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Environmental Protection Technology Series

# EFFECTS OF DESIGN AND OPERATING VARIABLES ON NOX FROM COAL-FIRED FURNACES -- PHASE II

OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

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EPA-650/2-74-002-b

# EFFECTS OF DESIGN AND OPERATING VARIABLES ON NOx FROM COAL-FIRED FURNACES -- PHASE II

by

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## ABSTRACT

The purpose of this contract was to investigate various combustion modification techniques for control of $NO_x$ which might find application on pulverized coal-fired boilers.

The laboratory tests were made on a single burner coal-fired test unit. The techniques studied were: (1) excess air, (2) air preheat, (3) firing rate, (4) flue gas recirculation, (5) staged combustion, (6) quench, and (7) swirl. Natural gas, No. 6 oil and two coals were used in the tests.

For coal combustion, reductions of up to 65% in NO emission levels were observed using staged combustion. Reduction of excess air from 30 to 0% yielded similar results. Flue gas recirculation reduced NO by a small amount, but apparently only thermally formed NO is reduced.

Fuel nitrogen conversion increases with increasing excess air. At substoichiometric conditions, the final precursors for NO formation from either fuel bound nitrogen conversion or thermal atmospheric fixation are identical.

For existing units, control of excess air appears to be the simplest method for $NO_x$ reduction. In addition, when possible staged combustion on existing units could be used to achieve further $NO_x$ reductions.

For new units, staged combustion combined with low excess air firing appears to be the most promising method of $NO_x$ control.



This report was submitted in fulfillment of Contract No. 68-02-0634 by The Babcock & Wilcox Company under the sponsorship of the Environmental Protection Agency. Work was completed as of October 31, 1974.

ACKNOWLEDGEMENTS

The results of this phase of the contract are due to the efforts of others as well at the Alliance Research Center. In particular, W. L. Sage and C. L. Wagoner were responsible for administrative help; E. D. Scott and F. M. Holsopple were responsible for furnace operation; and E. W. Stoffer, J. M. Kibler, and F. M. Holsopple were responsible for instrumentation.

F. M. Holsopple also contributed to two Appendices and Figures in Section II.

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TABLE OF CONTENTS


| | Page |
|---|---|
| SYMBOLS AND ABBREVIATIONS | xi |
| I. INTRODUCTION | 1 |
| A. Objectives of the Contract | 1 |
| B. Phase I | 1 |
| C. Phase II | 2 |
| D. Background and Description of Work | 2 |
| E. Significant Results of the Phase II Work | 3 |
| II. APPARATUS | 5 |
| A. Description of the Basic Combustion Test Unit | 5 |
| B. Furnace and Burner Detail | 14 |
| C. Instrumentation and Sampling | 16 |
| III. PROCEDURES | 19 |
| IV. MEASUREMENTS | 21 |
| A. Variables Studied | 21 |
| B. Variable Testing | 21 |
| C. Range of Variables | 22 |
| D. Measurements Taken | 22 |
| V. PHASE II RESULTS | 23 |
| VI. ANALYSIS OF DATA AND RESULTS | 25 |
| A. Data | 25 |
| B. Colorado Coal Results | 40 |
| VII. COMPARISON OF PHASE I AND PHASE II RESULTS | 55 |
| VIII. DISCUSSION | 63 |
| A. Results | 63 |
| B. Data and Testing Effects | 77 |
| C. Final Presentation | 81 |
| D. Interrelated Variables | 81 |
| IX. CONCLUSIONS | 83 |
| X. REMARKS (Recommendations) | 87 |
| APPENDIX A, FUELS DATA, ANALYSES, AND CALCULATIONS | 89 |
| APPENDIX B, OPERATING CONDITIONS, MEASUREMENTS AND CALCULATIONS | 95 |
| APPENDIX C, PRELIMINARY TEST DATA | 99 |
| APPENDIX D, PRELIMINARY DATA PLOTS | 109 |

TABLE OF CONTENTS (Cont'd)


| | Page |
|---|---|
| APPENDIX E, MATHEMATICAL DERIVATIONS AND CALCULATIONS | 125 |
| APPENDIX F, FUEL NITROGEN CONTENT OF THE OHIO AND COLORADO COALS | 131 |
| APPENDIX G, COMPARATIVE DATA FOR THE OHIO COAL AND NATURAL GAS | 133 |
| APPENDIX H, TABLE OF CONVERSION FACTORS FOR SI UNITS | 135 |
| APPENDIX I, COMBUSTIBLES AND $NO_x$ | 137 |


List of Tables


| Table | | |
|---|---|---|
| 6.1 | Base Line Tests for Colorado Coal (Series VII) | 26 |
| 6.2 | Fineness Tests for Colorado Coal (Series VIII) | 27 |
| 6.3 | Flue Gas Recirculation Tests for Colorado Coal (Series IX) | 27 |
| 6.4 | Staged Combustion Tests for Colorado Coal (Series X) | 28 |
| 6.5 | Slot Changes for Colorado Coal (Series XI) | 29 |
| 6.6 | Burner Changes for Colorado Coal (Series XII) | 30 |
| 6.7 | Summary of Series IX, Part 1 | 32 |
| 6.8 | Summary of Series IX, Part 2 | 32 |
| 6.9 | Summary of Series X, Part 1 | 33 |
| 6.10 | Summary of Series X, Part 2 | 33 |
| 6.11 | Summary of Series XI, Part 1 | 34 |
| 6.12 | Summary of Series XI, Part 2 | 35 |
| 6.13 | Summary of Series XII, Part 1 | 36 |
| 6.14 | Summary of Series XII, Part 2 | 37 |
| 6.15 | Carbon Loss and Burner Efficiency | 38 |
| 6.16 | Slot Changes — Staged Combustion | 39 |
| 6.17 | Burner Changes — Excess Air | 41 |
| 6.18 | Burner Changes — Staged Combustion | 41 |
| 8.1 | Relative Effects on NO in the Flue Gas | 81 |

## TABLE OF CONTENTS (Cont'd)


| Table | | Page |
|---|---|---|
| A.1 | Colorado Coal Analysis | 93 |
| A.2 | Natural Gas Analysis | 94 |
| A.3 | Ohio Coal Analysis | 94 |
| C.1-C.4 | Series VII, Preliminary Data | 101 |
| C.5-C.8 | Series VIII, Preliminary Data | 102 |
| C.9-C.12 | Series IX, Preliminary Data | 102 |
| C.13-C.16 | Series X, Preliminary Data | 103 |
| C.17-C.20 | Series XI, Preliminary Data | 105 |
| C.21-C.24 | Series XII, Preliminary Data | 106 |
| F.1 | Fuel Bound Nitrogen Content | 132 |
| I.1 | Comparison of All Phase I and Phase II Work | 138 |


## List of Figures


| Figure | | |
|---|---|---|
| 2.1 | Basic Combustion Unit | 7 |
| 2.2 | Coal Burner | 7 |
| 2.3 | Coal Impeller | 7 |
| 2.4 | Coal Impeller | 8 |
| 2.5 | Coal Impeller | 8 |
| 2.6 | Coal Impeller | 9 |
| 2.7 | Coal Burner Assembly | 9 |
| 2.8 | Front Slot Positions | 10 |
| 2.9 | Side Slot Positions | 10 |
| 2.10 | Slots — No Change | 10 |
| 2.11 | Slots — No Change | 12 |
| 2.12 | Slots — First Change | 12 |
| 2.13 | Slots — Second Change | 12 |
| 2.14 | Slots — No Change | 13 |
| 2.15 | Slots — Final Change | 13 |
| 2.16 | Furnace Cross Section | 14 |
| 2.17 | Burner Cross Section | 15 |

TABLE OF CONTENTS (Cont'd)


| Figure | | Page |
|---|---|---|
| 2.18 | Burner Changes | 15 |
| 2.19 | Sample System | 17 |
| 2.20 | Instrumentation | 17 |
| 6.1 | Excess Air | 43 |
| 6.2 | Load | 43 |
| 6.3 | Preheat | 44 |
| 6.4 | Fineness – Excess Air | 44 |
| 6.5 | Fineness – Load | 45 |
| 6.6 | Fineness – Preheat | 45 |
| 6.7 | Flue Gas Recirculation | 46 |
| 6.8 | Staging Options | 47 |
| 6.9 | Staged Combustion | 48 |
| 6.10 | Slot Changes | 48 |
| 6.11 | Slot Changes | 51 |
| 6.12 | Burner Changes | 51 |
| 6.13 | Burner Changes | 52 |
| 6.14 | Burner Changes | 52 |
| 6.15 | Burner Changes | 53 |
| 6.16 | Burner Efficiency | 53 |
| 6.17 | Burner Efficiency | 54 |
| 7.1 | Excess Air | 57 |
| 7.2 | Load | 57 |
| 7.3 | Preheat, Normal Excess Air | 59 |
| 7.4 | Preheat, High Excess Air | 59 |
| 7.5 | Secondary Flue Gas Recirculation | 60 |
| 7.6 | Staged Combustion | 62 |
| D.1-D.14 | Preliminary Data, Colorado Coal | 111 |
| D.15-D.20 | Fineness | 114 |
| D.21,D.22 | Flue Gas Recirculation | 116 |
| D.23,D.24 | Substoichiometric Tests | 116 |
| D.25-D.34 | Staged Combustion | 117 |

TABLE OF CONTENTS (Cont'd)


| Figure | | Page |
|---|---|---|
| D.35-D.42 | Slot Changes | 119 |
| D.43-D.54 | Burner Changes | 121 |
| D.55 | Substoichiometric Tests | 124 |
| F.1 | Fuel Nitrogen Content | 132 |
| G.1 | Excess Air | 133 |
| G.2 | Load | 133 |
| G.3 | Preheat | 133 |
| G.4 | Preheat, High Excess Air | 134 |
| G.5 | Secondary Flue Gas Recirculation | 134 |
| G.6 | Coal Staged Combustion | 134 |
| G.7 | Gas, Staged Combustion | 134 |
| I.1 | CO Versus NO (Ohio Coal) | 141 |
| I.2 | CO Versus No (Ohio Coal) | 141 |
| I.3 | CO Versus $O_2$ (Ohio Coal) | 141 |
| I.4 | CO Versus $O_2$ (Ohio Coal) | 141 |
| I.5 | CO Versus NO (Natural Gas) | 142 |
| I.6 | CO Versus NO (Natural Gas) | 142 |
| I.7 | CO Versus $O_2$ (Natural Gas) | 142 |
| I.8 | CO Versus $O_2$ (Natural Gas) | 142 |

## SYMBOLS AND ABBREVIATIONS

This list of symbols and abbreviations is included so that all items in the text may be easily interpreted. All air weights and measurements are calculated dry unless otherwise noted. All items without specific units are used in a "general" form of descriptive equation not requiring numerical calculation.

| Symbol, Abbreviation | Definition |
|---|---|
| A | Pre-exponential rate constant |
| Aver | The average of two measurements |
| BTU | Fuel enthalpy release, BTU/hr |
| $BTU_a$ | Air enthalpy, BTU/lb |
| $BTU_f$ | Flue gas enthalpy, BTU/lb |
| BTUG | Total enthalpy release in furnace, BTU/hr |
| $BTU_m$ | Humidity (in air) enthalpy, BTU/lb of air |
| d | Differential |
| $D_1$ | Diameter of orifice, inches |
| $D_2$ | Diameter of pipe, inches |
| e | Natural constant |
| E | Activation energy |
| f | Subscript indicating forward |
| FB | Fraction of total air at burner |
| FCO2 | Fraction of $CO_2$ in flue gas |
| FGR | Flue gas recirculation, % |
| FH2O | Fraction of $H_2O$ in flue gas |
| k | Kinetic rate constant |
| $L_1$ | Measured value #1, base point |
| $L_1'$ | Standard deviation on base point measurement |
| $L_2$ | Measured value #2, reduced point |
| $L_2'$ | Standard deviation on reduced point measurement |
| $L_3$ | Calculated reduction |
| $L_3'$ | Standard deviation of calculated reduction |
| MA | Moles of stoichiometric air/lb fuel |

## SYMBOLS AND ABBREVIATIONS (Continued)

| Symbol, Abbreviation | Definition |
|---|---|
| MAI | Moles of stoichiometric igniter air/lb igniter fuel |
| MAR | Moles of stoichiometric test air/lb test fuel |
| MC | Moles of $CO_2$ in flue gas/lb fuel |
| MCI | Moles of $CO_2$ in igniter flue gas/lb igniter fuel |
| MCR | Moles of $CO_2$ in test flue gas/lb test fuel |
| MF | Moles of flue gas/lb fuel |
| MFI | Moles of igniter flue gas/lb igniter fuel |
| MFR | Moles of test flue gas/lb test fuel |
| MM | Moles of moisture in flue gas/lb fuel |
| MMF | Moles of moisture from the fuel |
| MMH | Moles of moisture from the air humidity |
| MMI | Moles of moisture in igniter flue gas/lb igniter fuel |
| MMR | Moles of moisture in test flue gas/lb test fuel |
| n | Temperature exponential in kinetic rate expression |
| NDIR | NO measurement from the NDIR instrument, ppm Also used for Beckman "Nondispersive Infrared" |
| NF | Fraction of full meter flow for natural gas igniter |
| NO | Nitric Oxide* |
| $NO_2$ | Nitrogen dioxide |
| $NO_x$ | A mixture of NO and $NO_2$ |
| $N_2$ | Nitrogen* |
| $O_2$ | Oxygen* |
| PB | Barometric pressure, atm |
| PBA | Percent of stoichiometric air at burner |

*This symbol in brackets; i.e., [NO], indicates the concentration of that gas. The units on concentration terms as used in calculations in this report are ppm (parts per million); ordinarily, the symbols are used only in descriptive equations not requiring numerical calculations.

## SYMBOLS AND ABBREVIATIONS (Continued)

| Symbol, Abbreviation | Definition |
|---|---|
| $P_{H_2O}$ | Partial pressure of $H_2O$ in atmosphere, atm |
| $P_{net}$ | Total pressure on orifice, atm |
| POF | Percent oxygen measured in flue gas, corrected for combustibles |
| PS | $P_{net} - P_{H_2O}$, atm |
| PT | PB - $P_{H_2O}$, atm |
| PTA | Percent stoichiometric (theoretical) air |
| r | Subscript indicating reverse |
| R | Gas constant |
| R-N | Specified an organic fuel bound nitrogen molecule |
| STDV | Standard deviation of Aver |
| t | Time |
| T | Temperature of orifice, $^oF$; also used as kinetic temperature for any reaction |
| TA | Ambient temperature, $^oF$ |
| TAG | Air preheat temperature, $^oF$ |
| TECo | NO measurement from TECo instrument, ppm; also used for "Thermo Electron Corp." chemiluminescence |
| TFG | Flue gas temperature, $^oF$ |
| TM | Total moles/lb fuel |
| Total | Subscript designating sum of all partial concentrations |
| W | Weight of gas flow, lb/hr |
| $W_a$ | Weight of air input to furnace, lb/hr |
| $W_f$ | Weight of fuel input to furnace, lb/hr |
| $W_{fg}$ | Weight of flue gas from furnace, lb/hr |
| $W_{fg}'$ | Weight of recycled flue gas, lb/hr |
| $W_N$ | Weight of natural gas flow, lb/hr |
| $W_{NI}$ | Weight of natural gas flow in igniter, lb/hr |

## SYMBOLS AND ABBREVIATIONS (Continued)

| Symbol, Abbreviation | Definition |
|---|---|
| $W_2$ | Weight of air through second stage, lb/hr |
| x | Subscript of variable type indicating any combination; i.e., r, l, etc. |
| $\Delta H$ | Differential pressure across orifice, inches $H_2O$ |
| 1,2,3... | Subscript indicating reaction number for partial value |

# I. INTRODUCTION

## A. Objectives of the Contract

The primary objective of this contract was to investigate on an experimental coal fired furnace, a variety of combustion techniques which could be applicable for control of $NO_x$ and related combustible emissions such as CO, carbon, and hydrocarbons. Additionally, details for defining the critical conditions for application of the most promising combustion control techniques to a single burner furnace were to be provided. Finally, the most successful techniques for pollution control in the burning of coal were to be optimized and potential problems in boiler operational and thermal performance were to be identified. The work for the contract was divided into two phases:

Phase I: Identification of the most promising control techniques using a single burner, pulverized coal fired furnace.

Phase II: Definition of the conditions for the most promising techniques as applied to the single burner unit used in Phase I.

The criteria applied to the testing included the degree to which nitrogen oxides were reduced and the effects on thermal and operational performance.

## B. Phase I

This phase concentrated on a comparison of the $NO_x$ and combustible emissions from an Ohio coal. Natural gas and a #6 fuel oil were

also tested for comparison with the coal. A general comparison of the $NO_x$ control techniques was made. The effects on thermal and operational performance for the application of these techniques were evaluated. The results of the Phase I effort were documented in Final Report EPA-650/2-74-002a.

C. Phase II

The primary objective of this phase was to verify and further define the major variables which were found to influence the formation of $NO_x$ and related combustible emissions in Phase I. A Colorado coal was burned in the single burner, experimental coal fired furnace during Phase II. A comparison of the combustion and $NO_x$ emission characteristics of the Ohio and Colorado coals was also required to determine the general applicability of the control techniques to all utility boiler types which fire coal.

D. Background and Description of Work

The contract work on Phase II was started in July, 1973 and was was completed in July, 1974. A Colorado coal was tested to determine if the same combustion control techniques would control or inhibit $NO_x$ formation to a similar degree as was shown in the Phase I work with the Ohio coal. Additionally the levels of $NO_x$ reduction for both coals were to be compared.

The design and operational variables studied with the Colorado coal were excess air, load, air preheat, staged combustion and port position, port geometry, burner velocity, and to a limited extent, flue gas recirculation. For all test series, except port position and

geometry, the variables were changed over a wide range to include both normal operating conditions and extreme operating conditions which would not ordinarily be practical.

A comparison of the two coals was made. The comparison was based on the percent reduction in $NO_x$ emission levels rather than by the absolute change in $NO_x$ emission levels for each control technique.

E. Significant Results of the Phase II Work

It was found that the Colorado coal yielded absolute $NO_x$ emission levels that were as much as 25% greater than the Ohio coal, apparently due to differences in the way fuel bound nitrogen is converted to $NO_x$. However, the responses of the two coals to the variable trends were similar. Both coals showed about the same percentage reduction in $NO_x$ emission levels over most of the variable ranges.

In the Colorado coal tests, major changes in $NO_x$ emission levels were due to excess air and load. Flue gas recirculation was not effective except at very high levels of recirculation. Staged combustion was the most promising and effective method for $NO_x$ control. Additionally variable port geometry indicated that optimization of the combustion patterns could yield even larger decreases in $NO_x$. Burner velocity changes had a minimal effect on $NO_x$ emission levels in these tests.

Conversion of fuel bound nitrogen to $NO_x$ was found to increase with increasing excess air. Apparently, the same free radicals are present in the final kinetic step for conversion of fuel bound nitrogen and thermal fixation of atmospheric nitrogen.

The variables studied for both the Ohio and Colorado coals were: 1) excess air, 2) load, 3) preheat, 4) staging, and 5) flue gas recirculation. Both coals showed the same qualitative trends to all of the above five control techniques. There is a distinct quantitative difference in the $NO_x$ emission levels for these two coals: this must be due to the percentage of the fuel bound nitrogen converted to NO since both fuels have the same amount of chemically bound nitrogen.

Both coals and natural gas show an identical relationship between $NO_x$ emission level and total combustion air when fired substoichiometrically. All three fuels show $NO_x$ emissions becoming zero at a total combustion air of 60% of stoichiometric. This would indicate a lower limit of 60% of stoichiometric air for the first stage of a multistage combustion process: no further reduction in $NO_x$ emission levels by reduction of the first stage combustion air would seem practical.

During Phase II, the effects of fineness, port geometry, and burner velocity were determined for the Colorado coal. These control techniques could not be studied for the Ohio coal since major changes were required in our pulverizer or furnace equipment. The time and cost of these changes did not permit more than one change and this was made during Phase II testing of the Colorado coal.

## II. APPARATUS

The single burner coal furnace used at the Alliance Research Center is called "The Basic Combustion Test Unit." Adjacent to the furnace is a laboratory area where the instrumentation for stack gas measurements was operated.

### A. Description of the Basic Combustion Test Unit

A schematic of the furnace is shown in Figure 2.1. It is of cylindrical construction with a water-cooled jacket and is partially lined with a 1-inch thick refractory brick. The air input at the burner is split into primary (fuel transport) and secondary air flows. The following burner input represents a typical loading of 5,000,000 Btu per hour for single stage combustion:

| | |
|---|---|
| Primary (fuel transport) | — ∿ 15% total air (∿ 500 lb/hr)<br>500 lb/hr coal |
| Secondary | — ∿ 85% total air (balance of the air or ∿ 3000 lb/hr) |

Figure 2.2 is an illustration of the burner used for coal firing. The spinning vanes are fixed with constant swirl applied to the secondary air. The coal spreader at the end of the primary pipe, Figures 2.3 through 2.6, is set at a 45 degree angle of divergence from the centerline to disperse the coal into the secondary air stream.

Figure 2.7 is a photograph of the coal burner hardware (no fuel supply is shown) as it looked before placement in the windbox. In summary, the following configuration was used for firing:

1) Coal — coal burner (6 vaned) for all tests — coal feed pipe carried primary air (∿ 15% total combustion air) for coal transport and had a divergent 45 degree spreader outlet.

2) Natural gas igniter — supplied up to 1% by weight of the fuel and up to 2% of the Btu release rate in furnace. Used about 3 lb natural gas per hour. Used during all coal tests to maintain stable burning, especially for low air and high load.

The positions of the staging ports are illustrated in Figures 2.8 and 2.9. Figure 2.10 is a photograph of the ports which were cut through the furnace. The front slots were set up to admit second stage air from 1-inch by 12-inch inlets parallel to the burner fuel/air feed. The side slots were set up to introduce air into the furnace from 2-inch by 6-inch slots perpendicular to the central axis but offset circumferentially and arranged so that the mixing swirl around the center axis is opposite to the secondary burner swirl. Only one set of second stage ports was operated at one time; both sets were never operated simultaneously.

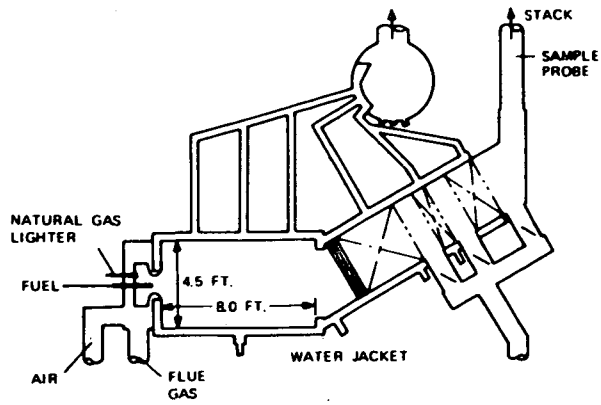


FIGURE 2.1 BASIC COMBUSTION UNIT (SINGLE BURNER)

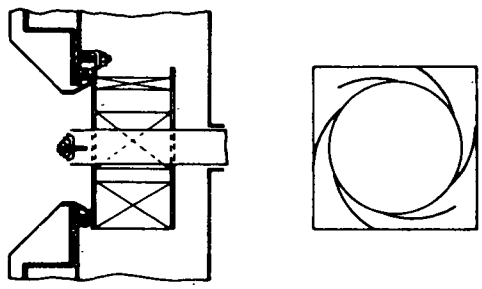

FIGURE 2.2 COAL BURNER

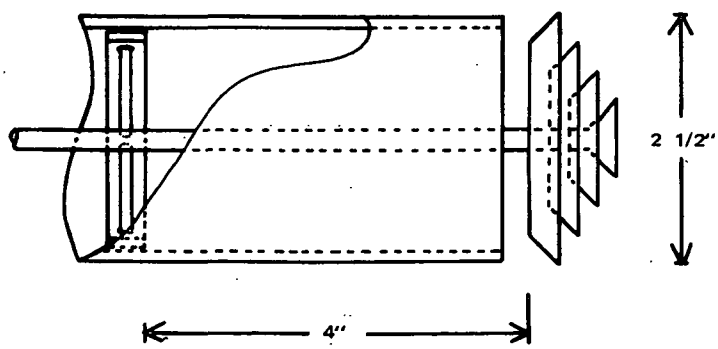


FIGURE 2.3 COAL IMPELLER

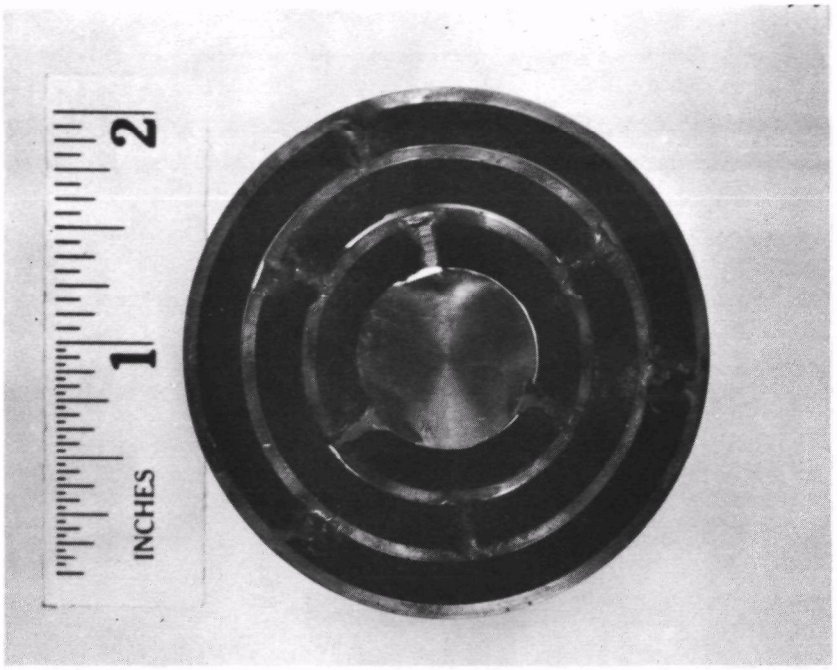


FIGURE 2.4 COAL IMPELLER

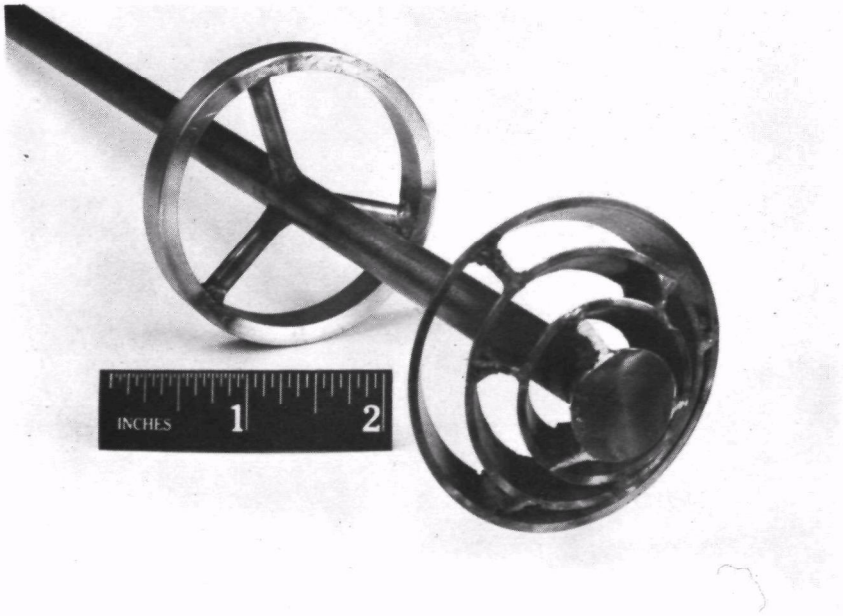


FIGURE 2.5 COAL IMPELLER

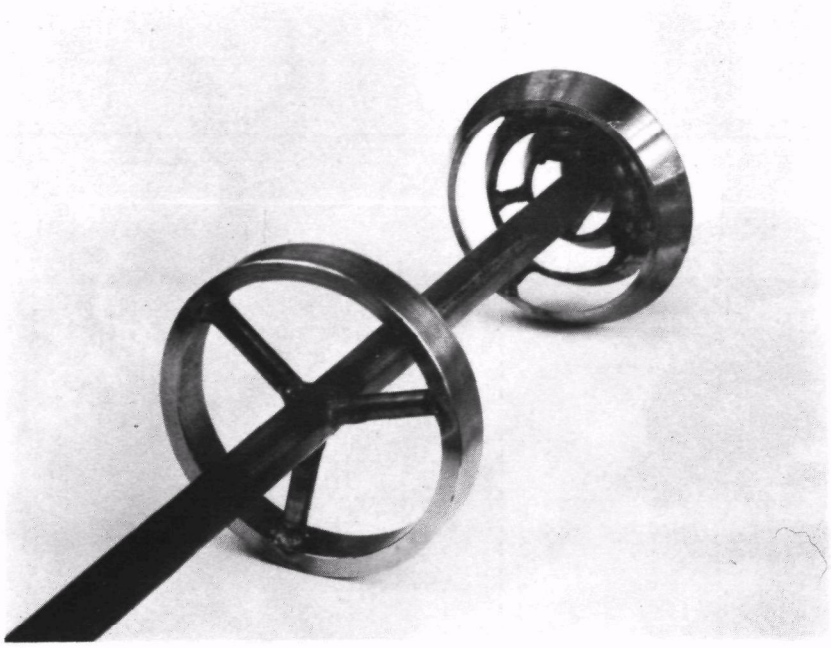

FIGURE 2.6 COAL IMPELLER

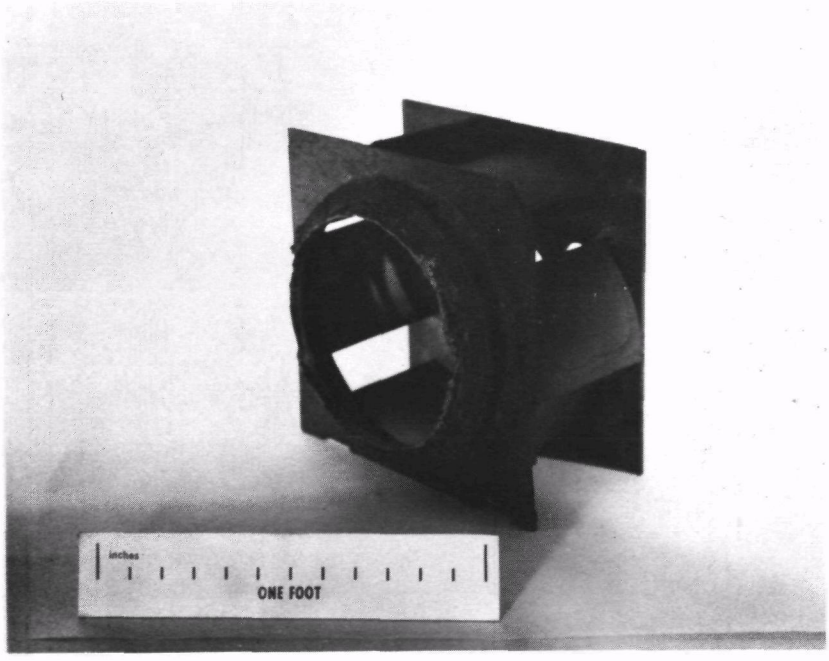


FIGURE 2.7 COAL BURNER ASSEMBLY

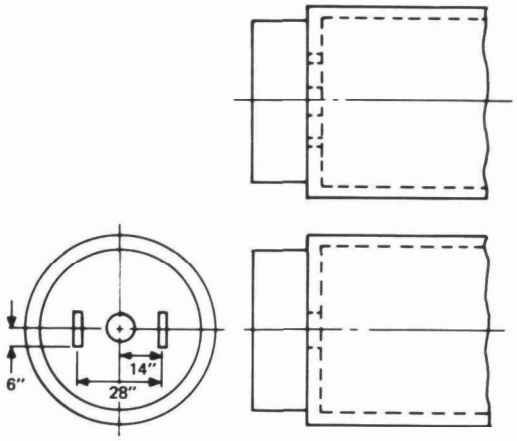


FIGURE 2.8 FRONT SLOT POSITIONS

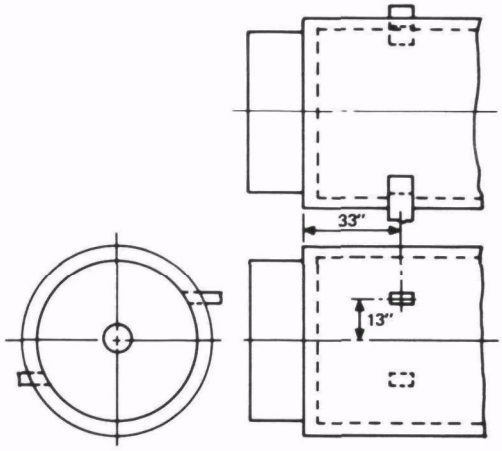


FIGURE 2.9 SIDE SLOT POSITIONS

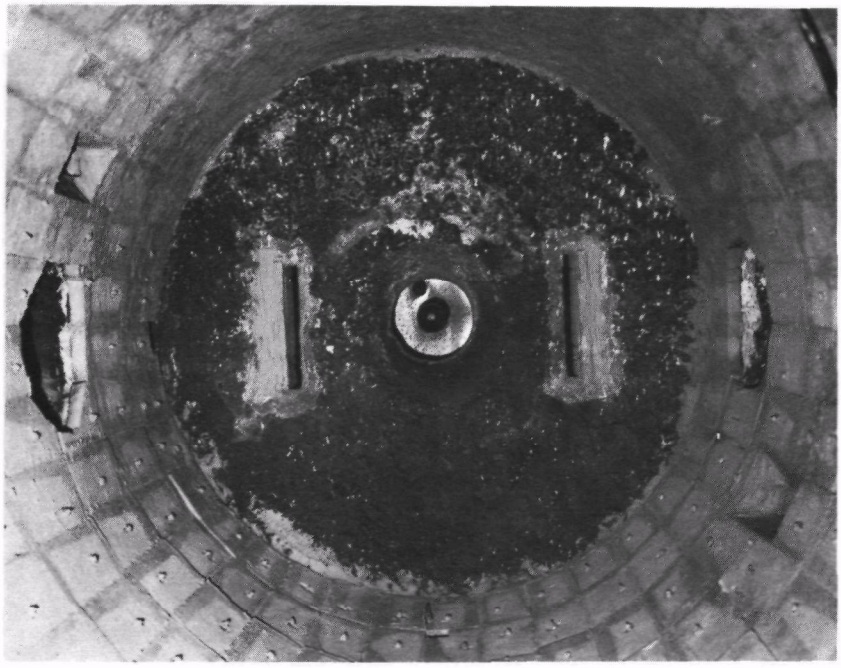

FIGURE 2.10 SLOTS – NO CHANGE

Two changes were made in each set of slots to test the effect of "geometry" of the second stage combustion. The slot geometry for each set of tests is shown below:

1) Base Line (see Figure 2.11)
   Front slots – air entered parallel to burner axis; area of slots 1 x 12 inches.
   Side slots – air entered perpendicular to burner axis on 26-inch diameter circle; area of slots 2 x 6 inches.

(2) First Change (see Figure 2.12)
   Front slots – air entered at a 30 degree inward angle at burner axis; area of slots 1 x 12 inches
   Side slots – air entered perpendicular to burner axis on 13-inch diameter circle, area of slots 3 x 6 inches (50% increase in slot area beyond base line tests)

(3) Second Change (see Figure 2.13)
   Front slots – air entered at a 30 degree outward angle to burner axis; area of slots 1 x 12 inches
   Side slots – air entered perpendicular to burner axis on 13-inch diameter circle, area of slots 4 x 6 inches (100% increase in slot area beyond base line tests)

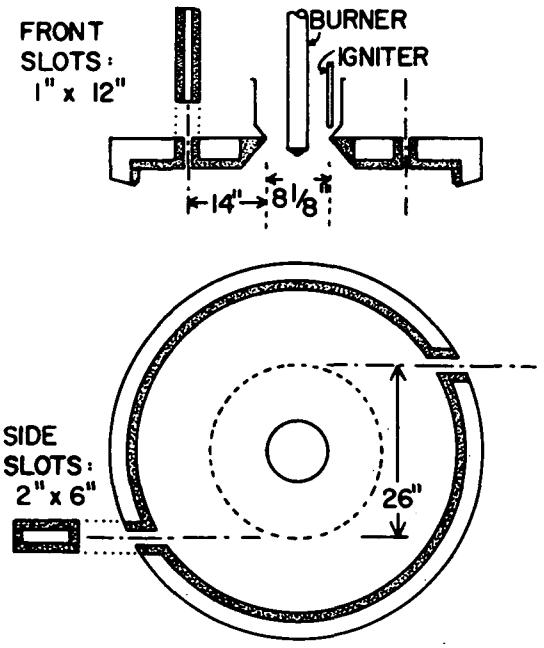


FIGURE 2.11 SLOTS – NO CHANGE

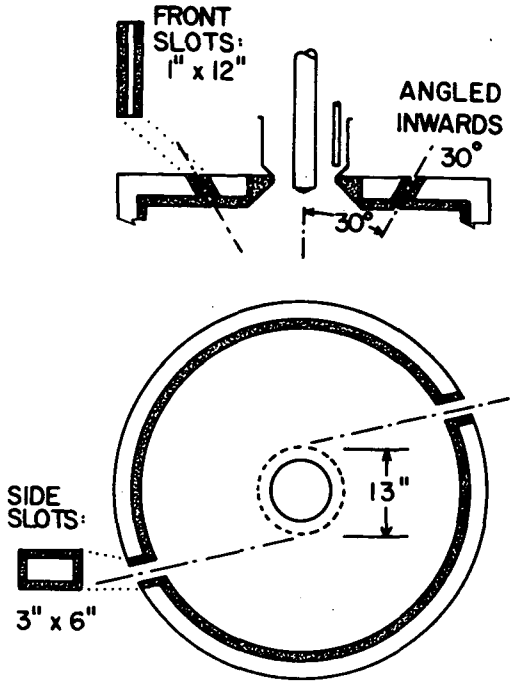


FIGURE 2.12 SLOTS – FIRST CHANGE

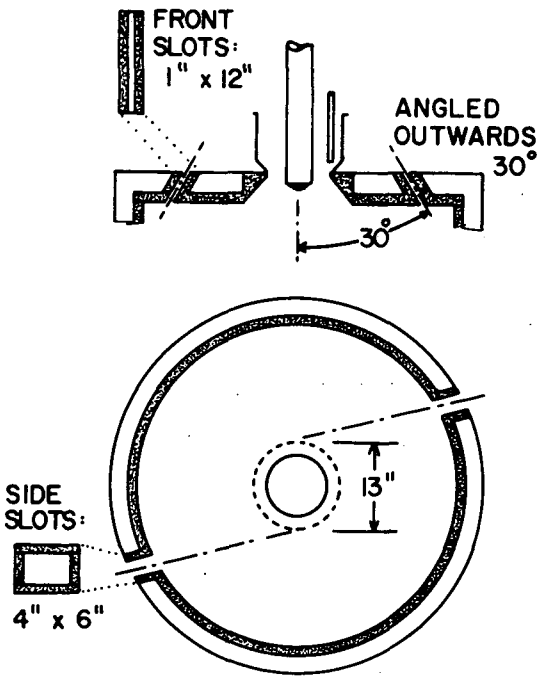


FIGURE 2.13 SLOTS – SECOND CHANGE

Figures 2.14 and 2.15 illustrate the first change in the front slots and are directly comparable to Figure 2.10.

FIGURE 2.14 SLOTS – NO CHANGE

FIGURE 2.15 SLOTS – FINAL CHANGE

B. Furnace and Burner Detail

Figures 2.16 and 2.17 illustrate the details of the furnace and burner cross sections. The impeller position is shown for the coal burner. The coal nozzle exit position is at the beginning of the throat flair.

Burner changes, to study the effect of combustion air burner velocity on $NO_x$ emissions, were made by welding cones of metal into the burner face. Figure 2.18 shows the burner changes that were made to reduce the area by fractions of 1/4 and 1/2. An error of 4% in the calculated area reductions is present because it was thought that the igniter would have to be extended past the burner insert cones to maintain ignition and the area of the igniter was subtracted from the overall area reductions of the throat. Actually, when tested, the flame from the ignition was found to pass smoothly around the inserts and the adjustments to the igniter were not made.

The refractory lining of the furnace is 1-inch brick. The refractory lining extends all around the furnace from the burner to the mid section of the furnace, or a length of 4 feet.

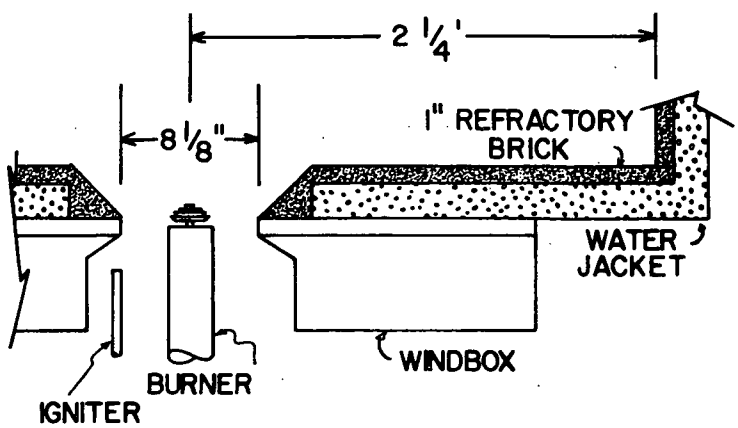


FIGURE 2.16 FURNACE CROSS SECTION

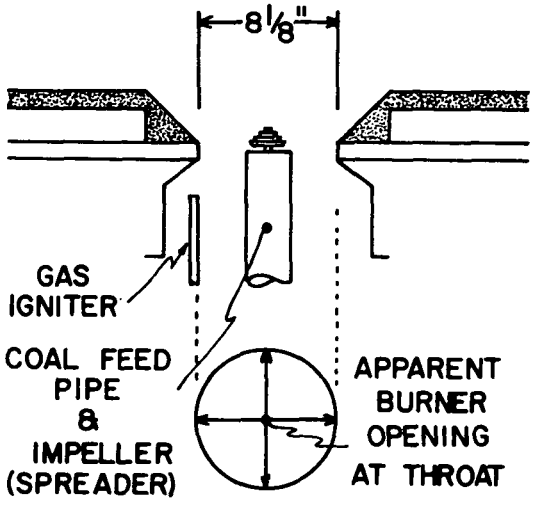


FIGURE 2.17 BURNER CROSS SECTION

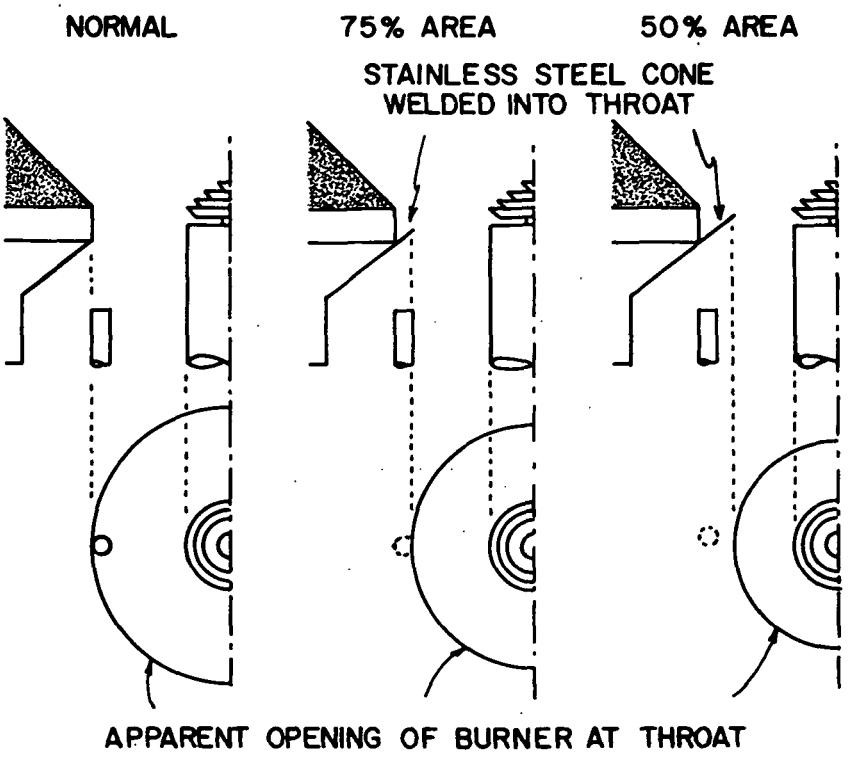


FIGURE 2.18 BURNER CHANGES

## C. Instrumentation and Sampling

There are two probes in the stack from which gases and ash were regularly taken for measurement. Figure 2.19 shows the probe penetration positions into the stack and the relative position of the gas sampling probe inside the stack during sampling. The first probe was used exclusively for pulling ash samples into a bag filter to determine the ash loading in the gas stream and to provide an ash sample for further analysis. The second probe was used exclusively for gas samples and subsequent measurements.

The instrumentation probe branched into two gas sample lines. The first line carried the gas sample into a pair of Bailey Meter hot-wire analyzers used for measuring $O_2$ and total gaseous combustibles. The output from these two meters was continually monitored and recorded. The second line carried the gas sample into a $50^{o}F$ ice bath (see Figure 2.20) before being carried into the instruments. This removed most of the water in the sampled flue gas. The temperature was maintained as closely as possible to $50^{o}F$. The gas sample then flowed separately into each of the following instruments:

1) A Thermo Electron Corporation (TECo) chemiluminescence $NO-NO_2$ monitor

2) A Whittaker NO chemical cell instrument with a Mallcosorb column to remove $SO_2$, $CO_2$, and $H_2O$ before NO measurement

3) A Beckman nondispersive infrared (NDIR) NO analyzer with a pretreatment chamber to remove most of the $H_2O$ which interferes in the NO measurement

4) A Whittaker chemical cell $SO_2$ analyzer

5) An MSA infrared analyzer (LIRA) for CO

6) An MSA paramagnetic $O_2$ analyzer

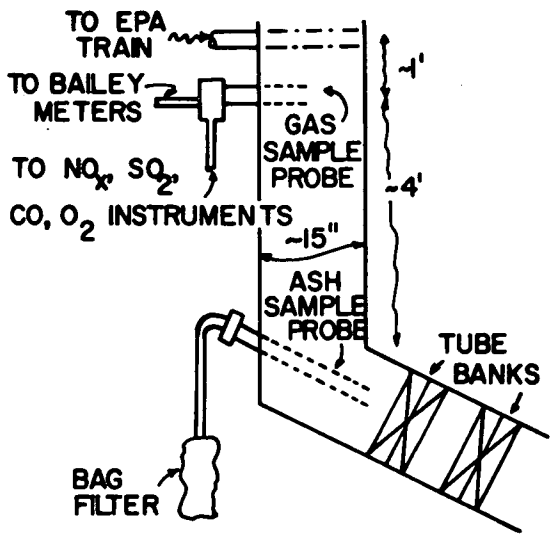


FIGURE 2.19 SAMPLE SYSTEM

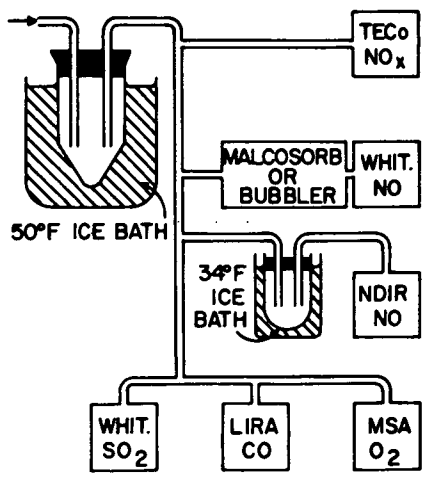


FIGURE 2.20 INSTRUMENTATION

All instrumental outputs except for the CO and $O_2$ analyzers were continuously recorded. The outputs of the CO and $O_2$ instruments were manually recorded for each test. The $50^{o}F$ water bath was sufficient for the TECo and the reading of the TECo was unaffected by minor changes of temperature in this bath.

It was found that a $34^{o}F$ water bath was the only successful treatment for flue gas measurement of NO with the NDIR infrared instrument in the presence of $SO_2$ and $O_2$. The temperature of the sample gas in the cold finger was maintained during testing at $34 \pm 0.5^{o}F$ by periodic addition of ice to the water in the bath. The water interference due to the humidity of $34^{o}F$ saturated flue gas was determined experimentally by bubbling warm air at $70\text{-}80^{o}F$ through water of the same temperature, passing it through the $50^{o}F$ water bath, and then through the $34^{o}F$ ice bath, noting condensation of water in the cold finger. The measured interference used to correct all future flue gas measurements was $55 \pm 5$ ppm NO (the instrument cannot be read to better than $\pm 5$ to 10 ppm NO).

## III. PROCEDURES

A day's testing always commenced with the furnace warmup period and instrument calibration. The test series to be carried out in the day's testing started with one or two base line tests at normal operating conditions to verify that everything was operating properly. Testing began only when the furnace, its related systems, and the instrumentation were functioning properly.

The sequence for a test run was to set furnace conditions and check the operation for all instruments. When all equipment and all temperatures were equilibrated to a constant state of firing, the data were taken; first, data were read from nonrecording instruments, and then, data were read off the strip charts for recording instruments on the basis of the time the test was made.

If there were to be comparison tests run in pairs to determine the relative decrease in emissions, both tests were always run together on the same day in order to minimize day-to-day variations.

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## IV. MEASUREMENTS

### A. Variables Studied

There are two types of control (operational and design) that can be used for reduction of $NO_x$. Operational control techniques are more easily applied to existing units; the physical change on the unit is minimized and the final cost of the change on the unit will be lower. Design methods are best applied to new unit designs to minimize redesign and construction costs. Additionally, it is important to realize that modifications of existing units can be physically impractical or economically unsound.

The design variables, which suggest physical and mechanical changes to a unit, include flue gas recirculation, staged combustion, and basic coal type. The operational variables used on existing units include reductions in excess air, fuel firing rate, and air preheat. These groups of variables are not meant to be mutually exclusive nor totally inclusive. In addition, the geometry of the second stage air addition and the burner air velocity represent important variables.

### B. Variable Testing

An attempt was made to hold all conditions constant and to change the one variable under study over a wide range. However, many of the variables are interrelated and thus as load, excess air, preheat, and the other variables were changed, the burner air velocities changed, leading to a variation in mix rate, turbulence, and combustion intensity. No attempt was made to correlate the interactions of all of these variables.

C. Range of Variables

As each variable was in turn studied, the other variables were held constant. Generally the two extremes and the middle of the range of a variable were tested.

The range of each variable was selected so that the entire practical range of field unit operation could be studied. The extremes of the range were usually outside the practical limits for normal operation of boilers. Conditions have occurred where our basic combustion unit showed unstable combustion tendencies and therefore no meaningful test data could be obtained. Each variable is specifically described under the results.

D. Measurements Taken

The raw flue gas analysis data* taken was: barometric pressure; temperature of the instrument area; oxygen from the MSA; carbon monoxide from the MSA; $SO_2$ from the Whittaker; and NO from the TECo, Whittaker (no $CO_2$, $SO_2$, or $H_2O$ in measured sample), and the NDIR (34$^{o}$F saturated). For substoichiometric firing, only gas chromatography could be used for carbon monoxide and other combustibles. Ash samples were also taken during some tests and the measurements required were: time, differential pressure, and absolute pressure. An ash sample was removed from the filter bag for analysis of unburned carbon.

The furnace data recorded was: the temperature, and absolute and differential pressures, across a flowmeter or an orifice for each of primary air, secondary air, the second stage air, the flue gas, and the natural gas igniter. The coal feeder rate was also recorded, but was used only as a check for the stoichiometric calculations. Finally, the Bailey oxygen and combustibles meter readings were recorded.

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*Unless otherwise specified, all instrumental flue gas measurements were made at the equivalent of 50$^{o}$F saturated.

## V. PHASE II RESULTS

There were six series of tests run during Phase II. A total of about 200 test points are available. Data are presented in tables in Appendix C, in figures in Appendix D, and the mathematical equations and derivations are in Appendix E.

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## VI. ANALYSIS OF DATA AND RESULTS

The data in final form are presented in two forms: tables and graphs. The data in the tables were used to prepare all of the graphs which are in this section.

### A. Data

The headings for Tables 6.1 to 6.6 are described below:

1) Original Series and Run Numbers — Self explanatory.

2) Total Air, % — The total air added as the percentage of 100% theoretical (stoichiometric) air. The excess air is simply 100% less than this number.

3) Heat, kBtu/ft$^3$/hr — The overall net heat release rate in the furnace in thousands of Btu per unit volume.

4) Gas Preheat, $^{o}$F — Combustion air preheat (this is a weighted average which includes the ambient primary air).

5) Flue Gas Input, % — The weight percentage of flue gas recycled back into the combustion air:

$$\frac{W'_{fg}}{W_a + W_f} \times 100$$

6) Air in Burner, % — The total air at the burner as percent of 100% theoretical (stoichiometric) air. The balance of the air (difference between columns 2 and 6) is the air which entered through the second stage ports.

7) $NO_x$, ppm — The NO content of the flue gas corrected to 3% oxygen, dry conditions.

8) CO, ppm — The as measured concentration of CO (and $H_2$ equivalent as CO) in the flue gas.

9) $O_2$, % — The as measured (except for combustibles) concentration of $O_2$ in the flue gas.

**TABLE 6.1 BASE LINE TESTS FOR COLORADO COAL (SERIES VII)**

SERIES VII - COLORADO COAL

FINAL DATA EVALUATION

| ORIGINAL SERIES AND RUN #-S | TOTAL AIR, % | HEAT, KBTU/ FT**3 / HR. | GAS PRE-HEAT DEG F | FLUE GAS INPUT (%) | AIR IN BURNER (%) | NOX PPM | CO PPM | O2 % |
|---|---|---|---|---|---|---|---|---|
| VII - 1 | 113.0 | 49.59 | 608 | 0.0 | 113.0 | 953 | 90 | 2.7 |
| VII - 2 | 138.0 | 50.77 | 635 | 0.0 | 138.0 | 1250 | 60 | 5.8 |
| VII - 3 | 101.5 | 48.96 | 599 | 0.0 | 101.5 | 643 | 3500 | 0.5 |
| VII - 4 | 119.2 | 30.26 | 548 | 0.0 | 119.2 | 820 | 40 | 3.6 |
| VII - 5 | 146.2 | 29.08 | 570 | 0.0 | 146.2 | 981 | 40 | 6.6 |
| VII - 6 | 105.0 | 25.15 | 500 | 0.0 | 105.0 | 510 | 850 | 1.1 |
| VII - 7 | 115.6 | 66.65 | 620 | 0.0 | 115.6 | 1085 | 120 | 3.1 |
| VII - 8 | 102.1 | 47.24 | 585 | 0.0 | 102.1 | 673 | 3000 | 0.6 |
| VII - 9 | 92.8 | 46.21 | 574 | 0.0 | 92.8 | 535 | 34490 | 0.2 |
| VII -10 | 77.4 | 45.66 | 542 | 0.0 | 77.4 | 207 | 95427 | 0.0 |
| VII -11 | 72.8 | 45.66 | 537 | 0.0 | 72.8 | 104 | 145000 | 0.0 |
| VII -12 | 66.5 | 45.58 | 520 | 0.0 | 66.5 | 79 | 205000 | 0.0 |
| VII -13 | 115.0 | 63.74 | 622 | 0.0 | 115.0 | 1196 | 70 | 3.0 |
| VII -14 | 140.0 | 63.19 | 631 | 0.0 | 140.0 | 1368 | 60 | 6.0 |
| VII -15 | 103.6 | 56.90 | 602 | 0.0 | 103.6 | 845 | 2600 | 0.9 |
| VII -16 | 114.9 | 46.76 | 296 | 0.0 | 114.9 | 917 | 150 | 3.0 |
| VII -17 | 141.0 | 45.66 | 298 | 0.0 | 141.0 | 1102 | 60 | 6.1 |
| VII -18 | 104.6 | 43.54 | 285 | 0.0 | 104.6 | 577 | 2600 | 1.1 |
| VII -19 | 115.6 | 58.40 | 286 | 0.0 | 115.6 | 945 | 240 | 3.1 |
| VII -20 | 115.0 | 59.10 | 290 | 0.0 | 115.0 | 912 | 115 | 3.0 |
| VII -21 | 138.9 | 56.67 | 289 | 0.0 | 138.9 | 1042 | 115 | 5.9 |
| VII -22 | 142.0 | 30.34 | 285 | 0.0 | 142.0 | 854 | 60 | 6.2 |
| VII -23 | 115.0 | 28.84 | 279 | 0.0 | 115.0 | 657 | 40 | 3.0 |
| VII -24 | 104.0 | 28.22 | 270 | 0.0 | 104.0 | 443 | 930 | 0.9 |
| VII -25 | 113.6 | 31.12 | 556 | 0.0 | 113.6 | 774 | 375 | 2.8 |
| VII -26 | 113.0 | 52.42 | 621 | 0.0 | 113.0 | 1064 | 100 | 2.7 |
| VII -27 | 142.0 | 51.64 | 637 | 0.0 | 142.0 | 1327 | 100 | 6.2 |
| VII -28 | 136.0 | 55.02 | 633 | 0.0 | 136.0 | 1305 | 150 | 5.6 |
| VII -29 | 104.5 | 48.89 | 600 | 0.0 | 104.5 | 862 | 950 | 1.0 |

## TABLE 6.2 FINENESS TESTS FOR COLORADO COAL (SERIES VIII)

SERIES VIII - FINENESS - COLORADO COAL

FINAL DATA EVALUATION

| ORIGINAL SERIES AND RUN #-S | TOTAL AIR, % | HEAT, KBTU/ FT**3 / HR. | GAS PRE-HEAT DEG F | FLUE GAS INPUT (%) | AIR IN BURNER (%) | NOX PPM | CO PPM | O2 % |
|---|---|---|---|---|---|---|---|---|
| VIII- 1 | 115.0 | 52.97 | 610 | 0.0 | 115.0 | 1044 | 80 | 3.0 |
| VIII- 2 | 113.7 | 52.97 | 615 | 0.0 | 113.7 | 1094 | 100 | 2.8 |
| VIII- 3 | 149.4 | 53.44 | 633 | 0.0 | 149.4 | 1309 | 80 | 6.9 |
| VIII- 4 | 102.8 | 49.91 | 592 | 0.0 | 102.8 | 727 | 2150 | 0.7 |
| VIII- 5 | 114.3 | 32.54 | 551 | 0.0 | 114.3 | 786 | 150 | 2.9 |
| VIII- 6 | 102.9 | 31.04 | 530 | 0.0 | 102.9 | 539 | 1700 | 0.7 |
| VIII- 7 | 150.5 | 33.09 | 583 | 0.0 | 150.5 | 1143 | 100 | 7.0 |
| VIII- 8 | 114.9 | 52.50 | 610 | 0.0 | 114.9 | 1086 | 150 | 3.0 |
| VIII- 9 | 144.1 | 54.86 | 629 | 0.0 | 144.1 | 1299 | 8 | 6.4 |
| VIII- 10 | 119.9 | 51.64 | 621 | 22.2 | 119.9 | 962 | 90 | 3.7 |
| VIII- 11 | 117.0 | 61.78 | 620 | 0.0 | 117.0 | 1226 | 100 | 3.3 |
| VIII- 12 | 115.6 | 47.63 | 293 | 0.0 | 115.6 | 856 | 105 | 3.1 |
| VIII- 13 | 143.0 | 49.20 | 282 | 0.0 | 143.0 | 1014 | 90 | 6.3 |
| VIII- 14 | 102.7 | 44.01 | 270 | 0.0 | 102.7 | 617 | 475 | 0.6 |

## TABLE 6.3 FLUE GAS RECIRCULATION TESTS FOR COLORADO COAL (SERIES IX)

SERIES IX - F. G. R. COLORADO COAL

FINAL DATA EVALUATION

| ORIGINAL SERIES AND RUN #-S | TOTAL AIR, % | HEAT, KBTU/ FT**3 / HR. | GAS PRE-HEAT DEG F | FLUE GAS INPUT (%) | AIR IN BURNER (%) | NOX PPM | CO PPM | O2 % |
|---|---|---|---|---|---|---|---|---|
| IX A - 1 | 112.4 | 52.58 | 615 | 0.0 | 112.4 | 1018 | 120 | 2.6 |
| IX A - 2 | 115.7 | 36.63 | 586 | 0.0 | 115.7 | 811 | 30 | 3.1 |
| IX B - 3 | 111.8 | 53.21 | 618 | 6.6 | 111.8 | 968 | 240 | 2.5 |
| IX B - 4 | 110.4 | 53.29 | 616 | 18.5 | 110.4 | 888 | 130 | 2.2 |
| IX B - 5 | 113.7 | 38.90 | 588 | 22.7 | 113.7 | 770 | 30 | 2.8 |

## TABLE 6.4 STAGED COMBUSTION TESTS FOR COLORADO COAL (SERIES X)

FINAL DATA EVALUATION

| ORIGINAL SERIES AND RUN #-S | TOTAL AIR, % | HEAT, KBTU/ FT**3 / HR. | GAS PRE-HEAT DEG F | FLUE GAS INPUT (%) | AIR IN BURNER (%) | NOX PPM | CO PPM | O2 % |
|---|---|---|---|---|---|---|---|---|
| X A - 1 | 103.9 | 34.35 | 555 | 0.0 | 103.9 | 568 | 1700 | 0.9 |
| X A - 2 | 116.3 | 38.43 | 580 | 0.0 | 116.3 | 917 | 130 | 3.2 |
| X A - 3 | 115.7 | 38.20 | 593 | 0.0 | 115.7 | 869 | 30 | 3.1 |
| X A - 4 | 133.2 | 36.63 | 606 | 0.0 | 133.2 | 1057 | 100 | 5.3 |
| X A - 5 | 148.3 | 39.61 | 620 | 0.0 | 148.3 | 1207 | 100 | 6.8 |
| X A - 6 | 112.3 | 52.42 | 610 | 0.0 | 112.3 | 986 | 325 | 2.6 |
| X A - 7 | 113.7 | 51.95 | 615 | 0.0 | 113.7 | 990 | 60 | 2.8 |
| X A - 8 | 114.3 | 50.93 | 594 | 0.0 | 114.3 | 965 | 150 | 2.9 |
| X A - 9 | 113.0 | 51.17 | 597 | 0.0 | 113.0 | 1056 | 120 | 2.7 |
| X A - 10 | 115.0 | 50.93 | 598 | 0.0 | 115.0 | 1135 | 90 | 3.0 |
| X A - 11 | 114.3 | 51.32 | 619 | 0.0 | 114.3 | 1068 | 100 | 2.9 |
| X A - 12 | 123.8 | 53.37 | 630 | 0.0 | 123.8 | 1248 | 70 | 4.2 |
| X A - 13 | 135.1 | 54.62 | 641 | 0.0 | 135.1 | 1391 | 75 | 5.5 |
| X A - 14 | 117.7 | 49.99 | 623 | 0.0 | 117.7 | 1129 | 180 | 3.4 |
| X A - 15 | 114.3 | 51.72 | 603 | 0.0 | 114.3 | 1121 | 150 | 2.9 |
| X A - 16 | 113.7 | 51.48 | 622 | 0.0 | 113.7 | 1035 | 120 | 2.8 |
| X A - 17 | 145.1 | 52.89 | 607 | 0.0 | 145.1 | 1364 | 60 | 6.5 |
| X A - 18 | 147.2 | 52.82 | 587 | 0.0 | 147.2 | 1396 | 60 | 6.7 |
| X A - 19 | 114.3 | 57.30 | 630 | 0.0 | 114.3 | 1038 | 180 | 2.9 |
| X A - 20 | 104.8 | 46.21 | 596 | 0.0 | 104.8 | 679 | 1600 | 1.1 |
| X A - 21 | 119.2 | 60.99 | 638 | 0.0 | 119.2 | 1182 | 120 | 3.6 |
| X A - 22 | 115.0 | 47.47 | 286 | 0.0 | 115.0 | 874 | 130 | 3.0 |
| X A - 23 | 144.1 | 34.42 | 290 | 0.0 | 144.1 | 897 | 30 | 6.4 |
| X A - 24 | 103.4 | 43.38 | 275 | 0.0 | 103.4 | 415 | 9500 | 1.2 |
| X B - 25 | 103.7 | 33.17 | 537 | 0.0 | 78.4 | 252 | 12500 | 1.4 |
| X B - 26 | 115.6 | 37.57 | 574 | 0.0 | 94.3 | 571 | 300 | 3.1 |
| X B - 27 | 115.0 | 34.82 | 583 | 0.0 | 67.7 | 288 | 1900 | 3.1 |
| X B - 28 | 144.0 | 39.06 | 606 | 0.0 | 117.2 | 990 | 100 | 6.4 |
| X B - 29 | 139.9 | 39.30 | 632 | 0.0 | 88.1 | 582 | 100 | 6.0 |
| X B - 30 | 114.9 | 51.72 | 593 | 0.0 | 104.4 | 935 | 180 | 3.0 |
| X B - 31 | 114.9 | 49.91 | 594 | 0.0 | 93.6 | 761 | 150 | 3.0 |
| X B - 32 | 111.3 | 52.50 | 620 | 0.0 | 72.1 | 398 | 360 | 2.4 |
| X B - 33 | 116.2 | 47.63 | 629 | 0.0 | 62.4 | 386 | 360 | 3.2 |
| X B - 34 | 119.7 | 46.61 | 639 | 0.0 | 54.4 | 389 | 510 | 3.7 |
| X B - 35 | 119.1 | 48.96 | 621 | 0.0 | 96.8 | 784 | 180 | 3.6 |
| X B - 36 | 113.6 | 47.16 | 636 | 0.0 | 70.6 | 412 | 360 | 2.8 |
| X B - 37 | 117.7 | 44.72 | 629 | 0.0 | 58.4 | 385 | 210 | 3.4 |
| X B - 38 | 112.3 | 45.27 | 634 | 0.0 | 45.5 | 329 | 360 | 2.6 |
| X B - 39 | 120.6 | 48.10 | 603 | 0.0 | 109.6 | 899 | 210 | 3.8 |
| X B - 40 | 132.3 | 43.07 | 585 | 0.0 | 107.3 | 898 | 30 | 5.2 |
| X B - 41 | 126.2 | 43.93 | 606 | 0.0 | 78.3 | 651 | 60 | 4.5 |
| X B - 42 | 123.8 | 44.48 | 606 | 0.0 | 66.5 | 539 | 90 | 4.2 |
| X B - 43 | 128.7 | 43.15 | 611 | 0.0 | 56.2 | 505 | 150 | 4.8 |
| X B - 44 | 120.6 | 48.89 | 592 | 0.0 | 98.7 | 748 | 240 | 3.8 |
| X B - 45 | 150.5 | 48.41 | 584 | 0.0 | 106.2 | 1039 | 60 | 7.0 |
| X B - 46 | 140.0 | 52.03 | 591 | 0.0 | 106.4 | 979 | 60 | 6.0 |
| X B - 47 | 152.8 | 46.53 | 606 | 0.0 | 70.2 | 771 | 60 | 7.2 |
| X B - 48 | 105.1 | 44.41 | 588 | 0.0 | 80.2 | 331 | 4400 | 1.3 |
| X B - 49 | 104.0 | 42.36 | 604 | 0.0 | 53.5 | 312 | 3100 | 1.0 |
| X B - 50 | 117.0 | 59.73 | 627 | 0.0 | 94.7 | 763 | 150 | 3.3 |
| X B - 51 | 119.1 | 56.75 | 644 | 0.0 | 72.5 | 496 | 340 | 3.6 |
| X B - 52 | 118.8 | 45.27 | 276 | 0.0 | 87.9 | 433 | 1200 | 3.6 |
| X B - 53 | 115.9 | 44.33 | 279 | 0.0 | 58.9 | 395 | 1200 | 3.2 |
| X B - 54 | 118.8 | 43.46 | 281 | 0.0 | 89.8 | 493 | 1100 | 3.6 |
| X B - 55 | 118.8 | 44.17 | 279 | 0.0 | 63.0 | 477 | 1100 | 3.6 |
| X B - 56 | 147.2 | 32.93 | 283 | 0.0 | 88.1 | 477 | 150 | 6.7 |
| X B - 57 | 104.7 | 41.89 | 273 | 0.0 | 46.9 | 255 | 4000 | 1.2 |

## TABLE 6.5 SLOT CHANGES FOR COLORADO COAL (SERIES XI)

FINAL DATA EVALUATION

| ORIGINAL SERIES AND RUN #-S | TOTAL AIR, % | HEAT, KBTU/ FT**3 / HR. | GAS PRE-HEAT DEG F | FLUE GAS INPUT (%) | AIR IN BURNER (%) | NOX PPM | CO PPM | O2 % |
|---|---|---|---|---|---|---|---|---|
| XI A - 1 | 115.6 | 49.44 | 618 | 0.0 | 115.6 | 1108 | 120 | 3.1 |
| XI A - 2 | 114.6 | 56.59 | 584 | 0.0 | 91.4 | 885 | 120 | 2.9 |
| XI A - 3 | 117.0 | 45.74 | 620 | 0.0 | 62.6 | 414 | 100 | 3.3 |
| XI A - 4 | 113.6 | 48.02 | 605 | 0.0 | 87.0 | 745 | 200 | 2.8 |
| XI A - 5 | 114.3 | 47.55 | 618 | 0.0 | 61.6 | 551 | 90 | 2.9 |
| XI A - 6 | 102.9 | 48.65 | 595 | 0.0 | 102.9 | 757 | 3700 | 0.8 |
| XI A - 7 | 103.9 | 46.45 | 593 | 0.0 | 75.4 | 467 | 3500 | 1.0 |
| XI A - 8 | 106.4 | 43.07 | 609 | 0.0 | 49.6 | 315 | 120 | 1.3 |
| XI A - 9 | 104.2 | 40.95 | 640 | 0.0 | 71.9 | 389 | 2200 | 1.0 |
| XI A -10 | 104.2 | 44.01 | 607 | 0.0 | 49.3 | 315 | 1200 | 0.9 |
| XI A -11 | 115.0 | 36.00 | 588 | 0.0 | 115.0 | 981 | 75 | 3.0 |
| XI A -12 | 116.3 | 33.80 | 587 | 0.0 | 81.9 | 557 | 60 | 3.2 |
| XI A -13 | 115.0 | 30.26 | 605 | 0.0 | 43.6 | 288 | 90 | 3.0 |
| XI A -14 | 115.6 | 32.77 | 594 | 0.0 | 48.8 | 342 | 100 | 3.1 |
| XI B - 1 | 113.7 | 51.01 | 649 | 0.0 | 113.7 | 1083 | 90 | 2.8 |
| XI B - 2 | 115.6 | 48.49 | 609 | 0.0 | 88.3 | 834 | 165 | 3.1 |
| XI B - 3 | 114.0 | 44.96 | 620 | 0.0 | 58.0 | 414 | 115 | 2.8 |
| XI B - 4 | 112.3 | 50.77 | 616 | 0.0 | 85.2 | 704 | 310 | 2.6 |
| XI B - 5 | 115.6 | 48.10 | 661 | 0.0 | 64.0 | 574 | 115 | 3.1 |
| XI B - 6 | 104.3 | 48.02 | 595 | 0.0 | 104.3 | 796 | 2700 | 1.0 |
| XI B - 7 | 104.0 | 43.93 | 594 | 0.0 | 76.6 | 434 | 2000 | 0.9 |
| XI B - 8 | 104.4 | 41.18 | 605 | 0.0 | 49.9 | 399 | 1200 | 1.0 |
| XI B - 9 | 102.1 | 47.31 | 601 | 0.0 | 77.3 | 401 | 8000 | 0.8 |
| XI B -10 | 104.0 | 45.35 | 606 | 0.0 | 55.9 | 318 | 3200 | 1.0 |
| XI B -11 | 114.0 | 36.31 | 591 | 0.0 | 114.0 | 857 | 165 | 2.8 |
| XI B -12 | 114.3 | 33.56 | 582 | 0.0 | 84.5 | 601 | 140 | 2.9 |
| XI B -13 | 116.3 | 31.91 | 590 | 0.0 | 57.4 | 434 | 150 | 3.2 |
| XI B -14 | 116.3 | 31.83 | 580 | 0.0 | 57.3 | 360 | 190 | 3.2 |
| XI C - 1 | 116.3 | 51.32 | 616 | 0.0 | 116.3 | 1096 | 150 | 3.2 |
| XI C - 2 | 114.2 | 48.65 | 598 | 0.0 | 87.1 | 673 | 430 | 2.9 |
| XI C - 3 | 114.1 | 46.45 | 628 | 0.0 | 60.2 | 295 | 810 | 2.9 |
| XI C - 4 | 115.9 | 48.18 | 604 | 0.0 | 88.0 | 611 | 1200 | 3.2 |
| XI C - 5 | 114.9 | 47.31 | 630 | 0.0 | 62.5 | 513 | 300 | 3.0 |
| XI C - 6 | 103.8 | 49.59 | 605 | 0.0 | 103.8 | 784 | 4000 | 1.0 |
| XI C - 7 | 103.7 | 46.29 | 608 | 0.0 | 75.7 | 338 | 6500 | 1.1 |
| XI C - 8 | 104.3 | 44.56 | 615 | 0.0 | 49.5 | 199 | 4000 | 1.1 |
| XI C - 9 | 100.8 | 43.23 | 603 | 0.0 | 70.7 | 385 | 9500 | 0.6 |
| XI C -10 | 101.1 | 45.82 | 623 | 0.0 | 47.7 | 226 | 9500 | 0.7 |
| XI C -11 | 113.6 | 37.02 | 595 | 0.0 | 113.6 | 940 | 125 | 2.8 |
| XI C -12 | 114.7 | 33.56 | 593 | 0.0 | 79.2 | 356 | 960 | 3.0 |
| XI C -13 | 113.5 | 32.62 | 613 | 0.0 | 48.1 | 250 | 500 | 2.8 |
| XI C -14 | 114.3 | 33.87 | 610 | 0.0 | 49.1 | 364 | 260 | 2.9 |

## TABLE 6.6 BURNER CHANGES FOR COLORADO COAL (SERIES XII)

FINAL DATA EVALUATION

| ORIGINAL SERIES AND RUN #-S | TOTAL AIR, % | HEAT, KBTU/ FT**3 / HR. | GAS PRE-HEAT DEG F | FLUE GAS INPUT (%) | AIR IN BURNER (%) | NOX PPM | CO PPM | O2 % |
|---|---|---|---|---|---|---|---|---|
| XII A- 1 | 116.3 | 49.83 | 620 | 0.0 | 116.3 | 1191 | 100 | 3.2 |
| XII A- 2 | 117.7 | 48.89 | 623 | 0.0 | 88.9 | 933 | 75 | 3.4 |
| XII A- 3 | 117.0 | 46.45 | 630 | 0.0 | 63.1 | 512 | 60 | 3.3 |
| XII A- 4 | 114.6 | 38.59 | 598 | 0.0 | 79.5 | 720 | 75 | 2.9 |
| XII A- 5 | 115.6 | 48.81 | 629 | 0.0 | 63.8 | 567 | 150 | 3.1 |
| XII A- 6 | 104.0 | 48.81 | 603 | 0.0 | 104.0 | 824 | 3200 | 1.0 |
| XII A- 7 | 105.6 | 47.39 | 607 | 0.0 | 79.4 | 538 | 1200 | 1.3 |
| XII A- 8 | 105.5 | 45.51 | 617 | 0.0 | 56.6 | 278 | 1600 | 1.3 |
| XII A- 9 | 104.1 | 48.26 | 606 | 0.0 | 79.1 | 434 | 2600 | 1.0 |
| XII A-10 | 105.6 | 47.71 | 616 | 0.0 | 58.1 | 363 | 2100 | 1.3 |
| XII A-11 | 153.8 | 55.65 | 650 | 0.0 | 153.8 | 1327 | 180 | 7.3 |
| XII A-12 | 116.3 | 50.22 | 620 | 0.0 | 116.3 | 1037 | 200 | 3.2 |
| XII A-13 | 113.7 | 37.02 | 590 | 0.0 | 113.7 | 892 | 90 | 2.8 |
| XII A-14 | 115.0 | 33.48 | 579 | 0.0 | 80.2 | 506 | 80 | 3.0 |
| XII A-15 | 118.4 | 31.36 | 605 | 0.0 | 48.0 | 341 | 75 | 3.5 |
| XII A-16 | 117.7 | 33.87 | 581 | 0.0 | 81.6 | 540 | 60 | 3.4 |
| XII A-17 | 114.3 | 33.80 | 609 | 0.0 | 49.5 | 332 | 150 | 2.9 |
| XII A-18 | 115.0 | 46.53 | 301 | 0.0 | 115.0 | 1002 | 100 | 3.0 |
| XII A-19 | 155.1 | 47.79 | 313 | 0.0 | 155.1 | 1192 | 60 | 7.4 |
| XII A-20 | 104.5 | 44.33 | 296 | 0.0 | 104.5 | 745 | 2000 | 1.0 |
| XII B- 1 | 114.6 | 51.01 | 620 | 0.0 | 114.6 | 1220 | 65 | 2.9 |
| XII B- 2 | 112.9 | 49.12 | 611 | 0.0 | 86.3 | 914 | 330 | 2.7 |
| XII B- 3 | 113.9 | 46.76 | 625 | 0.0 | 60.3 | 420 | 300 | 2.8 |
| XII B- 4 | 113.3 | 48.18 | 598 | 0.0 | 86.2 | 865 | 60 | 2.8 |
| XII B- 5 | 114.0 | 47.00 | 623 | 0.0 | 61.4 | 566 | 100 | 2.8 |
| XII B- 6 | 103.7 | 45.58 | 587 | 0.0 | 103.7 | 871 | 2400 | 0.9 |
| XII B- 7 | 104.4 | 44.88 | 601 | 0.0 | 76.9 | 576 | 4300 | 1.1 |
| XII B- 8 | 104.4 | 42.28 | 603 | 0.0 | 51.2 | 303 | 1400 | 1.0 |
| XII B- 9 | 102.0 | 48.34 | 597 | 0.0 | 77.1 | 524 | 3600 | 0.6 |
| XII B-10 | 104.7 | 45.03 | 611 | 0.0 | 53.7 | 304 | 2150 | 1.1 |
| XII B-11 | 155.0 | 53.44 | 642 | 0.0 | 155.0 | 1401 | 120 | 7.4 |
| XII B-12 | 114.0 | 50.69 | 618 | 0.0 | 114.0 | 1216 | 100 | 2.8 |
| XII B-13 | 113.6 | 36.63 | 589 | 0.0 | 113.6 | 1022 | 200 | 2.8 |
| XII B-14 | 113.0 | 35.13 | 593 | 0.0 | 79.0 | 631 | 140 | 2.7 |
| XII B-15 | 114.3 | 32.22 | 609 | 0.0 | 44.8 | 357 | 75 | 2.9 |
| XII B-16 | 115.0 | 34.66 | 594 | 0.0 | 80.5 | 607 | 55 | 3.0 |
| XII B-17 | 115.6 | 34.58 | 600 | 0.0 | 52.7 | 383 | 115 | 3.1 |
| XII B-18 | 113.5 | 47.94 | 289 | 0.0 | 113.5 | 1046 | 450 | 2.8 |
| XII B-19 | 150.5 | 47.94 | 288 | 0.0 | 150.5 | 1183 | 30 | 7.0 |
| XII B-20 | 102.9 | 45.11 | 280 | 0.0 | 102.9 | 748 | 3900 | 0.8 |
| XII C- 1 | 114.0 | 51.32 | 628 | 0.0 | 114.0 | 1108 | 60 | 2.8 |
| XII C- 2 | 112.6 | 48.34 | 616 | 0.0 | 85.4 | 875 | 330 | 2.6 |
| XII C- 3 | 115.0 | 45.11 | 637 | 0.0 | 60.2 | 426 | 100 | 3.0 |
| XII C- 4 | 113.7 | 47.86 | 628 | 0.0 | 86.4 | 726 | 120 | 2.8 |
| XII C- 5 | 113.9 | 46.92 | 635 | 0.0 | 61.1 | 489 | 300 | 2.8 |
| XII C- 6 | 101.8 | 46.06 | 600 | 0.0 | 101.8 | 726 | 4400 | 0.6 |
| XII C- 7 | 102.1 | 42.76 | 594 | 0.0 | 72.9 | 408 | 5000 | 0.7 |
| XII C- 8 | 104.5 | 40.48 | 609 | 0.0 | 44.7 | 326 | 1000 | 1.0 |
| XII C- 9 | 102.8 | 45.11 | 598 | 0.0 | 74.2 | 420 | 3950 | 0.8 |
| XII C-10 | 105.5 | 42.99 | 609 | 0.0 | 48.0 | 238 | 2800 | 1.3 |
| XII C-11 | 145.0 | 51.24 | 639 | 0.0 | 145.0 | 1395 | 200 | 6.5 |
| XII C-12 | 112.4 | 51.56 | 614 | 0.0 | 112.4 | 1172 | 200 | 2.6 |
| XII C-13 | 112.1 | 37.18 | 583 | 0.0 | 112.1 | 1048 | 100 | 2.5 |
| XII C-14 | 111.5 | 47.00 | 605 | 0.0 | 86.4 | 549 | 500 | 2.4 |
| XII C-15 | 113.0 | 34.03 | 596 | 0.0 | 49.3 | 351 | 155 | 2.7 |
| XII C-16 | 111.5 | 36.86 | 584 | 0.0 | 79.0 | 569 | 240 | 2.4 |
| XII C-17 | 111.7 | 34.50 | 605 | 0.0 | 47.1 | 287 | 330 | 2.5 |
| XII C-18 | 114.2 | 47.24 | 294 | 0.0 | 114.2 | 1062 | 500 | 2.9 |
| XII C-19 | 148.3 | 50.30 | 302 | 0.0 | 148.3 | 1165 | 180 | 6.8 |
| XII C-20 | 103.1 | 45.19 | 285 | 0.0 | 103.1 | 714 | 3700 | 0.8 |

In addition, Tables 6.7 to 6.14 inclusive are the final calculations based on the data from Tables 6.1 to 6.6 for use in evaluation of the NO reduction for flue gas recirculation and/or staged combustion. Each of the series is described by two tables; part 1 and part 2. The tabular headings are described as:

Part 1

1) Original Test Numbers: When coupled with the Series Number in the table title, this is self-explanatory.

2) Averages for Tests: These values are the average values for the two tests for:

   a) Load, %: The percentage of fuel Btu input based on 5,000,000 Btu/hr.

   b) Excess Air, %: The percent of air based on stoichiometric air added over and above the 100% theoretical air level.

   c) Temperature, $^{o}F$: The total preheat for the fuel/air input.

3) Burner air, %: The percentage of 100% theoretical (stoichiometric) air coming through the burner as first stage air.

4) Side or Front Slots: The slot position used for second stage air if the tests involved staged combustion.

5) Flue Gas Recycled, %: The percentage of

flue gas recycled from the stack into the combustion air.

6) Burner or Ports: Not applicable to Phase II.

Part 2 7) NO (ppm): The NO measurements in the flue gas corrected to dry, 3% oxygen conditions for the following tests:

a) Base Value: The test before any NO reduction methods were used.

b) With Changes: The test made with NO reduction methods(s) applied.

c) Reduction: The difference between columns a and b.

8) Reduction in NO, %: The percentage reduction from columns 7a and 7b based on the initial value in 7a.

**TABLE 6.7 SUMMARY OF SERIES IX, PART 1**

FINAL REDUCTIONS (PART 1)

| ORIGINAL TEST NOS. | AVERAGES FOR TESTS | | | BURNER AIR, % | SIDE OR FRONT SLOTS | FLUE GAS RECYC. % | BURNER OR PORTS |
|---|---|---|---|---|---|---|---|
| | LOAD, % | EXCESS AIR, % | TEMP. DEG F | | | | |
| IX - 1/3 | 119.8 | 12.1 | 616 | 112.1 | ---- | 6.6 | BURNER |
| IX - 1/4 | 119.3 | 11.4 | 615 | 111.4 | ---- | 18.5 | BURNER |
| IX - 2/5 | 85.0 | 14.7 | 587 | 114.7 | ---- | 22.7 | BURNER |

**TABLE 6.8 SUMMARY OF SERIES IX, PART 2**

FINAL REDUCTIONS (PART 2)

| ORIGINAL TEST NOS. | NO (PPM) | | | REDUCTION IN NO, % |
|---|---|---|---|---|
| | BASE VALUE | WITH CHANGES | REDUCTION | |
| IX - 1/3 | 1018 ± 12 | 968 ± 11 | 50 ± 16 | 4.9 ± 1.6 |
| IX - 1/4 | 1018 ± 12 | 888 ± 28 | 130 ± 30 | 12.8 ± 3.0 |
| IX - 2/5 | 811 ± 7 | 770 ± 11 | 41 ± 13 | 5.1 ± 1.6 |

## TABLE 6.9 SUMMARY OF SERIES X, PART 1

FINAL REDUCTIONS (PART 1)

| ORIGINAL TEST NOS. | AVERAGES FOR TESTS: LOAD, % | EXCESS AIR, % | TEMP. DEG F | BURNER AIR, % | SIDE OR FRONT SLOTS | FLUE GAS RECYC. % | BURNER OR PORTS |
|---|---|---|---|---|---|---|---|
| X - 1/25 | 79.7 | 3.8 | 546 | 78.4 | FRONT | 0.0 | ---- |
| X - 2/26 | 88.1 | 15.9 | 577 | 94.3 | FRONT | 0.0 | ---- |
| X - 3/27 | 86.1 | 15.3 | 568 | 67.7 | FRONT | 0.0 | ---- |
| X - 5/28 | 88.3 | 46.1 | 613 | 117.2 | FRONT | 0.0 | ---- |
| X - 5/29 | 89.9 | 44.1 | 626 | 88.1 | FRONT | 0.0 | ---- |
| X -15/30 | 118.3 | 14.6 | 598 | 104.4 | FRONT | 0.0 | ---- |
| X -10/31 | 116.4 | 14.9 | 596 | 93.6 | FRONT | 0.0 | ---- |
| X -19/32 | 127.5 | 12.8 | 625 | 72.1 | FRONT | 0.0 | ---- |
| X -10/33 | 115.9 | 15.6 | 613 | 62.4 | FRONT | 0.0 | ---- |
| X -14/34 | 113.7 | 18.7 | 631 | 54.4 | FRONT | 0.0 | ---- |
| X -14/35 | 113.2 | 18.4 | 622 | 96.8 | FRONT | 0.0 | ---- |
| X -11/36 | 114.4 | 13.9 | 627 | 70.6 | FRONT | 0.0 | ---- |
| X -14/37 | 111.1 | 17.7 | 626 | 58.4 | FRONT | 0.0 | ---- |
| X -11/38 | 114.2 | 13.3 | 626 | 45.5 | FRONT | 0.0 | ---- |
| X -14/39 | 111.6 | 19.1 | 613 | 109.6 | SIDE | 0.0 | ---- |
| X -13/40 | 110.1 | 33.7 | 613 | 107.3 | SIDE | 0.0 | ---- |
| X -12/41 | 112.1 | 25.0 | 618 | 78.3 | SIDE | 0.0 | ---- |
| X -12/42 | 113.5 | 23.8 | 618 | 66.5 | SIDE | 0.0 | ---- |
| X -13/43 | 113.3 | 31.9 | 626 | 56.2 | SIDE | 0.0 | ---- |
| X -14/44 | 113.0 | 19.1 | 607 | 98.7 | SIDE | 0.0 | ---- |
| X -18/45 | 114.8 | 48.8 | 585 | 106.2 | FRONT | 0.0 | ---- |
| X -13/46 | 120.4 | 37.5 | 616 | 106.4 | SIDE | 0.0 | ---- |
| X -18/47 | 114.9 | 50.0 | 596 | 70.2 | SIDE | 0.0 | ---- |
| X -20/48 | 105.9 | 4.9 | 592 | 80.2 | FRONT | 0.0 | ---- |
| X -20/49 | 105.4 | 4.4 | 600 | 53.5 | FRONT | 0.0 | ---- |
| X -21/50 | 137.7 | 18.1 | 632 | 94.7 | FRONT | 0.0 | ---- |
| X -21/51 | 136.1 | 19.1 | 641 | 72.5 | FRONT | 0.0 | ---- |
| X -22/52 | 113.7 | 16.9 | 281 | 87.9 | FRONT | 0.0 | ---- |
| X -22/53 | 113.3 | 15.4 | 282 | 58.9 | FRONT | 0.0 | ---- |
| X -22/54 | 111.5 | 16.9 | 283 | 89.8 | SIDE | 0.0 | ---- |
| X -22/55 | 113.0 | 16.9 | 282 | 63.0 | SIDE | 0.0 | ---- |
| X -23/56 | 82.4 | 45.6 | 286 | 88.1 | FRONT | 0.0 | ---- |
| X -24/57 | 105.9 | 4.0 | 274 | 46.9 | FRONT | 0.0 | ---- |

## TABLE 6.10 SUMMARY OF SERIES X, PART 2

FINAL REDUCTIONS (PART 2)

| ORIGINAL TEST NOS. | NO (PPM): BASE VALUE | WITH CHANGES | REDUCTION | REDUCTION IN NO, % |
|---|---|---|---|---|
| X - 1/25 | 568 ± 9 | 252 ± 5 | 316 ± 10 | 55.6 ± 2.0 |
| X - 2/26 | 917 ± 37 | 571 ± 6 | 346 ± 37 | 37.7 ± 4.4 |
| X - 3/27 | 869 ± 26 | 288 ± 1 | 581 ± 26 | 66.9 ± 3.6 |
| X - 5/28 | 1207 ± 64 | 990 ± 22 | 217 ± 68 | 18.0 ± 5.7 |
| X - 5/29 | 1207 ± 64 | 582 ± 3 | 625 ± 64 | 51.8 ± 6.0 |
| X -15/30 | 1121 ± 34 | 935 ± 40 | 186 ± 52 | 16.6 ± 4.7 |
| X -10/31 | 1135 ± 9 | 761 ± 36 | 374 ± 37 | 33.0 ± 3.3 |
| X -19/32 | 1038 ± 16 | 398 ± 12 | 640 ± 20 | 61.7 ± 2.1 |
| X -10/33 | 1135 ± 9 | 386 ± 2 | 749 ± 9 | 66.0 ± 1.0 |
| X -14/34 | 1129 ± 16 | 389 ± 6 | 740 ± 17 | 65.5 ± 1.8 |
| X -14/35 | 1129 ± 16 | 784 ± 48 | 345 ± 51 | 30.6 ± 4.5 |
| X -11/36 | 1068 ± 23 | 412 ± 55 | 656 ± 60 | 61.4 ± 5.7 |
| X -14/37 | 1129 ± 16 | 385 ± 2 | 744 ± 16 | 65.9 ± 1.7 |
| X -11/38 | 1068 ± 23 | 329 ± 2 | 739 ± 23 | 69.2 ± 2.6 |
| X -14/39 | 1129 ± 16 | 899 ± 19 | 230 ± 25 | 20.4 ± 2.2 |
| X -13/40 | 1391 ± 73 | 898 ± 29 | 493 ± 79 | 35.4 ± 5.9 |
| X -12/41 | 1248 ± 40 | 651 ± 19 | 597 ± 44 | 47.8 ± 3.9 |
| X -12/42 | 1248 ± 40 | 539 ± 14 | 709 ± 42 | 56.8 ± 3.9 |
| X -13/43 | 1391 ± 73 | 505 ± 18 | 886 ± 75 | 63.7 ± 6.4 |
| X -14/44 | 1129 ± 16 | 748 ± 7 | 381 ± 17 | 33.7 ± 1.6 |
| X -18/45 | 1396 ± 11 | 1039 ± 5 | 357 ± 12 | 25.6 ± 0.9 |
| X -13/46 | 1391 ± 73 | 979 ± 17 | 412 ± 75 | 29.6 ± 5.6 |
| X -18/47 | 1396 ± 11 | 771 ± 31 | 625 ± 33 | 44.8 ± 2.4 |
| X -20/48 | 679 ± 10 | 331 ± 5 | 348 ± 11 | 51.3 ± 1.8 |
| X -20/49 | 679 ± 10 | 312 ± 2 | 367 ± 10 | 54.1 ± 1.7 |
| X -21/50 | 1182 ± 20 | 763 ± 7 | 419 ± 21 | 35.4 ± 1.9 |
| X -21/51 | 1182 ± 20 | 496 ± 10 | 686 ± 22 | 58.0 ± 2.1 |
| X -22/52 | 874 ± 26 | 433 ± 2 | 441 ± 26 | 50.5 ± 3.3 |
| X -22/53 | 874 ± 26 | 395 ± 2 | 479 ± 26 | 54.8 ± 3.4 |
| X -22/54 | 874 ± 26 | 493 ± 9 | 381 ± 28 | 43.6 ± 3.4 |
| X -22/55 | 874 ± 26 | 477 ± 9 | 397 ± 28 | 45.4 ± 3.4 |
| X -23/56 | 897 ± 4 | 477 ± 7 | 420 ± 8 | 46.8 ± 0.9 |
| X -24/57 | 415 ± 14 | 255 ± 18 | 160 ± 23 | 38.6 ± 5.6 |

## TABLE 6.11 SUMMARY OF SERIES XI, PART 1

FINAL REDUCTIONS (PART 1)

| ORIGINAL TEST NOS. | AVERAGES FOR TESTS LOAD, % | EXCESS AIR, % | TEMP. DEG F | BURNER AIR, % | SIDE OR FRONT SLOTS | FLUE GAS RECYC. % | BURNER OR PORTS |
|---|---|---|---|---|---|---|---|
| A 1/ 2 | 120.6 | 15.1 | 601 | 91.4 | FRONT | 0.0 | ---- |
| A 1/ 3 | 111.3 | 16.3 | 619 | 62.6 | FRONT | 0.0 | ---- |
| A 1/ 4 | 112.3 | 14.6 | 611 | 87.0 | SIDE | 0.0 | ---- |
| A 1/ 5 | 113.7 | 14.9 | 618 | 61.6 | SIDE | 0.0 | ---- |
| A 6/ 7 | 111.3 | 3.4 | 594 | 75.4 | FRONT | 0.0 | ---- |
| A 6/ 8 | 109.2 | 4.6 | 602 | 49.6 | FRONT | 0.0 | ---- |
| A 6/ 9 | 104.6 | 3.5 | 617 | 71.9 | SIDE | 0.0 | ---- |
| A 6/10 | 110.4 | 3.5 | 601 | 49.3 | SIDE | 0.0 | ---- |
| A 11/12 | 81.2 | 15.6 | 587 | 81.9 | FRONT | 0.0 | ---- |
| A 11/13 | 79.0 | 15.0 | 596 | 43.6 | FRONT | 0.0 | ---- |
| A 11/14 | 82.0 | 15.3 | 591 | 48.8 | SIDE | 0.0 | ---- |
| B 1/ 2 | 114.3 | 14.6 | 629 | 88.3 | FRONT | 0.0 | ---- |
| B 1/ 3 | 112.3 | 13.8 | 634 | 58.0 | FRONT | 0.0 | ---- |
| B 1/ 4 | 117.1 | 13.0 | 632 | 85.2 | SIDE | 0.0 | ---- |
| B 1/ 5 | 115.3 | 14.6 | 655 | 64.0 | SIDE | 0.0 | ---- |
| B 6/ 7 | 107.6 | 4.1 | 594 | 76.6 | FRONT | 0.0 | ---- |
| B 6/ 8 | 106.3 | 4.3 | 600 | 49.9 | FRONT | 0.0 | ---- |
| B 6/ 9 | 111.5 | 3.2 | 598 | 77.3 | SIDE | 0.0 | ---- |
| B 6/10 | 110.9 | 4.1 | 600 | 55.9 | SIDE | 0.0 | ---- |
| B 11/12 | 81.3 | 14.1 | 586 | 84.5 | FRONT | 0.0 | ---- |
| B 11/13 | 80.9 | 15.1 | 590 | 57.4 | FRONT | 0.0 | ---- |
| B 11/14 | 80.9 | 15.1 | 585 | 57.3 | SIDE | 0.0 | ---- |
| C 1/ 2 | 115.1 | 15.2 | 607 | 87.1 | FRONT | 0.0 | ---- |
| C 1/ 3 | 114.4 | 15.2 | 622 | 60.2 | FRONT | 0.0 | ---- |
| C 1/ 4 | 114.5 | 16.1 | 610 | 88.0 | SIDE | 0.0 | ---- |
| C 1/ 5 | 115.3 | 15.6 | 623 | 62.5 | SIDE | 0.0 | ---- |
| C 6/ 7 | 112.0 | 3.7 | 606 | 75.7 | FRONT | 0.0 | ---- |
| C 6/ 8 | 112.1 | 4.0 | 610 | 49.5 | FRONT | 0.0 | ---- |
| C 6/ 9 | 108.8 | 2.3 | 604 | 70.7 | SIDE | 0.0 | ---- |
| C 6/10 | 113.6 | 2.4 | 614 | 47.7 | SIDE | 0.0 | ---- |
| C 11/12 | 82.4 | 14.1 | 594 | 79.2 | FRONT | 0.0 | ---- |
| C 11/13 | 83.0 | 13.5 | 604 | 48.1 | FRONT | 0.0 | ---- |
| C 11/14 | 84.5 | 13.9 | 602 | 49.1 | SIDE | 0.0 | ---- |

## TABLE 6.12 SUMMARY OF SERIES XI, PART 2

FINAL REDUCTIONS (PART 2)

| ORIGINAL TEST NOS. | NO (PPM) BASE VALUE | NO (PPM) WITH CHANGES | NO (PPM) REDUCTION | REDUCTION IN NO, % |
|---|---|---|---|---|
| A 1/ 2 | 1108 ± 63 | 885 ± 29 | 223 ± 69 | 20.1 ± 6.4 |
| A 1/ 3 | 1108 ± 63 | 414 ± 17 | 694 ± 65 | 62.6 ± 6.9 |
| A 1/ 4 | 1108 ± 63 | 745 ± 32 | 363 ± 71 | 32.8 ± 6.6 |
| A 1/ 5 | 1108 ± 63 | 551 ± 20 | 557 ± 66 | 50.3 ± 6.6 |
| A 6/ 7 | 757 ± 20 | 467 ± 12 | 290 ± 23 | 38.3 ± 3.2 |
| A 6/ 8 | 757 ± 20 | 315 ± 8 | 442 ± 22 | 58.4 ± 3.2 |
| A 6/ 9 | 757 ± 20 | 389 ± 13 | 368 ± 24 | 48.6 ± 3.4 |
| A 6/10 | 757 ± 20 | 315 ± 11 | 442 ± 23 | 58.4 ± 3.4 |
| A 11/12 | 981 ± 48 | 557 ± 17 | 424 ± 51 | 43.2 ± 5.6 |
| A 11/13 | 981 ± 48 | 288 ± 6 | 693 ± 48 | 70.6 ± 6.0 |
| A 11/14 | 981 ± 48 | 342 ± 11 | 639 ± 49 | 65.1 ± 5.9 |
| B 1/ 2 | 1083 ± 30 | 834 ± 18 | 249 ± 35 | 23.0 ± 3.3 |
| B 1/ 3 | 1083 ± 30 | 414 ± 13 | 669 ± 33 | 61.8 ± 3.5 |
| B 1/ 4 | 1083 ± 30 | 704 ± 21 | 379 ± 37 | 35.0 ± 3.5 |
| B 1/ 5 | 1083 ± 30 | 574 ± 17 | 509 ± 34 | 47.0 ± 3.4 |
| B 6/ 7 | 796 ± 26 | 434 ± 15 | 362 ± 30 | 45.5 ± 4.1 |
| B 6/ 8 | 796 ± 26 | 399 ± 8 | 397 ± 27 | 49.9 ± 3.8 |
| B 6/ 9 | 796 ± 26 | 401 ± 11 | 395 ± 28 | 49.6 ± 3.9 |
| B 6/10 | 796 ± 26 | 318 ± 5 | 478 ± 26 | 60.1 ± 3.9 |
| B 11/12 | 857 ± 11 | 601 ± 6 | 256 ± 13 | 29.9 ± 1.5 |
| B 11/13 | 857 ± 11 | 434 ± 12 | 423 ± 16 | 49.4 ± 2.0 |
| B 11/14 | 857 ± 11 | 360 ± 9 | 497 ± 14 | 58.0 ± 1.8 |
| C 1/ 2 | 1096 ± 45 | 673 ± 67 | 423 ± 81 | 38.6 ± 7.5 |
| C 1/ 3 | 1096 ± 45 | 295 ± 6 | 801 ± 45 | 73.1 ± 5.1 |
| C 1/ 4 | 1096 ± 45 | 611 ± 17 | 485 ± 48 | 44.3 ± 4.8 |
| C 1/ 5 | 1096 ± 45 | 513 ± 13 | 583 ± 47 | 53.2 ± 4.8 |
| C 6/ 7 | 784 ± 16 | 338 ± 8 | 446 ± 18 | 56.9 ± 2.6 |
| C 6/ 8 | 784 ± 16 | 199 ± 1 | 585 ± 16 | 74.6 ± 2.5 |
| C 6/ 9 | 784 ± 16 | 385 ± 4 | 399 ± 16 | 50.9 ± 2.3 |
| C 6/10 | 784 ± 16 | 226 ± 8 | 558 ± 18 | 71.2 ± 2.7 |
| C 11/12 | 940 ± 10 | 356 ± 2 | 584 ± 10 | 62.1 ± 1.3 |
| C 11/13 | 940 ± 10 | 250 ± 6 | 690 ± 12 | 73.4 ± 1.5 |
| C 11/14 | 940 ± 10 | 364 ± 9 | 576 ± 13 | 61.3 ± 1.6 |

## TABLE 6.13 SUMMARY OF SERIES XII, PART 1

FINAL REDUCTIONS (PART 1)

| ORIGINAL TEST NOS. | AVERAGES FOR TESTS LOAD, % | EXCESS AIR, % | TEMP. DEG F | BURNER AIR, % | SIDE OR FRONT SLOTS | FLUE GAS RECYC. % | BURNER OR PORTS |
|---|---|---|---|---|---|---|---|
| A 1/ 2 | 113.9 | 17.0 | 621 | 88.9 | FRONT | 0.0 | ---- |
| A 1/ 3 | 112.9 | 16.6 | 625 | 63.1 | FRONT | 0.0 | ---- |
| A 1/ 4 | 102.4 | 15.4 | 609 | 79.5 | SIDE | 0.0 | ---- |
| A 1/ 5 | 115.6 | 15.9 | 624 | 63.8 | SIDE | 0.0 | ---- |
| A 6/ 7 | 112.3 | 4.8 | 605 | 79.4 | FRONT | 0.0 | ---- |
| A 6/ 8 | 111.7 | 4.8 | 610 | 56.6 | FRONT | 0.0 | ---- |
| A 6/ 9 | 113.3 | 4.0 | 604 | 79.1 | SIDE | 0.0 | ---- |
| A 6/10 | 114.3 | 4.8 | 609 | 58.1 | SIDE | 0.0 | ---- |
| A 13/14 | 82.4 | 14.3 | 584 | 80.2 | FRONT | 0.0 | ---- |
| A 13/15 | 81.5 | 16.0 | 597 | 48.0 | FRONT | 0.0 | ---- |
| A 13/16 | 82.8 | 15.7 | 585 | 81.6 | SIDE | 0.0 | ---- |
| A 13/17 | 84.4 | 14.0 | 599 | 49.5 | SIDE | 0.0 | ---- |
| B 1/ 2 | 115.5 | 13.7 | 615 | 86.3 | FRONT | 0.0 | ---- |
| B 1/ 3 | 114.6 | 14.2 | 622 | 60.3 | FRONT | 0.0 | ---- |
| B 1/ 4 | 114.4 | 13.9 | 609 | 86.2 | SIDE | 0.0 | ---- |
| B 1/ 5 | 114.9 | 14.3 | 621 | 61.4 | SIDE | 0.0 | ---- |
| B 6/ 7 | 105.9 | 4.0 | 594 | 76.9 | FRONT | 0.0 | ---- |
| B 6/ 8 | 104.9 | 4.0 | 595 | 51.2 | FRONT | 0.0 | ---- |
| B 6/ 9 | 110.1 | 2.8 | 592 | 77.1 | SIDE | 0.0 | ---- |
| B 6/10 | 108.0 | 4.2 | 599 | 53.7 | SIDE | 0.0 | ---- |
| B 13/14 | 83.8 | 13.3 | 591 | 79.0 | FRONT | 0.0 | ---- |
| B 13/15 | 82.2 | 13.9 | 599 | 44.8 | FRONT | 0.0 | ---- |
| B 13/16 | 83.1 | 14.3 | 591 | 80.5 | SIDE | 0.0 | ---- |
| B 13/17 | 84.8 | 14.6 | 594 | 52.7 | SIDE | 0.0 | ---- |
| C 1/ 2 | 114.8 | 13.3 | 622 | 85.4 | FRONT | 0.0 | ---- |
| C 1/ 3 | 112.9 | 14.5 | 632 | 60.2 | FRONT | 0.0 | ---- |
| C 1/ 4 | 114.1 | 13.8 | 628 | 86.4 | SIDE | 0.0 | ---- |
| C 1/ 5 | 115.0 | 13.9 | 631 | 61.1 | SIDE | 0.0 | ---- |
| C 6/ 7 | 104.3 | 1.9 | 597 | 72.9 | FRONT | 0.0 | ---- |
| C 6/ 8 | 103.5 | 3.1 | 604 | 44.7 | FRONT | 0.0 | ---- |
| C 6/ 9 | 106.9 | 2.3 | 599 | 74.2 | SIDE | 0.0 | ---- |
| C 6/10 | 106.4 | 3.6 | 604 | 48.0 | SIDE | 0.0 | ---- |
| C 13/14 | 98.0 | 11.8 | 594 | 86.4 | FRONT | 0.0 | ---- |
| C 13/15 | 85.0 | 12.5 | 589 | 49.3 | FRONT | 0.0 | ---- |
| C 13/16 | 86.6 | 11.8 | 583 | 79.0 | SIDE | 0.0 | ---- |
| C 13/17 | 85.6 | 11.9 | 594 | 47.1 | SIDE | 0.0 | ---- |

## TABLE 6.14 SUMMARY OF SERIES XII, PART 2

FINAL REDUCTIONS (PART 2)

| ORIGINAL TEST NOS. | NO (PPM) BASE VALUE | NO (PPM) WITH CHANGES | NO (PPM) REDUCTION | REDUCTION IN NO, % |
|---|---|---|---|---|
| A 1/ 2 | 1191 ± 13 | 933 ± 8 | 258 ± 15 | 21.7 ± 1.3 |
| A 1/ 3 | 1191 ± 13 | 512 ± 21 | 679 ± 25 | 57.0 ± 2.2 |
| A 1/ 4 | 1191 ± 13 | 720 ± 23 | 471 ± 26 | 39.5 ± 2.3 |
| A 1/ 5 | 1191 ± 13 | 567 ± 21 | 624 ± 25 | 52.4 ± 2.2 |
| A 6/ 7 | 824 ± 20 | 538 ± 22 | 286 ± 30 | 34.7 ± 3.7 |
| A 6/ 8 | 824 ± 20 | 278 ± 8 | 546 ± 22 | 66.3 ± 3.1 |
| A 6/ 9 | 824 ± 20 | 434 ± 15 | 390 ± 25 | 47.3 ± 3.2 |
| A 6/10 | 824 ± 20 | 363 ± 15 | 461 ± 25 | 55.9 ± 3.3 |
| A 13/14 | 892 ± 29 | 506 ± 24 | 386 ± 38 | 43.3 ± 4.4 |
| A 13/15 | 892 ± 29 | 341 ± 13 | 551 ± 32 | 61.8 ± 4.1 |
| A 13/16 | 892 ± 29 | 540 ± 14 | 352 ± 32 | 39.5 ± 3.8 |
| A 13/17 | 892 ± 29 | 332 ± 13 | 560 ± 32 | 62.9 ± 4.1 |
| B 1/ 2 | 1220 ± 34 | 914 ± 18 | 306 ± 38 | 25.1 ± 3.2 |
| B 1/ 3 | 1220 ± 34 | 420 ± 8 | 800 ± 35 | 65.6 ± 3.4 |
| B 1/ 4 | 1220 ± 34 | 865 ± 15 | 355 ± 37 | 29.1 ± 3.2 |
| B 1/ 5 | 1220 ± 34 | 566 ± 17 | 654 ± 38 | 53.6 ± 3.5 |
| B 6/ 7 | 871 ± 14 | 576 ± 16 | 295 ± 21 | 33.9 ± 2.5 |
| B 6/ 8 | 871 ± 14 | 303 ± 7 | 568 ± 16 | 65.2 ± 2.1 |
| B 6/ 9 | 871 ± 14 | 524 ± 6 | 347 ± 15 | 39.9 ± 1.9 |
| B 6/10 | 871 ± 14 | 304 ± 7 | 567 ± 16 | 65.1 ± 2.1 |
| B 13/14 | 1022 ± 15 | 631 ± 10 | 391 ± 18 | 38.3 ± 1.9 |
| B 13/15 | 1022 ± 15 | 357 ± 2 | 665 ± 15 | 65.1 ± 1.8 |
| B 13/16 | 1022 ± 15 | 607 ± 3 | 415 ± 15 | 40.6 ± 1.6 |
| B 13/17 | 1022 ± 15 | 383 ± 14 | 639 ± 21 | 62.5 ± 2.2 |
| C 1/ 2 | 1108 ± 12 | 875 ± 8 | 233 ± 14 | 21.0 ± 1.3 |
| C 1/ 3 | 1108 ± 12 | 426 ± 3 | 682 ± 12 | 61.6 ± 1.3 |
| C 1/ 4 | 1108 ± 12 | 726 ± 16 | 382 ± 20 | 34.5 ± 1.8 |
| C 1/ 5 | 1108 ± 12 | 489 ± 13 | 619 ± 18 | 55.9 ± 1.7 |
| C 6/ 7 | 726 ± 0 | 408 ± 2 | 318 ± 2 | 43.8 ± 0.3 |
| C 6/ 8 | 726 ± 0 | 326 ± 0 | 400 ± 0 | 55.1 ± 0.0 |
| C 6/ 9 | 726 ± 0 | 420 ± 8 | 306 ± 8 | 42.1 ± 1.1 |
| C 6/10 | 726 ± 0 | 238 ± 0 | 488 ± 0 | 67.2 ± 0.0 |
| C 13/14 | 1048 ± 22 | 549 ± 3 | 499 ± 22 | 47.6 ± 2.3 |
| C 13/15 | 1048 ± 22 | 351 ± 2 | 697 ± 22 | 66.5 ± 2.5 |
| C 13/16 | 1048 ± 22 | 569 ± 3 | 479 ± 22 | 45.7 ± 2.3 |
| C 13/17 | 1048 ± 22 | 287 ± 4 | 761 ± 22 | 72.6 ± 2.6 |

**TABLE 6.15 CARBON LOSS AND BURNER EFFICIENCY**

| SERIES AND TEST NUMBER | FIRING DATA | | | WEIGHTS, LB./HR. | | ASH IN F.G. % | C IN ASH, % | BURNER EFFIC. IN % BY WT. |
|---|---|---|---|---|---|---|---|---|
| | AIR % | FLUE HEAT | DEG F | FUEL (DRY) | FLUE GAS | | | |
| VII - 1 | 113 | 49.59 | 608 | 428 ***** | 5684 | 0.39 | 28.0 | 98.6 |
| VII - 3 | 102 | 48.96 | 599 | 427 | 5133 | 0.36 | 43.2 | 98.1 |
| VII - 5 | 142 | 29.08 | 570 | 244 | 4062 | 0.40 | 3.8 | 99.7 |
| VII - 10 | 77 | 45.66 | 542 | 413 (SUB) | 3783 | 0.80 | 50.2 | 96.3 |
| VII - 11 | 73 | 45.66 | 537 | 414 (SUB) | 3594 | 0.85 | 52.1 | 96.2 |
| VII - 15 | 104 | 56.90 | 602 | 496 | 6015 | 0.82 | ?? | ?? |
| VIII- 1 | 115 | 52.97 | 610 | 454 | 5911 | 0.45 | 13.3 | 99.2 |
| VIII- 11 | 117 | 61.78 | 620 | 530 | 7059 | 0.45 | 3.3 | 99.8 |
| VIII- 14 | 103 | 44.01 | 270 | 410 | 4858 | 0.65 | 31.5 | 97.6 |
| X - 5 | 148 | 39.61 | 620 | 329 | 5467 | 0.28 | 18.1 | 99.2 |
| X - 6 | 112 | 52.42 | 610 | 453 | 5825 | 0.78 | 26.1 | 97.4 |
| X - 22 | 115 | 47.47 | 286 | 439 | 5851 | 0.69 | 15.6 | 98.6 |
| X - 26 | 116 | 37.57 | 574 | 334 (S) | 4376 | 0.61 | ?? | ?? |
| X - 32 | 111 | 52.50 | 620 | 477 (S) | 6064 | 0.91 | 39.0 | 95.5 |
| X - 40 | 132 | 43.07 | 585 | 379 (S) | 5710 | 0.59 | 20.9 | 98.1 |
| X - 42 | 124 | 44.48 | 606 | 410 (S) | 5814 | 0.54 | 17.9 | 98.6 |
| X - 43 | 129 | 43.15 | 611 | 404 (S) | 5913 | 0.51 | 25.3 | 98.1 |
| X - 45 | 151 | 48.41 | 584 | 428 (S) | 7214 | 0.45 | 9.1 | 99.3 |
| X - 47 | 153 | 46.53 | 606 | 429 (S) | 7386 | 0.44 | 8.2 | 99.4 |
| X - 48 | 105 | 44.41 | 588 | 401 (S) | 4958 | 1.03 | 35.1 | 95.5 |
| X - 53 | 116 | 44.33 | 279 | 421 (S) | 5590 | 0.99 | 33.4 | 95.6 |
| X - 55 | 119 | 44.17 | 279 | 419 (S) | 5690 | 0.83 | 29.0 | 96.7 |

***** - (SUB) INDICATES SUBSTOICHIOMETRIC
- (S) INDICATES STAGED COMBUSTION

Table 6.15 is the table showing burner efficiency calculated from combustibles (mostly solid carbon found in ash samples) from a wide sampling of coal tests. The tabular headings are:

1) Test and Series Number — Self explanatory.

2) Firing Data — The fuel/air input data:

   a) Air, % — The percent of 100% theoretical air.

   b) Flue Heat — Net heat release rate in the furnace in kBtu/ft$^3$/hr.

   c) Deg F — The total air preheat in $^{o}$F.

3) Weights, lb/hr — For dry fuel (coal only) and total flue gas weight.

4) Ash in F.G., % — The total weight percent of solid ash in the flue gas.

5) C in Ash, % — The total weight percent of carbon in the solid ash.

6) Burner Efficiency in Percent by Weight — The amount of coal burned to total flue gas after correction due to unburned solid (and gaseous for all except substoichiometric tests) combustibles.

**TABLE 6.16 SLOT CHANGES – STAGED COMBUSTION**

STAGED COMBUSTION TESTS: PERCENT REDUCTION IN NO

| Test No.* | "A" No Change | "B" First Change | "C" Second Change |
|---|---|---|---|
| 1/2 (F) | 20 ± 6 | 23 ± 3 | 39 ± 8 |
| 1/3 (F) | 63 ± 7 | 62 ± 4 | 73 ± 5 |
| 1/4 (S) | 33 ± 7 | 35 ± 4 | 44 ± 5 |
| 1/5 (S) | 50 ± 7 | 47 ± 3 | 53 ± 5 |
| 6/7 (F) | 38 ± 3 | 46 ± 4 | 57 ± 3 |
| 6/8 (F) | 58 ± 3 | 50 ± 4 | 75 ± 3 |
| 6/9 (S) | 49 ± 3 | 50 ± 4 | 51 ± 2 |
| 6/10 (S) | 58 ± 3 | 60 ± 4 | 71 ± 3 |
| 11/12 (F) | 43 ± 6 | 30 ± 2 | 62 ± 1 |
| 11/13 (F) | 71 ± 6 | 49 ± 2 | 73 ± 2 |
| 11/14 (S) | 65 ± 6 | 58 ± 2 | 61 ± 2 |

*F indicates front slots for staging; S indicates side slots

Tables 6.16 tabularizes in a simple form the differences in No emission levels for each of the changes in the slots. The column headings in the table represent:

1) "A", No Change (—these are the base line tests):
   front slot air entered parallel to the burner
   side slot air entered perpendicular to the burner axis on a 26-inch diameter circle

2) "B", First change:
front slot air entered at a 30 degree inward angle
side slot air entered perpendicular to the burner axis on a 13-inch diameter circle with a 50% increase in slot area opening

3) "C", Second Change:
front slot air entered at a 30 degree outward angle
side slot air entered perpendicular to the burner axis on a 13-inch diameter circle with a 100% increase (over "A") in slot area opening

Tables 6.17 and 6.18 tabularize in the same way as Table 6.16 the differences in NO emission levels for each of the changes in the burner. The column headings in these tables represent:

1) "A", No change – the original burner opening with no cone inserted (These are the base line tests)

2) "B", First change – insertion of a cone into the burner inlet to reduce the effective throat area by 25% and therefore increasing the burner velocity by 33%.

3) "C", Second change – insertion of another cone into the burner inlet to reduce the effective throat area by 50% and thereby increasing the burner velocity by 100%.

B. Colorado Coal Results

All of the figures which follow are the final results of the trends determined in Phase II for the Colorado coal tests. No other fuel was studied in Phase II.

## TABLE 6.17 BURNER CHANGES – EXCESS AIR

EXCESS AIR TESTS: PPM NO

| Test No.* | "A" No Change | "B" First Change | "C" Second Change |
|---|---|---|---|
| 1 (15%) | 1191 ± 13 | 1220 ± 34 | 1108 ± 12 |
| 6 (<5%) | 824 ± 20 | 871 ± 14 | 726 ± 0 |
| 11 (35%) | 1327 ± 13 | 1401 ± 58 | 1395 ± 29 |
| 12 (15%) | 1037 ± 27 | 1216 ± 38 | 1172 ± 27 |
| 13 (15%)** | 892 ± 29 | 1022 ± 15 | 1048 ± 22 |
| 18 (15%)*** | 1002 ± 35 | 1046 ± 8 | 1062 ± 20 |
| 19 (35%)*** | 1192 ± 46 | 1183 ± 24 | 1165 ± 5 |
| 20 (<5%)*** | 745 ± 10 | 748 ± 12 | 714 ± 12 |

*Number in parenthesis is excess air level.

**Low load.

***Low preheat.

## TABLE 6.18 BURNER CHANGES – STAGED COMBUSTION

STAGED COMBUSTION TESTS: PERCENT REDUCTION OF NO

| Test No.* | "A" No Change | "B" First Change | "C" Second Change |
|---|---|---|---|
| 1/2 (F) | 22 ± 1 | 25 ± 3 | 21 ± 1 |
| 1/3 (F) | 57 ± 2 | 66 ± 3 | 62 ± 1 |
| 1/4 (S) | 40 ± 2 | 29 ± 3 | 35 ± 2 |
| 1/5 (S) | 52 ± 2 | 54 ± 4 | 56 ± 2 |
| 6/7 (F) | 35 ± 4 | 34 ± 3 | 44 ± 0 |
| 6/8 (F) | 66 ± 3 | 65 ± 2 | 55 ± 0 |
| 6/9 (S) | 47 ± 3 | 46 ± 2 | 42 ± 1 |
| 6/10 (S) | 56 ± 3 | 65 ± 2 | 67 ± 0 |
| 13/14 (F) | 43 ± 4 | 38 ± 2 | 48 ± 2 |
| 13/15 (F) | 62 ± 4 | 65 ± 2 | 67 ± 3 |
| 13/16 (S) | 40 ± 4 | 41 ± 2 | 46 ± 2 |
| 13/17 (S) | 63 ± 4 | 63 ± 2 | 75 ± 3 |

*F indicates front slots used for staging; S indicates side slots

Figures 6.1 to 6.3 illustrate the typical major effects observed for the Colorado coal. The variables observed are excess air, firing intensity, and preheat. For these figures, two of the three variables were held constant, and the third is shown on the abscissa. The constant conditions observed in these figures are:

Excess air level – about 15%
Preheat level – about 600°F
Firing intensity – about 40,000 Btu/ft$^3$/hr.

The important trends observed were:

Excess air – rapid increase in NO emission level peaking at about 30 to 35% excess air
Firing intensity (load or rate of heat release) – increasing NO with increasing load with no apparent leveling or turnover
Preheat – a slight increasing trend of about 35 ppm per 100°F

Figures 6.4 to 6.6 show a comparison of a fine and coarse pulverization* of the Colorado coal for these same three variables. The fine pulverization is ∿90% through a 200 mesh screen and the coarse pulverization is ∿70% through 200 mesh. Fineness is not a major variable in our coal fired test unit. (Ordinarily, for all tests other than fineness, the 70%/-200 mesh pulverization is used for the Colorado coal tests.)

Figure 6.7 illustrates the effect of secondary flue gas recirculation. The flue gas was added to the windbox so that there was thorough mixing of the flue gas and secondary air stream. Very little reduction of NO emission levels was seen for FGR with the Colorado coal.

*See Appendix A for the sieving analyses for the Colorado coal.

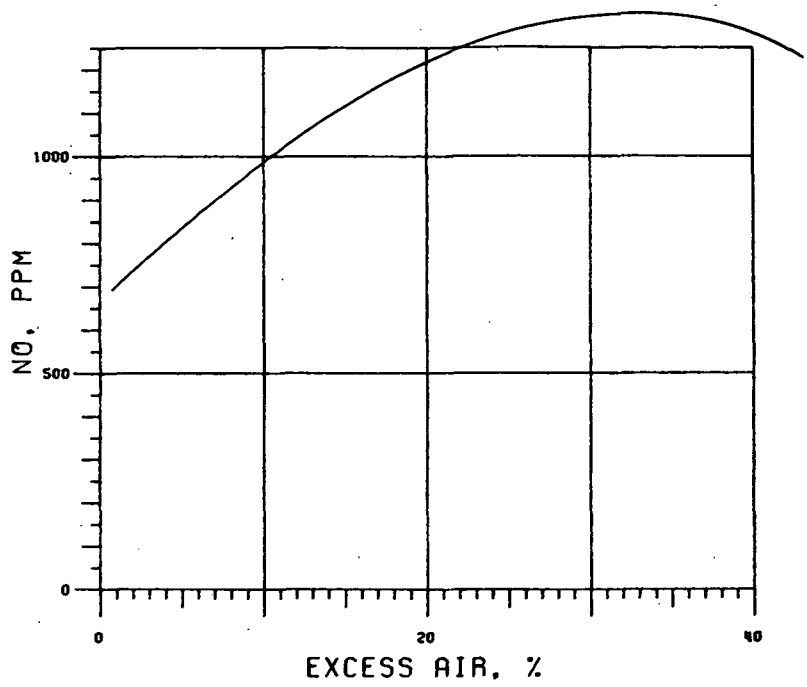


FIGURE 6.1 COLORADO COAL

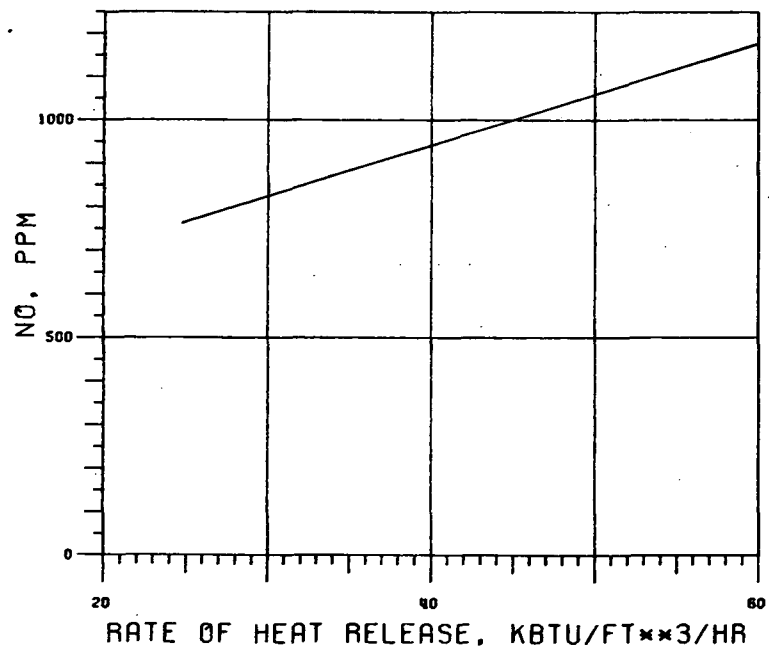


FIGURE 6.2 COLORADO COAL

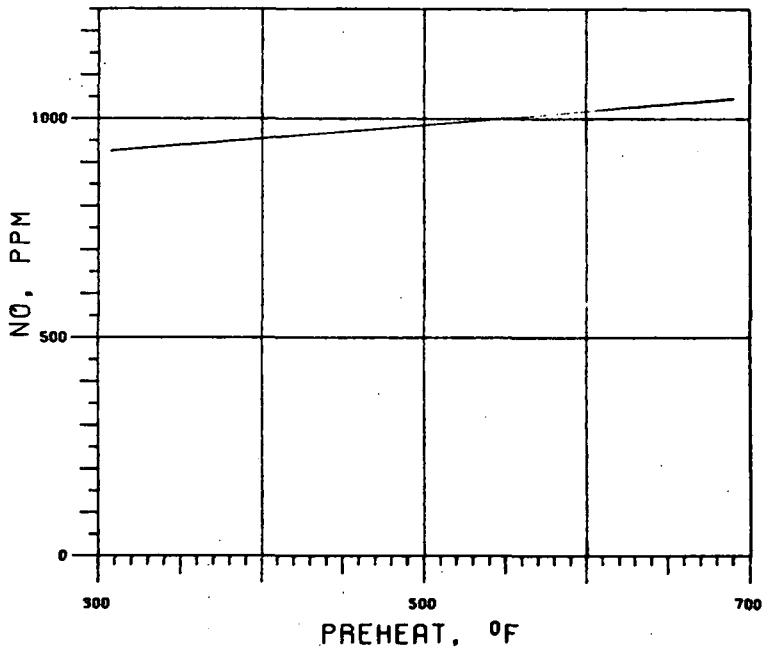


FIGURE 6.3 COLORADO COAL

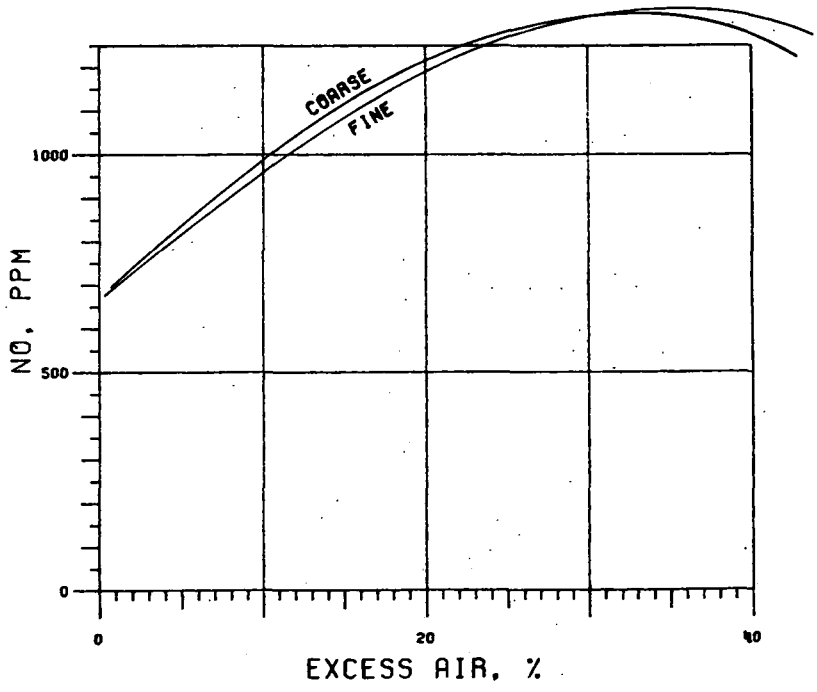


FIGURE 6.4 COLORADO COAL – FINENESS

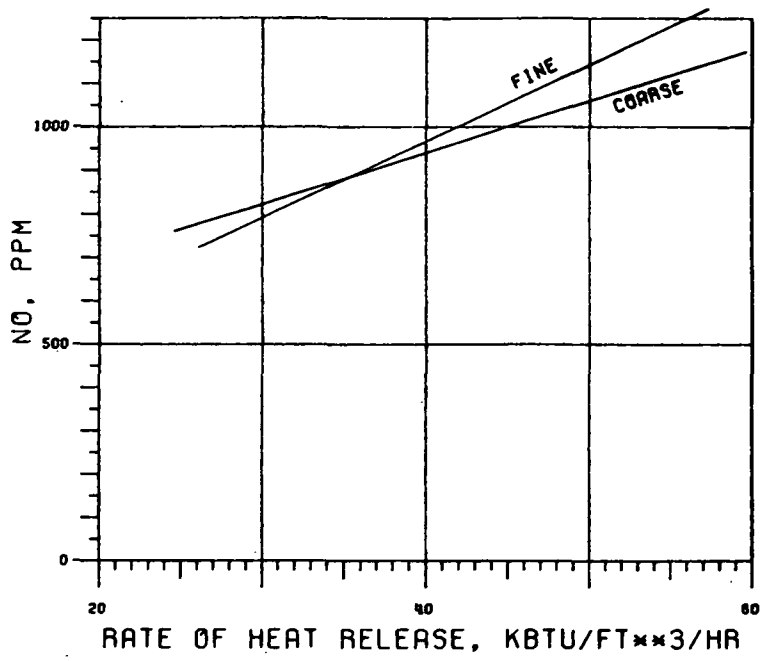


FIGURE 6.5 COLORADO COAL – FINENESS

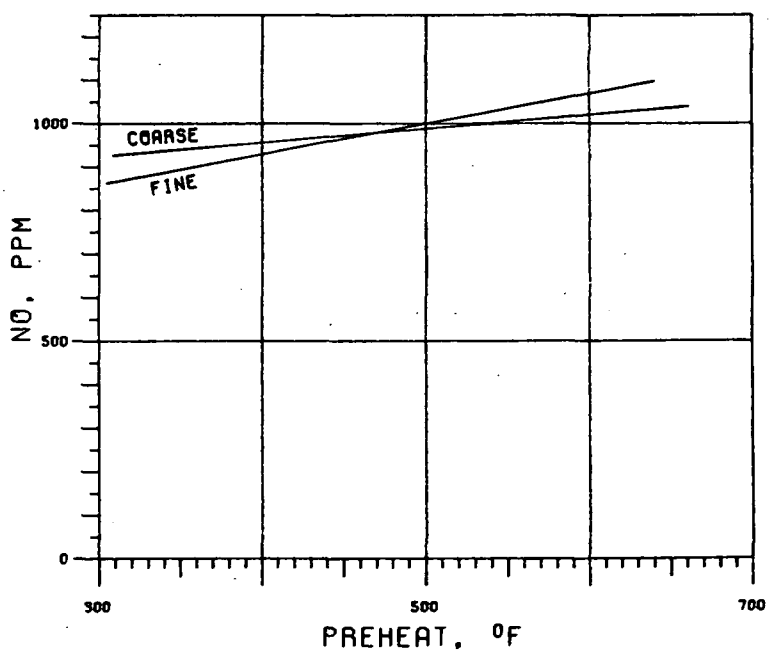


FIGURE 6.6 COLORADO COAL – FINENESS

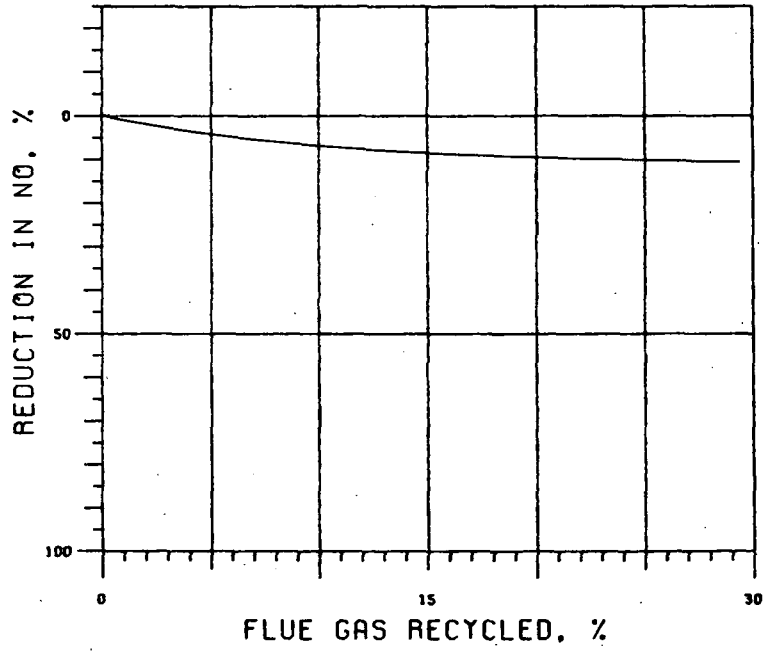


**FIGURE 6.7 FLUE GAS RECIRCULATION**

Second stage combustion air can be added to our furnace in two ways (see Figure 6.8). The front slots produce a "progressive mixing" and involve addition of the air in the burner area. The side slots, however, produce a defined second stage addition downstream of the burner area. When using the side slots for Colorado coal combustion, incomplete combustion occurred in the center core of the flame at low burner air to total combustion air ratios.

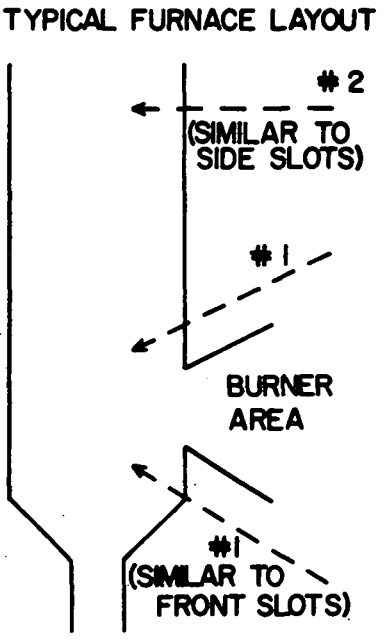


FIGURE 6.8 STAGED COMBUSTION OPTIONS

Figure 6.9 shows the normal (front slot) staged combustion with a total excess air of 15%. The substoichiometric curve was generated by simply shutting off the second stage air. Two important points to be noted in these curves are:

1) The maximum reduction of NO emission level for normal, staged combustion is about 65%.

2) The substoichiometric curve shows no NO emission below about 60% of stoichiometric air.

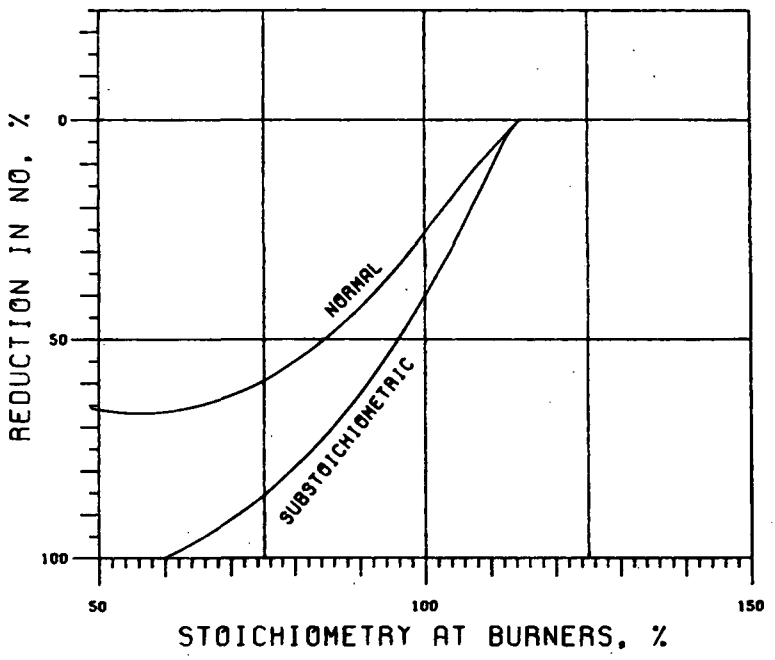


FIGURE 6.9 STAGED – 15% EXCESS AIR

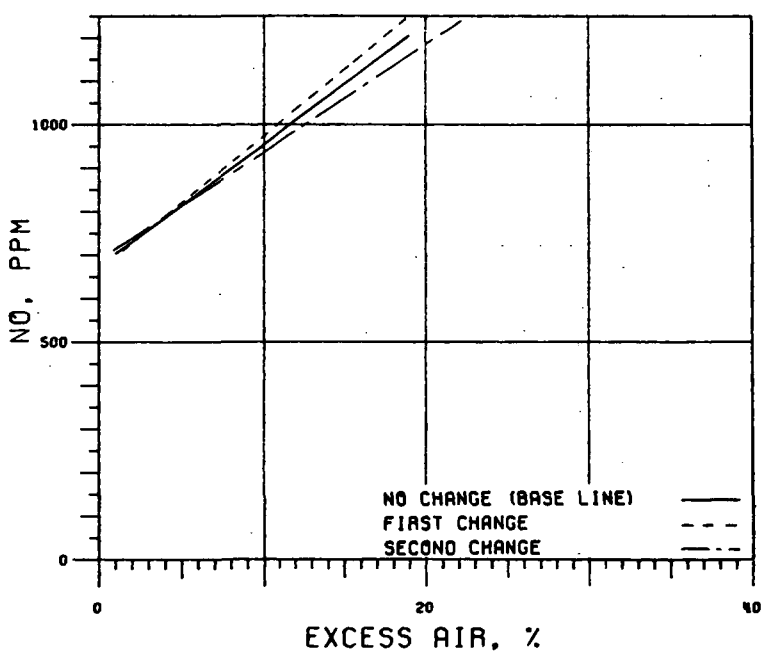


FIGURE 6.10 SLOT CHANGES

Figure 6.10 is a curve showing excess air (a variable which should be unaffected by the slot changes) and giving an idea of the nonreproducible day-to-day fluctuations that were seen, especially at higher excess air levels.

Two changes in the second stage air addition were made to determine the effect of mixing. The front slots were changed to add either the second stage air earlier or later to the first stage combustion. The side slots were changed to lower the mixing velocity of the air. Figure 6.11 represents the effect of these changes:

| | Change in: | |
|---|---|---|
| | Front Slots | Side Slots |
| No change: baseline | air parallel to burner | air perpendicular to burner axis on 26-inch diameter circle |
| First change | air angled inward at 30 degrees | air perpendicular to burner axis on 13-inch diameter circle, slot area increased 50% |
| Second change | air angled outward at 30 degrees | air perpendicular to burner axis on 13-inch diameter circle, slot area increase 100% |

The first change in slot geometry and size did not affect the NO reduction. The second change did have some effect — the change in side slots and in front slots had the same effect. The difference in NO reduction is not large.

Additionally, to compensate for differences in air velocity when excess air was varied or staging occurred, the burner cross section was modified twice to approximate constant velocity conditions. Figures 6.12 to 6.15 show the effects of these changes:

- No change or base line is 100% burner cross sectional area or no change in burner velocity

- First change is a reduction of the burner area by 25% and an increase in burner velocity of 33%

- Second change is a reduction of the burner area by 50% and an increase in burner velocity of 100%.

The changes in burner velocity produced a minimum or no change in the NO emission levels. The variation in day-to-day testing and experimental variations observed in the NO emission levels were of the same order of magnitude of any changes in NO emission due to the burner velocity changes. As a result no significant changes in NO emission levels were evident for changes in burner velocity. (See Figures D.43 to D.48 in Appendix D.)

Figures 6.16 and 6.17 illustrate the effect of load and stoichiometry on the burner efficiency and carbon loss. These figures indicate an interdependence of load and stoichiometry on carbon loss and burner efficiency.

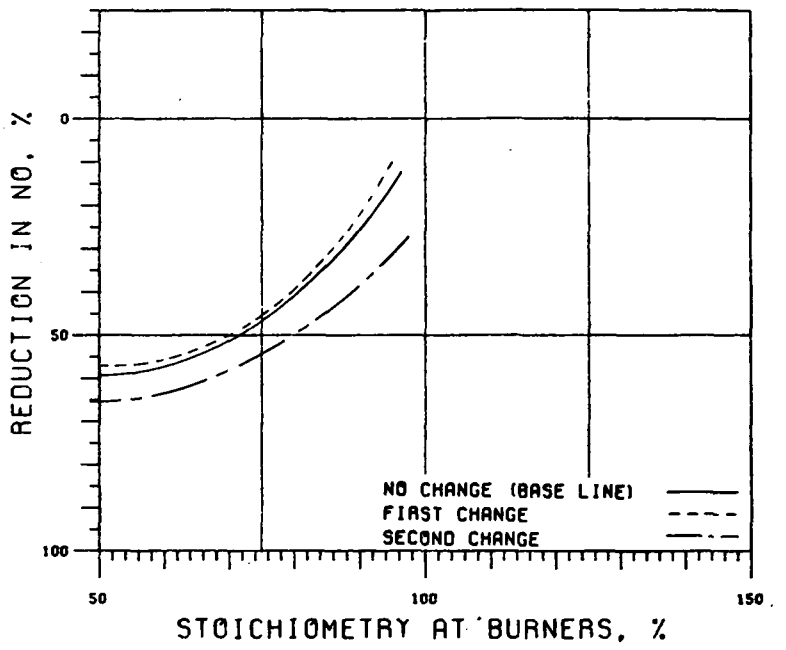


FIGURE 6.11 SLOT CHANGES – 15% AIR

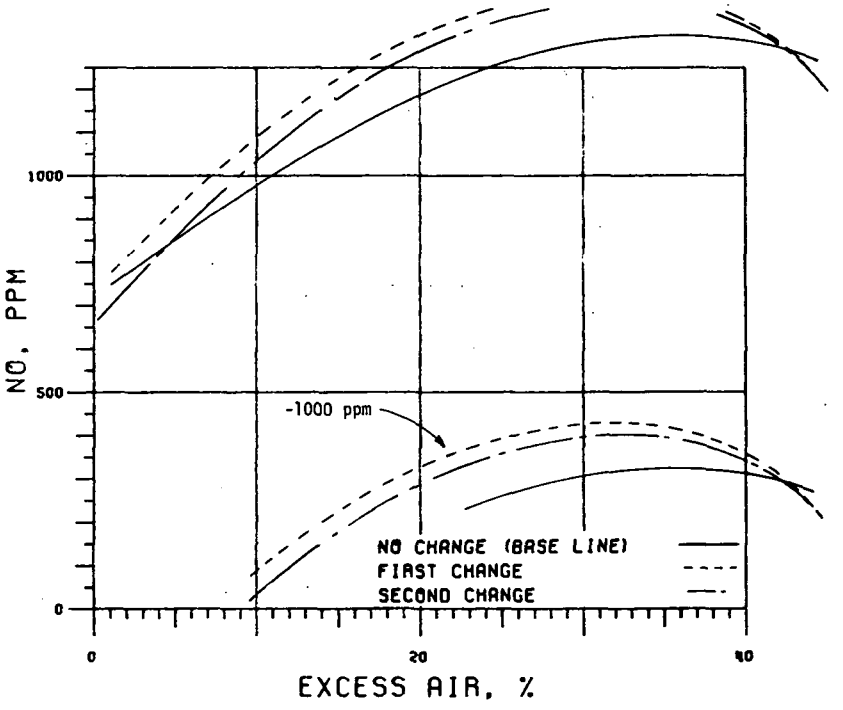


FIGURE 6.12 BURNER CHANGES

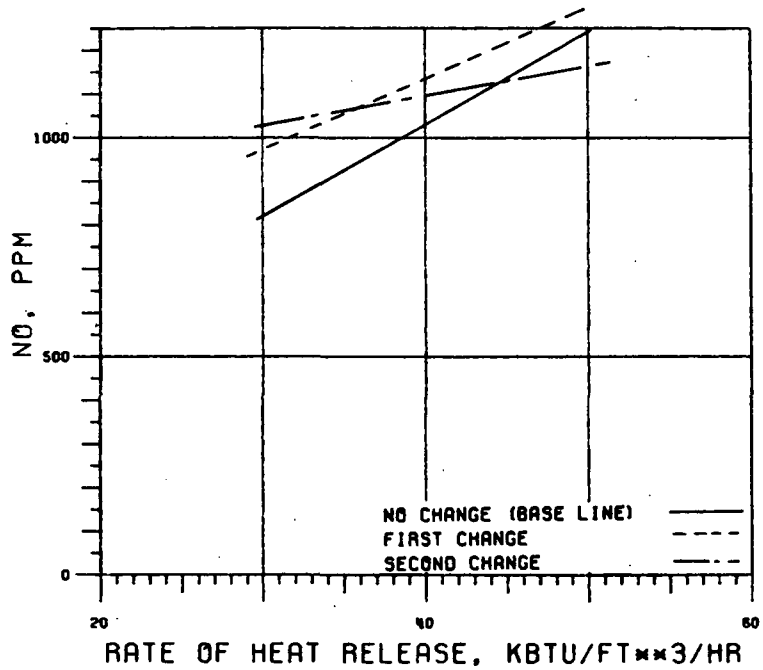


**FIGURE 6.13 BURNER CHANGES**

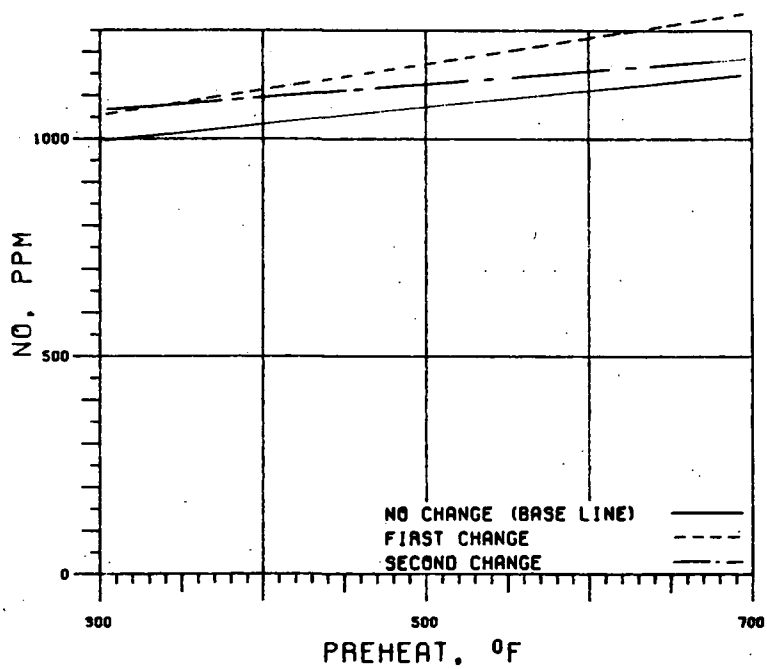


**FIGURE 6.14 BURNER CHANGES – 15% AIR**

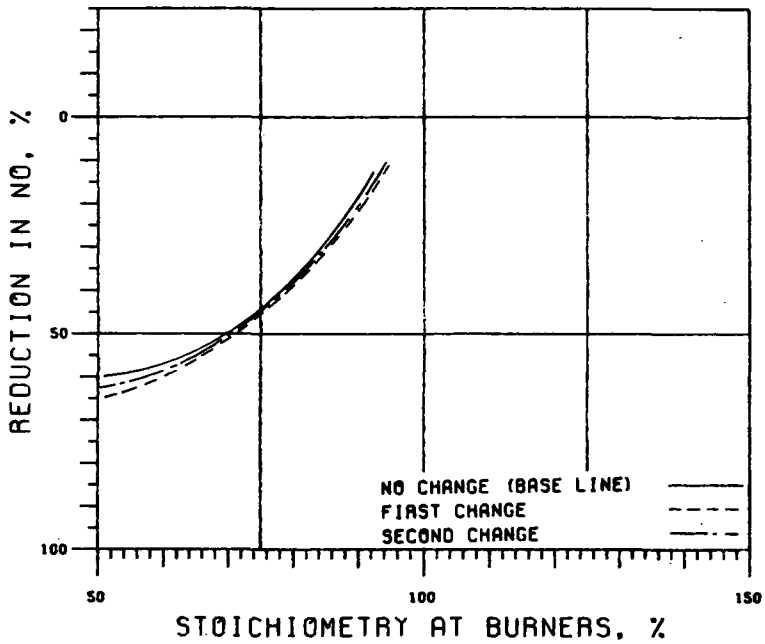


FIGURE 6.15 BURNER CHANGES – 15% AIR

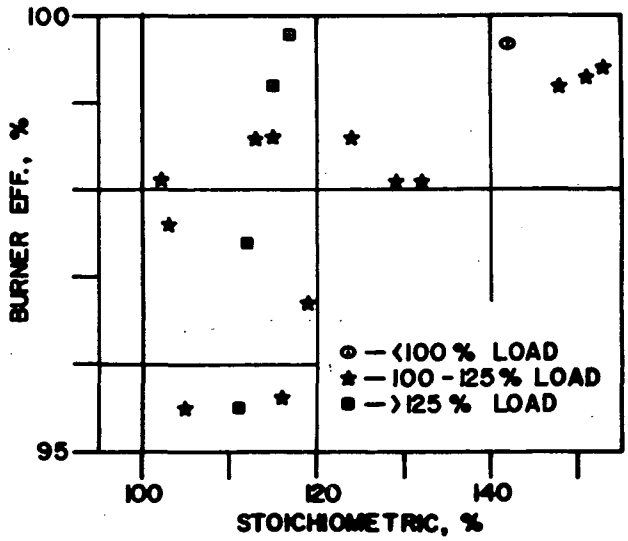


FIGURE 6.16 CARBON LOSS AND BURNER EFFICIENCY

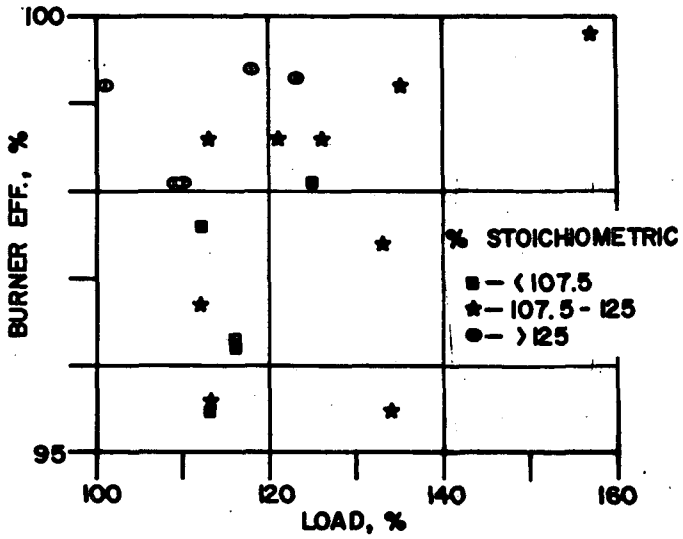


FIGURE 6.17 CARBON LOSS AND BURNER EFFICIENCY

## VII. COMPARISON OF PHASE I AND PHASE II RESULTS*

The data variables which are to be compared in this section are shown in the following table:

| Variables (x if tested) | Phase I Ohio Coal | Phase II Colorado coal | Phase I Natural Gas | To be Compared |
|---|---|---|---|---|
| Excess Air | x | x | x | yes |
| Load (heat release rate) | x | x | x | yes |
| Preheat | x | x | x | yes |
| Fineness | | x | | no |
| Swirl | | | x | no |
| Quench | x | | | no |
| Staged Combustion | x | x | x | yes |
| Flue Gas Recirculation | x | x | x | yes |
| Port Geometry | | x | | no |
| Burner Velocity | | x | | no |

Each variable to be compared will be shown on a single figure and a table of results will be given in the text. These tables of results will be presented again, in duplicate form, in Section VIII, the Discussion.

*The Phase I results for the Ohio coal and natural gas tests are taken from the Phase I Final Report, EPA 650/2-74-002a. The original data for Phase I used for comparison are in Appendix G.

Excess Air (Figure 7.1)

The comparison of NO emission level dependency on excess air for the three fuels follows:

| | Colorado Coal | Ohio Coal | Gas |
|---|---|---|---|
| Effect | Major | Major | Strong |
| Average Emission (under standard conditions) | 1100 ppm | 700 ppm | 300 ppm |
| Peak Position (percent excess air) | 1350 ppm (35%) | 1000 ppm (35%) | 350 ppm (20%) |
| Variation from Maximum to Minimum Emission | ±350 ppm<br>650-1350 ppm | ±300 ppm<br>400-1000 ppm | ±65 ppm<br>220-350 ppm |
| Percent Variation About Mean | ∿35% | ∿40% | ∿25% |

The trends of the Colorado coal and the Ohio coal are qualitatively identical — the absolute NO levels are quantitatively different, however. Natural gas shows a different qualitative trend with peak NO emission levels at lower excess air.

Load (Figure 7.2, Rate of Heat Release)

The dependency of NO emission level on load or heat release rate resulted in:

Colorado coal — very strong effect; varied from 700-1150 ppm under normal conditions

Ohio coal — very strong effect; varied from 400-800 ppm under normal conditions

Gas — no dependence; 300 ppm under normal conditions.

The trends are almost identical for the two coals. The change over the whole range of load is about 400 ppm for both coals. Again, the trend for gas is different with the result that load is not a variable for gas.

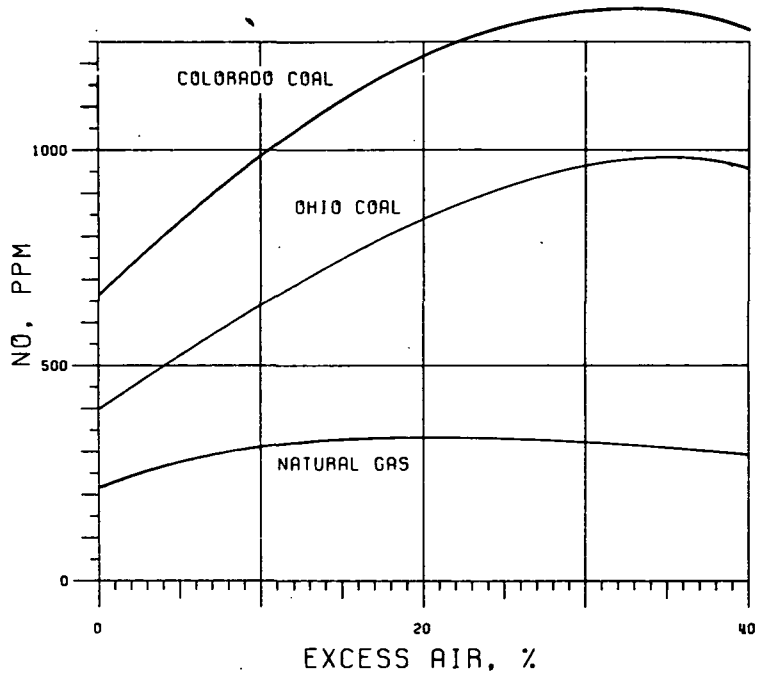


**FIGURE 7.1 EXCESS AIR**

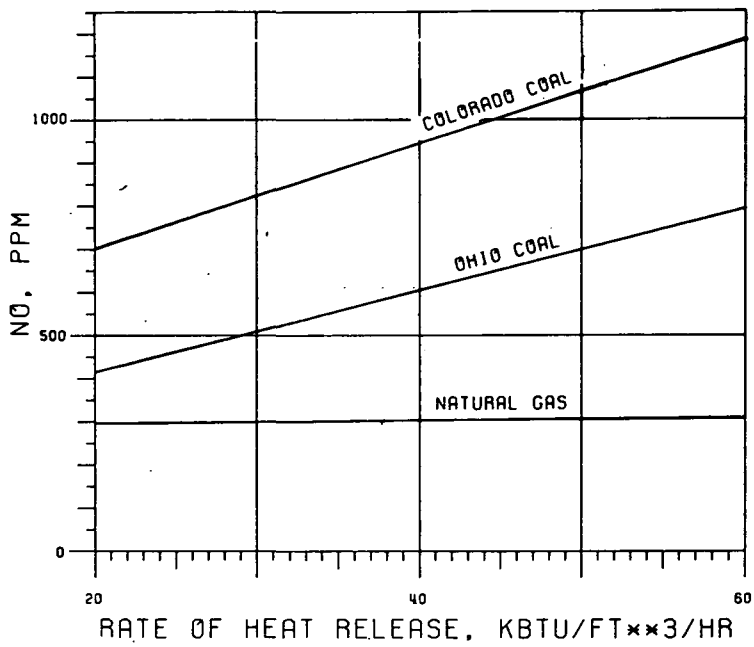


**FIGURE 7.2 LOAD**

Preheat (Figures 7.3 and 7.4)

Figure 7.3, for normal excess air yields the following dependence:

| Fuel | Dependence | NO Range, ppm (Deviation about Mean) |
|---|---|---|
| Colorado Coal | Slight | 925-1050 (∿6%) |
| Ohio Coal | None | 725 (∿0%) |
| Gas | Strong | 100-300 (∿50%) |

On a part per million basis, the gas is most dependent at about 50 ppm/100°F slope to the line, Colorado coal is next with about 30 ppm/100°F slope, and Ohio coal is least dependent with 0 ppm/100°F slope. In general, the coals behave similarly on a percentage change basis; on a basis of quantitative change, no two of the fuels behave similarly.

At high excess air (Figure 7.4), the comparision yields the following:

| Fuel | Dependence | NO Range, ppm (Deviation about Mean) |
|---|---|---|
| Colorado Coal | Slight | 1100-1350 (±∿10%) |
| Ohio Coal | Moderate | 750-1000 (±∿15%) |
| Natural Gas | Strong | 100-300 (±∿50%) |

The three fuels behave identically on a quantative basis; the slope of the lines is 50-60 ppm/100°F. On a percentage basis, the two coals behave similarly.

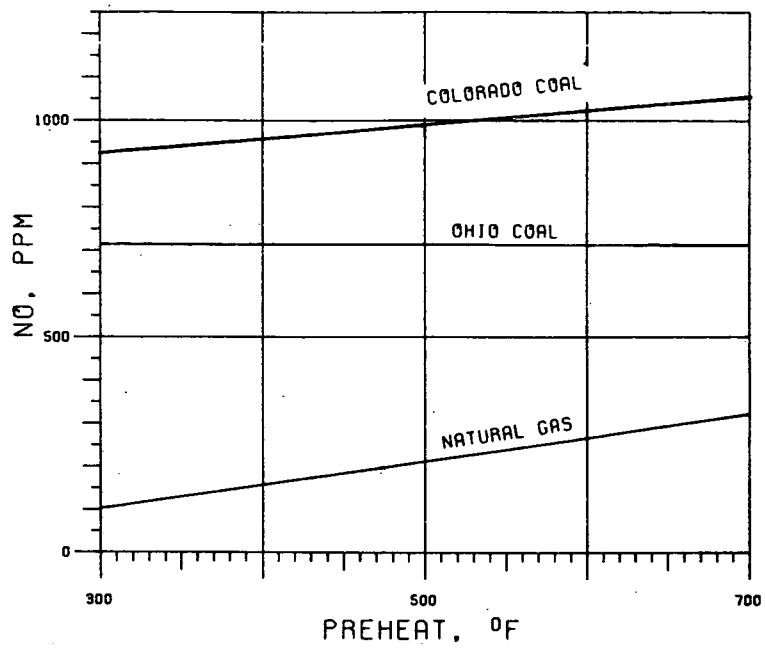


**FIGURE 7.3 PREHEAT, NORMAL EXCESS AIR**

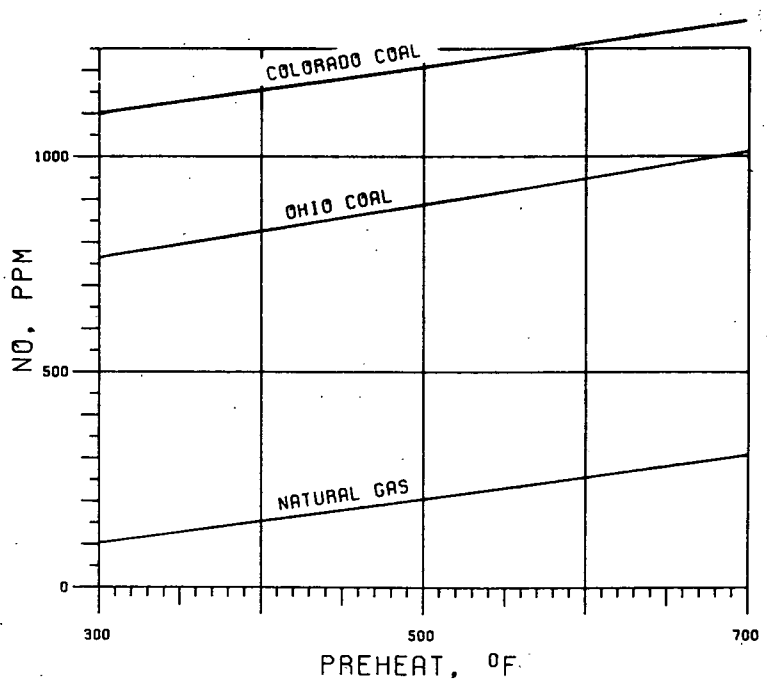


**FIGURE 7.4 PREHEAT, HIGH EXCESS AIR**

Flue Gas Recirculation (Figure 7.5)

The following results were observed for (secondary) flue gas recirculation:

| Fuel | Effect | Reduction of NO, % (at 30% FGR) |
|---|---|---|
| Colorado Coal | Little | ∿12% (extrapolated) |
| (Ohio Coal (primary) | Little | <5% (at 5% FGR)) |
| Ohio Coal (secondary) | Moderate | 30% |
| Natural Gas | Very Strong | 85% |

Natural gas NO emission levels are greatly affected by flue gas recirculation. There is only a moderate effect on coal emissions at best.

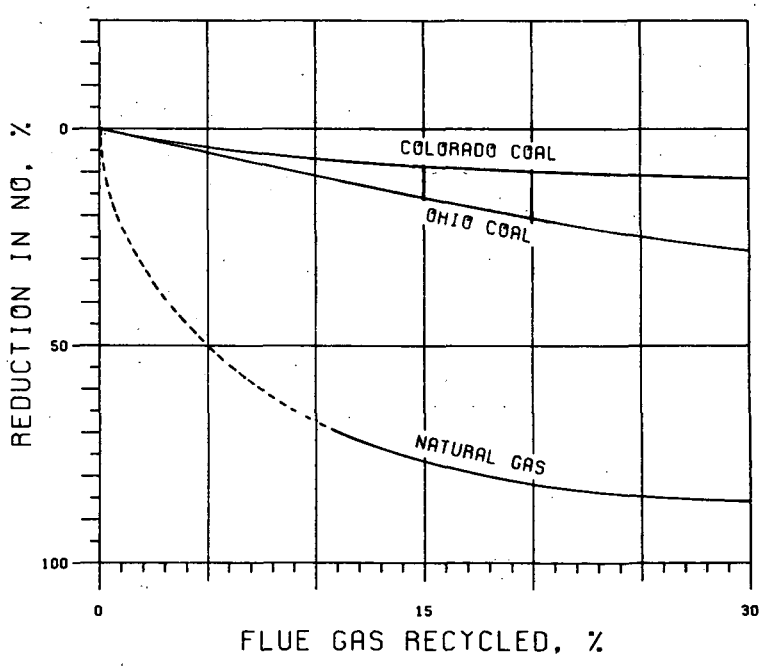


FIGURE 7.5 SECONDARY FLUE GAS REC.

Staged Combustion (Figure 7.6)

The results are:

| | Colorado Coal | Ohio Coal | Gas |
|---|---|---|---|
| Normal Firing: | | | |
| Effect on NO | Strong | Strong | Very Strong |
| Maximum Reduction, % | 70 | 60 | 90 |
| Burner Air at Max. Red., % Stoich. | ∿55 | ∿55 | ∿50(?)* |
| Substoichiometric: | | | |
| Maximum Reduction, % | 100 | 100 | 100 |
| Burner Air at Max. Red., % Stoich. | ∿60 | ∿60 | ∿60 |
| Variable Port Position | Some Effect (Not extended to low burner air for side ports) | Some Effect (Max. Red.: Side Ports 50 Front Ports 60) | No Effect |

*Unknown if maximum reduction occurs at 50% air.

The substoichiometric curves for all three fuels are identical — the NO emission level goes to 0 ppm at 60% stoichiometry.

The reduction of NO emission levels for two stage combustion of all three fuels are similar between 60 and 115% stoichiometry at the burner. Below 60% burner stoichiometry, natural gas does not show a distinct valley in the curve at 50 to 60% burner stoichiometry. In addition, gas shows a greater maximum reduction than the two coals.

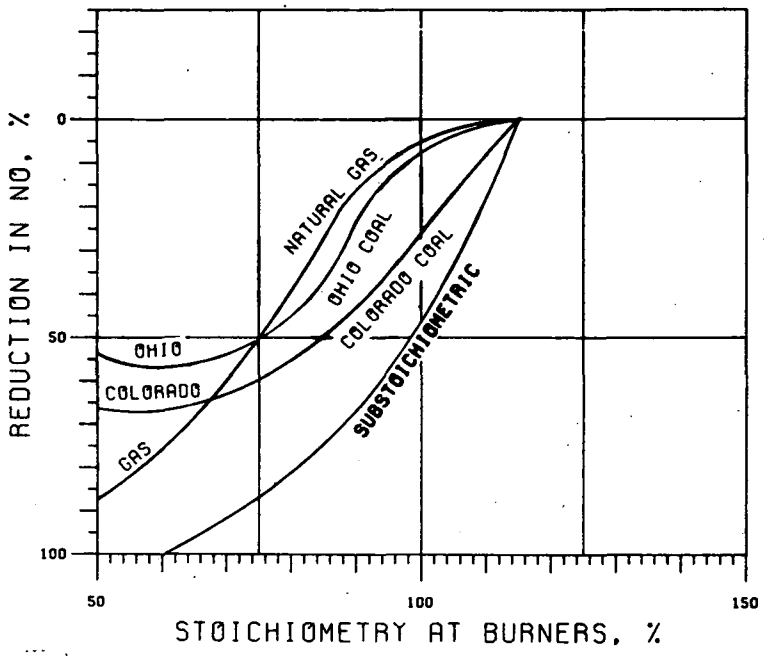


**FIGURE 7.6 STAGED COMBUSTION**

## VIII. DISCUSSION

The discussion section is divided into four sections. These sections deal with the data results, special effects observed in the testing, final data discussion, and possible correlated interrelationships. The discussion presents the data as measured and interpreted.

### A. Results

The effects of each variable studied were usually straightforward for the Colorado coal when surveying a single variable; the simplest curve was drawn through the available data. These data were usually taken at the extremes and middle of the range for each variable; but in a few cases, only at the extremes of the range. In most cases, if a straight line did not fit the data, a slightly curving line did. It must be emphasized that in many cases the extremes of a single variable are beyond the range of what is currently considered acceptable operating practice. In addition, these results apply only to a small single burner test unit. Even so, it is believed that the trends will probably hold for large multiburner units, although the magnitude of these changes may be appreciably different. Finally, some of these variable changes may not be acceptable on large units.

In reviewing these results, it should be borne in mind that NO emissions are due to a combination of thermal fixation and fuel bound nitrogen conversion. During combustion of natural gas, only thermal fixation of atmospheric nitrogen is possible since there is no fuel bound nitrogen:

$$N_2 + O_2 \longrightarrow 2\,NO \qquad (1)$$

(Only the overall formation is discussed here, not the mechanism of formation.) In contrast, coal contains fuel bound nitrogen and an additional source of nitric oxide is oxidation of this fuel bound nitrogen to NO:

$$N_2 + O_2 \longrightarrow 2\ NO \qquad (1)$$

and

$$2\ R\text{-}N + O_2 \longrightarrow 2\ NO \qquad (2)$$

where R is the fuel portion of the molecule.

The kinetic form of these equations is given by:

$$\text{from (1): } \frac{d[NO]}{dt} = k_{f,1}\ [N_2][O_2] - k_{r,1}\ [NO]^2 \qquad (3a)$$

$$\text{from (2): } \frac{d[NO]}{dt} = k_{f,2}\ [R\text{-}N]^2[O_2] - k_{r,2}\ [NO]^2 \qquad (3b)$$

where $k_{f,1}$, $k_{f,2}$, $k_{r,1}$, and $k_{r,2}$ are of the form:

$$k_x = A_x\ (T)^n\ e^{-E_x/RT} \qquad (3c)$$

(Note: by definition: $k_{r,1} \equiv k_{r,2}$)

It should be noted that the reverse reactions of (1) and (2) are identical and therefore it is not valid to say:

$$[NO]_{total} = [NO]_{(1)} + [NO]_{(2)}$$

if reactions (1) and (2) are considered separately. If this happens to be true for a given case, it is simply coincidential.

Excess Air

The results of the excess air tests show:

| | Colorado Coal | Ohio Coal | Gas |
|---|---|---|---|
| Effect | Major | Major | Strong |
| Average Emission (under standard conditions) | 1100 ppm | 700 ppm | 300 ppm |
| Peak Position (percent excess air) | 1350 ppm (35%) | 1000 ppm (35%) | 350 ppm (20%) |
| Variation from Maximum to Minimum Emission | ±350 ppm | ±300 ppm | ±65 ppm |
| | 650-1350 ppm | 400-1000 ppm | 220-350 ppm |
| Percent Variation About Mean | ∿35% | ∿40% | ∿25% |

The Phase I results, showed that there were significant differences in the NO emission levels of gas and the Ohio coal which are at least partially attributable to fuel bound nitrogen. Although there are differences between the two fuels in flame temperature, combustion rate, physical state of the fuel, and even gas velocities, these differences would be expected to produce less change in $NO_x$ than the fuel bound nitrogen. In particular, the difference in the shape of the curve is expected to be a change due to fuel bound nitrogen.

The NO emission from gas, the thermal fixation of atmospheric nitrogen, depends upon temperature and excess air level. At low excess air levels, the effect of increasing oxygen level more than offsets the decreasing flame temperature, thus the curve initially rises. In addition, the flame can be more luminous at lower excess air level; this can lead to more rapid quench rates. At high excess air levels, the decreasing temperature becomes the overriding effect and the curve drops after passing through a maximum.

In contrast, the coal, which contains fuel bound nitrogen as a second source of NO, shows both a different position of an NO maximum which is shifted to higher excess air, and an increase in formation of NO at all excess air levels. These differences are, at least qualitatively, due to the fuel bound nitrogen. The trend thus shown indicates a positive correlation between increasing fuel bound nitrogen conversion to NO and increasing excess air. It is felt that the fuel bound nitrogen conversion cannot be quantitatively evaluated. (An additional factor is the apparent greater luminosity, and therefore greater rate of radiation, of the coal flame as compared to the gas flame at low excess air. Also, the coal flame luminosity appears to be insensitive to excess air level whereas the gas flame luminosity is very greatly dependent upon excess air.)

The Colorado coal shows the same qualitative dependence upon excess air as the Ohio coal. But quantitatively, the NO emission levels from the Colorado coal are 25% to 50% higher than from the Ohio coal. In addition, the Colorado coal had a different type of flame structure than the Ohio coal. Under normal or high excess air, the flame was clear, like a natural gas flame, and almost nonluminous. Only at low excess air did the flame become similar to the large, luminous Ohio coal flame.

The overall differences between the Ohio and Colorado coals are:

1) Less luminosity of the Colorado coal flame (this would be expected to cause the Colorado coal to have a higher flame temperature than the Ohio coal)

2) Higher (wet) Btu content of the Colorado coal (this would also be expected to yield a higher flame temperature)

3) Lower sulfur content of the Colorado coal.

The fuel bound nitrogen content of the Colorado coal is about the same in quantity as the Ohio coal; both have ∿1.1% fuel bound nitrogen by weight.

The Colorado coal curve is the same shape as the Ohio coal curve and so, qualitatively, the increase in the NO emission at any given quantity of excess air was probably due to a change in the conversion of fuel bound nitrogen to NO. This could have been due to any or all of the following for the Colorado coal (as compared to the Ohio coal):

1) The flame structure at higher excess air levels indicated more rapid combustion due to shortened flame; and probably with higher flame temperature, at least momentarily during the initially more rapid burning

2) The flame structure indicated more complete combustion (as does the stack measurement of burner efficiency) due to clearer flame and less carbon emission in the flame

3) The Colorado coal could have a greater fraction of the fuel bound nitrogen as a volatile nitrogen content (as opposed to a nonvolatile slow burning char content)

4) No. 1). 2) and 3) would imply a lower residence time for the reduced fuel bound nitrogen constituents in a reducing atmosphere and less carryover of these reduced species

The overall result could be 1) increased conversion of fuel bound nitrogen to NO, due to lack of time for recombination to $N_2$ or reduction to $N_2$; 2) higher rate of reaction of fuel bound nitrogen fragments to NO, due to higher temperature; and 3) higher free radical concentrations, as would be observed from the higher temperatures. These conclusions agree with the NO levels of the Ohio and Colorado coals which tend to differ less at low excess air where the flame patterns tend to become similar. The staged combustion results also indicate this since two stage combustion on the Colorado coal, although giving somewhat greater percentage NO reduction than the Ohio coal (60 to 75% versus 50 to 60%), tends to yield about the same absolute NO emission levels, in ppm, as the Ohio coal when the flame patterns are almost identical.

However, it may be argued that the increase of NO emission level is due to thermal conversion of atmospheric nitrogen from the higher flame temperature. This is definitely a contributor to the higher NO emission level, but the question is, is it the major source of NO increase? (The fuel bound conversion is not likely to be the only contributor to the increased NO emission because the overall increase is about 350 ppm at 35% excess air (1000 ppm versus 1350 ppm absolute for the Ohio and Colorado coals respectively), and at a 1% fuel bound nitrogen equivalence of 2300 ppm NO for total conversion, this would indicate a 15% increase in the fuel bound nitrogen conversion efficiency from the Ohio to the Colorado coal.) There are three fundamental reasons for believing that the increase is <u>not</u> primarily due to increases in thermal NO:

1) The shape of the curve does not show a dependence on flame temperature between 20% to 30% excess air (at constant flame luminosity) where a thermal conversion peak would be expected. The shape of the Colorado coal curve matches the Ohio coal

curve and does not show an intermediate shape between the Ohio coal and natural gas. For natural gas, beyond 20% excess air, the lower temperature at higher excess air levels indicates stronger dependence on temperature than on excess air — not the case for the coal curves.

2) The high NO levels from the two coals are not unrealistic and would be compatible with a 25% to 50% fuel bound nitrogen conversion to NO. This would correspond to 600 ppm to 1250 ppm for a 1.05% to 1.15% nitrogen coal. (This should not be interpreted as a quantitative evaluation of the fuel bound nitorogen conversion to NO. It is a relative estimate only.)

3) The ineffectiveness of flue gas recirculation indicates that this increase is not due to thermal NO since the flue gas recirculation would have been more effective for the Colorado coal than for the Ohio coal since flue gas recirculation reduces thermal NO significantly.

Finally, it cannot be ruled out that the change in $NO_x$ is due to a synergistic effect caused by the reduced sulfur content. Some preliminary, unpublished results of other investigators indicate that higher sulfur levels can lower NO emission levels. Although this is a possible explanation for the difference in NO emission levels for the Ohio and Colorado coals, it can be neither proven nor disproven by the results of this study.

Load

The result of load change shows:

| | |
|---|---|
| Colorado coal | — very strong effect; varied from 700 - 1150 ppm under normal conditions |
| Ohio coal | — very strong effect; varied from 400-800 ppm under normal conditions. |
| Gas | — No dependence; 300 ppm under normal conditions. |

Again it should be pointed out that with the burner arrangement used for these tests, both the air velocity through the burner and the turbulence changed with load. However, there is no indication of a peak level having been reached under increasing load conditions. (There is refractory shielding in the front half of the furnace.) The two coals respond in a similar manner with identical qualitative trends (the rate of change over the whole range is 450 ppm for the Colorado coal and 400 ppm for the Ohio coal).

Preheat

The dependence of NO emission level on air preheat is interesting. Normal conditions (15% excess air and 100% load) result in:

| Fuel | Dependence | NO Range, ppm (Deviation About Mean) |
|---|---|---|
| Colorado coal | Slight | 925-1050 (∿6%) |
| Ohio Coal | None | 725 (∿0%) |
| Gas | Strong | 100-300 (∿50%) |

and for high excess air and normal load:

| | | |
|---|---|---|
| Colorado coal | Slight | 1100-1350 (±∿10%) |
| Ohio coal | Moderate | 750-1000 (±∿15%) |
| Gas | Strong | 100-300 (±∿50%) |

The indication from the natural gas is that thermal production of NO is increasing at a rate of about 50 ppm per 100°F preheat increase regardless of excess air level. This is determined from the total change over the range of the curve for gas. This same type of increase of thermal emission of NO should, but does not, occur for the Ohio coal and for the Colorado coal. Both coals would be expected to show the same effect on preheat by excess air as gas. Since little is known of the local temperature history of the flames any conclusions based on these observations would be very speculative.

The different dependence of the Colorado and Ohio coal preheat curve slopes on excess air can be considered on either a ppm basis or a percentage basis. The normal excess air to high excess air responses of the preheat curve slopes for the Ohio and Colorado coals are:

| | Slope of preheat curve normal excess air range | | Slope of preheat curve high excess air range | |
|---|---|---|---|---|
| | %* | ppm | % | ppm |
| Ohio coal | ± 0 | ± 0 | ± 15 | ± 125 |
| Colorado coal | ± 6 | ± 65 | ± 10 | ± 125 |

The effect of the flame temperature change would probably explain the different preheat dependence, for the two coals, especially at the normal excess air level of 15% below which the flame color, shape, and luminosity begin to change.

*Expressed as a deviation about the mean: i.e., in the previous table, Colorado coal showed a range of 1100 to 1350 ppm at high excess air from low to high preheat. The mean (straight line) is 1225 ppm and the deviation about the mean is ± 125 ppm (or ± 10%).

## Fineness

Fineness is not a major variable in our basic combustion unit when comparing the excess air, load, or preheat as variables. The slight variation curve for any one of the variables is less than 5% and less than the maximum error of measurement or reproducibility.

## Flue Gas Recirculation

The following results were obtained for flue gas recirculation:

| Fuel | Effect | Reduction of NO, % (at 30% FGR) |
|---|---|---|
| Colorado coal | Little | ∿12% (extrapolated) |
| Ohio Coal, primary | Little | <5% (at 5% FGR) |
| Ohio coal, secondary | Moderate | 30 |
| Gas | Very Strong | 85 |

Since the primary transport air for coal represents about 15% of the total combustion air, a high level of primary flue gas recirculation is not possible, even if a maximum amount of primary flue gas substitution is used. Primary flue gas recirculation did not significantly lower the NO emission levels for the Ohio coal tests. For this reason, primary flue gas recirculation was not run with the Colorado coal. In addition, primary flue gas recirculation experience with the Ohio coal resulted in decreased burner performance and ignition problems. It is felt, however, that any reduction of NO on coal fired units by use of this approach is relatively insignificant. The effect of flue gas recirculation on the Colorado coal indicated little or no reduction of NO emission levels. Addition of 10 to 15% flue gas recirculation reduced the NO emission levels in the Ohio coal by 10 to 15% and in the Colorado coal by 5 to 10%.

The overall effect of flue gas recirculation (secondary flue gas recirculation for coal) appears to be reduction of thermal NO emissions as evidenced by the natural gas data. The effect of flue gas recirculation on conversion of fuel bound nitrogen is unknown, but the reduction of this component is probably minimal.

Staged Combustion

The results of the staged combustion data are as follows:

REDUCTION IN NO, %

| Staging Test | Colorado Coal | Ohio Coal | Gas |
|---|---|---|---|
| Normal: | | | |
| Effect on NO | Strong | Strong | Very Strong |
| Maximum Reduction | 70 | 60 | 90 |
| Burner Air at Max. Red., % Stoich. | ∿55 | ∿55 | ∿50?* |
| Substoichiometric: | | | |
| Maximum Reduction | 100 | 100 | 100 |
| Burner Air at Max. Red., % Stoich | ∿60 | ∿60 | ∿60 |
| Variable Port Position | Some effect (Not extended to low burner air for side ports) | Some effect (Max. Red.: Side Ports 50 Front Ports 60) | No effect |

The difference in the second stage port position was moderately important for the Colorado coal firing tests. Although the reduction of NO is not significantly different numerically at lower burner to total air ratios** for the two slot positions, the visible

*Unknown if maximum reduction occurs at 50% air.

**The burner to (total) air ratio is defined as the weight of air through the burner divided by the total weight of air into the furnace.

flame pattern indicated a low second stage combustion efficiency for the side slots. In particular, a large cylindrical, highly turbulent flame envelope surrounded a blacker carbon containing core. Carbon became visible in the smoke from the stack. Therefore, only the front slot, or "progressive combustion" data are used for discussion of further results.

It should be noted that these staged combustion data were obtained with fixed burner and slot openings. Thus, as the burner to total air ratio decreased and staging increased, the air velocity through the burner decreased and the air velocity through the ports increased. It is for this reason that the performance and the effect on two stage combustion was unsatisfactory at lower burner to air ratios when using the side slots.

The greatest effect of staging was found with gas. Almost all of the NO was eliminated by staging the gas combustion. (The addition of flue gas recirculation can remove all or most of the rest of the NO emission.)

Coal tests showed reduction of up to 60% of the NO emission levels for staged combustion. An apparent maximum reduction of the NO is reached at about 50% burner to total air ratio. This minimum is not unexpected because it represents the diminishing return on the reduction of the thermal NO precursors and conversion of the fuel bound nitrogen in the first stage as contrasted to increasing thermal NO formation in the second stage due to increasing enthalpy release in the second stage combustion. In addition, it is possible that significant amounts of fuel bound nitrogen fragments (such as HCN, CN, etc.) may be formed which survive long enough to be oxidized to NO in the second stage.

An attempt was made to determine if a valley in the reduction curve for coal emissions really exists at the 50%-60% burner stoichiometry. Although the curve leveled out below 70% burner stoichiometry, it never clearly indicated a rise from the curve valley again, even down to 45-50% burner stoichiometry.

The substoichiometric tests for gas and the two coals, when superimposed, are the same curve and intercept 100% reduction of NO emission level (0 ppm NO) at 60% of stoichiometry. These results seem to mean that both thermal NO formation and fuel bound nitrogen conversion to NO under substoichiometric combustion conditions have the same final precursors in atomic or free radical form such as NH, N, etc. In other words, the reactions directly leading to NO are independent of the source which provides these free radicals. In addition, it would appear that there is a lower level of burner air below which NO formation in the first stage drops to zero and it is of no further use to decrease the burner to air ratio. Obviously, this is a function of second stage geometry, spacing, gas temperature, etc. Actual staged tests indicate that the residence time in the first stage is really too short and a greater physical separation is required between stages. If so, the burner area may not be the place to add second stage air. An alternative might be to increase swirl and mixing in the first stage, but increased temperature and combustion intensity will result.

Slot Changes

Little or no effect on NO emission levels was observed for the slot changes which were made. It would appear from observation of the NO emission levels and the reduction of these levels that there was no overall effect. However, two of these modifications greatly affected the combustion patterns.

The angling of the front slots outward had little effect except to somewhat broaden the oblong shape of the flame. The inward angling (the first change) showed an extreme change in flame pattern: the first stage combustion was wiped out and a new long, circular pattern of flame appeared. Apparently, the internal recirculation zones of the first stage combustion extended up to and beyond the intersection of the second stage addition of air and the burner air; the result was loss of ignition at the burner and ignition held (by hot wall radiation and new post burner recirculation patterns) at the intersection of the two air streams. The combustion pattern showed up as a new longer, lazier, single stage combustion pattern.

Both changes in the side slots involved a halving of the radius of the "circle of air injection" for the second stage air. At the center of the flame, the smokey core surrounded by a bright firing halo disappeared and the overall flame became thoroughly bright with little or no radial changes apparent.

In testing the effect of port position for staging, no significant difference in NO emission levels from the side or front ports was observed. All points were used to draw a single curve.

Burner Changes

The effect of velocity on NO emission levels was minimal. The effect of velocity on overall excess air levels, load levels, and preheat levels showed some slight variation, but this was less than the error in the experimental measurement.

The effect of burner velocity on the staged combustion tests was also unimportant. In general, it appears that velocity is not a major variable in our basic combustion unit.

The flame patterns were usually unaffected by the velocity changes.

B Data and Testing Effects

NDIR/TECo

The NDIR and TECo instruments are very easy to use and require only minimum maintenance. Both instruments or one instrument and another independent method of NO measurement should be used at the same time. Either instrument may slowly drift away from the true NO measurement and require recalibration. An indication of some problem is indicated almost immediately when the instruments do not agree on an NO measurement. The most common problems encountered were due to changing temperature in the furnace area where the instrumentation is located:

1) Loss of the temperature controller on the NDIR and subsequent drift.
2) Loss of calibration on the TECo due to increased temperature and an increase in the dark current.
3) Loss of NO in the 34$^{o}$F ice bath at the highest excess air levels.

Any of these problems for either instrument is easily corrected if it is recognized; during our testing all of these problems were easily identified.

Temperature changes in the furnace room were unavoidable and since the instrumentation was in the same area, it was inevitable that these changes affected the TECo and NDIR. These changes were minimized by calibrating after the furnace was warmed up and the room became hot.

Preventative maintenance eliminated almost all other problems that had appeared in Phase I with the instruments. Whenever measurements were made, the instruments had to agree within $\pm$ 10 ppm or $\pm$ 5%

(whichever is larger) or a problem was suspected and the situation corrected. Calibration checks were made several times a day and usually no significant drift for either instrument over a single day was noticed. When a drift was noticed it was usually due to one of the three problems listed above and recalibration solved the problem.

The only gaseous interferent observed for either instrument was $H_2O$ which absorbs infrared like NO when measured by the NDIR. The presence of CO with NO does not reduce the NO measurement, even when passed through the heated stainless steel coil used for the $NO_2$ conversion in the TECo.

It was noticed that the NDIR/TECo error is greatest at the highest excess air levels. Inevitably, the NDIR read low when compared to the TECo. In some cases this error exceeded 5% and could not be reconciled with any calibration checks. Recently some time was spent working on this problem and the results were:

1) $NO_x$ disappeared in the $34^oF$ ice bath but not to any large extent in the $50^oF$ ice bath, although the smell of $NO_2$ was present in the $50^oF$ bath.

2) When the flue gas was replaced by air, there was a "lingering, but decreasing" NO level recorded on the NDIR and TECo from the $34^oF$ ice bath.

3) When the $34^oF$ cold finger was opened, a strong smell of $NO_2$ was present on warming.

4) No increase of NO (from the $50^oF$ ice bath) was indicated by the TECo.

It is suspected that at 34$^{o}$F the glass surface may aid in oxidizing NO to $NO_2$, especially at high levels of excess air where the oxygen concentration is 7% (versus 3% and <1% at lower excess air levels) and then $NO_2$ dissolves in the water of condensation to produce nitrous acid:

$$H_2O + \left\{ \begin{array}{c} NO + NO_2 \\ \rightleftarrows \\ N_2O_3 \end{array} \right\} \rightleftharpoons 2\ HNO_2$$

In addition, irreversible oxidation to nitric acid is also possible:

$$O_2 + 2\ HNO_2 \longrightarrow 2\ HNO_3$$

Whittaker ($NO_x$)

The Whittaker chemical cell NO monitor has shown unreconcilable differences when compared to readings from the NDIR and TECo during most coal testing. It did not respond to the true NO levels in the flue gas. Although it read correctly at times, it did not do so consistently. When the reading was in error (greater than ± 10% deviation), it always read a value higher than the NDIR and TECo. This higher reading cannot be reconciled and it does not seem to involve the following:

1) Calibration – This was checked even before and after bad measurements.

2) $SO_2$ – Fresh Malcosorb and calibration steps rule this out because of the very rapid response.

3) $CO/CO_2$ – Test gases with these, even when saturated with water, had no effect except at very high concentrations of CO (>1% CO).

The higher reading appears to be the result of some component in the flue gas which is not taken out completely by the filters, water bath, or Malcosorb. Substitution of Dynascience's "$SO_2$ Scrubber Solution" in a normal bubbler did not remove the interferences in the NO measurement either. The solution bubbler made the instrument somewhat more erratic and the maximum errors in any single reading seemed greater. The average error of all readings appeared to be somewhat lower with the bubbler, however.

Fluctuation in Coal Data

From day to day, changes in the NO emission levels for duplicate tests occurred. The causes of these changes are unknown. The following suggestions have been made, but it is not known if these even contribute to the problem:

1) Air temperature variations (no air preheat in primary)

2) Changes in air humidity

3) Moisture variations in coal

4) Slight changes in fraction of total air used for primary coal transport (changes primary air to coal weight by a much larger amount)

5) Changes in the coal, chemically, as day by day slightly different grindings are used.

The magnitude of these changes is usually less than the error of measurement ($\pm$ 5%) but can sometimes become $\pm$ 10%. It was considered not to be a major problem however and was usually ignored.

## Carbon Loss

The carbon loss (as opposed to burner efficiency) from the coal fired tests on our unit (there is no observable solid carbon loss during oil or gas fired tests on our unit) is dependent upon the excess air. The efficiency for the combustion of the Colorado coal was above 95% and usually about 98%.

## C. Final Presentation

Table 8.1 shows the final results for the Phase II studies. This table is used to indicate the effect of each variable on NO emission levels. The number of pluses or minuses is meant only to be a relative indication of NO reduction.

## D. Interrelated Variables

Some of the variables are interrelated and should be considered only in combination. (For example, see preheat and excess air effect upon preheat as shown in Table 8.1.) In addition, many of the variables studied could be defined by a new set of variables such as enthalpy content, temperature, velocity, etc.

TABLE 8.1 RELATIVE EFFECTS ON NO IN THE FLUE GAS*

| | Phase II | From Phase I | |
|---|---|---|---|
| Under Normal Conditions Increasing Level of Variable | Colorado Coal | Ohio Coal | Gas |
| Excess Air | ++++ | ++++ | ++/-- |
| Load | +++ | ++++ | 0 |
| Preheat (normal air) | ++ | 0 | +++ |
| (high air) | +++ | +++ | +++ |
| Fineness | 0 | no data | no data |
| Flue Gas Recirculation | - | -- | ---- |
| Staged Combustion | ----/ | ----/ | --- |
| Slot Changes (added effect) | 0 to + | no data | no data |
| Burner Changes (added effect) | + to 0 | no data | no data |

*+ Indicates increasing; number of +'s indicates relative magnitude.
- Indicates decreasing; number of -'s indicates relative magnitude.
/ Indicates maximum or minimum is reached.

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## IX. CONCLUSIONS

The following conclusions have been derived from the work performed in Phases I and II for coal firing on the single burner test unit:

1) There is a distinct difference in NO emissions from the Ohio and Colorado coals attributable to fuel bound nitrogen and possibly flame temperature.

2) The conversion of fuel bound nitrogen increases with increasing excess air level for both coals.

3) Air preheat affects the coal NO emission levels differently for different excess air levels. The reasons for this are unknown.

4) A very small reduction of NO for the Colorado coal and a moderate reduction for the Ohio coal for secondary flue gas recirculation has been shown, and apparently only thermally formed NO is reduced.

5) A minimum of 60% burner air (total burner to 100% theoretical air) for reduction of NO is indicated for staged combustion of both coals. No further first stage reduction of NO seems to occur at lower percentages of burner air.

6) A definite physical separation appears to be required for addition of the second stage air for reduction of NO from coal combustion. Progressive

mixing may be adequate. Even so, a separately spaced second stage probably is better.

7) It appears that the same free radicals are responsible for conversion of fuel bound nitrogen and thermal fixation of NO in the final steps of NO production under substoichiometric conditions.

8) It has not been possible in Phase II to determine quantitatively what fraction of the NO is from fuel bound nitrogen for either coal. About 10%-15% more of the Colorado coal fuel bound nitrogen appears to be converted to NO than for the Ohio coal.

The final conclusions to be drawn from the Phase I and Phase II work shows that for coal testing on our basic combustion unit and applicable to single burner units (no consideration of burner design is attempted):

1) Thermal fixation/fuel bound nitrogen conversion NO emission effects are different. Conditions to reduce one source of NO are not the same as those to reduce the other.

2) Flue gas recirculation does <u>not</u> show promise for NO reduction in coal flames.

3) For existing units, excess air level shows the most promising means of controlling flue gas emissions of NO.

4) For new units, staged combustion and total air control show the most effective means of reducing NO emissions.

5) The second stage air probably should not be added with the burner air for greatest effect, but from separate $NO_x$ ports.

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## X. REMARKS (Recommendations)

The indications from the Phase I single burner work have been reinforced by the Phase II single burner work. The most promising NO reduction method for existing units without construction or costly modification is control of excess air. This requires lowered excess air, probably below 10%. Another method for new units is staged combustion. Again the requirement appears to be a separate first stage with reducing conditions prevalent. Since these concepts require a change in overall utility design and manufacturing, there will be a long period of development and testing required to demonstrate the practicality of these ideas. Much of the problem will be fears of increased corrosion (which may or may not be substantiated in the future), increased carbon loss, decrease in burner stability (which may or may not exist), slagging, etc. There is a need for continuing research so that the anticipated problems either can be shown to be nonexistent or can be solved by the utility and manufacturing people.

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# APPENDIX A

## FUELS DATA, ANALYSES, AND CALCULATIONS

### A. Fuel Data

The coal used in all of our coal fired tests during Phase II was a Colorado coal from the Bear Mine in Somerset Colorado. The time lag for an analysis was at least 30 days from the time of submission of samples. Therefore all calculations pertaining to stoichiometry and load were carried out based on a prior, but recent coal analysis. This analysis and the average moisture used in calculations are shown in Table A.1. Although there was some variation in the moisture analyses, the calculations were not corrected since any error was considered smaller than the experimental measurement techniques.

The natural gas analysis used for the igniter is shown in Table A.2. The analyses first used were averaged and all calculations based on these numbers. Later, a new analysis was found and although the molecular constituents were about the same, the density and Btu value were different. However the new analysis was not used in the calculations due to the small effect that the igniter gas would have in the coal fired tests.

In addition to those analyses listed in Table A.1, other coal fuel bound nitrogen and moisture analyses were also run. Below follows the listing of these:

| Coal | | | |
|---|---|---|---|
| Date of Sample | 2/13/74 | 3/18/74 | 4/11/74 |
| Nitrogen, % dry | 1.2 | -- | -- |
| Moisture | 4.9 | 5.3 | 5.6 |

## B. Fuels Analyses

No fuels analyses were done at B&W ARC for natural gas. All values were reported to B&W by the Columbia Gas Company at regular intervals.

All of the important fuels analyses for coal are shown below by the method used at B&W ARC:

| | |
|---|---|
| Moisture | ASTM by heating and weight difference in samples |
| Btu | ASTM by bomb calorimetry |
| Total — carbon | ASTM by collection of $CO_2$ in ultimate train |
| — hydrogen | ASTM by collection of $H_2O$ in ultimate train |
| — nitrogen | Kjeldahl distillation and titration |
| — sulfur | ASTM by bomb calorimetry washings as $BaSO_4$ |
| — ash | ASTM by complete combustion and residual weight |
| — oxygen | By difference |

## C. Fuels Calculations

In the chemical description of the coal for mathematical purposes, all weight percent contents including moisture were converted to atomic percentages. The ash was considered to be $SiO_2$. An ash analysis indicated large amounts of $Al_2O_3$ and $Fe_2O_3$ and so the $SiO_2$ was a good average in molecular weight between $AlO_{1.5}$ and $FeO_{1.5}$. The fuel values on conversion showed the following atomic ratios for chemical balance at stoichiometric conditions:

| | | | |
|---|---|---|---|
| Colorado coal (wet) | C = 1.0000 | Stoichiometric Air (dry) | N = 8.6808 |
| | H = 0.91614 | | O = 2.3273 |
| | N = 0.01408 | | |
| | S = 0.00564 | | |
| | Si = 0.02680 | | |
| | O = 0.19563 | | |
| Natural gas | C = 1.0000 | Stoichiometric Air (dry) | N = 14.639 |
| | H = 3.8851 | | O = 3.9267 |
| | N = 0.0087 | | |
| | O = 0.0158 | | |

(For reference, the following are included:

| | | | |
|---|---|---|---|
| Ohio coal (wet) | C = 1.0000 | Stoichiometric Air (dry) | N = 9.1830 |
| | H = 0.94309 | | O = 2.3294 |
| | N = 0.01328 | | |
| | S = 0.01504 | | |
| | Si = 0.03519 | | |
| | O = 0.24269) | | |

The theoretical air requirement for the coals and gas above yielded a curve of excess air versus oxygen concentration in the flue gas after combustion had taken place. Suitable curves were chosen* rather than calculating each case separately. The curves chosen are:

Either coal: If $0.0 \leq \% O_2 \leq 2.5102$

Then $PTA = 100 + 4.7279 (POF)$

If $\% O_2 > 2.5102$

Then $PTA = 100 + \frac{10}{3} (POF) + \frac{5}{9} (POF)^2$

Gas: If $0.0 \leq \% O_2 \leq 2.4588$

Then $PTA = 100 + 4.7279 (POF)$

If $\% O_2 > 2.4588$

Then $PTA = 100 + \frac{7}{2} (POF) + \frac{1}{2} (POF)^2$

where: PTA = % theoretical air

and POF = % oxygen as measured in the flue gas

*Useful Tables for Engineers and Steam Users, 11th Ed., 1969, The Babcock & Wilcox Company.

The two sizes of Colorado coal used in the fineness tests were:

| Percent through | Coarse (Series VII, IX, X, XI, and XII) | Fine (Series VIII) |
|---|---|---|
| 30 mesh | 99.6 | 99.7 |
| 50 | 98.5 | 99.2 |
| 100 | 91.8 | 98.5 |
| 140 | 81.5 | 96.1 |
| 200 | 70.0 | 91.6 |
| 270 | 58.8 | 85.2 |
| 375 | 50.0 | 76.8 |

The coarse pulverization was used for all Colorado coal tests except Series VIII.

**TABLE A.1 COLORADO COAL ANALYSIS**

| B&W Lab Serial No. | C-13864 | -- | -- | Average | C-13864 |
|---|---|---|---|---|---|
| Date | 2/11/74 | 3/5/74 | 2/13/74 | | 3/17/75 |
| % Volatile | -- | -- | -- | | 38.5 |
| Fixed Carbon | -- | -- | -- | | 52.6 |
| Ash | 9.8 | -- | -- | | 8.9 |
| % Total Moisture | 4.4 | 4.1,5.2 | 4.9 | 4.65 | 3.3 |
| Btu/lb, Dry | 12980 | -- | 00 | | -- |
| <u>Ultimate, Dry %</u> | | | | | |
| C | 73.1 | | | | |
| H | 5.1 | | | | |
| N (determined) | 1.2 | | | | |
| S | 1.1 | | | | |
| Ash | 9.8 | | | | |
| O (difference) | 9.7 | | | | |

## TABLE A.2 NATURAL GAS ANALYSIS

| Type | Columbia Gas Transmission Corp Pittsburgh Group, Steubenville | | | Average of three groups | New Analysis (Not Used) |
|---|---|---|---|---|---|
| Date | 12/20/71 | 6/21/71 | 1/23/71 | -- | 12/18/72 |
| Mole %* | | | | | |
| $N_2$ | 0.47 | 0.40 | 0.49 | 0.45 | 0.40 |
| $CO_2$ | 0.72 | 0.97 | 0.77 | 0.82 | 0.78 |
| $CH_4$ | 95.01 | 95.57 | 95.08 | 95.22 | 95.84 |
| $C_2H_6$ | 3.19 | 2.63 | 2.93 | 2.92 | 2.54 |
| $C_3H_8$ | 0.41 | 0.30 | 0.49 | 0.40 | 0.30 |
| $C_4H_{10}$ | 0.15 | 0.10 | 0.19 | 0.15 | 0.11 |
| $C_5H_{12}$ | 0.05 | 0.03 | 0.05 | 0.04 | 0.03 |
| $C_6H_{14}$* | -- | -- | -- | -- | -- |
| $\rho_{(calc.)}$ | 0.5864 | 0.5835 | 0.5872 | 0.5857 | 0.5814 |
| Btu (calc.) | 1038.7 | 1029.0 | 1038.1 | 1035.3 | 1030.5 |

*Sulfur bearing materials were small and therefore not entered into the calculations.

## TABLE A.3 OHIO COAL ANALYSIS

COAL ANALYSIS DATA

| B&W Lab Serial No. | C-13688 | C-13689 | C-13692 | Average Used in Calculations | C-13762 (Not used in Average) |
|---|---|---|---|---|---|
| Date of Sample | 4/20/72 | 5/9/72 | 5/15/72 | -- | 1/18/73 |
| % Volatile | 38.6 | 38.1 | 39.6 | -- | -- |
| Fixed Carbon | 49.4 | 48.7 | 49.2 | -- | -- |
| Ash | 12.0 | 13.2 | 11.2 | -- | -- |
| % Total Moisture | 5.7 | 6.4 | 6.3 | 6.13 | 5.4 |
| Btu/lb, Dry | 12290 | 12020 | 12410 | 12240 | -- |
| Ultimate, Dry % | | | | | |
| C | 69.1 | 67.9 | 69.7 | 68.9 | 72.8 |
| H | 4.8 | 4.6 | 4.9 | 4.77 | 5.0 |
| N (determined) | 1.1 | 1.0 | 1.1 | 1.07 | 1.1 |
| S | 2.8 | 2.7 | 2.8 | 2.77 | -- |
| Ash | 12.0 | 13.2 | 11.2 | 12.1 | 7.6 |
| O (difference) | 10.2 | 10.6 | 10.3 | 10.4 | -- |

## APPENDIX B

## OPERATING CONDITIONS, MEASUREMENTS, AND CALCULATIONS

### A. Operating Conditions

Before any data runs for a day's testing commenced, the furnace was warmed up and all instruments were calibrated. The furnace warmup period was at least one half to one hour. During this time, all instruments were zeroed and calibrated with at least one standard gas.

The $NO_x$ instrumentation was checked with at least three or four Matheson gas standards of ∿200, ∿500, ∿800, and ∿1300 ppm NO in nitrogen. As standard tanks of gas neared the point of being empty, new standards of the same concentration were ordered with a certified analysis. These new standards were checked against the old ones to verify the analysis before use as calibration gases.

The standard operating conditions selected for our basic combustion tunnel were 115% theoretical air, 600$^{o}$F preheat for the secondary air, and a 5,000,000 Btu (5 MBtu)/hour load or heat release rate. During all coal tests, the natural gas igniter was operated at three lb/hr and a heat release rate of about 70,000 Btu (70 kBtu)/hr.

### B. Calculations

The orifice calculations used are based on the ASTM Fluid Meter Report, 1940. The important equations are:

$$W = 358.9\ (D_1)^2\ KEY\ \sqrt{\rho_{true}\ \Delta H}$$

where:

$$KEY = 0.935\ (0.7 - D_1/D_2)^{5/4} + D_1/D_2$$

and

$$\rho_{true} = 0.0741\ \frac{273.16\ (P_{net})}{0.55556\ (T + 459.67)}$$

For all inlets the air calculations for the furnace firing reduce to:

$$W = K \sqrt{\frac{(PS)(\Delta H)}{T + 459.67}}$$

Where:

| Dry air inlet description | $D_1$ | $D_2$ | K, a constant |
|---|---|---|---|
| Primary air | 2.25 | 4.00 | 7028. |
| Secondary air | 7.0 | 12.0 | 68689. |
| Secondary flue gas | 5.0 | 12.0 | 33601. |
| Second stage air | 4.5 | 8.0 | 28110. |

The addition of humidity in the air is easily accomplished:

$$W_{H_2O} = W_{air} \sqrt{\frac{(\rho_{H_2O})(PS_{H_2O})}{(\rho_{air})(PS_{air})}}$$

$$= W_{air} \sqrt{0.62133\ \frac{PS_{H_2O}}{PS_{air}}}$$

Where:

$W_{H_2O}$ is the weight of water in lb/hr

and

$W_{air}$ is the weight of air in lb/hr (previously calculated above)

The ash sampling probe also reduces to the same type of equation whereby $D_1$ is 0.625, $D_2$ is 1.5, and K is 525.3. For the natural gas igniter, the orifice equation is:

$$W = \frac{10.0^{(0.61278 + \log(NF))} \cdot 21.3480(0.0072527 \cdot \Delta H + P_{net})}{(T + 459.7)}$$

Although the form is awkward, it shows the flowmeter/orifice constants.

# APPENDIX C

## PRELIMINARY TEST DATA

The preliminary data is presented in the tables on the following pages. Six series of tests were run. Each series of tests is described by four tables. The series of data are:

VII. Base line Colorado coal tests (included substoichiometric tests)

VIII. Fineness tests with Colorado coal

IX. Flue gas recirculation for Colorado coal (secondary FGR only)

- A. Base line (no FGR)
- B. FGR

X. Staged combustion tests with Colorado coal

- A. Base line (no staging)
- B. Staged

XI. Slot changes with Colorado coal

- A. Base line (original configuration)
- B. Change #1
- C. Change #2

XII. Burner changes with Colorado coal

- A. Base line (original configuration)
- B. Change #1
- C. Change #2

The table headings are discussed below also:

Table 1 — Furnace input data in pounds per hour for the natural gas igniter, fuel, primary air (used as transport air for coal only), secondary air, second stage air, and flue gas recycled. (The two numbers for VII-1, fuel are 428/448 and are respectively the fuel weight dry and the fuel weight with normal moisture.)

Table 2 — Total amount of air, in percent of stoichiometric; the heat release rate in $10^3$ Btu per cubic foot per hour; the total, averaged gas preheat for all air and any recirculated flue gas; the weight percent of flue gas recycled; and the percent of stoichiometric air which enters through the burner (primary and secondary summed together).

Table 3 — The three $NO_x$ instrument readings in ppm NO reduced to 3% oxygen and dry for the Beckman NDIR, TECo chemiluminescence, and the Whittaker chemical cell; the average of the NDIR and TECo expressed as ppm NO $\pm$ the standard deviation of the average; and the conversion of the ppm NO to pounds of NO (not $NO_2$) per million Btu input as fuel Btu only.

Table 4 — The humidity and barometric pressure in mm Hg; the uncorrected ("raw, as recorded") concentration of oxygen, carbon monoxide, sulfur dioxide, and carbon dioxide; and the ash loadings as weight percent of ash in the flue gas (pounds of ash per hundred pounds of flue gas) and weight percents of carbon and nitrogen as found in the ash (pounds of total carbon and total nitrogen, forms undeterminable, per hundred pounds of ash).

## TABLE C.1 SERIES VII – COLORADO COAL, FURNACE DATA (INPUT)

| ORIGINAL RUN # AND SERIES OF RUNS | LB. / HR. (DRY WT. / WET WT.) IGNITER (GAS) | FUEL | PRIMARY AIR | SECONDARY AIR | 2ND STAGE AIR | FLUE GAS |
|---|---|---|---|---|---|---|
| VII - 1 | 3.0 | 428/448 | 583/644 | 4153/4589 | 0/ 0 | 0 |
| VII - 2 | 3.0 | 423/444 | 590/648 | 5137/5638 | 0/ 0 | 0 |
| VII - 3 | 2.9 | 427/448 | 577/635 | 3670/4047 | 0/ 0 | 0 |
| VII - 4 | 3.1 | 261/274 | 565/609 | 2510/2709 | 0/ 0 | 0 |
| VII - 5 | 3.1 | 244/256 | 573/617 | 2954/3186 | 0/ 0 | 0 |
| VII - 6 | 3.1 | 221/232 | 549/594 | 1755/1901 | 0/ 0 | 0 |
| VII - 7 | 3.2 | 573/601 | 609/650 | 5867/6269 | 0/ 0 | 0 |
| VII - 8 | 3.1 | 413/434 | 613/653 | 3529/3762 | 0/ 0 | 0 |
| VII - 9 | 3.0 | 410/430 | 619/660 | 3109/3320 | 0/ 0 | 0 |
| VII -10 | 3.1 | 413/433 | 628/669 | 2509/2678 | 0/ 0 | 0 |
| VII -11 | 3.1 | 414/434 | 604/643 | 2355/2514 | 0/ 0 | 0 |
| VII -12 | 3.1 | 416/437 | 611/652 | 2102/2244 | 0/ 0 | 0 |
| VII -13 | 3.1 | 547/574 | 674/733 | 5474/5950 | 0/ 0 | 0 |
| VII -14 | 3.1 | 527/552 | 675/742 | 6538/7173 | 0/ 0 | 0 |
| VII -15 | 3.0 | 496/520 | 667/728 | 4362/4764 | 0/ 0 | 0 |
| VII -16 | 3.0 | 433/454 | 589/647 | 4288/4715 | 0/ 0 | 0 |
| VII -17 | 3.0 | 416/437 | 595/651 | 5159/5649 | 0/ 0 | 0 |
| VII -18 | 3.0 | 405/425 | 596/653 | 3560/3910 | 0/ 0 | 0 |
| VII -19 | 3.1 | 541/567 | 674/730 | 5640/5900 | 0/ 0 | 0 |
| VII -20 | 3.1 | 546/573 | 681/722 | 5463/5794 | 0/ 0 | 0 |
| VII -21 | 3.1 | 519/545 | 681/724 | 6380/6788 | 0/ 0 | 0 |
| VII -22 | 3.1 | 276/290 | 518/553 | 3352/3583 | 0/ 0 | 0 |
| VII -23 | 3.0 | 266/279 | 514/550 | 2507/2684 | 0/ 0 | 0 |
| VII -24 | 3.1 | 261/274 | 519/551 | 2167/2302 | 0/ 0 | 0 |
| VII -25 | 3.0 | 270/284 | 520/556 | 2510/2683 | 0/ 0 | 0 |
| VII -26 | 3.1 | 452/474 | 606/646 | 4397/4685 | 0/ 0 | 0 |
| VII -27 | 3.0 | 431/452 | 598/635 | 5402/5729 | 0/ 0 | 0 |
| VII -28 | 3.1 | 463/485 | 674/716 | 5491/5831 | 0/ 0 | 0 |
| VII -29 | 3.1 | 426/446 | 606/644 | 3756/3994 | 0/ 0 | 0 |

## TABLE C.2 SERIES VII – COLORADO COAL, FURNACE DATA (FINAL)

| ORIGINAL RUN # AND SERIES OF RUNS | TOTAL AIR, % | HEAT, KBTU/FT**3 / HR. | GAS PRE-HEAT DEG. F | FLUE GAS RECYCLED TO INPUT (%) | AIR AT BURNER (%) |
|---|---|---|---|---|---|
| VII - 1 | 113.0 | 49.59 | 608 | 0.0 | 113.0 |
| VII - 2 | 138.0 | 50.77 | 635 | 0.0 | 138.0 |
| VII - 3 | 101.5 | 48.96 | 599 | 0.0 | 101.5 |
| VII - 4 | 119.2 | 30.26 | 568 | 0.0 | 119.2 |
| VII - 5 | 146.2 | 29.08 | 570 | 0.0 | 146.2 |
| VII - 6 | 105.0 | 25.15 | 500 | 0.0 | 105.0 |
| VII - 7 | 115.6 | 66.65 | 620 | 0.0 | 115.6 |
| VII - 8 | 102.1 | 47.24 | 585 | 0.0 | 102.1 |
| VII - 9 | 92.8 | 46.21 | 574 | 0.0 | 92.8 |
| VII -10 | 77.4 | 45.66 | 542 | 0.0 | 77.4 |
| VII -11 | 72.8 | 45.66 | 537 | 0.0 | 72.8 |
| VII -12 | 66.5 | 45.58 | 520 | 0.0 | 66.5 |
| VII -13 | 115.0 | 63.74 | 622 | 0.0 | 115.0 |
| VII -14 | 140.0 | 63.19 | 631 | 0.0 | 140.0 |
| VII -15 | 103.6 | 56.90 | 602 | 0.0 | 103.6 |
| VII -16 | 114.9 | 46.76 | 296 | 0.0 | 114.9 |
| VII -17 | 141.0 | 45.66 | 298 | 0.0 | 141.0 |
| VII -18 | 104.6 | 43.54 | 285 | 0.0 | 104.6 |
| VII -19 | 115.6 | 58.40 | 286 | 0.0 | 115.6 |
| VII -20 | 115.0 | 59.10 | 290 | 0.0 | 115.0 |
| VII -21 | 138.9 | 56.67 | 289 | 0.0 | 138.9 |
| VII -22 | 142.0 | 30.34 | 285 | 0.0 | 142.0 |
| VII -23 | 115.0 | 28.84 | 279 | 0.0 | 115.0 |
| VII -24 | 104.0 | 28.22 | 270 | 0.0 | 104.0 |
| VII -25 | 113.6 | 31.12 | 556 | 0.0 | 113.6 |
| VII -26 | 113.0 | 52.42 | 621 | 0.0 | 113.0 |
| VII -27 | 142.0 | 51.64 | 637 | 0.0 | 142.0 |
| VII -28 | 136.0 | 55.02 | 633 | 0.0 | 136.0 |
| VII -29 | 104.5 | 48.89 | 600 | 0.0 | 104.5 |

## TABLE C.3 SERIES VII – COLORADO COAL, NOx MEASUREMENTS

| ORIGINAL SERIES - RUN #-S | PPM NOX 3% O2, DRY NOIR | TFCO | WHIT | PPM NOX IN DRY, 3% O2 FLUE GAS | LB. NOX / 10**6 BTU INPUT |
|---|---|---|---|---|---|
| VII - 1 | 951 | 955 | 941 | 953 ± 2 | 0.96 ± .0 |
| VII - 2 | 1217 | 1282 | 1077 | 1250 ± 46 | 1.51 ± .06 |
| VII - 3 | 641 | 645 | 669 | 643 ± 3 | 0.59 ± .0 |
| VII - 4 | 808 | 832 | 848 | 820 ± 17 | 0.85 ± .02 |
| VII - 5 | 957 | 1005 | 1049 | 981 ± 34 | 1.23 ± .04 |
| VII - 6 | 505 | 515 | 595 | 510 ± 7 | 0.47 ± .01 |
| VII - 7 | 1099 | 1071 | 1063 | 1085 ± 20 | 1.08 ± .02 |
| VII - 8 | 675 | 671 | 691 | 673 ± 3 | 0.60 ± .0 |
| VII - 9 | 532 | 538 | 533 | 535 ± 4 | 0.44 ± .0 |
| VII -10 | 208 | 206 | 251 | 207 ± 2 | 0.14 ± .0 |
| VII -11 | 109 | 99 | 155 | 104 ± 7 | 0.07 ± .0 |
| VII -12 | 81 | 78 | 138 | 79 ± 2 | 0.05 ± .0 |
| VII -13 | 1169 | 1223 | 1195 | 1196 ± 38 | 1.21 ± .04 |
| VII -14 | 1324 | 1411 | 1380 | 1368 ± 62 | 1.67 ± .08 |
| VII -15 | 843 | 847 | 858 | 845 ± 3 | 0.78 ± .0 |
| VII -16 | 937 | 897 | 859 | 917 ± 28 | 0.94 ± .03 |
| VII -17 | 1132 | 1072 | 1050 | 1102 ± 43 | 1.35 ± .05 |
| VII -18 | 589 | 565 | 591 | 577 ± 17 | 0.54 ± .02 |
| VII -19 | 952 | 938 | 991 | 945 ± 10 | 0.96 ± .01 |
| VII -20 | 861 | 963 | 922 | 912 ± 72 | 0.90 ± .07 |
| VII -21 | 966 | 1118 | 1033 | 1042 ± 107 | 1.23 ± .13 |
| VII -22 | 869 | 900 | 847 | 854 ± 65 | 1.03 ± .08 |
| VII -23 | 665 | 649 | 671 | 657 ± 11 | 0.65 ± .01 |
| VII -24 | 450 | 435 | 470 | 443 ± 11 | 0.40 ± .01 |
| VII -25 | 762 | 787 | 806 | 774 ± 18 | 0.76 ± .02 |
| VII -26 | 1050 | 1077 | 1118 | 1064 ± 19 | 1.04 ± .02 |
| VII -27 | 1298 | 1356 | 1375 | 1327 ± 41 | 1.59 ± .05 |
| VII -28 | 1307 | 1303 | 1363 | 1305 ± 3 | 1.51 ± .0 |
| VII -29 | 869 | 856 | 923 | 862 ± 9 | 0.78 ± .01 |

## TABLE C.4 SERIES VII – COLORADO COAL, OTHER MEASUREMENTS

| ORIGINAL SERIES - RUN #-S | HUM. (PM WET) | BAR. (MM WET) | O2 % | PPM CO | PPM SO2 | CO2 % | ASH % | C IN ASH % | N IN ASH % |
|---|---|---|---|---|---|---|---|---|---|
| VII - 1 | 13.1 | 726 | 2.7 | 90 | 550 | ---- | 0.39 | 28.0 | ---- |
| VII - 2 | 11.6 | 725 | 5.8 | 60 | 500 | ---- | ---- | ---- | ---- |
| VII - 3 | 12.4 | 724 | 0.5 | 1500 | 600 | ---- | 0.36 | 43.2 | ---- |
| VII - 4 | 7.4 | 733 | 3.4 | 40 | 650 | ---- | ---- | ---- | ---- |
| VII - 5 | 7.3 | 733 | 6.6 | 40 | 500 | ---- | 0.40 | 3.8 | ---- |
| VII - 6 | 8.1 | 727 | 1.1 | 850 | 575 | ---- | ---- | ---- | ---- |
| VII - 7 | 5.8 | 735 | 3.1 | 120 | 550 | ---- | ---- | ---- | ---- |
| VII - 8 | 5.2 | 735 | 0.6 | 3000 | 600 | ---- | ---- | ---- | ---- |
| VII - 9 | 5.5 | 735 | 0.2 | 34490 | 620 | ---- | ---- | ---- | ---- |
| VII -10 | 5.4 | 735 | 0.0 | 95427 | 580 | ---- | 0.80 | 50.2 | ---- |
| VII -11 | 5.4 | 735 | 0.0 | 145000 | 450 | ---- | 0.85 | 52.1 | ---- |
| VII -12 | 5.4 | 735 | 0.0 | 205000 | 480 | ---- | ---- | ---- | ---- |
| VII -13 | 9.4 | 733 | 3.0 | 70 | 660 | ---- | ---- | ---- | ---- |
| VII -14 | 12.0 | 732 | 6.0 | 60 | 575 | ---- | ---- | ---- | ---- |
| VII -15 | 10.3 | 732 | 0.9 | 2600 | 675 | ---- | 0.42 | -77- | ---- |
| VII -16 | 11.9 | 737 | 3.0 | 150 | 325 | ---- | ---- | ---- | ---- |
| VII -17 | 10.9 | 737 | 6.1 | 60 | 290 | ---- | ---- | ---- | ---- |
| VII -18 | 11.5 | 737 | 1.1 | 2600 | 375 | ---- | ---- | ---- | ---- |
| VII -19 | 8.8 | 738 | 3.1 | 240 | 450 | ---- | ---- | ---- | ---- |
| VII -20 | 4.4 | 729 | 3.0 | 115 | 425 | ---- | ---- | ---- | ---- |
| VII -21 | 5.0 | 729 | 5.9 | 115 | 400 | ---- | ---- | ---- | ---- |
| VII -22 | 5.6 | 730 | 6.2 | 60 | 380 | ---- | ---- | ---- | ---- |
| VII -23 | 5.9 | 731 | 3.0 | 40 | 200 | ---- | ---- | ---- | ---- |
| VII -24 | 4.6 | 730 | 0.9 | 930 | 500 | ---- | ---- | ---- | ---- |
| VII -25 | 5.6 | 730 | 2.8 | 375 | 375 | ---- | ---- | ---- | ---- |
| VII -26 | 5.2 | 730 | 2.7 | 100 | 310 | ---- | ---- | ---- | ---- |
| VII -27 | 4.6 | 730 | 6.2 | 100 | 300 | ---- | ---- | ---- | ---- |
| VII -28 | 4.8 | 731 | 5.6 | 150 | 300 | ---- | ---- | ---- | ---- |
| VII -29 | 4.8 | 730 | 1.0 | 950 | 400 | ---- | ---- | ---- | ---- |

TABLE C.5 SERIES VIII – FINENESS – COLORADO COAL, FURNACE DATA (INPUT)

| ORIGINAL RUN # AND SERIES OF RUNS | LB. / HR. (DRY WT. / WET WT.) IGNITER (GAS) | FUEL | PRIMARY AIR | SECONDARY AIR | 2ND STAGE AIR | FLUE GAS |
|---|---|---|---|---|---|---|
| VIII- 1 | 3.3 | 454/478 | 622/659 | 4499/4773 | 0/ 0 | 0 |
| VIII- 2 | 3.2 | 456/478 | 616/651 | 4464/4722 | 0/ 0 | 0 |
| VIII- 3 | 3.4 | 442/464 | 620/666 | 5892/6188 | 0/ 0 | 0 |
| VIII- 4 | 3.4 | 435/456 | 637/674 | 3752/3972 | 0/ 0 | 0 |
| VIII- 5 | 3.4 | 282/296 | 585/620 | 2600/2758 | 0/ 0 | 0 |
| VIII- 6 | 3.2 | 273/286 | 575/610 | 2197/2333 | 0/ 0 | 0 |
| VIII- 7 | 3.2 | 276/289 | 575/610 | 3524/3740 | 0/ 0 | 0 |
| VIII- 8 | 3.2 | 451/473 | 617/655 | 4469/4743 | 0/ 0 | 0 |
| VIII- 9 | 3.2 | 456/479 | 617/656 | 5827/6191 | 0/ 0 | 0 |
| VIII- 10 | 3.2 | 429/450 | 620/674 | 4417/4732 | 0/ 0 | 1298 |
| VIII- 11 | 3.2 | 530/556 | 666/713 | 5404/5787 | 0/ 0 | 0 |
| VIII- 12 | 3.2 | 439/461 | 613/659 | 4368/4697 | 0/ 0 | 0 |
| VIII- 13 | 3.2 | 450/472 | 613/653 | 5701/6069 | 0/ 0 | 0 |
| VIII- 14 | 3.2 | 410/430 | 621/664 | 3510/3761 | 0/ 0 | 0 |

TABLE C.6 SERIES VIII – FINENESS – COLORADO COAL, FURNACE DATA (FINAL)

| ORIGINAL RUN # AND SERIES OF RUNS | TOTAL AIR, % | HEAT, KBTU/FT**3 / HR. | GAS PRE-HEAT DEG. F | FLUE GAS RECYCLED TO INPUT (%) | AIR AT BURNER (%) |
|---|---|---|---|---|---|
| VIII- 1 | 115.0 | 52.97 | 610 | 0.0 | 115.0 |
| VIII- 2 | 113.7 | 52.97 | 615 | 0.0 | 113.7 |
| VIII- 3 | 149.4 | 53.44 | 633 | 0.0 | 149.4 |
| VIII- 4 | 102.8 | 49.91 | 592 | 0.0 | 102.8 |
| VIII- 5 | 114.3 | 32.54 | 551 | 0.0 | 114.3 |
| VIII- 6 | 102.9 | 31.04 | 530 | 0.0 | 102.9 |
| VIII- 7 | 150.5 | 33.09 | 583 | 0.0 | 150.5 |
| VIII- 8 | 114.9 | 52.50 | 610 | 0.0 | 114.9 |
| VIII- 9 | 144.1 | 54.86 | 629 | 0.0 | 144.1 |
| VIII- 10 | 119.9 | 51.64 | 621 | 22.2 | 119.9 |
| VIII- 11 | 117.0 | 61.78 | 620 | 0.0 | 117.0 |
| VIII- 12 | 115.6 | 47.63 | 293 | 0.0 | 115.6 |
| VIII- 13 | 143.0 | 49.20 | 282 | 0.0 | 143.0 |
| VIII- 14 | 102.7 | 44.01 | 270 | 0.0 | 102.7 |

TABLE C.7 SERIES VIII – FINENESS – COLORADO COAL, NOx MEASUREMENTS

| ORIGINAL SERIES - RUN #-S | PPM NOX 3% O2, DRY NDIR | TECO | WHIT | PPM NOX IN DRY, 3% O2 FLUE GAS | LB. NOX / 10**6 BTU INPUT |
|---|---|---|---|---|---|
| VIII- 1 | 1002 | 1085 | 1057 | 1044 ± 58 | 1.03 ± .04 |
| VIII- 2 | 1096 | 1091 | 1084 | 1094 ± 4 | 1.07 ± .0 |
| VIII- 3 | 1292 | 1326 | 1287 | 1309 ± 24 | 1.64 ± .03 |
| VIII- 4 | 738 | 716 | 723 | 727 ± 16 | 0.65 ± .01 |
| VIII- 5 | 796 | 776 | 783 | 786 ± 14 | 0.77 ± .01 |
| VIII- 6 | 552 | 527 | 561 | 539 ± 18 | 0.48 ± .02 |
| VIII- 7 | 1152 | 1134 | 1151 | 1143 ± 13 | 1.45 ± .02 |
| VIII- 8 | 1058 | 1115 | 1090 | 1086 ± 41 | 1.07 ± .04 |
| VIII- 9 | 1248 | 1350 | 1258 | 1299 ± 72 | 1.58 ± .09 |
| VIII- 10 | 985 | 939 | 924 | 962 ± 33 | 1.00 ± .03 |
| VIII- 11 | 1224 | 1227 | 1155 | 1226 ± 2 | 1.24 ± .0 |
| VIII- 12 | 861 | 851 | 853 | 856 ± 7 | 0.86 ± .01 |
| VIII- 13 | 1011 | 1018 | 1002 | 1014 ± 5 | 1.23 ± .01 |
| VIII- 14 | 631 | 604 | 621 | 617 ± 19 | 0.55 ± .02 |

TABLE C.8 SERIES VIII – FINENESS – COLORADO COAL, OTHER MEASUREMENTS

| ORIGINAL SERIES - RUN #-S | HUM. (MM WET) | BAR. (MM WET) | O2 % | PPM CO | PPM SO2 | CO2 % | ASH % | C IN ASH % | N IN ASH % |
|---|---|---|---|---|---|---|---|---|---|
| VIII- 1 | 4.6 | 737 | 3.0 | 80 | 67 | ---- | 0.45 | 13.3 | ---- |
| VIII- 2 | 4.1 | 735 | 2.8 | 100 | 675 | ---- | ---- | ---- | ---- |
| VIII- 3 | 4.3 | 761 | 6.9 | 80 | 540 | ---- | ---- | ---- | ---- |
| VIII- 4 | 4.3 | 761 | 0.7 | 2150 | 790 | ---- | ---- | ---- | ---- |
| VIII- 5 | 4.6 | 760 | 2.9 | 150 | 650 | ---- | ---- | ---- | ---- |
| VIII- 6 | 4.6 | 735 | 0.7 | 1700 | 700 | ---- | ---- | ---- | ---- |
| VIII- 7 | 4.6 | 735 | 7.0 | 100 | 525 | ---- | ---- | ---- | ---- |
| VIII- 8 | 4.6 | 733 | 3.0 | 150 | 700 | ---- | ---- | ---- | ---- |
| VIII- 9 | 4.9 | 733 | 6.4 | 8 | 510 | ---- | ---- | ---- | ---- |
| VIII- 10 | 6.3 | 733 | 3.7 | 90 | 640 | ---- | ---- | ---- | ---- |
| VIII- 11 | 6.3 | 732 | 3.3 | 100 | 700 | ---- | 0.45 | 3.3 | ---- |
| VIII- 12 | 6.8 | 732 | 3.1 | 105 | 1125 | ---- | ---- | ---- | ---- |
| VIII- 13 | 5.1 | 731 | 6.3 | 90 | 900 | ---- | ---- | ---- | ---- |
| VIII- 14 | 6.1 | 731 | 0.6 | 475 | 1250 | ---- | 0.65 | 31.5 | ---- |

TABLE C.9 SERIES IX – F. G. R. COLORADO COAL, FURNACE DATA (INPUT)

| ORIGINAL RUN # AND SERIES OF RUNS | LB. / HR. (DRY WT. / WET WT.) IGNITER (GAS) | FUEL | PRIMARY AIR | SECONDARY AIR | 2ND STAGE AIR | FLUE GAS |
|---|---|---|---|---|---|---|
| IX A - 1 | 3.1 | 454/476 | 605/648 | 4394/4706 | 0/ 0 | 0 |
| IX A - 2 | 2.9 | 317/332 | 518/551 | 3086/3283 | 0/ 0 | 0 |
| IX B - 3 | 3.1 | 456/478 | 598/638 | 4396/4690 | 0/ 0 | 382 |
| IX B - 4 | 3.1 | 452/474 | 598/636 | 4289/4563 | 0/ 0 | 1052 |
| IX B - 5 | 3.1 | 326/342 | 514/562 | 3134/3424 | 0/ 0 | 985 |

TABLE C.10 SERIES IX – F. G. R. COLORADO COAL, FURNACE DATA (FINAL)

| ORIGINAL RUN # AND SERIES OF RUNS | TOTAL AIR, % | HEAT, KBTU/FT**3 / HR. | GAS PRE-HEAT DEG. F | FLUE GAS RECYCLED TO INPUT (%) | AIR AT BURNER (%) |
|---|---|---|---|---|---|
| IX A - 1 | 112.4 | 52.58 | 615 | 0.0 | 112.4 |
| IX A - 2 | 115.7 | 36.63 | 586 | 0.0 | 115.7 |
| IX B - 3 | 111.8 | 53.21 | 618 | 6.6 | 111.8 |
| IX B - 4 | 110.4 | 53.29 | 616 | 18.5 | 110.4 |
| IX B - 5 | 113.7 | 38.90 | 588 | 22.7 | 113.7 |

TABLE C.11 SERIES IX – F. G. R. COLORADO COAL, NOx MEASUREMENTS

| ORIGINAL SERIES - RUN #-S | PPM NOX 3% O2, DRY NDIR | TECO | WHIT | PPM NOX IN DRY, 3% O2 FLUE GAS | LB. NOX / 10**6 BTU INPUT |
|---|---|---|---|---|---|
| IX A - 1 | 1010 | 1027 | 890 | 1018 ± 12 | 0.99 ± .01 |
| IX A - 2 | 806 | 816 | 726 | 811 ± 7 | 0.81 ± .01 |
| IX B - 3 | 960 | 976 | 868 | 968 ± 11 | 0.94 ± .01 |
| IX B - 4 | 868 | 908 | 780 | 888 ± 28 | 0.85 ± .03 |
| IX B - 5 | 762 | 778 | 654 | 770 ± 11 | 0.77 ± .01 |

TABLE C.12 SERIES IX – F. G. R. COLORADO COAL, OTHER MEASUREMENTS

| ORIGINAL SERIES - RUN #-S | HUM. (MM WET) | BAR. (MM WET) | O2 % | PPM CO | PPM SO2 | CO2 % | ASH % | C IN ASH % | N IN ASH % |
|---|---|---|---|---|---|---|---|---|---|
| IX A - 1 | 6.2 | 737 | 2.6 | 120 | 500 | ---- | ---- | ---- | ---- |
| IX A - 2 | 4.9 | 737 | 3.1 | 30 | 550 | ---- | ---- | ---- | ---- |
| IX B - 3 | 5.5 | 737 | 2.5 | 240 | 400 | ---- | ---- | ---- | ---- |
| IX B - 4 | 5.0 | 737 | 2.2 | 130 | 590 | ---- | ---- | ---- | ---- |
| IX B - 5 | 10.3 | 737 | 2.8 | 30 | 550 | ---- | ---- | ---- | ---- |

## TABLE C.13 SERIES X – STAGING COLORADO COAL, FURNACE DATA (INPUT)

| ORIGINAL RUN # AND SERIES OF RUNS | LB. / HR. (DRY WT. / WET WT.) IGNITER (GAS) | FUEL | PRIMARY AIR | SECONDARY AIR | 2ND STAGE AIR | FLUE GAS |
|---|---|---|---|---|---|---|
| X A - 1 | 3.2 | 301/316 | 528/560 | 2553/2707 | 0/ 0 | 0 |
| X A - 2 | 3.2 | 332/348 | 536/565 | 3269/3448 | 0/ 0 | 0 |
| X A - 3 | 3.1 | 330/346 | 518/553 | 3238/3455 | 0/ 0 | 0 |
| X A - 4 | 2.9 | 310/325 | 520/567 | 3542/3864 | 0/ 0 | 0 |
| X A - 5 | 3.1 | 329/345 | 522/556 | 4281/4563 | 0/ 0 | 0 |
| X A - 6 | 3.1 | 453/475 | 610/655 | 4375/4692 | 0/ 0 | 0 |
| X A - 7 | 3.1 | 447/469 | 609/655 | 4375/4711 | 0/ 0 | 0 |
| X A - 8 | 3.1 | 442/464 | 607/651 | 4345/4660 | 0/ 0 | 0 |
| X A - 9 | 2.7 | 443/465 | 596/652 | 4309/4715 | 0/ 0 | 0 |
| X A - 10 | 3.1 | 440/462 | 595/637 | 4369/4683 | 0/ 0 | 0 |
| X A - 11 | 3.2 | 439/461 | 590/651 | 4335/4787 | 0/ 0 | 0 |
| X A - 12 | 3.2 | 451/473 | 596/659 | 4882/5397 | 0/ 0 | 0 |
| X A - 13 | 3.2 | 456/478 | 578/641 | 5464/6058 | 0/ 0 | 0 |
| X A - 14 | 2.6 | 429/450 | 602/657 | 4335/4733 | 0/ 0 | 0 |
| X A - 15 | 3.2 | 446/468 | 606/655 | 4389/4742 | 0/ 0 | 0 |
| X A - 16 | 2.9 | 444/466 | 606/652 | 4337/4668 | 0/ 0 | 0 |
| X A - 17 | 2.6 | 444/466 | 597/649 | 5713/6213 | 0/ 0 | 0 |
| X A - 18 | 2.9 | 445/466 | 602/646 | 5813/6234 | 0/ 0 | 0 |
| X A - 19 | 2.9 | 492/516 | 594/652 | 4908/5386 | 0/ 0 | 0 |
| X A - 20 | 2.9 | 403/423 | 598/658 | 3542/3898 | 0/ 0 | 0 |
| X A - 21 | 2.9 | 520/546 | 665/728 | 5396/5900 | 0/ 0 | 0 |
| X A - 22 | 3.1 | 439/460 | 600/653 | 4345/4735 | 0/ 0 | 0 |
| X A - 23 | 3.1 | 314/329 | 515/553 | 3934/4197 | 0/ 0 | 0 |
| X A - 24 | 3.1 | 403/423 | 607/651 | 3687/3747 | 0/ 0 | 0 |
| X B - 25 | 3.2 | 300/315 | 519/551 | 1805/1915 | 747/ 792 | 0 |
| X B - 26 | 3.1 | 334/350 | 533/564 | 2568/2720 | 697/ 739 | 0 |
| X B - 27 | 3.1 | 321/337 | 522/556 | 1619/1726 | 1497/1597 | 0 |
| X B - 28 | 3.1 | 338/355 | 522/556 | 3391/3606 | 893/ 954 | 0 |
| X B - 29 | 3.1 | 351/368 | 522/557 | 2521/2690 | 1786/1908 | 0 |
| X B - 30 | 3.1 | 452/474 | 614/659 | 4016/4315 | 467/ 502 | 0 |
| X B - 31 | 3.1 | 443/464 | 606/649 | 3457/3698 | 926/ 992 | 0 |
| X B - 32 | 3.1 | 477/500 | 605/647 | 2766/2956 | 1829/1958 | 0 |
| X B - 33 | 3.1 | 439/460 | 600/655 | 2088/2275 | 2314/2529 | 0 |
| X B - 34 | 2.9 | 435/456 | 615/660 | 1709/1831 | 2781/2988 | 0 |
| X B - 35 | 3.3 | 431/452 | 598/663 | 3476/3877 | 942/1047 | 0 |
| X B - 36 | 3.2 | 429/450 | 598/662 | 2375/2626 | 1801/1999 | 0 |
| X B - 37 | 2.6 | 416/436 | 597/652 | 1783/1940 | 2413/2634 | 0 |
| X B - 38 | 2.6 | 428/449 | 598/650 | 1312/1424 | 2797/3045 | 0 |
| X B - 39 | 2.7 | 420/440 | 614/658 | 3891/4177 | 453/ 486 | 0 |
| X B - 40 | 3.1 | 379/397 | 598/645 | 3393/3659 | 932/1006 | 0 |
| X B - 41 | 3.1 | 399/418 | 597/653 | 2469/2701 | 1875/2056 | 0 |
| X B - 42 | 3.1 | 410/430 | 598/646 | 2079/2244 | 2301/2491 | 0 |
| X B - 43 | 2.9 | 404/423 | 590/636 | 1636/1758 | 2869/3093 | 0 |
| X B - 44 | 2.7 | 430/451 | 603/671 | 3556/3958 | 920/1026 | 0 |
| X B - 45 | 2.8 | 428/448 | 602/646 | 3847/4124 | 1855/1993 | 0 |
| X B - 46 | 2.7 | 459/481 | 605/658 | 4173/4533 | 1503/1636 | 0 |
| X B - 47 | 2.6 | 429/449 | 612/663 | 2339/2525 | 3456/3746 | 0 |
| X B - 48 | 2.9 | 401/420 | 591/649 | 2561/2813 | 976/1073 | 0 |
| X B - 49 | 2.9 | 397/416 | 587/643 | 1495/1637 | 1963/2155 | 0 |
| X B - 50 | 2.9 | 528/554 | 667/728 | 4224/4612 | 1148/1257 | 0 |
| X B - 51 | 2.9 | 516/541 | 660/722 | 2998/3274 | 2346/2571 | 0 |
| X B - 52 | 3.1 | 424/445 | 593/638 | 3066/3296 | 1283/1381 | 0 |
| X B - 53 | 2.9 | 421/442 | 602/647 | 1832/1967 | 2354/2531 | 0 |
| X B - 54 | 3.1 | 407/427 | 610/652 | 2978/3186 | 1158/1240 | 0 |
| X B - 55 | 2.9 | 419/440 | 603/647 | 1989/2137 | 2290/2463 | 0 |
| X B - 56 | 2.9 | 309/324 | 525/561 | 2156/2303 | 1794/1919 | 0 |
| X B - 57 | 3.1 | 400/419 | 594/637 | 1246/1334 | 2269/2433 | 0 |

## TABLE C.14 SERIES X – STAGING COLORADO COAL, FURNACE DATA (FINAL)

| ORIGINAL RUN # AND SERIES OF RUNS | TOTAL AIR % | HEAT, KBTU/ FT**3 / HR. | GAS PRE-HEAT DEG. F | FLUE GAS RECYCLED TO INPUT (%) | AIR AT BURNER (%) |
|---|---|---|---|---|---|
| X A - 1 | 103.9 | 34.35 | 555 | 0.0 | 103.9 |
| X A - 2 | 116.3 | 38.43 | 580 | 0.0 | 116.3 |
| X A - 3 | 115.7 | 38.20 | 593 | 0.0 | 115.7 |
| X A - 4 | 133.2 | 36.63 | 606 | 0.0 | 133.2 |
| X A - 5 | 148.3 | 39.61 | 620 | 0.0 | 148.3 |
| X A - 6 | 112.3 | 52.42 | 610 | 0.0 | 112.3 |
| X A - 7 | 113.7 | 51.95 | 615 | 0.0 | 113.7 |
| X A - 8 | 114.3 | 50.93 | 594 | 0.0 | 114.3 |
| X A - 9 | 113.0 | 51.17 | 597 | 0.0 | 113.0 |
| X A - 10 | 115.0 | 50.93 | 598 | 0.0 | 115.0 |
| X A - 11 | 116.3 | 51.32 | 619 | 0.0 | 116.3 |
| X A - 12 | 123.8 | 53.37 | 630 | 0.0 | 123.8 |
| X A - 13 | 135.1 | 54.62 | 641 | 0.0 | 135.1 |
| X A - 14 | 117.7 | 49.99 | 623 | 0.0 | 117.7 |
| X A - 15 | 114.3 | 51.72 | 603 | 0.0 | 114.3 |
| X A - 16 | 113.7 | 51.48 | 622 | 0.0 | 113.7 |
| X A - 17 | 145.1 | 52.89 | 607 | 0.0 | 145.1 |
| X A - 18 | 147.2 | 52.82 | 587 | 0.0 | 147.2 |
| X A - 19 | 114.3 | 57.30 | 630 | 0.0 | 114.3 |
| X A - 20 | 104.8 | 46.21 | 596 | 0.0 | 104.8 |
| X A - 21 | 119.2 | 60.99 | 638 | 0.0 | 119.2 |
| X A - 22 | 115.0 | 47.47 | 286 | 0.0 | 115.0 |
| X A - 23 | 144.1 | 34.42 | 290 | 0.0 | 144.1 |
| X A - 24 | 103.4 | 43.38 | 275 | 0.0 | 103.4 |
| X B - 25 | 103.7 | 33.17 | 537 | 0.0 | 78.4 |
| X B - 26 | 115.6 | 37.57 | 574 | 0.0 | 94.3 |
| X B - 27 | 115.0 | 34.82 | 583 | 0.0 | 67.7 |
| X B - 28 | 144.0 | 39.06 | 606 | 0.0 | 117.2 |
| X B - 29 | 139.9 | 39.30 | 632 | 0.0 | 88.1 |
| X B - 30 | 114.9 | 51.77 | 593 | 0.0 | 104.4 |
| X B - 31 | 114.9 | 49.91 | 594 | 0.0 | 93.6 |
| X B - 32 | 111.3 | 52.50 | 620 | 0.0 | 72.1 |
| X B - 33 | 116.2 | 47.63 | 629 | 0.0 | 62.4 |
| X B - 34 | 114.7 | 46.61 | 639 | 0.0 | 94.4 |
| X B - 35 | 119.1 | 48.96 | 621 | 0.0 | 96.8 |
| X B - 36 | 113.6 | 47.16 | 636 | 0.0 | 70.6 |
| X B - 37 | 117.7 | 44.72 | 629 | 0.0 | 58.4 |
| X B - 38 | 112.3 | 45.27 | 634 | 0.0 | 45.5 |
| X B - 39 | 120.6 | 48.10 | 603 | 0.0 | 109.6 |
| X B - 40 | 132.3 | 43.07 | 585 | 0.0 | 107.3 |
| X B - 41 | 126.2 | 43.93 | 606 | 0.0 | 78.3 |
| X B - 42 | 123.8 | 44.48 | 606 | 0.0 | 66.5 |
| X B - 43 | 128.7 | 43.15 | 611 | 0.0 | 56.2 |
| X B - 44 | 120.6 | 48.89 | 592 | 0.0 | 98.7 |
| X B - 45 | 150.5 | 48.41 | 584 | 0.0 | 106.2 |
| X B - 46 | 140.0 | 52.03 | 591 | 0.0 | 106.4 |
| X B - 47 | 152.8 | 46.53 | 606 | 0.0 | 70.2 |
| X B - 48 | 105.1 | 44.41 | 588 | 0.0 | 80.2 |
| X B - 49 | 104.0 | 42.36 | 604 | 0.0 | 53.5 |
| X B - 50 | 117.0 | 59.73 | 627 | 0.0 | 94.7 |
| X B - 51 | 119.1 | 56.75 | 644 | 0.0 | 72.5 |
| X B - 52 | 118.8 | 45.27 | 276 | 0.0 | 87.9 |
| X B - 53 | 115.9 | 44.33 | 279 | 0.0 | 58.9 |
| X B - 54 | 118.8 | 43.46 | 281 | 0.0 | 89.8 |
| X B - 55 | 118.8 | 44.17 | 279 | 0.0 | 63.0 |
| X B - 56 | 147.2 | 32.93 | 283 | 0.0 | 88.1 |
| X B - 57 | 104.7 | 41.89 | 273 | 0.0 | 46.9 |

**TABLE C.15 SERIES X – STAGING COLORADO COAL, NOx MEASUREMENTS**

| ORIGINAL SERIES - RUN #-S | PPM NOX 3% O2, DRY NOIR | TECO | WHIT | PPM NOX IN DRY, 3% O2 FLUE GAS | LB. NOX / 10**6 BTU INPUT |
|---|---|---|---|---|---|
| X A - 1 | 562 | 574 | 462 | 568 ± 9 | 0.51 ± .01 |
| X A - 2 | 891 | 943 | 791 | 917 ± 37 | 0.91 ± .04 |
| X A - 3 | 851 | 887 | 726 | 869 ± 26 | 0.87 ± .03 |
| X A - 4 | 1028 | 1047 | 944 | 1057 ± 42 | 1.23 ± .05 |
| X A - 5 | 1162 | 1253 | 1054 | 1207 ± 64 | 1.52 ± .08 |
| X A - 6 | 955 | 1016 | 865 | 986 ± 43 | 0.96 ± .04 |
| X A - 7 | 987 | 993 | 828 | 990 ± 5 | 0.98 ± .0 |
| X A - 8 | 962 | 968 | 833 | 965 ± 4 | 0.96 ± .0 |
| X A - 9 | 1041 | 1072 | 886 | 1056 ± 23 | 1.06 ± .02 |
| X A - 10 | 1128 | 1141 | 931 | 1135 ± 9 | 1.13 ± .01 |
| X A - 11 | 1052 | 1086 | 916 | 1068 ± 23 | 1.09 ± .02 |
| X A - 12 | 1220 | 1277 | 1075 | 1248 ± 40 | 1.37 ± .04 |
| X A - 13 | 1340 | 1443 | 1183 | 1391 ± 73 | 1.66 ± .09 |
| X A - 14 | 1118 | 1141 | 947 | 1129 ± 16 | 1.17 ± .02 |
| X A - 15 | 1097 | 1146 | 933 | 1121 ± 34 | 1.12 ± .03 |
| X A - 16 | 1021 | 1048 | 910 | 1035 ± 19 | 1.02 ± .02 |
| X A - 17 | 1313 | 1416 | 1170 | 1364 ± 76 | 1.71 ± .09 |
| X A - 18 | 1388 | 1404 | 1200 | 1396 ± 11 | 1.75 ± .01 |
| X A - 19 | 1027 | 1049 | 883 | 1038 ± 16 | 1.05 ± .02 |
| X A - 20 | 672 | 686 | 586 | 679 ± 10 | 0.64 ± .01 |
| X A - 21 | 1167 | 1196 | 1048 | 1182 ± 23 | 1.24 ± .02 |
| X A - 22 | 856 | 892 | 709 | 874 ± 26 | 0.98 ± .03 |
| X A - 23 | 904 | 930 | 790 | 897 ± 4 | 1.10 ± .0 |
| X A - 24 | 425 | 405 | 401 | 415 ± 14 | 0.39 ± .01 |
| X B - 25 | 256 | 248 | 256 | 252 ± 5 | 0.23 ± .0 |
| X B - 26 | 567 | 576 | 494 | 571 ± 6 | 0.57 ± .01 |
| X B - 27 | 287 | 289 | 219 | 288 ± 1 | 0.29 ± .0 |
| X B - 28 | 975 | 1006 | 881 | 990 ± 22 | 1.21 ± .03 |
| X B - 29 | 580 | 584 | 521 | 582 ± 3 | 0.69 ± .0 |
| X B - 30 | 907 | 963 | 830 | 935 ± 40 | 0.93 ± .04 |
| X B - 31 | 735 | 786 | 688 | 761 ± 36 | 0.76 ± .04 |
| X B - 32 | 390 | 407 | 350 | 398 ± 12 | 0.38 ± .01 |
| X B - 33 | 387 | 384 | 323 | 386 ± 2 | 0.39 ± .0 |
| X B - 34 | 393 | 385 | 334 | 389 ± 6 | 0.40 ± .01 |
| X B - 35 | 750 | 818 | 672 | 784 ± 49 | 0.83 ± .05 |
| X B - 36 | 373 | 451 | 339 | 412 ± 55 | 0.42 ± .06 |
| X B - 37 | 386 | 384 | 336 | 385 ± 2 | 0.40 ± .0 |
| X B - 38 | 330 | 327 | 286 | 329 ± 2 | 0.32 ± .0 |
| X B - 39 | 885 | 912 | 779 | 899 ± 19 | 0.94 ± .02 |
| X B - 40 | 878 | 918 | 774 | 898 ± 29 | 1.03 ± .03 |
| X B - 41 | 638 | 664 | 568 | 651 ± 19 | 0.72 ± .02 |
| X B - 42 | 529 | 549 | 469 | 539 ± 14 | 0.58 ± .02 |
| X B - 43 | 492 | 518 | 428 | 505 ± 18 | 0.56 ± .02 |
| X B - 44 | 743 | 753 | 637 | 748 ± 7 | 0.81 ± .01 |
| X B - 45 | 1036 | 1043 | 925 | 1039 ± 5 | 1.33 ± .01 |
| X B - 46 | 967 | 992 | 844 | 979 ± 17 | 1.19 ± .02 |
| X B - 47 | 749 | 793 | 665 | 771 ± 31 | 1.01 ± .04 |
| X B - 48 | 328 | 335 | 320 | 331 ± 5 | 0.31 ± .0 |
| X B - 49 | 311 | 313 | 293 | 312 ± 2 | 0.29 ± .0 |
| X B - 50 | 758 | 768 | 676 | 763 ± 7 | 0.79 ± .01 |
| X B - 51 | 490 | 503 | 441 | 496 ± 10 | 0.52 ± .01 |
| X B - 52 | 431 | 434 | 383 | 433 ± 2 | 0.45 ± .0 |
| X B - 53 | 396 | 394 | 356 | 395 ± 2 | 0.40 ± .0 |
| X B - 54 | 499 | 486 | 444 | 493 ± 9 | 0.51 ± .01 |
| X B - 55 | 483 | 471 | 427 | 477 ± 9 | 0.49 ± .01 |
| X B - 56 | 482 | 472 | 429 | 477 ± 7 | 0.60 ± .01 |
| X B - 57 | 268 | 242 | 252 | 255 ± 19 | 0.23 ± .02 |

**TABLE C.16 SERIES X – STAGING COLORADO COAL, OTHER MEASUREMENTS**

| ORIGINAL SERIES - RUN #-S | HUM. (MM WET) | BAR. (MM WET) | O2 % | PPM CO | PPM SO2 | CO2 % | ASH % | C IN ASH % | N IN ASH % |
|---|---|---|---|---|---|---|---|---|---|
| X A - 1 | 4.3 | 734 | 0.9 | 1700 | 525 | ---- | ---- | ---- | ---- |
| X A - 2 | 3.6 | 735 | 3.2 | 130 | 430 | ---- | ---- | ---- | ---- |
| X A - 3 | 5.5 | 742 | 3.1 | 30 | 500 | ---- | ---- | ---- | ---- |
| X A - 4 | 9.9 | 733 | 5.3 | 100 | 600 | ---- | ---- | ---- | ---- |
| X A - 5 | 5.3 | 742 | 6.8 | 100 | 400 | ---- | 0.28 | 18.1 | -??- |
| X A - 6 | 6.4 | 730 | 2.6 | 325 | 500 | ---- | 0.78 | 26.1 | -??- |
| X A - 7 | 7.3 | 738 | 2.8 | 60 | 600 | ---- | ---- | ---- | ---- |
| X A - 8 | 6.5 | 740 | 2.9 | 150 | 620 | ---- | ---- | ---- | ---- |
| X A - 9 | 10.8 | 738 | 2.7 | 120 | 700 | ---- | ---- | ---- | ---- |
| X A - 10 | 6.4 | 742 | 3.0 | 90 | 700 | ---- | ---- | ---- | ---- |
| X A - 11 | 13.2 | 737 | 2.9 | 100 | 610 | ---- | ---- | ---- | ---- |
| X A - 12 | 13.6 | 736 | 4.2 | 70 | 570 | ---- | ---- | ---- | ---- |
| X A - 13 | 14.7 | 736 | 5.5 | 75 | 475 | ---- | ---- | ---- | ---- |
| X A - 14 | 10.3 | 740 | 3.4 | 180 | 550 | ---- | ---- | ---- | ---- |
| X A - 15 | 8.0 | 737 | 2.9 | 150 | 600 | ---- | ---- | ---- | ---- |
| X A - 16 | 7.1 | 738 | 2.8 | 120 | 570 | ---- | ---- | ---- | ---- |
| X A - 17 | 9.6 | 738 | 6.5 | 60 | 620 | ---- | ---- | ---- | ---- |
| X A - 18 | 6.6 | 742 | 6.7 | 60 | 575 | ---- | ---- | ---- | ---- |
| X A - 19 | 11.4 | 728 | 2.9 | 180 | 700 | ---- | ---- | ---- | ---- |
| X A - 20 | 12.1 | 729 | 1.1 | 1600 | 650 | ---- | ---- | ---- | ---- |
| X A - 21 | 10.8 | 730 | 3.6 | 120 | 650 | ---- | ---- | ---- | ---- |
| X A - 22 | 9.6 | 728 | 3.0 | 130 | 400 | ---- | 0.69 | 15.6 | -??- |
| X A - 23 | 5.3 | 736 | 6.4 | 30 | 450 | ---- | ---- | ---- | ---- |
| X A - 24 | 6.6 | 730 | 1.2 | 9500 | 575 | ---- | ---- | ---- | ---- |
| X B - 25 | 4.4 | 734 | 1.4 | 12500 | 510 | ---- | ---- | ---- | ---- |
| X B - 26 | 4.2 | 735 | 3.1 | 300 | 430 | ---- | 0.61 | -??- | -??- |
| X B - 27 | 5.3 | 742 | 3.1 | 1900 | 490 | ---- | ---- | ---- | ---- |
| X B - 28 | 5.5 | 742 | 6.4 | 100 | 375 | ---- | ---- | ---- | ---- |
| X B - 29 | 5.7 | 742 | 6.0 | 100 | 390 | ---- | ---- | ---- | ---- |
| X B - 30 | 6.8 | 731 | 3.0 | 180 | 500 | ---- | ---- | ---- | ---- |
| X B - 31 | 5.9 | 731 | 3.0 | 150 | 500 | ---- | ---- | ---- | ---- |
| X B - 32 | 5.9 | 732 | 2.4 | 360 | 500 | ---- | 0.91 | 39.0 | -??- |
| X B - 33 | 10.4 | 738 | 3.2 | 360 | 575 | ---- | ---- | ---- | ---- |
| X B - 34 | 6.8 | 738 | 3.7 | 510 | 525 | ---- | ---- | ---- | ---- |
| X B - 35 | 14.4 | 735 | 3.6 | 180 | 500 | ---- | ---- | ---- | ---- |
| X B - 36 | 13.9 | 735 | 2.8 | 360 | 600 | ---- | ---- | ---- | ---- |
| X B - 37 | 10.1 | 740 | 3.4 | 210 | 550 | ---- | ---- | ---- | ---- |
| X B - 38 | 9.6 | 740 | 2.6 | 360 | 520 | ---- | ---- | ---- | ---- |
| X B - 39 | 6.6 | 738 | 3.8 | 210 | 525 | ---- | ---- | ---- | ---- |
| X B - 40 | 7.5 | 739 | 5.7 | 30 | 620 | ---- | 0.59 | 20.9 | -??- |
| X B - 41 | 11.2 | 739 | 4.5 | 60 | 600 | ---- | ---- | ---- | ---- |
| X B - 42 | 8.2 | 739 | 4.2 | 90 | 600 | ---- | 0.54 | 17.9 | -??- |
| X B - 43 | 7.5 | 739 | 4.8 | 150 | 550 | ---- | 0.51 | 25.3 | -??- |
| X B - 44 | 15.6 | 740 | 3.8 | 240 | 500 | ---- | ---- | ---- | ---- |
| X B - 45 | 6.6 | 742 | 7.0 | 60 | 500 | ---- | 0.45 | 9.1 | -??- |
| X B - 46 | 9.4 | 738 | 6.0 | 60 | 550 | ---- | ---- | ---- | ---- |
| X B - 47 | 8.7 | 742 | 7.2 | 60 | 550 | ---- | 0.44 | 8.2 | -??- |
| X B - 48 | 11.6 | 729 | 1.3 | 6400 | 640 | ---- | 1.03 | 35.1 | -??- |
| X B - 49 | 11.3 | 729 | 1.0 | 3100 | 700 | ---- | ---- | ---- | ---- |
| X B - 50 | 10.5 | 731 | 3.3 | 150 | 625 | ---- | ---- | ---- | ---- |
| X B - 51 | 11.0 | 730 | 3.6 | 340 | 625 | ---- | ---- | ---- | ---- |
| X B - 52 | 6.8 | 728 | 3.6 | 1200 | 450 | ---- | ---- | ---- | ---- |
| X B - 53 | 6.7 | 729 | 3.2 | 1200 | 450 | ---- | 0.99 | 33.4 | -??- |
| X B - 54 | 9.8 | 729 | 3.6 | 1100 | 490 | ---- | ---- | ---- | ---- |
| X B - 55 | 6.8 | 729 | 3.6 | 1100 | 500 | ---- | 0.83 | 29.0 | -??- |
| X B - 56 | 5.7 | 737 | 6.7 | 150 | 450 | ---- | ---- | ---- | ---- |
| X B - 57 | 6.2 | 730 | 1.2 | 4000 | 575 | ---- | ---- | ---- | ---- |

## TABLE C.17 SERIES XI – SLOT CHANGES, FURNACE DATA (INPUT)

| ORIGINAL RUN # AND SERIES OF RUNS | LB. / HR. (DRY WT. / WET WT.) IGNITER (GAS) | FUEL | PRIMARY AIR | SECONDARY AIR | 2ND STAGE AIR | FLUE GAS |
|---|---|---|---|---|---|---|
| XI A - 1 | 2.9 | 423/444 | 578/653 | 4220/4770 | 0/ 0 | 0 |
| XI A - 2 | 3.7 | 492/516 | 641/723 | 3771/4251 | 1119/1264 | 0 |
| XI A - 3 | 2.9 | 422/443 | 585/661 | 2009/2264 | 2247/2541 | 0 |
| XI A - 4 | 2.9 | 429/450 | 586/662 | 3076/3478 | 1119/1267 | 0 |
| XI A - 5 | 2.9 | 440/461 | 589/668 | 2069/2342 | 2270/2577 | 0 |
| XI A - 6 | 2.9 | 425/445 | 580/655 | 3704/4187 | 0/ 0 | 0 |
| XI A - 7 | 2.9 | 421/441 | 587/663 | 2523/2852 | 1174/1329 | 0 |
| XI A - 8 | 2.9 | 404/424 | 579/656 | 1391/1573 | 2244/2551 | 0 |
| XI A - 9 | 2.9 | 369/387 | 583/207 | 2423/2739 | 1169/1323 | 0 |
| XI A -10 | 2.9 | 414/434 | 579/655 | 1421/1603 | 2225/2517 | 0 |
| XI A -11 | 2.9 | 309/324 | 498/564 | 3002/3407 | 0/ 0 | 0 |
| XI A -12 | 2.9 | 305/319 | 494/564 | 1960/2221 | 1030/1169 | 0 |
| XI A -13 | 2.9 | 288/302 | 498/562 | 738/ 830 | 2021/2278 | 0 |
| XI A -14 | 2.9 | 310/325 | 498/562 | 993/1117 | 2033/2299 | 0 |
| XI B - 1 | 3.0 | 435/456 | 597/656 | 4261/4765 | 0/ 0 | 0 |
| XI B - 2 | 3.0 | 432/454 | 596/655 | 3159/3548 | 1157/1302 | 0 |
| XI B - 3 | 3.0 | 418/434 | 576/647 | 1798/2014 | 2290/2572 | 0 |
| XI B - 4 | 3.0 | 454/476 | 593/662 | 3200/3594 | 1203/1354 | 0 |
| XI B - 5 | 2.9 | 440/462 | 183/206 | 2609/2844 | 2195/2464 | 0 |
| XI B - 6 | 2.9 | 419/440 | 580/649 | 3707/4151 | 0/ 0 | 0 |
| XI B - 7 | 2.9 | 399/417 | 572/643 | 2617/2719 | 1069/1203 | 0 |
| XI B - 8 | 2.9 | 387/406 | 564/635 | 1334/1497 | 2069/2329 | 0 |
| XI B - 9 | 2.9 | 428/448 | 582/652 | 2658/2980 | 1040/1167 | 0 |
| XI B -10 | 2.9 | 423/444 | 583/654 | 1736/1946 | 1992/2239 | 0 |
| XI B -11 | 2.9 | 313/329 | 502/561 | 3012/3375 | 0/ 0 | 0 |
| XI B -12 | 2.9 | 301/316 | 510/569 | 1997/2230 | 886/ 998 | 0 |
| XI B -13 | 3.0 | 299/313 | 504/563 | 1144/1320 | 1730/1932 | 0 |
| XI B -14 | 3.0 | 298/313 | 504/562 | 1180/1315 | 1779/1930 | 0 |
| XI C - 1 | 3.1 | 439/460 | 594/652 | 4405/4835 | 0/ 0 | 0 |
| XI C - 2 | 3.0 | 436/457 | 584/642 | 3138/3446 | 1157/1272 | 0 |
| XI C - 3 | 3.0 | 430/451 | 592/652 | 1949/2142 | 2267/2499 | 0 |
| XI C - 4 | 3.0 | 431/452 | 600/655 | 3120/3406 | 1178/1288 | 0 |
| XI C - 5 | 3.0 | 437/458 | 594/650 | 2054/2279 | 2240/2456 | 0 |
| XI C - 6 | 3.0 | 432/453 | 607/665 | 3786/4154 | 0/ 0 | 0 |
| XI C - 7 | 3.0 | 419/439 | 589/647 | 2521/2770 | 1145/1260 | 0 |
| XI C - 8 | 3.0 | 419/439 | 589/645 | 1445/1580 | 2246/2462 | 0 |
| XI C - 9 | 3.0 | 394/413 | 592/649 | 2141/2350 | 1165/1280 | 0 |
| XI C -10 | 3.0 | 431/452 | 584/640 | 1433/1568 | 2249/2468 | 0 |
| XI C -11 | 3.0 | 319/335 | 510/558 | 3060/3352 | 0/ 0 | 0 |
| XI C -12 | 3.0 | 303/318 | 501/550 | 1863/2047 | 1060/1165 | 0 |
| XI C -13 | 3.0 | 308/323 | 509/562 | 951/1047 | 1985/2191 | 0 |
| XI C -14 | 3.0 | 320/335 | 519/569 | 1027/1126 | 2049/2252 | 0 |

## TABLE C.18 SERIES XI – SLOT CHANGES, FURNACE DATA (FINAL)

| ORIGINAL RUN # AND SERIES OF RUNS | TOTAL AIR, % | HEAT, KBTU/FT**3 / HR. | GAS PRE-HEAT DEG. F | FLUE GAS RECYCLED TO INPUT (%) | AIR AT BURNER (%) |
|---|---|---|---|---|---|
| XI A - 1 | 115.6 | 49.44 | 618 | 0.0 | 115.6 |
| XI A - 2 | 114.6 | 56.59 | 584 | 0.0 | 91.4 |
| XI A - 3 | 117.0 | 45.74 | 620 | 0.0 | 62.6 |
| XI A - 4 | 113.6 | 48.02 | 605 | 0.0 | 87.0 |
| XI A - 5 | 114.3 | 47.55 | 618 | 0.0 | 61.6 |
| XI A - 6 | 102.9 | 48.65 | 595 | 0.0 | 102.9 |
| XI A - 7 | 103.9 | 46.44 | 593 | 0.0 | 79.4 |
| XI A - 8 | 104.4 | 43.07 | 605 | 0.0 | 49.6 |
| XI A - 9 | 104.2 | 40.95 | 640 | 0.0 | 71.9 |
| XI A -10 | 104.2 | 44.01 | 607 | 0.0 | 49.3 |
| XI A -11 | 115.0 | 36.00 | 588 | 0.0 | 115.0 |
| XI A -12 | 116.3 | 33.80 | 587 | 0.0 | 91.9 |
| XI A -13 | 115.0 | 30.26 | 605 | 0.0 | 43.6 |
| XI A -14 | 115.6 | 32.77 | 594 | 0.0 | 49.8 |
| XI B - 1 | 113.7 | 51.01 | 649 | 0.0 | 113.7 |
| XI B - 2 | 115.6 | 48.49 | 609 | 0.0 | 88.3 |
| XI B - 3 | 114.0 | 44.96 | 620 | 0.0 | 54.0 |
| XI B - 4 | 112.3 | 50.77 | 618 | 0.0 | 95.2 |
| XI B - 5 | 115.6 | 48.10 | 661 | 0.0 | 64.0 |
| XI B - 6 | 104.3 | 48.02 | 595 | 0.0 | 104.3 |
| XI B - 7 | 104.0 | 43.93 | 594 | 0.0 | 76.6 |
| XI B - 8 | 104.4 | 41.18 | 605 | 0.0 | 49.9 |
| XI B - 9 | 102.1 | 47.31 | 601 | 0.0 | 77.3 |
| XI B -10 | 104.0 | 45.35 | 606 | 0.0 | 55.9 |
| XI B -11 | 114.0 | 36.31 | 591 | 0.0 | 114.0 |
| XI B -12 | 114.3 | 33.56 | 582 | 0.0 | 86.5 |
| XI B -13 | 116.3 | 31.91 | 590 | 0.0 | 57.4 |
| XI B -14 | 116.3 | 31.83 | 580 | 0.0 | 57.3 |
| XI C - 1 | 116.3 | 51.32 | 616 | 0.0 | 116.3 |
| XI C - 2 | 114.2 | 48.65 | 598 | 0.0 | 87.1 |
| XI C - 3 | 114.1 | 46.45 | 628 | 0.0 | 60.2 |
| XI C - 4 | 115.9 | 48.18 | 604 | 0.0 | 88.0 |
| XI C - 5 | 114.9 | 47.31 | 630 | 0.0 | 62.5 |
| XI C - 6 | 103.8 | 49.50 | 605 | 0.0 | 103.8 |
| XI C - 7 | 103.7 | 46.29 | 608 | 0.0 | 75.7 |
| XI C - 8 | 104.3 | 44.56 | 615 | 0.0 | 49.5 |
| XI C - 9 | 100.8 | 43.23 | 603 | 0.0 | 70.7 |
| XI C -10 | 101.1 | 45.92 | 623 | 0.0 | 47.7 |
| XI C -11 | 113.6 | 37.02 | 595 | 0.0 | 113.6 |
| XI C -12 | 114.7 | 33.56 | 593 | 0.0 | 79.2 |
| XI C -13 | 113.5 | 32.62 | 613 | 0.0 | 48.1 |
| XI C -14 | 114.3 | 33.87 | 610 | 0.0 | 49.1 |

## TABLE C.19 SERIES XI – SLOT CHANGES, NOx MEASUREMENTS

| ORIGINAL SERIES - RUN #-S | PPM NOX 3% O2, DRY NDIR | TECO | WHIT | PPM NOX IN DRY, 3% O2 FLUE GAS | LB. NOX / 10**6 BTU INPUT |
|---|---|---|---|---|---|
| XI A - 1 | 1064 | 1153 | 1354 | 1108 ± 63 | 1.17 ± .07 |
| XI A - 2 | 864 | 905 | 1110 | 885 ± 29 | 0.92 ± .03 |
| XI A - 3 | 402 | 426 | 484 | 414 ± 17 | 0.44 ± .02 |
| XI A - 4 | 722 | 767 | 829 | 745 ± 32 | 0.77 ± .03 |
| XI A - 5 | 536 | 565 | 628 | 551 ± 20 | 0.58 ± .02 |
| XI A - 6 | 743 | 771 | 915 | 757 ± 20 | 0.72 ± .02 |
| XI A - 7 | 459 | 475 | 559 | 467 ± 12 | 0.45 ± .01 |
| XI A - 8 | 309 | 321 | 361 | 315 ± 9 | 0.31 ± .01 |
| XI A - 9 | 379 | 398 | 464 | 389 ± 13 | 0.37 ± .01 |
| XI A -10 | 307 | 323 | 362 | 315 ± 11 | 0.30 ± .01 |
| XI A -11 | 947 | 1015 | 1098 | 981 ± 48 | 1.03 ± .05 |
| XI A -12 | 545 | 570 | 649 | 557 ± 17 | 0.59 ± .02 |
| XI A -13 | 284 | 292 | 316 | 288 ± 4 | 0.30 ± .01 |
| XI A -14 | 334 | 350 | 385 | 342 ± 11 | 0.36 ± .01 |
| XI B - 1 | 1061 | 1104 | 1284 | 1083 ± 30 | 1.11 ± .03 |
| XI B - 2 | 821 | 847 | 869 | 834 ± 19 | 0.87 ± .02 |
| XI B - 3 | 405 | 423 | 457 | 416 ± 13 | 0.43 ± .01 |
| XI B - 4 | 690 | 719 | 792 | 704 ± 21 | 0.72 ± .02 |
| XI B - 5 | 562 | 587 | 642 | 574 ± 17 | 0.59 ± .02 |
| XI B - 6 | 777 | 814 | 832 | 796 ± 26 | 0.76 ± .02 |
| XI B - 7 | 423 | 444 | 477 | 434 ± 15 | 0.41 ± .01 |
| XI B - 8 | 394 | 405 | 428 | 399 ± 8 | 0.38 ± .01 |
| XI B - 9 | 353 | 409 | 487 | 401 ± 11 | 0.37 ± .01 |
| XI B -10 | 315 | 322 | 367 | 318 ± 5 | 0.30 ± .0 |
| XI B -11 | 849 | 865 | 891 | 857 ± 11 | 0.48 ± .01 |
| XI B -12 | 596 | 605 | 650 | 601 ± 5 | 0.62 ± .01 |
| XI B -13 | 443 | 426 | 459 | 434 ± 12 | 0.45 ± .01 |
| XI B -14 | 367 | 354 | 383 | 360 ± 9 | 0.38 ± .01 |
| XI C - 1 | 1065 | 1128 | 1105 | 1096 ± 45 | 1.13 ± .05 |
| XI C - 2 | 626 | 721 | 707 | 673 ± 67 | 0.68 ± .07 |
| XI C - 3 | 290 | 299 | 324 | 295 ± 6 | 0.30 ± .01 |
| XI C - 4 | 599 | 624 | 677 | 611 ± 17 | 0.63 ± .02 |
| XI C - 5 | 504 | 522 | 561 | 513 ± 13 | 0.52 ± .01 |
| XI C - 6 | 772 | 796 | 922 | 784 ± 16 | 0.73 ± .02 |
| XI C - 7 | 332 | 343 | 380 | 338 ± 8 | 0.31 ± .01 |
| XI C - 8 | 199 | 200 | 221 | 199 ± 1 | 0.19 ± .0 |
| XI C - 9 | 388 | 382 | 395 | 385 ± 4 | 0.35 ± .0 |
| XI C -10 | 231 | 220 | 265 | 226 ± 8 | 0.20 ± .01 |
| XI C -11 | 947 | 933 | 943 | 940 ± 10 | 0.95 ± .01 |
| XI C -12 | 357 | 354 | 356 | 356 ± 2 | 0.36 ± .0 |
| XI C -13 | 254 | 246 | 240 | 250 ± 6 | 0.25 ± .01 |
| XI C -14 | 371 | 358 | 354 | 364 ± 9 | 0.37 ± .01 |

## TABLE C.20 SERIES XI – SLOT CHANGES, OTHER MEASUREMENTS

| ORIGINAL SERIES - RUN #-S | HUM. (MM WET) | BAR. (MM WET) | O2 % | PPM CO | PPM SO2 | CO2 % | ASH % | C IN ASH % | N IN ASH % |
|---|---|---|---|---|---|---|---|---|---|
| XI A - 1 | 20.3 | 729 | 3.1 | 120 | 800 | ---- | ---- | ---- | ---- |
| XI A - 2 | 19.4 | 729 | 2.9 | 120 | 775 | ---- | ---- | ---- | ---- |
| XI A - 3 | 20.2 | 729 | 3.3 | 100 | 620 | ---- | ---- | ---- | ---- |
| XI A - 4 | 20.5 | 731 | 2.8 | 200 | 710 | ---- | ---- | ---- | ---- |
| XI A - 5 | 21.8 | 731 | 2.9 | 90 | 635 | ---- | ---- | ---- | ---- |
| XI A - 6 | 20.2 | 731 | 0.8 | 3700 | 840 | ---- | ---- | ---- | ---- |
| XI A - 7 | 20.3 | 731 | 1.0 | 3500 | 740 | ---- | ---- | ---- | ---- |
| XI A - 8 | 21.6 | 731 | 1.3 | 120 | 640 | ---- | ---- | ---- | ---- |
| XI A - 9 | 20.3 | 730 | 1.0 | 2200 | 660 | ---- | ---- | ---- | ---- |
| XI A -10 | 20.5 | 730 | 0.9 | 1200 | 660 | ---- | ---- | ---- | ---- |
| XI A -11 | 21.2 | 730 | 3.0 | 75 | 840 | ---- | ---- | ---- | ---- |
| XI A -12 | 21.0 | 730 | 3.2 | 60 | 690 | ---- | ---- | ---- | ---- |
| XI A -13 | 19.1 | 730 | 3.0 | 90 | 560 | ---- | ---- | ---- | ---- |
| XI A -14 | 19.4 | 730 | 3.1 | 100 | 540 | ---- | ---- | ---- | ---- |
| XI B - 1 | 17.0 | 740 | 2.9 | 90 | 860 | ---- | ---- | ---- | ---- |
| XI B - 2 | 18.4 | 740 | 3.1 | 165 | 810 | ---- | ---- | ---- | ---- |
| XI B - 3 | 18.1 | 740 | 2.8 | 115 | 670 | ---- | ---- | ---- | ---- |
| XI B - 4 | 18.4 | 740 | 2.6 | 310 | 810 | ---- | ---- | ---- | ---- |
| XI B - 5 | 17.9 | 739 | 3.1 | 115 | 760 | ---- | ---- | ---- | ---- |
| XI B - 6 | 17.2 | 738 | 1.0 | 2700 | 990 | ---- | ---- | ---- | ---- |
| XI B - 7 | 18.7 | 737 | 0.9 | 2000 | 820 | ---- | ---- | ---- | ---- |
| XI B - 8 | 18.7 | 737 | 1.0 | 1200 | 800 | ---- | ---- | ---- | ---- |
| XI B - 9 | 17.6 | 737 | 0.8 | 8000 | 770 | ---- | ---- | ---- | ---- |
| XI B -10 | 18.2 | 737 | 1.0 | 3200 | 720 | ---- | ---- | ---- | ---- |
| XI B -11 | 17.2 | 737 | 2.8 | 165 | 900 | ---- | ---- | ---- | ---- |
| XI B -12 | 16.1 | 737 | 2.9 | 140 | 780 | ---- | ---- | ---- | ---- |
| XI B -13 | 16.2 | 737 | 3.2 | 150 | 700 | ---- | ---- | ---- | ---- |
| XI B -14 | 16.0 | 737 | 3.2 | 190 | 650 | ---- | ---- | ---- | ---- |
| XI C - 1 | 11.7 | 739 | 3.2 | 150 | 900 | ---- | ---- | ---- | ---- |
| XI C - 2 | 11.8 | 739 | 2.9 | 430 | 840 | ---- | ---- | ---- | ---- |
| XI C - 3 | 12.6 | 739 | 2.9 | 810 | 700 | ---- | ---- | ---- | ---- |
| XI C - 4 | 10.3 | 739 | 3.2 | 1200 | 850 | ---- | ---- | ---- | ---- |
| XI C - 5 | 11.2 | 738 | 3.0 | 300 | 815 | ---- | ---- | ---- | ---- |
| XI C - 6 | 11.4 | 737 | 1.0 | 4000 | 710 | ---- | ---- | ---- | ---- |
| XI C - 7 | 11.8 | 737 | 1.1 | 6500 | 570 | ---- | ---- | ---- | ---- |
| XI C - 8 | 11.0 | 737 | 1.1 | 4000 | 530 | ---- | ---- | ---- | ---- |
| XI C - 9 | 11.4 | 737 | 0.6 | 9500 | 580 | ---- | ---- | ---- | ---- |
| XI C -10 | 11.3 | 736 | 0.7 | 9500 | 520 | ---- | ---- | ---- | ---- |
| XI C -11 | 10.9 | 735 | 2.9 | 125 | 660 | ---- | ---- | ---- | ---- |
| XI C -12 | 11.7 | 735 | 3.0 | 960 | 490 | ---- | ---- | ---- | ---- |
| XI C -13 | 12.8 | 735 | 2.8 | 500 | 440 | ---- | ---- | ---- | ---- |
| XI C -14 | 11.6 | 735 | 2.9 | 260 | 470 | ---- | ---- | ---- | ---- |

## TABLE C.21 SERIES XII – BURNER CHANGES, FURNACE DATA (INPUT)

| ORIGINAL RUN # AND SERIES OF RUNS | LB. / HR. (DRY WT. / WET WT.) IGNITER (GAS) | FUEL | PRIMARY AIR | SECONDARY AIR | 2ND STAGE AIR | FLUE GAS |
|---|---|---|---|---|---|---|
| XII A- 1 | 3.0 | 429/449 | 587/641 | 4299/4692 | 0/ 0 | 0 |
| XII A- 2 | 3.0 | 436/457 | 589/645 | 3212/3515 | 1230/1349 | 0 |
| XII A- 3 | 3.0 | 429/450 | 586/643 | 2067/2263 | 2266/2486 | 0 |
| XII A- 4 | 3.0 | 348/365 | 596/656 | 2127/2341 | 1201/1325 | 0 |
| XII A- 5 | 3.0 | 450/472 | 588/648 | 2226/2445 | 2282/2515 | 0 |
| XII A- 6 | 3.0 | 426/446 | 588/649 | 3749/4139 | 0/ 0 | 0 |
| XII A- 7 | 3.0 | 427/448 | 581/640 | 2746/3029 | 1096/1211 | 0 |
| XII A- 8 | 3.0 | 423/443 | 580/642 | 1768/1953 | 2026/2243 | 0 |
| XII A- 9 | 3.0 | 435/456 | 580/642 | 2792/3089 | 1063/1178 | 0 |
| XII A-10 | 3.0 | 443/465 | 580/642 | 1943/2147 | 2061/2282 | 0 |
| XII A-11 | 3.0 | 456/478 | 588/649 | 6285/6930 | 0/ 0 | 0 |
| XII A-12 | 3.0 | 431/452 | 594/651 | 4317/4732 | 0/ 0 | 0 |
| XII A-13 | 3.0 | 319/335 | 513/562 | 3059/3353 | 0/ 0 | 0 |
| XII A-14 | 3.0 | 303/319 | 518/569 | 1980/2067 | 1037/1141 | 0 |
| XII A-15 | 3.0 | 297/311 | 507/558 | 897/ 987 | 2058/2267 | 0 |
| XII A-16 | 3.0 | 307/321 | 509/561 | 1954/2155 | 1090/1203 | 0 |
| XII A-17 | 3.0 | 319/335 | 507/559 | 1047/1152 | 2034/2242 | 0 |
| XII A-18 | 2.8 | 431/452 | 586/645 | 4262/4695 | 0/ 0 | 0 |
| XII A-19 | 2.9 | 434/455 | 579/637 | 6006/6603 | 0/ 0 | 0 |
| XII A-20 | 2.8 | 412/432 | 586/644 | 3637/4005 | 0/ 0 | 0 |
| XII B- 1 | 2.9 | 439/459 | 592/651 | 4324/4755 | 0/ 0 | 0 |
| XII B- 2 | 3.0 | 439/461 | 583/639 | 3135/3436 | 1144/1257 | 0 |
| XII B- 3 | 3.0 | 433/454 | 600/660 | 1961/2153 | 2270/2498 | 0 |
| XII B- 4 | 3.0 | 431/452 | 600/660 | 3044/3351 | 1148/1266 | 0 |
| XII B- 5 | 3.0 | 435/456 | 600/658 | 2019/2209 | 2240/2458 | 0 |
| XII B- 6 | 2.9 | 399/418 | 608/665 | 3445/3772 | 0/ 0 | 0 |
| XII B- 7 | 2.9 | 405/425 | 592/657 | 2465/2737 | 1090/1212 | 0 |
| XII B- 8 | 3.0 | 397/416 | 593/651 | 1402/1537 | 2071/2274 | 0 |
| XII B- 9 | 2.9 | 437/458 | 586/641 | 2716/2974 | 1065/1168 | 0 |
| XII B-10 | 2.9 | 421/441 | 593/650 | 1624/1778 | 2101/2307 | 0 |
| XII B-11 | 2.9 | 438/460 | 593/652 | 6066/6657 | 0/ 0 | 0 |
| XII B-12 | 3.0 | 436/457 | 585/648 | 4286/4749 | 0/ 0 | 0 |
| XII B-13 | 3.0 | 316/331 | 504/560 | 3030/3370 | 0/ 0 | 0 |
| XII B-14 | 3.0 | 317/333 | 503/561 | 1963/2189 | 1062/1186 | 0 |
| XII B-15 | 3.0 | 306/320 | 506/562 | 842/ 933 | 2091/2324 | 0 |
| XII B-16 | 3.0 | 313/328 | 512/571 | 1965/2192 | 1060/1184 | 0 |
| XII B-17 | 3.0 | 325/341 | 515/571 | 1173/1299 | 2012/2232 | 0 |
| XII B-18 | 3.1 | 443/465 | 593/653 | 4331/4808 | 0/ 0 | 0 |
| XII B-19 | 3.0 | 439/460 | 598/650 | 5986/6504 | 0/ 0 | 0 |
| XII B-20 | 3.0 | 421/441 | 588/650 | 3657/4044 | 0/ 0 | 0 |
| XII C- 1 | 3.1 | 440/461 | 593/655 | 4319/4771 | 0/ 0 | 0 |
| XII C- 2 | 3.0 | 432/453 | 597/661 | 3020/3349 | 1154/1276 | 0 |
| XII C- 3 | 3.0 | 417/438 | 590/654 | 1877/2075 | 2239/2483 | 0 |
| XII C- 4 | 2.8 | 427/448 | 587/650 | 3024/3348 | 1140/1264 | 0 |
| XII C- 5 | 2.9 | 434/455 | 590/653 | 2011/2221 | 2241/2483 | 0 |
| XII C- 6 | 2.9 | 402/422 | 590/652 | 3424/3786 | 0/ 0 | 0 |
| XII C- 7 | 2.8 | 389/408 | 595/656 | 2188/2412 | 1117/1233 | 0 |
| XII C- 8 | 2.8 | 383/402 | 590/639 | 1102/1212 | 2245/2474 | 0 |
| XII C- 9 | 2.8 | 410/430 | 588/648 | 2393/2641 | 1147/1267 | 0 |
| XII C-10 | 2.9 | 405/425 | 590/652 | 1318/1452 | 2282/2520 | 0 |
| XII C-11 | 2.9 | 426/447 | 598/647 | 5461/5999 | 0/ 0 | 0 |
| XII C-12 | 3.0 | 444/465 | 590/655 | 4294/4771 | 0/ 0 | 0 |
| XII C-13 | 3.0 | 322/337 | 508/565 | 3040/3370 | 0/ 0 | 0 |
| XII C-14 | 3.0 | 421/441 | 505/564 | 3058/3412 | 1034/1154 | 0 |
| XII C-15 | 3.0 | 321/336 | 506/563 | 1054/1170 | 2008/2236 | 0 |
| XII C-16 | 3.0 | 333/350 | 506/563 | 2085/2321 | 1066/1189 | 0 |
| XII C-17 | 3.0 | 326/342 | 503/559 | 1007/1117 | 2072/2303 | 0 |
| XII C-18 | 3.2 | 436/457 | 585/646 | 4298/4751 | 0/ 0 | 0 |
| XII C-19 | 3.1 | 458/480 | 585/647 | 6062/6694 | 0/ 0 | 0 |
| XII C-20 | 3.2 | 420/440 | 585/646 | 3664/4050 | 0/ 0 | 0 |

## TABLE C.22 SERIES XII – BURNER CHANGES, FURNACE DATA (FINAL)

| ORIGINAL RUN # AND SERIES OF RUNS | TOTAL AIR, % | HEAT, KBTU/FT**3 / HR. | GAS PRE-HEAT DEG. F | FLUE GAS RECYCLED TO INPUT (%) | AIR AT BURNER (%) |
|---|---|---|---|---|---|
| XII A- 1 | 116.3 | 49.83 | 620 | 0.0 | 116.3 |
| XII A- 2 | 117.7 | 48.89 | 623 | 0.0 | 88.9 |
| XII A- 3 | 117.0 | 46.45 | 630 | 0.0 | 63.1 |
| XII A- 4 | 116.6 | 38.59 | 598 | 0.0 | 79.5 |
| XII A- 5 | 115.6 | 48.81 | 629 | 0.0 | 63.8 |
| XII A- 6 | 104.0 | 48.91 | 603 | 0.0 | 104.0 |
| XII A- 7 | 105.6 | 47.39 | 607 | 0.0 | 79.4 |
| XII A- 8 | 105.5 | 45.51 | 617 | 0.0 | 56.6 |
| XII A- 9 | 104.1 | 48.26 | 606 | 0.0 | 79.1 |
| XII A-10 | 105.6 | 47.71 | 616 | 0.0 | 59.1 |
| XII A-11 | 153.8 | 55.65 | 650 | 0.0 | 153.8 |
| XII A-12 | 116.3 | 50.22 | 620 | 0.0 | 116.3 |
| XII A-13 | 113.7 | 37.02 | 590 | 0.0 | 113.7 |
| XII A-14 | 115.0 | 33.48 | 579 | 0.0 | 80.2 |
| XII A-15 | 118.4 | 31.36 | 605 | 0.0 | 44.0 |
| XII A-16 | 117.7 | 33.87 | 581 | 0.0 | 91.6 |
| XII A-17 | 114.3 | 33.80 | 609 | 0.0 | 49.5 |
| XII A-18 | 115.0 | 46.53 | 301 | 0.0 | 115.0 |
| XII A-19 | 155.1 | 47.79 | 313 | 0.0 | 155.1 |
| XII A-20 | 104.5 | 44.33 | 296 | 0.0 | 104.5 |
| XII B- 1 | 114.6 | 51.01 | 620 | 0.0 | 114.6 |
| XII B- 2 | 112.9 | 49.12 | 611 | 0.0 | 86.3 |
| XII B- 3 | 113.9 | 46.76 | 625 | 0.0 | 60.3 |
| XII B- 4 | 113.3 | 48.18 | 598 | 0.0 | 86.2 |
| XII B- 5 | 114.0 | 47.00 | 623 | 0.0 | 61.4 |
| XII B- 6 | 103.7 | 45.58 | 587 | 0.0 | 103.7 |
| XII B- 7 | 104.4 | 44.88 | 601 | 0.0 | 76.9 |
| XII B- 8 | 104.4 | 42.28 | 603 | 0.0 | 91.2 |
| XII B- 9 | 102.0 | 48.34 | 597 | 0.0 | 77.1 |
| XII B-10 | 104.7 | 45.03 | 611 | 0.0 | 91.7 |
| XII B-11 | 155.0 | 53.44 | 647 | 0.0 | 155.0 |
| XII B-12 | 114.0 | 50.69 | 618 | 0.0 | 114.0 |
| XII B-13 | 113.6 | 36.63 | 589 | 0.0 | 113.6 |
| XII B-14 | 113.0 | 35.13 | 593 | 0.0 | 79.0 |
| XII B-15 | 114.3 | 32.22 | 609 | 0.0 | 44.8 |
| XII B-16 | 115.0 | 34.66 | 594 | 0.0 | 80.5 |
| XII B-17 | 115.6 | 34.58 | 600 | 0.0 | 57.7 |
| XII B-18 | 113.5 | 47.94 | 289 | 0.0 | 113.5 |
| XII B-19 | 150.5 | 47.94 | 288 | 0.0 | 150.5 |
| XII B-20 | 102.9 | 45.11 | 280 | 0.0 | 102.9 |
| XII C- 1 | 114.0 | 51.32 | 628 | 0.0 | 114.0 |
| XII C- 2 | 112.6 | 48.34 | 616 | 0.0 | 89.4 |
| XII C- 3 | 115.0 | 45.11 | 637 | 0.0 | 60.2 |
| XII C- 4 | 113.7 | 47.86 | 628 | 0.0 | 86.4 |
| XII C- 5 | 113.9 | 46.92 | 635 | 0.0 | 61.1 |
| XII C- 6 | 101.8 | 46.06 | 600 | 0.0 | 101.8 |
| XII C- 7 | 102.1 | 42.76 | 594 | 0.0 | 72.9 |
| XII C- 8 | 104.5 | 40.48 | 609 | 0.0 | 44.7 |
| XII C- 9 | 102.8 | 45.11 | 598 | 0.0 | 74.2 |
| XII C-10 | 105.5 | 42.99 | 609 | 0.0 | 48.0 |
| XII C-11 | 145.0 | 51.24 | 639 | 0.0 | 145.0 |
| XII C-12 | 112.4 | 51.56 | 614 | 0.0 | 112.4 |
| XII C-13 | 112.1 | 37.18 | 583 | 0.0 | 112.1 |
| XII C-14 | 111.5 | 47.00 | 605 | 0.0 | 86.4 |
| XII C-15 | 113.0 | 34.03 | 596 | 0.0 | 49.3 |
| XII C-16 | 111.5 | 36.86 | 584 | 0.0 | 79.0 |
| XII C-17 | 111.7 | 34.50 | 605 | 0.0 | 47.1 |
| XII C-18 | 114.2 | 47.24 | 294 | 0.0 | 114.2 |
| XII C-19 | 148.3 | 50.30 | 302 | 0.0 | 148.3 |
| XII C-20 | 103.1 | 45.19 | 285 | 0.0 | 103.1 |

## TABLE C.23 SERIES XII – BURNER CHANGES, NOx MEASUREMENTS

| ORIGINAL SERIES - RUN #-S | PPM NOX 3% O2, DRY NDIR | TECO | WHIT | PPM NOX IN DRY, 3% O2 FLUE GAS | LB. NOX / 10**6 BTU INPUT |
|---|---|---|---|---|---|
| XII A- 1 | 1182 | 1200 | 1281 | 1191 ± 13 | 1.22 ± .01 |
| XII A- 2 | 927 | 939 | 1058 | 933 ± 8 | 0.97 ± .01 |
| XII A- 3 | 497 | 526 | 579 | 512 ± 21 | 0.53 ± .02 |
| XII A- 4 | 703 | 736 | 841 | 720 ± 23 | 0.73 ± .02 |
| XII A- 5 | 552 | 581 | 655 | 567 ± 21 | 0.58 ± .02 |
| XII A- 6 | 810 | 838 | 1017 | 824 ± 20 | 0.77 ± .02 |
| XII A- 7 | 522 | 553 | 659 | 538 ± 22 | 0.51 ± .02 |
| XII A- 8 | 273 | 284 | 324 | 278 ± 8 | 0.26 ± .01 |
| XII A- 9 | 424 | 445 | 533 | 434 ± 15 | 0.41 ± .01 |
| XII A-10 | 353 | 374 | 442 | 363 ± 15 | 0.34 ± .01 |
| XII A-11 | 1336 | 1318 | 1629 | 1327 ± 13 | 1.78 ± .02 |
| XII A-12 | 1019 | 1056 | 1334 | 1037 ± 27 | 1.07 ± .03 |
| XII A-13 | 872 | 913 | 1126 | 892 ± 29 | 0.90 ± .03 |
| XII A-14 | 489 | 522 | 564 | 506 ± 24 | 0.52 ± .02 |
| XII A-15 | 332 | 350 | 319 | 341 ± 13 | 0.36 ± .01 |
| XII A-16 | 531 | 550 | 624 | 540 ± 14 | 0.56 ± .01 |
| XII A-17 | 323 | 341 | 319 | 332 ± 13 | 0.34 ± .01 |
| XII A-18 | 977 | 1027 | 1164 | 1002 ± 35 | 1.02 ± .04 |
| XII A-19 | 1160 | 1225 | 1368 | 1192 ± 46 | 1.61 ± .06 |
| XII A-20 | 738 | 752 | 846 | 745 ± 10 | 0.70 ± .01 |
| XII B- 1 | 1156 | 1244 | 1393 | 1220 ± 34 | 1.24 ± .03 |
| XII B- 2 | 901 | 927 | 1043 | 914 ± 18 | 0.92 ± .02 |
| XII B- 3 | 414 | 425 | 400 | 420 ± 8 | 0.42 ± .01 |
| XII B- 4 | 855 | 875 | 985 | 865 ± 15 | 0.87 ± .01 |
| XII B- 5 | 555 | 578 | 585 | 566 ± 17 | 0.57 ± .02 |
| XII B- 6 | 861 | 881 | 968 | 871 ± 14 | 0.81 ± .01 |
| XII B- 7 | 565 | 587 | 655 | 576 ± 16 | 0.54 ± .01 |
| XII B- 8 | 298 | 308 | 265 | 303 ± 7 | 0.28 ± .01 |
| XII B- 9 | 520 | 528 | 598 | 524 ± 6 | 0.48 ± .01 |
| XII B-10 | 299 | 309 | 270 | 304 ± 7 | 0.28 ± .01 |
| XII B-11 | 1360 | 1442 | 1573 | 1401 ± 58 | 1.89 ± .08 |
| XII B-12 | 1189 | 1242 | 1232 | 1216 ± 38 | 1.24 ± .04 |
| XII B-13 | 1011 | 1033 | 1075 | 1022 ± 15 | 1.04 ± .02 |
| XII B-14 | 624 | 639 | 665 | 631 ± 10 | 0.64 ± .01 |
| XII B-15 | 356 | 358 | 371 | 357 ± 2 | 0.37 ± .0 |
| XII B-16 | 605 | 609 | 652 | 607 ± 3 | 0.63 ± .0 |
| XII B-17 | 373 | 393 | 401 | 383 ± 14 | 0.40 ± .01 |
| XII B-18 | 1040 | 1052 | 1176 | 1046 ± 8 | 1.06 ± .01 |
| XII B-19 | 1166 | 1199 | 1303 | 1183 ± 24 | 1.56 ± .03 |
| XII B-20 | 756 | 739 | 850 | 748 ± 12 | 0.69 ± .01 |
| XII C- 1 | 1099 | 1117 | 1129 | 1108 ± 12 | 1.13 ± .01 |
| XII C- 2 | 869 | 880 | 908 | 875 ± 8 | 0.88 ± .01 |
| XII C- 3 | 428 | 424 | 461 | 426 ± 3 | 0.44 ± .0 |
| XII C- 4 | 737 | 719 | 798 | 726 ± 16 | 0.74 ± .02 |
| XII C- 5 | 479 | 498 | 554 | 489 ± 13 | 0.50 ± .01 |
| XII C- 6 | 726 | 726 | 850 | 726 ± 0 | 0.67 ± .0 |
| XII C- 7 | 406 | 409 | 499 | 408 ± 2 | 0.37 ± .0 |
| XII C- 8 | 326 | 326 | 372 | 326 ± 0 | 0.31 ± .0 |
| XII C- 9 | 414 | 425 | 512 | 420 ± 8 | 0.39 ± .01 |
| XII C-10 | 238 | 238 | 282 | 238 ± 0 | 0.22 ± .0 |
| XII C-11 | 1375 | 1415 | 1603 | 1395 ± 29 | 1.77 ± .04 |
| XII C-12 | 1153 | 1190 | 1215 | 1172 ± 27 | 1.18 ± .03 |
| XII C-13 | 1032 | 1064 | 1111 | 1048 ± 22 | 1.05 ± .02 |
| XII C-14 | 547 | 551 | 622 | 549 ± 3 | 0.55 ± .0 |
| XII C-15 | 352 | 349 | 387 | 351 ± 2 | 0.36 ± .0 |
| XII C-16 | 567 | 571 | 653 | 569 ± 3 | 0.57 ± .0 |
| XII C-17 | 289 | 284 | 327 | 287 ± 4 | 0.29 ± .0 |
| XII C-18 | 1076 | 1048 | 1079 | 1062 ± 20 | 1.08 ± .02 |
| XII C-19 | 1162 | 1169 | 1192 | 1165 ± 5 | 1.51 ± .01 |
| XII C-20 | 723 | 705 | 752 | 714 ± 12 | 0.66 ± .01 |

## TABLE C.24 SERIES XII – BURNER CHANGES, OTHER MEASUREMENTS

| ORIGINAL SERIES - RUN #-S | MUM. (MM WET) | BAR. (MM WET) | O2 % | PPM CO | PPM SO2 | CO2 % | ASH % | C IN ASH % | N IN ASH % |
|---|---|---|---|---|---|---|---|---|---|
| XII A- 1 | 10.2 | 734 | 3.2 | 100 | 1025 | ---- | ---- | ---- | ---- |
| XII A- 2 | 11.0 | 734 | 3.4 | 75 | 960 | ---- | ---- | ---- | ---- |
| XII A- 3 | 11.5 | 734 | 3.3 | 60 | 820 | ---- | ---- | ---- | ---- |
| XII A- 4 | 12.4 | 733 | 2.9 | 75 | 920 | ---- | ---- | ---- | ---- |
| XII A- 5 | 12.6 | 733 | 3.1 | 150 | 850 | ---- | ---- | ---- | ---- |
| XII A- 6 | 13.0 | 733 | 1.0 | 3200 | 1100 | ---- | ---- | ---- | ---- |
| XII A- 7 | 12.9 | 733 | 1.3 | 1200 | 1000 | ---- | ---- | ---- | ---- |
| XII A- 8 | 13.7 | 733 | 1.3 | 1600 | 820 | ---- | ---- | ---- | ---- |
| XII A- 9 | 13.7 | 733 | 1.0 | 2600 | 840 | ---- | ---- | ---- | ---- |
| XII A-10 | 13.8 | 732 | 1.3 | 2100 | 820 | ---- | ---- | ---- | ---- |
| XII A-11 | 13.3 | 732 | 7.3 | 180 | 920 | ---- | ---- | ---- | ---- |
| XII A-12 | 11.2 | 735 | 3.2 | 200 | 820 | ---- | ---- | ---- | ---- |
| XII A-13 | 11.0 | 735 | 2.8 | 90 | 920 | ---- | ---- | ---- | ---- |
| XII A-14 | 11.9 | 735 | 3.0 | 80 | 760 | ---- | ---- | ---- | ---- |
| XII A-15 | 12.5 | 735 | 3.5 | 75 | 690 | ---- | ---- | ---- | ---- |
| XII A-16 | 12.6 | 735 | 3.4 | 60 | 760 | ---- | ---- | ---- | ---- |
| XII A-17 | 12.6 | 735 | 2.9 | 150 | 680 | ---- | ---- | ---- | ---- |
| XII A-18 | 12.4 | 735 | 3.0 | 100 | 940 | ---- | ---- | ---- | ---- |
| XII A-19 | 12.2 | 735 | 7.4 | 60 | 780 | ---- | ---- | ---- | ---- |
| XII A-20 | 12.2 | 735 | 1.0 | 2000 | 960 | ---- | ---- | ---- | ---- |
| XII B- 1 | 12.2 | 731 | 2.9 | 65 | 1050 | ---- | ---- | ---- | ---- |
| XII B- 2 | 11.3 | 731 | 2.7 | 330 | 1000 | ---- | ---- | ---- | ---- |
| XII B- 3 | 12.2 | 730 | 2.8 | 300 | 850 | ---- | ---- | ---- | ---- |
| XII B- 4 | 12.4 | 730 | 2.8 | 60 | 1000 | ---- | ---- | ---- | ---- |
| XII B- 5 | 11.4 | 730 | 2.8 | 100 | 900 | ---- | ---- | ---- | ---- |
| XII B- 6 | 10.9 | 731 | 0.9 | 2400 | 1025 | ---- | ---- | ---- | ---- |
| XII B- 7 | 14.5 | 731 | 1.1 | 4300 | 1000 | ---- | ---- | ---- | ---- |
| XII B- 8 | 11.5 | 731 | 1.0 | 1400 | 850 | ---- | ---- | ---- | ---- |
| XII B- 9 | 10.9 | 731 | 0.6 | 3600 | 950 | ---- | ---- | ---- | ---- |
| XII B-10 | 11.4 | 731 | 1.1 | 2150 | 800 | ---- | ---- | ---- | ---- |
| XII B-11 | 12.1 | 731 | 7.4 | 120 | 975 | ---- | ---- | ---- | ---- |
| XII B-12 | 14.2 | 735 | 2.8 | 100 | 980 | ---- | ---- | ---- | ---- |
| XII B-13 | 15.0 | 735 | 2.9 | 200 | 980 | ---- | ---- | ---- | ---- |
| XII B-14 | 15.8 | 735 | 2.7 | 140 | 850 | ---- | ---- | ---- | ---- |
| XII B-15 | 14.8 | 735 | 2.9 | 75 | 715 | ---- | ---- | ---- | ---- |
| XII B-16 | 15.9 | 735 | 3.0 | 55 | 840 | ---- | ---- | ---- | ---- |
| XII B-17 | 14.2 | 735 | 3.1 | 115 | 730 | ---- | ---- | ---- | ---- |
| XII B-18 | 14.6 | 735 | 2.8 | 450 | 1100 | ---- | ---- | ---- | ---- |
| XII B-19 | 13.8 | 735 | 7.0 | 30 | 910 | ---- | ---- | ---- | ---- |
| XII B-20 | 13.4 | 735 | 0.8 | 3900 | 1050 | ---- | ---- | ---- | ---- |
| XII C- 1 | 13.3 | 735 | 2.8 | 60 | 1025 | ---- | ---- | ---- | ---- |
| XII C- 2 | 13.9 | 735 | 2.6 | 330 | 980 | ---- | ---- | ---- | ---- |
| XII C- 3 | 14.3 | 735 | 3.0 | 100 | 830 | ---- | ---- | ---- | ---- |
| XII C- 4 | 13.9 | 735 | 2.8 | 120 | 960 | ---- | ---- | ---- | ---- |
| XII C- 5 | 14.1 | 735 | 2.8 | 300 | 870 | ---- | ---- | ---- | ---- |
| XII C- 6 | 13.3 | 734 | 0.6 | 4400 | 1050 | ---- | ---- | ---- | ---- |
| XII C- 7 | 12.6 | 735 | 0.7 | 5000 | 1000 | ---- | ---- | ---- | ---- |
| XII C- 8 | 12.6 | 734 | 1.0 | 1000 | 830 | ---- | ---- | ---- | ---- |
| XII C- 9 | 12.9 | 734 | 0.8 | 3950 | 900 | ---- | ---- | ---- | ---- |
| XII C-10 | 13.3 | 734 | 1.3 | 2800 | 810 | ---- | ---- | ---- | ---- |
| XII C-11 | 12.2 | 734 | 6.5 | 200 | 950 | ---- | ---- | ---- | ---- |
| XII C-12 | 15.0 | 735 | 2.6 | 200 | 880 | ---- | ---- | ---- | ---- |
| XII C-13 | 14.8 | 735 | 2.5 | 100 | 950 | ---- | ---- | ---- | ---- |
| XII C-14 | 15.9 | 734 | 2.4 | 500 | 800 | ---- | ---- | ---- | ---- |
| XII C-15 | 15.4 | 734 | 2.7 | 155 | 700 | ---- | ---- | ---- | ---- |
| XII C-16 | 15.3 | 734 | 2.4 | 240 | 800 | ---- | ---- | ---- | ---- |
| XII C-17 | 14.8 | 734 | 2.5 | 330 | 700 | ---- | ---- | ---- | ---- |
| XII C-18 | 13.3 | 734 | 2.9 | 500 | 1020 | ---- | ---- | ---- | ---- |
| XII C-19 | 13.4 | 734 | 6.8 | 180 | 850 | ---- | ---- | ---- | ---- |
| XII C-20 | 13.2 | 734 | 0.8 | 3700 | 1010 | ---- | ---- | ---- | ---- |

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## APPENDIX D

## PRELIMINARY DATA PLOTS

The data plots are split up into two groups. First, the original data points are plotted and the appropriate data line(s) drawn to describe the points. Secondly, a blank graph is presented with the "normal", mid air, mid load data line drawn on it. The data plots require the grouping of data into variable ranges which are defined below:

| Variable | Range | | |
|---|---|---|---|
| | Low | Mid | High |
| Excess Air, % | < 7.5 | 7.5 - 25. | > 25. |
| Load, % | <100. | 100. - 125. | >125. |
| (kBtu/ft$^3$/hr | < 40. | 40. - 50. | > 50.) |
| Preheat, $^0$F | <450. | 450. - 550. | >550. |

These data groupings, although arbitrary, recognize the fact that data were gathered at the extremes and center of the variable ranges studied. The representation of these ranges is:

| Variable | Range | | |
|---|---|---|---|
| | Low | Mid | High |
| Excess Air, % | ∿ 3 | ∿ 15 | ∿ 35 |
| Load, % | ∿ 75 | ∿115 | ∿140 |
| Preheat $^0$F | ∿350 | ∿500 | ∿650 |

The lines which are drawn through the data points are "eyeball" fits and are simply used to describe the apparent trend of the data. These lines are drawn from visual fitting and no mathematical correlation has been used. The simplest form of line has been drawn through the data points — straight where possible.

Figure D.23 shows the substoichiometric tests plotted as ppm NO. The line drawn in D.24 was used to calculate the line data for plotting D.55. The data below show these calculations:

| % Stoichiometry Burners | NO, ppm; D.23/D.24 | % Reduction, NO; D.55 |
|---|---|---|
| 115 | 1045 | ≡ 0 |
| 112.5 | 1000 | 4 |
| 100 | 625 | 40 |
| 95 | 500 | 52 |
| 85 | 288 | 72 |
| 70 | 75 | 93 |
| 60 | 0 | ≡ 100 |

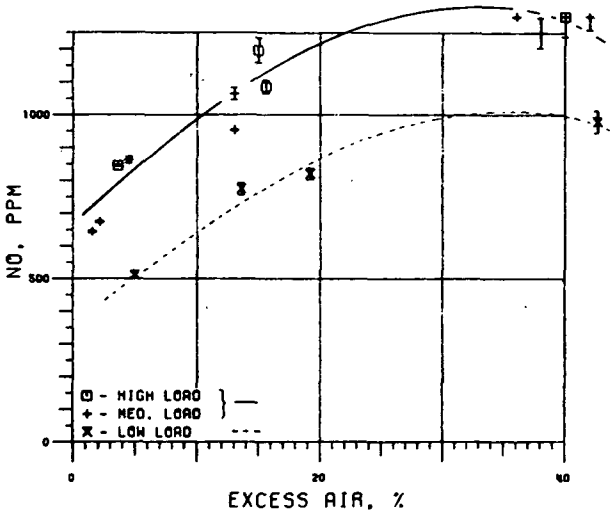


FIGURE D.1 COLORADO – HIGH PREHEAT

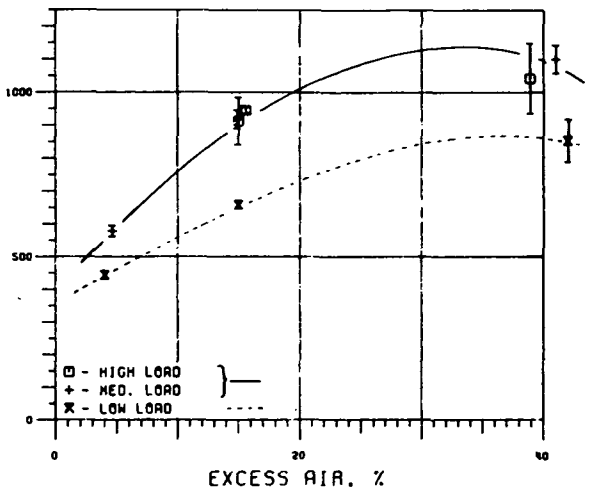


FIGURE D.2 COLORADO – LOW PREHEAT

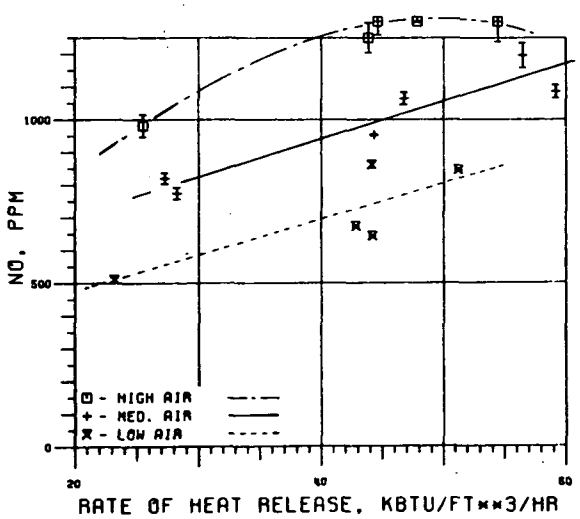


FIGURE D.3 COLORADO – HIGH PREHEAT

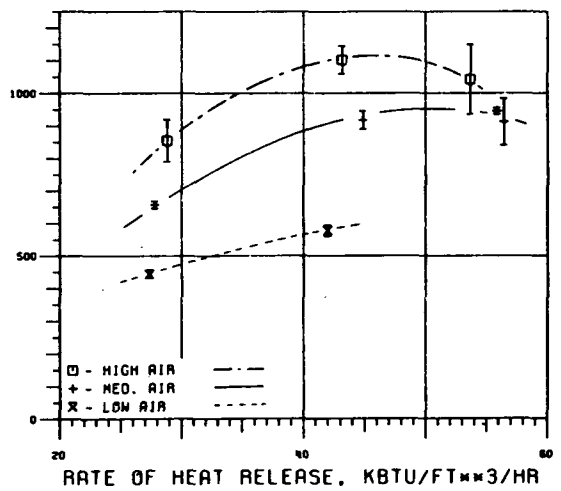


FIGURE D.4 COLORADO – LOW PREHEAT

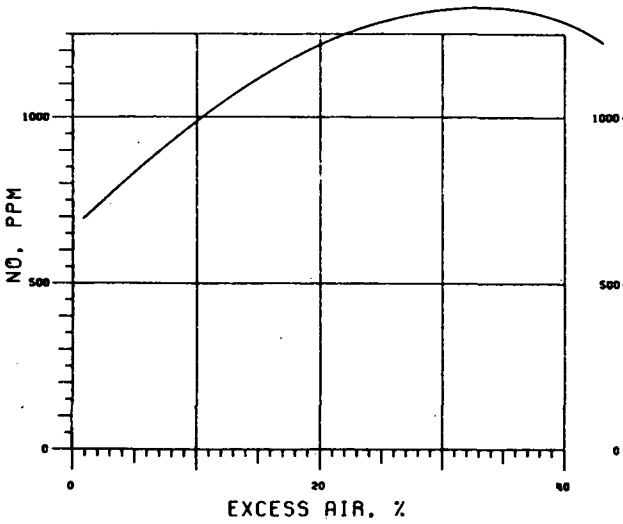


FIGURE D.5 COLORADO – HIGH PREHEAT

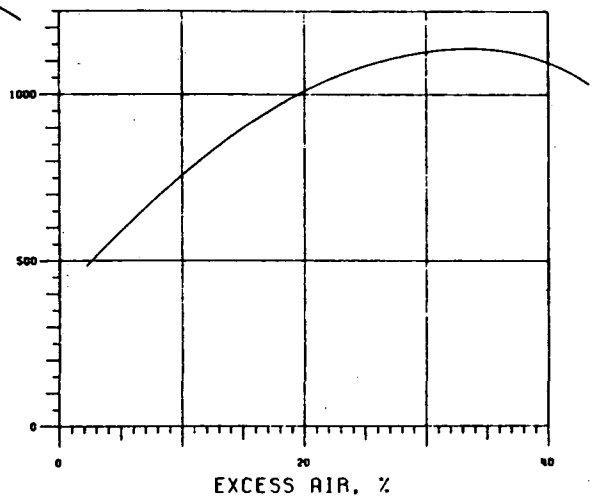


FIGURE D.6 COLORADO – LOW PREHEAT

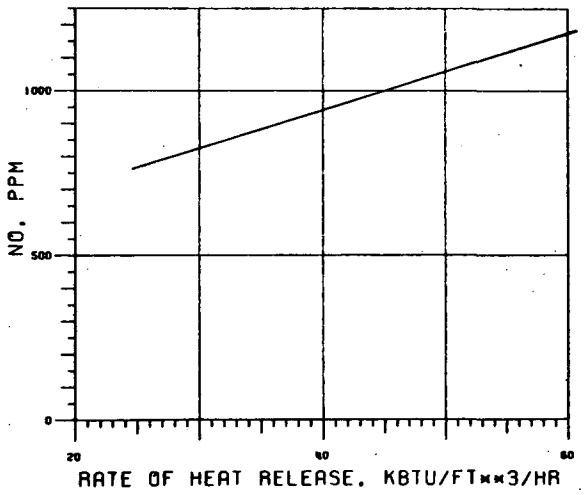


FIGURE D.7 COLORADO – HIGH PREHEAT

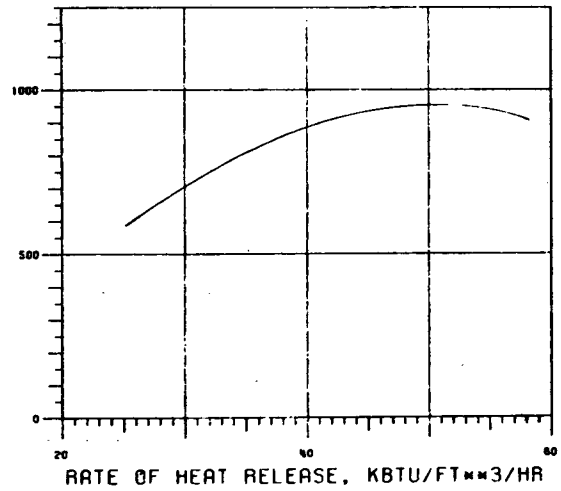


FIGURE D.8 COLORADO – LOW PREHEAT

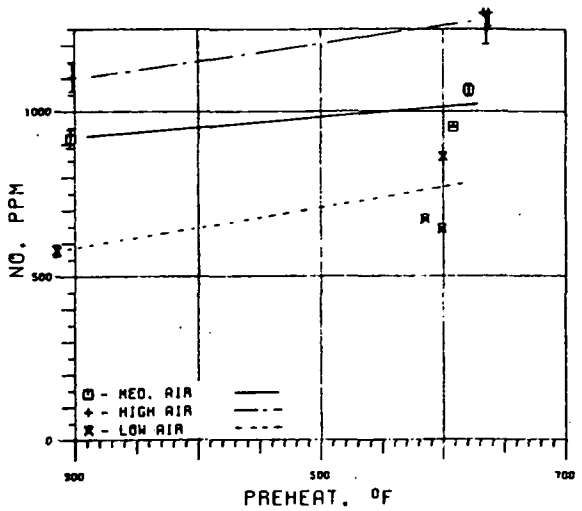


FIGURE D.9 COLORADO – MEDIUM LOAD

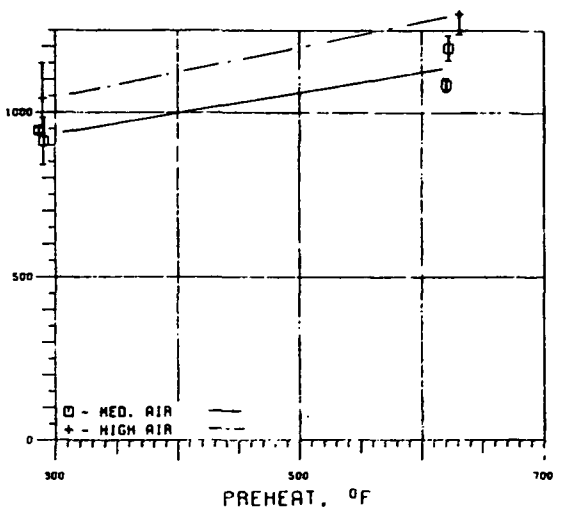


FIGURE D.10 COLORADO – HIGH LOAD

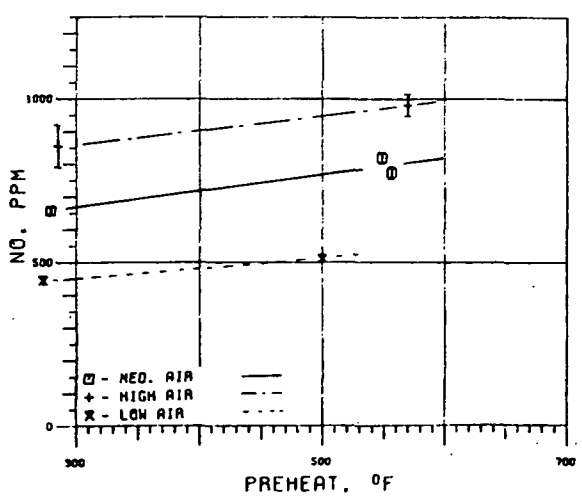


FIGURE D.11 COLORADO – LOW LOAD

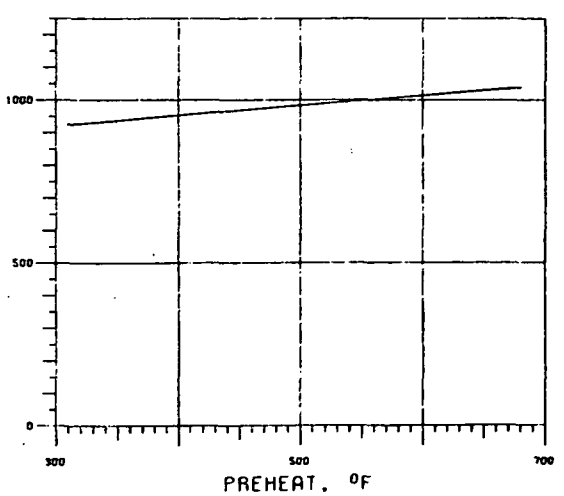


FIGURE D.12 COLORADO – MEDIUM LOAD

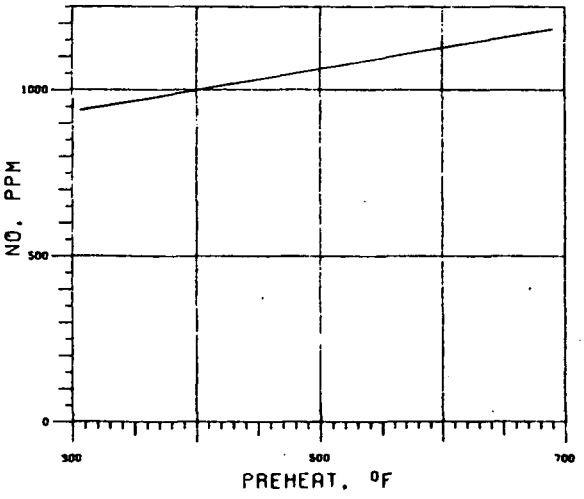


FIGURE D.13 COLORADO – HIGH LOAD

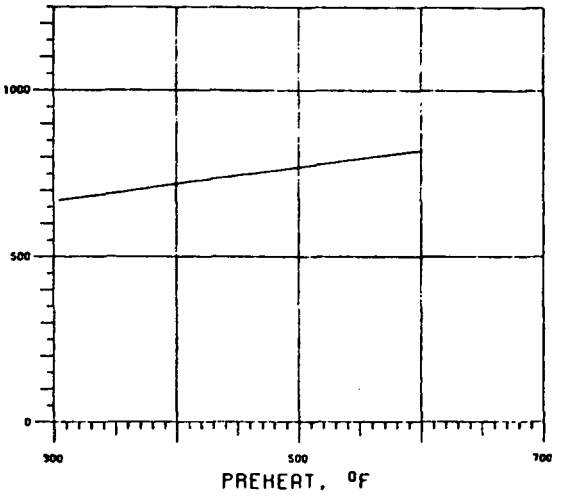


FIGURE D.14 COLORADO – LOW LOAD

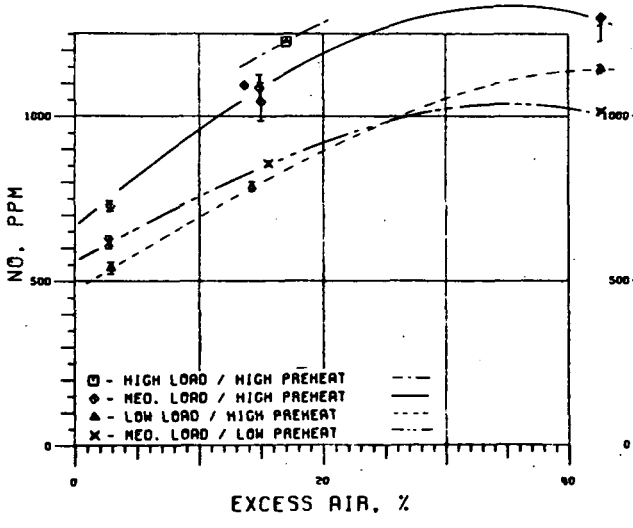


FIGURE D.15 FINE COAL – AIR

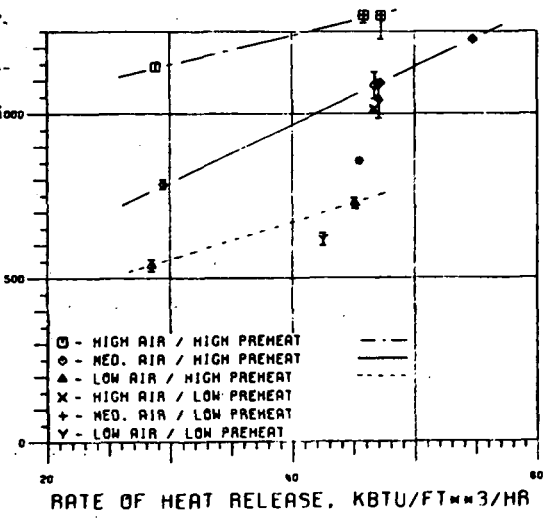


FIGURE D.16 FINE COAL – LOAD

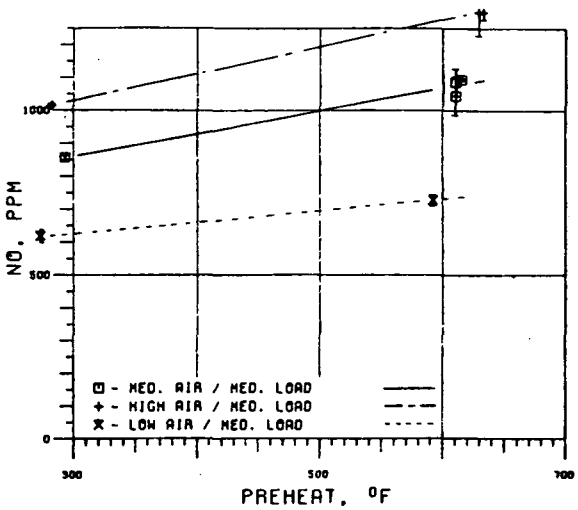


FIGURE D.17 FINE COAL – PREHEAT

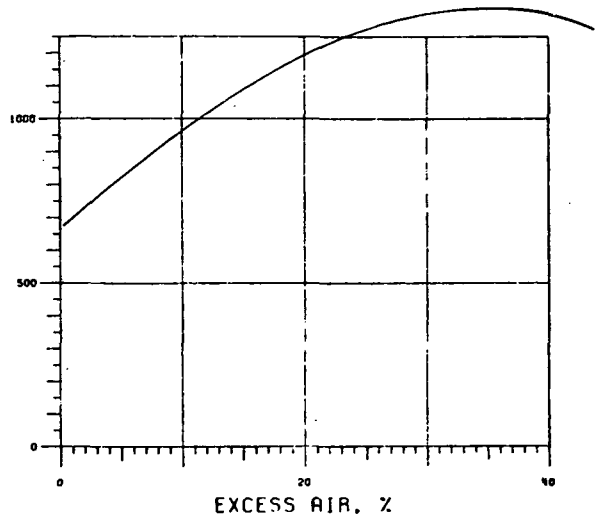


FIGURE D.18 FINE COAL – AIR

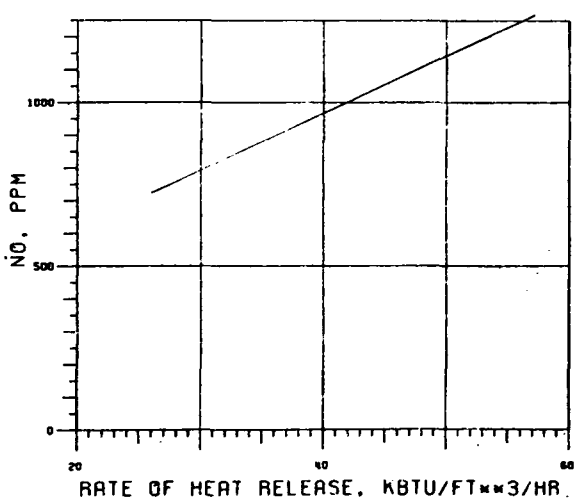


FIGURE D.19 FINE COAL – LOAD

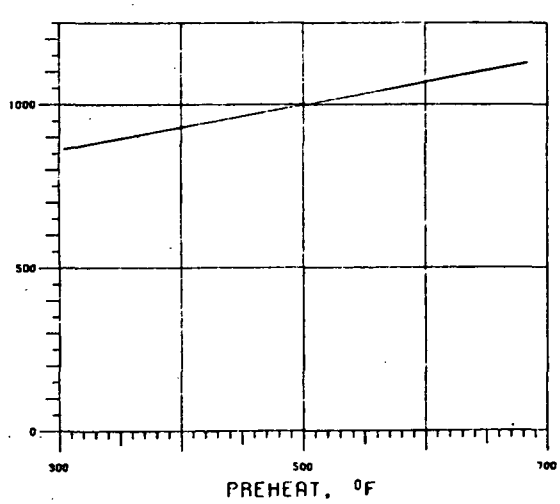


FIGURE D.20 FINE COAL – PREHEAT

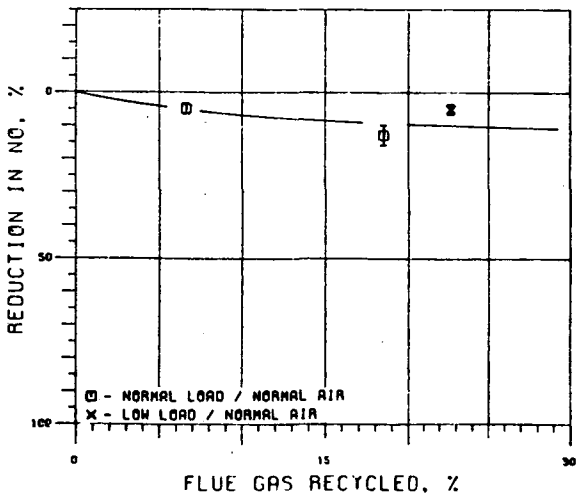


FIGURE D.21 FLUE GAS RECIRCULATION

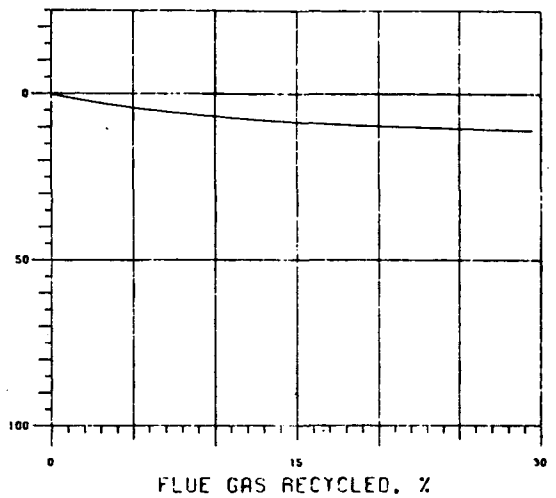


FIGURE D.22 FLUE GAS RECIRCULATION

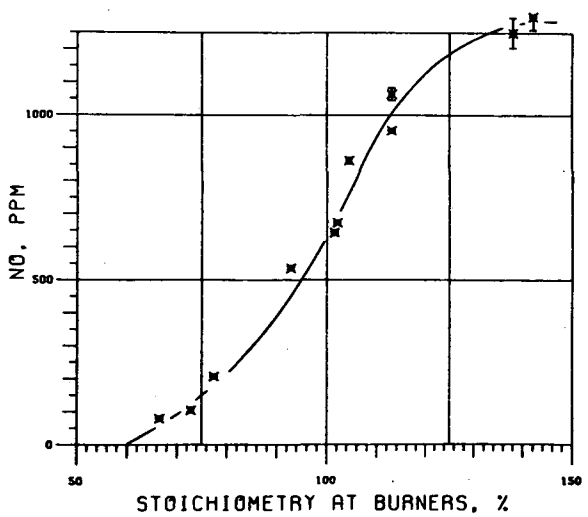


FIGURE D.23 SUBSTOICHIOMETRIC TESTS

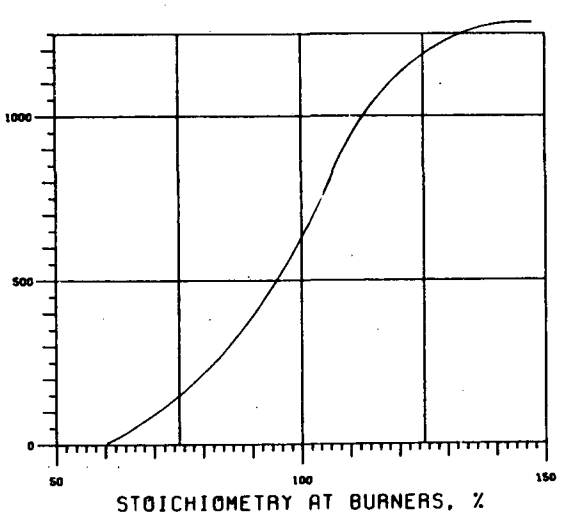


FIGURE D.24 SUBSTOICHIOMETRIC TESTS

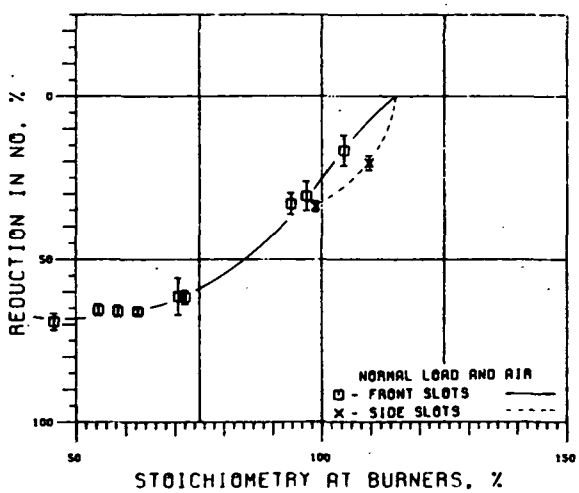


FIGURE D.25 STAGED – PORT VARIABLE

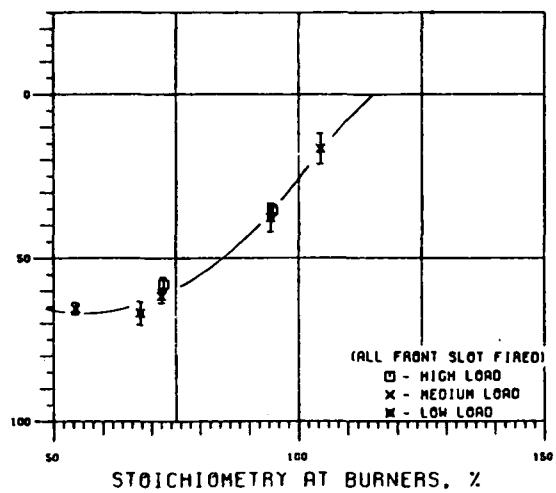


FIGURE D.26 STAGED – 15% EXCESS AIR

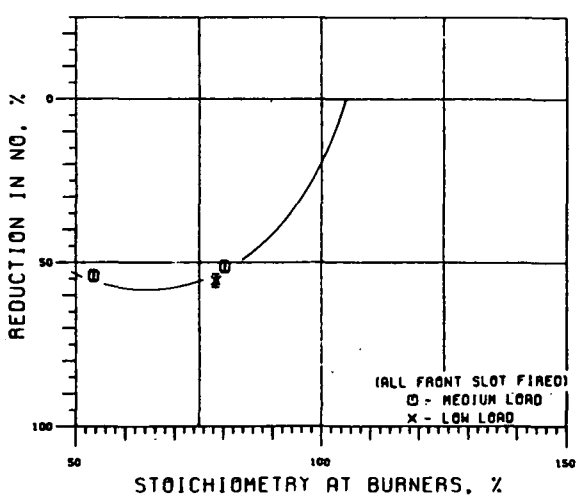


FIGURE D.27 STAGED – 3% EXCESS AIR

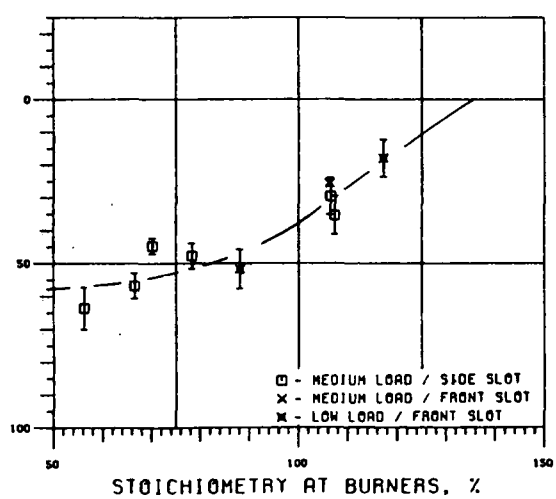


FIGURE D.28 STAGED – 35% EXCESS AIR

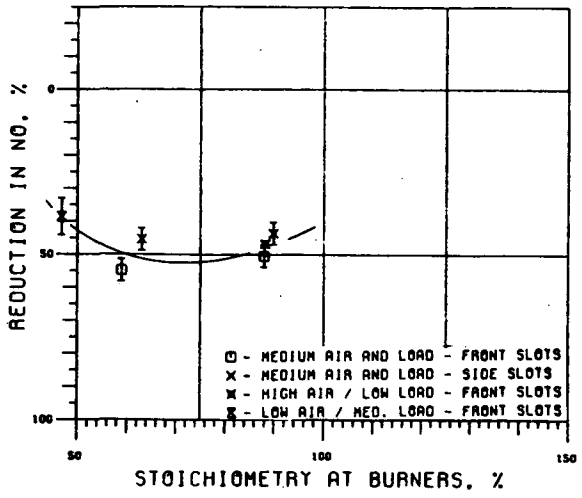


FIGURE D.29 STAGED – LOW PREHEAT

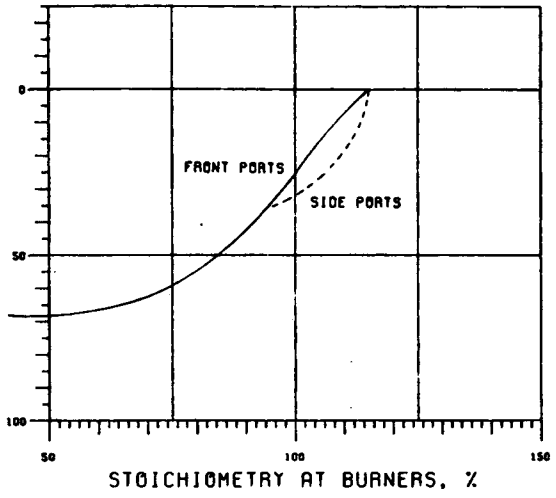


FIGURE D.30 STAGED – PORT VARIABLE

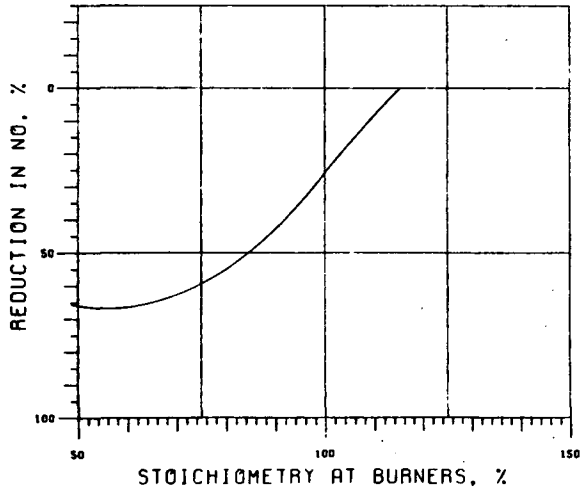


FIGURE D.31 STAGED – 15% EXCESS AIR

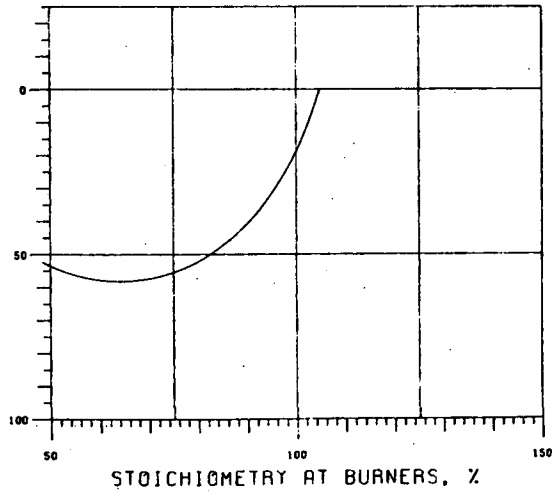


FIGURE D.32 STAGED – 3% EXCESS AIR

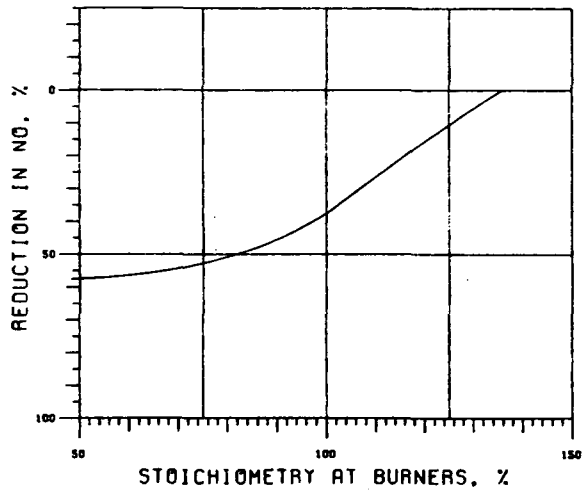


FIGURE D.33 STAGED – 35% EXCESS AIR

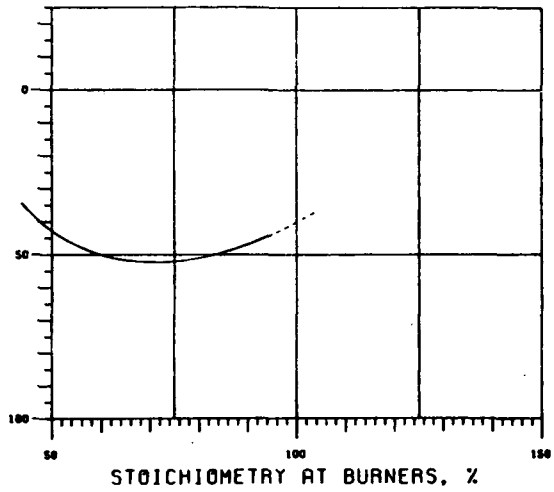


FIGURE D.34 STAGED – LOW PREHEAT

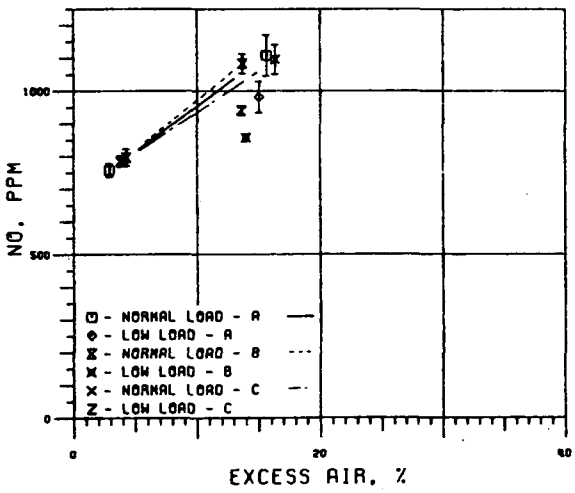


FIGURE D.35 SLOT CHANGES

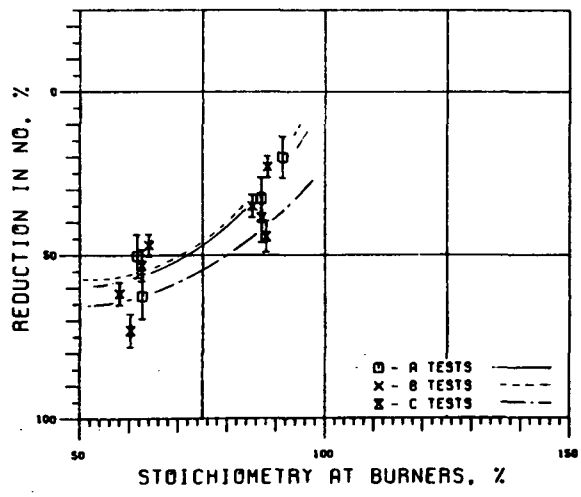


FIGURE D.36 SLOT CHANGES – 15% AIR

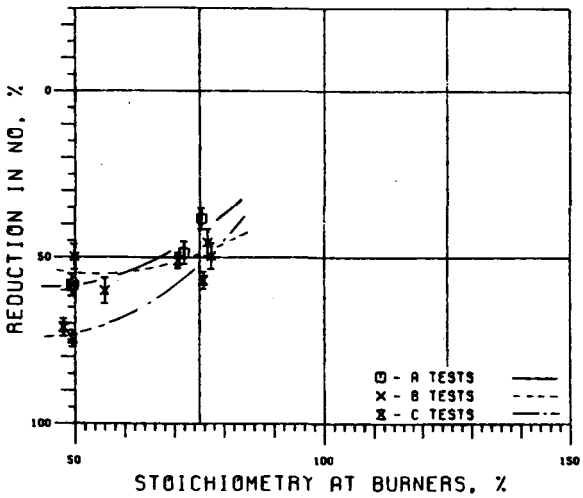


FIGURE D.37 SLOT CHANGES – LOW AIR

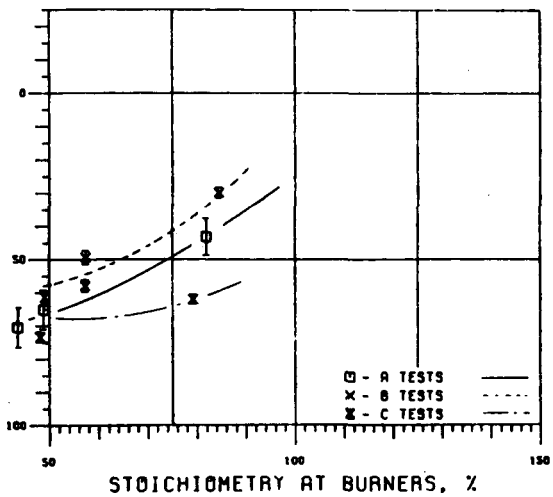


FIGURE D.38 SLOT CHANGES – LOW LOAD

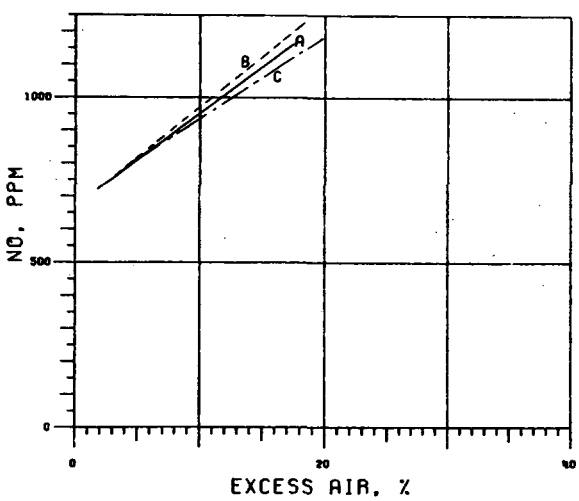


FIGURE D.39 SLOT CHANGES

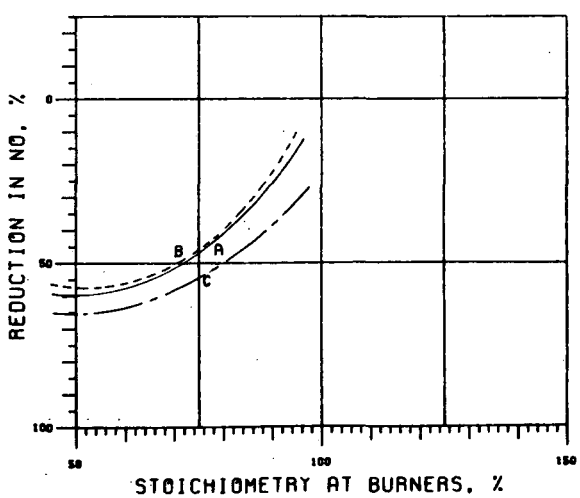


FIGURE D.40 SLOT CHANGES – 15% AIR

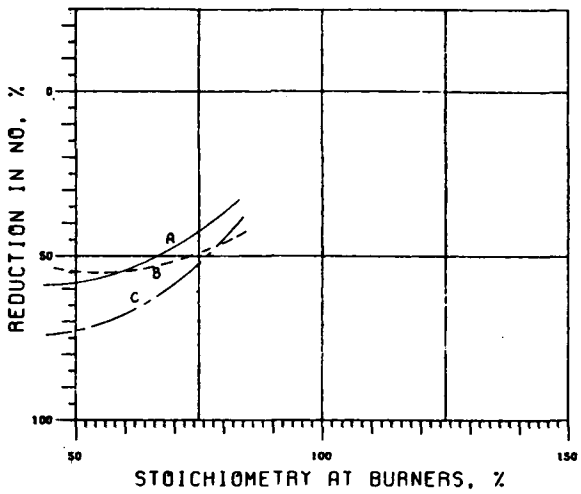


FIGURE D.41 SLOT CHANGES – LOW AIR

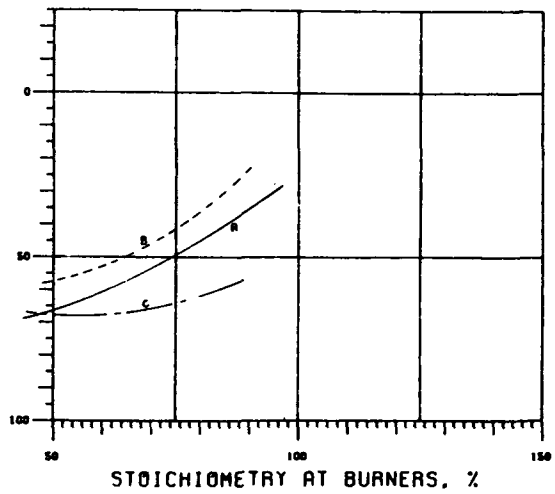


FIGURE D.42 SLOT CHANGES – LOW LOAD

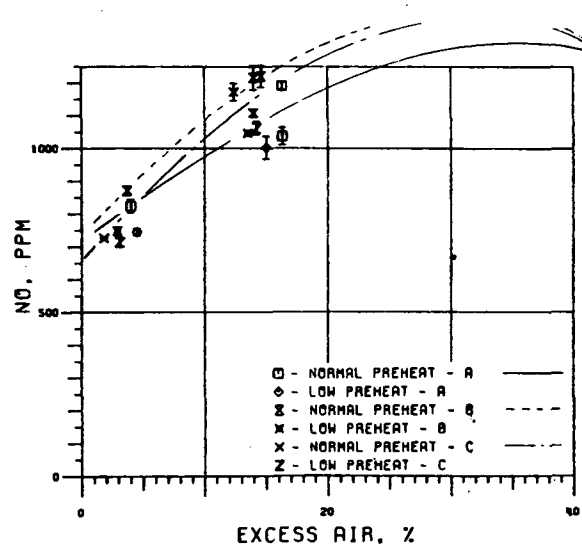


FIGURE D.43 BURNER CHANGES

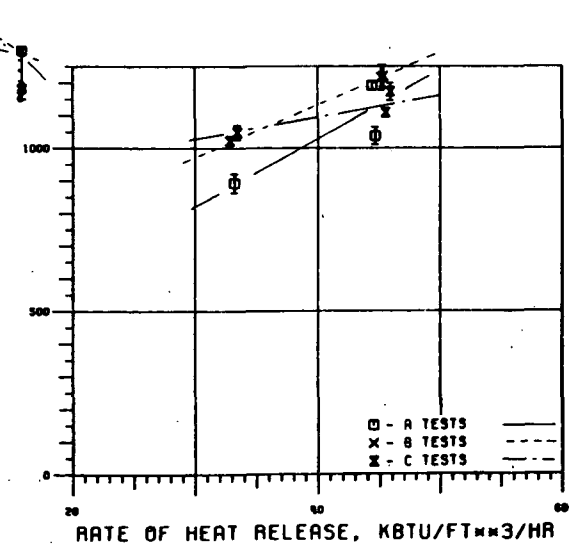


FIGURE D.44 BURNER CHANGES

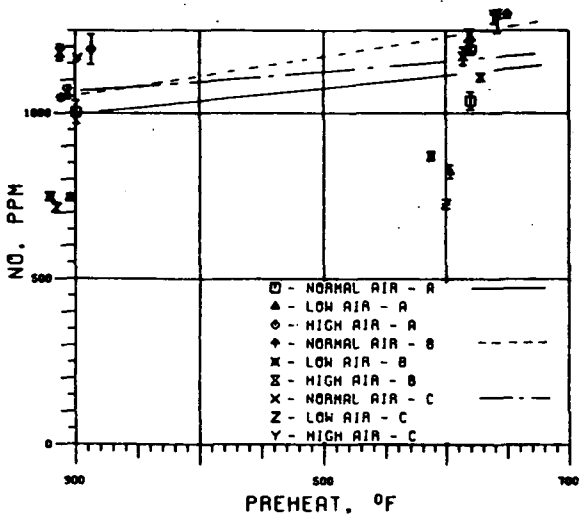


FIGURE D.45 BURNER CHANGES

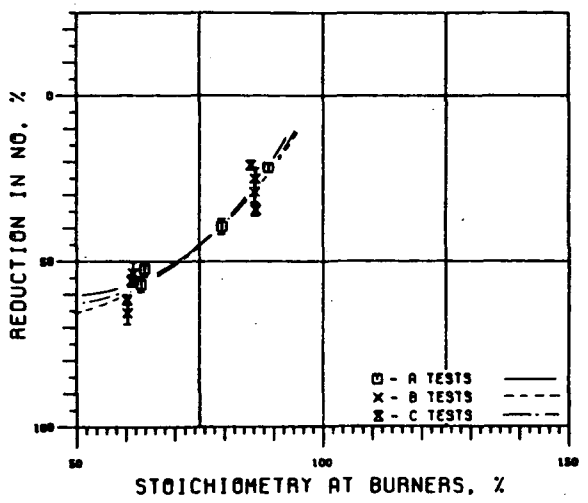


FIGURE D.46 BURNER CHANGES – 15% AIR

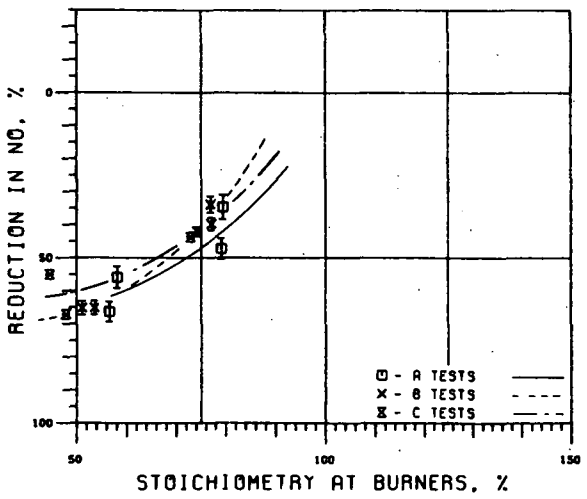


FIGURE D.47 BURNER CHANGES – LOW AIR

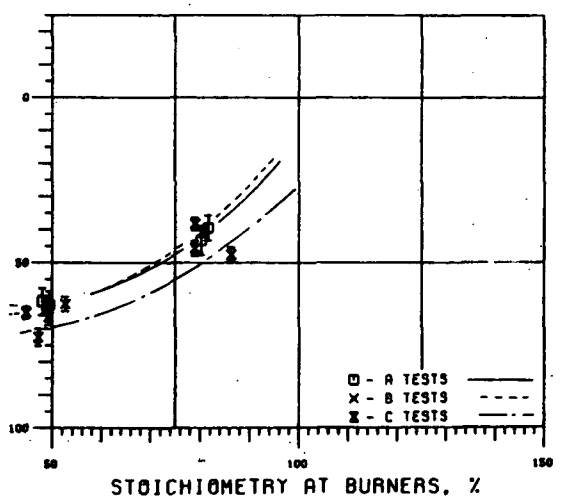


FIGURE D.48 BURNER CHANGES – LOW LOAD

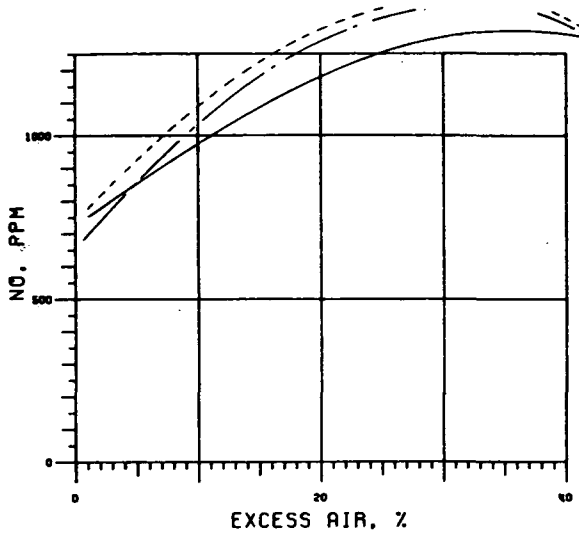


FIGURE D.49 BURNER CHANGES

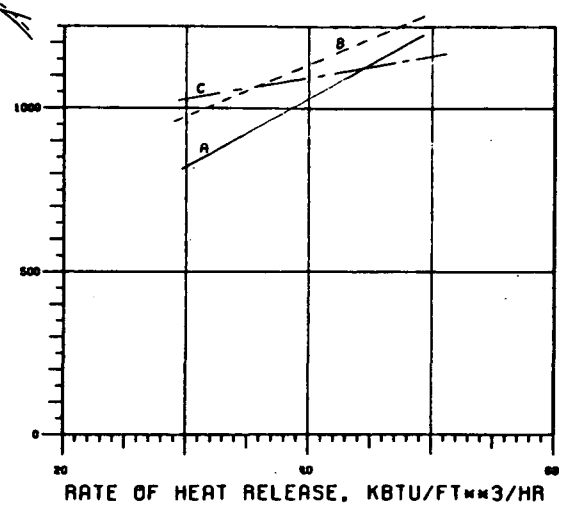


FIGURE D.50 BURNER CHANGES

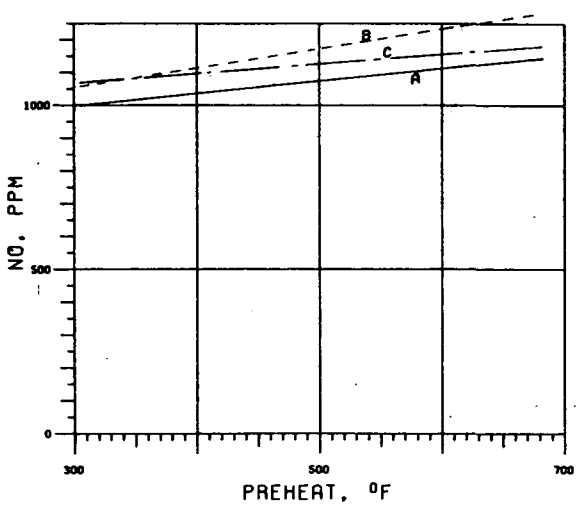


FIGURE D.51 BURNER CHANGES

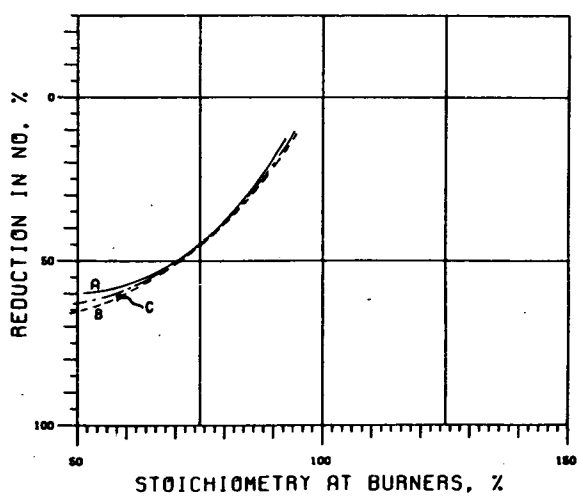


FIGURE D.52 BURNER CHANGES – 15% AIR

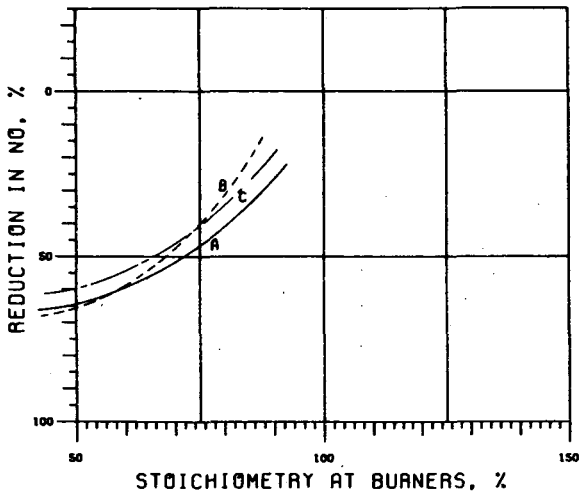


FIGURE D.53 BURNER CHANGES – LOW AIR

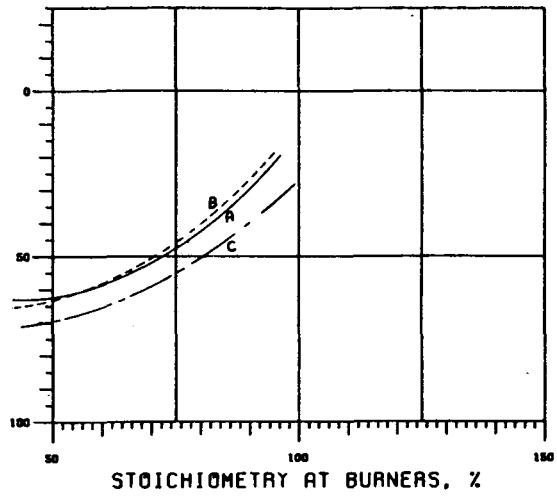


FIGURE D.54 BURNER CHANGES – LOW LOAD

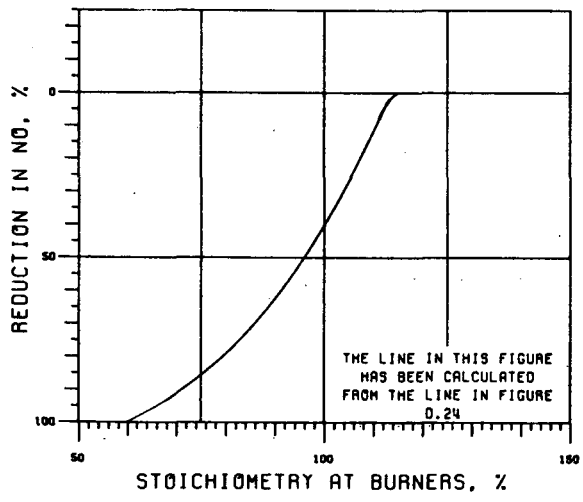


FIGURE D.55 SUBSTOICHIOMETRIC TESTS

## APPENDIX E

### MATHEMATICAL DERIVATIONS AND CALCULATIONS

Initial calculations were done by computer and yielded the weight of fuel, air, and natural gas from the igniter including any moisture if present (see Appendices A and B). In addition, the percentage of theoretical air was calculated. For large amounts of combustibles (>3%) in the flue gas during substoichiometric tests, a gas chromatographic sample was analyzed for CO and $H_2$ (and $CH_4$) to determine equivalent combustibles as CO; or the equivalent CO was hand calculated if the fuel feed had remained steady and primary air rate constant from the previous base test. (The equivalent CO for combustibles assumed all combustible gas was present as CO for ease of excess air calculations – $H_2$ and CO both required 1/2 $O_2$ and no other combustibles were found in the flue gas except solid carbon. Since there was little unburned carbon in all coal tests and the amount was relatively constant, it was ignored in these excess air calculations.)

The flue gas recirculation was calculated by taking the ratio of flue gas recycled to the total weight of fuel and air in the combustion:

$$FGR = 100.0 \times \frac{W'_{fg}}{W_a + W_f}$$

The criterion for staging was the stoichiometry at the burner which is given by:

$$PBA = \frac{PTA \times FB}{100.0}$$

where

$$FB = W_2/W_a$$

In addition, corrections were applied to the $NO_x$ instrument readings for $CO_2$ and $H_2O$. The following series of constants were used:

| Constant Used | | Colorado Ohio | Ohio Coal | Gas* |
|---|---|---|---|---|
| $\frac{\text{Wt of stoich. air}}{\text{Wt of Fuel}}$ | | 9.237 | 8.588 | 16.48 |
| Wt of moisture/ 100 lb fuel | | 4.65 | 6.13 | 0.0 |
| MF | MFI | 0.6298 | 0.6298 | 0.6315 |
| | MFR | 0.3380 | 0.3154 | 0.6315 |
| MA | MAI | 0.5694 | 0.5694 | 0.5709 |
| | MAR | 0.02664 | 0.02549 | 0.1197 |
| MM | MMI | 0.1192 | 0.1192 | 0.1197 |
| | MMR | 0.02664 | 0.02549 | 0.1197 |
| MC | MCI | 0.06135 | 0.06135 | 0.06138 |
| | MCR | 0.05816 | 0.05405 | 0.06138 |

The equations are thus given as:

$$TM = MF + \frac{(PTA - 100.0)}{100} \times MA + MMH + MMF$$

where

$$MF = MFI \times W_{NI} + MFR \times W_f$$

$$MA = MAI \times W_{NI} + MAR \times W_f$$

$$NMH = MA \times \frac{P_{H_2O}}{(PB - P_{H_2O})}$$

*Gas analysis used for coal igniter firing.

$$MMF = 0.0465 \text{ lb } H_2O/\text{lb coal (only for Colorado coal)}$$

$$FCO2 = \frac{MC}{TM}$$

$$= \frac{MCI \times W_{NI} + MCR \times W_f}{TM}$$

$$FH2O = \frac{MMI \times W_{NI} + MMR \times W_f}{TM} + \frac{MMH + MMF}{TM}$$

Corrections applied to the $NO_x$ instrumentation are:

Whittaker: Multiply by (1.0 - FH2O - FCO2)
[With bubbler solution, multiply by
(1.0 - FH2O + 0.029268*/(1.0 - FH2O))]

TECo: Multiply by (1.0 - FH2O + 0.012117*/(1.0 - FH2O))

NDIR: Multiply by (1.0 - FH2O + 0.0065342*/(1.0 - FH2O))
after subtraction of 50 ppm correction due to water absorption.†

(The NDIR correction due to water absorption at 34°F saturation was determined experimentally.)

For all: correction to dry, 3% $O_2$ in flue gas, multiply by:

$$\frac{18.0}{PT \times (21.0 - POF)} \times \frac{1}{(1.0 - FH2O)}$$

The average of the NDIR and TECo, Aver, was calculated by:

$$Aver = \frac{NDIR + TECo}{2.0}$$

and the standard deviation, STDV, by:

---

*Saturation factor at temperature of measurement.

†Infrared absorption correction for actual water content of sampled flue gas.

$$STDV = \sqrt{(NDIR - Aver)^2 + (TECo - Aver)^2}$$

$$= \sqrt{2.0} \times |TECo - Aver|$$

The Btu value from the fuel enthalpy release is given by these equations, one for each fuel:

Colorado Coal: $BTU = 23855 \times W_{NI} + 12404 \times W_f$

Ohio Coal: $BTU = 23855 \times W_{NI} + 11533 \times W_f$

Gas: $BTU = 23920 \times (W_{NI} + W_f)$

The air and recycled flue gas preheat adds enthalpy to the flue gas during combustion also. This addition is given by (no primary preheat):

$$BTUG = BTU + W_a \times BTU_a + (MM \times W_f \times 18.016 + (MMH + MMF) \times 18.016) \times BTU_m + W'_{fg} \times BTU_f$$

where

$$BTU_a = (TAG - TA) \times (0.240 + 10^{-5} \times TAG)$$

$$BTU_m = (TAG - TA) \times (0.444 + 2 \times 10^{-5} \times TAG)$$

and

$$BTU_f = (TFG - TA) \times (0.252 + 10^{-5} \times TFG)$$

For correction of ppm $NO_x$ at 3% $O_2$, dry flue gas conditions to lb $NO_x$ (as NO) per million Btu (fuel Btu only) input, the NO value is multiplied by:

$\frac{W_{fg}}{BTU}$ (No conversion constant is necessary since the Btu and ppm must both be divided by $10^6$.)

In conversion of load percentages to thousands of Btu per $ft^3$ per hour, the factors to be remembered are:

1) furnace volume - ∿127 $ft^3$ (8 ft long, 4.5 ft diameter)

2) 100% load ≡ 5,000,000 Btu per hr

and therefore if million Btu load is divided by 0.1272, the result is in $kBtu/ft^3/hr$.

For calculation of the fractional reduction, $L_3$, of the measured values $L_1$ (base point) and $L_2$ (reduced value with reduction modification in firing test):

$$L_3 = \frac{L_1 - L_2}{L_1}$$

and since the values were

$$L_1 \pm L_1' \quad \text{and} \quad L_2 \pm L_2'$$

then

$$L_3' = \sqrt{\frac{\left(L_1'^2 + L_2'^2\right)^2}{L_1^2} + \left(\frac{\left(L_1 - L_2\right) \times L_1'}{L_1^2}\right)^2}$$

The calculations as used in data tables and graphs do not include conversion to the SI/metric system. It is intended that these conversions can be made by consultation of Appendix H. In this way, all data presented in the Phase II final report is consistent and directly comparable to the data in the previous Phase I final report.

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## APPENDIX F

### FUEL NITROGEN CONTENT OF THE OHIO AND COLORADO COALS

A direct comparison of the fuel bound nitrogen content* of the Ohio and Colorado coals was necessary to determine the effect on the $NO_x$ emission levels. There were six samples of Ohio coal and five samples of Colorado coal analyzed for total nitrogen content simultaneously for statistical purposes. All of the samples had been collected at different times and therefore were representative of the nitrogen content and its variability over a long period of time. In the case of the Ohio coal, the samples covered the entire period of Phase I. For the Colorado coal, the samples covered the first half of Phase II.

A blank was run at the same time the eleven samples were analyzed. The results of the analyses are shown in Table F.1. Figure F.1 shows a one dimensional illustration of these samples with nitrogen percentage in the horizontal: the banded regions are the average with $\pm$ 1 $\sigma$ shown as the total band width.

As can be seen from these data, the two separate sets of fuel bound nitrogen as determined for the coals are statistically identical. The two coals do not differ in fuel bound nitrogen content.

---

*The fuel bound nitrogen was determined by the Kjeldahl method.

TABLE F.1 FUEL BOUND NITROGEN CONTENT

| Sample No. | Nitrogen Content, % Ohio Coal | Colorado Coal |
|---|---|---|
| 1 | 1.18 | 1.18 |
| 2 | 1.15 | 1.20 |
| 3 | 1.13 | 1.07 |
| 4 | 1.11 | 1.12 |
| 5 | 0.98 | 1.25 |
| 6 | 1.07 | -- |
| Average of above | 1.105 | 1.164 |
| Standard deviation on average, $\sigma$ | ±0.073 | ±0.070 |
| Statistical band | 1.032 - 1.178 | 1.094 - 1.234 |
| Statistically determined fuel bound nitrogen | 1.1 ± 0.1 | 1.2 ± 0.1 |

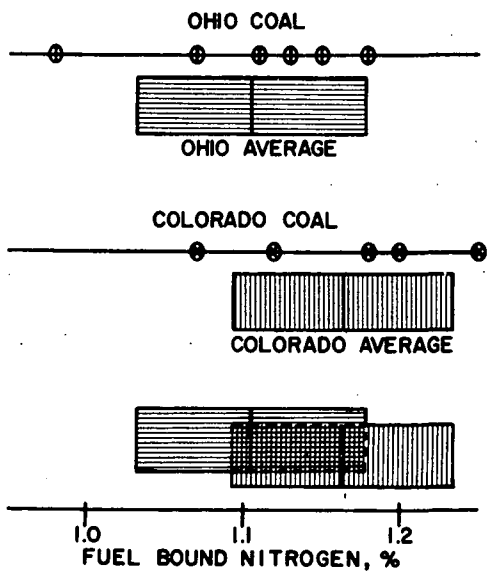


FIGURE F.1 FUEL BOUND NITROGEN CONTENT

## APPENDIX G

### COMPARATIVE DATA FOR THE OHIO COAL AND NATURAL GAS

The figures included, G.1 to G.7, show the most important trends of the $NO_x$ emission levels from the Ohio coal and natural gas tests. All of these test results have been taken from the Phase I report.

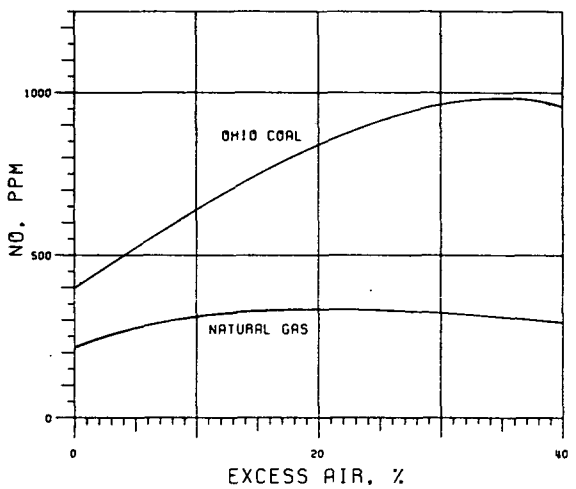


FIGURE G.1 EXCESS AIR

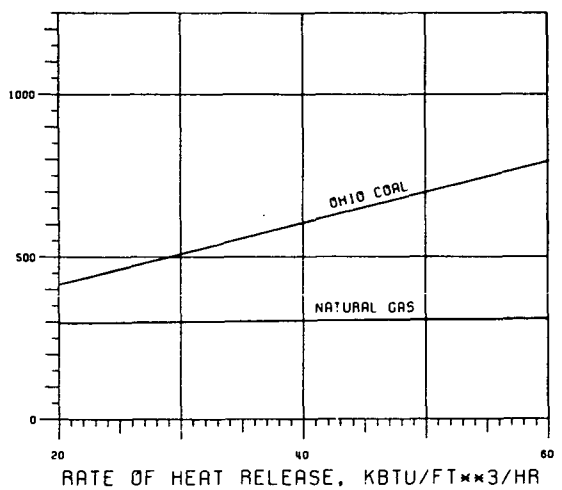


FIGURE G.2 LOAD

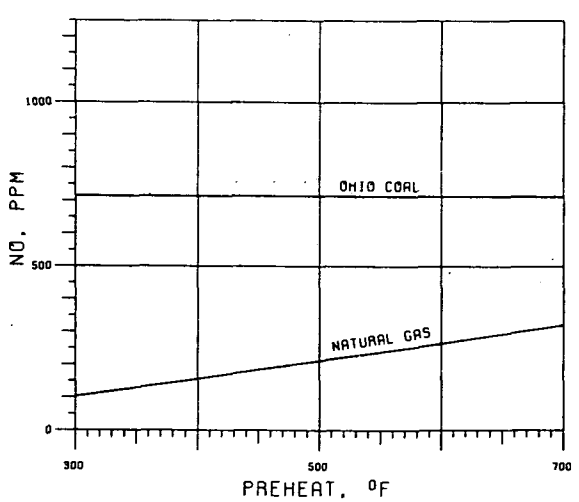


FIGURE G.3 PREHEAT

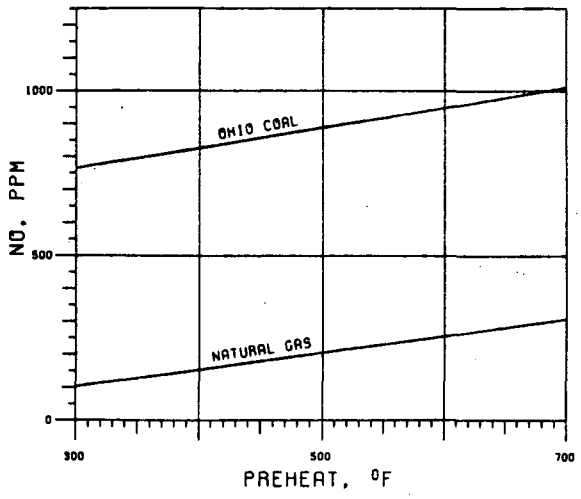


FIGURE G.4 PREHEAT, HIGH EXCESS AIR

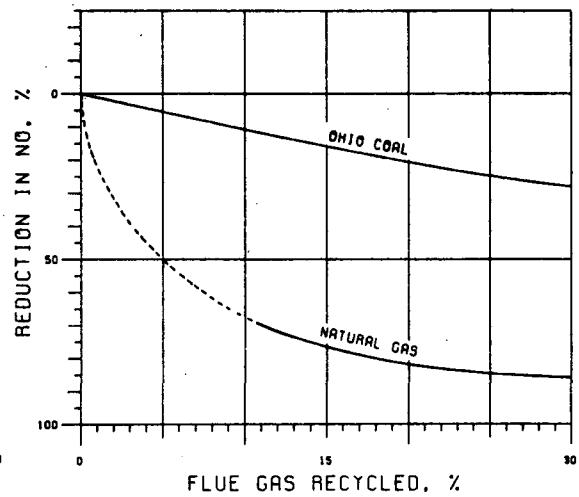


FIGURE G.5 SECONDARY FLUE GAS REC.

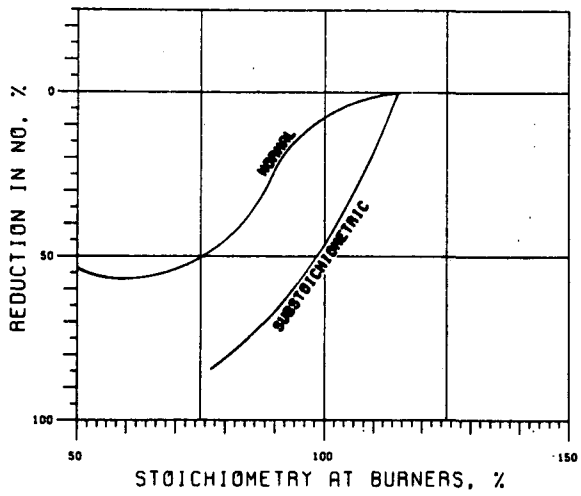


FIGURE G.6 COAL, STAGED COMBUSTION

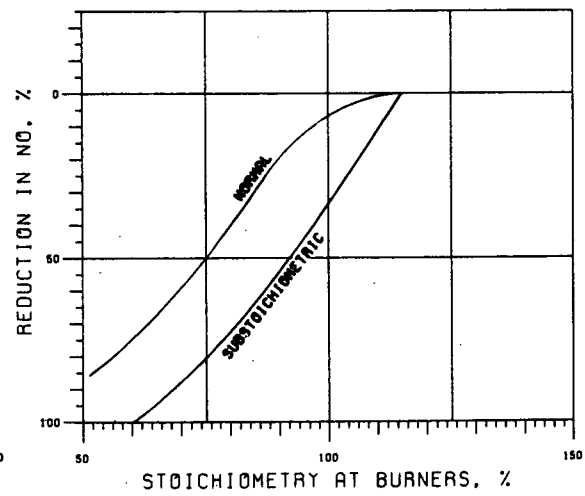


FIGURE G.7 GAS, STAGED COMBUSTION

## APPENDIX H

### TABLE OF CONVERSION FACTORS FOR SI UNITS

The most important factors for conversion from the English system of measurements to the SI system are:

(One of each of the following)

| English units | to | SI Units (to 4 significant figures)* |
|---|---|---|
| atmosphere (normal) | = | 1.013 E + 05 pascals (Pa)† |
| atmosphere (technical is 1 $kgf/cm^2$) | = | 9.807 E + 04 " " |
| British thermal unit (Inter. Table) | = | 1.055 E + 03 joules (J) |
| Btu (mean) | = | 1.056 E + 03 " (J) |
| Btu (thermochemical) | = | 1.054 E + 03 " (J) |
| Btu/pound mass | = | 2.326 E + 03 joules/kilogram (J/kg) |
| Btu/lbm·$^{o}$F | = | 4.187 E + 03 joules/kg·Kelvin (J/kgK) |
| Btu/hour | = | 2.931 E - 01 watts (W) |
| degrees Farenheit | = | ($t^{o}$F + 459.7)/1.8 Kelvins (K) |
| foot | = | 3.048 E - 01 meters (m) |
| pound-mass | = | 4.536 E - 01 kilograms (kg) |
| pound-force | = | 4.448 E + 00 newtons (N) |
| poundal | = | 1.383 E - 01 newtons (N) |

*The number 1.013 E + 05 is equivalent to $1.013 \times 10^5$

†The symbol for the unit follows in parentheses

The following table is included for sample conversions from English units to metric units:

(One of each of the following)

| English units | to | Metric units |
|---|---|---|
| atmosphere | = | 76 cm Hg<br>1.01 3E + 06 degrees/sq.cm<br>1.03 3E + 00 kg/sq.cm |
| British thermal unit (International)<br>Btu (mean)<br>Btu (thermochemical) | | 2.520 E + 02 (g)cal<br>2.520 E - 01 (kg)Cal |
| Btu/pound mass | | 5.556 E-01 (g)cal/gram<br>5.556 E-01 (kg)Cal/kg |
| Btu/lbm$^{o}$F | | 1.0 E + 00 (g)cal/gram $^{o}$C<br>1.0 E + 00 (kg)Cal/kg$^{o}$C |
| Btu/hour | | 2.520 E + 02 (g)cal/hr<br>2.520 E - 01 (kg)Cal/hr |
| degrees Farenheit | = | (tF - 32)/1.8 degrees Centrigrade |
| foot | = | 3.048 E - 01 meters (m) |
| pound-mass | = | 4.536 E - 01 kilograms (kg) |
| pound-force | = | 4.448 E + 00 newtons (N) |
| Poundal | = | 1.383 E - 01 newtons (N) |

## APPENDIX I

### COMBUSTIBLE AND $NO_X$

Table I.1 is all of the data from the coal and natural gas testing that has been run for this EPA contract. The data include:

| | | |
|---|---|---|
| Test Numbers | – | the series number and test number within the series (all Phase I and Phase II tests are included) |
| Comments | – | deviations to the usual base testing such as staging, flue gas recirculation, etc. |
| CO, ppm | – | the as read, "raw" data |
| NO, ppm | – | corrected to 3% $O_2$, dry |
| $O_2$, ppm | – | the as read, "raw" data |
| | – | subheadings separate the Ohio coal, natural gas, and Colorado coal. |

The figures I.1 to I.12 show the CO emission levels plotted against either the NO emission levels or the $O_2$ levels in the flue gas for single tests. (For any single test, a point is plotted.) It should be noted that odd numbered graphs (I.1, I.3, I.5, etc.) are log (CO) and the even numbered graphs are just CO.

Observations

For the Ohio coal, the log (CO) plots show a better picture of the pattern. A somewhat linear dependency of the log (CO) on $O_2$ is indicated.

The natural gas curves show the same type of variation with NO and $O_2$, although the absolute values of CO are lower than for the Ohio coal. The dependency of the log (CO) on $O_2$ is less linear and shows a leveling out at >3% $O_2$.

The Colorado coal again shows the same trends as the Ohio coal and natural gas. The absolute values of CO emission are similar to the Ohio coal. (A single curve could fit all data I.3 and I.11) The log (CO) versus $O_2$ is almost linear.

## TABLE I.1 COMPARISON OF ALL PHASE I AND PHASE II WORK

| TEST NUS. | COMMENTS | CO, PPM | NO, PPM | O2, % |
|---|---|---|---|---|
| | OHIO COAL | | | |
| I - 1 | | 205 | 725 | 3.2 |
| I - 2 | | 80 | 913 | 6.2 |
| I - 3 | | 8300 | 431 | 0.8 |
| I - 4 | | 180 | 714 | 2.6 |
| I - 5 | | 90 | 948 | 5.5 |
| I - 6 | | 8000 | 431 | 0.8 |
| I - 7 | | 260 | 746 | 2.7 |
| I - 8 | | 115 | 998 | 5.7 |
| I - 9 | | 15000 | 546 | 1.0 |
| I - 10 | | 115 | 534 | 2.9 |
| I - 11 | | 9000 | 292 | 0.8 |
| I - 12 | | 85 | 795 | 5.6 |
| I - 13 | | 240 | 546 | 2.4 |
| I - 14 | | 360 | 808 | 2.9 |
| I - 15 | | 500 | 683 | 2.7 |
| I - 16 | | 8000 | 420 | 0.7 |
| I - 17 | | 70 | 834 | 6.0 |
| I - 18 | | 65 | 821 | 5.5 |
| I - 19 | | 240 | 460 | 2.5 |
| I - 20 | | 3200 | 321 | 1.1 |
| I - 21 | | 60 | 681 | 5.9 |
| I - 22 | | 90 | 985 | 6.0 |
| I - 23 | | 165 | 791 | 2.5 |
| I - 24 | | 20000 | 282 | 0.8 |
| I - 25 | | 400 | 746 | 2.2 |
| I - 26 | | 4000 | 538 | 0.9 |
| I - 27 | | 140 | 956 | 5.5 |
| I - 28 | | 100 | 676 | 2.7 |
| I - 29 | | 800 | 428 | 2.3 |
| I - 30 | | 400 | 601 | 2.4 |
| I - 31 | | 18000 | 312 | 1.6 |
| I - 32 | | 375 | 731 | 3.1 |
| I - 33 | | 50 | 958 | 6.1 |
| I - 34 | | 4500 | 466 | 0.9 |
| I - 35 | | 260 | 789 | 3.2 |
| I - 36 | | 400 | 749 | 6.2 |
| I - 37 | | 50 | 922 | 6.0 |
| I - 38 | | 750 | 834 | 3.1 |
| I - 39 | | 3000 | 558 | 1.3 |
| I - 40 | | 90 | 739 | 3.7 |
| I - 41 | | 3200 | 449 | 1.2 |
| I - 42 | | 360 | 764 | 3.4 |
| I - 43 | | 7000 | 509 | 0.7 |
| IIA - 1 | | 90 | 774 | 2.9 |
| IIA - 2 | PRIMARY FGR | 80 | 694 | 2.6 |
| IIA - 3 | PRIMARY FGR | 90 | 659 | 2.7 |
| IIA - 4 | | 100 | 898 | 5.3 |
| IIA - 5 | PRIMARY FGR | 90 | 898 | 5.2 |
| IIA - 6 | | 4000 | 449 | 0.8 |
| IIA - 7 | PRIMARY FGR | 3200 | 472 | 0.7 |
| IIA - 8 | | 90 | 829 | 2.8 |
| IIA - 9 | PRIMARY FGR | 90 | 740 | 2.8 |
| IIA - 10 | | 140 | 980 | 5.7 |
| IIA - 11 | PRIMARY FGR | 140 | 969 | 6.0 |
| IIA - 12 | | 100 | 762 | 2.8 |
| IIA - 13 | PRIMARY FGR | 85 | 794 | 2.8 |
| IIA - 14 | | 1500 | 571 | 0.9 |
| IIA - 15 | PRIMARY FGR | 2600 | 552 | 0.8 |
| IIA - 16 | | 660 | 470 | 2.8 |
| IIA - 17 | PRIMARY FGR | 240 | 494 | 2.8 |
| IIA - 18 | PRIMARY FGR | 90 | 699 | 5.5 |
| IIA - 19 | | 90 | 658 | 5.1 |
| IIA - 20 | | 4000 | 246 | 1.0 |
| IIA - 21 | PRIMARY FGR | 4500 | 251 | 0.9 |
| IIA - 22 | | 90 | 654 | 2.8 |
| IIA - 23 | PRIMARY FGR | 125 | 635 | 2.4 |
| IIA - 24 | PRIMARY FGR | 115 | 868 | 5.6 |
| IIA - 25 | | 105 | 913 | 5.5 |
| IIA - 26 | | 4000 | 444 | 0.5 |
| IIA - 27 | PRIMARY FGR | 4000 | 387 | 0.6 |
| IIA - 28 | PRIMARY FGR | 240 | 630 | 2.6 |
| IIA - 29 | | 180 | 667 | 2.5 |
| IIA - 30 | | 350 | 452 | 2.5 |
| IIA - 31 | PRIMARY FGR | 200 | 501 | 3.3 |
| IIA - 32 | | 165 | 613 | 2.6 |
| IIA - 33 | PRIMARY FGR | 260 | 622 | 2.3 |
| IIA - 34 | | 90 | 706 | 5.0 |
| IIA - 35 | PRIMARY FGR | 90 | 734 | 5.0 |
| IIA - 36 | | 115 | 910 | 5.4 |
| IIA - 37 | PRIMARY FGR | 115 | 791 | 5.3 |
| IIB - 1 | | 115 | 828 | 3.3 |
| IIB - 2 | SECONDARY FGR | 115 | 708 | 3.0 |
| IIB - 3 | | 165 | 499 | 3.6 |
| IIB - 4 | SECONDARY FGR | 115 | 416 | 3.8 |
| IIB - 5 | SECONDARY FGR | 100 | 532 | 6.2 |
| IIB - 6 | | 100 | 722 | 6.0 |
| IIB - 7 | | 2600 | 333 | 1.8 |
| IIB - 8 | SECONDARY FGR | 1500 | 258 | 1.5 |
| IIB - 9 | | 80 | 832 | 2.9 |
| IIB - 10 | | 40 | 1080 | 6.3 |
| IIB - 11 | | 4000 | 289 | 0.9 |
| IIB - 12 | | 90 | 1014 | 6.2 |
| IIB - 13 | | 80 | 833 | 3.3 |
| IIB - 14 | SECONDARY FGR | 70 | 549 | 3.4 |
| IIB - 15 | | 80 | 1048 | 5.9 |
| IIB - 16 | SECONDARY FGR | 80 | 797 | 6.0 |
| IIB - 17 | | 2000 | 552 | 1.0 |
| IIB - 18 | SECONDARY FGR | 1400 | 372 | 1.0 |
| IIB - 19 | | 100 | 576 | 3.3 |
| IIB - 20 | SECONDARY FGR | 90 | 392 | 3.3 |
| IIB - 21 | | 80 | 810 | 6.3 |
| IIB - 22 | SECONDARY FGR | 80 | 596 | 6.2 |
| IIB - 23 | | 3500 | 320 | 1.1 |
| IIB - 24 | SECONDARY FGR | 450 | 242 | 1.1 |
| IIB - 25 | | 70 | 1013 | 5.5 |
| IIB - 26 | SECONDARY FGR | 90 | 814 | 5.3 |
| IIB - 27 | | 5000 | 538 | 0.8 |
| IIIA - 1 | | 50 | 882 | 3.0 |
| IIIA - 2 | | 60 | 1051 | 5.5 |
| IIIA - 3 | | 1000 | 580 | 0.4 |
| IIIA - 4 | | 80 | 939 | 2.5 |
| IIIA - 5 | | 160 | 1123 | 6.1 |
| IIIA - 6 | | 150 | 624 | 3.0 |
| IIIA - 7 | | 115 | 865 | 5.6 |
| IIIA - 8 | | 90 | 830 | 2.8 |
| IIIA - 9 | | 500 | 797 | 3.1 |
| IIIA - 10 | | 0 | 869 | 3.1 |
| IIIA - 11 | | 225 | 765 | 3.1 |
| IIIA - 12 | | 3000 | 534 | 0.8 |
| IIIA - 13 | | 1350 | 641 | 0.9 |
| IIIA - 14 | | 1035 | 885 | 3.0 |
| IIIA - 15 | | 1375 | 591 | 0.9 |
| IIIA - 16 | | 200 | 942 | 5.7 |
| IIIA - 17 | | 260 | 739 | 2.8 |
| IIIA - 18 | | 165 | 1001 | 5.6 |
| IIIA - 19 | | 210 | 605 | 3.4 |
| IIIA - 20 | | 240 | 770 | 5.6 |
| IIIA - 21 | | 7000 | 294 | 0.9 |
| IIIB - 1 | STAGED | 115 | 677 | 3.2 |
| IIIB - 2 | STAGED | 140 | 408 | 3.2 |
| IIIB - 3 | STAGED | 130 | 505 | 3.8 |
| IIIB - 4 | STAGED | 170 | 711 | 3.4 |
| IIIB - 5 | STAGED | 175 | 343 | 3.2 |
| IIIB - 6 | STAGED | 475 | 295 | 3.0 |
| IIIB - 7 | STAGED | 650 | 467 | 3.2 |
| IIIB - 8 | STAGED | 1050 | 359 | 3.2 |
| IIIB - 9 | STAGED | 1125 | 432 | 3.2 |
| IIIB - 10 | STAGED | 300 | 733 | 3.2 |
| IIIB - 11 | STAGED | 285 | 385 | 3.3 |
| IIIB - 12 | STAGED | 300 | 350 | 3.6 |
| IIIB - 13 | STAGED | 205 | 374 | 2.9 |
| IIIB - 14 | STAGED | 210 | 389 | 3.1 |
| IIIB - 15 | STAGED | 4000 | 399 | 0.8 |
| IIIB - 16 | STAGED | 3250 | 283 | 0.9 |
| IIIB - 17 | STAGED | 2600 | 371 | 0.9 |
| IIIB - 18 | STAGED | 1175 | 693 | 3.2 |
| IIIB - 19 | STAGED | 1100 | 409 | 3.1 |
| IIIB - 20 | STAGED | 1600 | 656 | 3.4 |
| IIIB - 21 | STAGED | 2350 | 524 | 0.8 |
| IIIB - 22 | STAGED | 1000 | 334 | 0.9 |
| IIIB - 23 | STAGED | 4000 | 469 | 1.5 |
| IIIB - 24 | STAGED | 200 | 689 | 5.7 |
| IIIB - 25 | STAGED | 250 | 685 | 5.8 |
| IIIB - 26 | STAGED | 260 | 674 | 3.0 |
| IIIB - 27 | STAGED | 200 | 807 | 5.4 |
| IIIB - 28 | STAGED | 210 | 844 | 5.7 |
| IIIB - 29 | STAGED | 2800 | 282 | 2.9 |
| IIIB - 30 | STAGED | 1500 | 362 | 2.6 |
| IIIB - 31 | STAGED | 285 | 410 | 5.8 |
| IIIB - 32 | STAGED | 285 | 524 | 6.0 |
| IIIC - 1 | FGR, STAGED | 240 | 320 | 3.1 |
| IIIC - 2 | FGR, STAGED | 310 | 465 | 3.3 |
| IIIC - 3 | FGR, STAGED | 0 | 366 | 3.0 |
| IIIC - 4 | FGR, STAGED | 660 | 411 | 3.2 |
| IIIC - 5 | FGR, STAGED | 3050 | 323 | 0.6 |
| IIIC - 6 | FGR, STAGED | 900 | 655 | 3.2 |
| IIID - 1 | SUBSTOICHIOMETRIC | 12000 | 377 | 0.0 |
| IIID - 2 | SUBSTOICHIOMETRIC | 47000 | 203 | 0.0 |
| VB - 13 | STAGED | 530 | 658 | 3.1 |
| VB - 14 | STAGED | 75 | 649 | 3.1 |
| VB - 15 | FGR | 2500 | 717 | 3.2 |
| VB - 16 | | 450 | 791 | 3.2 |
| VB - 17 | | 200 | 971 | 5.4 |
| VB - 18 | | 1050 | 750 | 3.1 |
| VB - 19 | | 285 | 934 | 5.3 |
| VB - 20 | | 2700 | 556 | 0.9 |
| VI - 1 | | 285 | 707 | 3.0 |
| VI - 2 | STAGED | 810 | 555 | 3.1 |
| VI - 3 | STAGED | 660 | 571 | 3.1 |
| VI - 4 | FGR | 500 | 603 | 3.3 |
| VI - 5 | | 420 | 829 | 5.0 |
| VI - 6 | | 2225 | 545 | 1.4 |
| VI - 7 | | 750 | 766 | 3.4 |
| VI - 8 | | 720 | 899 | 5.2 |

## TABLE I.1 (CON'T) COMPARISON OF ALL PHASE I AND PHASE II WORK

| TEST NOS. | COMMENTS | CO, PPM | NO, PPM | O2, % |
|---|---|---|---|---|
| | NATURAL GAS | | | |
| IVA - 1 | | 150 | 322 | 2.9 |
| IVA - 2 | | 103 | 320 | 5.5 |
| IVA - 3 | | 113 | 267 | 0.6 |
| IVA - 4 | | 70 | 308 | 3.0 |
| IVA - 5 | | 53 | 310 | 5.9 |
| IVA - 6 | | 810 | 249 | 0.7 |
| IVA - 7 | | 40 | 303 | 2.8 |
| IVA - 8 | | 40 | 311 | 5.9 |
| IVA - 9 | | 690 | 245 | 0.6 |
| IVA - 10 | | 40 | 148 | 2.8 |
| IVA - 11 | | 40 | 135 | 5.6 |
| IVA - 12 | | 1070 | 123 | 0.7 |
| IVA - 13 | | 35 | 144 | 2.8 |
| IVA - 14 | | 90 | 127 | 5.6 |
| IVA - 15 | | 1020 | 124 | 0.7 |
| IVA - 16 | | 23 | 156 | 2.8 |
| IVA - 17 | | 960 | 109 | 0.9 |
| IVA - 18 | | 15 | 139 | 5.6 |
| IVA - 19 | FGR | 7 | 44 | 3.1 |
| IVA - 20 | FGR | 22 | 74 | 3.1 |
| IVA - 21 | FGR | 22 | 47 | 5.8 |
| IVA - 22 | FGR | 200 | 60 | 0.8 |
| IVA - 23 | FGR | 133 | 33 | 0.7 |
| IVA - 24 | FGR | 22 | 54 | 2.9 |
| IVA - 25 | FGR | 480 | 24 | 0.6 |
| IVA - 26 | | 0 | 346 | 3.1 |
| IVA - 27 | STAGED | 0 | 256 | 3.0 |
| IVA - 28 | FGR, STAGED | 3 | 23 | 2.7 |
| IVA - 29 | FGR, STAGED | 7 | 178 | 2.9 |
| IVA - 30 | STAGED | 40 | 90 | 3.2 |
| IVA - 31 | FGR, STAGED | 8 | 53 | 3.3 |
| IVA - 32 | STAGED | 0 | 310 | 2.9 |
| IVA - 33 | FGR, STAGED | 0 | 28 | 3.0 |
| IVA - 34 | FGR, STAGED | 0 | 220 | 3.0 |
| IVA - 35 | STAGED | 760 | 120 | 0.8 |
| IVA - 36 | FGR, STAGED | 323 | 70 | 0.9 |
| IVA - 37 | | 0 | 330 | 5.8 |
| IVA - 38 | STAGED | 0 | 269 | 5.6 |
| IVA - 39 | FGR, STAGED | 0 | 198 | 5.8 |
| IVA - 40 | | 0 | 365 | 3.1 |
| IVA - 41 | SUBSTOICHIOMETRIC | 10500 | 251 | 0.4 |
| IVA - 42 | SUBSTOICHIOMETRIC | 64038 | 128 | 0.0 |
| IVA - 43 | SUBSTOICHIOMETRIC | 151622 | 53 | 0.0 |
| IVA - 44 | | 22 | 332 | 2.7 |
| IVA - 45 | | 15 | 235 | 2.5 |
| IVA - 46 | | 675 | 194 | 0.7 |
| IVA - 47 | | 460 | 278 | 0.8 |
| IVA - 48 | | 15 | 314 | 5.9 |
| IVA - 49 | | 15 | 293 | 5.7 |
| VA - 1 | | 60 | 330 | 2.8 |
| VA - 2 | | 80 | 329 | 2.9 |
| VA - 3 | | 75 | 283 | 2.7 |
| VA - 4 | | 70 | 261 | 2.8 |
| VA - 5 | | 335 | 212 | 0.7 |
| VA - 6 | | 70 | 275 | 5.6 |
| VA - 7 | | 6 | 269 | 2.8 |
| VA - 8 | | 810 | 230 | 0.6 |
| VA - 9 | | 70 | 265 | 5.7 |
| VA - 10 | | 75 | 270 | 2.8 |
| VA - 11 | | 360 | 239 | 0.6 |
| VA - 12 | | 90 | 245 | 5.6 |
| | COLORADO COAL | | | |
| VII - 1 | | 90 | 953 | 2.7 |
| VII - 2 | | 60 | 1250 | 5.8 |
| VII - 3 | | 3500 | 643 | 0.5 |
| VII - 4 | | 40 | 820 | 3.6 |
| VII - 5 | | 40 | 981 | 6.6 |
| VII - 6 | | 850 | 510 | 1.1 |
| VII - 7 | | 120 | 1085 | 3.1 |
| VII - 8 | | 3000 | 673 | 0.6 |
| VII - 9 | SUBSTOICHIOMETRIC | 34490 | 535 | 0.2 |
| VII - 10 | SUBSTOICHIOMETRIC | 95427 | 207 | 0.0 |
| VII - 11 | SUBSTOICHIOMETRIC | 145000 | 104 | 0.0 |
| VII - 12 | SUBSTOICHIOMETRIC | 205000 | 79 | 0.0 |
| VII - 13 | | 70 | 1196 | 3.0 |
| VII - 14 | | 60 | 1368 | 6.0 |
| VII - 15 | | 2600 | 845 | 0.9 |
| VII - 16 | | 150 | 917 | 3.0 |
| VII - 17 | | 60 | 1102 | 6.1 |
| VII - 18 | | 2600 | 577 | 1.1 |
| VII - 19 | | 240 | 945 | 3.1 |
| VII - 20 | | 115 | 917 | 3.0 |
| VII - 21 | | 115 | 1042 | 5.9 |
| VII - 22 | | 60 | 854 | 6.2 |
| VII - 23 | | 40 | 657 | 3.0 |
| VII - 24 | | 930 | 443 | 0.9 |
| VII - 25 | | 375 | 774 | 2.8 |
| VII - 26 | | 100 | 1064 | 2.7 |
| VII - 27 | | 100 | 1327 | 6.2 |
| VII - 28 | | 150 | 1305 | 5.6 |
| VII - 29 | | 950 | 862 | 1.0 |
| VIII - 1 | | 80 | 1044 | 3.0 |
| VIII - 2 | | 100 | 1094 | 2.8 |
| VIII - 3 | | 80 | 1309 | 6.9 |
| VIII - 4 | | 2150 | 727 | 0.7 |
| VIII - 5 | | 150 | 786 | 2.9 |
| VIII - 6 | | 1700 | 539 | 0.7 |
| VIII - 7 | | 100 | 1143 | 7.0 |
| VIII - 8 | | 150 | 1086 | 3.0 |
| VIII - 9 | | 8 | 1299 | 6.4 |
| VIII - 10 | FGR | 90 | 962 | 3.7 |
| VIII - 11 | | 100 | 1226 | 3.3 |
| VIII - 12 | | 105 | 856 | 3.1 |
| VIII - 13 | | 90 | 1014 | 6.3 |
| VIII - 14 | | 475 | 617 | 0.6 |
| IXA - 1 | | 120 | 1018 | 2.6 |
| IXA - 2 | | 30 | 811 | 3.1 |
| IXB - 3 | FGR | 240 | 968 | 2.5 |
| IXB - 4 | FGR | 130 | 888 | 2.2 |
| IXB - 5 | FGR | 30 | 770 | 2.8 |
| XA - 1 | | 1700 | 568 | 0.9 |
| XA - 2 | | 130 | 917 | 3.2 |
| XA - 3 | | 30 | 869 | 3.1 |
| XA - 4 | | 100 | 1057 | 5.3 |
| XA - 5 | | 100 | 1207 | 6.8 |
| XA - 6 | | 325 | 986 | 2.6 |
| XA - 7 | | 60 | 990 | 2.8 |
| XA - 8 | | 150 | 965 | 2.9 |
| XA - 9 | | 120 | 1056 | 2.7 |
| XA - 10 | | 90 | 1135 | 3.0 |
| XA - 11 | | 100 | 1068 | 2.9 |
| XA - 12 | | 70 | 1248 | 4.2 |
| XA - 13 | | 75 | 1391 | 5.5 |
| XA - 14 | | 180 | 1129 | 3.4 |
| XA - 15 | | 150 | 1121 | 2.9 |
| XA - 16 | | 120 | 1035 | 2.8 |
| XA - 17 | | 60 | 1364 | 6.5 |
| XA - 18 | | 60 | 1396 | 6.7 |
| XA - 19 | | 180 | 1038 | 2.9 |
| XA - 20 | | 1600 | 679 | 1.1 |
| XA - 21 | | 120 | 1182 | 3.6 |
| XA - 22 | | 130 | 874 | 3.0 |
| XA - 23 | | 30 | 897 | 6.4 |
| XA - 24 | | 9500 | 415 | 1.2 |
| XB - 25 | STAGED | 12500 | 252 | 1.4 |
| XB - 26 | STAGED | 300 | 571 | 3.1 |
| XB - 27 | STAGED | 1900 | 288 | 3.1 |
| XB - 28 | STAGED | 100 | 990 | 6.4 |
| XB - 29 | STAGED | 100 | 582 | 6.0 |
| XB - 30 | STAGED | 180 | 935 | 3.0 |
| XB - 31 | STAGED | 150 | 761 | 3.0 |
| XB - 32 | STAGED | 360 | 398 | 2.4 |
| XB - 33 | STAGED | 360 | 388 | 3.2 |
| XB - 34 | STAGED | 510 | 380 | 3.7 |
| XB - 35 | STAGED | 180 | 784 | 3.6 |
| XB - 36 | STAGED | 360 | 412 | 2.8 |
| XB - 37 | STAGED | 210 | 385 | 3.4 |
| XB - 38 | STAGED | 360 | 329 | 2.6 |
| XB - 39 | STAGED | 210 | 899 | 3.8 |
| XB - 40 | STAGED | 30 | 898 | 5.2 |
| XB - 41 | STAGED | 60 | 651 | 4.5 |
| XB - 42 | STAGED | 90 | 539 | 4.2 |
| XB - 43 | STAGED | 150 | 505 | 4.8 |
| XB - 44 | STAGED | 240 | 748 | 3.9 |
| XB - 45 | STAGED | 60 | 1039 | 7.0 |
| XB - 46 | STAGED | 60 | 979 | 6.0 |
| XB - 47 | STAGED | 60 | 771 | 7.2 |
| XB - 48 | STAGED | 4400 | 331 | 1.3 |
| XB - 49 | STAGED | 3100 | 312 | 1.0 |
| XB - 50 | STAGED | 150 | 763 | 3.3 |
| XB - 51 | STAGED | 340 | 496 | 3.6 |
| XB - 52 | STAGED | 1200 | 433 | 3.6 |
| XB - 53 | STAGED | 1200 | 395 | 3.2 |
| XB - 54 | STAGED | 1100 | 493 | 3.6 |
| XB - 55 | STAGED | 1100 | 477 | 3.6 |
| XB - 56 | STAGED | 150 | 477 | 6.7 |
| XB - 57 | STAGED | 4000 | 255 | 1.2 |
| XIA - 1 | | 120 | 1108 | 3.1 |
| XIA - 2 | STAGED | 120 | 885 | 2.9 |
| XIA - 3 | STAGED | 100 | 414 | 3.3 |
| XIA - 4 | STAGED | 200 | 745 | 2.8 |
| XIA - 5 | STAGED | 90 | 551 | 2.9 |
| XIA - 6 | | 3700 | 757 | 0.8 |
| XIA - 7 | STAGED | 3500 | 467 | 1.0 |
| XIA - 8 | STAGED | 120 | 315 | 1.3 |
| XIA - 9 | STAGED | 2200 | 389 | 1.0 |
| XIA - 10 | STAGED | 1200 | 315 | 0.9 |
| XIA - 11 | | 75 | 981 | 3.0 |
| XIA - 12 | STAGED | 60 | 557 | 3.2 |
| XIA - 13 | STAGED | 90 | 288 | 3.0 |
| XIA - 14 | STAGED | 100 | 342 | 3.1 |
| XIB - 1 | | 90 | 1083 | 2.8 |
| XIB - 2 | STAGED | 165 | 834 | 3.1 |
| XIB - 3 | STAGED | 115 | 414 | 2.8 |
| XIB - 4 | STAGED | 310 | 704 | 2.6 |
| XIB - 5 | STAGED | 115 | 574 | 3.1 |
| XIB - 6 | | 2700 | 796 | 1.0 |
| XIB - 7 | STAGED | 2000 | 434 | 0.9 |
| XIB - 8 | STAGED | 1700 | 399 | 1.0 |
| XIB - 9 | STAGED | 8030 | 401 | 0.8 |
| XIB - 10 | STAGED | 3200 | 318 | 1.0 |
| XIB - 11 | | 165 | 857 | 2.8 |
| XIB - 12 | STAGED | 140 | 601 | 2.9 |
| XIB - 13 | STAGED | 150 | 436 | 3.2 |
| XIB - 14 | STAGED | 140 | 360 | 3.2 |
| XIC - 1 | | 150 | 1096 | 3.2 |
| XIC - 2 | STAGED | 430 | 673 | 2.9 |
| XIC - 3 | STAGED | 810 | 295 | 2.9 |
| XIC - 4 | STAGED | 1200 | 611 | 3.2 |
| XIC - 5 | STAGED | 300 | 513 | 3.0 |
| XIC - 6 | | 4000 | 784 | 1.0 |
| XIC - 7 | STAGED | 6500 | 338 | 1.1 |
| XIC - 8 | STAGED | 4000 | 199 | 1.1 |
| XIC - 9 | STAGED | 9500 | 385 | 0.6 |
| XIC - 10 | STAGED | 9500 | 226 | 0.7 |
| XIC - 11 | | 125 | 940 | 2.8 |
| XIC - 12 | STAGED | 960 | 356 | 3.0 |
| XIC - 13 | STAGED | 500 | 250 | 2.9 |
| XIC - 14 | STAGED | 260 | 364 | 2.9 |
| XIIA - 1 | | 100 | 1191 | 3.2 |
| XIIA - 2 | STAGED | 75 | 933 | 3.4 |
| XIIA - 3 | STAGED | 60 | 512 | 3.3 |

TABLE I.1 (CON'T) COMPARISON OF ALL PHASE I AND PHASE II WORK

| TEST NOS. | COMMENTS | CO, PPM | NO, PPM | O2, % |
|---|---|---|---|---|
| XIIA - 4 | STAGED | 75 | 720 | 2.9 |
| XIIA - 5 | STAGED | 150 | 567 | 3.1 |
| XIIA - 6 | | 3200 | 824 | 1.0 |
| XIIA - 7 | STAGED | 1200 | 538 | 1.3 |
| XIIA - 8 | STAGED | 1600 | 278 | 1.3 |
| XIIA - 9 | STAGED | 2600 | 434 | 1.0 |
| XIIA - 10 | STAGED | 2100 | 363 | 1.3 |
| XIIA - 11 | | 180 | 1327 | 7.3 |
| XIIA - 12 | | 200 | 1037 | 3.2 |
| XIIA - 13 | | 90 | 892 | 2.8 |
| XIIA - 14 | STAGED | 80 | 506 | 3.0 |
| XIIA - 15 | STAGED | 75 | 341 | 3.5 |
| XIIA - 16 | STAGED | 60 | 540 | 3.4 |
| XIIA - 17 | STAGED | 150 | 332 | 2.9 |
| XIIA - 18 | | 100 | 1002 | 3.0 |
| XIIA - 19 | | 60 | 1192 | 7.4 |
| XIIA - 20 | | 2300 | 745 | 1.0 |
| XIIB - 1 | | 65 | 1220 | 2.9 |
| XIIB - 2 | STAGED | 330 | 914 | 2.7 |
| XIIB - 3 | STAGED | 330 | 420 | 2.9 |
| XIIB - 4 | STAGED | 60 | 865 | 2.8 |
| XIIB - 5 | STAGED | 100 | 506 | 2.8 |
| XIIB - 6 | | 2400 | 871 | 0.9 |
| XIIB - 7 | STAGED | 4300 | 576 | 1.1 |
| XIIB - 8 | STAGED | 1400 | 303 | 1.0 |
| XIIB - 9 | STAGED | 3600 | 524 | 0.6 |
| XIIB - 10 | STAGED | 2150 | 304 | 1.1 |
| XIIB - 11 | | 120 | 1401 | 7.4 |
| XIIB - 12 | | 100 | 1216 | 2.8 |
| XIIB - 13 | | 200 | 1022 | 2.8 |
| XIIB - 14 | STAGED | 140 | 631 | 2.7 |
| XIIB - 15 | STAGED | 75 | 357 | 2.9 |
| XIIB - 16 | STAGED | 55 | 607 | 3.0 |
| XIIB - 17 | STAGED | 115 | 383 | 3.1 |
| XIIB - 18 | | 450 | 1046 | 2.8 |
| XIIB - 19 | | 30 | 1183 | 7.0 |
| XIIB - 20 | | 3900 | 748 | 0.8 |
| XIIC - 1 | | 60 | 1108 | 2.8 |
| XIIC - 2 | STAGED | 330 | 875 | 2.6 |
| XIIC - 3 | STAGED | 100 | 426 | 3.0 |
| XIIC - 4 | STAGED | 120 | 726 | 2.8 |
| XIIC - 5 | STAGED | 300 | 489 | 2.8 |
| XIIC - 6 | | 4400 | 726 | 0.6 |
| XIIC - 7 | STAGED | 5000 | 408 | 0.7 |
| XIIC - 8 | STAGED | 1000 | 326 | 1.0 |
| XIIC - 9 | STAGED | 3950 | 420 | 0.8 |
| XIIC - 10 | STAGED | 2800 | 238 | 1.3 |
| XIIC - 11 | | 200 | 1395 | 6.5 |
| XIIC - 12 | | 200 | 1172 | 2.6 |
| XIIC - 13 | | 100 | 1048 | 2.5 |
| XIIC - 14 | STAGED | 500 | 549 | 2.4 |
| XIIC - 15 | STAGED | 155 | 351 | 2.7 |
| XIIC - 16 | STAGED | 240 | 569 | 2.4 |
| XIIC - 17 | STAGED | 330 | 287 | 2.5 |
| XIIC - 18 | | 500 | 1062 | 2.9 |
| XIIC - 19 | | 180 | 1165 | 6.8 |
| XIIC - 20 | | 3700 | 714 | 0.8 |

## Summary

The CO emission levels are dependent on $O_2$ levels, and in general CO is a function of $O_2$ – i.e., low $O_2$ levels (for lower $NO_x$ emission levels) yield greater CO emission levels. However, CO is not as closely associated to NO but rather both CO and NO, although somewhat interdependent, are both a function of $O_2$. Operation of our coal fired unit below 1% $O_2$ yields substantial quantities of CO.

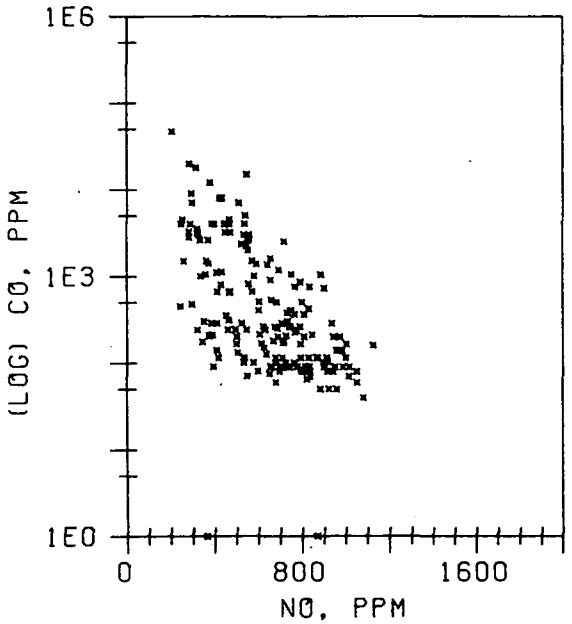


FIGURE I.1 CO VERSUS NO (OHIO COAL)

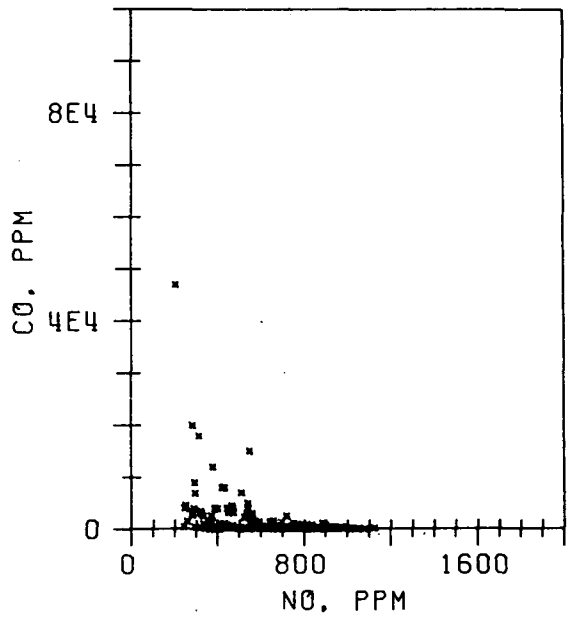


FIGURE I.2 CO VERSUS NO (OHIO COAL)

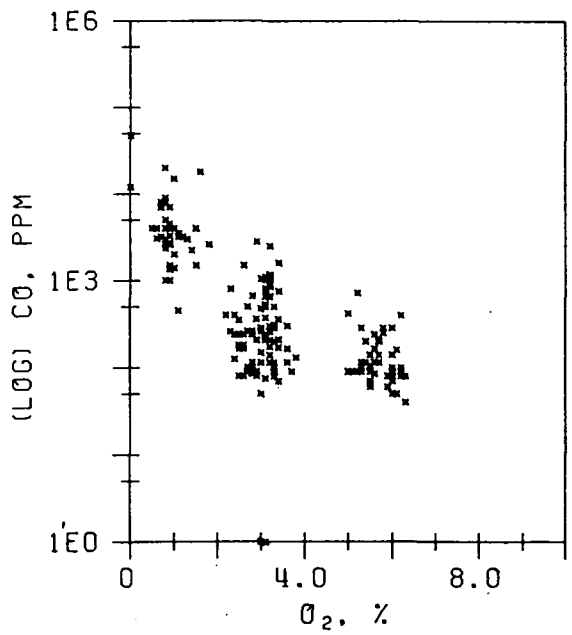


FIGURE I.3 CO VERSUS $O_2$ (OHIO COAL)

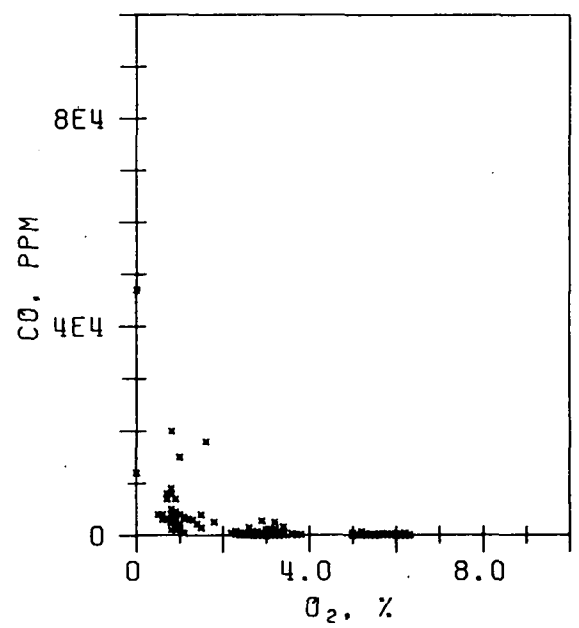


FIGURE I.4 CO VERSUS $O_2$ (OHIO COAL)

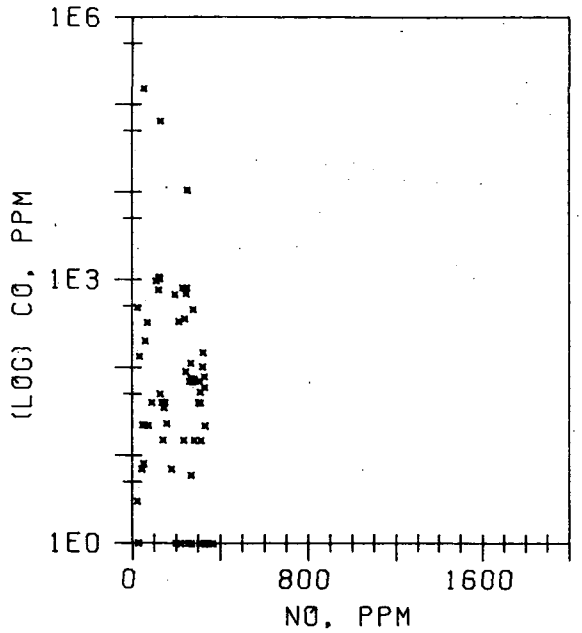


FIGURE I.5 CO VERSUS NO (NATURAL GAS)

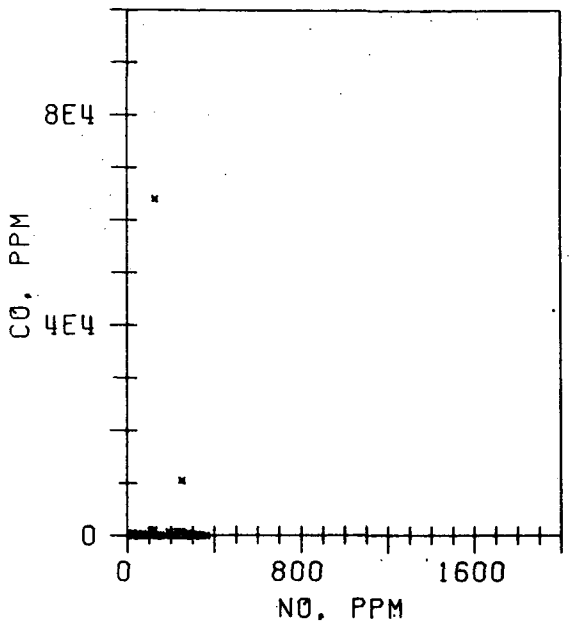


FIGURE I.6 CO VERSUS NO (NATURAL GAS)

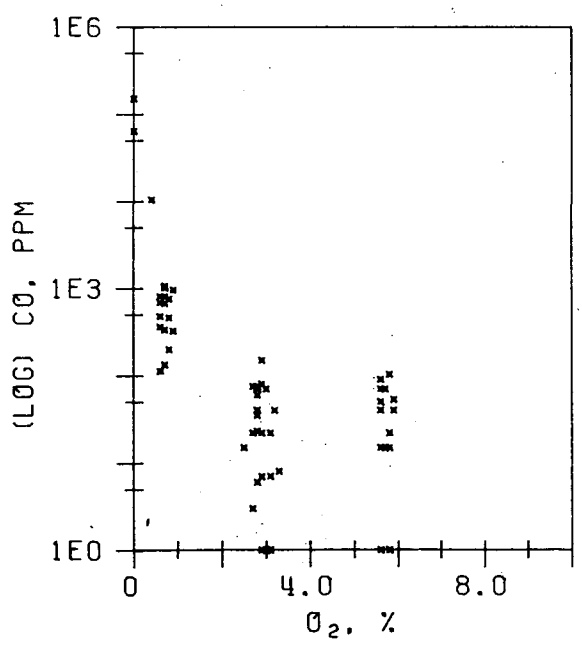


FIGURE I.7 CO VERSUS $O_2$ (NATURAL GAS)

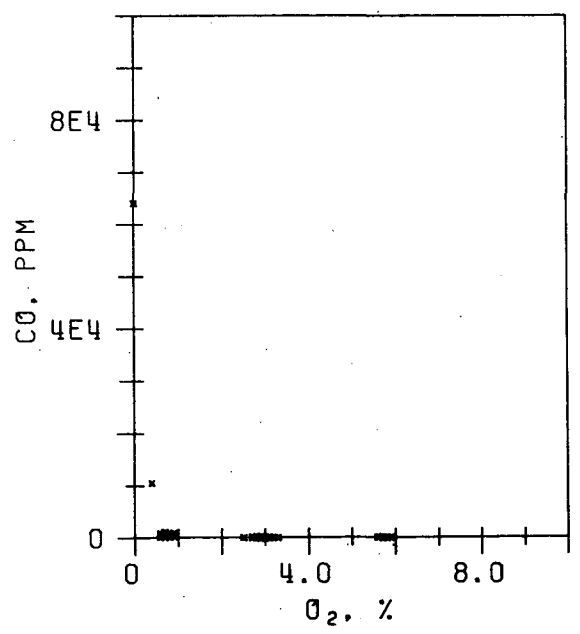


FIGURE I.8 CO VERSUS $O_2$ (NATURAL GAS)

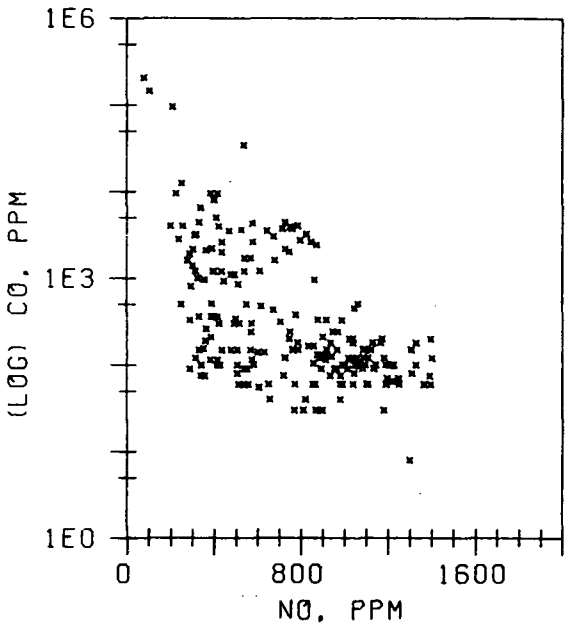


FIGURE I.9 CO VERSUS NO (COLORADO COAL)

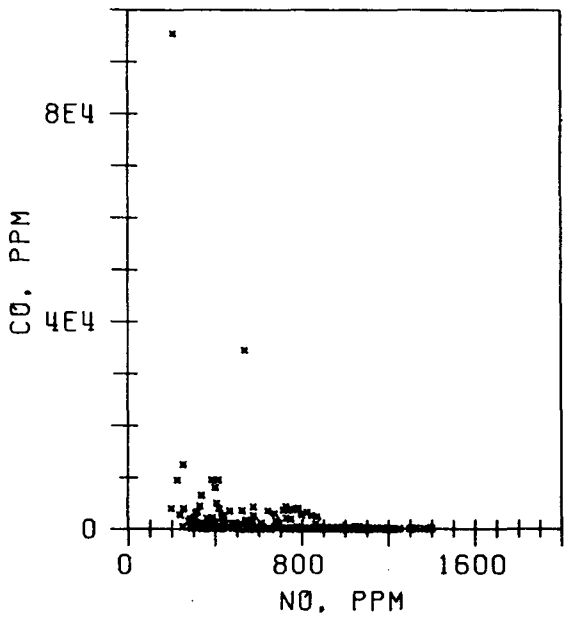


FIGURE I.10 CO VERSUS NO (COLORADO COAL)

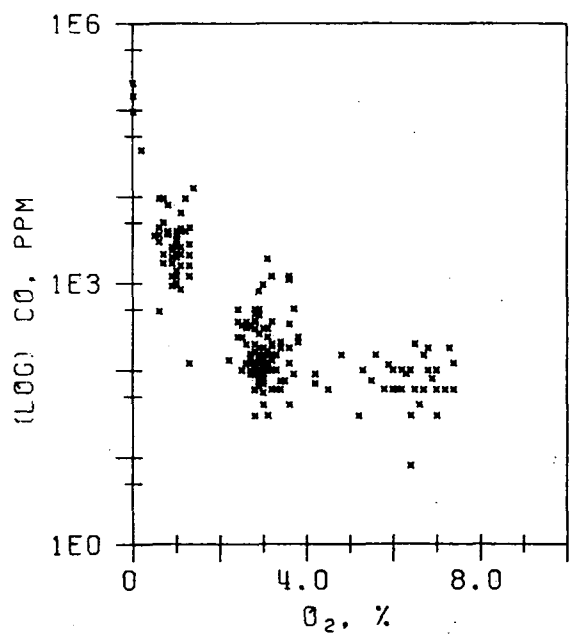


FIGURE I.11 CO VERSUS $O_2$ (COLORADO COAL)

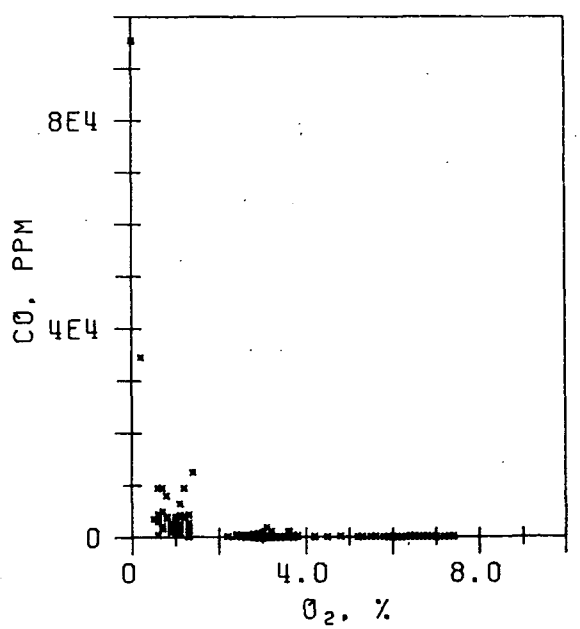


FIGURE I.12 CO VERSUS $O_2$ (COLORADO COAL)

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## TECHNICAL REPORT DATA
*(Please read Instructions on the reverse before completing)*

| | | |
|---|---|---|
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| | | 6. PERFORMING ORGANIZATION CODE |
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16. ABSTRACT The report gives results of Phase II of an investigation of combustion modification techniques for controlling NOx emissions that have application to pulverized coal-fired utility boilers. The techniques, studied on a 5 million Btu/hr single-burner pilot unit, included: excess air, air preheat, firing rate, flue gas recirculation, staged combustion, quench, and swirl. Phase II tests, conducted with a Colorado coal, showed that NOx reductions of up to 65% were possible by using staged combustion or by lowering excess air levels from 30 to zero %. Flue gas recirculation yielded only moderate NOx reductions for coal. For existing units, control of excess air appears to be the simplest method for NOx reduction. Where possible, staged combustion could be retrofitted on existing units to achieve further NOx reductions. For new units, staged combustion combined with low excess air firing appears to be the most promising method for NOx control.

17. KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
|---|---|---|---|
| Air Pollution | Quenching (Cooling) | Air Pollution Control | 13B, 13H |
| Nitrogen Oxides | Swirling | Stationary Sources | 07B, 07A |
| Combustion Control | | NOx Reduction | 21B |
| Coal | | Staged Combustion | 21D |
| Combustion Chambers | | Flue Gas Recirculation | |
| Flue Gases | | Air Preheat | |
| Thermodynamics | | Excess Air | 20M |

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