent of the total project cost.

The primary objective of the Plant Hammond 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 modifications has been established for the project. Specifically, the objectives of the projects are:

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

    a. Advanced overfire air (AOFA)
    b. Low NOx burners (LNB)
    c. LNB with AOFA
    d. Advanced Digital Controls and Optimization Strategies

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.

2. PROJECT DESCRIPTION

2.1. Test Program Methodology

In order to accomplish the project objectives, a Statement of Work (SOW) was developed which included the Work Breakdown Structure (WBS) found in Table 1. The WBS is designed around a chronological flow of the project. The chronology requires design, construction, and operation activities in each of the first three phases following project award.

Table 1: Work Breakdown Structure

Phase	Task	Description	Date
0	0	Phase 0 Pre-Award Negotiations	
1	1	Phase 1 Baseline Characterization	
	1.1	Project Management and Reporting	8/89 - 4/90
	1.2	Site Preparation	8/89 - 10/89
	1.3	Flow Modeling	9/89 - 6/90
	1.4	Instrumentation	9/89 - 10/89
	1.5	Baseline Testing	11/89 - 4/90
2	2	Phase 2 Advanced Overfire Air Retrofit	
	2.1	Project Management and Reporting	4/90 - 3/91
	2.2	AOFA Design and Retrofit	4/90 - 5/90
	2.3	AOFA Testing	6/90 - 3/91
3	3	Phase 3 Low NOx Burner Retrofit	
	3.1	Project Management and Reporting	3/91 - 8/93*
	3.2	LNB Design and Retrofit	4/91 - 5/91
	3.3	LNB Testing with and without AOFA	5/91 - 8/93*
4*	4*	Advanced Low NOx Digital Control System*	8/93 - 4/95*
5*	5*	Final Reporting and Disposition	
	5.1	Project Management and Reporting	5/95 - 12/95*
	5.2	Disposition of Hardware	12/95*

* Indicates change from original work breakdown structure.

The stepwise approach to evaluating the NOx control technologies requires that three plant outages be used to successively install: (1) the test instrumentation, (2) the AOFA system, and (3) the LNBs. These outages were scheduled to coincide with existing plant maintenance outages in the fall of 1989, spring of 1990, and spring of 1991. The planned retrofit progression has allowed for an evaluation of the AOFA system while operating with the existing pre-retrofit burners. As shown in Figures 1, the AOFA air supply is separately ducted from the existing forced draft secondary air system. Backpressure dampers are provided on the secondary air ducts to allow for the introduction of greater quantities of higher pressure overfire air into the boiler. The burners are designed to be plug-in replacements for the existing circular burners.

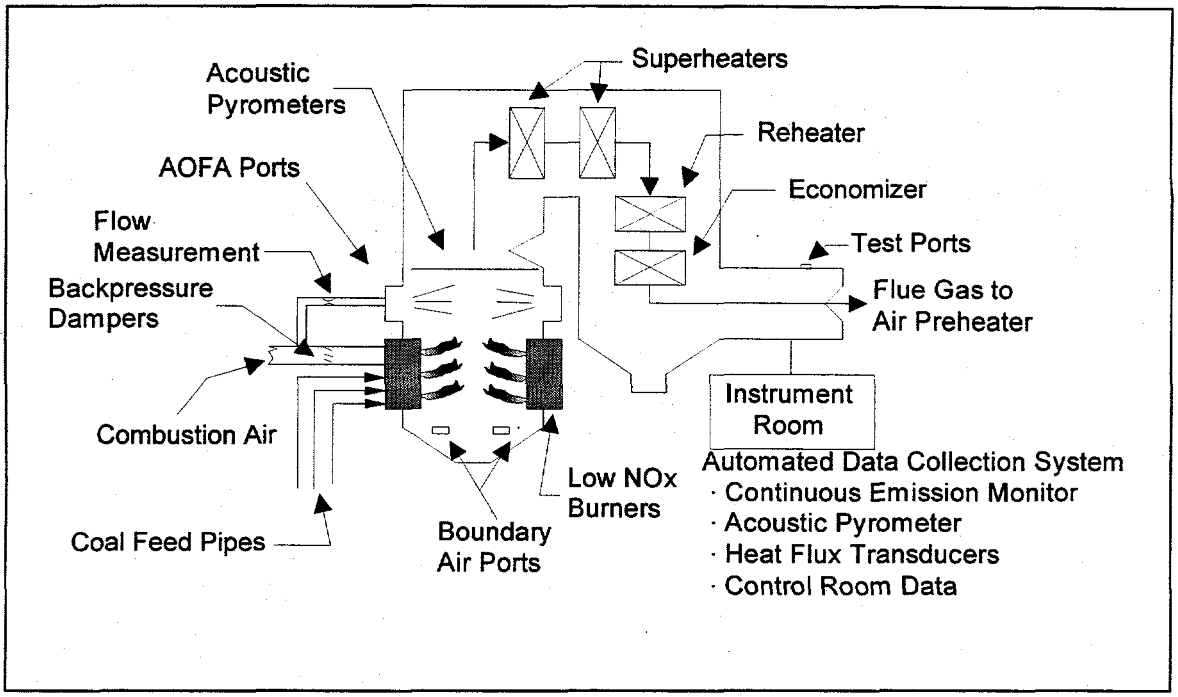

Figure 1: Plant Hammond Unit 4 Boiler

The data acquisition system (DAS) for the Hammond Unit 4 ICCT project is a custom designed microcomputer based system used to collect, format, calculate, store, and transmit data derived from power plant mechanical, thermal, and fluid processes. The extensive process data selected for input to the DAS has in common a relationship with either boiler performance or boiler exhaust gas properties. This system includes a continuous emissions monitoring system (NOx, SO_2, O_2, THC, CO) with a multi-point flue gas sampling and conditioning system, an acoustic pyrometry and thermal mapping system, furnace tube heat flux transducers, and boiler efficiency instrumentation. The instrumentation system is designed to provide data collection flexibility to meet the schedule and needs of the various testing efforts throughout the demonstration program. A summary of the type of data collected is shown in Table 2.

Following each outage, a series of four groups of tests are planned. These are: (1) diagnostic, (2) performance, (3) long-term, and (4) verification. The diagnostic, performance, and verification tests consist of short-term data collection during carefully established operating conditions. The diagnostic tests are designed to map the effects of changes in boiler operation on NOx emissions. The performance tests evaluate a more comprehensive set of boiler and combustion performance indicators. The results from these tests will include particulate characteristics, boiler efficiency, and boiler outlet emissions. Mill performance and air flow distribution are also tested. The verification tests are performed following the end of the long-term testing period and serve to identify any potential changes in plant operating conditions.

Table 2: Inputs to Data Acquisition System	
Boiler Drum Pressure	Superheat Outlet Pressure
Cold Reheat Pressure	Hot Reheat Pressure
Barometric Pressure	Superheat Spray Flow
Reheat Spray Flow	Main Steam Flow
Feedwater Flow	Coal Flows
Secondary Air Flows	Primary Air Flows
Main Steam Temperature	Cold Reheat Temperature
Hot Reheat Temperature	Feedwater Temperature
Desuperheater Outlet Temp.	Desuperheater Inlet Temp.
Economizer Outlet Temp.	Air Heater Air Inlet Temp.
Air Heater Air Outlet Temp.	Ambient Temperature
BFP Discharge Temperature	Relative Humidity
Stack NOx	Stack SO2
Stack O2	Stack Opacity
Generation	Overfire Air Flows

As stated previously, the primary objective of the demonstration is to collect long-term, statistically significant quantities of data under normal operating conditions with and without the various NOx reduction technologies. Earlier demonstrations of emissions control technologies have relied solely on data from a matrix of carefully established short-term (one to four hour) tests. However, boilers are not typically operated in this manner, considering plant equipment inconsistencies and economic dispatch strategies. Therefore, statistical analysis methods for long-term data are available that can be used to determine the achievable emissions limit or projected emission tonnage of an emissions control technology. These analysis methods have been developed over the past fifteen years by the Control Technology Committee of the Utility Air Regulatory Group (UARG). Because the uncertainty in the analysis methods is reduced with increasing data set size, UARG recommends that acceptable 30 day rolling averages can be achieved with data sets of at least 51 days with each day containing at least 18 valid hourly averages.

2.2. Unit 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 (two each during the spring 1991, spring 1992, and fall 1993 outages). 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, to be described later. 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. The unit, equipped with a Bailey pneumatic boiler control system during the baseline, AOFA, LNB, and LNB+AOFA phases of the project, is being retrofit with a Foxboro I/A distributed digital control system.

2.3. Advanced Overfire Air (AOFA) System

Generally, combustion NOx reduction techniques attempt to stage the introduction of oxygen into the furnace. This staging reduces NOx production by creating a delay in fuel and air mixing that lowers combustion temperatures. The staging also reduces the quantity of oxygen available to the fuel-bound nitrogen. Typical overfire air (OFA) systems accomplish this staging by diverting 10 to 20 percent of the total combustion air to ports located above the primary combustion zone. AOFA improves this concept by introducing the OFA through separate ductwork with more control and accurate measurement of the AOFA airflow, thereby providing the capability of improved mixing (Figure 2).

Foster Wheeler Energy Corporation (FWEC) was competitively selected to design, fabricate, and install the advanced overfire air system and the opposed-wall, low NOx burners described below. The FWEC design diverts air from the secondary air ductwork and incorporates four flow control dampers at the corners of the overfire air windbox and four overfire air ports on both the front and rear furnace walls. Due to budgetary and physical constraints, FWEC designed an AOFA system more suitable to the project and unit than that originally proposed. Six air ports per wall were proposed instead of the as-installed configuration of four per wall.

2.4. Low NOx Burners

Low NOx burner systems attempt to stage the combustion without the need for the additional ductwork and furnace ports required by OFA and AOFA systems. These commercially-available burner systems introduce the air and coal into the furnace in a well controlled, reduced turbulence manner. To achieve this, the burner must regulate the initial fuel/air mixture, velocities and turbulence to create a fuel-rich core, with sufficient air to sustain combustion at a severely sub-stoichiometric air/fuel ratio. The burner must then control the rate at which additional air, necessary to complete combustion, is mixed with the flame solids and gases to maintain a deficiency of oxygen until the remaining combustibles fall below the peak NOx producing temperature (around 2800°F). The final excess air can then be allowed to mix with the unburned products so that the combustion is completed at lower temperatures. Burners have been developed for single wall and opposed wall boilers.

In the FWEC Controlled Flow/Split Flame (CFSF) burner (Figure 3), secondary combustion air is divided between inner and outer flow cylinders. A sliding sleeve damper regulates the total secondary air flow entering the burner and is used to balance the burner air flow distribution. An adjustable outer register assembly divides the burners secondary air into two concentric paths and also imparts some swirl to the air streams. The secondary air which traverses the inner path, flows across an adjustable inner register assembly that, by providing a variable pressure drop, apportions the flow between the inner and outer flow paths. The inner register also controls the degree of additional swirl imparted to the coal/air mixture in the near throat region. The outer air flow enters the furnace axially, providing the remaining air necessary to complete combustion. An axially movable inner sleeve tip provides a means for varying the primary air velocity while maintaining a constant primary flow. The split flame nozzle segregates the coal/air mixture into four concentrated streams, each of which forms an individual flame when entering the furnace. This segregation minimizes mixing between the coal and the primary air, assisting in the staged combustion process. The adjustments to the sleeve dampers, inner registers, outer registers, and tip position are made during the burner optimization process and thereafter remain fixed unless changes in plant operation or equipment condition dictate further adjustments.

2.5. Application of Advanced Digital Control Methodologies

The objective of Phase 4 of the project is to implement and evaluate an advanced digital control/optimization system for use with the combustion NOx abatement technologies installed on Plant Hammond Unit 4. The advanced system will be customized to minimize NOx production while simultaneously maintaining and/or improving boiler performance and safety margins. This project will provide documented effectiveness of an advanced digital control /optimization strategy on NOx emissions and guidelines for retrofitting boiler combustion controls for NOx emission reduction. It is anticipated that a commercial or near-commercial control/optimization package will be utilized in this demonstration. Modifications and extensions will be made to the software package as necessary to make it more appropriate for this application.

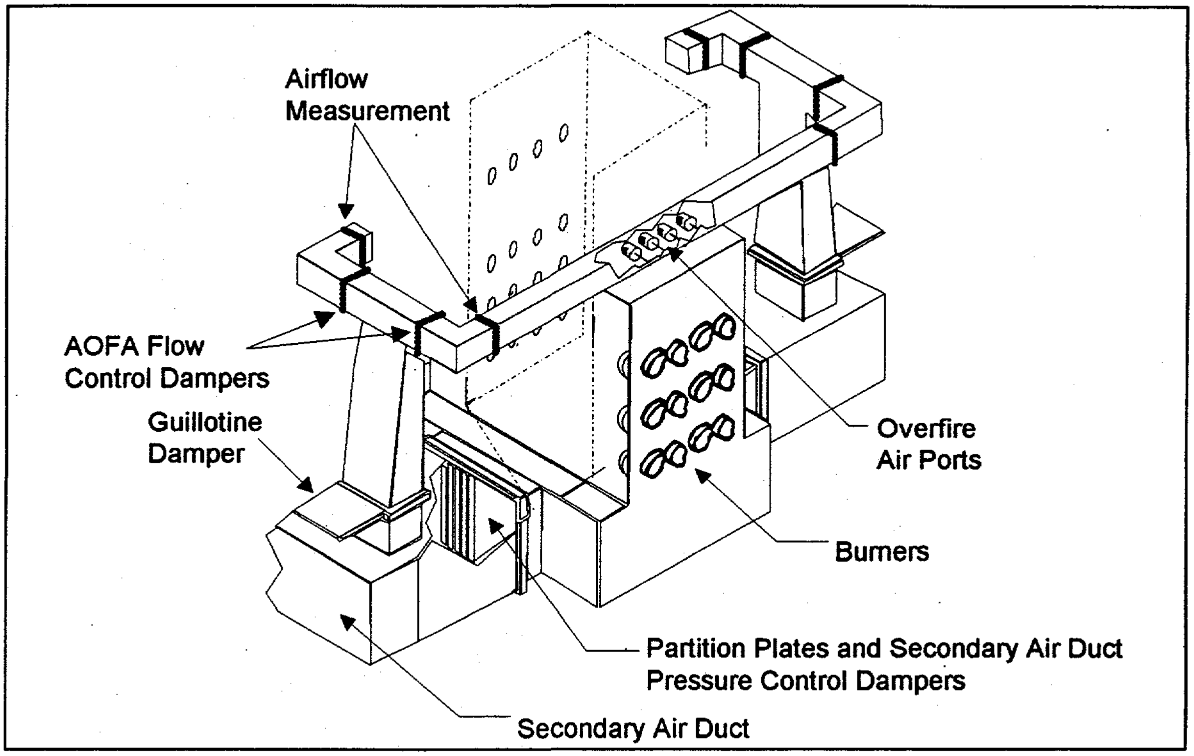

Figure 2: Advanced Overfire Air System

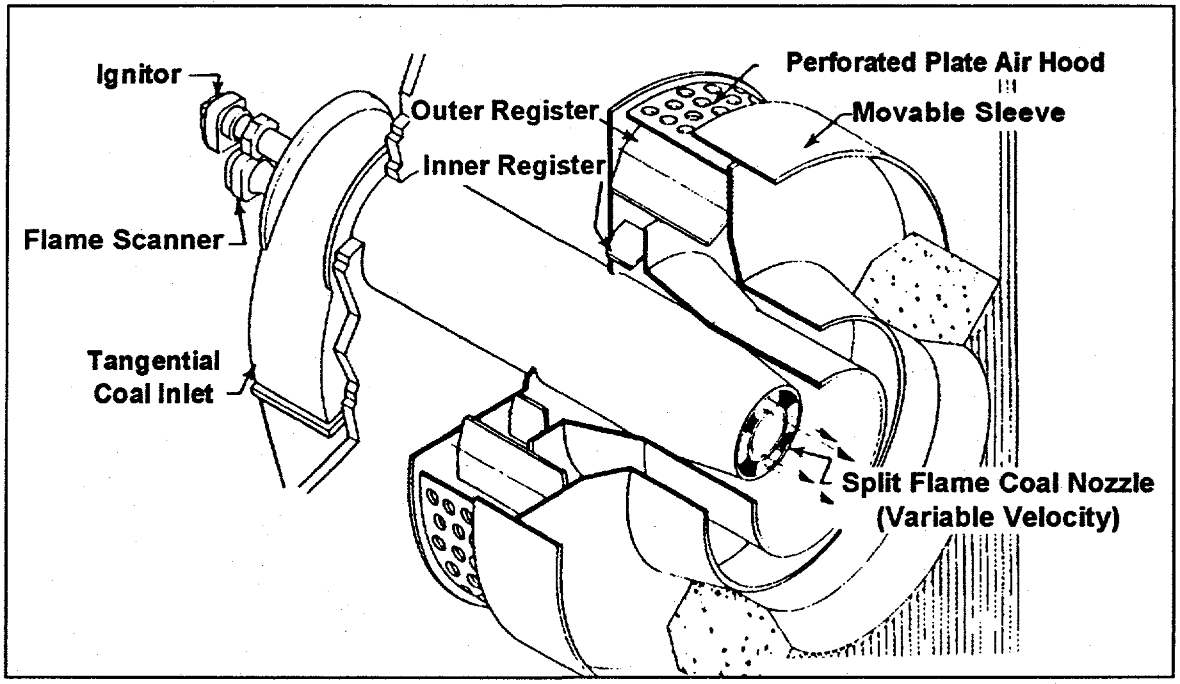

Figure 3: Low NOx Burner Installed at Plant Hammond

3. PROJECT STATUS

3.1. Project Summary

Baseline, AOFA, LNB, and LNB+AOFA test phases have been completed. Details of the testing conducted each phase can be found in the following reports:

- Phase 1 Baseline Tests Report [1],
- Phase 2 AOFA Tests Report [2],
- Phase 3A Low NOx Burner Tests Report [3], and
- Phase 3B Low NOx Burner plus AOFA Tests Report [4].

Chemical emissions testing was also conducted as part of the project and the results have been previously reported [5]. Phase 4 of the project -- evaluation of advanced low NOx digital controls / optimization strategies as applied to NOx abatement -- is now in progress. A summary of the milestones for Phase 4 are shown in Table 3.

3.2. Current Quarter Activities

Following a nine month outage, coal-fired operation resumed at Hammond Unit 4 on June 5. Installation of the digital control system (DCS) installed during this outage and as part of this project has been completed and the system is operational. All control loops have now been tuned and are in automatic. Drawings for the DCS installation are now being finalized and instruction manuals are being prepared.

Preliminary diagnostic testing was conducted during August 1994. The purpose of these initial tests was to determine the emissions and performance characteristics of the unit prior to activation of the advanced control/optimization strategies. Based on short- and long-term testing to date, full load NOx emissions are approximately 0.45 to 0.50 lb/MBtu, slightly higher than that seen during the LNB+AOFA test phase. The cause of this increase is still being investigated.

Design of the advanced controls/optimization portion of the project is continuing. Following extensive evaluation, a final selection on the core optimization technology has been made. Modeling efforts with data collected from Hammond 4 during the LNB+AOFA test phase is in progress. The version of the commercial software necessary for a successful demonstration will not be available until December 1994, however, an "Alpha" version of the software is now being tested at SCS and a "Beta" release of this software will be made available to the project during October.

Two on-line carbon-in-ash monitors are being installed at Hammond Unit 4 as part of the Wall-Fired Project. These monitors will be used in the closed loop control strategies being developed. Purchase orders for the two monitors have been issued and they are scheduled for installation fall 1994 and winter 1995.

Due to turbine problems, a four week outage has been planned for Hammond 4 starting October 1. Although testing has been rescheduled to accommodate this outage, overall project scheduled should not be impacted.

3.3. Phase 4A Testing

3.3.1. Diagnostic Testing

Preliminary diagnostic testing was conducted from August 5, 1994 to August 8, 1994. In total, seventeen tests were conducted at three nominal load conditions (300 MW, 400 MW, and 480 MW). A summary of these tests can be found in Appendix A.

<u>NOx Emissions</u>

The primary purpose of these preliminary tests was to determine the short-term NOx emissions characteristics particularly as a function of excess O_2. As shown in Figure 4, excess O_2 levels were exercised well above and below the design excess O_2 levels yielding variations in NOx emissions (Figure 5) from 0.40 to 0.57 lb/MBtu at full load (480 MW) and 0.36 to 0.46 lb/MBtu at the low intermediate load (300 MW). Based on these O_2 variations, the NOx vs. O_2 gradient was determined for each of the three loads tested. As can be seen in Figure 6, at 480 MW, NOx emissions were highly dependent on excess O_2 and, apparently, to a great extent, a linear function of excess O_2 over the range tested ($R^2 \cong 0.98$). Similar results were found at 400 MW and 300 MW load levels (Figures 7 and 8). A comparison of the sensitivities at the three loads tested are shown in Table 4 and Figure 9. NOx emissions sensitivity to excess O_2 decreased with decreasing load (Figure 10). For comparison, the sensitivities determined from prior phases of the project are also shown in Table 4. As can be seen, sensitivities varied greatly from phase-to-phase for a given load. The explanation for the variation is unknown at this time, however, a contributing factor is likely the relative (as compared to Phase 4A) non-repeatability of the short-term tests during prior phases (Phases 1, 2, 3A, and 3B) and the resultant influence of this non-repeatability on sensitivity determination. For the testing conducted during August 1994, NOx emission characteristics were much repeatable than what had been observed in prior phases. A thorough discussion of the difficulties in repeating experiments has been previously reported [1, 2, 3, 4].

As can be seen in Figure 11, short-term, full load NOx emission levels were near 0.49 lb/MBtu at design excess O_2 levels. This NOx emission level is above that experienced during the prior LNB plus AOFA test phase (Phase 3B) for which full load, normal excess O_2 emission levels were approximately 0.40 lb/MBtu. This increase in NOx emissions was also evident at the lower test loads (400 MW and 300 MW). A thorough examination of the causes for the increase in NOx emissions has not yet been conducted; however, the reduction could be the result of several factors including:

- AOFA Flow Rates - Indicated AOFA flow rates were below that used in the previous phase. Design AOFA flow rate is 800 klbm/hr at full load whereas during the August 1994 tests, AOFA rates were approximately 640 klbm/hr.
- Mill Biasing - The inadvertent mill bias existing during Phase 3B which led to reduced NOx emissions may no longer exist.
- Coal Properties - The coal could have been less NOx friendly during the August 1994 testing.

- Selection of short-term test conditions which were not representative of long-term operation (see section 3.3.2 below).

More insight into this difference will be forthcoming following completion of the performance tests scheduled forth quarter 1994.

CO Emissions

As experienced during prior phases, CO emissions were relatively low -- generally below 50 ppm -- at recommended excess O_2 levels. At full load, as excess O_2 levels were reduced, CO emission levels rose producing the familiar "knee" in emissions (Figure 12). A similar CO vs. excess O_2 characteristic was evident in the 400 MW tests (Figure 13). At the 300 MW load, excess O_2 was not reduced sufficiently to generate increased CO emissions.

NOx vs. CO Tradeoff

An example of the tradeoffs which may be of consideration in this phase of the project is the NOx vs. CO tradeoff. As previously described, NOx emissions generally increase with increased excess O_2 whereas CO emissions generally decrease thereby producing a conflict of goals; i.e. to reduce both NOx and CO emissions to a minimum. As can be seen in Figure 14, using excess O_2 alone, NOx emissions could be reduced to below 0.45 lb/MBtu while maintaining CO emissions below 50 ppm. Of course other important parameters impacted by excess O_2 levels, such as fly ash carbon-in-ash, should be considered prior to making recommendations concerning the normal operating excess O_2 level. The impact of on fly ash carbon-in-ash and other parameters are be investigated using results obtained from planned diagnostic, performance, and long-term tests.

3.3.2. Long-Term Generation and Emissions

A summary of long-term unit generation, NOx emissions, and CO emissions are shown in Table 5 and Figures 15 through 23. From July 12 through September 30, the unit was above 100 MW for approximately 1400 hours out of 1944 hours total and averaged 316 MW for the entire period. As can be seen in these figures, the unit operated frequently in the lower load range (100 - 250 MW) during this period with 45 percent of the time in this load range. NOx emissions averaged 0.41 lb/MBtu for the quarter, similar to Phase 3B emission levels. July NOx emissions were considerably higher than the quarter average, in part due to higher O_2 levels. Also, during much of July, the AOFA control loop was not in automatic.

A comparison of the NOx emission distributions at full (450 - 500 MW) and low load (200 - 250 MW) for the entire quarter are shown in Figure 24. As can be seen, NOx emissions for the low load set exhibited a much smaller variance about the mean than the higher load grouping. This distribution difference is again in large part the result of the unit using overfire air more extensively during the latter part of the quarter. The change in the full load distribution with time is shown in Figure 25. A similar change in the low load distribution was not observed (Figure 26).

Time series NOx, SOx, and CO emissions data along with unit generation for Hammond Unit 4 for this quarter are provided in Appendix B.

3.4. On-Line Carbon-in-Ash Monitors

SCS is pursuing the procurement and installation of two carbon-in-ash monitors at Hammond 4. An evaluation of these systems will be made as to their:

- Reliability and maintenance.
- Accuracy and repeatability, and
- Suitability for use in the control strategies being demonstrated at Hammond Unit 4,

Based on bids from three vendors, SCS selected the Clyde-Sturdevant SEKAM and CAMRAC CAM for demonstration. The SEKAM unit (System A) will sample from two locations at the economizer outlet while the CAM unit (System B) will sample from a single location at the precipitator inlet (Figure 27).

A brief description of the SEKAM and CAM units is provided in the following paragraphs.

Clyde-Sturdevant SEKAM

Based on an interest to reduce fly ash carbon content, the U.K. Central Electric Generating Board (CEGB) began development of two on-line carbon-in-ash measurement techniques during the early 1980s. One system sampled a small quantity of ash which was then combusted with the resulting CO_2 indicating the original carbon content. The second system that was developed by the CEGB required a relatively large sample of ash and inferred carbon content by the sample's capacitance as measured using a Kajaani cell. Following privatization of the CEGB during 1989, the intellectual property associated with these two instruments were passed on to private entities with Bristol Babcock obtaining rights to the system using combustion principles. Rights to the capacitance based system were transferred to Sturdevant Engineering, hence the name SEKAM (Sturdevant Engineering Kajaani Ash Monitor). Sturdevant Engineering was subsequently acquired by Clyde Blowers, plc. The first commercial applications of the SEKAM design were at National Power's Didcot Power Station in 1990.

A sketch of the SEKAM system is shown in Figure 28 and vendor supplied specifications are provided in Table 6. Ash and flue gases are drawn from the duct using an exhauster. A cyclone separates the entrained fly ash from the flue gas after which the fly ash passes through the first of three batch valves (Valve 1) to be held by Valve 2. After five minutes, Valve 1 closes and Valve 2 opens to permit passage of the ash into the measurement chamber. Valve 3 is closed during this interval. The above stage is repeated until the level sensor in the measurement cell indicates the cell is full and at this time a measurement is made. Valve 3 is then opened momentarily to allow some of the ash to flow from the measurement cell into the outlet flow of the exhauster and transported back into the duct. If desired, the collected sample can be retrieved from the cell for further analysis and compared to the output of the SEKAM.

As mentioned previously, the basis of the SEKAM device is the measurement of capacitance of the fly ash sample using a Kajaani cell which was developed by the Finish firm Kajaani Limited. Ash collected from the flue gas stream (or other locations) is deposited in a glass chamber of rectangular cross section measuring 150x70x20 mm (5.91x2.76x0.79 inches) placed between two capacitance sensors. The cell, flyash, and sensors are integrated into a circuit such that the output voltage of the circuit is a function of the measured capacitance. Since capacitance of the ash is a function of it's constituents, with pure fly ash being non-conducting and carbon being conducting, the percentage of carbon in the fly ash can be inferred from the voltage output of the circuit.

The installation at Hammond Unit 4 will sample from either the "A" or "B" side economizer outlet gas stream or from both probes simultaneously. It is expected that, except for short-term testing, the SEKAM will be configured to extract flue gas from both the "A" and "B" sides simultaneously thus shortening the sampling cycle time and improving the likelihood of obtaining a representative fly ash sample.

Since the SEKAM device requires a relatively large fly ash sample (approximately 150 $cm^3 \sim 375$ g), in order to reduce the overall sampling time, the system samples super-isokinetically. An exhauster is used to supply the motive force to transport the flue gas and fly ash. Super-isokinetic sampling can have either a positive or negative impact on overall sampling accuracy.

Since one purpose of the SEKAM monitor at Hammond Unit 4 is its use in closed-loop control, an important facet of its operation is the response time. As shown in Figure 29, the response time of the unit is on the order of twenty minutes. As to be expected, the response time is primarily dependent on the time required to collect the requisite sample and any averaging performed by the unit, numerical or physical. The time required to collect the sample is proportional to the economizer outlet ash loading.

CAMRAC CAM

CAMRAC Company's (Pittsburgh, PA) CAM (Carbon-Ash-Monitor) unit was developed during the 1980s by GAI Consultants (an affiliate of CAMRAC Company) with financial support from Allegheny Power Services Corporation, Duquesne Light Company, New England Power Services, NYSEG, Southern Company Services, Virginia Power, and EPRI. The CAM system uses the relative microwave absorbance between carbon and carbon-free fly ash to infer the carbon content of the sample.

A schematic of a CAM system is shown in Figure 30 and vendor supplied specifications are provided in Table 7. Ash and flue gas are drawn from the flue gas stream isokinetically and a cyclone separates the flue gas from the fly ash. On command from the computer, the snubber valve opens depositing the collected fly ash in the interrogation cell which is enclosed in a microwave waveguide. An analysis cycle is then initiated where the forward, reflected, and transmitted microwave power levels and weight of the sample are determined. At this point, the snubber valve again opens, permitting more ash to enter the interrogation cell and the microwave levels and ash weight are again determined. This load-measure cycle continues until the measured microwave properties show little change. Based on the above measurements, a proprietary algorithm is used to determine the carbon content of the collected fly ash sample. At the completion of an analysis cycle, plant air is used to purge the interrogation cell of the fly ash with the ash being conveyed back into the flue gas stream. The ash sample can also be dumped and saved for further analysis. The volume of sample used in the analysis is near 8 cm^3 or approximately 20 grams. The inferred carbon levels are transmitted back to the digital control system for use in operator displays, reporting, and potential control strategies. Remote diagnostics and maintenance is available via a modem and phone line.

As mentioned earlier, the CAM system uses the difference in microwave absorbance properties of carbon and carbon-free fly ash to determine the unburned carbon levels. A microwave frequency of 2,450 MHz -- the same frequency used in off-the-shelf microwave ovens -- with a power level of approximately 100~150 milliwatts is used for excitation. The selection of this frequency is the result of two considerations. First, since the frequency and power levels are commensurate with that used in microwave ovens, no special FCC permitting is required. As in microwave ovens, shielding is provided around the device to reduce the already low microwave power to levels well below safety requirements outside the device. The second consideration is that at this frequency, carbon is highly susceptible to microwave energy whereas carbon-free fly ash has low susceptibility. An indicator of the difference of response to microwave energy is that the dielectric loss coefficient for carbon is 200 times greater than the typical carbon-free fly ash. According to CAMRAC, typical fly ash constituents (other than carbon) will have little impact on the results of the analysis and a single calibration will suffice for all Eastern bituminous coals.

The installation at Hammond Unit 4 will sample from one of twenty sample ports located at the inlet to the precipitator. The system is being designed such that vertical traverses of the flue gas stream can be conducted. During long-term testing, fly ash samples will be drawn from a single location. For short-term testing, several sample ports and depths will be used so that a spatial distribution of the unburned carbon can be obtained.

Consideration is being given to the use of the CAM monitor installed Hammond Unit 4 for feedback to the digital control system for closed-loop control of unburned carbon and, therefore, an important facet of its operation is the response time. As shown in Figure 31, the typical response time of the unit is on the order of five minutes. As to be expected, the response time is primarily dependent on the time required to collect the requisite sample and any averaging performed by the unit, whether numerical or physical. The time required to collect the sample is proportional to the economizer outlet ash loading.

3.5. Advanced Low NOx Digital Controls System

The objective of this scope addition to the project at Plant Hammond is to evaluate and demonstrate the effectiveness of advance digital control/optimization methodologies as applied to the NOx abatement technologies installed at this site (LNB and AOFA). This scope addition will provide documented effectiveness of these control/optimization methods on NOx emissions and boiler efficiency improvements and guidelines for retrofitting boiler combustion controls for NOx emission reduction. The major tasks for this project addition included: (1) design and installation of a distributed digital control system, (2) instrumentation upgrades, (3) advanced controls/optimization design and implementation, and (4) characterization of the unit both before and after activation of the advanced strategies. Major milestones for this phase are shown in Table 3.

3.5.1. Digital Control System

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

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

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

3.5.2. Advanced Controls and Optimization

The software and methodology to be demonstrated at Hammond Unit 4 is the Generic NOx Control Intelligent System (GNOCIS) whose development is being funded by a consortium consisting of the Electric Power Research Institute, PowerGen (a U.K. power producer), The Southern Company, U.K. Department of Trade and Industry, and U.S. Department of Energy [6]. The objective of the GNOCIS project is to develop an on-line enhancement to existing digital control systems that will result in reduced NOx emissions, while meeting other operational constraints on the unit (principally heat rate and other regulated emissions). The core of the system will be a model of the NOx generation characteristics of a boiler, that will reflect both short-term and longer-term shifts in boiler emission characteristics. The software will apply an optimizing procedure to identify the best set points for the plant. The recommended set points will be used for closed-loop control of the process or, at the plants discretion, the set points will be conveyed to the plant operators via the DCS. The software will incorporate sensor validation techniques and be able to operate during plant transients (i.e. load ramping, fuel disturbances, and others).

The GNOCIS software and methodology is currently under development and is scheduled to be implemented at PowerGen's Kingsnorth Unit 1 (a 500 MW tangentially-fired unit with an ICL Level 3 Low NOx Concentric Firing System) and Alabama Power's Gaston Unit 4 (a 250 MW B&W unit with B&W XCL low NOx burners) prior to comprehensive testing at Hammond. Following "re-characterization" of Hammond 4, the advanced

* Not in Wall-Fired Project scope of work.

controls and optimization strategies will be activated and run open-loop. If the results from the open-loop testing warrant, the advanced controls/optimization package will be operated closed-loop with testing (short- and long-term) starting in first quarter 1995.

During third quarter 1994, discussions continued with the core technology supplier in an effort to enhance their product to meet the requirements of the GNOCIS project. These requirements were identified during the initial evaluation process and include combinatorial constraints and on-line retraining. The developer is actively pursuing the inclusion of these enhancements in a new major release of their product currently scheduled for commercial deployment during December 1994. PowerGen and SCS are both in receipt of the previous release of the software and an Alpha version of the new software was made available to both parties during August 1994. The Alpha release is undergoing testing at SCS, PowerGen, and elsewhere.

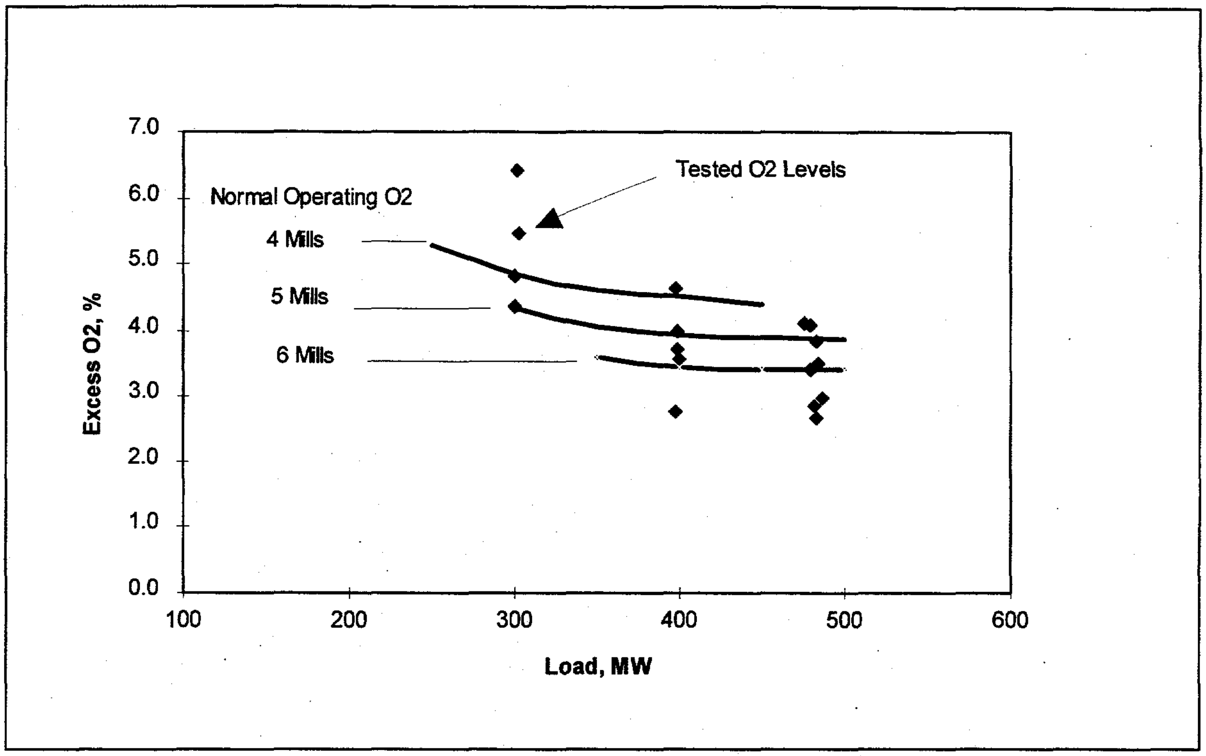

Figure 4: Excess O_2 Levels Tested

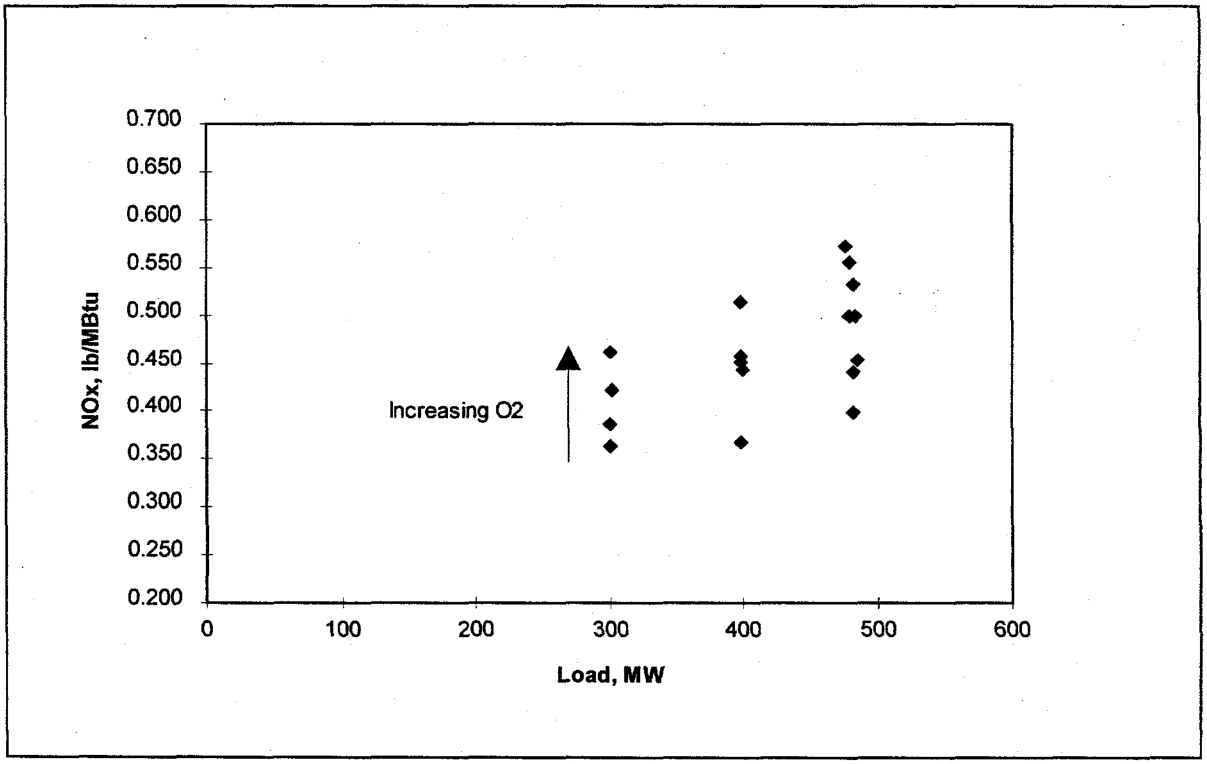

Figure 5: NOx vs. Load

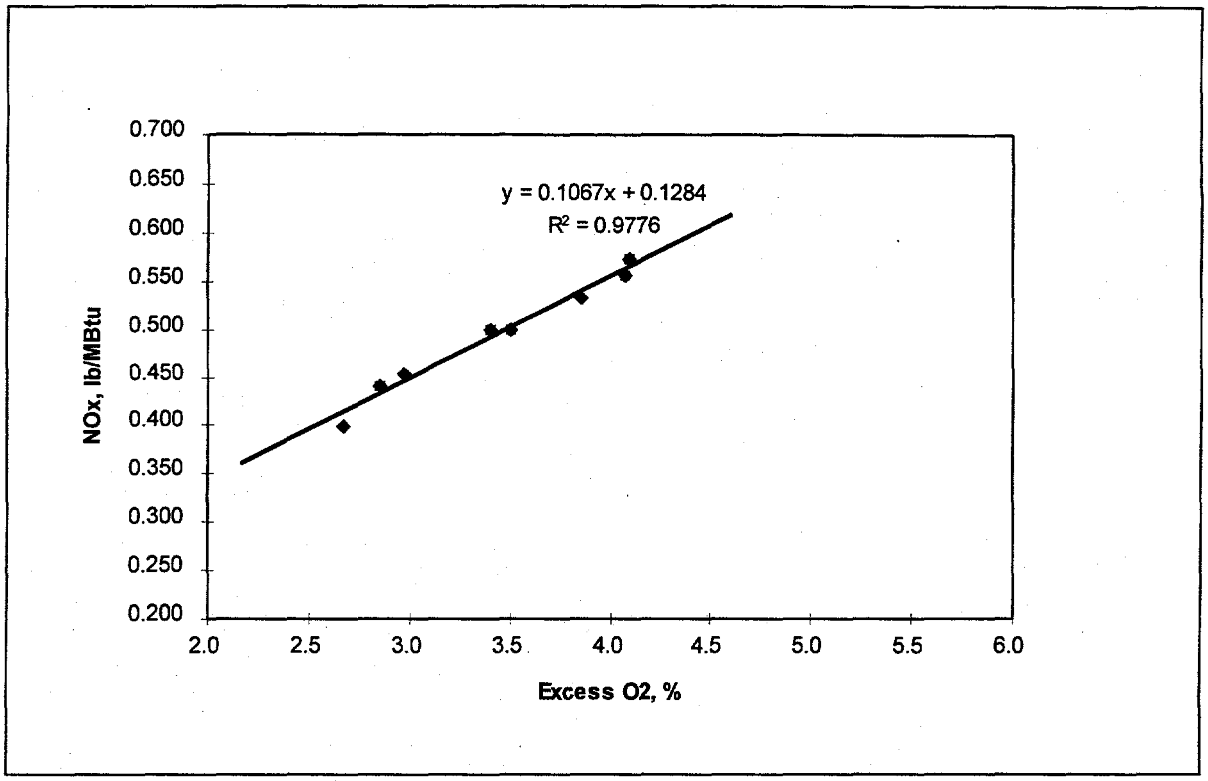

Figure 6: NOx vs. Excess O_2 - 480 MW

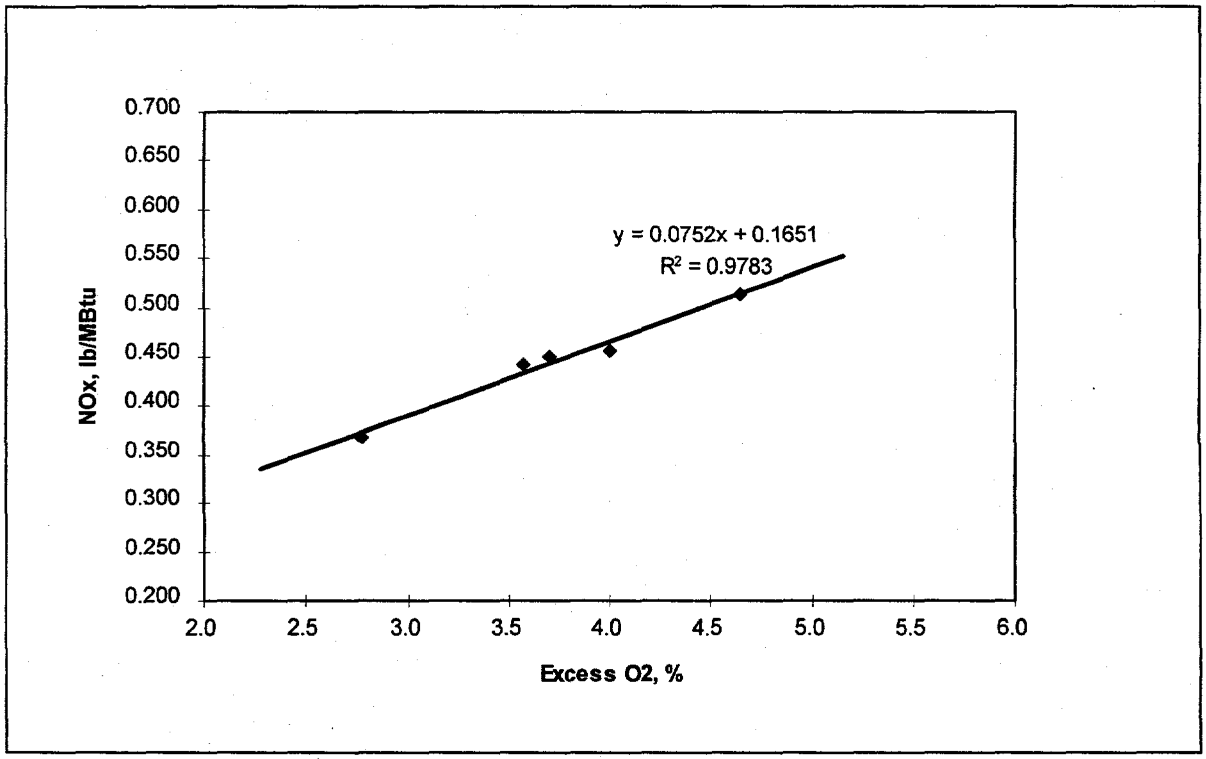

Figure 7: NOx vs. Excess O_2 - 400 MW

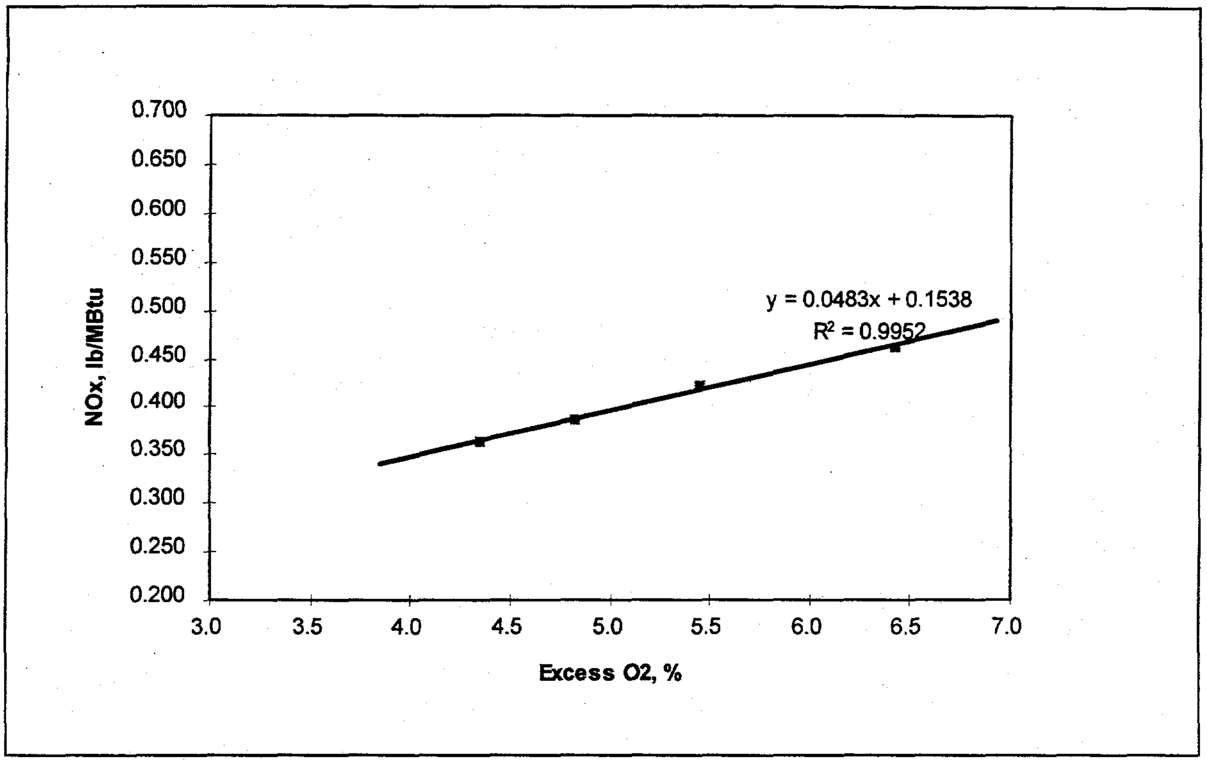

Figure 8: NOx vs. Excess O_2 - 300 MW

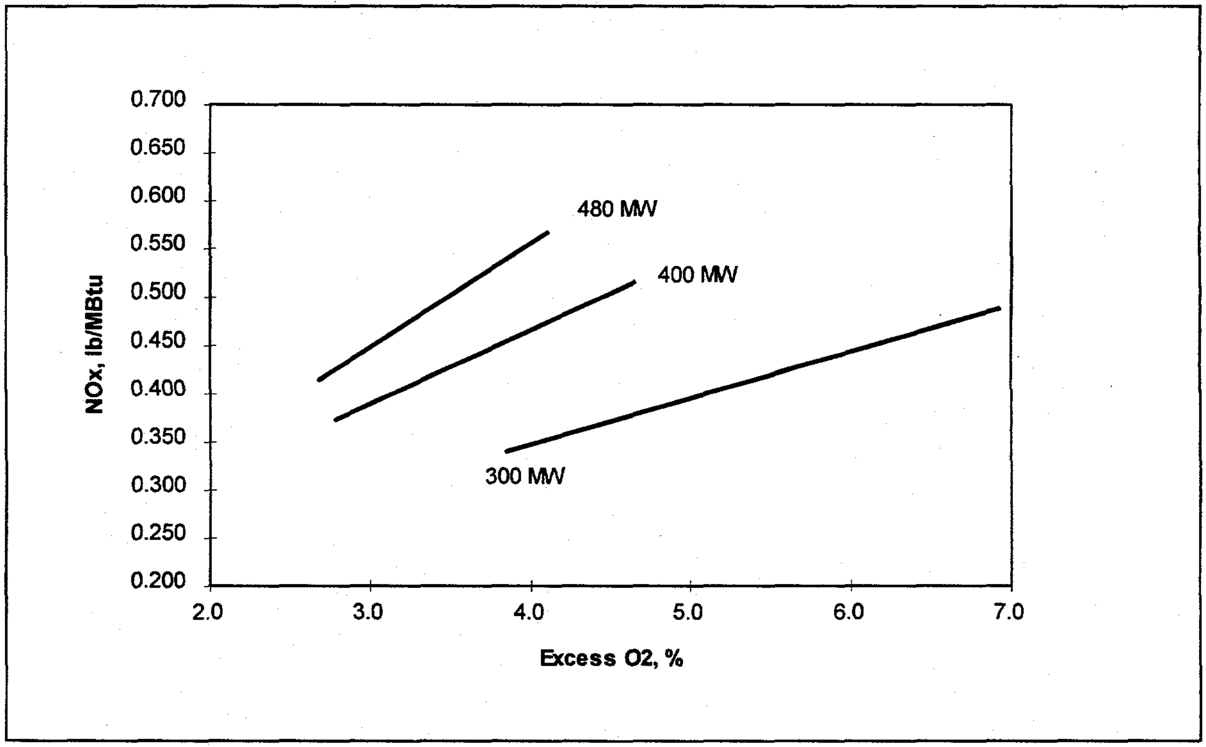

Figure 9: NOx vs. Excess O_2 - All Loads

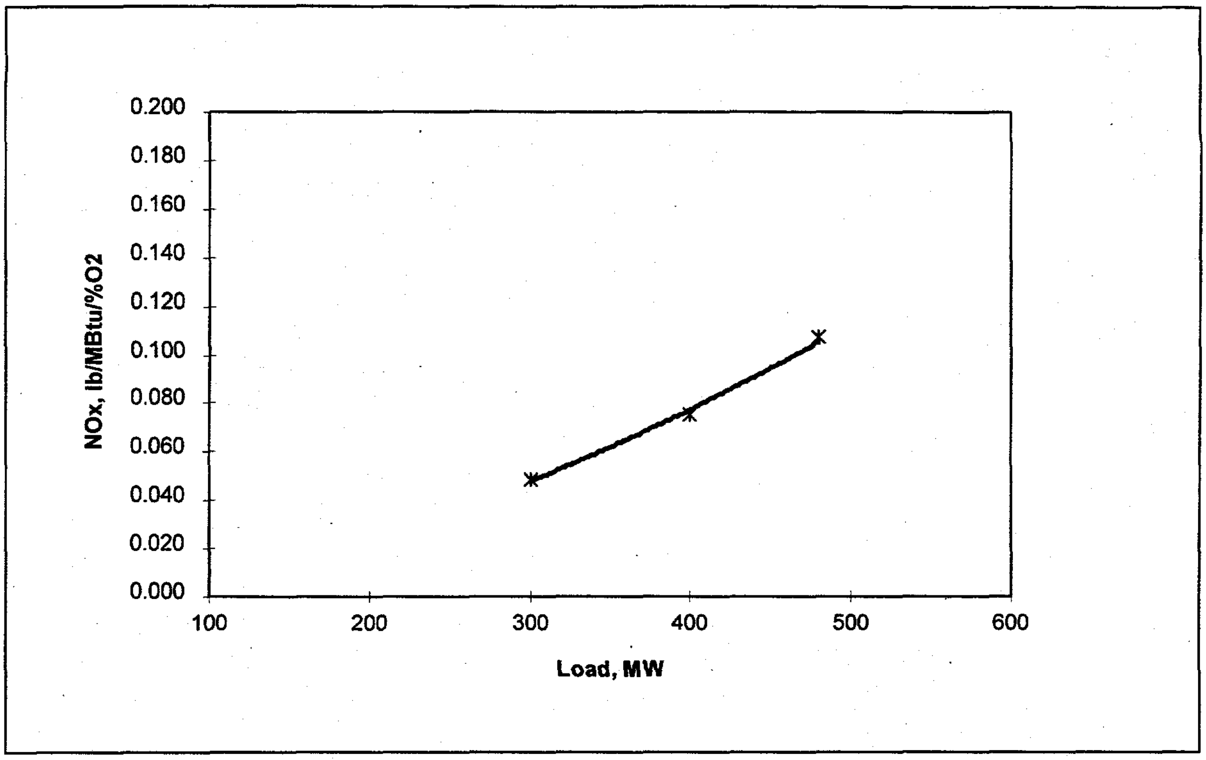

Figure 10: NOx vs. Excess O_2 Sensitivity

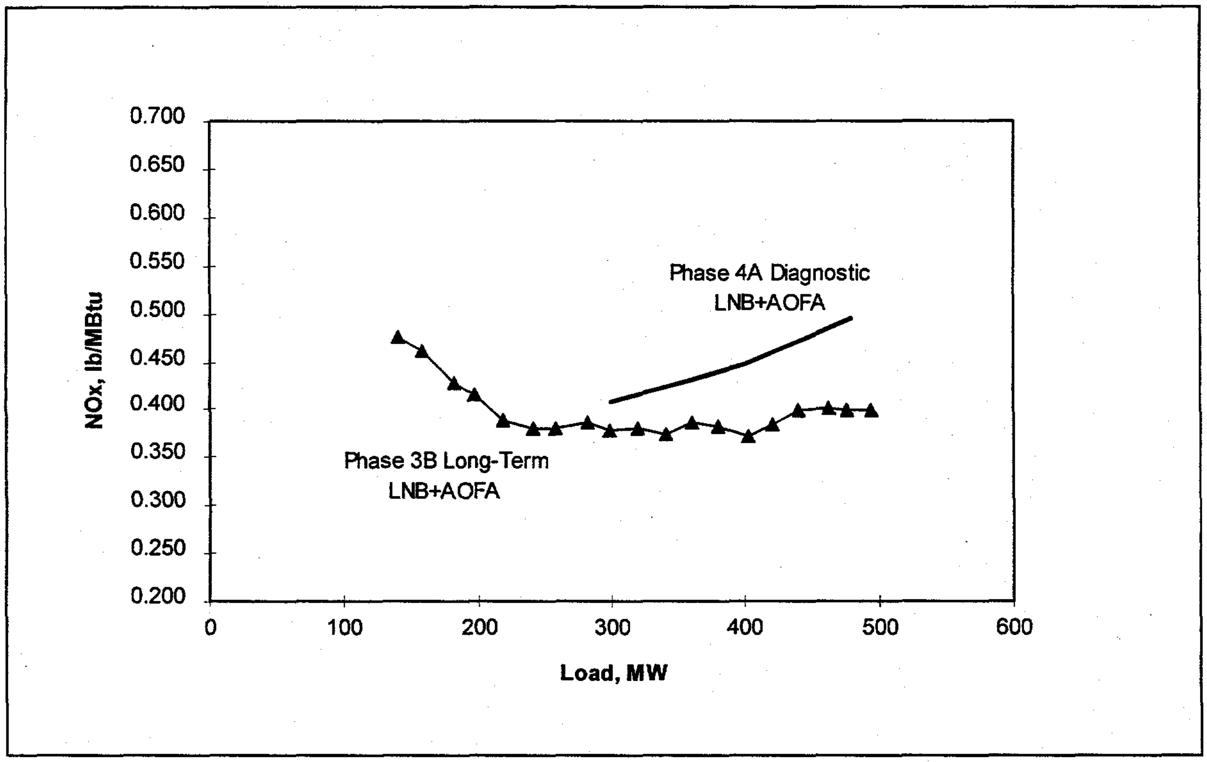

Figure 11: Comparison of Phase 3B and Phase 4A NOx Emissions

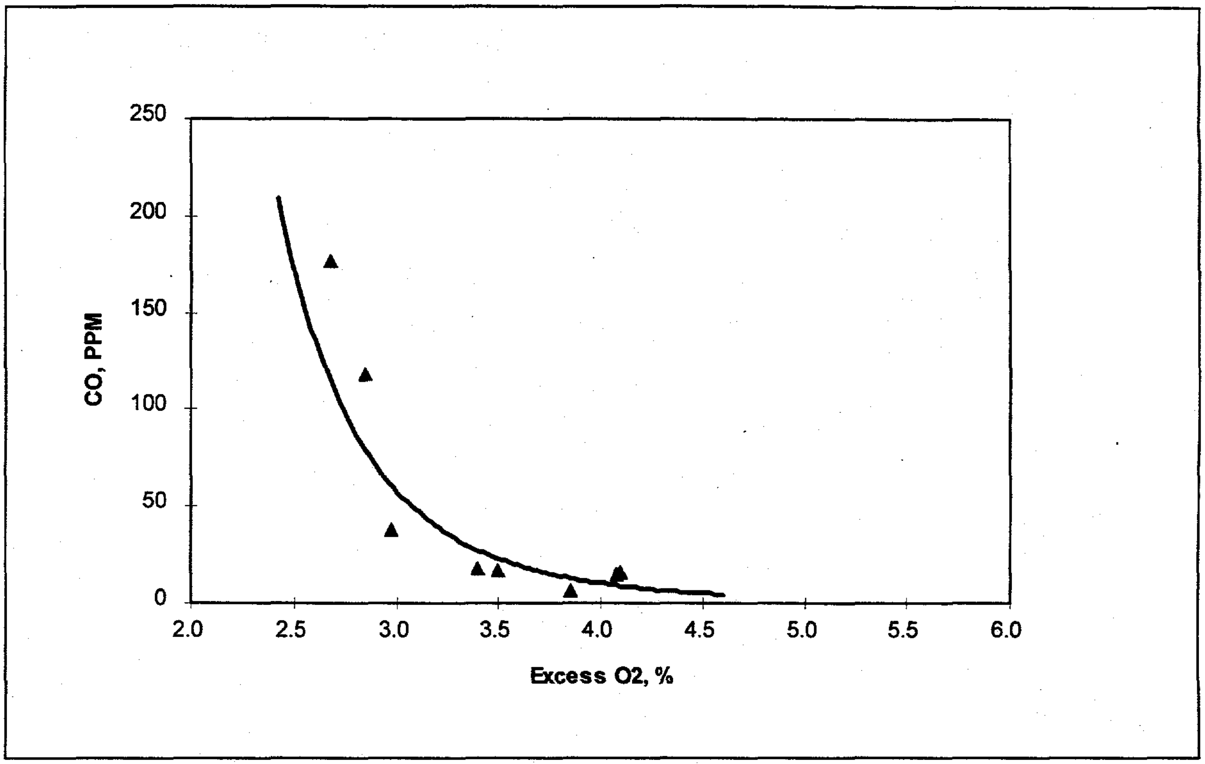

Figure 12: CO Emissions vs. Excess O_2 - 480 MW

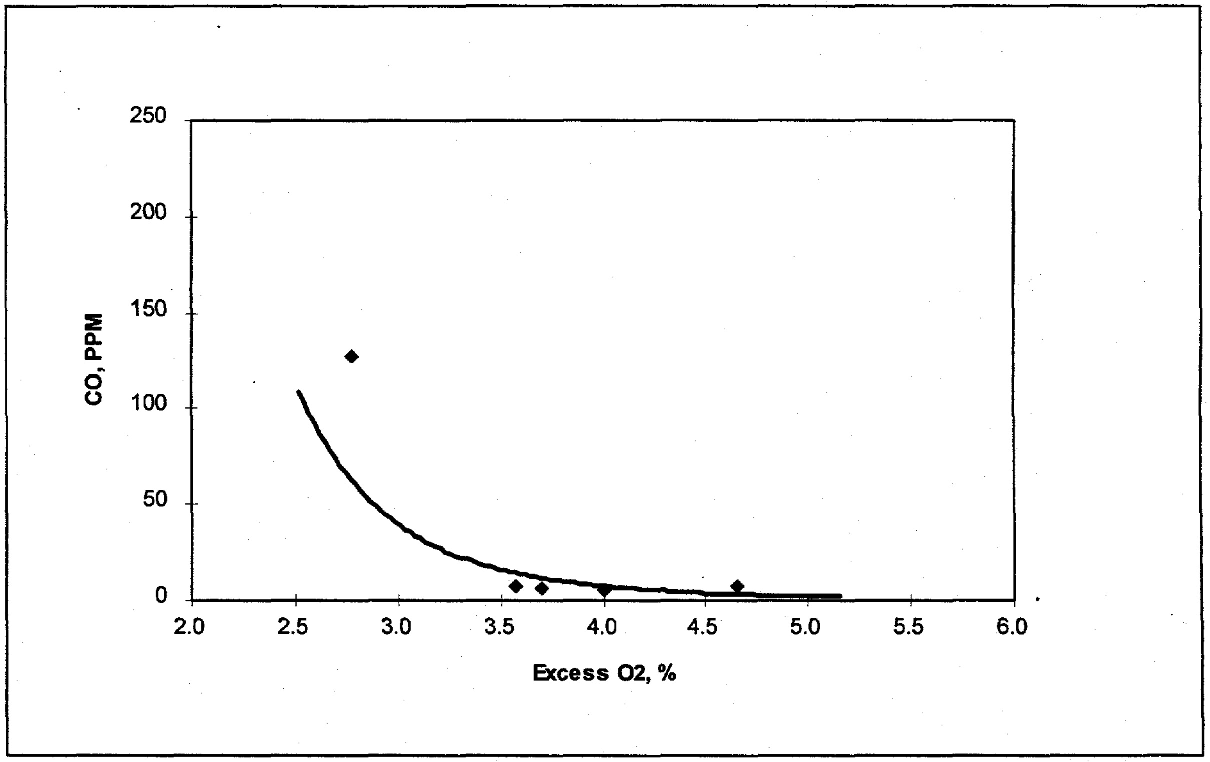

Figure 13: CO Emissions vs. Excess O_2 - 400 MW

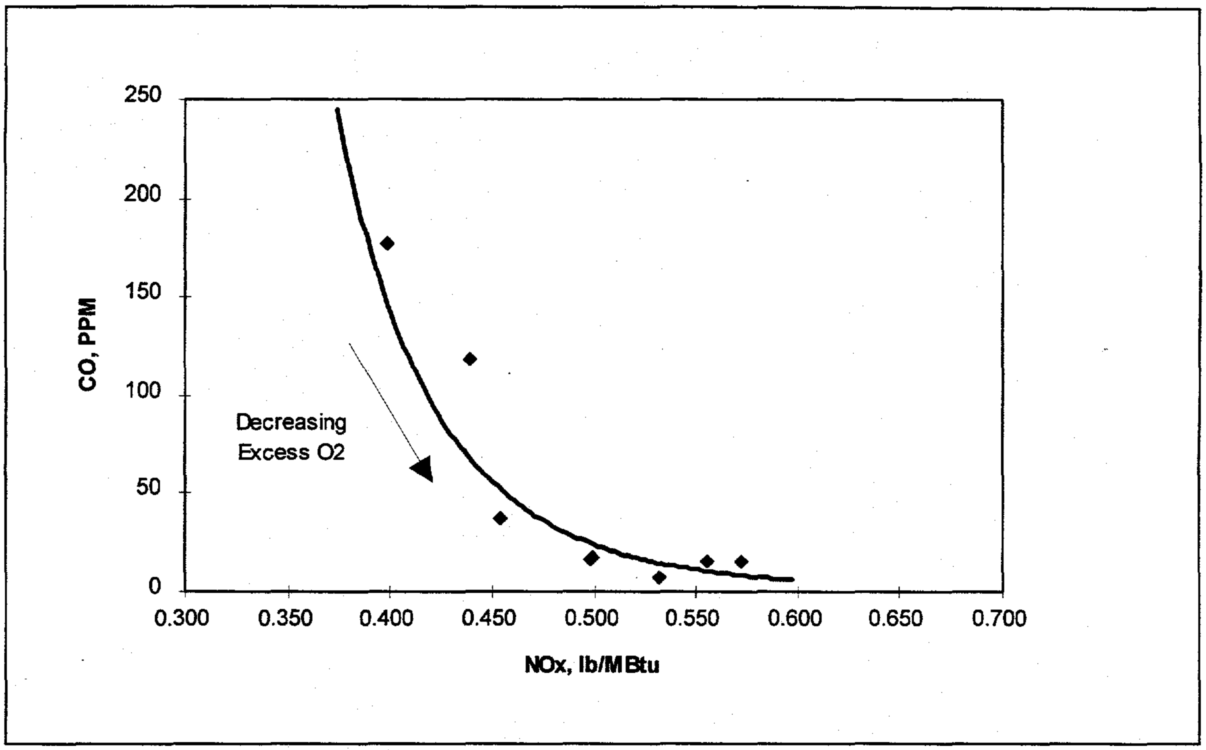

Figure 14: CO vs. NOx Tradeoff - 480 MW

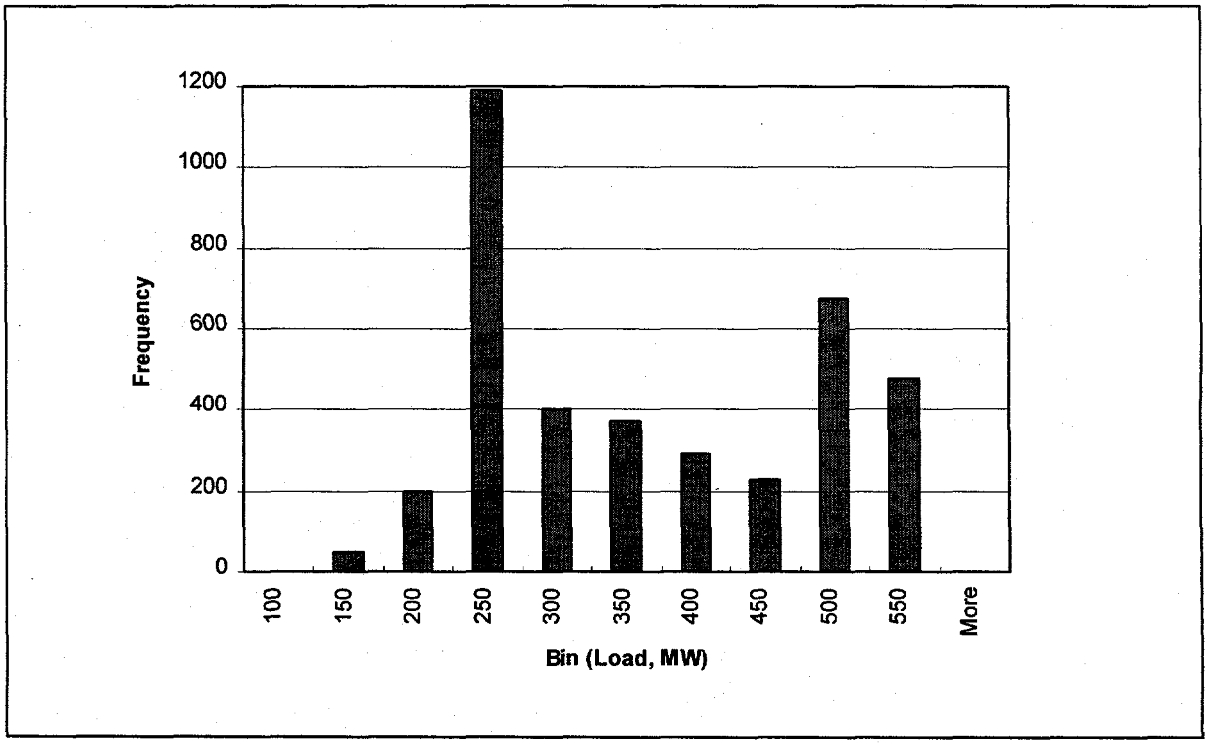

Figure 15: Load Profile - July 1994

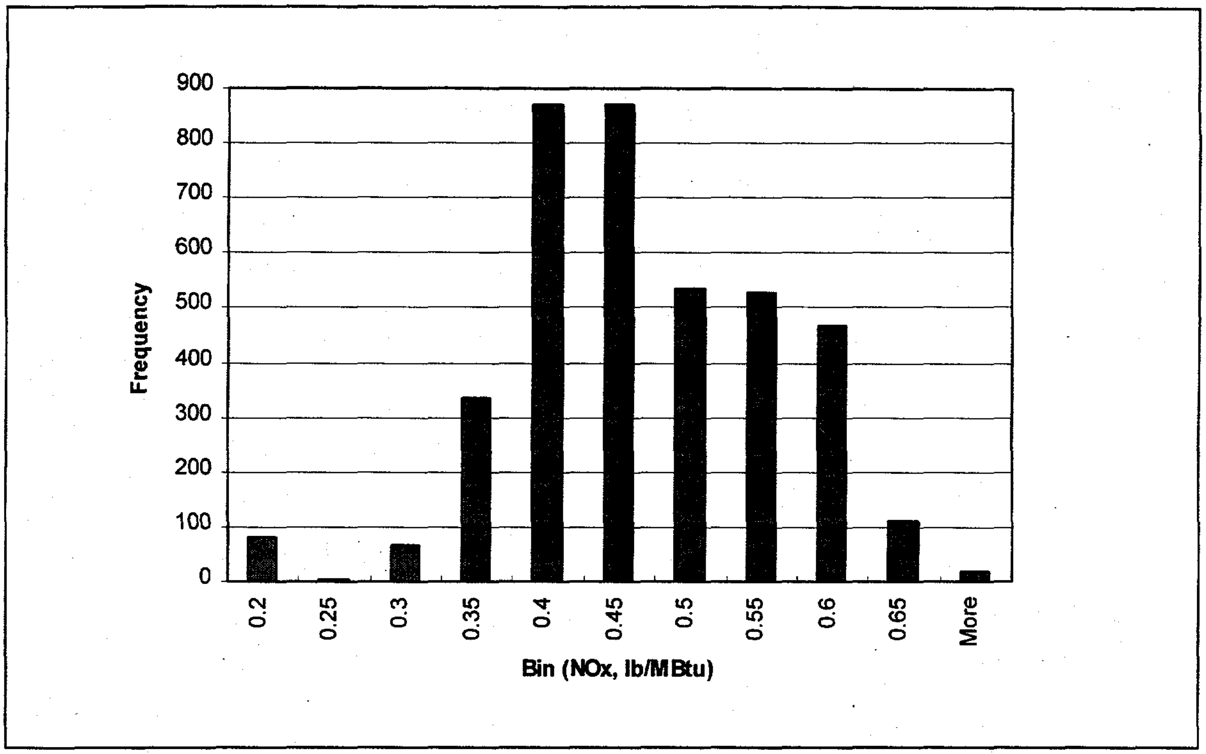

Figure 16: NOx Profile - July 1994

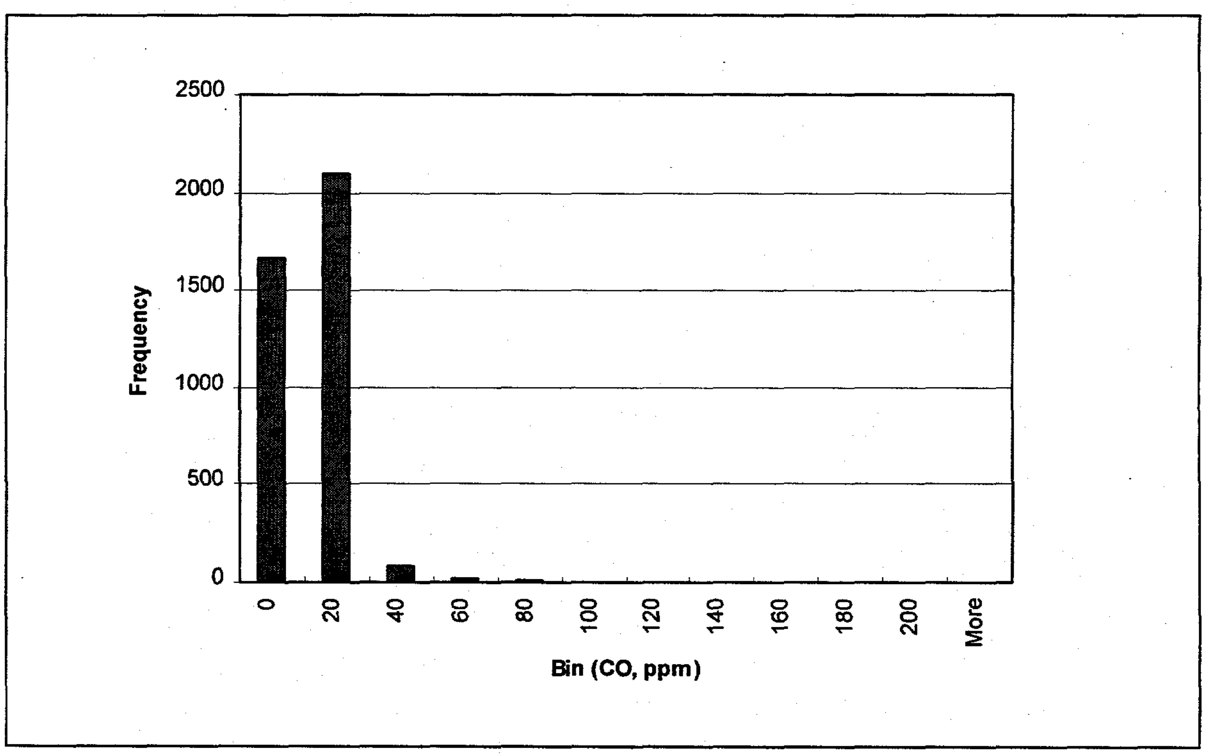

Figure 17: CO Profile - July 1994

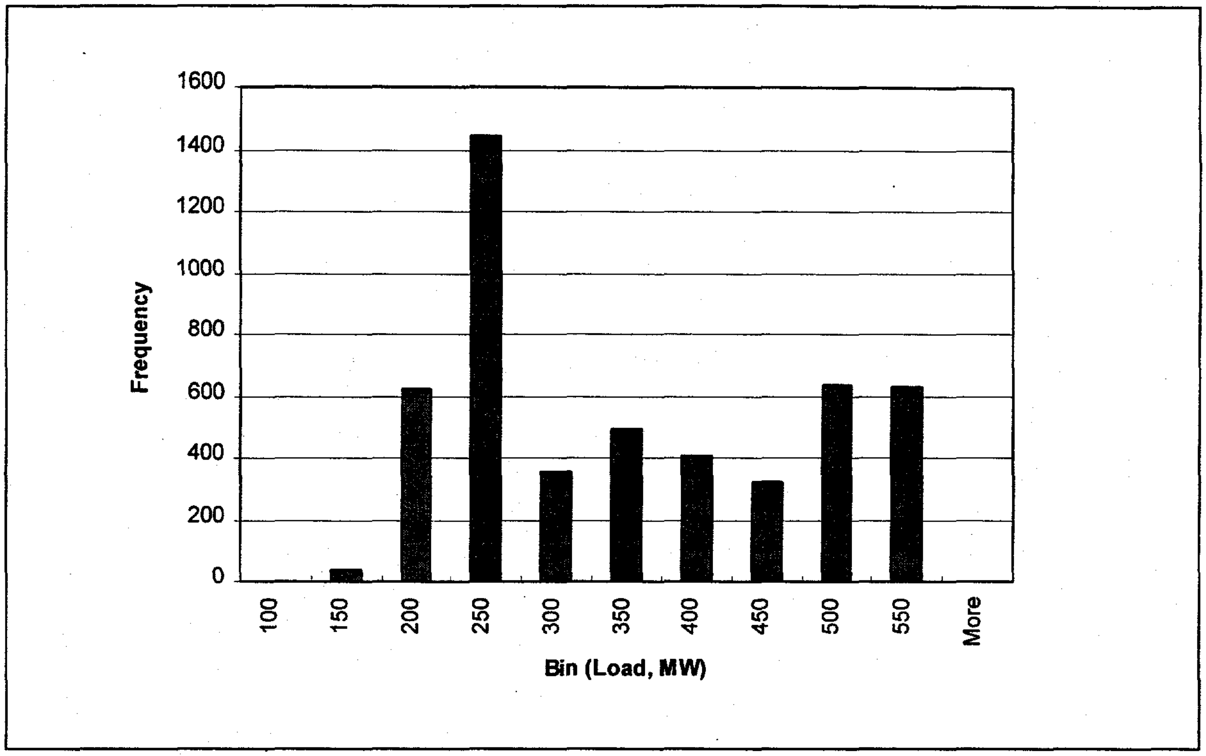

Figure 18: Load Profile - August 1994

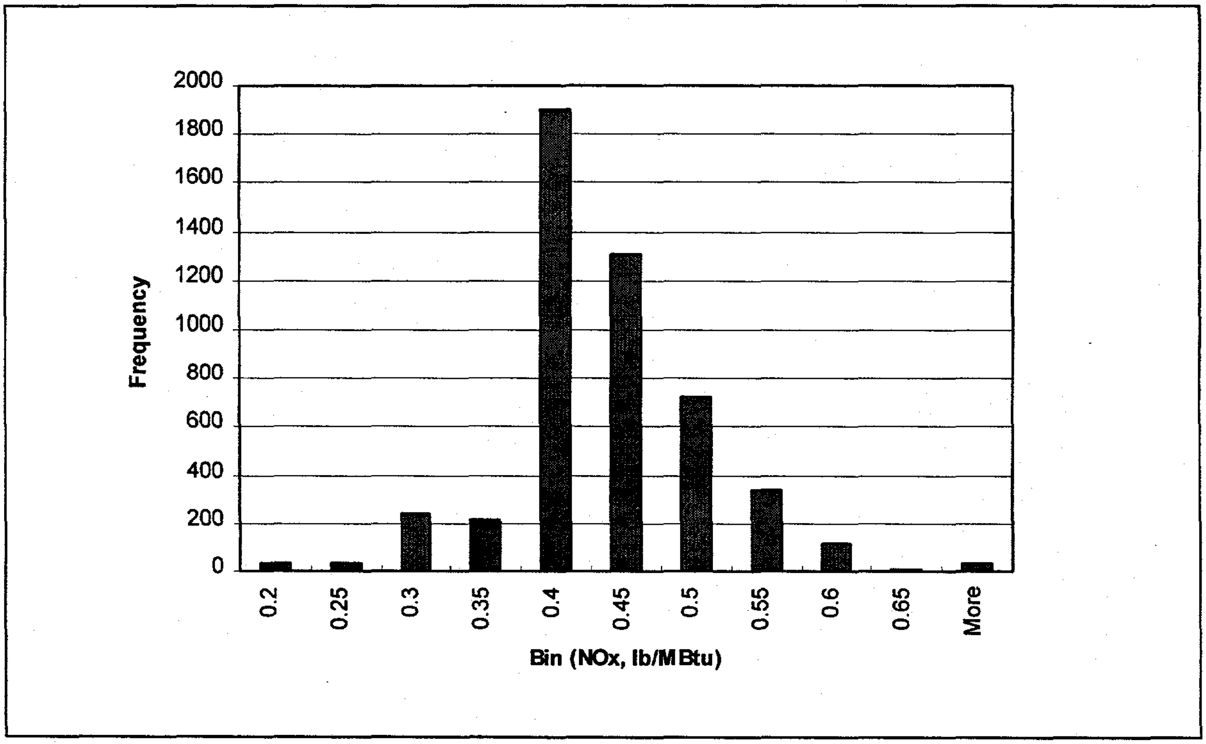

Figure 19: NOx Profile - August 1994

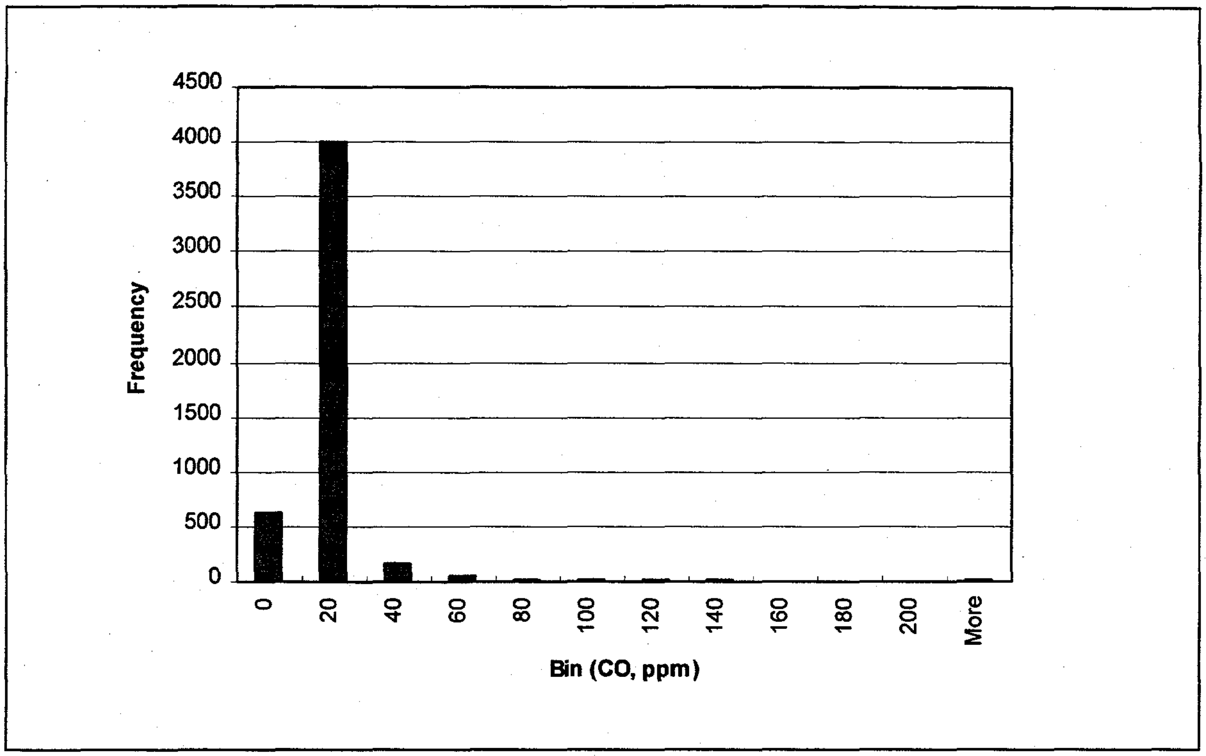

Figure 20: CO Profile - August 1994

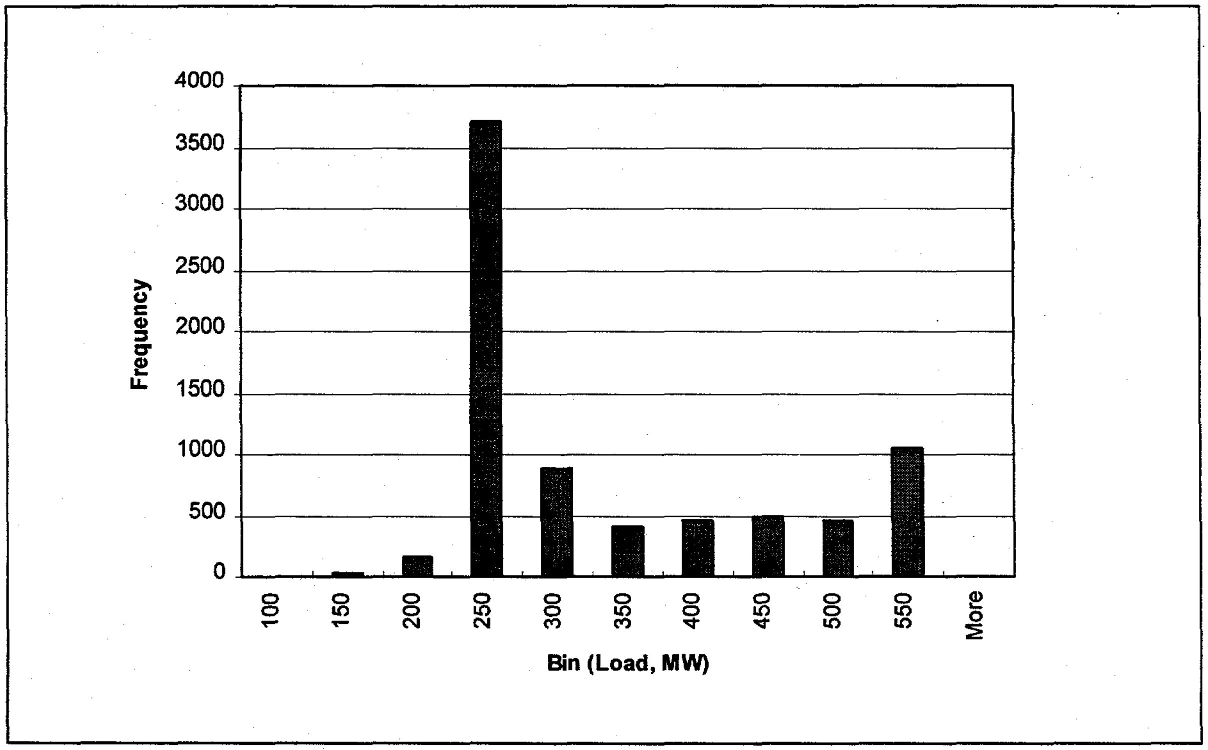

Figure 21: Load Profile - September 1994

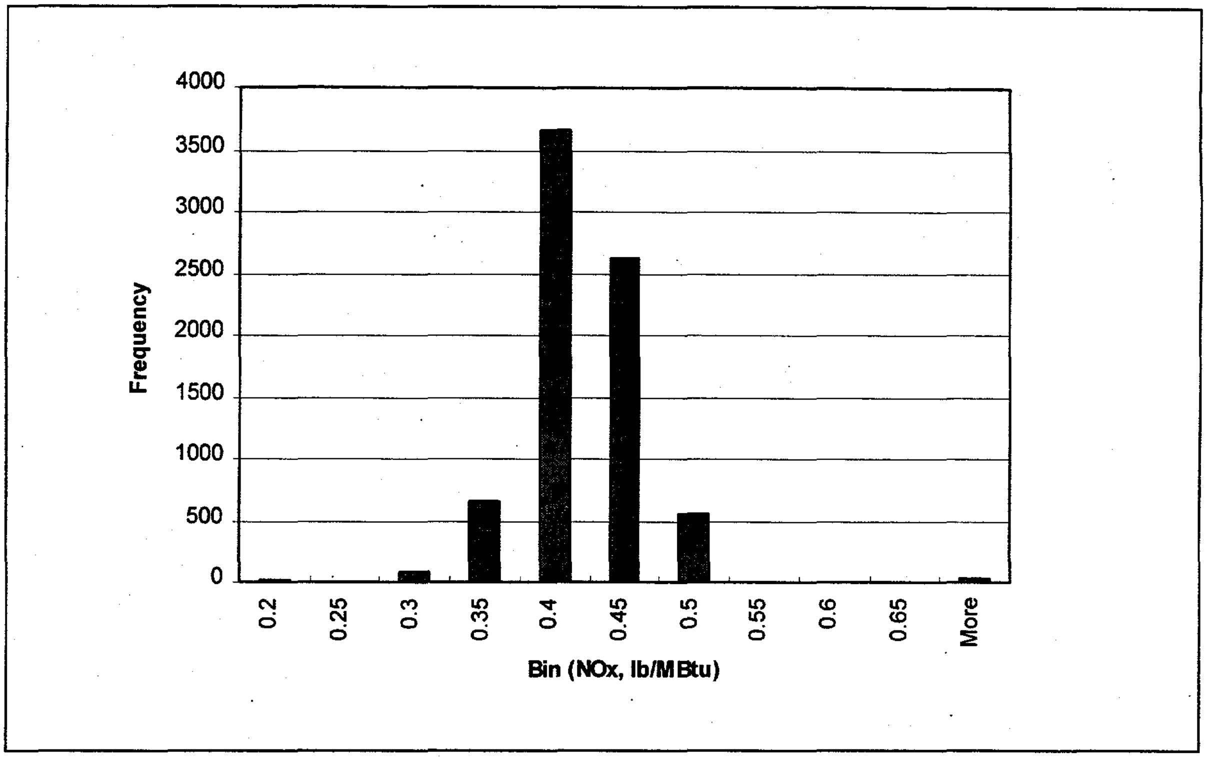

Figure 22: NOx Profile - September 1994

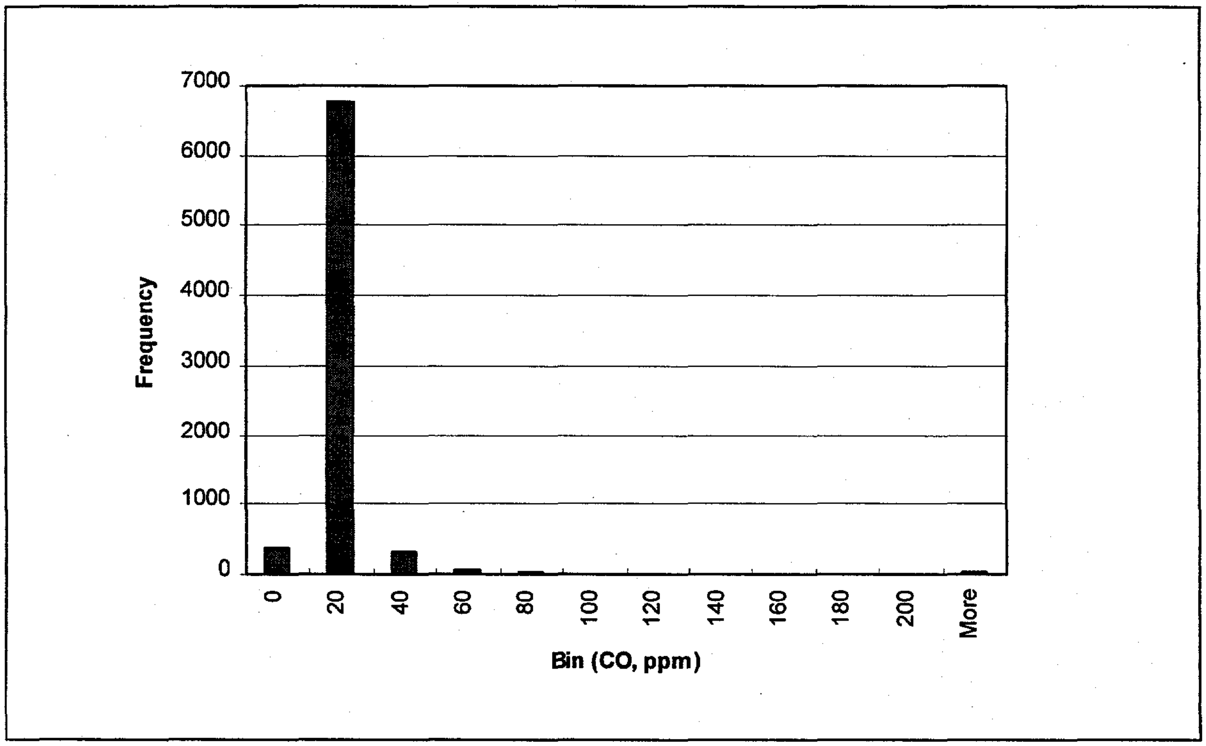

Figure 23: CO Profile - September 1994

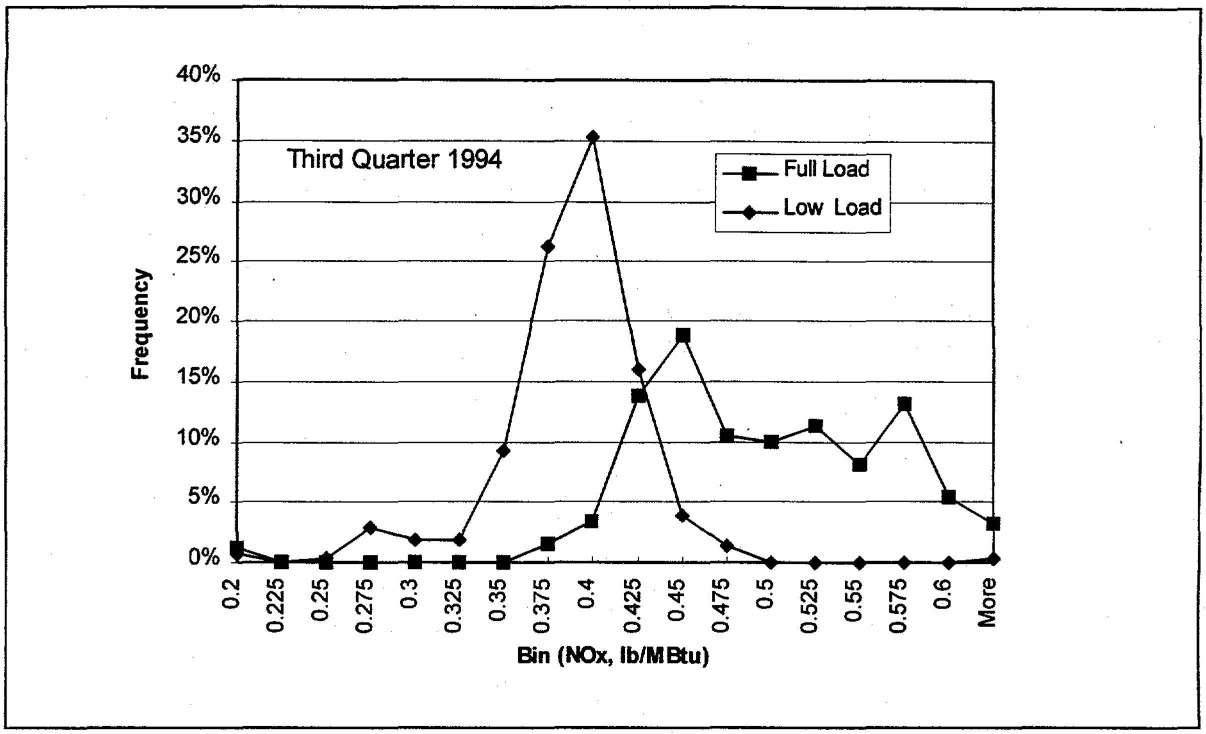

Figure 24: NOx Distribution Comparison - Full Load and Low Load

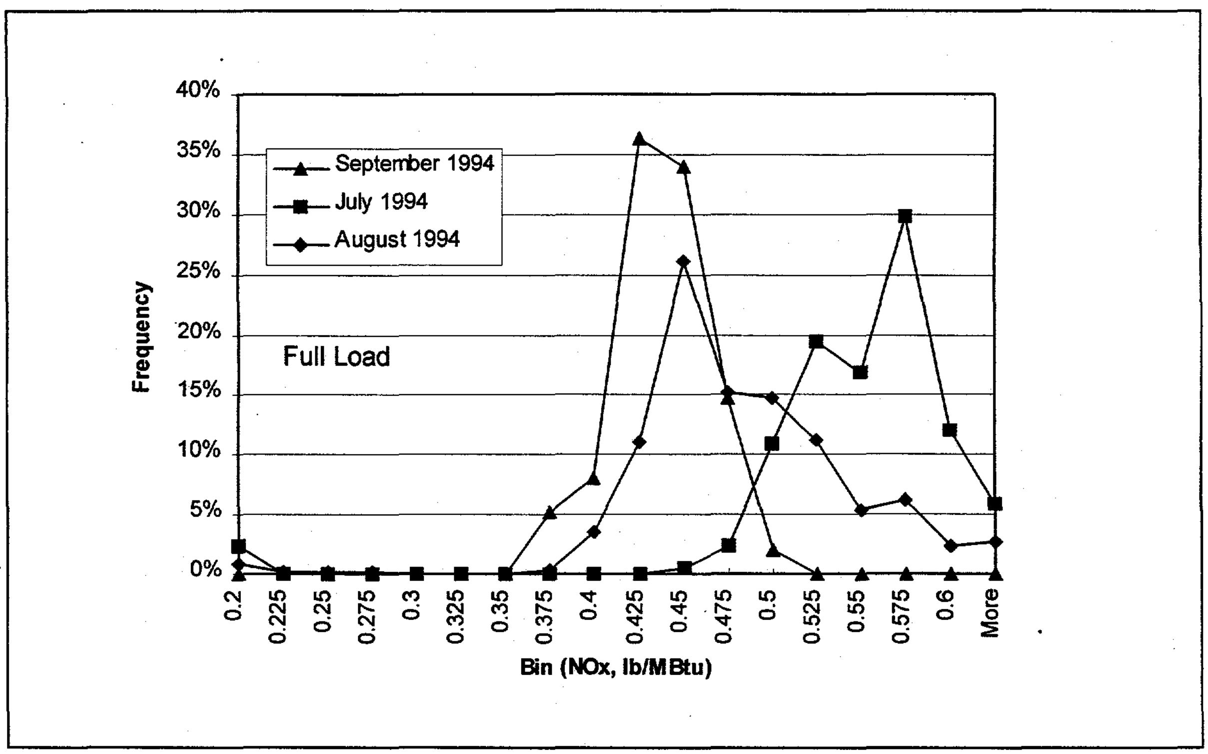

Figure 25: NOx Distribution Comparison - Full Load

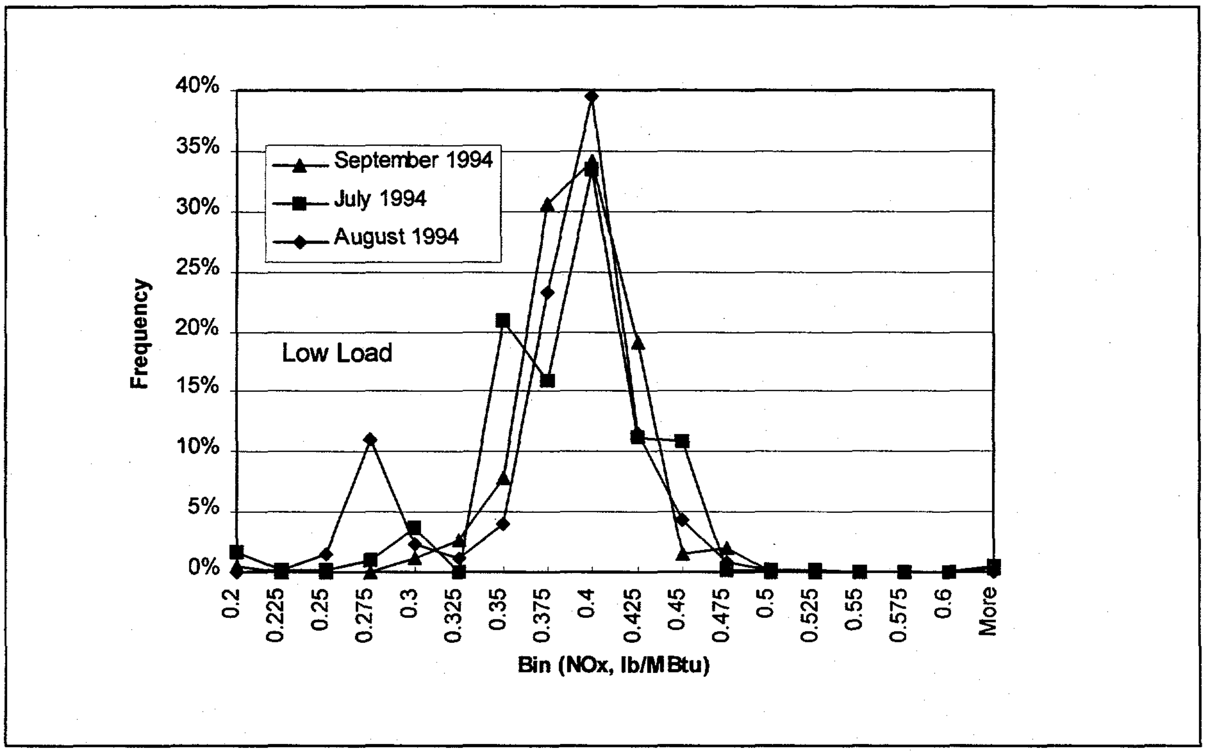

Figure 26: NOx Distribution Comparison - Low Load

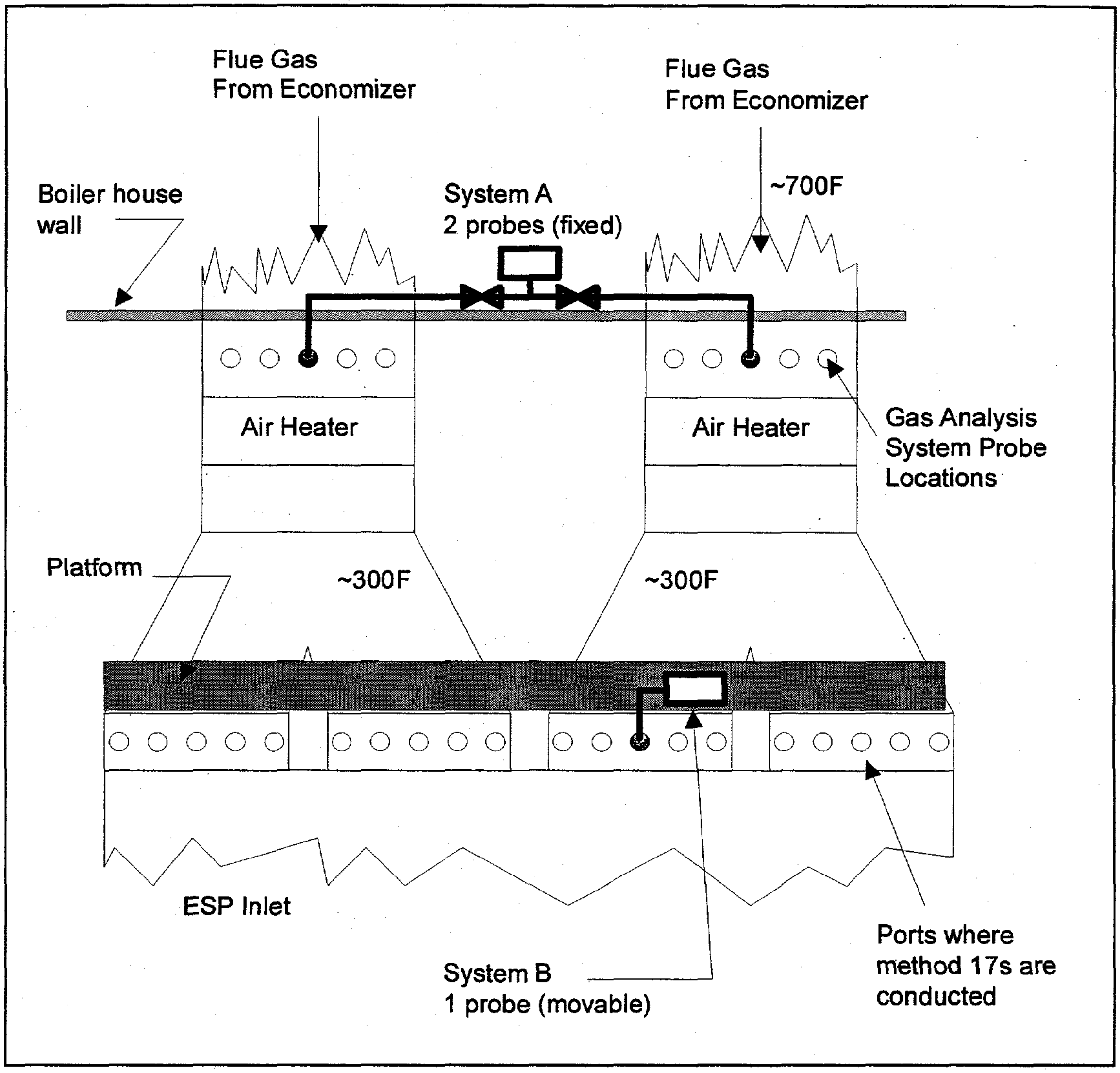

Figure 27: On-Line Carbon-in-Ash Sampling Locations

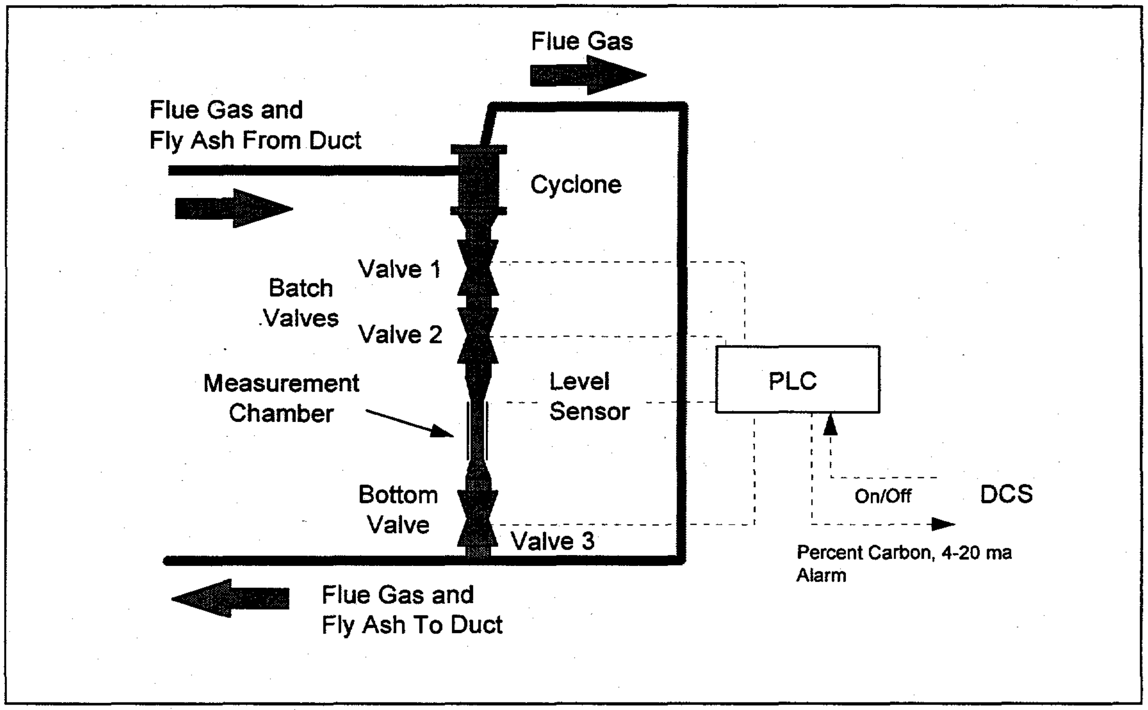

Figure 28: SEKAM General Arrangement

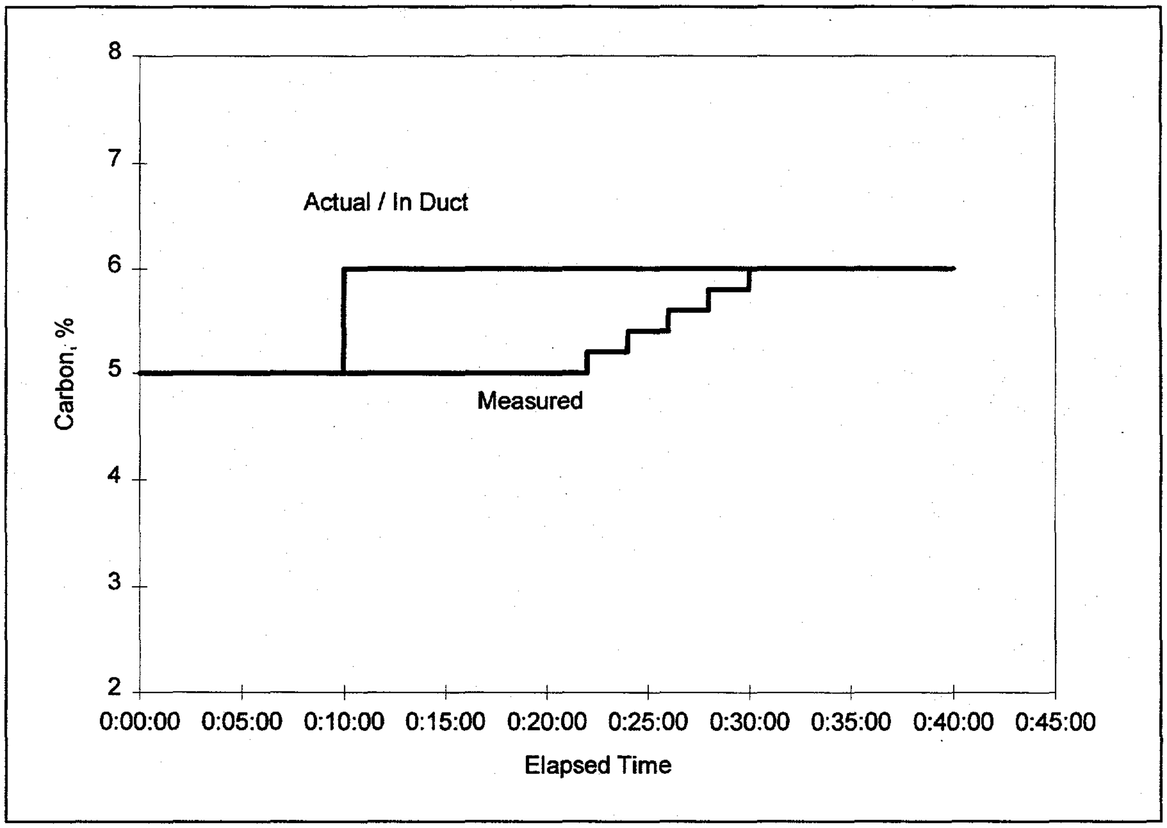

Figure 29: SEKAM Response Time

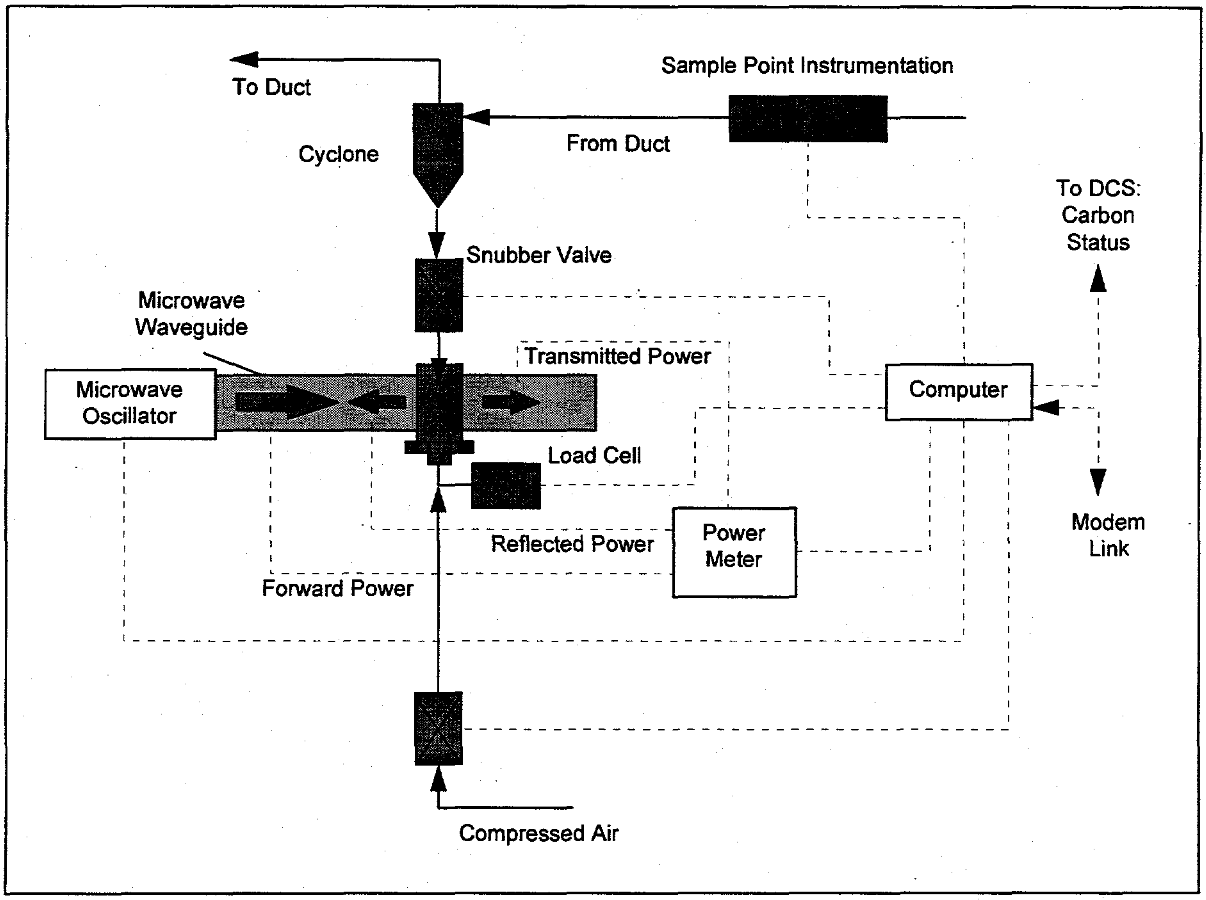

Figure 30: CAM General Arrangement

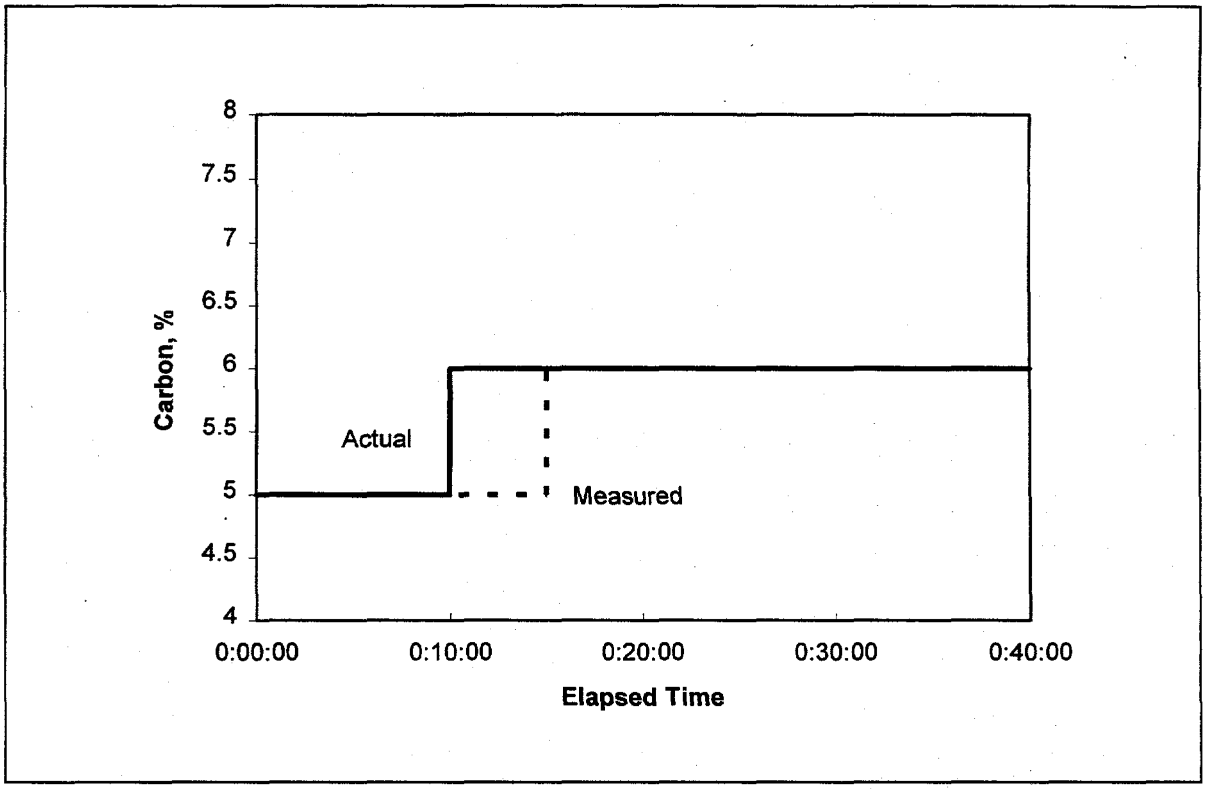

Figure 31: CAM Response Time

Table 3: Phase 4 Milestones / Status	
Milestone	Status
Digital control system design, configuration, and installation	Completed
Digital control system startup	Completed
Instrumentation upgrades	In Progress
Advanced controls/optimization design	In Progress
Characterization of the unit pre- activation of advanced strategies	In Progress
Characterization of the post- activation of advanced strategies	1/95 - 3/95

Table 4: NOx Sensitivity to Excess O_2						
Phase 4A Preliminary Diagnostic Tests August 1994			Prior Phases NOx Sensitivity[#,*] (lb/MBtu)/(% O_2)			
Nominal Load	NOx Sensitivity[*]	R^2	Phase			
MW	(lb/MBtu)/(% O_2)		1	2	3A	3B
480	0.1067	0.9776	~0.10	~0.09	~0.06	~0.05
400	0.0752	0.9783	~0.10	~0.11	~0.05	~0.08
300	0.0483	0.9980	~0.08	~0.14	~0.04	~0.06

[*]Based on short-term diagnostic tests.
[#]See phase topical reports for a discussion on the uncertainty of these results.

Table 5: Long-Term Generation and Emissions					
		Average			
	5 Minute Samples	Load MW	NOx lb/MBtu	O_2 Percent	CO ppm
July 1994	3888	336	0.442	7.95	4
August 1994	4939	322	0.415	6.33	12
September 1994	7633	302	0.394	6.59	9
Third Quarter 1994	*16460*	*316*	*0.412*	*6.83*	*9*

Table 6: SEKAM Overview	
Technology	Capacitance
Operating Range	0-20% Carbon
Accuracy	±1.2% (0-15% Carbon)
Time Constant	~6 minutes
Sample Delay	~10 minutes
Sample Required	~150 cm^3
Gas Temperature	<800°F
Ambient	14°F to 122°F 10% to 95% Relative Humidity
Size (h x w x d)	7.25 ft x 5.2 ft x 1.25 ft
Weight	~1500 lb
Plant Air Requirements	80-100 psi / 70 scfm
Instrument Air Requirements	80-100 psi / 2 scfm
Power	110 VAC / 20 amps

Table 7: CAM Overview	
Technology	Microwave Reflection/Absorbance
Operating Range	0-30% Carbon
Accuracy	±0.5% (0-5% Carbon) ±1% (5-30% Carbon)
Time Constant	-------
Sample Delay	~5 minutes
Sample Required	~8 cm^3
Gas Temperature	<1000°F
Ambient	10°F to 140°F 0% to 100% Relative Humidity
Size (h x w x d)	6.5 ft x 2.25 ft x 3 ft
Weight	~200 lb
Plant Air Requirements	100 psi / 10 scfm
Instrument Air Requirements	Not Required
Power	110 VAC / 10 amps

4. FUTURE PLANS

The following table is a quarterly outline of the activities scheduled for the remainder of the project:

Table 8: Future Plans

Quarter	Activity
Forth Quarter 1994	• Continue Re-Baseline Unit
First Quarter 1995	• Advanced Controls Testing
Second Quarter 1995	• Complete Advanced Controls Testing
Third Quarter 1995	• Final Reporting & Disposition
Forth Quarter 1995	• Final Reporting & Disposition

5. ACKNOWLEDGMENTS

The following project participants are recognized for their dedicated efforts toward the success of the wall-fired low NOx demonstration: Mr. Ernie Padgett and Mr. W.C. Dunaway, Georgia Power Company, and Mr. Mike Nelson and Mr. Robert Kelly, Southern Company Services, for their coordination of the design and retrofit efforts and Mr. Jose Perez, full-time Instrumentation Specialist from Spectrum Systems, Inc. Also Mr. Jim Witt and Mr. Jimmy Horton of Southern Company Services for design, procurement, and installation of the instrumentation systems. The following companies have provided outstanding testing and data analysis efforts: Energy Technology Consultants, Inc., Flame Refractories, Inc., Innovative Combustion Technologies, Southern Research Institute, W. S. Pitts Consulting, and Radian Corporation. Finally, the support from Mr. Art Baldwin, DOE ICCT Project Manager, Dr. Rick Squires, EPRI Project Manager, Mr. Russ Pflasterer, EPRI Project Manager, and Mr. Stratos Tavoulareas, Energy Technologies Enterprises Corporation, is greatly appreciated.

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6. Holmes, R., Squires, R., Sorge, J., Chakraborty, R., McIlvried, T., "Progress Report on the Development of a Generic NOx Control Intelligent System (GNOCIS)," EPRI 1994 Workshop on NOx Controls for Utility Boilers, May 11-13, 1994, Scottsdale, Arizona.

Appendix A

Phase 4A Diagnostic Tests (August 1994)

Wall-Fired Project
Phase 4A Diagnostic Tests

TEST NO.	DATE	TEST CONDITIONS	LOAD MWe	MOOS PATRN	TOTAL AIR Klb/HR	FLUE GAS FLOW Klb/HR	FUEL FLOW Klb/HR	OFA FLOW KPPH	DAS O2 DRY (%)	DAS CO DRY (%)	NOx lb/MBtu
129-1	08/05/94	HI-LOAD NORMAL O2	486	AMIS	3988	1288	362	NA	3.0	38	0.454
129-2	08/05/94	HI-LOAD LOW O2	483	AMIS	3820	1240	363	NA	2.7	177	0.399
129-3	08/05/94	HI-LOAD HIGH O2	483	AMIS	4302	1313	363	NA	3.9	7	0.533
130-1	08/06/94	MID-LOAD LOW O2	398	B	3300	914	298		2.8	128	0.368
130-2	08/06/94	MID-LOAD NORM O2	400	B	3548	1054	298	297	3.6	7	0.442
130-3	08/06/94	MID-LOAD HIGH O2	398	B	3859	1178	298	318	4.7	7	0.513
130-4	08/06/94	MID-LOAD NORM O2, DECR OFA	399	B	3564	1034	298	211	4.0	6	0.457
130-5	08/06/94	MID-LOAD NORM O2	399	E	3563	1109	298	294	3.7	6	0.451
131-1	08/07/94	MD/LO LOAD LOW O2	300	B,E	2881	822	234	119	4.4	20	0.363
131-2	08/07/94	MD/LO LOAD NORM O2	300	B,E	2993	856	234	134	4.8	13	0.386
131-3	08/07/94	MD/LO LOAD HIGH O2	302	B,E	3176	962	235	143	5.5	10	0.421
131-4	08/07/94	MD/LO LOAD HIGHER O2	301	B,E	3433	997	234	133	6.4	8	0.462
132-1	08/08/94	HI-LOAD LOW O2	482	AMIS	3933	1254	363	650	2.9	118	0.440
132-2	08/08/94	HI-LOAD NORM O2	484	AMIS	4120	1286	363	658	3.5	16	0.498
132-3	08/08/94	HI-LOAD HIGH O2	479	AMIS	4350	1354	364	666	4.1	15	0.556
132-4	08/08/94	HI-LOAD FUEL BIASED TO UPPER MILLS	476	AMIS	4315	1359	359	613	4.1	16	0.573
132-5	08/08/94	HI-LOAD FUEL BIASED TO UPPER MILLS	479	AMIS	4070	1197	360	596	3.4	18	0.500

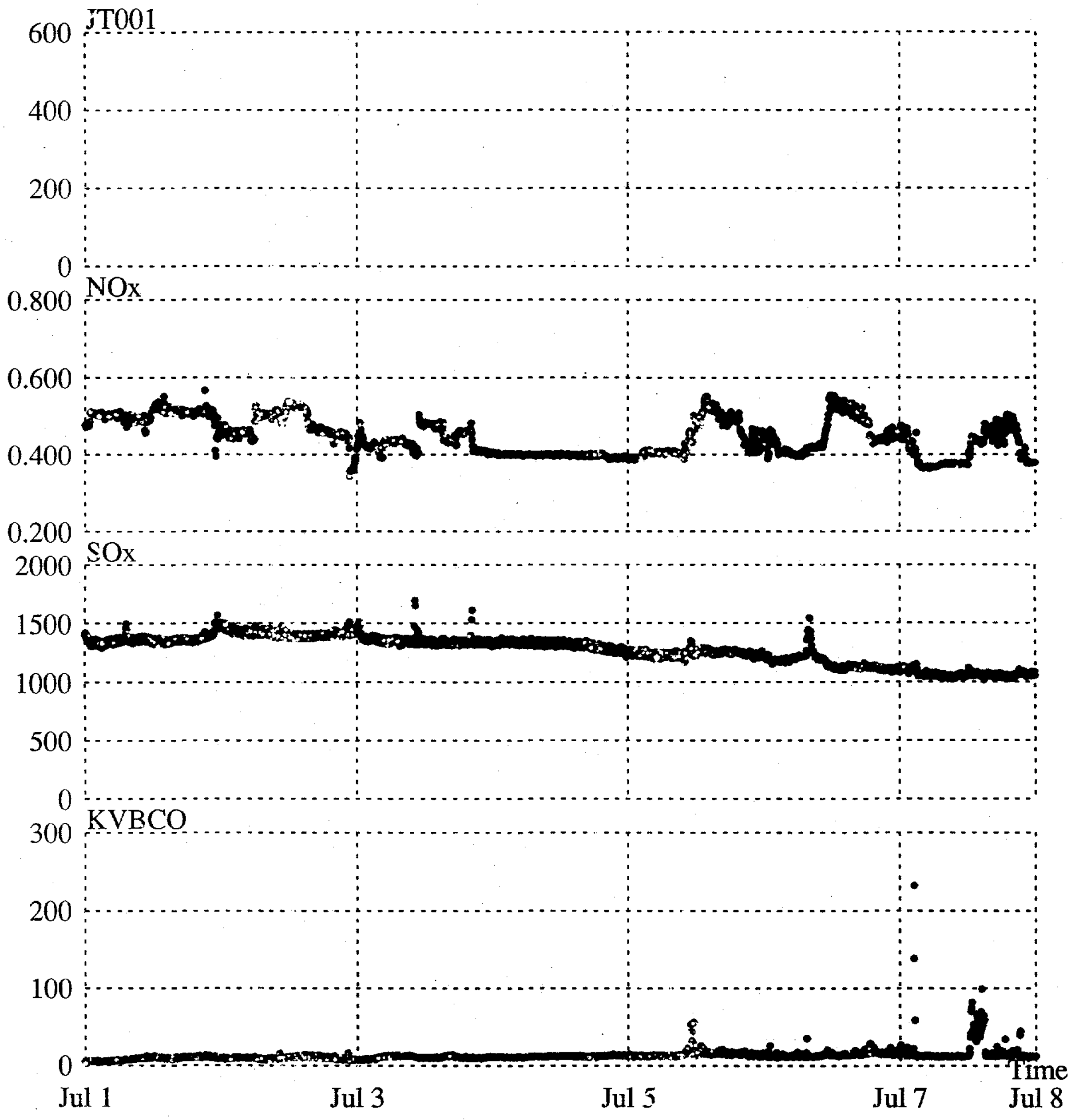
Appendix B

Phase 4A Long-Term Emissions (July - September 1994)

Table B-1: Tagname Descriptors and Units		
Tagname	Description	Units
JT001	Gross Generation	MW
NOx	NOx Emissions	lb/MBtu
SOx	SO_2 Emissions (Corrected to 3% O_2)	ppm
CO	CO Emissions	ppm

Table B-2: Data Invalid Log		
Date	Parameter	Reason
July 1 - July 11	Generation	Signal wire to data acquistion system disconnected
July 22 - July 25	All	Unit offline
July 29 - Aug 1	All	Unit offline
Aug 16 - Aug 24	All	Unit offline
Aug 27 - Aug 31	All	Unit offline
Sep 24 - Sep 26	All	Unit offline

Data:
Date: 02/07/95 14:11:34



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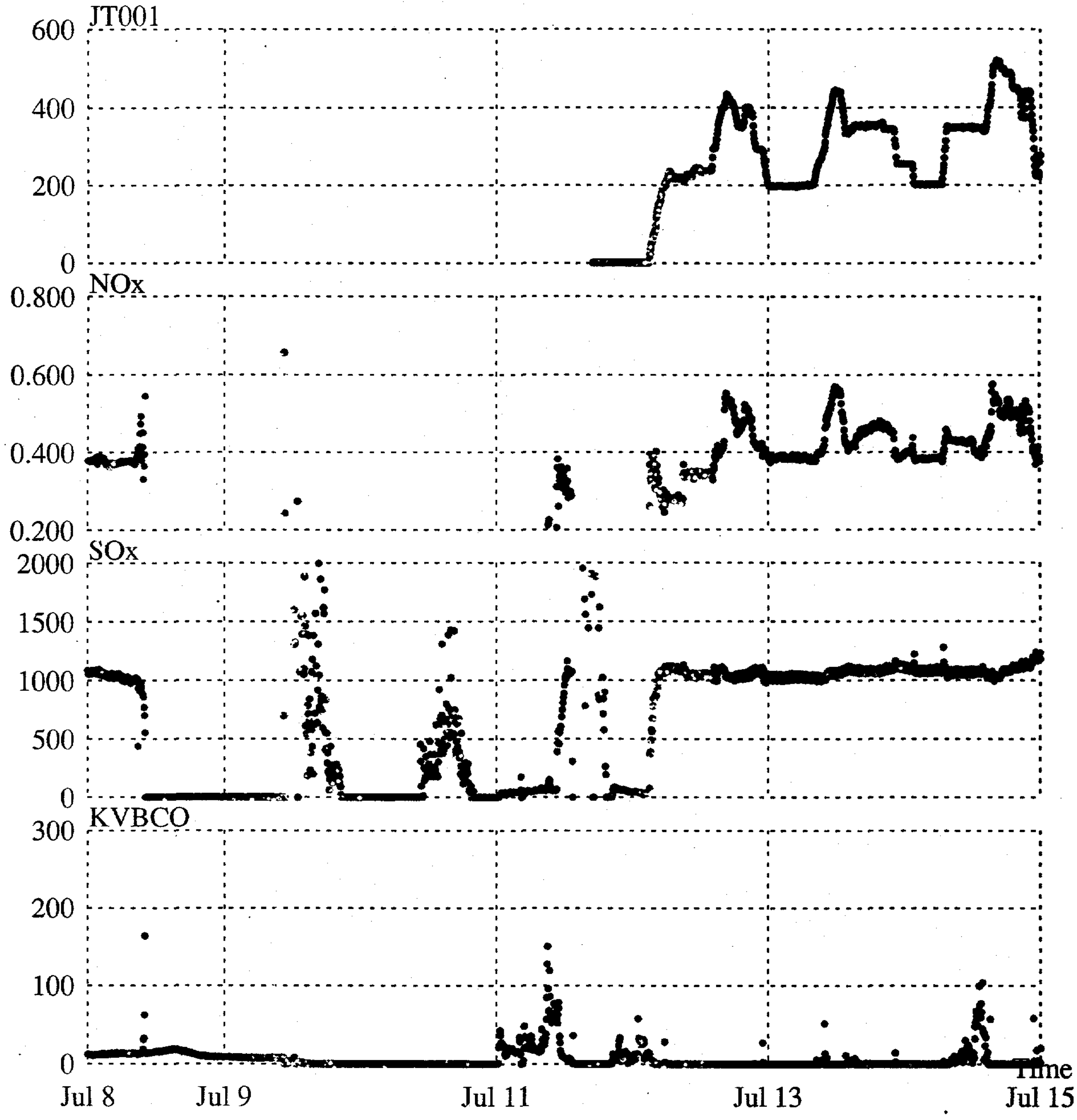

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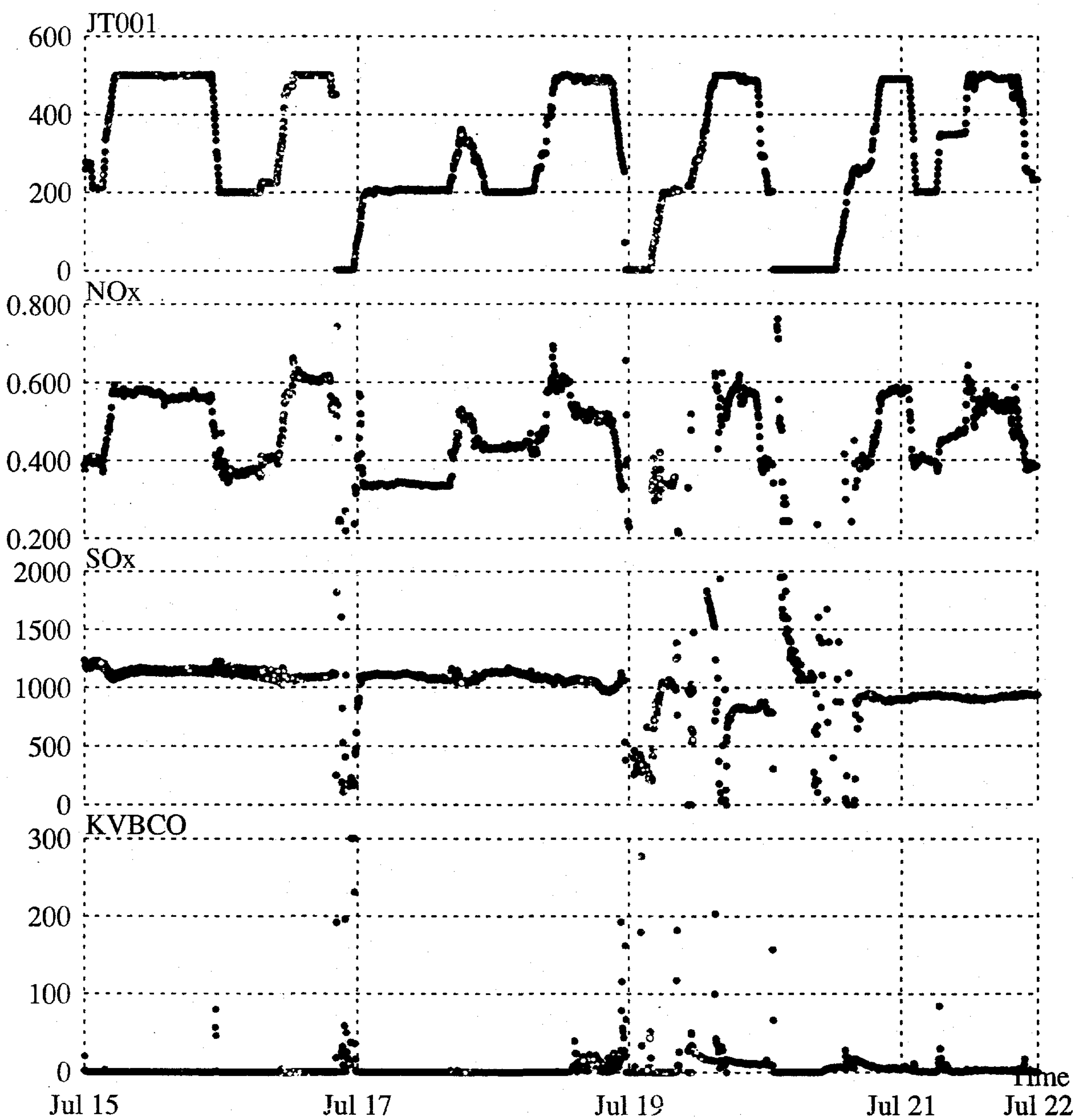

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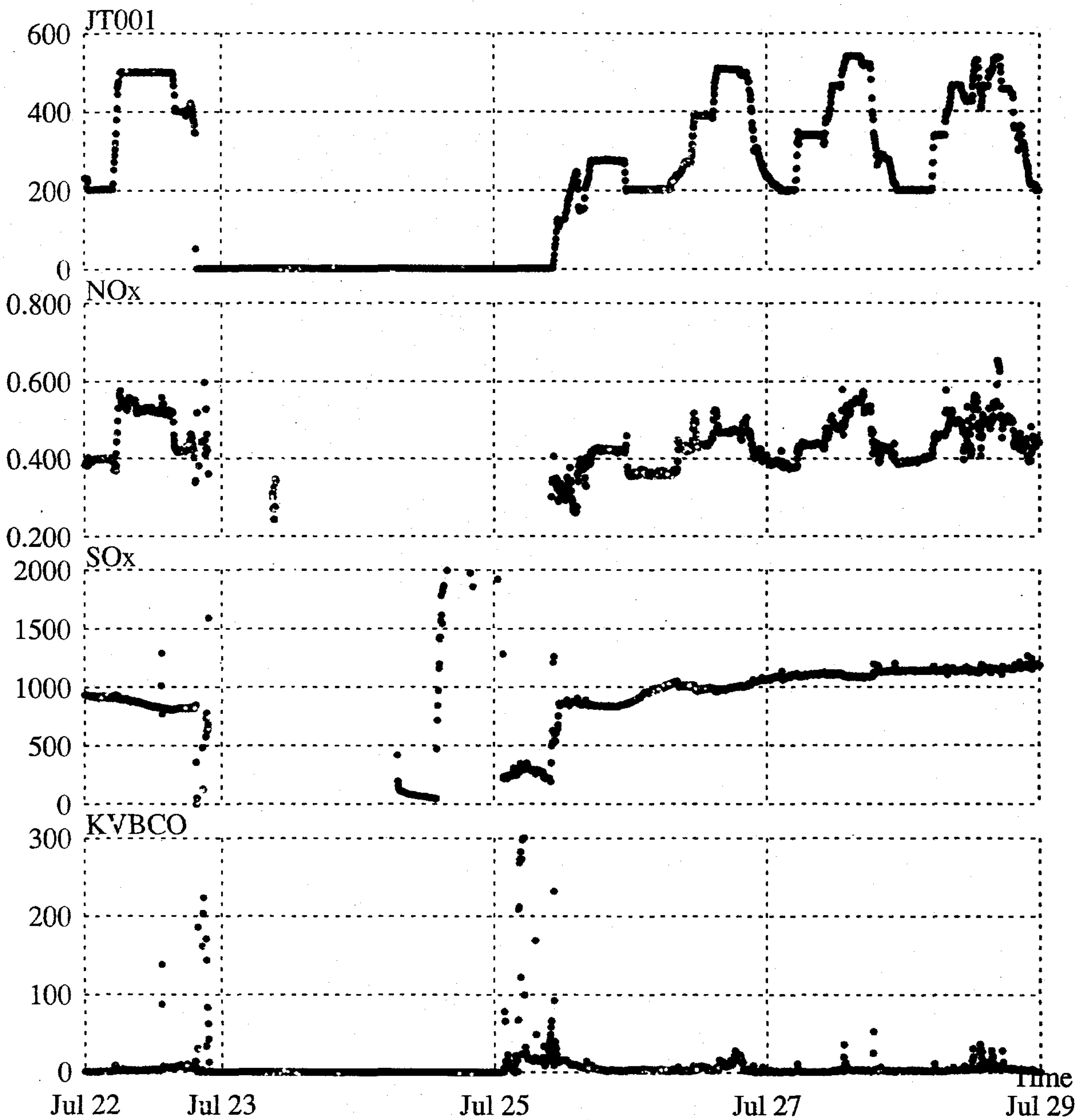

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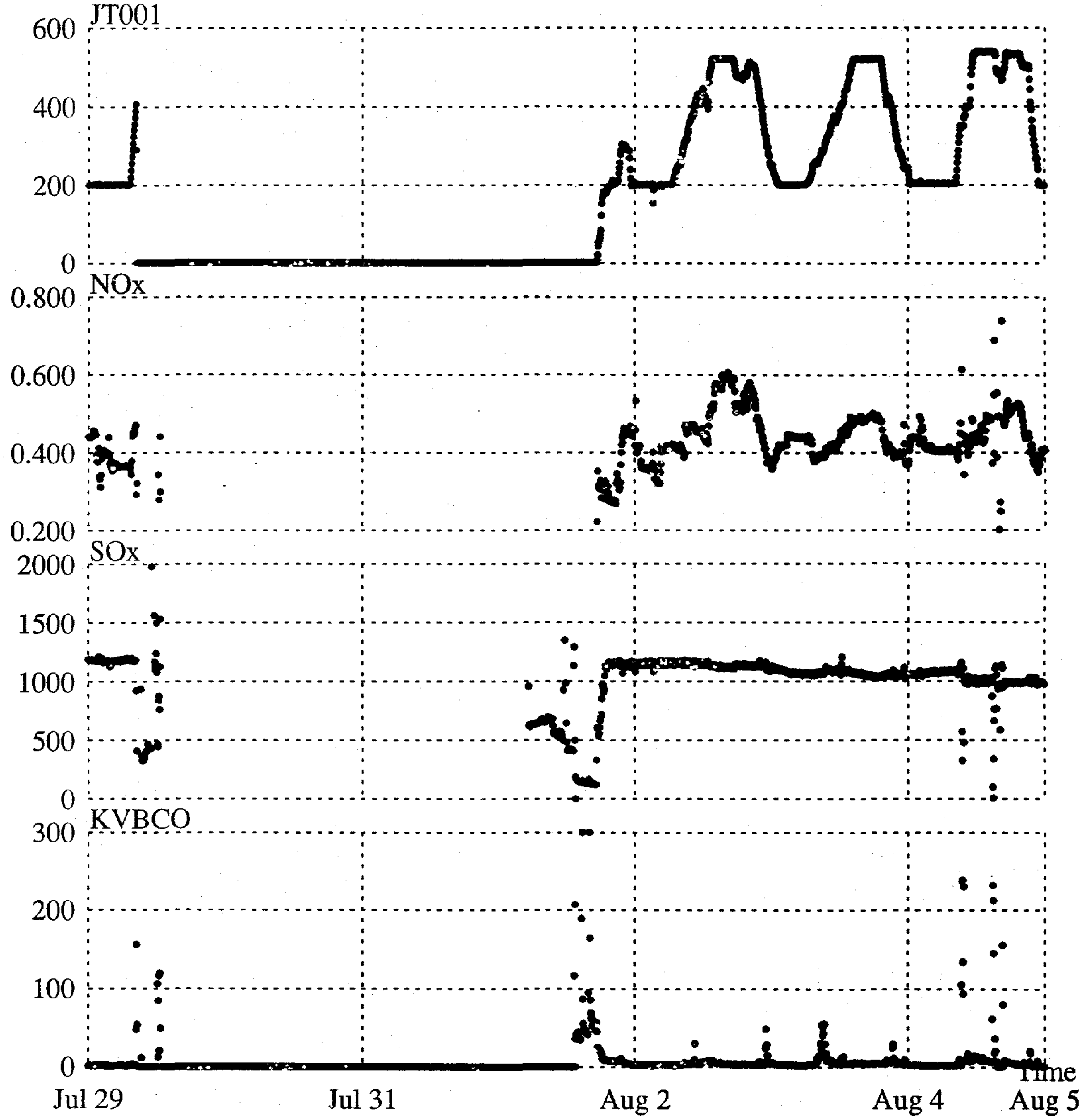

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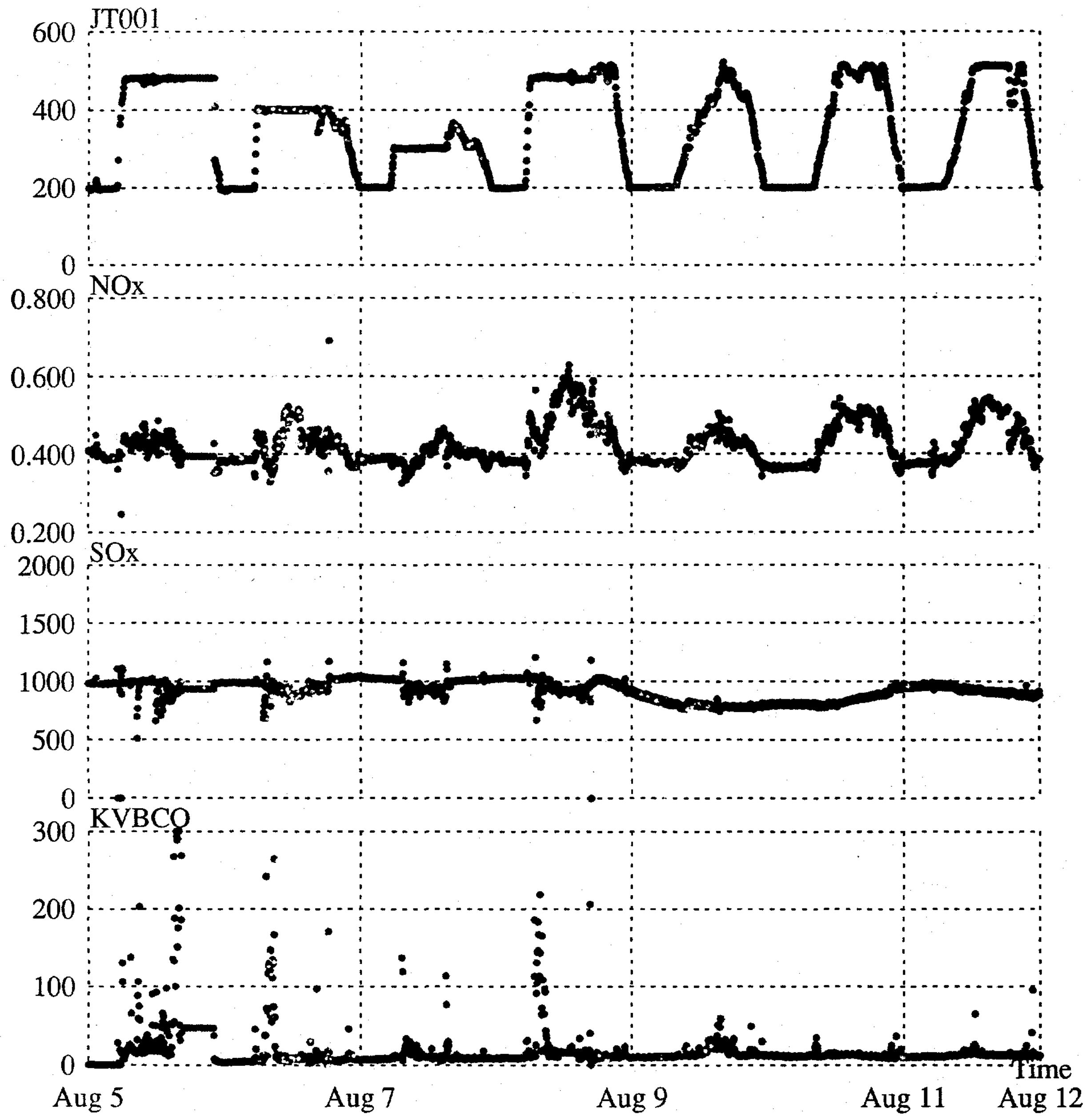

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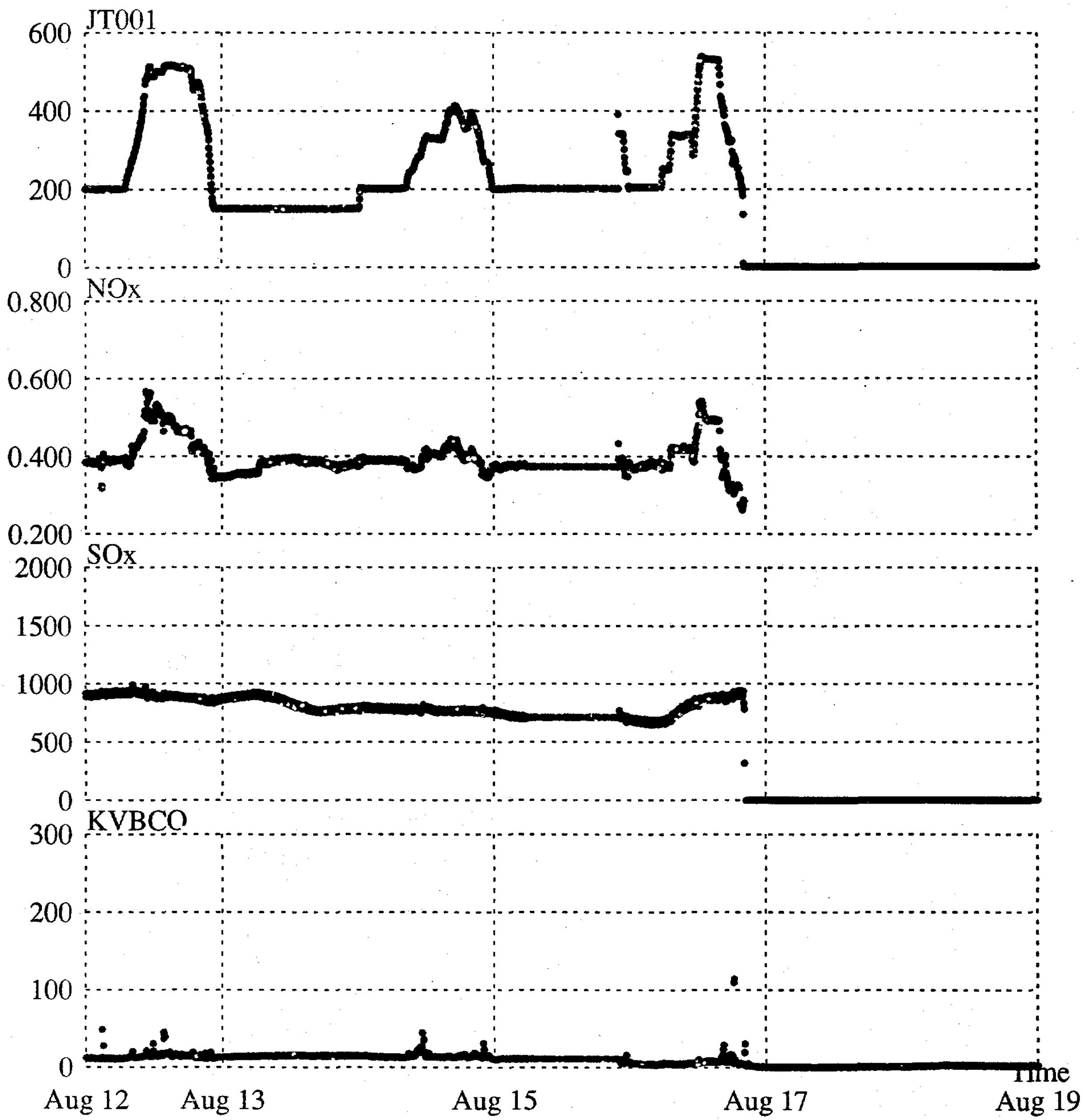

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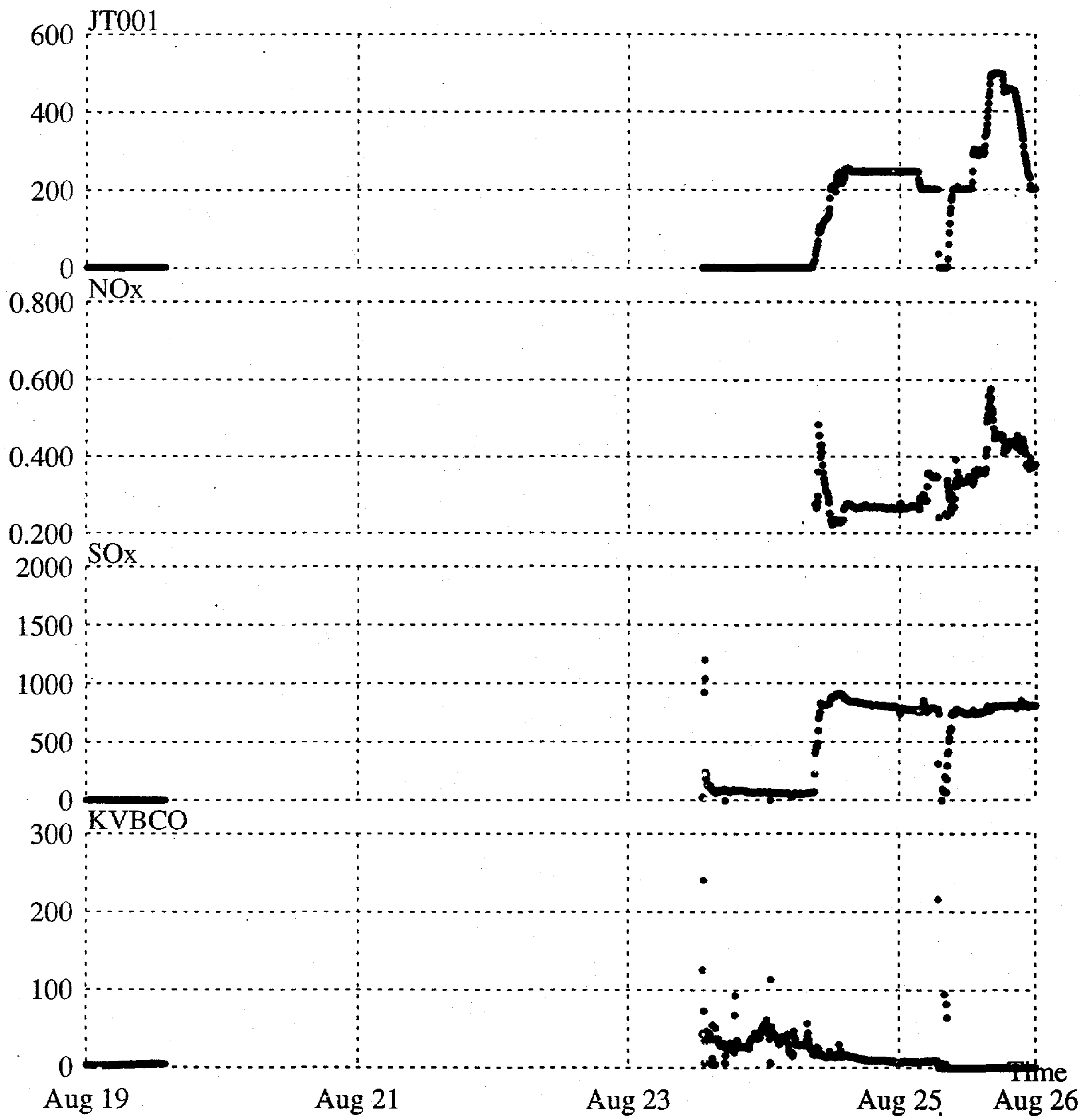

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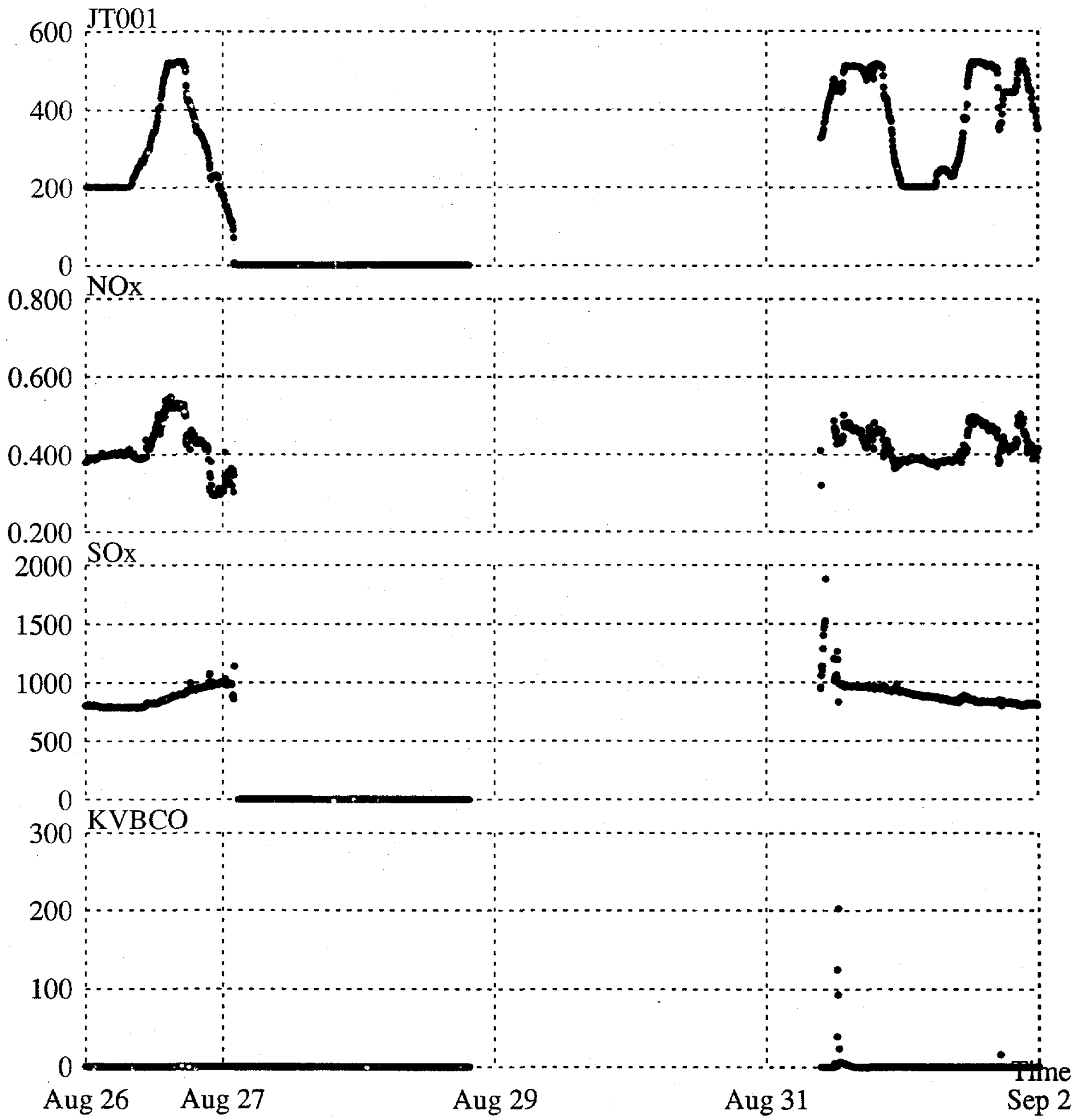

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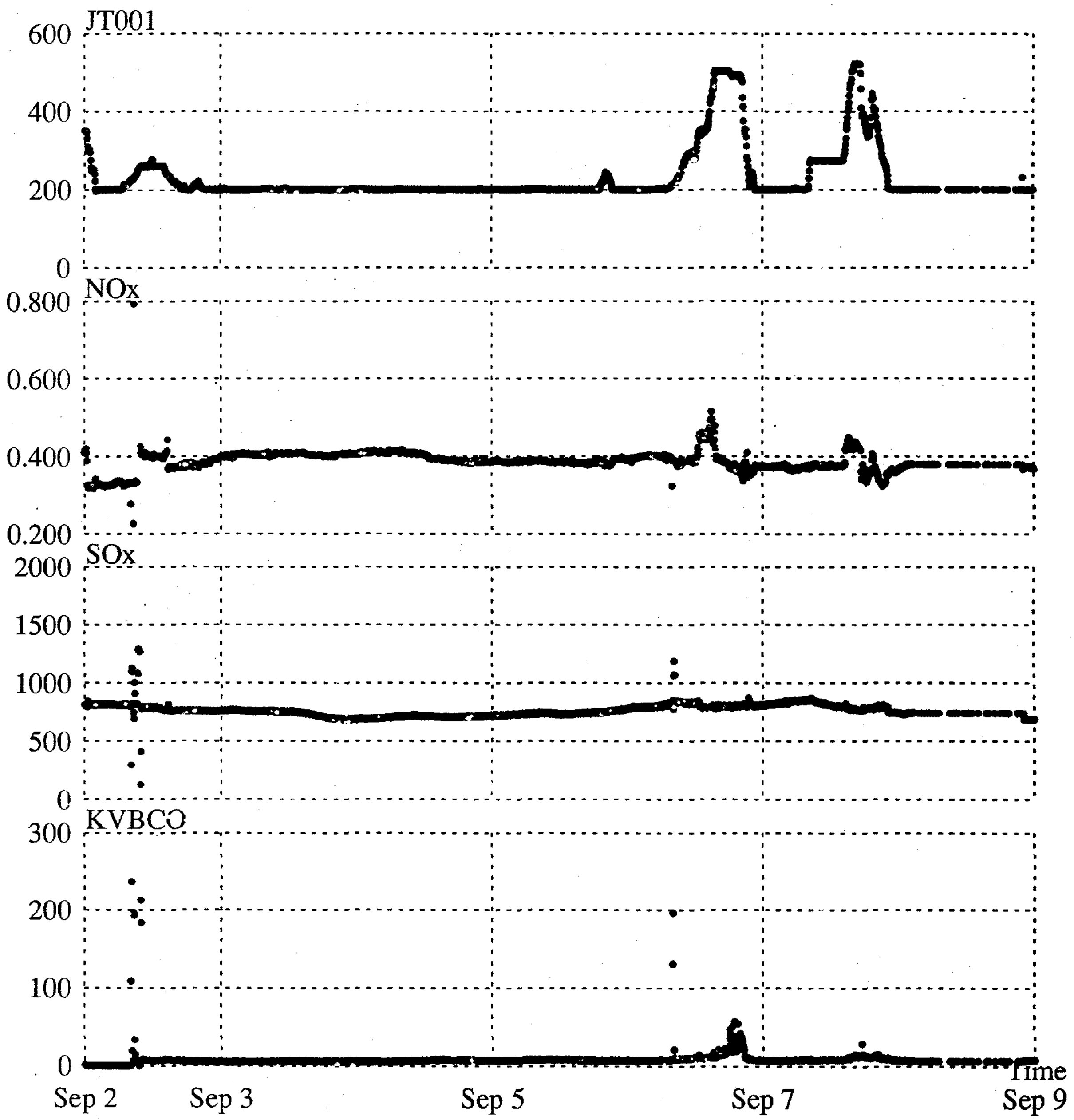

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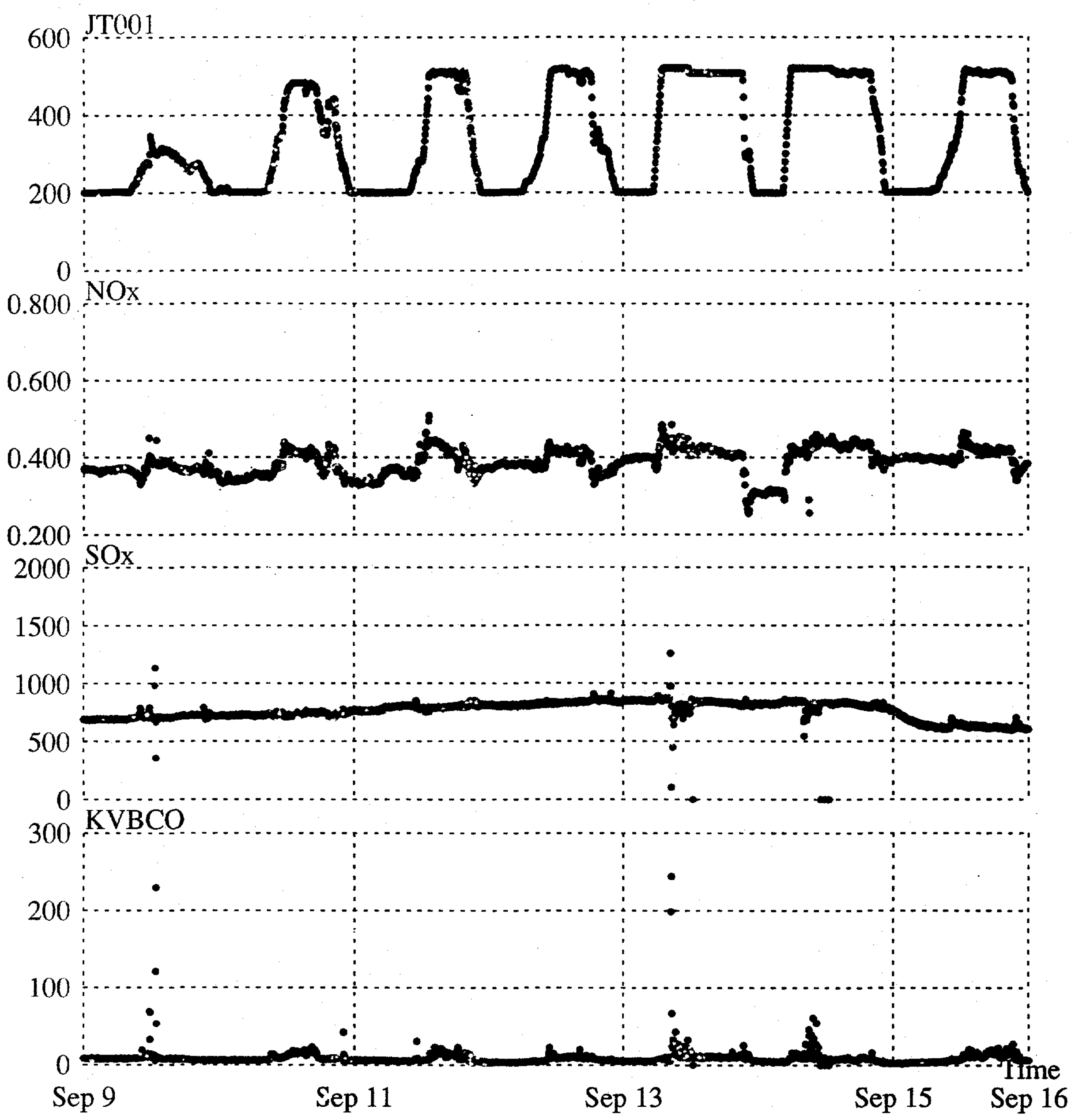

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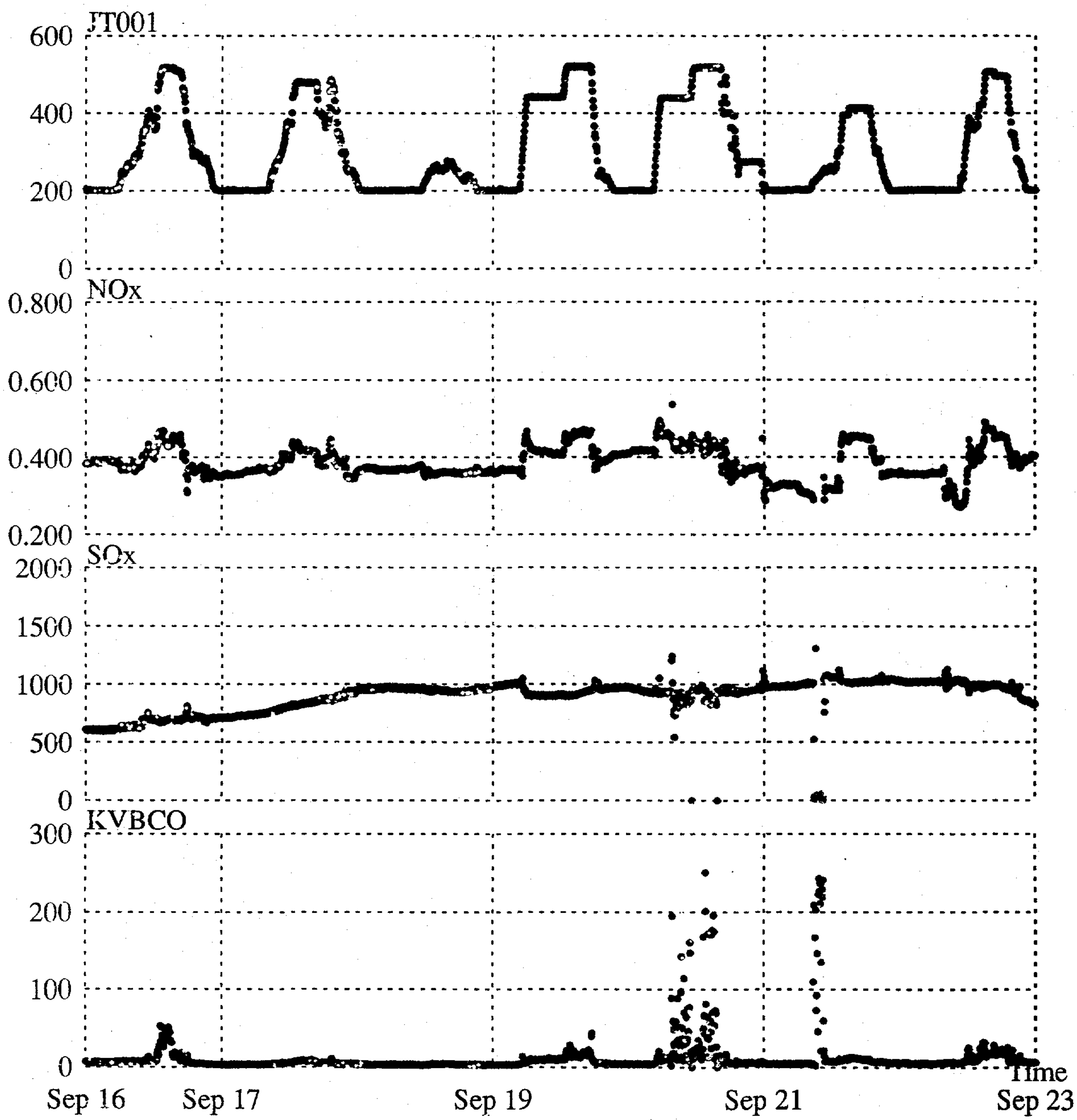

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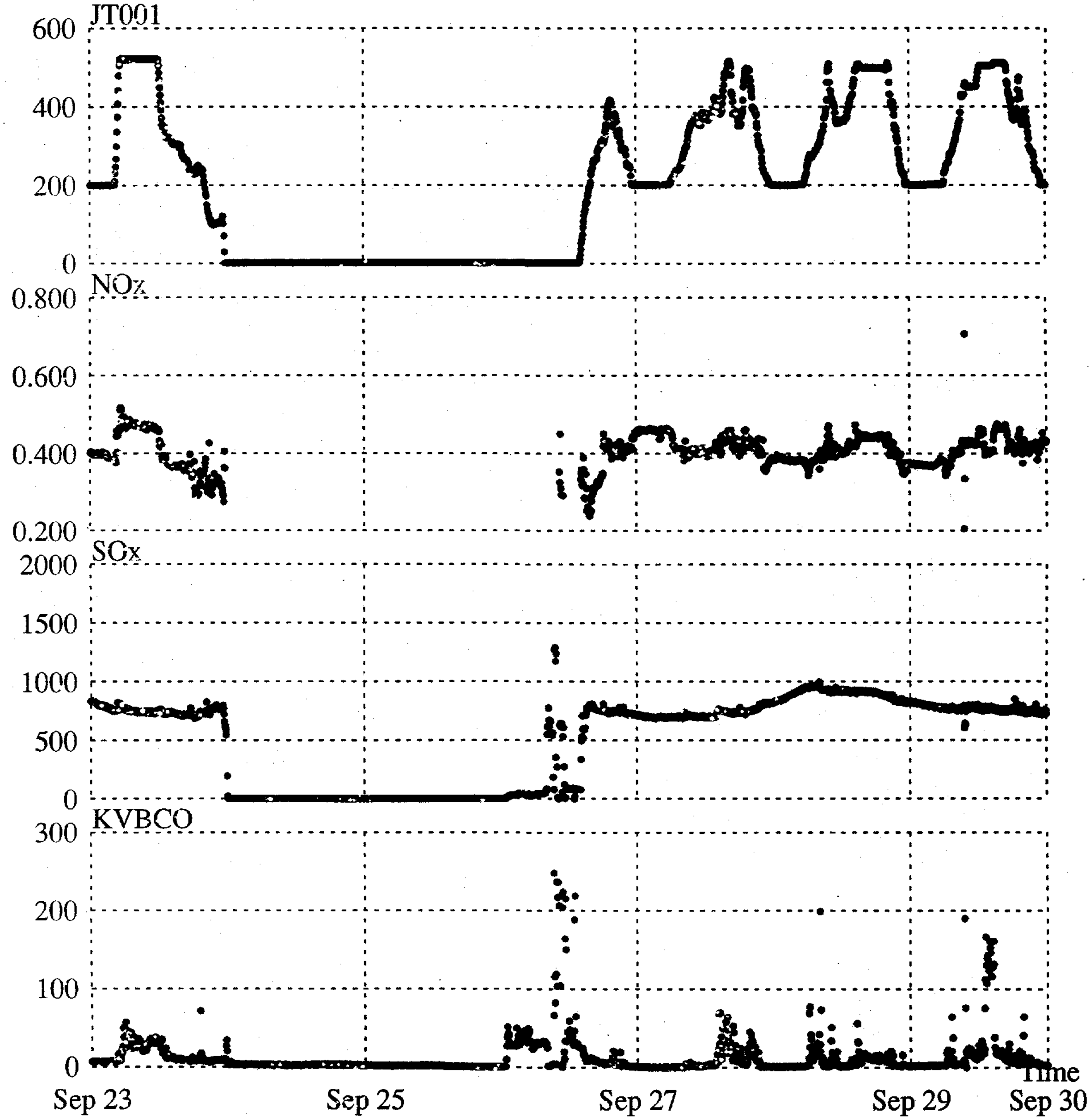

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