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EFFECTS OF DESIGN AND OPERATING VARIABLES ON NO_x FROM COAL-FIRED FURNACES--PHASE I

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EFFECTS OF DESIGN AND OPERATING VARIABLES ON NO_x FROM COAL-FIRED FURNACES-- PHASE I

by

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ABSTRACT

The purpose of this contract is to investigate various combustion modification techniques which might be applicable for control of NO_x on pulverized coal fired utility boilers and to compare the relative effectiveness of these methods for gas and oil combustion.

These combustion techniques have been applied to a single burner coal fired unit. The techniques studied were: (1) excess air, (2) air preheat, (3) rating, (4) flue gas recirculation, (5) staged combustion, (6) quench, and (7) swirl.

Reductions of up to 50% in NO emission levels are possible using staged combustion. Reduction of excess air levels from 30 to 0% can yield similar results. Flue gas recirculation shows only moderate reduction.

Fuel bound nitrogen conversion increases with increasing excess air level and decreasing temperature. 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 promises to be the best method for NO_x reduction.

For new units, staging is the most promising with a physical separation of the two stages.

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ACKNOWLEDGMENTS

The results of this phase of the contract are due to the efforts of others at the Alliance Research Center. In particular, W. L. Sage was 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.

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SYMBOLS AND ABBREVIATIONS

This list of symbols and abbreviations includes all items from the text from which confusion may result. All air weights and measurements are calculated dry unless otherwise noted.

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

SYMBOLS AND ABBREVIATIONS (Continued)

Symbol, Abbreviation	Definition
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
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

Symbol, Abbreviation	Definition
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 "Non dispersive 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
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

* This symbol in brackets; i.e., [NO], indicates the concentration of that gas.

Symbol, Abbreviation	
R	Gas constant
R-N	Specifies an organic fuel bound nitrogen molecule*
STDV	Standard deviation of Aver
t	Time
T	Temperature of orifice, °F; also used as kinetic temperature for any reaction
TA	Ambient temperature, °F
TAG	Air preheat temperature, °F
TECo	NO measurement from TECo instrument, ppm; also used for "Thermo Electron Corp." chemiluminescence
TFG	Flue gas temperature, °F
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

* This symbol in brackets; i.e., [NO], indicates the concentration of that gas.

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.
ΔH	Differential pressure across orifice, inches H_2O
1,2,3...	Subscript indicating reaction number for partial value

I. INTRODUCTION

A. Objectives

The primary objective of this contract is to investigate on experimental coal fired furnaces, a variety of combustion techniques which could be applicable for control of NO_x and related combustible emissions such as CO, carbon, and hydrocarbons. In addition, we are to provide detailed correlations and to define the critical conditions for application of the most promising combustion control techniques to a single burner furnace. And finally we are to optimize the most successful techniques for pollution control in the burning of coal and to identify potential problems in boiler operational and thermal performance. The work for the contract is divided into three phases:

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

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

Phase III: Optimization of the most successful techniques from Phase II as applied to a multiburner, pulverized coal fired furnace.

The criteria applied to the testing will include the degree to which nitrogen oxides are reduced, effects on thermal and operational performance, and applicability and cost of modification to existing or new boilers.

B. Phase I

The primary objective of this phase is to identify the major variables which influence the formation of NO_x and the related combustible emissions in an experimental single burner, coal fired furnace. In addition, it is necessary to compare the effectiveness of the various combustion control techniques for gas and oil and to determine the general applicability of control techniques to all utility boiler types and fuels.

C. Background and Description of Work

The contract work for Phase I was started October, 1972, and was planned to continue for about 30 weeks. The criteria utilized for Phase I were the degree to which combustion techniques will control or inhibit NO_x formation, the effects of these techniques on thermal and operational performance of the unit, and the general applicability and cost for application of these techniques to existing units or new units under design.

The design and operational variables studied were fuel type, ratio of air to fuel, heat liberation rate, air preheat, flue gas recirculation, staged combustion and port position, quench, and swirl. Most of the testing was done using one coal, although natural gas and a heavy residual fuel oil were investigated on a limited basis for comparison. For all operational and design variables except port position, quench, and swirl, the variable was changed over a wide range to include both normal operating conditions and extreme operating conditions which are not ordinarily practical.

D. Significant Results

It has been found that fuel type is of extreme importance and that a change in the type of fuel produces entirely different effects for the major variables studied. In particular, gas and coal are significantly different in most responses to operational variables and although they behave similarly for the design variables, they show far different reduction effects. Oil has NO_x emission levels similar to gas but its responses to variables are similar to coal.

In the coal firing tests, the major changes were due to excess air and load at moderate or high excess air. Flue gas recirculation was only effective at high levels of recirculation. Staged combustion was the most promising but only moderately effective and flue gas recirculation in combination with staged combustion showed no further reduction over staging alone. Preheat of air showed only very small effects. The quench rate (heat removal rate) showed some effect on NO_x emission levels.

The NO_x levels for natural gas were greatly affected by air preheat, flue gas recirculation, staged combustion, and flue gas recirculation in combination with staging. Minor effects on NO_x emission are found from changes in excess air and load. A change in swirl also produced a minor change in NO_x emissions. Impeller position was an important variable also.

Although the magnitude of the NO_x emissions for oil are similar to gas under most conditions, many of the responses to variables are the same as for coal. The major variable effecting NO_x emission for oil was found to be staged combustion. A small effect is noted for flue gas recirculation. Little or no effect on NO_x emissions is noticed for preheat, load, or excess air except at low excess air.

II. APPARATUS

The single burner coal furnace used at the Alliance Research Center is called "The Basic Combustion Test Unit." Next to the furnace is a laboratory area where the instrumentation for stack gas measurements is 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 partially lined with a 1-inch thick refractory brick. The fuel and air input at the burner is split into the primary (fuel) and secondary (air) flows. Depending upon fuel type, the following input is a normal loading of 5,000,000 BTU per hour:

1) Coal - primary air - ∿ 15% total combustion air
   - coal in primary air - ∿ 500 lb per hour
   - secondary air - balance of burner combustion air

2) Gas - primary fuel feed of about 250 lb gas per hour
   - secondary air - burner combustion air

3) Oil - primary fuel feed of about 300 lb per hour
   - primary atomization with steam (∿ 10 lb per hour)
   - secondary air - burner combustion air

Figure 2.2 is an illustration of the burner used for coal firing. The spinning vanes are fixed and therefore only one swirl can be applied to the secondary air. The coal spreader at the end of the primary pipe is set at a 45° angle of divergence from the centerline to disperse the coal into the secondary air stream. Figures 2.3 and 2.4 show the burner used for gas and oil. There are 16 movable vanes (not illustrated, but in the same relative position as shown in Figure 2.2) which are symmetrically placed around the burner. The vane angle can be varied from 0°, or no swirl, to a maximum of 30°, or the maximum swirl used during this test period. Figure 2.5 illustrates a typical oil sprayer plate; the atomization is accomplished by use of steam. The gas/oil

FIGURE 2.1

BASIC COMBUSTION UNIT (SINGLE BURNER)

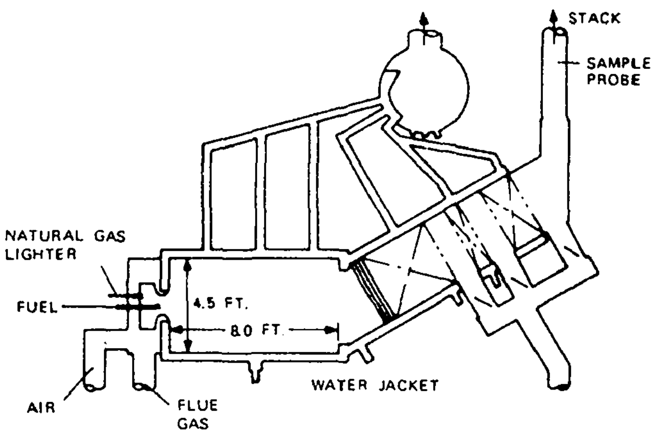


FIGURE 2.2

COAL BURNER

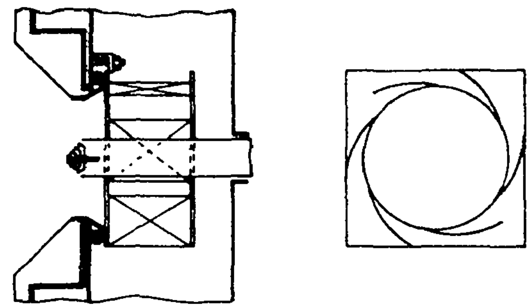


FIGURE 2.3

GAS BURNER

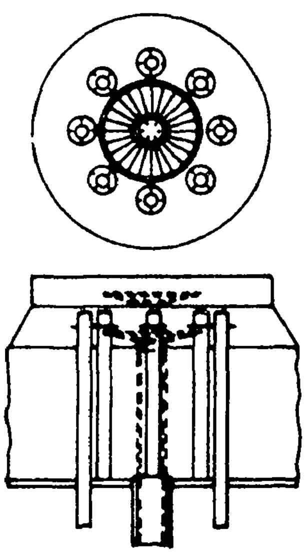


FIGURE 2.4

OIL BURNER

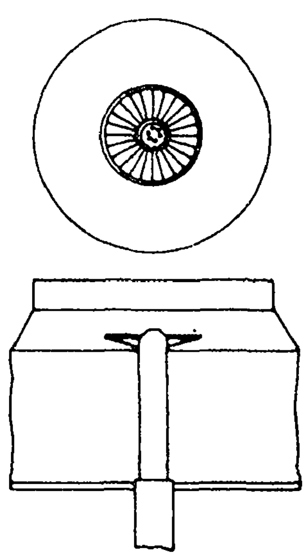
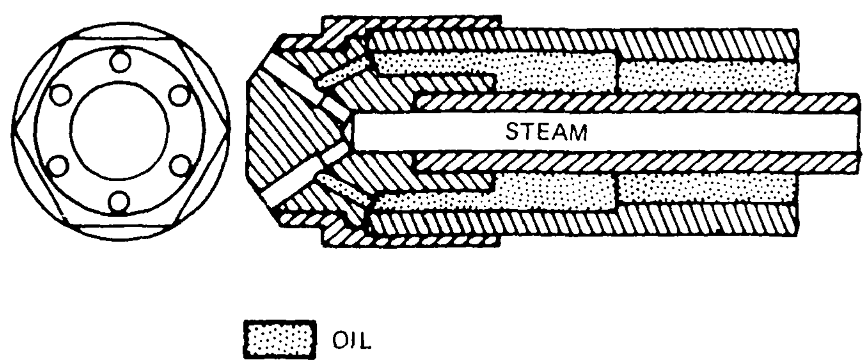


FIGURE 2.5

OIL ATOMIZER



burner was only used for coal when unsuccessful attempts were made to determine the effect of swirl on coal firing. Figures 2.6 and 2.7 are photographs of the coal and gas/oil secondary burner hardware respectively (no fuel supply is shown) as they look before placement in the windbox. In summary, the following configurations have been used for firing:

1) Coal - coal burner (6 vaned) for all tests except swirl at immovable vane setting - coal feed pipe carries primary air ($\sim$ 15% total combustion air) for coal transport and has a divergent 45° spreader outlet.

2) Swirl (coal) - gas/oil burner - gas spuds and oil impeller were removed and replaced with coal feed as used in No. 1. Vanes always set at 30° (fire unstable at lower angles, with loss of ignition at 0°).

3) Gas - all tests used eight spuds with ring feed and impeller in place. Variable setting of impeller used only for specific tests. Vanes always set at 30° (maximum angle) except for swirl tests.

4) Oil - all tests used oil feed in center pipe with impeller in place. Impeller setting was varied only for specific tests. Gas spuds removed. Gas feed ring left in place. Vanes always set at 30° (maximum angle) for all tests.

5) Igniter - supplied up to 1% by weight fuel and up to 2% BTU release rate in furnace. Uses about 3 lb natural gas per hour at 20% flow. <u>Only</u> used during tests for coal to maintain stable firing at low air and high load. Used for <u>all</u> coal tests for consistency at 3 lb per hour except when required for one test at 7 lb per hour. For <u>all</u> gas and oil tests, used only for initial flame ignition and then shut off.

FIGURE 2.6

BURNER WITH FIXED VANES

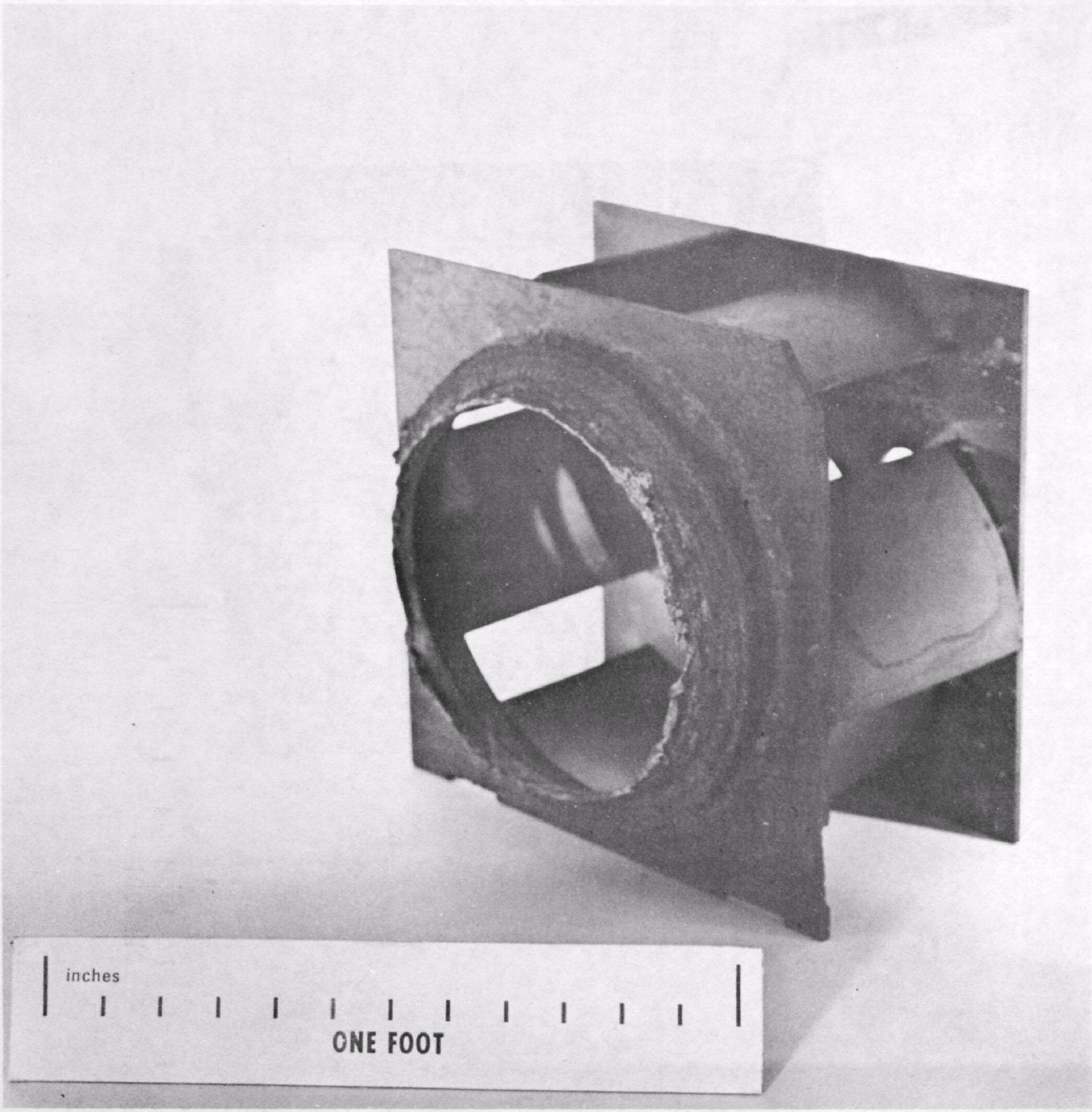
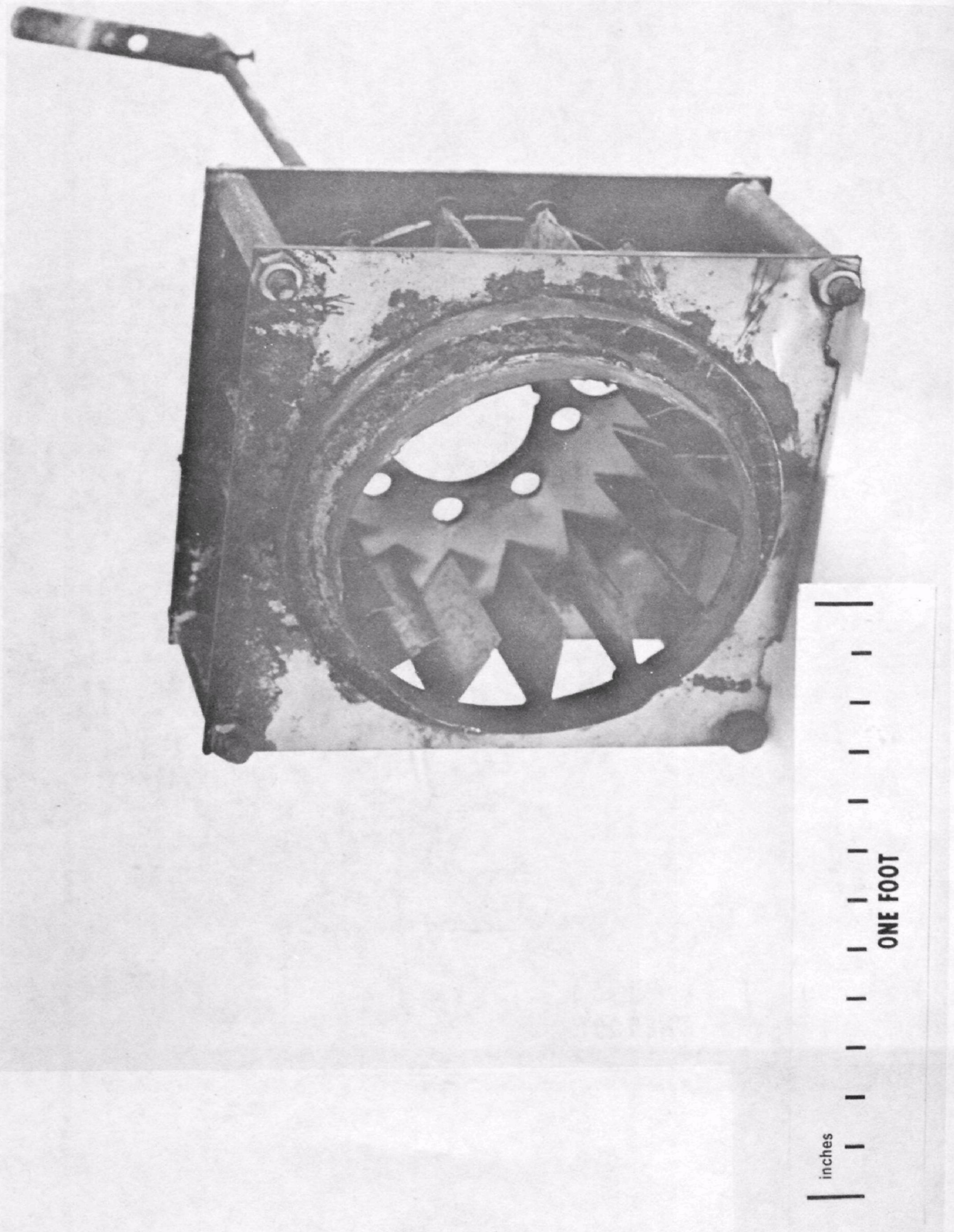


FIGURE 2.7

BURNER WITH ADJUSTABLE VANES



The positions of the staging ports are illustrated in Figures 2.8 and 2.9. Figure 2.10 is a photograph of the ports as placed inside the furnace. The front slots are set up to admit second stage air from 12-in. by 1-in. inlets parallel to the burner fuel/air feed. The side slots are set up to allow air into the furnace from 2-in. by 6-in. 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 swirl. Only one set of second stage ports is operated at one time; never both sets simultaneously.

The refractory lining of the furnace is 1-in. brick. The refractory lining extends from the burner down to the mid section of the furnace for a length of 4 ft. During the tests using a higher quench rate, the refractory was removed from the last 2 ft and covered only the area from the burner down one-quarter length of the furnace.

B. Instrumentation and Sampling

There are two probes in the stack from which gases and ash are regularly taken for measurement. Figure 2.11 shows the relative probe positions on the stack and the relative position of the gas sampling probe inside the stack. The first probe is 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 is used exclusively for gas samples and subsequent measurements. A third probe position is available 1 ft above and slightly offset from the gas sample probe for availability of an EPA train and for traverses of the stack.

The instrumentation probe branches into two gas sample lines. The first line carries 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 is continually monitored and recorded. The second line carries the gas sample into a 50°F ice bath (see Figure 2.12) before being

FIGURE 2.8

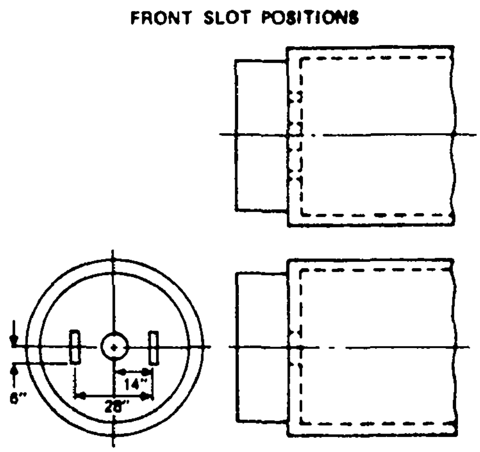


FIGURE 2.9

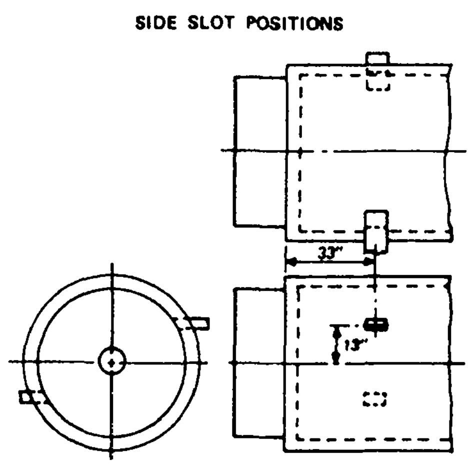


FIGURE 2.10

VIEW OF BURNER AND SLOTS

FIGURE 2.11

SAMPLE SYSTEM

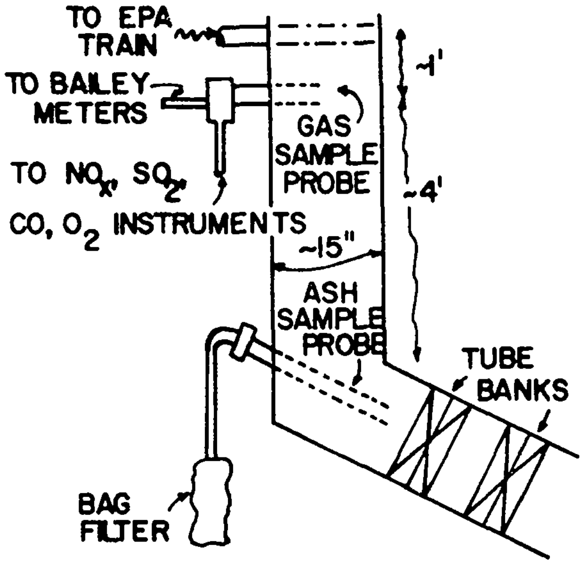
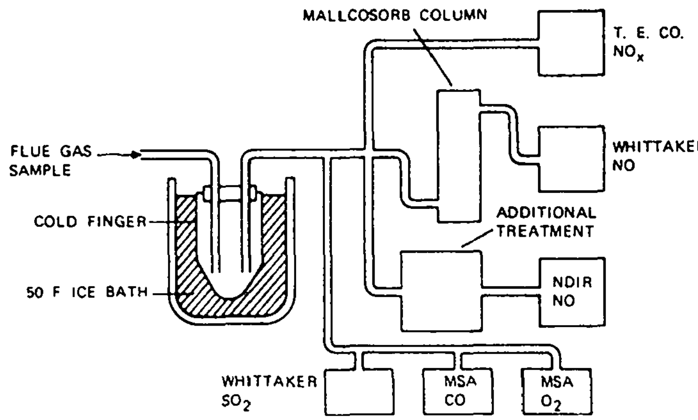


FIGURE 2.12

INSTRUMENTATION



carried into the instruments. This removes most of the water in the sampled flue gas. The temperature is maintained as closely as possible to 50°F. The gas sample then flows 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 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

All instrumental outputs except for the CO and O_2 analyzers are continuously recorded. The outputs of the CO and O_2 instruments are manually recorded for each test however.

Large discrepancies were found between the NDIR and TECo in our early tests. These discrepancies could not be attributed to water interference because the TECo usually had a higher reading than the NDIR; a water interference would have been indicated only if the TECo read lower than the NDIR. The following pretreatments were tried before the NDIR gas measurement cell, but after the 50°F water bath:*

1) No pretreatment

2) A 3 Å mole sieve with small amounts of silica gel as an indicator

3) A 3 Å mole sieve with no silica gel

4) Silica gel

5) A dry ice bath

6) A dual dry ice bath (two baths in tandem)

7) Anhydrous $CaCl_2$

8) $CaCl_2 \cdot 2H_2O$ (dihydrate)

9) A 34°F water bath

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* The 50°F water bath was sufficient for the TECo and the reading of the TECo was unaffected by minor changes of temperature in this bath.

The results of each unsatisfactory method are summarized below by method number:

1) Small variations in the temperature of the 50°F water bath led to changes in the H_2O content of the gas sample and large variations in the NDIR reading.

2-4) Loss of NO from flue gas when SO_2 and O_2 were present.

5-6) When compared, treatment 6 gave lower NO readings than treatment 5 suggesting both treatment methods were unreliable.

7-8) Same results as methods 2-4.

Thus it was found that treatment No. 9, the 34°F water bath, was the only successful treatment for flue gas measurement of NO 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°F by addition of ice to the water in the bath periodically. The water interference due to the humidity of 34°F saturated flue gas was determined experimentally by bubbling warm air at 70-80°F through water of the same temperature, passing it through the 50°F water bath, and then through the 34°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). No further problems were experienced either with loss of NO or increased water interference in NDIR readings.

C. Furnace and Burner Detail

Figures 2.13 and 2.14 illustrate the details of the furnace and burner cross sections. The impeller positional extremes are shown for the oil and gas burner. The coal nozzle exit position is just at the beginning of the throat flair of 27° (to the burner axis).

FIGURE 2.13

FURNACE CROSS SECTION

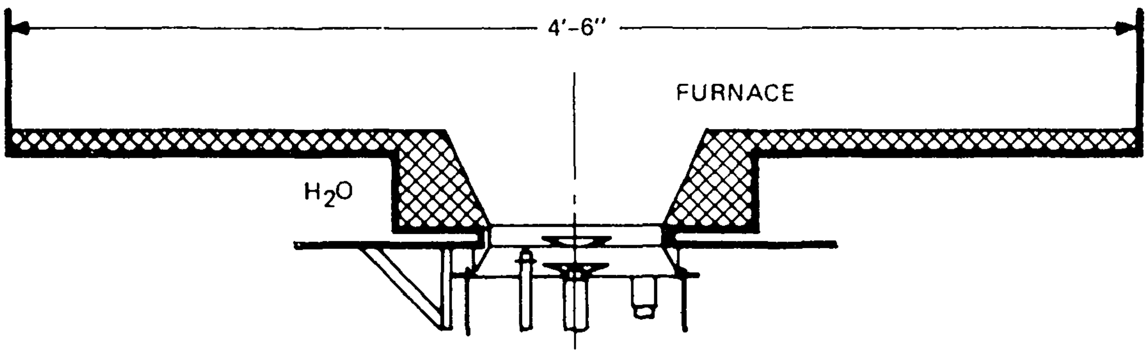
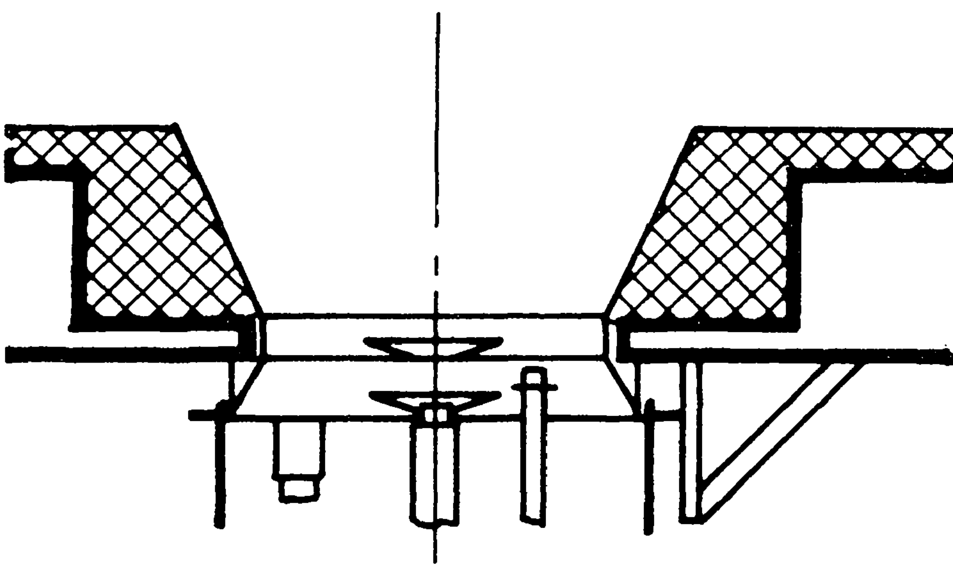


FIGURE 2.14

BURNER CROSS SECTION



III. PROCEDURES

The 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. Only when the furnace, its related systems, and the instrumentation were working properly did testing begin.

The sequence for a test run would be to set furnace conditions and check the operation of all instruments. When all equipment and all temperatures were equilibrated to a constant state of firing, the data would be taken; first data were read from non-recording 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.

IV. MEASUREMENTS AND CALCULATIONS

A. Variables Studied

There are two types of control 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 would be applied to new units yet to be constructed and, therefore, in this manner a minimum of redesign and reconstruction costs would be entailed. In addition, it is important to realize that modification of existing units might be physically impractical or economically unattractive.

The design variables, which suggest physical and mechanical changes which would be made in the unit, include flue gas recirculation, staged combustion, quench rate, and basic fuel type. On the other hand, the operational variables used to modify control on existing units include excess air, fuel firing rate, air preheat, and swirl. These groups of variables are not meant to be mutually exclusive.

An attempt was made to hold all conditions constant and to change the one variable under study over a wide range. However, many of these are interrelated and thus as load, excess air, preheat, and the other variables were changed, the air velocities changed leading to a variation in mix rate, turbulence, and combustion intensity. No attempt has been made to relate all of these variables, but an attempt to do so is projected as part of Phases II and III.

B. 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. The exceptions have occurred where our basic combustion unit would have shown unstable combustion tendencies and no meaningful test data could be attained. Each variable will be specifically described under the results.

C. Measurements Taken

For each of the test run measurement sequences, the time was noted; all recording instruments were read at the equivalent of that time after all non-recording instruments were read. There were always two people to take measurements; one for the flue gas analysis instrumentation and one for the furnace conditions.

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°F saturated). In addition, spot checks were made by ORSAT of oxygen, carbon monoxide, and carbon dioxide; for substoichiometric firing, only ORSAT could be used for carbon monoxide. Ash samples were also taken during some tests and the measurements required were: time duration of test; change in weight of ash filter bag; and the orifice temperature, differential pressure, and absolute pressure. An ash sample was removed from the filter bag for further analysis; always for unburned carbon and sometimes for nitrogen.

The furnace data accumulated was: the temperature, differential, and absolute pressures across a flow meter on an orifice for each of primary air, secondary air, the flue gas for all recirculation methods individually including primary, secondary, and second stage; the natural gas burner, and the natural gas igniter. The oil supply and return pressures and the coal feeder rate were also recorded, but were only used as checks for the stoichiometric calculations. Finally, the Bailey oxygen and combustibles meter was also recorded.

* Unless otherwise specified, all instrumental flue gas measurements were made at the equivalent of 50°F saturated.

V. RESULTS

There were six series of tests run for this phase of the contract. A total of about 200 test points are available. The data are presented completely in tables in Appendix C, in figures in Appendix D, and the mathematical equations and derivations are in Appendix E. Some preliminary work with the data was necessary for the data to reach a readily usable form, therefore, the "raw, as recorded" data are not included in the report.

VI. ANALYSIS OF DATA AND RESULTS

The data in final form are presented in Tables 6.1 to 6.7. These data were used to prepare all of the final data graphs for this section. The headings for the tabular columns are:

1) Original Series and Run Numbers - Self explanatory.

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

3) Heat, $kBTU/ft^3/hr$ - This is the overall net heat release rate in the furnace in thousands of BTU per unit volume.

4) Gas Preheat, °F - Self explanatory.

5) Flue Gas Input, % - This is the weight percentage of flue gas recycled back through the air input.

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

7) NO_x, ppm - This is the NO content of the flue gas corrected to 3% oxygen, dry conditions.

8) CO, ppm - This is the as measured, uncorrected concentration of CO (and H_2 equivalent as CO) in the flue gas.

9) O_2, % - This is the as measured, uncorrected (except for combustibles) concentration of O_2 in the flue gas.

In addition, Tables 6.8 to 6.15 inclusive are the final calculations based on Tables 6.1 to 6.7 for use in evaluation of NO reduction for flue gas

TABLE 6.1

INITIAL TESTS (SERIES I FOR 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 %
I - 1	116.3	51.55	608	0.0	116.3	725	205	3.2
I - 2	142.0	52.58	629	0.0	142.0	913	80	6.2
I - 3	101.9	50.30	587	0.0	101.9	431	8000	0.8
I - 4	112.4	53.60	611	0.0	112.4	714	180	2.6
I - 5	135.1	54.62	622	0.0	135.1	948	90	5.5
I - 6	101.9	50.85	592	0.0	101.9	431	8000	0.8
I - 7	113.0	65.00	620	0.0	113.0	746	260	2.7
I - 8	137.0	66.41	647	0.0	137.0	998	115	5.7
I - 9	101.2	59.65	605	0.0	101.2	546	15000	1.0
I - 10	113.3	33.48	570	0.0	113.3	534	115	2.8
I - 11	101.7	29.63	534	0.0	101.7	292	9000	0.8
I - 12	136.0	33.87	595	0.0	136.0	795	85	5.6
I - 13	111.3	32.46	565	0.0	111.3	546	240	2.4
I - 14	114.2	64.68	638	0.0	114.2	808	360	2.9
I - 15	112.9	58.08	384	0.0	112.9	683	500	2.7
I - 16	101.4	47.31	371	0.0	101.4	420	8000	0.7
I - 17	140.0	50.30	393	0.0	140.0	834	70	6.0
I - 18	135.1	52.11	389	0.0	135.1	821	65	5.5
I - 19	111.8	31.20	384	0.0	111.8	460	240	2.5
I - 20	104.4	28.37	366	0.0	104.4	321	3200	1.1
I - 21	139.0	39.85	367	0.0	139.0	681	60	5.9
I - 22	140.0	52.89	643	0.0	140.0	985	90	6.0
I - 23	112.1	65.78	639	0.0	112.1	791	165	2.5
I - 24	99.1	30.81	547	0.0	99.1	282	20000	0.8
I - 25	110.3	65.31	507	0.0	110.3	746	400	2.2
I - 26	103.3	60.75	503	0.0	103.3	538	4000	0.9
I - 27	135.1	64.68	534	0.0	135.1	956	140	5.5
I - 28	113.0	51.56	505	0.0	113.0	676	100	2.7
I - 29	110.7	31.91	470	0.0	110.7	428	800	2.3
I - 30	111.3	49.28	279	0.0	111.3	601	400	2.4
I - 31	103.3	29.71	263	0.0	103.3	312	18000	1.6
I - 32	115.5	51.17	529	0.0	115.5	731	375	3.1
I - 33	141.0	50.69	548	0.0	141.0	958	50	6.1
I - 34	103.2	47.63	515	0.0	103.2	466	4500	0.9
I - 35	116.3	62.33	553	0.0	116.3	789	260	3.2
I - 36	141.8	31.99	527	0.0	141.8	749	400	6.2
I - 37	140.0	52.50	563	0.0	140.0	922	50	6.0
I - 38	115.8	62.01	550	0.0	115.8	834	750	3.1
I - 39	105.2	48.96	613	0.0	105.2	558	3000	1.3
I - 40	119.9	47.47	376	0.0	119.9	739	90	3.7
I - 41	104.9	43.46	354	0.0	104.9	449	3200	1.2
I - 42	117.6	59.02	373	0.0	117.6	764	360	3.4
I - 43	101.7	57.22	363	0.0	101.7	509	7000	0.7

TABLE 6.2

FLUE GAS RECIRCULATION TESTS (SERIES II FOR 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 %
IIA - 1	114.3	52.34	630	0.0	114.3	774	90	2.9
IIA - 2	112.7	51.87	645	1.8	112.7	694	80	2.6
IIA - 3	113.0	50.69	649	3.2	113.0	659	90	2.7
IIA - 4	133.2	55.57	648	0.0	133.2	858	100	5.3
IIA - 5	132.3	54.70	653	1.3	132.3	898	90	5.2
IIA - 6	102.8	50.38	609	0.0	102.8	449	4000	0.8
IIA - 7	102.6	48.65	624	2.0	102.6	472	3200	0.7
IIA - 8	113.3	48.89	631	0.0	113.3	829	90	2.8
IIA - 9	113.3	62.95	660	1.4	113.3	740	90	2.8
IIA - 10	137.0	65.08	662	0.0	137.0	980	140	5.7
IIA - 11	139.9	63.74	675	1.2	139.9	969	140	6.0
IIA - 12	114.0	63.50	649	0.0	114.0	762	100	2.8
IIA - 13	114.0	63.03	660	1.5	114.0	794	85	2.8
IIA - 14	103.9	59.65	633	0.0	103.9	571	1500	0.9
IIA - 15	102.9	58.95	649	1.9	102.9	552	2600	0.8
IIA - 16	113.5	32.39	551	0.0	113.5	470	660	2.8
IIA - 17	113.9	31.44	577	3.0	113.9	494	240	2.8
IIA - 18	135.1	32.15	600	2.8	135.1	699	90	5.5
IIA - 19	131.4	33.72	578	0.0	131.4	658	90	5.1
IIA - 20	103.8	28.53	515	0.0	103.8	246	4000	1.0
IIA - 21	103.2	27.35	547	4.3	103.2	251	4500	0.9
IIA - 22	114.0	61.39	521	0.0	114.0	654	90	2.8
IIA - 23	111.6	60.99	529	1.6	111.6	635	125	2.4
IIA - 24	136.0	60.91	541	1.2	136.0	868	115	5.6
IIA - 25	135.1	63.19	527	0.0	135.1	913	105	5.5
IIA - 26	101.4	56.82	505	0.0	101.4	444	4000	0.5
IIA - 27	101.9	54.86	520	1.8	101.9	387	4000	0.6
IIA - 28	112.7	48.65	518	1.9	112.7	630	240	2.6
IIA - 29	111.8	50.54	506	0.0	111.8	667	180	2.5
IIA - 30	111.7	31.67	459	0.0	111.7	452	350	2.5
IIA - 31	117.0	30.34	484	2.4	117.0	501	200	3.3
IIA - 32	112.4	49.04	394	0.0	112.4	613	165	2.6
IIA - 33	111.0	48.57	404	1.9	111.0	622	260	2.3
IIA - 34	130.5	52.42	400	0.0	130.5	706	90	5.0
IIA - 35	130.5	50.46	409	1.5	130.5	734	90	5.0
IIA - 36	134.1	62.64	401	0.0	134.1	910	115	5.4
IIA - 37	133.2	61.93	403	1.4	133.2	791	115	5.3
IIB - 1	116.7	63.11	630	0.0	116.7	829	115	3.3
IIB - 2	115.0	65.08	629	12.1	115.0	708	115	3.0
IIB - 3	119.1	30.26	560	0.0	119.1	499	165	3.6
IIB - 4	119.2	30.81	565	21.0	119.2	416	115	3.6
IIB - 5	142.0	31.52	579	17.5	142.0	532	100	6.2
IIB - 6	139.9	40.63	596	0.0	139.9	722	100	6.0
IIB - 7	108.1	27.98	538	0.0	108.1	333	2600	1.8
IIB - 8	106.7	29.00	540	21.4	106.7	258	1500	1.5
IIB - 9	114.6	52.27	626	0.0	114.6	832	80	2.9
IIB - 10	143.0	53.44	636	0.0	143.0	1080	70	6.3
IIB - 11	103.3	28.84	524	0.0	103.3	289	4000	0.9
IIB - 12	142.0	58.95	420	0.0	142.0	1014	90	6.2
IIB - 13	117.0	51.48	623	0.0	117.0	833	80	3.3
IIB - 14	117.7	53.13	623	30.9	117.7	548	70	3.4
IIB - 15	139.0	56.98	644	0.0	139.0	1048	80	5.9
IIB - 16	140.0	55.25	642	18.4	140.0	797	80	6.0
IIB - 17	104.3	49.75	601	0.0	104.3	552	2000	1.0
IIB - 18	104.4	50.22	595	31.5	104.4	372	1400	1.0
IIB - 19	117.0	31.20	573	0.0	117.0	576	100	3.3
IIB - 20	117.4	31.52	557	34.0	117.4	392	90	3.3
IIB - 21	143.0	31.36	586	0.0	143.0	810	80	6.3
IIB - 22	142.0	32.62	593	22.8	142.0	596	80	6.2
IIB - 23	104.4	28.69	530	0.0	104.4	320	3500	1.1
IIB - 24	105.1	28.45	523	41.1	105.1	242	450	1.1
IIB - 25	135.6	60.91	656	0.0	135.6	1013	70	5.5
IIB - 26	133.2	63.27	646	20.4	133.2	814	90	5.3
IIB - 27	102.6	56.27	612	0.0	102.6	538	5000	0.8

TABLE 6.3

TWO STAGE COMBUSTION TESTS (SERIES III FOR 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 %
III A- 1	115.0	51.56	615	0.0	115.0	882	50	3.0
III A- 2	135.1	53.99	635	0.0	135.1	1051	60	5.5
III A- 3	103.5	66.65	613	0.0	103.5	580	1000	0.8
III A- 4	111.8	64.84	625	0.0	111.8	939	80	2.5
III A- 5	140.9	66.57	650	0.0	140.9	1123	160	6.1
III A- 6	114.9	30.26	553	0.0	114.9	624	150	3.0
III A- 7	136.0	31.83	580	0.0	136.0	865	115	5.6
III A- 8	113.7	51.56	610	0.0	113.7	830	90	2.8
III A- 9	115.5	51.72	607	0.0	115.5	797	500	3.1
III A-10	116.0	51.24	612	0.0	116.0	869	0	3.1
III A-11	115.6	51.64	614	0.0	115.6	765	225	3.1
III A-12	103.1	50.22	586	0.0	103.1	534	3000	0.8
III A-13	103.9	50.14	597	0.0	103.9	641	1350	0.9
III A-14	114.7	65.39	628	0.0	114.7	885	1035	3.0
III A-15	103.9	63.90	619	0.0	103.9	591	1375	0.9
III A-16	137.0	51.17	632	0.0	137.0	942	200	5.7
III A-17	113.6	52.74	621	0.0	113.6	739	260	2.8
III A-18	136.0	65.55	645	0.0	136.0	1001	165	5.6
III A-19	117.7	31.44	568	0.0	117.7	605	210	3.4
III A-20	136.0	34.66	586	0.0	136.0	770	240	5.6
III A-21	102.6	28.69	529	0.0	102.6	294	7000	0.9
III B- 1	116.3	49.04	606	0.0	91.3	677	115	3.2
III B- 2	116.3	47.55	604	0.0	68.2	488	140	3.2
III B- 3	120.6	45.19	624	0.0	54.8	505	130	3.8
III B- 4	117.7	48.18	614	0.0	93.0	711	170	3.4
III B- 5	116.3	48.07	639	0.0	68.0	343	175	3.2
III B- 6	114.8	47.63	644	0.0	52.4	295	475	3.0
III B- 7	116.1	46.69	629	0.0	65.9	467	650	3.2
III B- 9	116.0	47.86	623	0.0	54.2	359	1050	3.2
III B- 9	116.0	48.26	619	0.0	67.8	432	1125	3.2
III B-10	116.3	48.65	602	0.0	90.9	733	300	3.2
III B-11	117.0	47.24	627	0.0	67.2	385	285	3.3
III B-12	119.1	45.90	638	0.0	54.3	350	300	3.6
III B-13	114.3	49.67	617	0.0	66.7	374	205	2.9
III B-14	115.6	48.57	644	0.0	46.3	389	210	3.1
III B-15	102.8	47.16	587	0.0	79.1	399	4000	0.8
III B-16	103.5	46.06	614	0.0	56.7	283	3250	0.9
III B-17	103.6	48.26	572	0.0	80.5	371	2600	0.9
III B-18	116.0	61.85	617	0.0	90.7	693	1175	3.2
III B-19	115.3	61.30	647	0.0	69.1	409	1100	3.1
III B-20	117.2	61.70	636	0.0	91.3	656	1600	3.4
III B-21	103.2	62.17	621	0.0	80.4	524	2350	0.8
III B-22	104.0	59.57	635	0.0	57.3	334	1000	0.9
III B-23	106.1	60.28	609	0.0	82.7	469	4000	1.5
III B-24	137.0	48.18	629	0.0	92.1	689	200	5.7
III B-25	137.9	47.63	625	0.0	93.1	685	250	5.8
III B-26	114.9	50.38	604	0.0	90.4	674	260	3.0
III B-27	134.1	62.56	647	0.0	95.8	807	200	5.4
III B-28	136.9	61.70	646	0.0	98.0	844	210	5.7
III B-29	113.4	31.28	566	0.0	77.4	282	2800	2.9
III B-30	112.0	31.36	550	0.0	77.4	362	1500	2.6
III B-31	137.9	32.46	593	0.0	93.3	410	285	5.8
III B-32	139.9	31.59	566	0.0	94.8	524	285	6.0
III C- 1	115.6	47.00	593	11.8	66.7	320	240	3.1
III C- 2	116.9	48.96	583	21.2	68.0	465	310	3.3
III C- 3	115.0	49.04	618	22.2	66.7	366	0	3.0
III C- 4	116.1	48.49	592	11.1	67.0	411	660	3.2
III C- 5	102.1	47.47	579	7.1	78.7	323	3050	0.6
III C- 6	116.0	62.17	623	9.9	97.0	655	900	3.2
III D- 1	97.2	48.10	587	0.0	97.2	377	12000	0.0
III D- 2	88.9	51.72	575	0.0	88.9	203	47000	0.0

TABLE 6.4

NATURAL GAS TESTS (SERIES IV A)

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 %
IV A- 1	114.3	55.41	655	0.0	114.3	322	150	2.9
IV A- 2	137.1	56.98	658	0.0	137.1	320	103	5.8
IV A- 3	102.8	55.80	689	0.0	102.8	267	113	0.6
IV A- 4	115.0	67.91	703	0.0	115.0	308	70	3.0
IV A- 5	138.0	67.67	709	0.0	138.0	310	53	5.9
IV A- 6	103.1	68.06	700	0.0	103.1	249	810	0.7
IV A- 7	113.7	37.10	664	0.0	113.7	303	40	2.8
IV A- 8	138.0	37.02	673	0.0	138.0	311	40	5.9
IV A- 9	102.7	37.18	665	0.0	102.7	245	690	0.6
IV A- 10	113.7	51.72	351	0.0	113.7	148	40	2.8
IV A- 11	135.3	52.19	358	0.0	135.3	135	40	5.6
IV A- 12	103.1	52.58	345	0.0	103.1	123	1070	0.7
IV A- 13	113.7	64.45	345	0.0	113.7	144	35	2.8
IV A- 14	135.3	64.29	346	0.0	135.3	127	50	5.6
IV A- 15	103.1	65.39	344	0.0	103.1	124	1020	0.7
IV A- 16	113.7	33.32	360	0.0	113.7	156	23	2.8
IV A- 17	104.0	32.77	333	0.0	104.0	109	960	0.9
IV A- 18	135.3	35.13	326	0.0	135.3	139	15	5.6
IV A- 19	115.7	57.37	684	27.1	115.7	44	7	3.1
IV A- 20	115.6	56.75	686	14.5	115.6	74	22	3.1
IV A- 21	137.1	58.08	691	24.7	137.1	47	22	5.8
IV A- 22	103.7	57.37	679	33.1	103.7	60	200	0.8
IV A- 23	103.3	57.14	676	26.4	103.3	33	133	0.7
IV A- 24	114.3	71.91	686	27.4	114.3	54	22	2.9
IV A- 25	102.7	36.55	644	30.5	102.7	24	480	0.6
IV A- 26	115.7	56.27	691	0.0	115.7	346	0	3.1
IV A- 27	115.0	54.23	662	0.0	87.0	256	0	3.0
IV A- 28	113.1	56.90	660	27.4	85.7	23	3	2.7
IV A- 29	114.4	53.92	649	26.1	86.1	178	7	2.9
IV A- 30	116.3	52.58	698	0.0	61.4	90	40	3.2
IV A- 31	117.0	51.72	663	23.1	60.4	53	8	3.3
IV A- 32	114.4	54.47	685	0.0	85.0	310	0	2.9
IV A- 33	115.0	55.65	660	26.0	86.5	28	0	3.0
IV A- 34	115.0	53.60	664	26.6	87.1	220	0	3.0
IV A- 35	103.6	37.80	712	0.0	52.6	120	760	0.8
IV A- 36	104.2	51.24	661	23.2	66.4	70	323	0.9
IV A- 37	137.1	69.79	696	0.0	137.1	330	0	5.8
IV A- 38	135.3	66.88	711	0.0	87.2	269	0	5.6
IV A- 39	137.1	65.76	688	18.1	87.6	198	0	5.8
IV A- 40	115.7	56.27	688	0.0	115.7	365	0	3.1
IV A- 41	99.4	63.27	688	0.0	99.4	251	10500	0.4
IV A- 42	84.9	73.01	688	0.0	84.9	128	64038	0.0
IV A- 43	76.4	68.77	688	0.0	76.4	53	151622	0.0
IV A- 44	113.1	55.88	653	0.0	113.1	332	22	2.7
IV A- 45	111.9	56.43	655	0.0	111.9	235	15	2.5
IV A- 46	103.1	55.88	659	0.0	103.1	194	675	0.7
IV A- 47	103.7	55.80	691	0.0	103.7	278	460	0.8
IV A- 48	137.1	56.43	659	0.0	137.1	314	15	5.8
IV A- 49	136.2	56.75	700	0.0	136.2	283	15	5.7

TABLE 6.5

OIL TESTS (SERIES IV B)

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 %
IV B- 1	113.1	53.37	693	0.0	113.1	257	25	2.7
IV B- 2	115.0	52.50	697	0.0	115.0	274	22	3.0
IV B- 3	115.0	52.50	691	0.0	115.0	300	15	3.0
IV B- 4	103.2	52.34	688	0.0	103.2	238	260	0.7
IV B- 5	103.8	52.11	686	0.0	103.8	210	90	0.8
IV B- 6	131.8	54.54	696	0.0	131.8	289	15	5.8
IV B- 7	131.8	54.54	701	0.0	131.8	343	10	5.8
IV B- 8	115.0	51.79	691	0.0	115.0	253	60	3.0
IV B- 9	130.8	54.54	696	0.0	130.8	284	40	5.7
IV B- 10	103.6	51.24	688	0.0	103.6	200	600	0.8
IV B- 11	115.0	64.37	699	0.0	115.0	279	60	3.0
IV B- 12	126.9	68.69	704	0.0	126.9	319	60	5.3
IV B- 13	102.8	63.50	696	0.0	102.8	222	320	0.6
IV B- 14	113.7	33.32	668	0.0	113.7	212	60	2.8
IV B- 15	129.8	35.84	674	0.0	129.8	245	40	5.6
IV B- 16	103.7	32.15	675	0.0	103.7	173	543	0.8
IV B- 17	115.6	47.86	386	0.0	115.6	219	50	3.1
IV B- 18	128.8	51.01	384	0.0	128.8	253	55	5.5
IV B- 19	104.1	47.94	333	0.0	104.1	174	500	0.9
IV B- 20	113.7	30.73	312	0.0	113.7	181	70	2.8
IV B- 21	130.8	30.97	306	0.0	130.8	218	60	5.7
IV B- 22	113.1	58.79	296	0.0	113.1	220	70	2.7
IV B- 23	103.3	58.32	301	0.0	103.3	182	178	0.7
IV B- 24	127.9	61.38	299	0.0	127.9	263	80	5.4
IV B- 25	115.6	51.40	698	0.0	115.6	260	50	3.1
IV B- 26	116.3	52.74	680	25.9	116.3	244	45	3.2
IV B- 27	117.0	51.64	686	14.6	117.0	235	45	3.3
IV B- 28	129.8	55.88	693	23.8	129.8	256	45	5.6
IV B- 29	104.2	51.56	679	14.5	104.2	193	90	0.9
IV B- 30	104.2	52.19	678	26.5	104.2	174	140	0.9
IV B- 31	115.0	65.31	695	14.4	115.0	252	60	3.0
IV B- 32	115.0	64.05	701	0.0	115.0	282	50	3.0
IV B- 33	114.3	33.40	669	0.0	114.3	214	50	2.9
IV B- 34	104.7	32.62	644	20.2	104.7	152	140	1.0
IV B- 35	115.6	51.32	692	0.0	115.6	255	50	3.1
IV B- 36	116.3	48.89	691	0.0	86.0	224	50	3.2
IV B- 37	114.3	50.06	670	14.7	84.4	203	45	2.9
IV B- 38	115.6	50.46	659	31.3	85.4	205	55	3.1
IV B- 39	115.0	48.34	700	0.0	70.3	175	55	3.0
IV B- 40	116.3	48.41	681	14.2	71.0	172	60	3.2
IV B- 41	114.3	51.79	700	0.0	114.3	262	80	2.9
IV B- 42	113.7	49.99	675	0.0	85.3	241	60	2.8
IV B- 43	113.7	49.04	651	14.5	84.0	213	210	2.8
IV B- 44	113.7	50.22	669	14.1	85.1	213	80	2.8
IV B- 45	115.6	48.26	666	13.7	86.5	198	80	3.1
IV B- 46	103.7	50.69	690	0.0	103.7	204	335	0.8
IV B- 47	103.6	47.94	690	0.0	65.9	145	660	0.8
IV B- 48	127.8	67.36	703	0.0	127.8	327	115	5.4
IV B- 49	127.8	62.72	710	0.0	77.0	235	125	5.4
IV B- 50	127.8	62.25	688	14.8	76.8	215	127	5.4

TABLE 6.6

SWIRL TESTS (SERIES V - A IS FOR NATURAL GAS AND B IS FOR 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 %
V A - 1	113.7	55.17	693	0.0	113.7	330	60	2.8
V A - 2	114.3	67.91	701	0.0	114.3	329	80	2.9
V A - 3	113.1	35.21	675	0.0	113.1	283	75	2.7
V A - 4	113.7	34.97	670	0.0	113.7	261	70	2.8
V A - 5	103.2	34.50	663	0.0	103.2	212	335	0.7
V A - 6	135.2	36.00	680	0.0	135.2	275	70	5.6
V A - 7	113.7	54.47	693	0.0	113.7	269	6	2.8
V A - 8	102.6	41.97	685	0.0	102.6	230	810	0.6
V A - 9	136.2	55.65	699	0.0	136.2	265	70	5.7
V A - 10	113.7	67.83	704	0.0	113.7	270	75	2.8
V A - 11	102.8	68.14	698	0.0	102.8	239	360	0.6
V A - 12	135.2	68.46	705	0.0	135.2	245	90	5.6
V B - 13	115.5	60.52	632	0.0	90.4	658	530	3.1
V B - 14	115.6	60.60	628	0.0	90.7	649	75	3.1
V B - 15	115.5	63.74	640	11.2	115.5	717	2500	3.2
V B - 16	116.1	62.72	632	0.0	116.1	791	850	3.2
V B - 17	134.1	63.74	645	0.0	134.1	971	200	5.4
V B - 18	115.3	50.93	613	0.0	115.3	750	1050	3.1
V B - 19	133.1	54.94	629	0.0	133.1	934	285	5.3
V B - 20	103.6	51.40	607	0.0	103.6	556	2700	0.9

TABLE 6.7

QUENCH TESTS FOR COAL (SERIES VI)

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 %
VI - 1	114.9	51.24	623	0.0	114.9	707	285	3.0
VI - 2	115.4	49.36	609	0.0	89.7	555	810	3.1
VI - 3	115.4	49.51	607	0.0	88.7	571	660	3.1
VI - 4	116.9	51.09	616	9.3	116.9	603	500	3.3
VI - 5	130.4	56.27	639	0.0	130.4	829	420	5.0
VI - 6	106.1	48.10	607	0.0	106.1	545	2225	1.4
VI - 7	117.5	62.25	634	0.0	117.5	766	750	3.4
VI - 8	132.0	62.80	655	0.0	132.0	899	720	5.2

TABLE 6.8

SUMMARY OF SERIES II --- F. G. R. FOR COAL

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	117.8	13.5	637	113.5	----	1.8	PRI.
A 1/ 3	116.3	13.6	639	113.6	----	3.2	PRI.
A 4/ 5	121.6	32.7	650	132.7	----	1.3	PRI.
A 6/ 7	113.4	2.7	616	102.7	----	2.0	PRI.
A 10/ 11	140.7	38.4	668	138.4	----	1.2	PRI.
A 12/ 13	142.0	14.0	654	114.0	----	1.5	PRI.
A 14/ 15	134.9	3.4	641	103.4	----	1.9	PRI.
A 16/ 17	73.1	13.7	564	113.7	----	3.0	PRI.
A 18/ 19	73.8	33.2	589	133.2	----	2.8	PRI.
A 20/ 21	65.1	3.5	531	103.5	----	4.3	PRI.
A 22/ 23	141.1	12.8	525	112.8	----	1.6	PRI.
A 24/ 25	140.2	35.5	534	135.5	----	1.2	PRI.
A 26/ 27	130.5	1.6	512	101.6	----	1.8	PRI.
A 28/ 29	114.9	12.2	512	112.2	----	1.9	PRI.
A 30/ 31	72.5	14.3	471	114.3	----	2.4	PRI.
A 32/ 33	116.0	11.7	399	111.7	----	1.9	PRI.
A 34/ 35	120.7	30.5	404	130.5	----	1.5	PRI.
A 36/ 37	146.0	33.6	402	133.6	----	1.4	PRI.
B 1/ 2	143.5	15.8	629	115.8	----	12.1	SEC.
B 3/ 4	65.1	19.1	562	119.1	----	21.0	SEC.
B 5/ 6	75.9	40.9	587	140.9	----	17.5	SEC.
B 7/ 8	65.5	7.4	539	107.4	----	21.4	SEC.
B 13/ 14	115.8	17.3	623	117.3	----	30.9	SEC.
B 15/ 16	121.8	39.5	643	139.5	----	18.4	SEC.
B 17/ 18	112.7	4.3	598	104.3	----	31.5	SEC.
B 19/ 20	70.4	17.2	565	117.2	----	34.0	SEC.
B 21/ 22	70.0	42.5	589	142.5	----	22.8	SEC.
B 23/ 24	65.1	4.7	526	104.7	----	41.1	SEC.
B 25/ 26	135.0	34.4	651	134.4	----	20.4	SEC.

TABLE 6.9

SUMMARY OF SERIES II --- F. G. R. FOR COAL

FINAL REDUCTIONS (PART 2)

ORIGINAL TEST NOS.	NO (PPM): BASE VALUE	WITH CHANGES	REDUCTION	REDUCTION IN NO, %
A 1/ 2	774 ± 11	694 ± 4	80 ± 12	10.3 ± 1.5
A 1/ 3	774 ± 11	659 ± 0	115 ± 11	14.9 ± 1.4
A 4/ 5	858 ± 70	898 ± 53	0 ± 88	0.0 ± 9.8
A 6/ 7	449 ± 2	472 ± 30	-23 ± 30	-5.1 ± 6.7
A 10/ 11	980 ± 5	969 ± 12	11 ± 13	1.1 ± 1.3
A 12/ 13	762 ± 25	794 ± 107	-32 ± 110	-4.2 ± 14.4
A 14/ 15	571 ± 13	552 ± 20	19 ± 24	3.3 ± 4.2
A 16/ 17	470 ± 34	494 ± 30	-24 ± 45	-5.1 ± 9.7
A 18/ 19	658 ± 11	699 ± 6	-41 ± 13	-6.2 ± 1.9
A 20/ 21	246 ± 24	251 ± 20	-5 ± 31	-2.0 ± 12.7
A 22/ 23	654 ± 49	635 ± 41	19 ± 64	2.9 ± 9.8
A 24/ 25	913 ± 91	868 ± 96	45 ± 132	4.9 ± 14.5
A 26/ 27	444 ± 8	387 ± 49	57 ± 50	12.8 ± 11.2
A 28/ 29	667 ± 69	630 ± 52	37 ± 86	5.5 ± 13.0
A 30/ 31	452 ± 30	501 ± 35	-49 ± 46	-10.8 ± 10.2
A 32/ 33	613 ± 129	622 ± 55	-9 ± 140	-1.5 ± 22.9
A 34/ 35	706 ± 245	734 ± 172	-28 ± 299	-4.0 ± 42.4
A 36/ 37	910 ± 120	791 ± 57	119 ± 133	13.1 ± 14.7
B 1/ 2	828 ± 80	708 ± 68	120 ± 105	14.5 ± 12.8
B 3/ 4	499 ± 28	416 ± 13	83 ± 31	16.6 ± 6.3
B 5/ 6	722 ± 46	532 ± 59	190 ± 75	26.3 ± 10.5
B 7/ 8	333 ± 25	258 ± 18	75 ± 31	22.5 ± 9.4
B 13/ 14	833 ± 18	548 ± 12	285 ± 22	34.2 ± 2.7
B 15/ 16	1048 ± 13	797 ± 16	251 ± 21	24.0 ± 2.0
B 17/ 18	552 ± 4	372 ± 2	180 ± 4	32.6 ± 0.8
B 19/ 20	576 ± 10	392 ± 6	184 ± 12	31.9 ± 2.1
B 21/ 22	810 ± 30	596 ± 20	214 ± 36	26.4 ± 4.6
B 23/ 24	320 ± 2	242 ± 1	78 ± 2	24.4 ± 0.7
B 25/ 26	1013 ± 13	814 ± 9	199 ± 16	19.6 ± 1.6

TABLE 6.10

SUMMARY OF SERIES III --- STAGED COMBUSTION

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 8/ B 1	115.7	15.0	608	91.3	SIDE	0.0	----
A 8/ B 2	115.9	15.0	607	68.2	SIDE	0.0	----
A 8/ B 3	114.0	17.1	617	54.8	SIDE	0.0	----
A 8/ B 4	114.6	15.7	612	93.0	FRONT	0.0	----
A 8/ B 5	116.1	15.0	624	68.0	FRONT	0.0	----
A 8/ B 6	116.9	14.2	627	52.4	FRONT	0.0	----
A 9/ B 7	114.9	15.8	618	65.9	SIDE	0.0	----
A 9/ B 8	117.4	15.8	615	54.2	SIDE	0.0	----
A 9/ B 9	116.8	15.8	613	67.8	SIDE	0.0	----
A10/ B10	114.8	16.1	607	90.9	FRONT	0.0	----
A10/ B11	114.8	16.5	619	67.2	FRONT	0.0	----
A10/ B12	114.2	17.5	625	54.3	FRONT	0.0	----
A11/ B13	118.4	14.9	615	66.7	FRONT	0.0	----
A11/ B14	118.5	15.6	629	46.3	FRONT	0.0	----
A12/ B15	113.8	2.9	586	79.1	FRONT	0.0	----
A12/ B16	113.9	3.3	600	56.7	FRONT	0.0	----
A13/ B17	115.1	3.7	584	80.5	SIDE	0.0	----
A14/ B18	146.1	15.3	622	90.7	FRONT	0.0	----
A14/ B19	147.1	15.0	637	69.1	FRONT	0.0	----
A14/ B20	145.5	15.9	632	91.3	SIDE	0.0	----
A15/ B21	146.3	3.5	620	80.4	FRONT	0.0	----
A15/ B22	145.4	3.9	627	57.3	FRONT	0.0	----
A15/ B23	144.0	5.0	614	82.7	SIDE	0.0	----
A16/ B24	112.8	37.0	630	92.1	FRONT	0.0	----
A16/ B25	112.2	37.4	628	93.1	SIDE	0.0	----
A17/ B26	118.8	14.2	612	90.4	FRONT	0.0	----
A18/ B27	144.2	35.0	646	95.8	FRONT	0.0	----
A18/ B28	143.0	36.4	645	98.0	SIDE	0.0	----
A19/ B29	73.2	15.5	577	77.4	FRONT	0.0	----
A19/ B30	73.6	14.8	559	77.4	SIDE	0.0	----
A20/ B31	77.0	36.9	589	93.3	FRONT	0.0	----
A20/ B32	76.4	37.9	586	94.8	SIDE	0.0	----
A 8/ C 1	115.9	14.6	601	66.7	FRONT	11.8	PORTS
A 9/ C 2	116.6	16.2	595	68.0	SIDE	21.2	BURNER
A 9/ C 3	116.2	15.3	612	66.7	FRONT	22.2	BURNER
A11/ C 4	117.7	15.8	603	67.0	SIDE	11.1	PORTS
A12/ C 5	114.5	2.6	582	78.7	FRONT	7.1	PORTS
A14/ C 6	146.1	15.3	625	97.0	FRONT	9.9	PORTS
A17/ D 1	115.4	5.4	604	105.4	----	0.0	----
A17/ D 2	120.2	1.3	598	101.2	----	0.0	----

TABLE 6.11

SUMMARY OF SERIES III --- STAGED COMBUSTION

FINAL REDUCTIONS (PART 2)

ORIGINAL TEST NOS.	NO (PPM) BASE VALUE	NO (PPM) WITH CHANGES	NO (PPM) REDUCTION	REDUCTION IN NO, %
A 8/ B 1	830 ± 10	677 ± 8	153 ± 13	18.4 ± 1.6
A 8/ B 2	830 ± 10	488 ± 9	342 ± 13	41.2 ± 1.7
A 8/ B 3	830 ± 10	505 ± 9	325 ± 13	39.2 ± 1.7
A 8/ B 4	830 ± 10	711 ± 0	119 ± 10	14.3 ± 1.2
A 8/ B 5	830 ± 10	343 ± 11	487 ± 15	58.7 ± 1.9
A 8/ B 6	830 ± 10	295 ± 9	535 ± 13	64.5 ± 1.8
A 9/ B 7	797 ± 18	467 ± 6	330 ± 19	41.4 ± 2.6
A 9/ B 8	797 ± 18	359 ± 2	438 ± 18	55.0 ± 2.6
A 9/ B 9	797 ± 18	432 ± 0	365 ± 18	45.8 ± 2.5
A10/ B10	869 ± 14	733 ± 14	136 ± 20	15.7 ± 2.3
A10/ B11	869 ± 14	385 ± 2	484 ± 14	55.7 ± 1.9
A10/ B12	869 ± 14	350 ± 2	519 ± 14	59.7 ± 1.9
A11/ B13	765 ± 7	374 ± 9	391 ± 11	51.1 ± 1.6
A11/ B14	765 ± 7	389 ± 2	376 ± 7	49.2 ± 1.1
A12/ B15	534 ± 6	399 ± 18	135 ± 19	25.3 ± 3.6
A12/ B16	534 ± 6	283 ± 8	251 ± 10	47.0 ± 1.9
A13/ B17	641 ± 22	371 ± 11	270 ± 25	42.1 ± 4.1
A14/ B18	885 ± 15	693 ± 18	192 ± 23	21.7 ± 2.7
A14/ B19	885 ± 15	409 ± 11	476 ± 19	53.8 ± 2.3
A14/ B20	885 ± 15	656 ± 1	229 ± 15	25.9 ± 1.8
A15/ B21	591 ± 4	524 ± 10	67 ± 11	11.3 ± 1.8
A15/ B22	591 ± 4	334 ± 5	257 ± 6	43.5 ± 1.1
A15/ B23	591 ± 4	469 ± 6	122 ± 7	20.6 ± 1.2
A16/ B24	942 ± 0	689 ± 28	253 ± 28	26.9 ± 3.0
A16/ B25	942 ± 0	685 ± 24	257 ± 24	27.3 ± 2.5
A17/ B26	739 ± 3	674 ± 7	65 ± 8	8.8 ± 1.0
A18/ B27	1001 ± 17	807 ± 16	194 ± 23	19.4 ± 2.4
A18/ B28	1001 ± 17	844 ± 12	157 ± 21	15.7 ± 2.1
A19/ B29	605 ± 3	282 ± 9	323 ± 9	53.4 ± 1.6
A19/ B30	605 ± 3	362 ± 9	243 ± 9	40.2 ± 1.6
A20/ B31	770 ± 1	410 ± 2	360 ± 2	46.8 ± 0.3
A20/ B32	770 ± 1	524 ± 2	246 ± 2	31.9 ± 0.3
A 8/ C 1	830 ± 10	320 ± 13	510 ± 16	61.4 ± 2.1
A 9/ C 2	797 ± 18	465 ± 2	332 ± 18	41.7 ± 2.5
A 9/ C 3	797 ± 18	366 ± 23	431 ± 29	54.1 ± 3.9
A11/ C 4	765 ± 7	411 ± 16	354 ± 17	46.3 ± 2.3
A12/ C 5	534 ± 6	323 ± 2	211 ± 6	39.5 ± 1.3
A14/ C 6	885 ± 15	655 ± 15	230 ± 21	26.0 ± 2.4
A17/ D 1	739 ± 3	377 ± 7	362 ± 8	49.0 ± 1.0
A17/ D 2	739 ± 3	203 ± 10	536 ± 10	72.5 ± 1.4

TABLE 6.12

SUMMARY OF SERIES IVA --- NATURAL GAS

FINAL REDUCTIONS (PART 1)

ORIGINAL TEST NOS.	AVERAGES FOR TESTS: LOAD, %	AVERAGES FOR TESTS: EXCESS AIR, %	AVERAGES FOR TESTS: TEMP. DEG F	BURNER AIR, %	SIDE OR FRONT SLOTS	FLUE GAS RECYC. %	BURNER OR PORTS
IVA 1/19	124.9	15.0	689	115.0	----	27.1	BURNER
IVA 1/20	125.0	14.9	690	114.9	----	14.5	BURNER
IVA 2/21	124.5	37.1	694	137.1	----	24.7	BURNER
IVA 3/22	126.8	3.2	684	103.2	----	33.1	BURNER
IVA 3/23	127.1	3.0	682	103.0	----	26.4	BURNER
IVA 4/24	154.8	14.6	694	114.6	----	27.4	BURNER
IVA 9/25	83.2	2.7	654	102.7	----	30.5	BURNER
IVA26/27	126.6	15.3	676	87.0	FRONT	0.0	----
IVA26/28	127.8	14.4	675	85.7	FRONT	27.4	BURNER
IVA26/29	127.1	15.0	670	86.1	FRONT	26.1	PORTS
IVA26/30	126.4	16.0	694	61.4	FRONT	0.0	----
IVA26/31	126.3	16.3	677	60.4	FRONT	23.1	PORTS
IVA26/32	126.9	15.0	688	85.0	SIDE	0.0	----
IVA26/33	126.5	15.3	675	86.5	SIDE	26.0	BURNER
IVA26/34	126.5	15.3	677	87.1	SIDE	26.6	PORTS
IVA 9/35	88.3	3.1	688	52.6	FRONT	0.0	----
IVA 3/36	125.5	3.5	675	66.4	FRONT	23.2	PORTS
IVA37/38	154.3	36.2	703	87.2	FRONT	0.0	----
IVA37/39	153.8	37.1	692	87.6	FRONT	18.1	PORTS

TABLE 6.13

SUMMARY OF SERIES IVA --- NATURAL GAS

FINAL REDUCTIONS (PART 2)

ORIGINAL TEST NOS.	NO (PPM): BASE VALUE	NO (PPM): WITH CHANGES	NO (PPM): REDUCTION	REDUCTION IN NO, %
IVA 1/19	322 ± 5	44 ± 2	278 ± 5	86.3 ± 2.1
IVA 1/20	322 ± 5	74 ± 7	248 ± 9	77.0 ± 2.9
IVA 2/21	320 ± 4	47 ± 7	273 ± 8	85.3 ± 2.7
IVA 3/22	267 ± 3	60 ± 5	207 ± 6	77.5 ± 2.4
IVA 3/23	267 ± 3	33 ± 4	234 ± 5	87.6 ± 2.1
IVA 4/24	308 ± 0	54 ± 16	254 ± 16	82.5 ± 5.2
IVA 9/25	245 ± 0	24 ± 4	221 ± 4	90.2 ± 1.6
IVA26/27	346 ± 6	256 ± 5	90 ± 8	26.0 ± 2.3
IVA26/28	346 ± 6	23 ± 2	323 ± 6	93.4 ± 2.4
IVA26/29	346 ± 6	178 ± 3	168 ± 7	48.6 ± 2.1
IVA26/30	346 ± 6	90 ± 0	256 ± 6	74.0 ± 2.2
IVA26/31	346 ± 6	53 ± 0	293 ± 6	84.7 ± 2.3
IVA26/32	346 ± 6	310 ± 0	36 ± 6	10.4 ± 1.7
IVA26/33	346 ± 6	28 ± 1	318 ± 6	91.9 ± 2.4
IVA26/34	346 ± 6	220 ± 7	126 ± 9	36.4 ± 2.7
IVA 9/35	245 ± 0	120 ± 10	125 ± 10	51.0 ± 4.1
IVA 3/36	267 ± 3	70 ± 3	197 ± 4	73.8 ± 1.8
IVA37/38	330 ± 7	269 ± 2	61 ± 7	18.5 ± 2.2
IVA37/39	330 ± 7	198 ± 1	132 ± 7	40.0 ± 2.3

TABLE 6.14

SUMMARY OF SERIES IVB --- #6 RESID. FUEL OIL

FINAL REDUCTIONS (PART 1)

ORIGINAL TEST NOS.	AVERAGES FOR TESTS: LOAD, %	AVERAGES FOR TESTS: EXCESS AIR, %	AVERAGES FOR TESTS: TEMP. DEG F	BURNER AIR, %	SIDE OR FRONT SLOTS	FLUE GAS RECYC. %	BURNER OR PORTS
IVB25/26	114.3	15.9	689	115.9	----	25.8	BURNER
IVB25/27	113.8	16.3	692	116.3	----	14.6	BURNER
IVB 6/28	115.0	30.8	694	130.8	----	23.8	BURNER
IVB 5/29	116.2	4.0	682	104.0	----	14.5	BURNER
IVB 5/30	116.1	4.0	682	104.0	----	26.5	BURNER
IVB11/31	143.1	15.0	697	115.0	----	14.4	BURNER
IVB16/34	72.8	4.2	659	104.2	----	20.2	BURNER
IVB35/36	113.6	15.9	691	86.0	FRONT	0.0	----
IVB35/37	114.3	14.9	681	84.4	FRONT	14.7	BURNER
IVB35/38	113.6	15.6	675	85.4	FRONT	31.3	BURNER
IVB35/39	114.1	15.3	696	70.3	FRONT	0.0	----
IVB35/40	113.4	15.9	686	71.0	FRONT	14.2	BURNER
IVB41/42	115.9	14.0	687	85.3	SIDE	0.0	----
IVB41/43	115.6	14.0	675	84.0	SIDE	14.5	PORTS
IVB41/44	115.2	14.0	684	85.1	SIDE	14.1	BURNER
IVB41/45	114.3	14.9	683	86.5	FRONT	13.7	PORTS
IVB46/47	114.0	3.6	690	65.9	FRONT	0.0	----
IVB48/49	147.2	27.8	706	77.0	FRONT	0.0	----
IVB48/50	147.4	27.8	695	76.8	FRONT	14.8	PORTS

TABLE 6.15

SUMMARY OF SERIES IVB --- #6 RESID. FUEL OIL

FINAL REDUCTIONS (PART 2)

ORIGINAL TEST NOS.	NO (PPM): BASE VALUE	NO (PPM): WITH CHANGES	NO (PPM): REDUCTION	REDUCTION IN NO, %
IVB25/26	260 ± 2	244 ± 4	16 ± 4	6.2 ± 1.7
IVB25/27	260 ± 2	235 ± 4	25 ± 4	9.6 ± 1.7
IVB 6/28	289 ± 1	256 ± 6	33 ± 6	11.4 ± 2.1
IVB 5/29	210 ± 2	193 ± 2	17 ± 3	8.1 ± 1.3
IVB 5/30	210 ± 2	174 ± 2	36 ± 3	17.1 ± 1.4
IVB11/31	279 ± 2	252 ± 0	27 ± 2	9.7 ± 0.7
IVB16/34	173 ± 2	152 ± 1	21 ± 2	12.1 ± 1.3
IVB35/36	255 ± 0	224 ± 1	31 ± 1	12.2 ± 0.4
IVB35/37	255 ± 0	203 ± 3	52 ± 3	20.4 ± 1.2
IVB35/38	255 ± 0	204 ± 5	51 ± 5	20.0 ± 2.0
IVB35/39	255 ± 0	175 ± 3	80 ± 3	31.4 ± 1.2
IVB35/40	255 ± 0	172 ± 4	83 ± 4	32.5 ± 1.6
IVB41/42	262 ± 3	241 ± 5	21 ± 6	8.0 ± 2.2
IVB41/43	262 ± 3	213 ± 5	49 ± 6	18.7 ± 2.2
IVB41/44	262 ± 3	213 ± 5	49 ± 6	18.7 ± 2.2
IVB41/45	262 ± 3	198 ± 3	64 ± 4	24.4 ± 1.6
IVB46/47	204 ± 2	145 ± 3	59 ± 4	28.9 ± 1.8
IVB48/49	327 ± 2	235 ± 1	92 ± 2	28.1 ± 0.7
IVB48/50	327 ± 2	215 ± 6	112 ± 6	34.3 ± 1.9

recirculation and/or staged combustion. The series are each 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, °F: The total preheat for the fuel/air input.

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

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

5) Flue Gas Recycled, %: This is the percentage of flue gas recycled back from the stack into the combustion air.

6) Burner or Ports: This is the position for addition of the flue gas. For coal, all flue gas additions of burners are secondary air additions; the only

exception is in Series II, flue gas recirculation, where primary and secondary are differentiated, but are both burner additions.

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 correction methods were tried.

b) With Changes: The test made with NO correction method(s) applied.

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

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

In addition, similar tables, Tables 6.16 to 6.19, have been prepared for the swirl and quench tests.

Table 6.20 is the table showing burner efficiency calculated from combustibles (mostly solid carbon found in ash samples) from a wide sampling of coal tests. The burner efficiency for gas and oil is 100%. The tabular headings are:

1) Test and Series Number - Self explanatory.

2) Firing Data - This is the fuel/air input data:

TABLE 6.16

SUMMARY OF SWIRL TESTS --- SERIES V (GAS)

FINAL REDUCTIONS (PART 1)

ORIGINAL TEST NOS.	AVERAGES FOR TESTS: LOAD, %	AVERAGES FOR TESTS: EXCESS AIR, %	AVERAGES FOR TESTS: TEMP. DEG F	BURNER AIR, %	SIDE OR FRONT SLOTS	FLUE GAS RECYC. %	BURNER OR PORTS
VA 3/ 4	79.3	13.4	672	113.4	------	0.0	------
IVA 9/ 5	82.0	2.9	664	102.9	------	0.0	------
IVA 8/ 6	80.5	36.6	676	136.6	------	0.0	------
VA 1/ 7	123.3	13.7	693	113.7	------	0.0	------
IVA 9/ 8	90.3	2.6	675	102.6	------	0.0	------
IVA 2/ 9	123.5	36.6	698	136.6	------	0.0	------
VA 2/10	152.1	14.0	702	114.0	------	0.0	------
IVA 6/11	154.6	2.9	695	102.9	------	0.0	------
IVA 5/12	149.1	36.6	707	136.6	------	0.0	------

TABLE 6.17

SUMMARY OF SWIRL TESTS --- SERIES V (GAS)

FINAL REDUCTIONS (PART 2)

ORIGINAL TEST NOS.	NO (PPM): BASE VALUE	NO (PPM): WITH CHANGES	NO (PPM): REDUCTION	REDUCTION IN NO, %
VA 3/ 4	283 ± 3	261 ± 3	22 ± 4	7.8 ± 1.5
IVA 9/ 5	245 ± 0	212 ± 4	33 ± 4	13.5 ± 1.6
IVA 8/ 6	311 ± 6	275 ± 3	36 ± 7	11.6 ± 2.2
VA 1/ 7	330 ± 2	269 ± 3	61 ± 4	18.5 ± 1.1
IVA 9/ 8	245 ± 0	230 ± 4	15 ± 4	6.1 ± 1.6
IVA 2/ 9	320 ± 4	265 ± 4	55 ± 6	17.2 ± 1.8
VA 2/10	329 ± 0	270 ± 2	59 ± 2	17.9 ± 0.6
IVA 6/11	249 ± 2	239 ± 1	10 ± 2	4.0 ± 0.9
IVA 5/12	310 ± 1	245 ± 4	65 ± 4	21.0 ± 1.3

TABLE 6.18

SUMMARY OF QUENCH TESTS --- SERIES VI - COAL

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				
IIIA 1/1	116.1	14.9	619	114.9	------	0.0	------
IIIB 1/2	115.1	15.8	607	90.5	------	0.0	------
IIIB10/3	114.8	15.8	604	89.8	------	0.0	------
II B 2/4	129.3	15.9	622	115.9	------	10.7	------
IIIA 2/5	121.8	32.7	637	132.7	------	0.0	------
IIIA13/6	112.5	5.0	602	105.0	------	0.0	------
IIIA14/7	143.8	16.1	631	116.1	------	0.0	------
IIIA18/8	141.0	34.0	650	134.0	------	0.0	------

TABLE 6.19

SUMMARY OF QUENCH TESTS --- SERIES VI - COAL

FINAL REDUCTIONS (PART 2)

ORIGINAL TEST NOS.	NO (PPM)			REDUCTION IN NO, %
	BASE VALUE	WITH CHANGES	REDUCTION	
IIIA 1/1	892 ± 15	707 ± 25	175 ± 29	19.8 ± 3.3
IIIB 1/2	677 ± 8	555 ± 13	122 ± 15	18.0 ± 2.3
IIIB1C/3	733 ± 14	571 ± 1	162 ± 14	22.1 ± 2.0
II B 2/4	708 ± 68	603 ± 8	105 ± 68	14.8 ± 9.8
IIIA 2/5	1051 ± 13	829 ± 4	222 ± 14	21.1 ± 1.3
IIIA13/6	641 ± 22	545 ± 17	96 ± 28	15.0 ± 4.4
IIIA14/7	885 ± 15	766 ± 22	119 ± 27	13.4 ± 3.0
IIIA18/8	1001 ± 17	899 ± 33	102 ± 37	10.2 ± 3.7

TABLE 6.20

CARBON LOSS AND BURNER EFFICIENCY

SERIES AND TEST NUMBER	FIRING DATA: AIR %	FIRING DATA: FLUE HEAT	FIRING DATA: DEG F	WEIGHTS, LB./HR.: FUEL (DRY)	WEIGHTS, LB./HR.: FLUE GAS	ASH IN F.G. %	C IN ASH, %	BURNER EFFIC. IN % BY WT.
I -6	102	50.85	592	469 *****	5284	0.89	54.6	94.5
I -20	104	28.37	366	272	3118	0.35	51.3	97.9
I -26	103	60.75	503	572	6482	1.55	57.3	89.9
I -41	105	43.46	354	419	4780	0.68	52.3	95.9
II A- 6	103	50.38	609	464	5220	0.61	55.8	96.2
II A-14	104	59.65	633	548	6285	0.83	59.5	94.3
II A-26	101	56.92	509	536	6118	0.78	60.6	94.6
II B- 2	115	65.08	629	583 (R)	7262	1.21	64.3	90.3
II B- 4	107	29.00	540	263 (R)	3092	0.32	52.2	98.0
II B-18	104	50.22	595	447 (R)	5111	0.95	56.1	93.9
III A- 1	115	51.56	615	468	5925	0.96	34.5	96.2
III A- 2	135	53.79	635	478	7046	0.58	43.3	95.1
III A- 5	141	66.57	650	586	8939	1.71	39.0	89.8
III A- 6	115	30.26	593	276	3556	0.24	24.4	99.2
III A- 9	116	51.72	607	471	5880	1.01	34.1	95.7
III B- 5	116	48.02	629	464 (S)	5854	0.63	37.7	97.0
III B- 6	115	47.63	644	470 (S)	5864	0.98	60.6	92.6
III B- 8	116	47.86	623	472 (S)	5908	1.04	35.[illegible]	95.4
III B-15	103	47.16	587	450 (S)	5007	0.98	30.7	96.7
III B-16	104	46.06	614	451 (S)	5027	1.24	34.9	95.2
III B-18	116	61.85	617	592 (S)	7203	1.59	34.1	93.5
III B-20	117	61.70	636	577 (S)	7235	1.21	31.1	95.3
III B-21	103	62.17	621	590 (S)	6570	2.42	45.6	87.7
III B-22	104	59.57	635	582 (S)	6589	2.31	49.3	87.1
III B-25	139	47.63	625	448 (S)	6577	1.15	25.8	95.6
III B-28	137	61.70	646	573 (S)	8592	1.13	31.9	94.6
III B-29	113	31.28	586	299 (S)	3777	0.53	36.2	97.6
III B-32	140	31.99	586	301 (S)	4591	1.19	19.8	96.4
III C- 1	116	47.00	593	463 (S-R)	5803	1.02	40.9	93.6
III C- 4	116	48.49	592	475 (S-R)	5907	0.88	24.5	97.[illegible]
III C- 6	116	62.17	623	582 (S-R)	7230	1.39	35.5	93.9
III D- 1	97	49.10	587	447 (SUB)	4766	1.04	51.7	94.[illegible]
III D- 2	[illegible]	51.72	575	486 (SUB)	4779	??	64.7	??

***** - (S) = STAGED COMBUSTION TEST
(R) = FLUE GAS RECIRCULATION TEST
(S-R) = STAGED COMBUSTION TEST WITH FLUE GAS RECIRCULATION
(SUB) = SUBSTOICHIOMETRIC TEST

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 °F.

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

4) Ash in F.G., % - This is the total weight percent of solid ash in the flue gas.

5) C in Ash, % - This is the total weight percent of carbon in the solid ash.

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

Figures 6.1 to 6.4 illustrate the typical major effects observed for coal, oil, and gas. The variables observed are excess air, firing intensity, and preheat. The constant conditions observed in these figures are:

Excess air level - about 15%
Preheat level - about 600°F
Firing rate - about 40,000 BTU/ft^3/hr
(High excess air - about 35%)

Figure 6.5 shows the air addition to the furnace for coal. Between 15% to 20% of the total air added to the furnace is used for coal transport and is primary air. Flue gas recirculation does not change the weight of gas in the primary since an equal weight of air is removed from the primary and added to the secondary. The weight of the secondary always changes with flue

FIGURE 6.2
LOAD

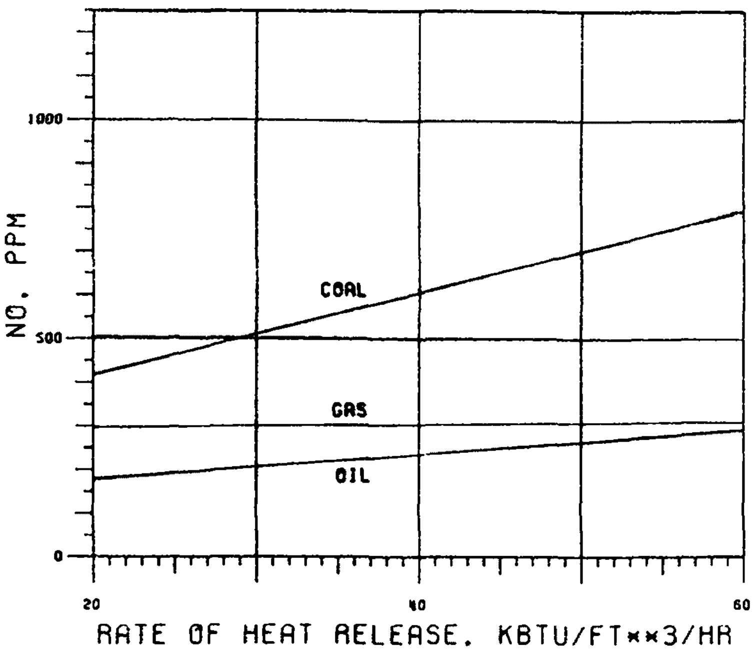


FIGURE 6.4
PREHEAT, HIGH EXCESS AIR

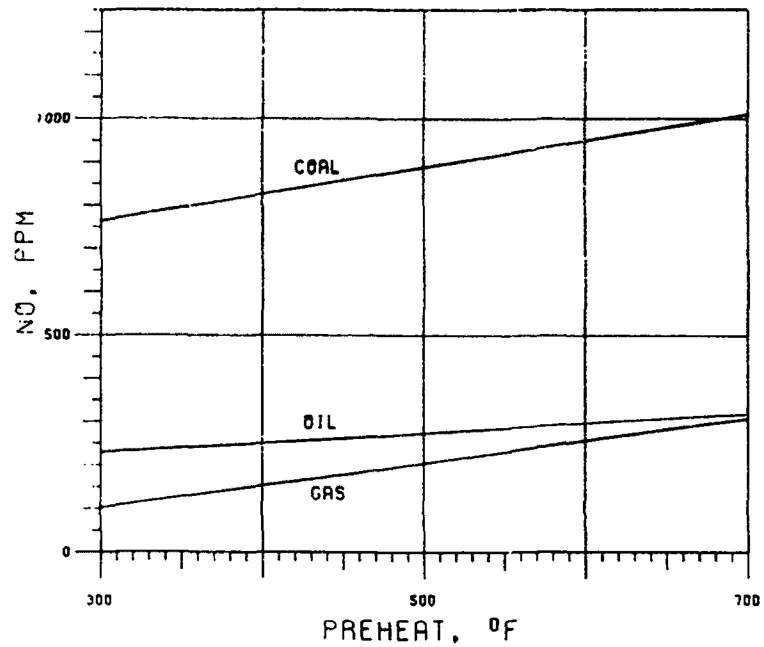


FIGURE 6.1
EXCESS AIR

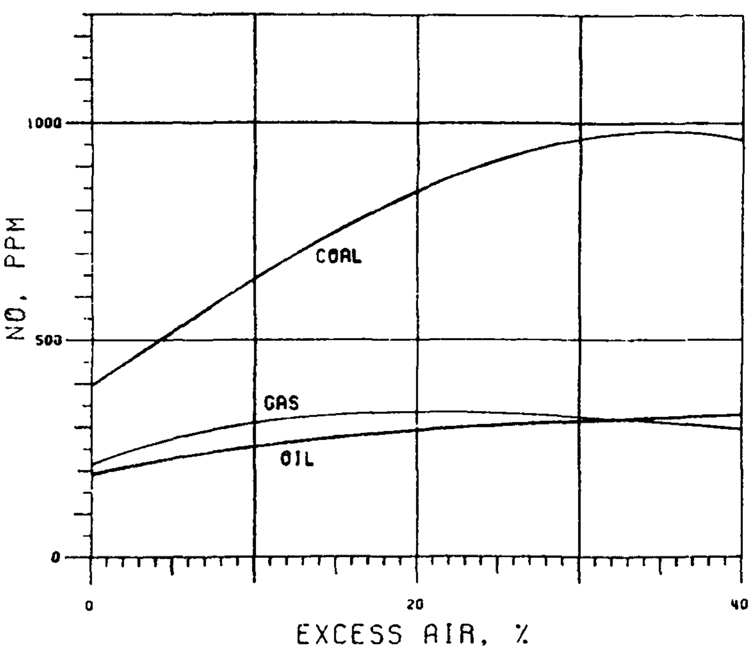


FIGURE 6.3
PREHEAT

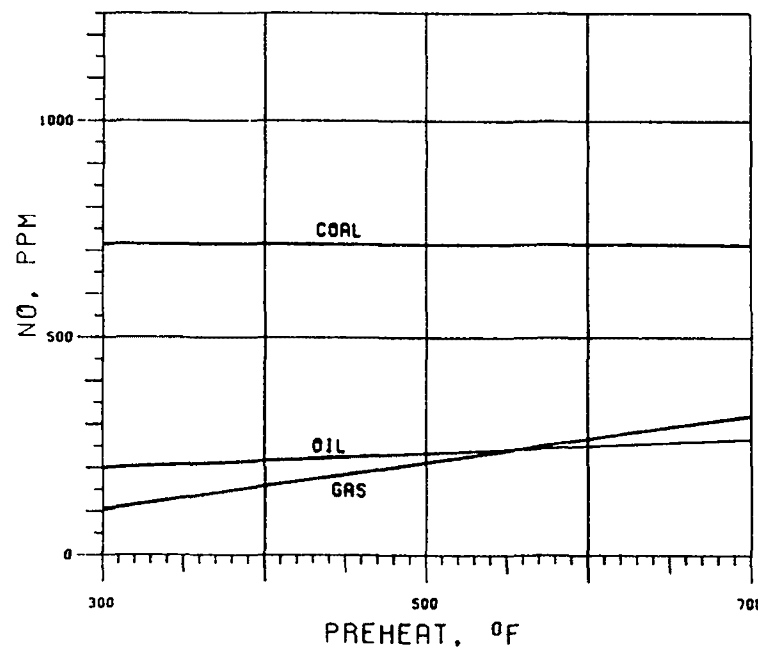
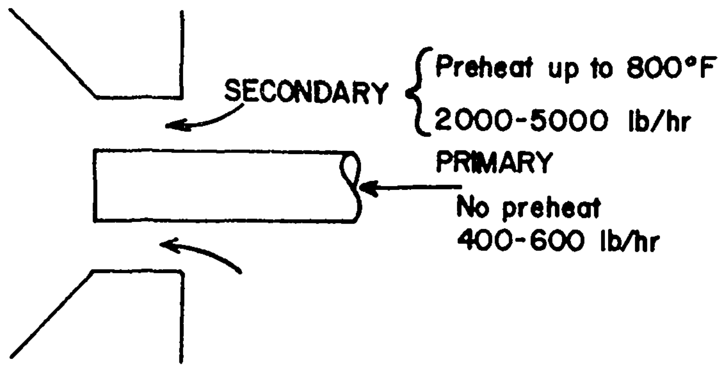


FIGURE 6.5
AIR INPUT WITH COAL



gas recirculation for single stage firing. Figure 6.6 is the result of primary flue gas recirculation for coal. Figure 6.7 is the overall result of flue gas recirculation for all fuels studied.

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, on the other hand, produce a defined second stage addition downstream of the burner area. Figures 6.9 to 6.12 show the result of the staged combustion tests. When flue gas recirculation was used in the ports, it was added to the port air.

Figures 6.13 and 6.14 illustrate the effect of load and stoichiometry on the burner efficiency and carbon loss. Figures 6.15 and 6.16 illustrate the interdependence of load and stoichiometry on carbon loss and burner efficiency.

The final two figures, 6.17 and 6.18, illustrate the effects of swirl for gas and quench for coal.

FIGURE 6.6
PRIMARY FLUE GAS RECIRC.

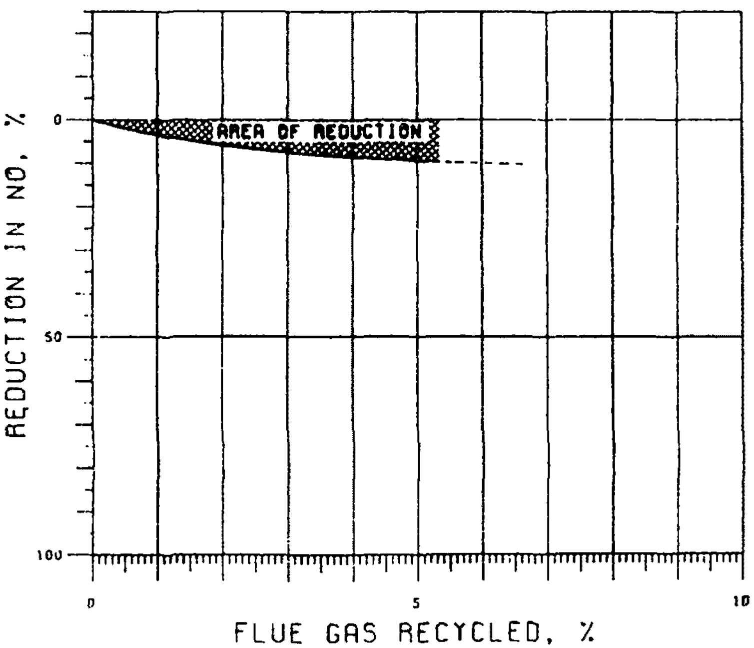


FIGURE 6.7
SECONDARY FLUE GAS REC.

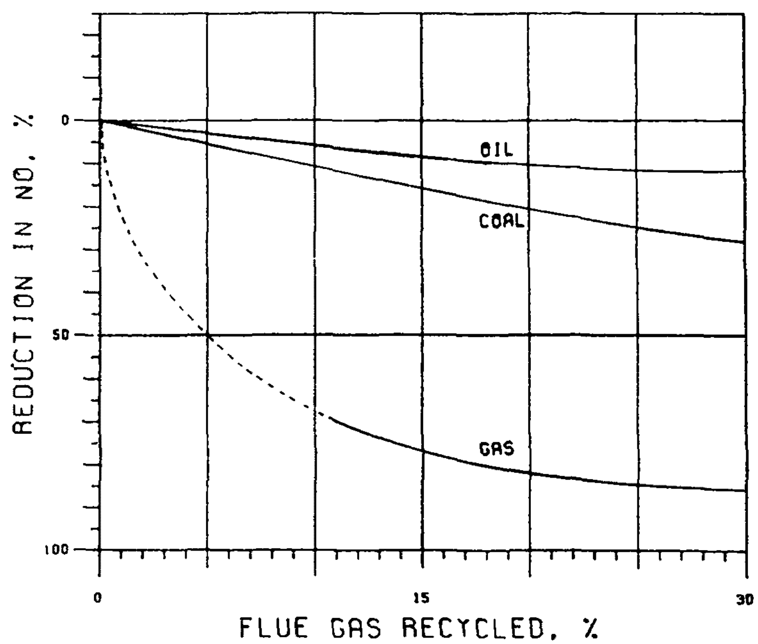


FIGURE 6.8
STAGED COMBUSTION OPTIONS

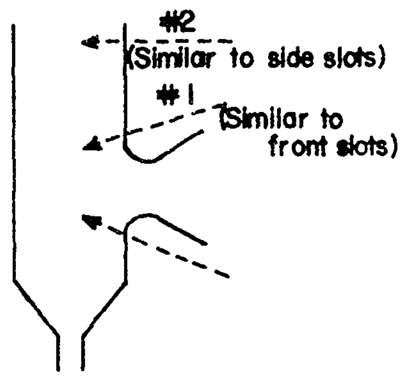


FIGURE 6. 9
COAL, VARIABLE PORT

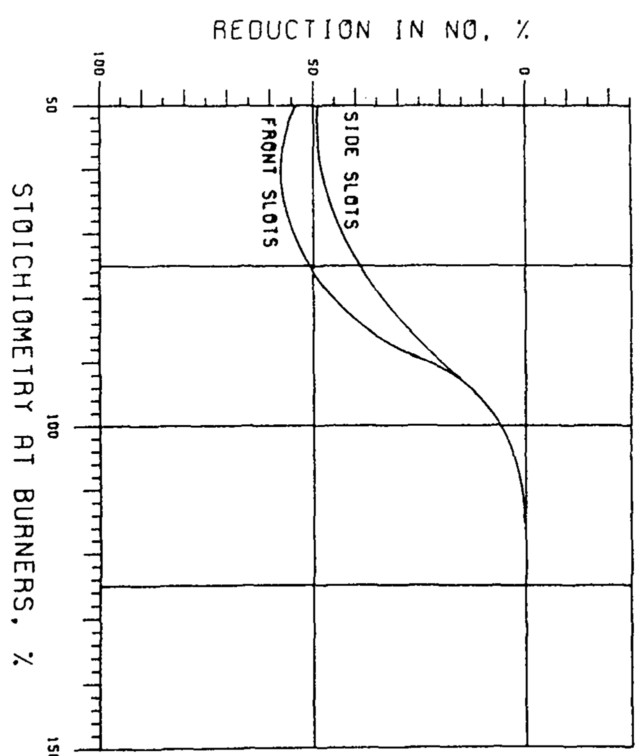


FIGURE 6.10
COAL, STAGED COMBUSTION

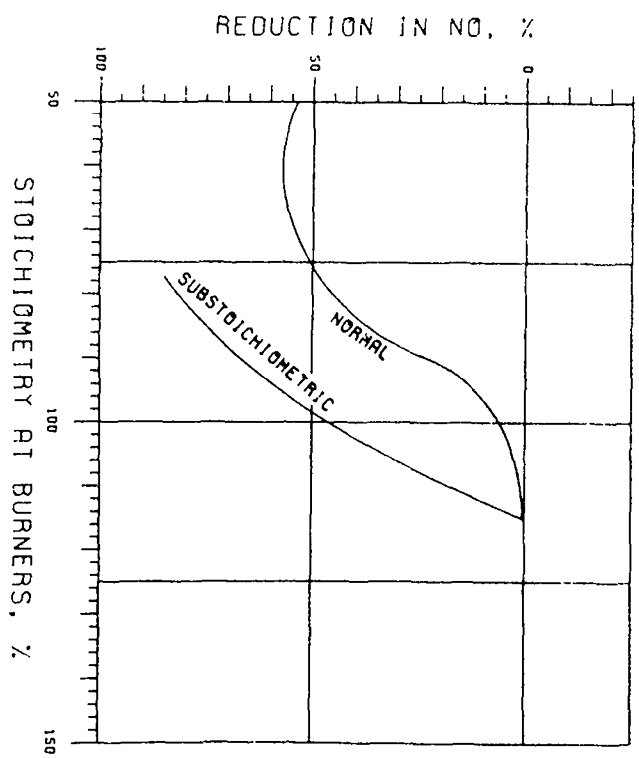


FIGURE 6.12
OIL, STAGED COMBUSTION

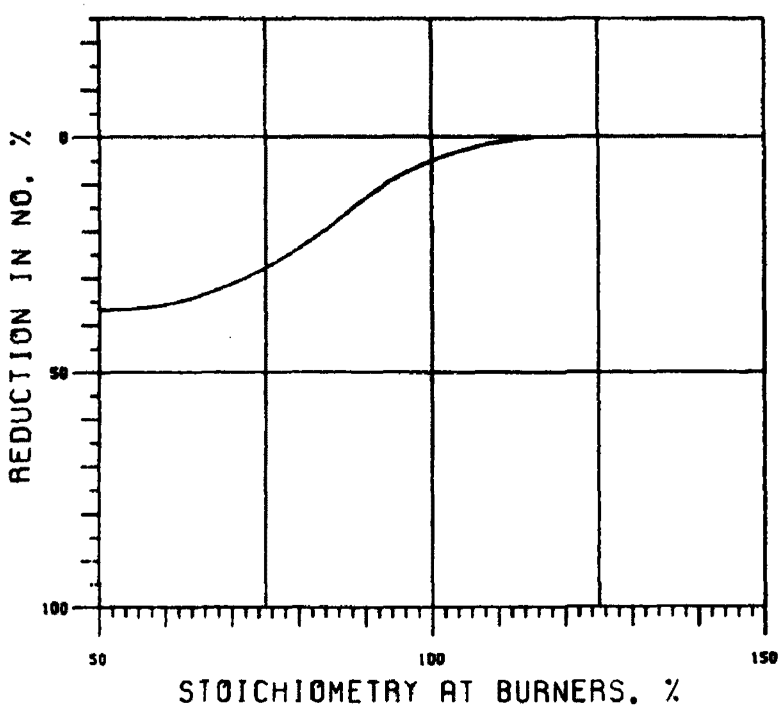


FIGURE 6.14
BURNER EFFICIENCY

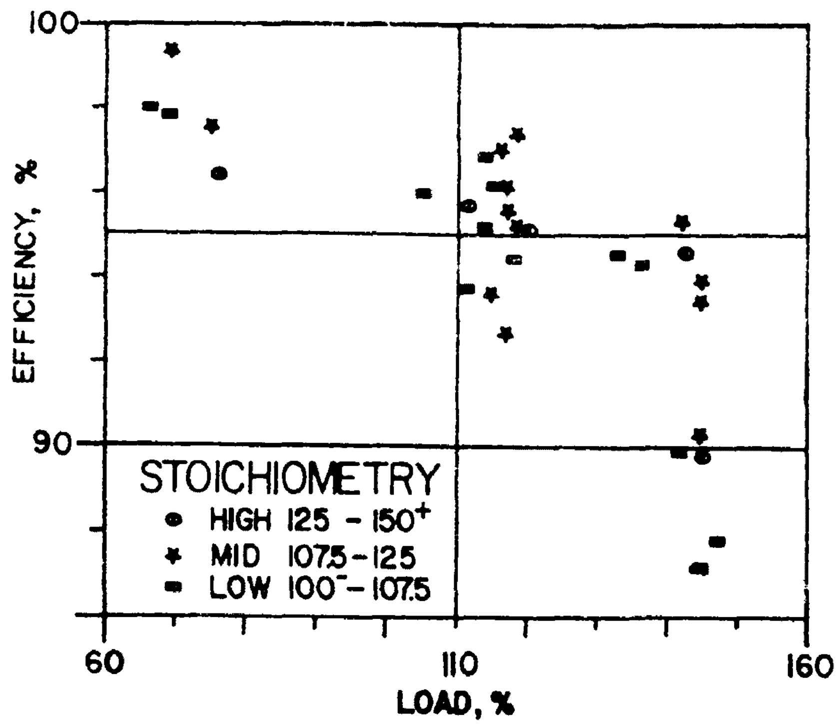


FIGURE 6.11
GAS, STAGED COMBUSTION

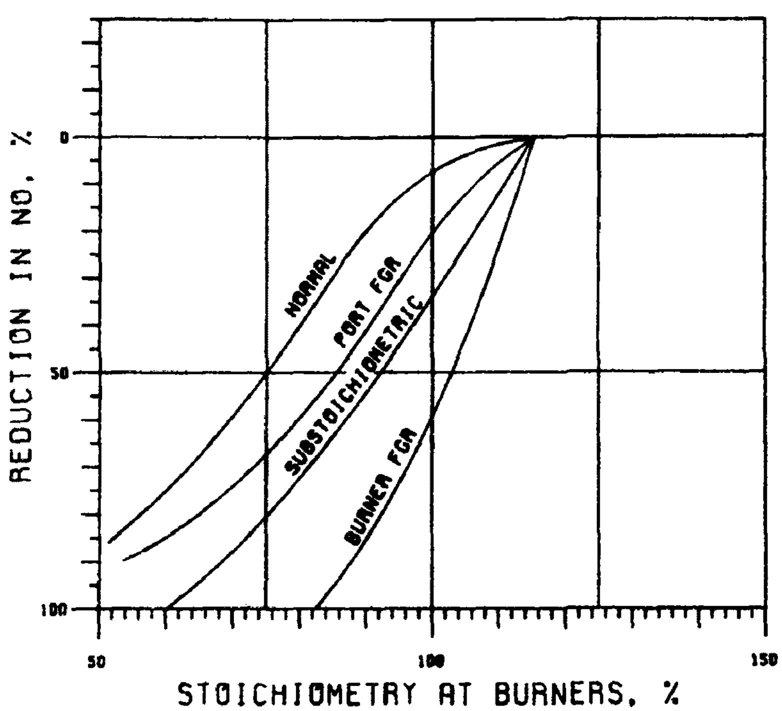


FIGURE 6.13
BURNER EFFICIENCY

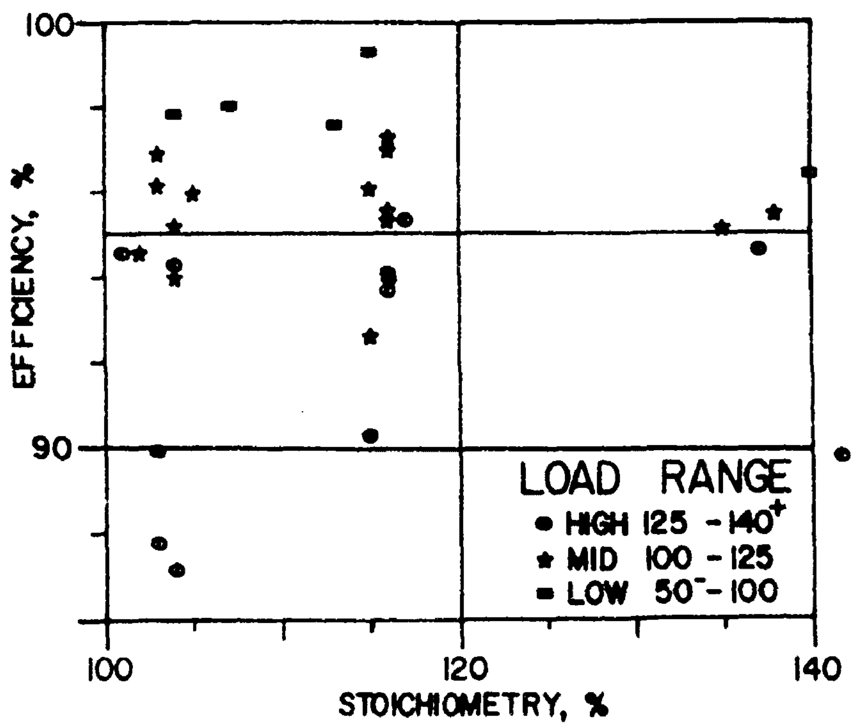


FIGURE 6.15
BURNER EFFICIENCY

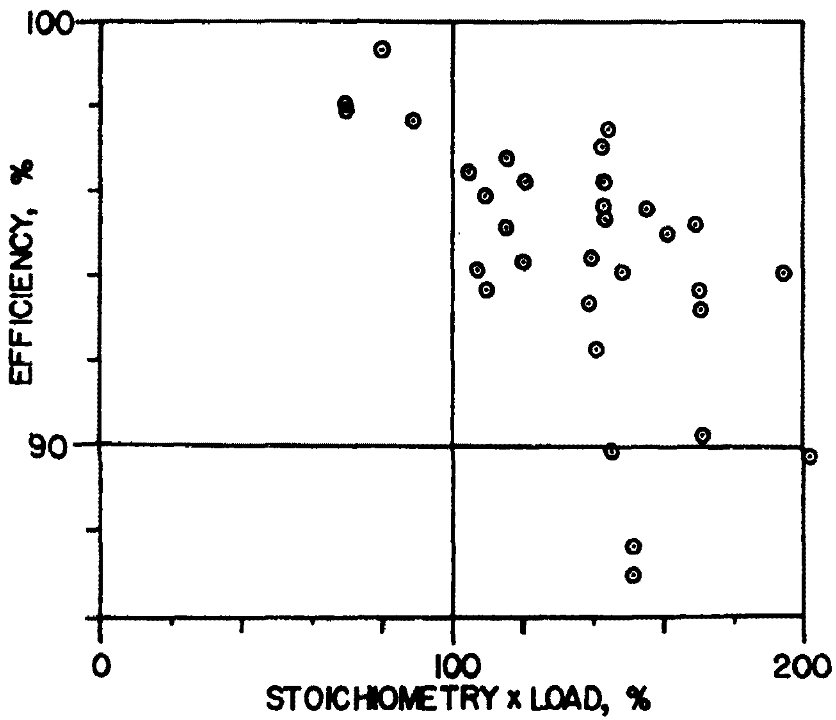


FIGURE 6.16
BURNER EFFICIENCY

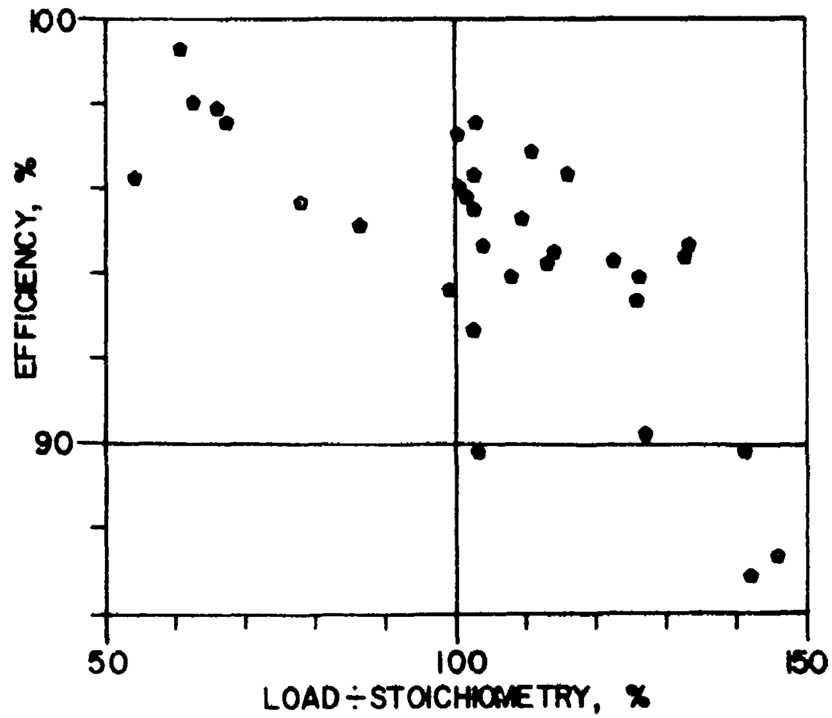


FIGURE 6.17

NO REDUCTION FOR SWIRL TESTS (GAS)

NO REDUCTION, %

	LOW AIR	MID AIR	HIGH AIR
LOW LOAD	10 (14, 6)	8	12
MID LOAD		19	17
HIGH LOAD	4	18	21

FIGURE 6.18

NO REDUCTION FOR QUENCH TESTS (COAL)

NO REDUCTION, %

	LOW AIR	MID AIR	HIGH AIR
LOW LOAD			
MID LOAD	15	20 18-STAG. 22-STAG. 15-F.G.R.	21
HIGH LOAD		13	10

VII. DISCUSSION

The discussion section has been divided into four sections. These sections will deal with the data results, special effects which were observed in the testing, final data discussion, and possible correlated interrelationships. The discussion will present the data as measured and a proposal for possible future considerations. The future work scheduled for Phase II will be discussed in a later section.

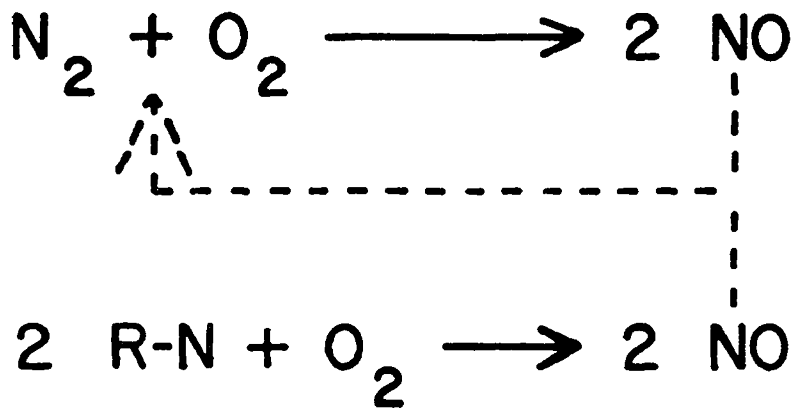
A. Results

The effects of each variable studied are usually significantly different for each of the three fuels studied 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 and fuel bound nitrogen sources. 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:



where R is the fuel portion of the molecule.

The kinetic form of these equations is given by a general form:

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

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

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 coincidental.

The initial thought for oil is that the NO_x concentrations observed should be higher than for gas due to the fuel bound nitrogen. In our unit, however, oil burns with a more luminous flame than gas and has a larger visible flame envelope. Hence, lower NO levels from oil combustion are attributed to better radiating properties and therefore a lower bulk gas temperature.

Excess Air

The results of the excess air tests show:

	Coal	Gas	Oil
Effect	Major	Strong	Strong
Mean Emission (under standard conditions)	700 ppm	300 ppm	250 ppm
Peak Position (percent excess air)	1000 ppm (35%)	350 ppm (20%)	300 ppm (40%)
Variation from Maximum to Minimum Emission	±300 ppm 400-1000 ppm	±65 ppm 220-350 ppm	±50 ppm 200-300 ppm
Percent Variation to Mean	∿40%	∿25%	∿20%

There are significant differences between gas and 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 a different position of peak maximum, shifted to higher excess air, and an increase in formation of NO at low excess air. These differences are, at least qualitatively, due to the fuel bound nitrogen. The trend thus shown indicates a positive correlation between increased fuel bound nitrogen conversion to NO and increased excess air. It is not felt that the fuel bound nitrogen can yet be quantitatively evaluated. (An additional factor which must be pointed out 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: in addition, the coal flame luminosity appears to be insensitive to excess air level whereas the gas flame luminosity is very greatly dependent upon excess air.)

Oil tends to behave in shape and peak of curve as though there is a fuel bound portion. The actual levels of NO are low, and as stated previously, are probably due to its high luminosity when compared to gas. The relative positions of the curves with coal highest, gas intermediate, and oil slightly below gas agree in general with field test data. The gas and oil NO emission levels fall in the low range and this could be due to the fairly conservative furnace heat liberation rate for these fuels in our test unit.

Load

The result of load change shows:

- Coal - Very strong effect; varies from 400-800 ppm under normal conditions.
- Gas - No dependence; 300 ppm under normal conditions.
- Oil - Intermediate between gas and coal; 175-275 ppm under normal conditions.

Again it should be pointed out that with the burner arrangement used for these tests, the air velocity through the burner and the turbulence change with load. However, there is no indication of a peak level being reached under increasing load conditions. In addition, due to the refractory shielding in the front half of the furnace, probably there is less response of NO to load than would be obtained with different quench rates.

Preheat

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

Fuel	Dependence	NO Range, ppm (Deviation of Mean)	
Coal	None	725	(∿0%)
Gas	Strong	100-300	(±∿50%)
Oil	Moderate	200-250	(±∿10%)

and for high excess air and normal load:

Coal	Moderate	750-1000	($\pm\sim$15%)
Gas	Strong	100-300	($\pm\sim$50%)
Oil	Moderate	225-300	($\pm\sim$15%)

The indication is that thermal production of NO is increasing at a rate of about 50 ppm per 100°F preheat increase. This is determined from the slope of the curve for gas. The slope for gas is unaffected by excess air. Since the same type of increase of thermal emission of NO should, but doesn't, occur for coal, and since it should be affected by excess air in the same manner as gas, then the fuel bound nitrogen conversion must be the reason for the differences in slope between gas and coal. Therefore, the results indicate that conversion of fuel bound nitrogen increases with decreasing air preheat. The increased slope of the two coal curves (from horizontal at normal air to 15% at high excess air) simply means that the total NO of the preheat curve is higher at higher excess air, not that the percent conversion of fuel bound nitrogen has changed with increased excess air.

Oil shows the tendency again to have a fuel bound nitrogen component like coal, but to be predominantly a thermal NO emitter. The oil curves are therefore consistent with the gas and coal.

Flue Gas Recirculation

The following results were obtained for flue gas recirculation:

Fuel	Effect	Reduction of NO, % (at 30% FGR)
Coal, primary	Little	<5% (at 5% FGR)
Coal, secondary	Moderate	30
Gas	Very Strong	85
Oil	Slight	10

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 when high levels of primary flue gas substitution are used. Blending the flue gas with the primary air affects the primary ignition zone and burner performance, further limiting the maximum levels of primary flue gas recirculation attainable. Also, as a result of the effect on burner stability, data for primary flue gas recirculation tests showed considerable scatter. It is felt, however, that this trend is realistic and that any reduction of NO by use of this approach is relatively insignificant.

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. In fact, reduction of thermal NO could be the cause of the lower overall reduction of NO in the coal tests. It is possible that with lower temperatures in the flue gas, the amount of NO from conversion of fuel bound nitrogen may actually increase, partially offsetting the decrease in thermal NO. Overall for coal then, the effect is moderate, but not overwhelming. For coal, the addition of 10 to 15% flue gas recirculation resulted in a reduction in NO emission levels of 10 to 15%.

For oil, the reduction of NO emissions by use of flue gas recirculation is small. The reason for this is probably that the base line data for oil are already so low, that little or no change is seen for basic reduction methods when applied to oil combustion.

Staged Combustion

The results of the staged combustion data are as follows:

REDUCTION IN NO, %

Staging Test	Coal	Gas	Oil
Normal:			
Effect on NO	Strong	Very Strong	Moderate
Maximum Reduction	60	90	35
Burner Air at Max. Red., % Stoich.	∿55	∿50?	∿55
Substoichiometric:			
Maximum Reduction	100	100	--
Burner Air at Max. Red., % Stoich.	∿60	∿60	--
With Port FGR	No Effect	95 at ∿50% Stoich.	No Effect
With Burner FGR	No Effect	100 at ∿80% Stoich.	No Effect
Variable Port Position	Some Effect (Max. Red.: Side Ports 50 Front Ports 60)	No Effect	No Effect

The difference in the second stage port position is important for the coal firing tests. Although the reduction in NO is not significantly different numerically at low burner to total air ratios* for the two slot positions, the visible flame pattern indicates a low second stage combustion efficiency for the side slots. In particular, a large cylindrical, highly turbulent flame envelope surrounds a blacker carbon containing core. Carbon becomes visible in the smoke from the stack. Although the transparency of

* 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.

the flame is much greater than this for gas and oil, incomplete burning and poor mixing is assumed to occur in the second stage for these fuels also. 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 decreases and staging increases, the air velocity through the burner decreases and the air velocity through the ports increases. It is for this reason that the performance and the effect on two stage combustion is unsatisfactory at lower burner to air ratios when using the side slots.

The greatest effect of staging is found with gas. Almost all of the NO is eliminated by staging the gas combustion. The addition of flue gas recirculation can remove most of the rest of the NO emission. The important item is that burner flue gas recirculation is more important than port flue gas recirculation. This indicates that precursors (free radicals, atoms, etc.) which later form thermal NO are formed in the first stage, even under highly substoichiometric conditions: if this were not the case, burner flue gas recirculation would show the same or less effect on NO than port flue gas recirculation. Therefore, the addition of flue gas recirculation effects more than just a lowering of the flame temperature in the combustion. The position of any maximum reduction of NO is uncertain, but is to be expected at about 50% burner air.

Again, in the case of oil, the reductions of NO for staged combustion are small due to the already low base values of NO emissions from oil.

Coal tests show 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 air 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.

The substoichiometric tests for gas and coal, when superimposed, indicate the same shape of curve and intercept for 100% reduction of NO. 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.

It is expected that flue gas recirculation would further reduce the staged reduction of NO for coal. It does not; therefore, the assumption is that staging has reduced all or most of the thermally produced NO, but only a portion of the fuel bound nitrogen conversion. This may indicate that the residence time in the first stage is too short and a greater physical separation is required between stages. If so, the burner area is not 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.

Swirl

A minor effect from swirl was noted for natural gas tests. In general, a greater reduction was noted for greater percentage of total air and/or for higher load. Both effects, separately or in combination, were important and lead to higher velocities and probably more rapid mixing.

The only exception is for increasing load at low air. In this case, increased mixing may not be important since the lower oxygen concentration may limit kinetics and thus the combustion reactions are not diffusion limited but kinetic limited.

Quench

Coal showed a quench dependence which indicates a trend for greater reductions in NO for either decreasing load or increasing air. There is insufficient data to indicate whether a combination of factors also produces the same effect. This could result from higher residence time and/or more rapid combustion and therefore higher temperatures in a shorter length (smaller volume) of furnace: this would then utilize to maximum efficiency the cooling surface of the furnace and the quench rate and thus reduce the overall time for formation of thermal NO. Therefore, all that is probably being observed is a quench of the thermal formation of NO and its subsequent reduction due to decreased temperature and decreased time at temperature.

B. Data and Testing Effects

NDIR/TECo

The NDIR and TECo instruments are very easy to use and only require minimum maintenance. Both instruments or one instrument and another 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 if this problem occurs. An indication of problems is seen almost immediately when the instruments do not agree on the NO measurement. The most common problems encountered for the NDIR were:

1) Dirty cell, inability to calibrate with wide range, insensitivity to changes in reading.

2) Method of water removal (before systematic use of 34°F water/ice bath), loss of NO.

3) Increase of temperature in final ice bath, increase of NO reading.

The most common problems encountered for the TECo were:

1) Leaks from a broken capillary (the yellow capillary chipped at both ends if the instrument was moved due to faulty alignment of the tube ends).

2) Clogging of capillaries over long periods of time by a "greasy" substance lowering sample flow.

3) Loss of total chamber pressure due to viscosity changes in pump oil by using commercial pump oil.

Any of these problems for either instrument is easily correctable if it is recognized. In our early testing, many of these problems occurred at once and it was difficult to track them all down. Now preventative maintenance has eliminated almost all differences between the instruments. Whenever measurements are currently made, the instruments must agree within ± 10 ppm or ± 5% (whichever is larger) or a problem is suspected and the situation corrected. Calibration checks are made several times a day and no significant drift for either instrument over a single day is noticed.

The only gaseous interferent observed for either instrument is 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.

Whittaker (NO_x)

The Whittaker chemical cell NO monitor shows unreconcilable differences when compared to readings from the NDIR and TECo during most coal testing. It does not respond to the true NO levels in the flue gas. Although it may read correctly at times, it does not do so consistently. When the reading is in error (greater than ± 10% deviation), it always reads 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 has been 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 have no effect except at very high concentrations of CO (>1% CO).

4) PNA (polynuclear aromatics) - No hydrocarbons can be found by gas chromatograph in even substoichiometric flue gas.

For gas and oil firing tests, the Whittaker agrees very well with the TECo and NDIR in most tests. In some tests (besides substoichiometric tests), an inconsistent and unexplainable deviation occurs; this deviation is always high. The Whittaker never adjusts as well as either the TECo or the NDIR and usually shows greater differences from the "true" NO measurement than either the TECo or NDIR.

Impeller Position

The oil impeller position was found to be important during some gas fired tests. Since this was not listed as a variable to be studied and since there is no impeller in position during coal tests, this variable is only of minor interest and therefore is only mentioned in passing. The results obtained showed:

NO Emission, ppm (all normal load)

	Impeller Withdrawn from Flame Front		Impeller Impinging on Flame Front
High Air	314	(10% reduction)	283
Mid Air	332	(29% reduction)	235
Low Air	278	(30% reduction)	194

The effect appears to be predominantly a mixing/turbulence effect which allows more rapid mixing, higher local oxygen concentration, and therefore more rapid combustion. More rapid mixing would indicate higher peak temperatures but may also yield a more rapid quenching of the flame by entrainment of recirculating cooler flue gas. Since thermal NO formation is somewhat delayed in time from peak temperature achievement, the result is a predominance of the lower quench and therefore a lower NO emission level. In the case of high excess air, this may no longer be dominantly diffusion limited but more kinetics limited and the mixing effect is less.

Scatter in Coal Data

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

1) Air temperature (no air preheat in primary)

2) Humidity in air

3) Moisture in coal

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

5) Barometric pressure fluctuations (could change velocities in furnace somewhat)

The magnitude of these changes is usually less than the error of measurement (± 5%) but can sometimes become ± 10%. It is not considered a major problem however and has usually been ignored.

Carbon Loss

The carbon loss (opposite of 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 both load and air as seen below:

Burner efficiency with increasing excess air

High Load	Strongly Increases
Mid Load	No Dependence
Low Load	Slightly Decreases

(Net effect is decreasing burner efficiency with increasing load for all air.)

When the burner efficiency is plotted against the product of load and percent of stoichiometric air, more scatter is evident. If the variable is load divided by percent of stoichiometric air, there is a greater correlation between this compound variable and burner efficiency.

The net effect is that carbon loss increases with increasing load and decreasing residence time; the oxygen effect is therefore not unexpected since although that also further decreases residence time, more combustion occurs in that time due to increased O_2 concentration and faster kinetics.

C. Final Presentation

Table 7.1 shows the final results for the Phase I studies. This table is used to indicate the effect of each variable on NO emission levels. The number of pluses or minuses is only meant to be a relative indication of NO reduction.

D. Interrelated Variables

Some of the variables are interrelated and should only be considered in combination. (For example, see preheat and excess air effect upon preheat as shown in Table 7.1.) In addition, many of the variables studied could be defined by a new set of variables such as enthalpy content, temperature, velocity, etc. It is possible that during Phase II, this will be tried during the mathematical correlation.

TABLE 7.1

RELATIVE EFFECTS ON NO IN FLUE GAS

Under Normal Conditions Increasing Level of Variable	Coal	Gas	Oil
Excess Air	++++*	++/--	++
Load	++++	0	++
Preheat (normal air)	0	+++	+
(high air)	+++	+++	++
Flue Gas Recirculation	--	----	-
Staged Combustion	----/	---	--/
(with FGR added-further effect	0	---/	0)
Quench	--	no data	no data
Swirl	no data	++	no data

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

VIII. CONCLUSIONS

The following conclusions have been derived from the work done in Phase I for coal firing on the single burner test unit:

1) There is a distinct difference in NO emissions from coal and gas attributable to fuel bound nitrogen.

2) The conversion of fuel bound nitrogen is directly proportional to the level of excess air.

3) The conversion of fuel bound nitrogen is inversely proportional to the level of air preheat.

4) Primary flue gas recirculation is insignificant in reduction of NO emissions.

5) A moderate reduction of NO from secondary flue gas recirculation has been shown, although only thermally formed NO is apparently reduced.

6) A minimum of 60% burner air (total burner to 100% theoretical air) is indicated for staged combustion. No further first stage reduction of NO would seem reasonable at lower percentages of burner air.

7) A definite physical separation is required for addition of the second stage air for reduction of NO. Progressive mixing may be good enough. Even so, a separately spaced second stage probably is required.

8) The same free radicals are responsible for conversion of fuel bound nitrogen and thermal NO in the final steps of NO production under substoichiometric conditions.

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

1) Thermal/fuel bound nitrogen conversion NO emission effects which are different. Conditions to change one are not the same to change the other.

2) Flue gas recirculation is <u>not</u> the method which shows most promise for new units for NO reduction.

3) For existing units, excess air level shows the most promising means of controlling flue 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 farther away in separate NO_x ports.

IX. FUTURE WORK

Appendix G includes the specific work plans for Phase II. The general steps in Phase II will be:

1) Further testing

2) Data correlation

3) Construction of a new multiburner test unit for use in Phase III

Phase III will be the testing phase for the new multiburner unit. Data correlation will continue into Phase III also.

X. REMARKS (Recommendations)

The indications from the Phase I single burner, coal fired data show several currently accepted philosophies will have to be modified if the EPA emission standards for NO_x become lower for coal fired utility boilers.* The obvious satisfactory NO reduction method for existing units without construction or costly modification is control of excess air. This requires lowered excess air, probably below 10% excess air. 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/manufacturing philosophy, there will be a long period of salesmanship and education required to convert people to 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. A general discussion of the economics can be found in Appendix F.

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* Most new coal units are being designed to meet current EPA limits. Many existing coal units also currently meet EPA limits, but may be on the borderline of acceptance.

APPENDIX A

FUELS DATA, ANALYSES, AND CALCULATIONS

A. Fuel Data

The coal used in all of our coal fired tests is an Ohio #5 and #6 seam coal. The time lag for analysis is at least 30 days from the time of submission of samples from the tests. Therefore all calculations pertaining to stoichiometry and load were carried out based on three prior, but recent coal analyses. These three analyses, the average used in calculations, and a later analysis are shown in Table A.1. Although the coal analysis in January, 1973, showed some change in the coal analysis, the calculations were not corrected since any error was considered smaller than the experimental measurement techniques.

The natural gas analysis used 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 and the new analysis was used in all final calculations. The oil analysis is shown in Table A.3. Again, the earlier analysis was used for preliminary calculations and the final analysis was used for all final calculations.

In addition to those analyses listed, coal fuel bound nitrogen analyses were also frequently run. Below follows the listing of these:

<u>Coal</u>

Date of Sample	10/25/72	11/21/72*	12/1/72	1/30/73
Nitrogen, % dry	1.05	1.31	1.15	1.02
Moisture	--	3.5	4.16	6.8
Carbon	--	74.1	--	--

* Coal was dumped from hopper and not used in coal firing tests.

TABLE A.1

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	--

TABLE A.2

NATURAL GAS ANALYSIS

Type	Columbia Gas Transmission Corp. Pittsburgh Group, Steubenville			Average of three groups	New Analysis later 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
$C_6H_{14}^+$	--	--	--	--	--
ρ (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

BUNKER C OIL ANALYSIS (#6 RESIDUAL)

B&W sample # F-680 (analysis used in final calculation)
F-367 (analysis used in preliminary data)

	F-367	F-680
Date of sample	7/2/71	3/2/73
Moisture	--	--
C	87.9	87.2
H	10.8	11.1
S	0.7	1.2
N (determined)	0.24	0.22, 0.23, 0.24, average = 0.23*
O (by difference)	0.34	0.26
Ash	0.02	0.02
BTU/lb.	18580	18620

*These analyses for fuel bound nitrogen were run on samples taken at least once a week.

B. Fuels Analyses

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

All of the important fuels analyses are shown below by method:

Moisture	ASTM; heating and weight difference in samples
BTU	ASTM; bomb calorimetry
Total - carbon	ASTM; collection of CO_2 in ultimate train
- hydrogen	ASTM; collection of H_2O in ultimate train
- nitrogen	Kjeldahl distillation and titration
- sulfur	ASTM; bomb calorimetry washings as $BaSO_4$
- ash	ASTM; 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 are converted to atom percentages. The ash is considered to be SiO_2. An ash analysis indicates large amounts of Al_2O_3 and Fe_2O_3 and so the SiO_2 is a good average in molecular weight between $AlO_{1.5}$ and $FeO_{1.5}$. The fuel values on conversion show the following atomic ratios:

Coal (wet)	- C = 54.049	Stoichiometric Air (dry)	- N = 469.33
	H = 50.973		O = 125.90
	N = 0.718		
	S = 0.813		
	Si = 1.902		
	O = 13.117		
Oil	- C = 7.2593	Stoichiometric Air (dry)	- N = 74.929
	H = 11.011		O = 20.100
	S = 0.0374		
	N = 0.0164		
	O = 0.0169		
	Si = 0.0003		
Gas	- N = 0.90	Stoichiometric Air (dry)	- N = 1520.7
	O = 1.64		O = 407.91
	H = 403.58		
	C = 103.88		

The theoretical air requirement as used above can then yield a curve of excess air versus oxygen concentration in the flue gas after combustion has taken place. Suitable curves were chosen* rather than calculating each case separately. The curves chosen are:

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

Coal: If $0.0 \leq \% O_2 \leq 2.5102$
(% theoretical air = PTA and % oxygen as measured in the flue gas = POF)

Then $PTA = 100 + 4.7279\ (POF)$

If $\% O_2 > 2.5102$

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

Oil: If $0.0 \leq \% O_2 \leq 4.8522$

Then $PTA = 100 + 4.7279\ (POF)$

If $\% O_2 > 4.8522$

Then $PTA = 100 + \frac{11}{13}\ (POF) + \frac{4}{5}\ (POF)^2$

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

Then $PTA = 100 + 4.7279\ (POF)$

If $\% O_2 > 2.4588$

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

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 always 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 near the point of being empty, new standards of the same concentration are ordered with a certified analysis. These new standards are checked against the old ones to verify the analysis before use as calibration gases.

The standard operating conditions selected for our basic combustion tunnel are 115% theoretical air, 600°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. The igniter was not used during natural gas and fuel oil firing tests.

B. Calculations

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

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

where:

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

and

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

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

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

Where:

Dry air inlet description	D_1	D_2	K, a constant
Normal primary air	2.25	4.00	7028.
Compressed primary air (with primary flue gas recirculation)	0.75	1.50	2808.
Primary air plus primary flue gas	1.625	2.50	3911.
Normal secondary air	7.0	12.0	68689.
Secondary flue gas	5.0	12.0	33601.
Second stage air, normal	4.5	8.0	28110.
Second stage flue gas	3.0	8.0	11785.
Natural gas (for ρ_{true} replace 0.0741 with 0.0434)	1.0	1.5	1127.

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 flow meter/orifice constants.

APPENDIX C

PRELIMINARY TEST DATA

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

I. Base line coal tests

II. A. Primary flue gas recirculation - coal
    B. Secondary flue gas recirculation - coal

III. A. More base line tests for coal
     B. Staged combustion with coal
     C. Staged combustion and flue gas recirculation with coal
     D. Substoichiometric firing with coal

IV. A. All natural gas tests
    B. All fuel oil (#6 residual) tests

V. A. Swirl tests with natural gas
   B. Swirl tests with coal

VI. Quench tests with coal

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 I-1, fuel are 471/502 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 ± 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

INITIAL TESTS (SERIES 1 FOR 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
1 - 1	3.2	471/502	606/652	4465/4799	0/ 0	0
1 - 2	3.2	462/493	606/653	5475/5895	0/ 0	0
1 - 3	3.2	465/498	606/655	3778/4086	0/ 0	0
1 - 4	3.2	488/520	606/655	4466/4821	0/ 0	0
1 - 5	3.2	485/517	606/656	5460/5898	0/ 0	0
1 - 6	3.2	469/499	606/656	3814/4126	0/ 0	0
1 - 7	3.2	592/631	666/717	5517/5940	0/ 0	0
1 - 8	3.1	586/625	678/731	6741/7252	0/ 0	0
1 - 9	3.1	550/586	678/732	4468/4822	0/ 0	0
1 - 10	3.1	306/326	538/581	2697/2910	0/ 0	0
1 - 11	3.2	274/292	541/582	2059/2218	0/ 0	0
1 - 12	3.2	301/320	549/593	3266/3531	0/ 0	0
1 - 13	3.2	297/317	541/584	2542/2747	0/ 0	0
1 - 14	3.2	586/624	667/720	5518/5951	0/ 0	0
1 - 15	3.2	558/594	608/649	5210/5560	0/ 0	0
1 - 16	3.2	456/498	606/650	3681/3940	0/ 0	0
1 - 17	3.2	473/504	608/651	5518/5902	0/ 0	0
1 - 18	3.2	493/525	664/705	5495/5860	0/ 0	0
1 - 19	3.1	297/316	518/554	2574/2751	0/ 0	0
1 - 20	3.1	272/290	518/552	2133/2273	0/ 0	0
1 - 21	3.2	377/401	520/556	4340/4630	0/ 0	0
1 - 22	3.2	467/497	605/645	5446/5806	0/ 0	0
1 - 23	3.2	598/637	665/714	5522/5921	0/ 0	0
1 - 24	3.1	286/305	517/556	2125/2285	0/ 0	0
1 - 25	3.2	612/652	683/729	5550/5925	0/ 0	0
1 - 26	3.1	572/610	678/728	4788/5143	0/ 0	0
1 - 27	3.1	591/630	676/725	6701/7180	0/ 0	0
1 - 28	3.1	481/513	601/646	4431/4760	0/ 0	0
1 - 29	3.1	298/317	516/559	2555/2771	0/ 0	0
1 - 30	3.1	484/515	601/647	4380/4718	0/ 0	0
1 - 31	3.1	292/311	514/556	2294/2481	0/ 0	0
1 - 32	3.2	473/504	650/696	4411/4722	0/ 0	0
1 - 33	3.2	457/487	622/661	5352/5666	0/ 0	0
1 - 34	3.2	446/476	614/655	3654/3896	0/ 0	0
1 - 35	3.2	574/612	654/701	5517/5909	0/ 0	0
1 - 36	3.2	288/306	540/582	3266/3516	0/ 0	0
1 - 37	3.2	471/502	606/647	5498/5864	0/ 0	0
1 - 38	3.2	573/610	682/724	5443/5772	0/ 0	0
1 - 39	3.2	450/479	609/648	3775/4017	0/ 0	0
1 - 40	3.2	453/491	621/660	4412/4686	0/ 0	0
1 - 41	3.2	419/447	630/668	3449/3662	0/ 0	0
1 - 42	3.2	566/602	696/738	5451/5776	0/ 0	0
1 - 43	3.2	554/591	681/722	4527/4799	0/ 0	0

TABLE C.2

INITIAL TESTS (SERIES 1 FOR 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 (%)
1 - 1	116.3	51.95	608	0.0	116.3
1 - 2	142.0	52.58	629	0.0	142.0
1 - 3	101.9	50.30	587	0.0	101.9
1 - 4	112.4	53.60	611	0.0	112.4
1 - 5	135.1	54.62	622	0.0	135.1
1 - 6	101.9	50.95	592	0.0	101.9
1 - 7	113.0	65.00	620	0.0	113.0
1 - 8	137.0	66.41	647	0.0	137.0
1 - 9	101.2	59.65	605	0.0	101.2
1 - 10	113.3	33.48	570	0.0	113.3
1 - 11	101.7	29.63	534	0.0	101.7
1 - 12	136.0	33.87	595	0.0	136.0
1 - 13	111.3	32.46	565	0.0	111.3
1 - 14	114.2	64.68	638	0.0	114.2
1 - 15	112.9	58.09	384	0.0	112.9
1 - 16	101.4	47.31	371	0.0	101.4
1 - 17	140.0	50.30	393	0.0	140.0
1 - 18	135.1	52.11	385	0.0	135.1
1 - 19	111.8	31.20	384	0.0	111.8
1 - 20	104.4	28.37	366	0.0	104.4
1 - 21	139.0	39.85	367	0.0	139.0
1 - 22	140.0	52.89	643	0.0	140.0
1 - 23	112.1	65.78	639	0.0	112.1
1 - 24	99.1	30.81	547	0.0	99.1
1 - 25	110.3	65.31	507	0.0	110.3
1 - 26	103.3	60.75	503	0.0	103.3
1 - 27	135.1	64.66	534	0.0	135.1
1 - 28	113.0	51.56	505	0.0	113.0
1 - 29	110.7	31.91	470	0.0	110.7
1 - 30	111.3	49.28	275	0.0	111.3
1 - 31	103.3	29.71	263	0.0	103.3
1 - 32	115.5	51.17	525	0.0	115.5
1 - 33	141.0	50.69	548	0.0	141.0
1 - 34	103.2	47.63	515	0.0	103.2
1 - 35	116.3	62.33	553	0.0	116.3
1 - 36	141.8	31.99	527	0.0	141.8
1 - 37	140.0	52.50	563	0.0	140.0
1 - 38	115.8	62.01	550	0.0	115.8
1 - 39	105.2	48.96	613	0.0	105.2
1 - 40	119.9	47.47	376	0.0	119.9
1 - 41	104.9	43.46	354	0.0	104.9
1 - 42	117.6	59.02	373	0.0	117.6
1 - 43	101.7	57.22	363	0.0	101.7

TABLE C.3

INITIAL TESTS (SERIES I FOR COAL)

NOX MEASUREMENTS

ORIGINAL SERIES - RUN #-S	PPM NOX 3% O2, DRY: ACIR	TECO	WHIT	PPM NOX IN DRY, 3% O2 FLUE GAS	LB. NOX / 10**6 BTU INPUT
I - 1	713	738	790	725 ± 18	0.74 ± .02
I - 2	845	990	1026	913 ± 96	1.12 ± .12
I - 3	433	430	529	431 ± 2	[illegible] ± .0
I - 4	660	769	809	714 ± 77	0.71 ± .06
I - 5	842	1054	1103	948 ± 150	1.11 ± .16
I - 6	466	457	600	431 ± 36	0.45 ± .03
I - 7	668	923	904	746 ± 109	0.74 ± .11
I - 8	906	1091	1221	558 ± 131	1.10 ± .14
I - 9	550	502	779	546 ± 62	0.55 ± .06
I - 10	458	570	644	534 ± 51	0.53 ± .05
I - 11	252	252	506	292 ± 0	0.26 ± .0
I - 12	742	847	930	795 ± 74	0.84 ± .09
I - 13	537	554	613	546 ± 12	0.51 ± .01
I - 14	775	842	916	[illegible] ± 67	0.81 ± .05
I - 15	653	673	731	[illegible] ± 14	0.67 ± .01
I - 16	452	348	547	420 ± 45	0.38 ± .04
I - 17	758	870	927	834 ± 51	1.00 ± .06
I - 18	801	842	932	821 ± 29	0.95 ± .03
I - 19	467	454	536	460 ± 9	0.45 ± .01
I - 20	350	291	384	321 ± 42	0.2[illegible] ± .04
I - 21	656	707	765	681 ± 36	0.81 ± .04
I - 22	524	1046	1094	585 ± 87	1.19 ± .10
I - 23	760	801	895	791 ± 15	0.78 ± .01
I - 24	323	741	450	282 ± 58	0.25 ± .05
I - 25	770	723	875	746 ± 33	0.72 ± .03
I - 26	576	499	668	538 ± 55	0.49 ± .05
I - 27	540	971	1102	556 ± 22	1.11 ± .03
I - 28	688	663	757	676 ± 18	0.67 ± .02
I - 29	442	414	488	428 ± 20	0.42 ± .02
I - 30	580	623	717	601 ± 30	0.59 ± .03
I - 31	337	289	524	312 ± 35	0.29 ± .03
I - 32	734	729	827	731 ± 4	0.74 ± .0
I - 33	549	967	1076	558 ± 13	1.15 ± .02
I - 34	469	463	561	466 ± 4	0.42 ± .0
I - 35	794	784	824	789 ± 7	0.80 ± .01
I - 36	747	751	809	749 ± 3	0.91 ± .0
I - 37	925	918	984	922 ± 4	1.10 ± .01
I - 38	847	822	888	834 ± 18	0.83 ± .02
I - 39	570	546	626	558 ± 17	0.51 ± .02
I - 40	749	728	792	739 ± 15	0.76 ± .02
I - 41	464	435	509	449 ± 21	0.41 ± .02
I - 42	777	751	814	764 ± 18	0.77 ± .02
I - 43	523	495	570	509 ± 19	0.45 ± .02

TABLE C.4

INITIAL TESTS (SERIES I FOR 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 %
I - 1	6.8	734	3.2	205	2425	15.0	----	----	----
I - 2	7.3	735	6.2	80	2200	----	----	----	----
I - 3	6.0	735	0.8	8000	2500	----	----	----	----
I - 4	7.7	736	2.6	180	2400	----	----	----	----
I - 5	8.0	736	5.5	90	2250	----	----	----	----
I - 6	8.0	736	0.8	9000	2700	----	0.89	54.6	0.70
I - 7	7.4	736	2.7	260	2450	----	----	----	----
I - 8	7.4	736	5.7	115	2200	----	----	----	----
I - 9	7.7	736	1.0	15000	2650	----	----	----	----
I - 10	7.5	736	2.8	115	2400	----	----	----	----
I - 11	7.1	736	0.8	9000	2650	----	----	----	----
I - 12	7.9	736	5.6	85	2100	12.8	----	----	----
I - 13	7.7	736	2.4	240	2375	----	----	----	----
I - 14	7.7	737	2.9	360	2400	----	----	----	----
I - 15	5.5	738	2.7	500	2500	----	----	----	----
I - 16	6.0	738	0.7	9000	2750	----	----	----	----
I - 17	6.0	738	6.0	70	2200	12.8	----	----	----
I - 18	5.5	738	5.5	65	2175	----	----	----	----
I - 19	5.6	738	2.5	240	2300	----	----	----	----
I - 20	5.2	738	1.1	3200	2450	----	0.35	51.3	0.55
I - 21	5.5	737	5.9	60	1950	13.0	----	----	----
I - 22	5.5	737	6.0	90	2125	----	----	----	----
I - 23	6.6	737	2.5	165	2125	----	----	----	----
I - 24	6.7	737	0.8	20000	2650	----	----	----	----
I - 25	5.7	737	2.2	400	2600	----	----	----	----
I - 26	6.8	737	0.9	4000	2750	----	1.55	57.3	----
I - 27	6.5	737	5.5	140	2200	----	----	----	----
I - 28	6.8	737	2.7	100	2400	15.1	----	----	----
I - 29	8.5	737	2.3	800	2325	----	----	----	----
I - 30	7.2	736	2.4	400	2500	15.4	----	----	----
I - 31	7.8	733	1.6	18000	2500	----	----	----	----
I - 32	6.0	730	3.1	175	2325	----	----	----	----
I - 33	4.8	730	6.1	50	2075	----	----	----	----
I - 34	5.3	731	0.9	4500	2525	----	----	----	----
I - 35	6.2	731	3.2	260	2325	----	----	----	----
I - 36	7.0	730	6.2	400	1850	----	----	----	----
I - 37	5.5	730	6.0	50	1950	13.0	----	----	----
I - 38	4.5	730	3.1	750	2225	----	----	----	----
I - 39	5.0	730	1.3	3000	2350	----	----	----	----
I - 40	4.6	729	3.7	50	2100	----	----	----	----
I - 41	4.5	728	1.2	3200	2300	16.8	0.68	52.3	0.65
I - 42	4.3	729	3.4	360	2150	----	----	----	----
I - 43	4.3	728	0.7	7000	2350	----	----	----	----

TABLE C.5

FLUE GAS RECIRCULATION TESTS (SERIES II FOR 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
IIA - 1	3.1	476/507	600/632	4439/4728	0/ 0	0
IIA - 2	3.0	470/501	371/392	4533/4828	0/ 0	101
IIA - 3	3.0	458/488	283/301	4512/4812	0/ 0	179
IIA - 4	3.1	494/526	613/647	5471/5837	0/ 0	0
IIA - 5	3.0	484/516	382/405	5549/5931	0/ 0	91
IIA - 6	3.0	464/495	601/636	3819/4056	0/ 0	0
IIA - 7	3.0	447/476	367/390	3878/4149	0/ 0	100
IIA - 8	3.0	445/474	598/632	4068/4348	0/ 0	0
IIA - 9	3.0	569/607	365/389	5595/5998	0/ 0	101
IIA - 10	3.0	576/613	601/636	6679/7138	0/ 0	0
IIA - 11	3.0	558/595	364/387	6853/7323	0/ 0	103
IIA - 12	3.1	576/614	617/659	5447/5900	0/ 0	0
IIA - 13	3.1	568/605	378/406	5601/6054	0/ 0	107
IIA - 14	3.1	548/584	598/639	4663/5059	0/ 0	0
IIA - 15	3.1	539/574	375/404	4750/5160	0/ 0	117
IIA - 16	3.1	297/316	623/667	2517/2741	0/ 0	0
IIA - 17	3.1	286/305	380/410	2661/2897	0/ 0	109
IIA - 18	3.1	285/304	336/357	3223/3505	0/ 0	119
IIA - 19	3.1	303/323	617/660	3094/3365	0/ 0	0
IIA - 20	3.1	266/283	615/659	1960/2133	0/ 0	0
IIA - 21	3.1	252/268	366/395	2064/2246	0/ 0	126
IIA - 22	3.1	571/608	617/671	5392/5958	0/ 0	0
IIA - 23	3.1	566/603	371/407	5465/6049	0/ 0	114
IIA - 24	3.1	552/599	376/412	6568/7263	0/ 0	102
IIA - 25	3.1	577/615	618/672	6580/7263	0/ 0	0
IIA - 26	3.1	536/571	616/670	4404/4874	0/ 0	0
IIA - 27	3.1	514/548	374/410	4472/4953	0/ 0	108
IIA - 28	3.1	457/487	368/404	4351/4827	0/ 0	109
IIA - 29	3.1	471/502	603/659	4275/4763	0/ 0	0
IIA - 30	3.1	297/316	622/678	2470/2748	0/ 0	0
IIA - 31	3.0	281/300	374/411	2696/2997	0/ 0	90
IIA - 32	3.1	469/500	605/657	4278/4731	0/ 0	0
IIA - 33	3.1	463/493	373/408	4390/4845	0/ 0	112
IIA - 34	3.1	496/528	626/677	5362/5909	0/ 0	0
IIA - 35	3.1	475/506	375/414	5362/5909	0/ 0	106
IIA - 36	3.1	592/631	609/650	6730/7277	0/ 0	0
IIA - 37	7.9	575/612	378/407	6802/7381	0/ 0	114
IIB - 1	3.1	573/611	665/711	5512/5891	0/ 0	0
IIB - 2	3.1	583/621	672/721	5519/5917	0/ 0	877
IIB - 3	3.1	276/294	536/576	2535/2727	0/ 0	0
IIB - 4	3.1	275/293	528/567	2528/2715	0/ 0	752
IIB - 5	3.1	275/293	525/568	3112/3341	0/ 0	738
IIB - 6	3.1	364/387	520/556	4208/4507	0/ 0	0
IIB - 7	3.1	258/275	520/557	2090/2241	0/ 0	0
IIB - 8	3.1	263/280	528/566	2093/2243	0/ 0	661
IIB - 9	3.2	476/507	602/632	4450/4674	0/ 0	0
IIB - 10	3.2	472/503	593/625	5656/5960	0/ 0	0
IIB - 11	3.2	267/285	538/576	2042/2188	0/ 0	0
IIB - 12	3.2	555/591	677/717	6604/6991	0/ 0	0
IIB - 13	3.2	467/497	607/646	4452/4738	0/ 0	0
IIB - 14	3.2	464/494	614/655	4445/4737	0/ 0	1822
IIB - 15	3.2	504/537	607/647	5871/6250	0/ 0	0
IIB - 16	3.2	475/506	606/649	5551/5932	0/ 0	1307
IIB - 17	3.2	458/488	606/649	3814/4083	0/ 0	0
IIB - 18	3.2	447/477	614/657	3713/3974	0/ 0	1608
IIB - 19	3.2	284/302	522/556	2577/2747	0/ 0	0
IIB - 20	3.2	277/295	524/555	2512/2663	0/ 0	1194
IIB - 21	3.2	277/296	525/559	3179/3389	0/ 0	0
IIB - 22	3.1	280/298	528/563	3184/3396	0/ 0	972
IIB - 23	3.2	265/282	524/558	2057/2192	0/ 0	0
IIB - 24	3.2	253/269	534/567	1954/2076	0/ 0	1197
IIB - 25	3.2	549/575	661/703	6099/6473	0/ 0	0
IIB - 26	3.2	547/583	675/717	6065/6430	0/ 0	1578
IIB - 27	3.2	519/553	665/710	4257/4517	0/ 0	0

TABLE C.6

FLUE GAS RECIRCULATION TESTS (SERIES II FOR 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 (%)
IIA - 1	114.3	52.34	630	0.0	114.3
IIA - 2	112.7	51.97	645	1.8	112.7
IIA - 3	113.0	50.69	649	3.2	113.0
IIA - 4	133.2	55.57	648	0.0	133.2
IIA - 5	132.3	54.70	653	1.3	132.3
IIA - 6	102.8	50.38	605	0.0	102.8
IIA - 7	102.6	48.65	624	2.0	102.6
IIA - 8	113.3	48.89	631	0.0	113.3
IIA - 9	113.3	62.95	660	1.4	113.3
IIA - 10	137.0	65.08	662	0.0	137.0
IIA - 11	139.9	63.74	675	1.2	139.9
IIA - 12	114.0	63.50	649	0.0	114.0
IIA - 13	114.0	63.03	660	1.5	114.0
IIA - 14	103.9	59.65	633	0.0	103.9
IIA - 15	102.9	58.95	649	1.9	102.9
IIA - 16	113.5	32.38	551	0.0	113.5
IIA - 17	113.9	31.44	577	3.0	113.9
IIA - 18	135.1	32.15	600	2.8	135.1
IIA - 19	131.4	33.72	578	0.0	131.4
IIA - 20	103.8	28.53	515	0.0	103.8
IIA - 21	103.2	27.39	567	4.3	103.2
IIA - 22	114.0	61.38	521	0.0	114.0
IIA - 23	111.6	60.49	529	1.6	111.6
IIA - 24	136.0	66.91	541	1.2	136.0
IIA - 25	135.1	63.19	527	0.0	135.1
IIA - 26	101.4	56.92	505	0.0	101.4
IIA - 27	101.9	54.86	520	1.8	101.9
IIA - 28	112.7	48.65	518	1.9	112.7
IIA - 29	111.8	50.54	506	0.0	111.8
IIA - 30	111.7	41.67	455	0.0	111.7
IIA - 31	117.0	40.34	484	2.4	117.0
IIA - 32	112.4	49.04	394	0.0	112.4
IIA - 33	111.0	48.57	404	1.9	111.0
IIA - 34	130.5	52.42	400	0.0	130.5
IIA - 35	130.5	50.46	405	1.5	130.5
IIA - 36	134.1	62.64	401	0.0	134.1
IIA - 37	133.2	61.93	403	1.4	133.2
IIB - 1	116.7	63.11	630	0.0	116.7
IIB - 2	115.0	65.08	629	12.1	115.0
IIB - 3	119.1	30.26	560	0.0	119.1
IIB - 4	119.2	30.81	565	21.0	119.2
IIB - 5	142.0	31.52	575	17.5	142.0
IIB - 6	139.9	40.62	596	0.0	139.9
IIB - 7	108.1	27.98	538	0.0	108.1
IIB - 8	106.7	29.03	540	21.4	106.7
IIB - 9	114.6	52.27	626	0.0	114.6
IIB - 10	143.0	53.44	636	0.0	143.0
IIB - 11	103.3	28.84	524	0.0	103.3
IIB - 12	142.0	57.95	420	0.0	142.0
IIB - 13	117.0	51.49	623	0.0	117.0
IIB - 14	117.7	53.13	623	30.9	117.7
IIB - 15	139.0	56.98	644	0.0	139.0
IIB - 16	140.0	55.25	642	18.4	140.0
IIB - 17	104.3	49.75	601	0.0	104.3
IIB - 18	104.4	50.22	555	31.5	104.4
IIB - 19	117.0	31.20	573	0.0	117.0
IIB - 20	117.4	31.57	557	34.0	117.4
IIB - 21	143.0	31.36	588	0.0	143.0
IIB - 22	142.0	32.77	593	22.8	142.0
IIB - 23	104.4	28.69	530	0.0	104.4
IIB - 24	105.1	28.45	523	41.1	105.1
IIB - 25	135.6	60.91	656	0.0	135.6
IIB - 26	133.2	63.27	646	20.4	133.2
IIB - 27	102.6	56.27	612	0.0	102.6

TABLE C.7

FLUE GAS RECIRCULATION TESTS (SERIES II FOR COAL)

NOX MEASUREMENTS

ORIGINAL SERIES - RUN #-S	PPM NOX 3% O2, DRY: NDIR	PPM NOX 3% O2, DRY: TECO	PPM NOX 3% O2, DRY: WHIT	PPM NOX IN DRY, 3% O2 FLUE GAS	LB. NOX / 10**6 BTU INPUT
IIA - 1	766	792	917	774 ± 11	0.77 ± .01
IIA - 2	651	656	820	694 ± 4	0.68 ± .0
IIA - 3	659	658	781	659 ± 0	0.65 ± .0
IIA - 4	848	947	1047	898 ± 70	1.03 ± .08
IIA - 5	860	935	1054	898 ± 53	1.02 ± .06
IIA - 6	450	448	564	449 ± 2	0.41 ± .0
IIA - 7	451	451	584	472 ± 30	0.43 ± .03
IIA - 8	809	850	969	829 ± 29	0.82 ± .03
IIA - 9	749	730	866	740 ± 14	0.73 ± .01
IIA - 10	976	984	1119	980 ± 5	1.15 ± .01
IIA - 11	978	961	1093	965 ± 12	1.16 ± .01
IIA - 12	744	779	864	762 ± 25	0.76 ± .03
IIA - 13	719	870	934	794 ± 107	0.80 ± .11
IIA - 14	580	561	623	571 ± 13	0.53 ± .01
IIA - 15	565	538	630	552 ± 20	0.51 ± .02
IIA - 16	494	446	513	470 ± 34	0.47 ± .03
IIA - 17	515	473	515	494 ± 30	0.50 ± .03
IIA - 18	702	695	752	699 ± 6	0.82 ± .01
IIA - 19	650	666	730	658 ± 11	0.75 ± .01
IIA - 20	229	262	384	246 ± 24	0.23 ± .02
IIA - 21	237	265	440	251 ± 20	0.24 ± .02
IIA - 22	620	689	760	654 ± 49	0.67 ± .05
IIA - 23	606	664	740	635 ± 41	0.64 ± .04
IIA - 24	801	936	1010	868 ± 96	1.05 ± .12
IIA - 25	848	977	1088	913 ± 91	1.09 ± .11
IIA - 26	438	450	587	444 ± 8	0.41 ± .01
IIA - 27	352	421	543	387 ± 49	0.36 ± .05
IIA - 28	593	666	705	630 ± 52	0.64 ± .05
IIA - 29	618	715	751	667 ± 69	0.67 ± .07
IIA - 30	431	473	511	452 ± 30	0.46 ± .03
IIA - 31	476	526	561	501 ± 35	0.51 ± .04
IIA - 32	522	704	762	613 ± 129	0.62 ± .13
IIA - 33	583	661	707	622 ± 55	0.62 ± .05
IIA - 34	533	878	917	706 ± 245	0.81 ± .28
IIA - 35	612	856	908	734 ± 172	0.85 ± .20
IIA - 36	825	994	955	910 ± 120	1.06 ± .14
IIA - 37	751	831	860	791 ± 57	0.92 ± .07
IIB - 1	771	884	870	828 ± 80	0.84 ± .08
IIB - 2	660	755	755	708 ± 67	0.71 ± .07
IIB - 3	479	519	588	499 ± 28	0.52 ± .03
IIB - 4	406	425	461	416 ± 13	0.43 ± .01
IIB - 5	490	573	651	532 ± 59	0.65 ± .07
IIB - 6	689	754	781	722 ± 46	0.87 ± .06
IIB - 7	315	350	453	333 ± 25	0.32 ± .02
IIB - 8	246	271	390	258 ± 18	0.24 ± .02
IIB - 9	814	849	819	832 ± 25	0.82 ± .02
IIB - 10	1042	1117	1056	1080 ± 53	1.30 ± .06
IIB - 11	290	288	400	289 ± 2	0.26 ± .0
IIB - 12	1017	1011	1037	1014 ± 4	1.22 ± .01
IIB - 13	820	846	859	833 ± 18	0.84 ± .02
IIB - 14	556	539	603	548 ± 12	0.56 ± .01
IIB - 15	1039	1057	1225	1048 ± 13	1.24 ± .02
IIB - 16	786	809	854	797 ± 16	0.96 ± .02
IIB - 17	555	550	622	552 ± 4	0.51 ± .0
IIB - 18	371	373	432	372 ± 2	0.34 ± .0
IIB - 19	569	583	642	576 ± 10	0.58 ± .01
IIB - 20	396	388	447	392 ± 6	0.40 ± .01
IIB - 21	789	832	907	810 ± 30	0.59 ± .04
IIB - 22	582	610	688	596 ± 20	0.72 ± .02
IIB - 23	321	318	469	320 ± 2	0.29 ± .0
IIB - 24	241	243	317	242 ± 1	0.22 ± .0
IIB - 25	1003	1022	986	1013 ± 13	1.17 ± .01
IIB - 26	920	908	829	914 ± 9	0.93 ± .01
IIB - 27	550	527	469	538 ± 16	0.48 ± .01

TABLE C.8

FLUE GAS RECIRCULATION TESTS (SERIES II FOR 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 %
IIA - 1	5.3	745	2.9	90	2200	----	----	----	----
IIA - 2	5.2	744	2.6	80	2700	----	----	----	----
IIA - 3	5.5	744	2.7	90	2725	----	----	----	----
IIA - 4	5.7	744	5.3	100	2500	----	----	----	----
IIA - 5	6.0	744	5.2	90	2500	----	----	----	----
IIA - 6	6.3	743	0.8	4000	2950	12.8	0.61	55.8	----
IIA - 7	6.0	743	0.7	3200	3050	15.0	----	----	----
IIA - 8	6.0	743	2.8	90	2700	----	----	----	----
IIA - 9	6.5	742	2.8	90	2650	----	----	----	----
IIA - 10	6.1	742	5.7	140	2400	----	----	----	----
IIA - 11	6.1	742	6.0	140	2300	----	----	----	----
IIA - 12	8.7	738	2.8	100	2500	14.6	----	----	----
IIA - 13	8.2	739	2.8	85	2450	----	----	----	----
IIA - 14	8.9	738	0.9	1500	2500	----	0.83	59.5	----
IIA - 15	9.2	738	0.8	2600	2500	----	----	----	----
IIA - 16	9.4	738	2.8	660	2300	15.0	----	----	----
IIA - 17	9.4	738	2.8	240	2275	----	----	----	----
IIA - 18	9.2	738	5.5	90	2100	----	----	----	----
IIA - 19	9.2	738	5.1	90	2100	----	----	----	----
IIA - 20	9.2	738	1.0	4000	2375	----	----	----	----
IIA - 21	9.2	738	0.9	4500	2350	----	----	----	----
IIA - 22	13.5	733	2.8	90	2325	14.8	----	----	----
IIA - 23	14.0	732	2.4	125	2325	----	----	----	----
IIA - 24	14.0	732	5.6	115	2075	----	----	----	----
IIA - 25	13.5	732	5.5	105	2075	----	----	----	----
IIA - 26	13.7	731	0.5	4000	2475	----	0.78	60.6	----
IIA - 27	13.9	731	0.6	4000	2450	----	----	----	----
IIA - 28	14.3	729	2.6	240	2100	----	----	----	----
IIA - 29	15.6	730	2.5	180	2075	----	----	----	----
IIA - 30	14.6	729	2.5	350	2050	----	----	----	----
IIA - 31	14.6	729	3.3	200	2025	14.5	----	----	----
IIA - 32	13.4	729	2.6	165	2100	----	----	----	----
IIA - 33	12.8	728	2.3	260	2125	----	----	----	----
IIA - 34	12.6	728	5.0	90	1875	----	----	----	----
IIA - 35	12.6	728	5.0	90	1875	----	----	----	----
IIA - 36	8.4	735	5.4	115	2450	----	----	----	----
IIA - 37	9.2	735	5.3	115	2300	----	----	----	----
IIB - 1	6.0	740	3.3	115	2700	----	----	----	----
IIB - 2	6.5	740	3.0	115	2600	----	1.21	64.1	1.09
IIB - 3	6.5	740	3.6	165	2300	----	----	----	----
IIB - 4	6.5	740	3.6	115	2250	----	----	----	----
IIB - 5	6.5	740	6.2	100	1950	----	----	----	----
IIB - 6	6.1	740	6.0	100	2000	----	----	----	----
IIB - 7	6.2	740	1.8	2600	2400	----	----	----	----
IIB - 8	6.1	740	1.5	1500	2450	----	0.32	52.2	0.79
IIB - 9	3.1	735	2.9	80	2775	----	----	----	----
IIB - 10	3.7	740	6.3	70	2575	----	----	----	----
IIB - 11	6.1	738	0.9	4000	2600	----	----	----	----
IIB - 12	4.4	734	6.2	50	2250	13.0	----	----	----
IIB - 13	5.1	742	3.3	60	2500	----	----	----	----
IIB - 14	5.4	742	3.4	70	2400	----	----	----	----
IIB - 15	5.3	742	5.9	80	2250	12.9	----	----	----
IIB - 16	6.0	741	6.0	80	2100	----	----	----	----
IIB - 17	6.1	741	1.0	2000	2625	----	----	----	----
IIB - 18	6.1	741	1.0	1400	2600	----	0.95	56.1	0.87
IIB - 19	5.7	741	3.3	100	2300	15.0	----	----	----
IIB - 20	4.4	741	3.1	50	2275	----	----	----	----
IIB - 21	5.3	740	6.3	80	2000	----	----	----	----
IIB - 22	5.4	740	6.2	80	1975	----	----	----	----
IIB - 23	5.2	740	1.1	3500	2475	----	----	----	----
IIB - 24	4.7	740	1.1	450	2500	----	----	----	----
IIB - 25	4.8	738	5.5	70	2175	13.0	----	----	----
IIB - 26	4.7	738	5.3	50	2225	----	----	----	----
IIB - 27	4.6	738	0.8	5000	2400	----	----	----	----

TABLE C.9

TWO STAGE COMBUSTION TESTS (SERIES III FOR 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
III A- 1	3.1	468/499	558/651	4385/4772	0/ 0	0
III A- 2	3.1	478/509	594/650	5386/5884	0/ 0	0
III A- 3	3.1	613/653	596/654	5267/5775	0/ 0	0
III A- 4	3.1	591/630	666/729	5437/5944	0/ 0	0
III A- 5	3.1	586/624	668/730	6958/7582	0/ 0	0
III A- 6	3.1	276/294	494/545	2461/2714	0/ 0	0
III A- 7	3.1	284/303	503/552	3100/3403	0/ 0	0
III A- 8	3.1	470/500	596/646	4344/4711	0/ 0	0
III A- 9	3.1	471/502	612/653	4424/4722	0/ 0	0
III A-10	3.1	465/495	592/649	4401/4821	0/ 0	0
III A-11	3.2	470/501	598/632	4437/4657	0/ 0	0
III A-12	3.2	464/494	606/640	3826/4042	0/ 0	0
III A-13	3.3	462/492	611/643	3841/4041	0/ 0	0
III A-14	3.3	595/633	678/714	5620/5909	0/ 0	0
III A-15	3.3	588/627	672/711	4977/5261	0/ 0	0
III A-16	3.2	453/483	612/652	5138/5411	0/ 0	0
III A-17	3.2	480/511	601/639	4449/4734	0/ 0	0
III A-18	3.1	579/617	653/720	6623/7287	0/ 0	0
III A-19	3.1	286/304	554/606	2580/2825	0/ 0	0
III A-20	3.1	309/329	570/618	3343/3629	0/ 0	0
III A-21	[illegible]	266/283	577/626	1972/2139	0/ 0	0
III B- 1	3.1	460/491	596/647	3298/3579	1065/1158	0
III B- 2	3.1	463/493	588/639	2334/2530	2060/2238	0
III B- 3	3.0	447/476	571/621	1698/1842	2725/2961	0
III B- 4	3.0	452/481	585/632	3306/3571	1034/1118	0
III B- 5	3.1	464/494	582/624	2342/2509	2072/2224	0
III B- 6	3.1	470/501	574/616	1708/1830	2716/2915	0
III B- 7	3.2	453/482	450/481	2316/2470	2103/2246	0
III B- 8	3.2	472/503	617/657	1757/1867	2701/2878	0
III B- 9	3.1	468/499	612/654	2331/2489	2084/2230	0
III B-10	3.1	458/488	586/640	3269/3564	1074/1172	0
III B-11	3.1	458/488	586/640	2261/2466	2108/2304	0
III B-12	3.1	453/483	575/629	1701/1841	2716/2949	0
III B-13	3.2	481/513	606/635	2375/2512	2118/2243	0
III B-14	3.2	482/513	590/624	1479/1559	3088/3265	0
III B-15	3.2	450/479	598/631	2702/2851	987/1043	0
III B-16	3.2	451/480	591/621	1779/1868	1955/2055	0
III B-17	3.3	462/492	602/631	2840/2579	990/1039	0
III B-18	3.2	587/620	675/712	4205/4433	1359/1435	0
III B-19	3.2	590/629	668/702	3102/3254	2519/2646	0
III B-20	3.2	577/615	682/722	4193/4435	1378/1460	0
III B-21	3.3	590/629	673/709	3713/3916	1243/1313	0
III B-22	3.3	582/621	665/708	2420/2578	2514/2679	0
III B-23	3.3	572/605	678/726	3694/3951	1236/1324	0
III B-24	3.2	453/482	605/643	3262/3464	1877/1997	0
III B-25	3.2	448/477	612/652	3258/3466	1856/1979	0
III B-26	3.2	474/505	614/654	3356/3571	1078/1148	0
III B-27	3.1	583/621	669/711	4516/4944	2058/2261	0
III B-28	3.1	573/610	659/727	4534/4984	2055/2268	0
III B-29	3.1	299/318	570/623	1588/1737	1002/1096	0
III B-30	3.1	302/321	559/612	1618/1774	969/1061	0
III B-31	3.1	306/326	565/620	2088/2274	1268/1382	0
III B-32	3.1	301/321	570/619	2093/2274	1264/1374	0
III C- 1	3.1	463/493	594/637	2266/2427	2090/2243	686
III C- 2	3.1	466/497	619/662	2319/2473	2110/2254	1251
III C- 3	3.1	463/494	633/676	2230/2378	2071/2212	1281
III C- 4	3.2	475/507	604/638	2347/2475	2162/2284	654
III C- 5	3.2	455/485	599/629	2724/2855	986/1036	358
III C- 6	3.2	582/620	667/707	4548/4816	1022/1084	716
III D- 1	3.2	447/476	606/644	3421/3643	0/ 0	0
III D- 2	3.2	486/518	575/616	3420/3642	0/ 0	0

TABLE C.10

TWO STAGE COMBUSTION TESTS (SERIES III FOR 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 (%)
III A- 1	115.0	51.56	615	0.0	115.0
III A- 2	135.1	53.99	625	0.0	135.1
III A- 3	103.5	66.65	613	0.0	103.5
III A- 4	111.8	64.84	625	0.0	111.8
III A- 5	140.9	66.57	650	0.0	140.9
III A- 6	114.9	30.26	553	0.0	114.9
III A- 7	136.0	31.83	580	0.0	136.0
III A- 8	113.7	51.56	610	0.0	113.7
III A- 9	115.5	51.72	607	0.0	115.5
III A-10	116.0	51.24	612	0.0	116.0
III A-11	115.6	51.64	614	0.0	115.6
III A-12	103.1	50.22	586	0.0	103.1
III A-13	103.9	50.14	597	0.0	103.9
III A-14	114.7	65.39	628	0.0	114.7
III A-15	103.9	63.90	615	0.0	103.9
III A-16	137.0	51.17	632	0.0	137.0
III A-17	113.6	52.74	621	0.0	113.6
III A-18	136.0	65.55	649	0.0	136.0
III A-19	117.7	31.44	568	0.0	117.7
III A-20	136.0	34.66	586	0.0	136.0
III A-21	102.6	28.65	525	0.0	102.6
III B- 1	116.3	49.04	606	0.0	91.3
III B- 2	116.3	47.95	604	0.0	68.2
III B- 3	120.6	45.15	624	0.0	54.8
III B- 4	117.7	48.18	614	0.0	93.0
III B- 5	116.3	48.02	635	0.0	68.0
III B- 6	114.8	47.63	644	0.0	52.4
III B- 7	116.1	46.69	629	0.0	65.9
III B- 8	116.0	47.86	623	0.0	54.2
III B- 9	116.6	48.26	619	0.0	67.9
III B-10	116.3	48.65	602	0.0	90.9
III B-11	117.0	47.24	627	0.0	67.2
III B-12	119.1	45.90	638	0.0	54.1
III B-13	114.3	49.67	617	0.0	66.7
III B-14	115.6	48.57	644	0.0	68.1
III B-15	102.8	47.16	587	0.0	79.1
III B-16	103.5	46.06	614	0.0	56.7
III B-17	103.6	48.26	572	0.0	80.5
III B-18	116.0	61.95	617	0.0	90.7
III B-19	115.3	61.30	647	0.0	65.1
III B-20	117.2	61.70	636	0.0	91.3
III B-21	103.2	62.17	621	0.0	80.4
III B-22	104.0	59.57	635	0.0	57.3
III B-23	106.1	60.26	605	0.0	82.7
III B-24	137.0	48.19	625	0.0	92.1
III B-25	137.5	47.63	625	0.0	93.1
III B-26	114.9	50.38	604	0.0	90.4
III B-27	134.1	62.56	647	0.0	95.8
III B-28	136.5	61.70	646	0.0	96.0
III B-29	113.4	31.28	586	0.0	77.4
III B-30	112.0	31.36	550	0.0	77.4
III B-31	137.5	32.46	553	0.0	93.3
III B-32	139.9	31.99	586	0.0	94.8
III C- 1	115.6	47.00	553	11.8	66.7
III C- 2	116.5	48.96	583	21.2	68.0
III C- 3	115.0	49.04	618	22.2	66.7
III C- 4	116.1	48.49	552	11.1	67.0
III C- 5	102.1	47.47	575	7.1	78.7
III C- 6	116.0	62.17	623	9.9	97.3
III D- 1	97.2	48.10	587	0.0	97.2
III D- 2	88.9	51.72	575	0.0	86.9

TABLE C.11

TWO STAGE COMBUSTION TESTS (SERIES III FOR COAL)

NOX MEASUREMENTS

ORIGINAL SERIES - RUN #-S	PPM NOX 3% O2, DRY: NCIR	PPM NOX 3% O2, DRY: TECO	PPM NOX 3% O2, DRY: WHIT	PPM NOX IN DRY, 3% O2 FLUE GAS	LB. NOX / 10**6 BTU INPUT
III A- 1	872	893	914	882 ± 15	0.90 ± .02
III A- 2	1041	1060	1031	1051 ± 13	1.24 ± .02
III A- 3	569	591	602	580 ± 16	0.54 ± .01
III A- 4	517	962	533	539 ± 32	0.54 ± .03
III A- 5	1101	1145	1128	1123 ± 31	1.38 ± .04
III A- 6	615	634	638	624 ± 14	0.64 ± .01
III A- 7	854	877	859	865 ± 17	1.01 ± .02
III A- 8	837	823	819	830 ± 10	0.83 ± .01
III A- 9	784	810	945	797 ± 18	0.80 ± .02
III A-10	879	859	954	869 ± 14	0.90 ± .01
III A-11	760	770	810	765 ± 7	0.76 ± .01
III A-12	530	538	544	534 ± 6	0.48 ± .01
III A-13	625	656	660	641 ± 22	0.58 ± .02
III A-14	874	895	899	885 ± 15	0.87 ± .01
III A-15	594	589	634	591 ± 4	0.53 ± .0
III A-16	942	942	967	942 ± 0	1.10 ± .0
III A-17	737	742	786	739 ± 3	0.73 ± .0
III A-18	589	1013	1035	1001 ± 17	1.20 ± .02
III A-19	603	607	638	605 ± 3	0.63 ± .0
III A-20	771	770	828	770 ± 1	0.91 ± .0
III A-21	302	286	332	294 ± 11	0.27 ± .01
III B- 1	683	672	659	677 ± 8	0.65 ± .01
III B- 2	494	482	480	488 ± 9	0.50 ± .01
III B- 3	511	499	505	505 ± 9	0.54 ± .01
III B- 4	711	710	699	711 ± 0	0.71 ± .0
III B- 5	351	335	357	343 ± 11	0.35 ± .01
III B- 6	302	289	302	295 ± 9	0.30 ± .01
III B- 7	463	471	577	467 ± 6	0.47 ± .01
III B- 8	361	358	356	359 ± 2	0.36 ± .0
III B- 9	432	432	419	432 ± 0	0.44 ± .0
III B-10	723	743	748	733 ± 14	0.75 ± .01
III B-11	384	387	394	385 ± 2	0.40 ± .0
III B-12	349	351	358	350 ± 2	0.37 ± .0
III B-13	381	368	379	374 ± 9	0.37 ± .01
III B-14	390	387	401	389 ± 2	0.39 ± .0
III B-15	387	412	391	399 ± 19	0.36 ± .02
III B-16	278	288	292	283 ± 8	0.25 ± .01
III B-17	363	379	391	371 ± 11	0.33 ± .01
III B-18	681	705	762	693 ± 18	0.69 ± .02
III B-19	402	417	421	409 ± 11	0.40 ± .01
III B-20	657	656	634	656 ± 1	0.66 ± .0
III B-21	531	517	552	524 ± 10	0.47 ± .01
III B-22	338	331	367	334 ± 5	0.30 ± .0
III B-23	465	473	490	465 ± 6	0.44 ± .01
III B-24	665	709	738	684 ± 29	0.61 ± .03
III B-25	668	702	718	685 ± 24	0.61 ± .03
III B-26	670	679	721	674 ± 7	0.67 ± .01
III B-27	756	819	825	807 ± 16	0.55 ± .02
III B-28	835	853	890	844 ± 12	1.02 ± .01
III B-29	288	275	289	282 ± 9	0.28 ± .01
III B-30	368	356	362	362 ± 9	0.36 ± .01
III B-31	411	408	359	410 ± 2	0.49 ± .0
III B-32	526	523	521	524 ± 2	0.64 ± .0
III C- 1	329	311	329	320 ± 13	0.32 ± .01
III C- 2	466	464	462	465 ± 2	0.47 ± .0
III C- 3	383	350	382	366 ± 23	0.37 ± .02
III C- 4	422	399	441	411 ± 16	0.41 ± .02
III C- 5	322	324	323	323 ± 2	0.29 ± .0
III C- 6	666	645	708	655 ± 15	0.66 ± .02
III D- 1	382	372	438	377 ± 7	0.32 ± .01
III D- 2	210	196	341	203 ± 10	0.16 ± .01

TABLE C.12

TWO STAGE COMBUSTION TESTS (SERIES III FOR COAL)

OTHER MEASUREMENTS

ORIGINAL SERIES - RUN #-S	HUM. (MM WET)	BAR. (MM HG)	O2 %	PPM CO	PPM SO2	CO2 %	ASH %	C IN ASH %	N IN ASH %
III A- 1	5.6	739	3.0	50	2400	15.1	0.46	34.5	0.48
III A- 2	10.7	738	5.5	60	2050	12.8	0.84	49.1	0.67
III A- 3	11.5	738	0.8	1000	2800	----	----	----	----
III A- 4	10.8	738	2.5	80	2550	----	----	----	----
III A- 5	10.4	737	6.1	160	2100	12.8	1.71	39.0	0.58
III A- 6	12.5	737	3.0	350	2350	----	[illegible]	24.4	0.32
III A- 7	11.4	736	5.6	115	1900	----	----	----	----
III A- 8	8.6	724	2.8	90	2375	----	----	----	----
III A- 9	5.5	729	3.1	500	2725	14.9	1.01	34.1	----
III A-10	11.2	747	3.1	0	2700	----	----	----	----
III A-11	4.2	736	3.1	225	2775	14.0	----	----	----
III A-12	4.9	736	0.8	3000	2950	----	----	----	----
III A-13	3.3	738	0.9	1340	2950	----	----	----	----
III A-14	3.3	737	3.0	1035	2850	15.1	----	----	----
III A-15	4.1	742	0.9	1375	5000	----	----	----	----
III A-16	5.3	741	5.7	200	2400	----	----	----	----
III A-17	5.1	741	2.9	260	2450	14.3	----	----	----
III A-18	12.6	724	5.6	165	2140	----	----	----	----
III A-19	10.5	723	3.4	210	2515	----	----	----	----
III A-20	8.6	721	5.6	240	2175	----	----	----	----
III A-21	8.4	721	0.4	7000	2515	----	----	----	----
III B- 1	8.8	724	3.2	115	2350	----	----	----	----
III B- 2	8.9	724	3.2	140	2400	15.0	----	----	----
III B- 3	5.2	724	3.8	130	2325	----	----	----	----
III B- 4	7.8	724	3.4	170	2200	----	----	----	----
III B- 5	6.1	725	3.2	175	2275	14.7	0.63	37.7	----
III B- 6	6.5	726	3.0	475	2250	14.8	0.98	60.6	----
III B- 7	5.5	729	3.2	650	2650	14.9	----	----	----
III B- 8	5.1	729	3.2	1050	2625	14.7	1.04	35.1	----
III B- 9	5.8	729	3.2	1125	2625	14.5	----	----	----
III B-10	10.0	737	3.2	300	2850	----	----	----	----
III B-11	10.3	736	3.3	285	2975	----	----	----	----
III B-12	9.0	736	3.6	300	3050	----	----	----	----
III B-13	4.2	736	2.9	205	2800	14.1	----	----	----
III B-14	4.0	736	3.1	210	2925	----	----	----	----
III B-15	3.7	737	0.8	4000	2800	16.0	0.94	30.7	----
III B-16	3.2	737	0.9	3250	2700	16.0	1.24	14.9	----
III B-17	2.9	737	0.9	2600	2800	----	----	----	----
III B-18	3.7	737	3.2	1175	2850	----	1.59	33.1	----
III B-19	3.2	737	3.1	1100	2600	----	----	----	----
III B-20	4.2	737	3.4	1600	2525	14.2	1.21	31.1	----
III B-21	3.8	743	0.8	2350	4000	15.9	2.42	45.6	0.44
III B-22	5.3	742	0.9	1000	3050	16.2	2.11	49.1	0.89
III B-23	6.1	742	1.5	4000	2650	----	----	----	----
III B-24	4.9	741	5.7	200	2500	----	----	----	----
III B-25	5.3	741	5.6	250	2450	----	1.15	25.8	0.42
III B-26	5.1	741	4.0	260	3000	----	----	----	----
III B-27	11.4	724	5.4	200	2325	12.4	----	----	----
III B-28	12.6	723	5.7	210	2255	12.2	1.11	31.9	----
III B-29	10.3	721	2.9	2400	2790	----	0.53	36.2	----
III B-30	10.9	721	2.6	1500	2475	----	----	----	----
III B-31	5.5	721	5.8	285	2175	----	----	----	----
III B-32	8.5	721	6.0	285	2175	[illegible]	1.19	15.8	----
III C- 1	6.4	727	4.1	240	2025	----	1.02	45.8	----
III C- 2	5.6	729	3.3	310	2625	14.4	----	----	----
III C- 3	5.6	730	3.0	0	2475	----	----	----	----
III C- 4	4.5	736	3.2	660	2900	----	0.88	24.5	----
III C- 5	3.0	737	0.6	2050	2650	----	----	----	----
III C- 6	4.4	737	3.2	900	2650	----	1.59	35.5	----
III D- 1	5.1	741	0.0	12000	2700	----	1.04	51.7	0.64
III D- 2	5.1	741	0.0	47000	1600	----	----	64.7	0.76

TABLE C.13

NATURAL GAS TESTS (SERIES IV A)

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
IV A- 1	0.0	261/261	0/ 0	4909/5220	0/ 0	0
IV A- 2	0.0	262/262	0/ 0	5915/6286	0/ 0	0
IV A- 3	0.0	266/266	0/ 0	4508/4795	0/ 0	0
IV A- 4	0.0	319/319	0/ 0	6042/6457	0/ 0	0
IV A- 5	0.0	310/310	0/ 0	7054/7524	0/ 0	0
IV A- 6	0.0	324/324	0/ 0	5497/5854	0/ 0	0
IV A- 7	0.0	176/176	0/ 0	3291/3517	0/ 0	0
IV A- 8	0.0	171/171	0/ 0	3883/4158	0/ 0	0
IV A- 9	0.0	178/178	0/ 0	3007/3216	0/ 0	0
IV A- 10	0.0	260/260	0/ 0	4878/5216	0/ 0	0
IV A- 11	0.0	260/260	0/ 0	5794/6152	0/ 0	0
IV A- 12	0.0	266/266	0/ 0	4518/4832	0/ 0	0
IV A- 13	0.0	325/325	0/ 0	6090/6485	0/ 0	0
IV A- 14	0.0	321/321	0/ 0	7162/7607	0/ 0	0
IV A- 15	0.0	332/332	0/ 0	5632/5980	0/ 0	0
IV A- 16	0.0	168/168	0/ 0	3145/3346	0/ 0	0
IV A- 17	0.0	167/167	0/ 0	2856/3041	0/ 0	0
IV A- 18	0.0	176/176	0/ 0	3931/4170	0/ 0	0
IV A- 19	0.0	262/262	0/ 0	4987/5310	0/ 0	1512
IV A- 20	0.0	262/262	0/ 0	4996/5320	0/ 0	809
IV A- 21	0.0	259/259	0/ 0	5841/6203	0/ 0	1595
IV A- 22	0.0	264/264	0/ 0	4515/4802	0/ 0	1677
IV A- 23	0.0	265/265	0/ 0	4514/4801	0/ 0	1336
IV A- 24	0.0	328/328	0/ 0	6181/6562	0/ 0	1890
IV A- 25	0.0	170/170	0/ 0	2880/3066	0/ 0	988
IV A- 26	0.0	264/264	0/ 0	5038/5247	0/ 0	0
IV A- 27	0.0	265/265	0/ 0	3801/3962	1221/1274	0
IV A- 28	0.0	270/270	0/ 0	3813/3974	1217/1270	1513
IV A- 29	0.0	267/267	0/ 0	3789/3953	1241/1256	1441
IV A- 30	0.0	264/264	0/ 0	2676/2790	2387/2451	0
IV A- 31	0.0	264/264	0/ 0	2625/2735	2456/2563	1286
IV A- 32	0.0	266/266	0/ 0	3727/3885	1288/1343	0
IV A- 33	0.0	264/264	0/ 0	3770/3929	1235/1293	1428
IV A- 34	0.0	264/264	0/ 0	3793/3953	1216/1269	1457
IV A- 35	0.0	191/191	0/ 0	1659/1729	1604/1673	0
IV A- 36	0.0	259/259	0/ 0	2833/2951	1609/1678	1132
IV A- 37	0.0	321/321	0/ 0	7240/7538	0/ 0	0
IV A- 38	0.0	325/325	0/ 0	4670/4853	2517/2677	0
IV A- 39	0.0	323/323	0/ 0	4660/4834	2629/2732	1430
IV A- 40	0.0	265/265	0/ 0	5046/5242	0/ 0	0
IV A- 41	0.0	303/303	0/ 0	4955/5147	0/ 0	0
IV A- 42	0.0	354/354	0/ 0	4955/5147	0/ 0	0
IV A- 43	0.0	337/337	0/ 0	4237/4402	0/ 0	0
IV A- 44	0.0	262/262	0/ 0	4886/5327	0/ 0	0
IV A- 45	0.0	265/265	0/ 0	4885/5338	0/ 0	0
IV A- 46	0.0	265/265	0/ 0	4498/4915	0/ 0	0
IV A- 47	0.0	264/264	0/ 0	4515/4929	0/ 0	0
IV A- 48	0.0	258/258	0/ 0	5835/6326	0/ 0	0
IV A- 49	0.0	260/260	0/ 0	5836/6315	0/ 0	0

TABLE C.14

NATURAL GAS TESTS (SERIES IV A)

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 (%)
IV A- 1	114.3	55.41	695	0.0	114.3
IV A- 2	137.1	56.58	696	0.0	137.1
IV A- 3	102.4	55.80	685	0.0	102.4
IV A- 4	115.0	67.91	703	0.0	115.0
IV A- 5	138.0	67.67	709	0.0	138.0
IV A- 6	103.1	68.06	700	0.0	103.1
IV A- 7	113.7	37.10	664	0.0	113.7
IV A- 8	138.0	37.02	673	0.0	138.0
IV A- 9	102.7	37.18	665	0.0	102.7
IV A- 10	113.7	51.72	351	0.0	113.7
IV A- 11	135.3	52.19	358	0.0	135.3
IV A- 12	103.1	52.58	345	0.0	103.1
IV A- 13	113.7	64.45	345	0.0	113.7
IV A- 14	135.3	64.29	346	0.0	135.3
IV A- 15	103.1	85.35	344	0.0	103.1
IV A- 16	113.7	33.32	360	0.0	113.7
IV A- 17	104.0	32.77	333	0.0	104.0
IV A- 18	135.3	35.13	326	0.0	135.3
IV A- 19	115.7	57.37	684	27.1	115.7
IV A- 20	115.6	56.75	686	14.5	115.6
IV A- 21	137.1	56.08	691	24.7	137.1
IV A- 22	103.7	57.37	679	33.1	103.7
IV A- 23	103.3	57.14	676	26.4	103.3
IV A- 24	114.3	71.91	686	27.4	114.3
IV A- 25	112.7	36.54	644	30.5	102.7
IV A- 26	115.7	56.27	651	0.0	115.7
IV A- 27	115.0	54.23	662	0.0	87.0
IV A- 28	113.1	56.50	660	27.4	65.7
IV A- 29	114.4	53.92	649	26.1	86.1
IV A- 30	116.3	52.56	658	0.0	61.4
IV A- 31	117.0	51.72	663	23.1	60.4
IV A- 32	114.4	54.47	685	0.0	65.0
IV A- 33	115.0	55.65	660	26.0	86.5
IV A- 34	115.0	53.60	664	26.6	87.1
IV A- 35	103.6	37.80	712	0.0	52.6
IV A- 36	104.2	51.24	661	23.2	66.4
IV A- 37	137.1	69.79	696	0.0	137.1
IV A- 38	135.2	66.88	711	0.0	67.2
IV A- 39	137.1	65.79	688	19.1	87.6
IV A- 40	115.7	56.27	688	0.0	115.7
IV A- 41	99.4	64.27	688	0.0	99.4
IV A- 42	64.5	73.01	688	0.0	64.5
IV A- 43	76.4	68.77	688	0.0	76.4
IV A- 44	113.1	55.68	653	0.0	113.1
IV A- 45	111.9	56.43	655	0.0	111.9
IV A- 46	103.1	55.88	699	0.0	103.1
IV A- 47	103.7	55.60	651	0.0	103.7
IV A- 48	137.1	56.43	[illegible]	0.0	137.1
IV A- 49	136.2	55.75	700	0.0	[illegible]

TABLE C.15

NATURAL GAS TESTS (SERIES IV A)

NOX MEASUREMENTS

ORIGINAL SERIES - RUN #-S	PPM NOX 3% O2, DRY NCIR	PPM NOX 3% O2, DRY TECO	PPM NOX 3% O2, DRY WHIT	PPM NOX IN DRY, 3% O2 FLUE GAS	LB. NOX / 10**6 BTU INPUT
IV A- 1	326	319	350	322 ± 5	0.28 ± .0
IV A- 2	323	317	349	320 ± 4	0.33 ± .0
IV A- 3	269	265	294	267 ± 3	0.21 ± .0
IV A- 4	308	308	345	308 ± 0	0.27 ± .0
IV A- 5	310	309	352	310 ± 1	0.33 ± .0
IV A- 6	250	248	284	249 ± 2	0.20 ± .0
IV A- 7	300	307	339	303 ± 5	0.27 ± .0
IV A- 8	307	315	343	311 ± 6	0.33 ± .01
IV A- 9	245	245	272	245 ± 0	0.20 ± .0
IV A- 10	150	146	149	148 ± 3	0.13 ± .0
IV A- 11	139	131	128	135 ± 6	0.14 ± .01
IV A- 12	127	119	127	123 ± 6	0.10 ± .0
IV A- 13	145	143	149	144 ± 1	0.13 ± .0
IV A- 14	130	125	139	127 ± 4	0.13 ± .0
IV A- 15	125	123	128	124 ± 1	0.10 ± .0
IV A- 16	160	153	167	156 ± 5	0.14 ± .0
IV A- 17	111	106	121	109 ± 3	0.09 ± .0
IV A- 18	142	136	150	139 ± 4	0.14 ± .0
IV A- 19	43	45	59	44 ± 2	0.04 ± .0
IV A- 20	79	70	88	74 ± 7	0.07 ± .01
IV A- 21	51	42	63	47 ± 7	0.05 ± .01
IV A- 22	63	56	73	60 ± 5	0.05 ± .0
IV A- 23	36	30	46	33 ± 4	0.03 ± .0
IV A- 24	65	43	59	54 ± 16	0.05 ± .01
IV A- 25	27	21	37	24 ± 4	0.02 ± .0
IV A- 26	342	350	346	346 ± 6	0.30 ± .0
IV A- 27	252	260	259	256 ± 5	0.22 ± .0
IV A- 28	22	25	27	23 ± 2	0.02 ± .0
IV A- 29	176	180	172	178 ± 3	0.15 ± .0
IV A- 30	90	90	89	90 ± 0	0.08 ± .0
IV A- 31	53	53	53	53 ± 0	0.05 ± .0
IV A- 32	310	311	309	310 ± 0	0.27 ± .0
IV A- 33	29	28	31	28 ± 1	0.02 ± .0
IV A- 34	225	216	220	220 ± 7	0.19 ± .01
IV A- 35	112	127	92	120 ± 10	0.09 ± .01
IV A- 36	72	68	71	70 ± 3	0.06 ± .0
IV A- 37	325	335	322	330 ± 7	0.34 ± .01
IV A- 38	268	271	265	269 ± 2	0.27 ± .0
IV A- 39	197	199	195	198 ± 1	0.20 ± .0
IV A- 40	366	363	359	365 ± 2	0.32 ± .0
IV A- 41	250	252	261	251 ± 2	0.19 ± .0
IV A- 42	129	129	176	128 ± 1	0.08 ± .0
IV A- 43	53	53	412	53 ± 0	0.03 ± .0
IV A- 44	332	332	354	332 ± 1	0.30 ± .0
IV A- 45	238	233	252	235 ± 4	0.21 ± .0
IV A- 46	199	189	211	194 ± 7	0.16 ± .01
IV A- 47	283	272	303	278 ± 8	0.23 ± .01
IV A- 48	320	307	336	314 ± 9	0.33 ± .01
IV A- 49	285	281	294	283 ± 3	0.30 ± .0

TABLE C.16

NATURAL GAS TESTS (SERIES IV A)

OTHER MEASUREMENTS

ORIGINAL SERIES - RUN #-S	NOM. INP (MWT)	BAR. (MM HG)	O2 %	PPM CO	PPM SO2	CO2 %	ASH %	C IN ASH %	N IN ASH %
IV A- 1	5.0	736	2.9	150	0	----	----	----	----
IV A- 2	5.0	736	5.8	103	0	----	----	----	----
IV A- 3	5.0	735	0.6	113	0	----	----	----	----
IV A- 4	5.9	734	3.0	70	0	----	----	----	----
IV A- 5	5.7	733	5.9	53	0	----	----	----	----
IV A- 6	5.3	733	0.7	810	0	----	----	----	----
IV A- 7	5.6	732	2.8	40	0	----	----	----	----
IV A- 8	6.1	732	5.9	40	0	----	----	----	----
IV A- 9	5.8	731	0.6	690	0	----	----	----	----
IV A- 10	5.8	730	2.8	40	0	----	----	----	----
IV A- 11	5.8	730	5.6	40	0	----	----	----	----
IV A- 12	5.8	729	0.7	1070	0	----	----	----	----
IV A- 13	5.2	728	2.8	35	0	----	----	----	----
IV A- 14	4.8	728	5.6	50	0	8.3	----	----	----
IV A- 15	4.8	728	0.7	1020	0	----	----	----	----
IV A- 16	4.8	729	2.8	23	0	----	----	----	----
IV A- 17	4.8	729	0.9	960	0	----	----	----	----
IV A- 18	5.1	729	5.6	15	0	----	----	----	----
IV A- 19	5.2	728	3.1	7	0	----	----	----	----
IV A- 20	5.2	728	3.1	22	0	----	----	----	----
IV A- 21	4.8	728	5.8	22	0	----	----	----	----
IV A- 22	4.9	728	0.9	200	0	----	----	----	----
IV A- 23	4.5	728	0.7	133	0	----	----	----	----
IV A- 24	4.8	728	2.5	22	0	----	----	----	----
IV A- 25	5.0	728	0.6	480	0	----	----	----	----
IV A- 26	2.1	737	3.1	0	0	----	----	----	----
IV A- 27	2.2	738	3.0	0	0	----	----	----	----
IV A- 28	2.2	738	2.7	3	0	----	----	----	----
IV A- 29	2.3	738	2.9	7	0	----	----	----	----
IV A- 30	2.3	738	3.2	40	0	----	----	----	----
IV A- 31	2.3	738	3.3	8	0	----	----	----	----
IV A- 32	2.2	738	2.9	0	0	----	----	----	----
IV A- 33	2.2	738	3.0	0	0	----	----	----	----
IV A- 34	2.2	738	3.0	0	0	----	----	----	----
IV A- 35	2.2	739	0.8	760	0	----	----	----	----
IV A- 36	2.2	739	0.9	321	0	----	----	----	----
IV A- 37	2.2	739	5.8	0	0	----	----	----	----
IV A- 38	2.0	739	5.6	0	0	----	----	----	----
IV A- 39	1.9	740	5.8	0	0	----	----	----	----
IV A- 40	1.9	740	3.1	0	0	----	----	----	----
IV A- 41	1.9	740	0.4	10500	0	----	----	----	----
IV A- 42	1.9	740	0.0	64038	0	----	----	----	----
IV A- 43	1.9	740	0.0	151622	0	----	----	----	----
IV A- 44	10.1	743	2.7	22	0	----	----	----	----
IV A- 45	10.5	743	2.5	19	0	----	----	----	----
IV A- 46	10.7	743	0.7	675	0	----	----	----	----
IV A- 47	10.3	743	0.8	460	0	----	----	----	----
IV A- 48	9.0	743	5.8	15	0	----	----	----	----
IV A- 49	8.7	743	5.7	15	0	----	----	----	----

TABLE C.17

OIL TESTS (SERIES IV B)

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
IV B- 1	0.0	320/320	0/ 0	4955/5385	0/ 0	0
IV B- 2	0.0	314/314	0/ 0	4951/5366	0/ 0	0
IV B- 3	0.0	314/314	0/ 0	4950/5372	0/ 0	0
IV B- 4	0.0	317/317	0/ 0	4493/4871	0/ 0	0
IV B- 5	0.0	316/316	0/ 0	4492/4877	0/ 0	0
IV B- 6	0.0	320/320	0/ 0	5798/6265	0/ 0	0
IV B- 7	0.0	320/320	0/ 0	5791/6249	0/ 0	0
IV B- 8	0.0	310/310	0/ 0	4890/5244	0/ 0	0
IV B- 9	0.0	321/321	0/ 0	5749/6206	0/ 0	0
IV B- 10	0.0	311/311	0/ 0	4413/4777	0/ 0	0
IV B- 11	0.0	385/385	0/ 0	6063/6547	0/ 0	0
IV B- 12	0.0	405/405	0/ 0	7047/7595	0/ 0	0
IV B- 13	0.0	385/385	0/ 0	5420/5854	0/ 0	0
IV B- 14	0.0	201/201	0/ 0	3134/3387	0/ 0	0
IV B- 15	0.0	212/212	0/ 0	3764/4100	0/ 0	0
IV B- 16	0.0	196/196	0/ 0	2781/3018	0/ 0	0
IV B- 17	0.0	306/306	0/ 0	4854/5275	0/ 0	0
IV B- 18	0.0	325/325	0/ 0	5732/6234	0/ 0	0
IV B- 19	0.0	312/312	0/ 0	4459/4852	0/ 0	0
IV B- 20	0.0	200/200	0/ 0	3122/3408	0/ 0	0
IV B- 21	0.0	201/201	0/ 0	3606/3926	0/ 0	0
IV B- 22	0.0	385/385	0/ 0	5961/6452	0/ 0	0
IV B- 23	0.0	382/382	0/ 0	5411/5886	0/ 0	0
IV B- 24	0.0	399/399	0/ 0	6957/7607	0/ 0	0
IV B- 25	0.0	307/307	0/ 0	4864/5283	0/ 0	0
IV B- 26	0.0	305/305	0/ 0	4870/5300	0/ 0	1449
IV B- 27	0.0	303/303	0/ 0	4856/5291	0/ 0	819
IV B- 28	0.0	318/318	0/ 0	5652/6157	0/ 0	1543
IV B- 29	0.0	307/307	0/ 0	4390/4796	0/ 0	739
IV B- 30	0.0	307/307	0/ 0	4385/4788	0/ 0	1349
IV B- 31	0.0	383/383	0/ 0	6033/6573	0/ 0	1003
IV B- 32	0.0	382/382	0/ 0	6020/6569	0/ 0	0
IV B- 33	0.0	201/201	0/ 0	3143/3441	0/ 0	0
IV B- 34	0.0	194/194	0/ 0	2791/3063	0/ 0	658
IV B- 35	0.0	306/306	0/ 0	4846/5322	0/ 0	0
IV B- 36	0.0	303/303	0/ 0	3578/3915	1258/1380	0
IV B- 37	0.0	307/307	0/ 0	3556/3851	1258/1380	821
IV B- 38	0.0	304/304	0/ 0	3558/3901	1255/1379	1748
IV B- 39	0.0	306/306	0/ 0	2953/3242	1874/2063	0
IV B- 40	0.0	302/302	0/ 0	2946/3232	1873/2059	755
IV B- 41	0.0	310/310	0/ 0	4856/5270	0/ 0	0
IV B- 42	0.0	312/312	0/ 0	3644/3974	1213/1326	0
IV B- 43	0.0	310/310	0/ 0	3568/3914	1258/1383	814
IV B- 44	0.0	308/308	0/ 0	3596/3965	1205/1332	792
IV B- 45	0.0	303/303	0/ 0	3595/3970	1205/1334	769
IV B- 46	0.0	306/306	0/ 0	4351/4832	0/ 0	0
IV B- 47	0.0	305/305	0/ 0	2757/3053	1577/1749	0
IV B- 48	0.0	396/396	0/ 0	6940/7656	0/ 0	0
IV B- 49	0.0	393/393	0/ 0	4164/4556	2731/3030	0
IV B- 50	0.0	394/394	0/ 0	4159/4607	2752/3063	1157

TABLE C.18

OIL TESTS (SERIES IV B)

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 (%)
IV B- 1	113.1	53.37	653	0.0	113.1
IV B- 2	115.0	52.50	657	0.0	115.0
IV B- 3	115.0	52.50	651	0.0	115.0
IV B- 4	103.2	52.34	688	0.0	103.2
IV B- 5	103.8	52.11	686	0.0	103.8
IV B- 6	131.8	54.54	656	0.0	131.8
IV B- 7	131.8	54.54	701	0.0	131.8
IV B- 8	115.0	51.79	691	0.0	115.0
IV B- 9	130.8	54.54	656	0.0	130.8
IV B- 10	103.6	51.24	688	0.0	103.6
IV B- 11	115.0	64.37	655	0.0	115.0
IV B- 12	126.9	68.65	704	0.0	126.9
IV B- 13	102.8	63.50	696	0.0	102.8
IV B- 14	113.7	33.32	668	0.0	113.7
IV B- 15	129.8	35.84	674	0.0	129.8
IV B- 16	103.7	32.15	675	0.0	103.7
IV B- 17	115.6	47.86	386	0.0	115.6
IV B- 18	128.8	51.01	384	0.0	128.8
IV B- 19	104.1	47.54	331	0.0	104.1
IV B- 20	113.7	30.73	312	0.0	113.7
IV B- 21	130.8	30.57	306	0.0	130.8
IV B- 22	113.1	58.79	296	0.0	113.1
IV B- 23	103.3	58.32	301	0.0	103.3
IV B- 24	127.9	61.38	299	0.0	127.9
IV B- 25	115.6	51.40	698	0.0	115.6
IV B- 26	116.3	52.74	680	25.9	116.3
IV B- 27	117.0	51.64	686	14.6	117.0
IV B- 28	129.8	55.88	693	23.8	129.8
IV B- 29	104.2	51.56	679	14.5	104.2
IV B- 30	104.2	52.19	678	26.5	104.2
IV B- 31	115.0	65.31	655	14.4	115.0
IV B- 32	115.0	64.05	701	0.0	115.0
IV B- 33	114.3	33.40	669	0.0	114.3
IV B- 34	104.7	32.62	644	20.2	104.7
IV B- 35	115.6	51.32	652	0.0	115.6
IV B- 36	116.3	48.89	651	0.0	86.0
IV B- 37	114.3	50.06	670	14.7	84.4
IV B- 38	115.6	50.46	659	31.3	85.4
IV B- 39	115.0	48.34	700	0.0	70.3
IV B- 40	116.3	48.41	681	14.2	71.0
IV B- 41	114.3	51.79	700	0.0	114.3
IV B- 42	113.7	49.95	675	0.0	85.3
IV B- 43	113.7	49.04	651	14.5	84.0
IV B- 44	113.7	50.22	669	14.1	85.1
IV B- 45	115.6	48.26	666	13.7	86.5
IV B- 46	103.7	50.69	690	0.0	103.7
IV B- 47	103.6	47.94	690	0.0	65.9
IV B- 48	127.8	67.36	705	0.0	127.0
IV B- 49	127.8	62.72	710	0.0	77.0
IV B- 50	127.8	62.25	688	14.0	76.8

TABLE C.19

OIL TESTS (SERIES IV B)

NOX MEASUREMENTS

ORIGINAL SERIES - RUN #-S	PPM NOX 3% O2, DRY NCIR	TECO	WHIT	PPM NOX IN DRY, 3% O2 FLUE GAS	LB. NOX / 10**6 BTU INPUT
IV B- 1	253	262	253	257 ± 6	0.25 ± .01
IV B- 2	269	279	271	274 ± 7	0.27 ± .01
IV B- 3	290	310	310	300 ± 14	0.29 ± .01
IV B- 4	237	239	254	238 ± 1	0.21 ± .0
IV B- 5	211	208	222	210 ± 2	0.19 ± .0
IV B- 6	290	288	297	289 ± 1	0.32 ± .0
IV B- 7	343	343	352	343 ± 0	0.38 ± .0
IV B- 8	255	252	267	253 ± 2	0.24 ± .0
IV B- 9	285	284	292	284 ± 0	0.31 ± .0
IV B- 10	202	199	216	200 ± 2	0.18 ± .0
IV B- 11	280	278	297	279 ± 2	0.27 ± .0
IV B- 12	318	320	334	319 ± 2	0.34 ± .0
IV B- 13	222	222	244	222 ± 0	0.19 ± .0
IV B- 14	214	209	221	212 ± 4	0.20 ± .0
IV B- 15	247	243	246	245 ± 3	0.27 ± .0
IV B- 16	175	172	184	173 ± 2	0.15 ± .0
IV B- 17	223	214	225	219 ± 6	0.21 ± .01
IV B- 18	258	248	254	253 ± 7	0.27 ± .01
IV B- 19	178	170	178	174 ± 6	0.15 ± .0
IV B- 20	180	181	187	181 ± 0	0.17 ± .0
IV B- 21	215	221	212	218 ± 4	0.24 ± .0
IV B- 22	223	217	230	220 ± 5	0.21 ± .0
IV B- 23	186	178	194	182 ± 5	0.16 ± .0
IV B- 24	267	258	249	263 ± 7	0.28 ± .01
IV B- 25	262	258	273	260 ± 2	0.25 ± .0
IV B- 26	247	241	248	244 ± 4	0.24 ± .0
IV B- 27	238	232	248	235 ± 4	0.23 ± .0
IV B- 28	260	251	266	256 ± 6	0.28 ± .01
IV B- 29	151	194	197	193 ± 2	0.17 ± .0
IV B- 30	176	173	185	174 ± 2	0.16 ± .0
IV B- 31	252	252	267	252 ± 0	0.25 ± .0
IV B- 32	282	281	301	282 ± 1	0.28 ± .0
IV B- 33	216	212	222	214 ± 3	0.21 ± .0
IV B- 34	152	151	167	152 ± 1	0.14 ± .0
IV B- 35	256	255	273	255 ± 0	0.25 ± .0
IV B- 36	224	223	237	224 ± 1	0.22 ± .0
IV B- 37	206	201	214	203 ± 3	0.20 ± .0
IV B- 38	208	201	216	205 ± 5	0.20 ± .0
IV B- 39	176	173	181	175 ± 3	0.17 ± .0
IV B- 40	175	169	179	172 ± 4	0.17 ± .0
IV B- 41	264	259	269	262 ± 3	0.25 ± .0
IV B- 42	244	238	238	241 ± 5	0.23 ± .0
IV B- 43	216	209	214	213 ± 5	0.21 ± .01
IV B- 44	216	209	214	213 ± 5	0.21 ± .01
IV B- 45	201	156	159	198 ± 3	0.20 ± .0
IV B- 46	205	203	204	204 ± 2	0.18 ± .0
IV B- 47	147	143	148	145 ± 3	0.13 ± .0
IV B- 48	326	328	338	327 ± 2	0.36 ± .0
IV B- 49	236	234	245	235 ± 1	0.26 ± .0
IV B- 50	219	211	230	215 ± 6	0.24 ± .01

TABLE C.20

OIL TESTS (SERIES IV B)

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 %
IV B- 1	9.3	742	2.7	25	630	----	----	----	----
IV B- 2	8.7	742	3.0	22	645	----	----	----	----
IV B- 3	9.0	742	3.0	15	650	----	----	----	----
IV B- 4	8.7	742	0.7	260	760	----	----	----	----
IV B- 5	9.0	742	0.8	90	790	----	----	----	----
IV B- 6	8.5	742	5.8	15	575	----	----	----	----
IV B- 7	7.9	742	5.8	10	590	----	----	----	----
IV B- 8	6.5	744	3.0	60	875	----	----	----	----
IV B- 9	8.0	744	5.7	40	590	11.7	----	----	----
IV B- 10	8.3	744	0.8	600	810	----	----	----	----
IV B- 11	8.1	744	3.0	60	745	----	----	----	----
IV B- 12	7.8	744	5.3	60	665	----	----	----	----
IV B- 13	8.0	744	0.6	320	860	15.2	----	----	----
IV B- 14	7.9	744	2.8	60	790	----	----	----	----
IV B- 15	9.6	744	5.6	40	620	----	----	----	----
IV B- 16	8.7	743	0.8	543	815	----	----	----	----
IV B- 17	9.4	743	3.1	50	725	----	----	----	----
IV B- 18	9.5	743	4.5	55	610	----	----	----	----
IV B- 19	9.4	743	0.9	500	780	----	----	----	----
IV B- 20	10.0	743	2.8	70	725	----	----	----	----
IV B- 21	9.5	743	5.7	60	630	----	----	----	----
IV B- 22	8.4	743	2.7	70	750	----	----	----	----
IV B- 23	9.4	743	0.7	178	835	----	----	----	----
IV B- 24	9.6	743	5.4	80	645	----	----	----	----
IV B- 25	9.1	738	3.1	50	710	----	----	----	----
IV B- 26	9.6	738	3.2	45	730	----	----	----	----
IV B- 27	9.9	738	3.3	45	715	----	----	----	----
IV B- 28	10.0	738	5.6	45	645	----	----	----	----
IV B- 29	10.4	738	0.9	90	840	14.8	----	----	----
IV B- 30	10.3	738	0.9	140	855	----	----	----	----
IV B- 31	10.1	738	3.0	60	770	----	----	----	----
IV B- 32	10.4	738	3.0	90	780	----	----	----	----
IV B- 33	10.8	738	2.9	90	745	13.2	----	----	----
IV B- 34	11.3	738	1.0	140	830	----	----	----	----
IV B- 35	11.8	738	3.1	50	750	----	----	----	----
IV B- 36	11.0	738	3.2	50	750	----	----	----	----
IV B- 37	11.0	738	2.9	45	750	----	----	----	----
IV B- 38	11.5	738	3.1	55	770	----	----	----	----
IV B- 39	12.0	738	3.0	55	760	----	----	----	----
IV B- 40	11.8	737	3.2	80	745	----	----	----	----
IV B- 41	9.0	742	2.9	80	720	13.2	----	----	----
IV B- 42	10.2	742	2.8	80	735	----	----	----	----
IV B- 43	11.7	742	2.8	210	760	----	----	----	----
IV B- 44	13.1	742	2.8	80	780	----	----	----	----
IV B- 45	13.5	742	3.1	80	745	13.2	----	----	----
IV B- 46	14.8	742	0.8	135	840	----	----	----	----
IV B- 47	14.2	742	0.8	660	810	----	----	----	----
IV B- 48	13.6	741	5.4	115	605	11.8	----	----	----
IV B- 49	14.4	741	5.4	125	610	----	----	----	----
IV B- 50	15.6	741	5.4	127	580	----	----	----	----

TABLE C.21

SWIRL TESTS (SERIES V - A IS FOR NATURAL GAS AND B IS FOR 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
V A - 1	0.0	259/255	0/ 0	4854/5287	0/ 0	0
V A - 2	0.0	318/318	0/ 0	5996/6533	0/ 0	0
V A - 3	0.0	166/166	0/ 0	3097/3385	0/ 0	0
V A - 4	0.0	165/165	0/ 0	3096/3390	0/ 0	0
V A - 5	0.0	165/165	0/ 0	2810/3071	0/ 0	0
V A - 6	0.0	166/166	0/ 0	3697/4053	0/ 0	0
V A - 7	0.0	256/256	0/ 0	4796/5258	0/ 0	0
V A - 8	0.0	200/200	0/ 0	3375/3711	0/ 0	0
V A - 9	0.0	255/255	0/ 0	5713/6284	0/ 0	0
V A - 10	0.0	318/318	0/ 0	5949/6531	0/ 0	0
V A - 11	0.0	323/323	0/ 0	5469/6021	0/ 0	0
V A - 12	0.0	313/313	0/ 0	6982/7685	0/ 0	0
V B - 13	3.2	566/603	625/689	4103/4492	1311/1435	0
V B - 14	3.2	568/605	644/704	4119/4500	1307/1431	0
V B - 15	3.2	569/606	653/712	5417/5919	0/ 0	811
V B - 16	3.2	567/604	673/738	5414/5938	0/ 0	0
V B - 17	3.2	565/602	666/729	6338/6931	0/ 0	0
V B - 18	3.2	462/492	621/685	4317/4765	0/ 0	0
V B - 19	3.2	489/521	632/692	5390/5907	0/ 0	0
V B - 20	3.2	473/504	626/691	3912/4307	0/ 0	0

TABLE C.22

SWIRL TESTS (SERIES V - A IS FOR NATURAL GAS AND B IS FOR 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 (%)
V A - 1	113.7	55.17	693	0.0	113.7
V A - 2	114.3	67.91	701	0.0	114.3
V A - 3	113.1	35.21	675	0.0	113.1
V A - 4	113.7	34.57	670	0.0	113.7
V A - 5	103.2	34.50	663	0.0	103.2
V A - 6	135.2	36.00	680	0.0	135.2
V A - 7	113.7	54.47	693	0.0	113.7
V A - 8	102.6	41.57	695	0.0	102.6
V A - 9	136.2	55.65	699	0.0	136.2
V A - 10	113.7	67.83	704	0.0	113.7
V A - 11	102.8	68.19	698	0.0	102.8
V A - 12	135.2	68.46	705	0.0	135.2
V B - 13	115.5	60.52	632	0.0	90.4
V B - 14	115.6	60.60	628	0.0	90.7
V B - 15	115.5	63.74	640	11.2	115.5
V B - 16	116.1	62.72	632	0.0	116.1
V B - 17	134.1	63.74	645	0.0	134.1
V B - 18	115.3	50.93	613	0.0	115.3
V B - 19	133.1	54.94	629	0.0	133.1
V B - 20	103.6	51.40	607	0.0	103.6

TABLE C.23

SWIRL TESTS (SERIES V - A IS FOR NATURAL GAS AND B IS FOR COAL)

NOX MEASUREMENTS

ORIGINAL SERIES - RUN #-S	PPM NOX 3% O2, DRY NEIH	TECO	WHIT	PPM NOX IN DRY, 3% O2 FLUE GAS	LB. NOX / 10**6 BTU INPUT
V A - 1	332	329	339	330 ± 2	0.30 ± .0
V A - 2	329	329	339	329 ± 0	0.30 ± .0
V A - 3	285	280	289	283 ± 3	0.25 ± .0
V A - 4	263	259	266	261 ± 3	0.23 ± .0
V A - 5	215	209	215	212 ± 4	0.17 ± .0
V A - 6	277	273	278	275 ± 3	0.29 ± .0
V A - 7	272	267	275	269 ± 3	0.24 ± .0
V A - 8	233	227	233	230 ± 4	0.19 ± .0
V A - 9	267	262	264	265 ± 4	0.28 ± .0
V A - 10	272	269	275	270 ± 2	0.24 ± .0
V A - 11	239	240	245	239 ± 1	0.20 ± .0
V A - 12	248	242	248	245 ± 4	0.26 ± .0
V B - 13	656	660	637	658 ± 3	0.68 ± .0
V B - 14	643	655	625	649 ± 8	0.67 ± .01
V B - 15	731	723	665	717 ± 9	0.74 ± .01
V B - 16	778	803	738	791 ± 18	0.82 ± .02
V B - 17	947	994	965	971 ± 33	1.14 ± .04
V B - 18	743	758	796	750 ± 11	0.78 ± .01
V B - 19	912	956	972	934 ± 31	1.09 ± .04
V B - 20	547	564	606	556 ± 12	0.52 ± .01

TABLE C.24

SWIRL TESTS (SERIES V - A IS FOR NATURAL GAS AND B IS FOR COAL)

OTHER MEASUREMENTS

ORIGINAL SERIES - RUN #-S	HUM. (MM WET)	BAR. (MM WET)	O2 %	PPM CO	PPM SO2	CO2 %	ASH %	C IN ASH %	H IN ASH %
V A - 1	9.7	736	2.8	60	0	----	----	----	----
V A - 2	10.0	735	2.9	80	0	----	----	----	----
V A - 3	10.2	735	2.7	75	0	----	----	----	----
V A - 4	10.7	735	2.6	70	0	----	----	----	----
V A - 5	10.2	735	0.7	135	0	----	----	----	----
V A - 6	11.1	735	5.6	70	0	----	----	----	----
V A - 7	11.3	735	2.8	6	0	----	----	----	----
V A - 8	12.0	735	0.6	810	0	----	----	----	----
V A - 9	12.1	735	5.7	70	0	----	----	----	----
V A - 10	11.9	734	2.8	75	0	----	----	----	----
V A - 11	12.5	734	0.6	360	0	----	----	----	----
V A - 12	12.8	734	5.6	90	0	----	----	----	----
V B - 13	11.3	742	3.1	530	2450	----	----	----	----
V B - 14	10.7	742	3.1	75	2550	----	----	----	----
V B - 15	10.6	742	3.2	2500	2550	----	----	----	----
V B - 16	11.6	742	3.2	850	2700	----	----	----	----
V B - 17	11.1	742	5.4	200	2380	----	----	----	----
V B - 18	13.1	742	3.1	1050	2250	----	----	----	----
V B - 19	11.4	742	5.3	285	2380	----	----	----	----
V B - 20	12.4	742	0.5	2700	3050	----	----	----	----

TABLE C.25

QUENCH TESTS FOR COAL (SERIES VI)

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
VI - 1	3.1	465/495	571/618	4373/4736	0/ 0	0
VI - 2	3.1	465/495	587/633	3272/3524	1105/1192	0
VI - 3	3.1	464/494	587/635	3228/3490	1147/1242	0
VI - 4	3.1	458/488	579/627	4377/4732	0/ 0	547
VI - 5	3.1	501/534	597/635	5455/5891	0/ 0	0
VI - 6	3.1	441/470	595/642	3743/4036	0/ 0	0
VI - 7	3.1	563/600	645/700	5469/5893	0/ 0	0
VI - 8	3.1	556/593	598/644	6191/6670	0/ 0	0

TABLE C.26

QUENCH TESTS FOR COAL (SERIES VI)

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 (%)
VI - 1	114.9	51.24	623	0.0	114.9
VI - 2	115.4	49.36	609	0.0	89.7
VI - 3	115.4	49.51	607	0.0	88.7
VI - 4	116.9	51.09	616	9.3	116.9
VI - 5	130.4	56.27	639	0.0	130.4
VI - 6	106.1	48.10	607	0.0	106.1
VI - 7	117.5	62.25	634	0.0	117.5
VI - 9	132.0	62.80	655	0.0	132.0

TABLE C.27

QUENCH TESTS FOR COAL (SERIES VI)

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
VI - 1	650	725	738	707 ± 25	0.72 ± .03
VI - 2	546	565	564	555 ± 13	0.56 ± .01
VI - 3	572	570	562	571 ± 1	0.58 ± .0
VI - 4	609	597	616	603 ± 8	0.62 ± .01
VI - 5	832	826	920	829 ± 4	0.94 ± .0
VI - 6	557	553	577	545 ± 17	0.51 ± .02
VI - 7	782	751	774	766 ± 22	0.74 ± .02
VI - 8	876	922	935	899 ± 33	1.03 ± .04

TABLE C.28

QUENCH TESTS FOR COAL (SERIES VI)

OTHER MEASUREMENTS

ORIGINAL SERIES - RUN #-S	HUM. (MM WET)	BAR. (MM WET)	O2 %	PPM CO	PPM SO2	CO2 %	ASH %	C IN ASH %	H IN ASH %
VI - 1	8.3	733	3.0	289	2550	----	----	----	----
VI - 2	7.3	734	3.1	810	2650	----	----	----	----
VI - 3	8.0	735	3.1	660	2700	----	----	----	----
VI - 4	8.0	734	3.3	500	2800	----	----	----	----
VI - 5	7.8	734	5.0	421	2550	----	----	----	----
VI - 6	7.4	734	3.4	2229	3050	----	----	----	----
VI - 7	7.5	735	3.4	350	3050	----	----	----	----
VI - 8	7.5	735	5.2	720	2950	----	----	----	----

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	Range Mid	Range High
Excess Air, %	< 7.5	7.5- 25.	> 25.
Load, %	<100.	100. -125.*	>125.*
($kBTU/ft^3/hr$	< 40.	40. - 50.*	> 50.*)
Preheat, °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	Range Mid	Range High
Excess Air, %	∿ 3	∿ 15	∿ 35
Load, %	∿ 75	∿115	∿140
Preheat, °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 done from visual fitting and no mathematical correlation has been used.

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* For natural gas only, the value is 130% instead of 125% (or 52. $kBTU/ft^3/hr$ instead of 50. $kBTU/ft^3/hr$).

The simplest form of line has been drawn through the data points - straight where possible.

The graphical descriptions follow:

Graph #'s	Comments
1-3	Solid line - high preheat - curved line required Dotted line - low and mid preheat - curved line required
4-6	All data on graph described by one line
7-12	Normal mid air or mid load and high preheat line
13-18	Solid line - low range of air or load Dotted line - mid range Dash/dot line - high range
19-24	Normal mid air/mid load line
25-30	For excess air, a curve was used for data Solid line - low preheat Dotted line - high preheat
31-36	For all graphs except #31, one line was used to describe all data even though slight, differential, consistent trends do seem to exist. The line drawn follows the trend of mid air or load since this condition is "normal." In graph #31, the solid line is low excess air and the dotted line is mid/high air.
37-48	Normal trends for mid air, mid load, and high preheat ranges.

Graph #'s	Comments
49-51	Solid line - low preheat Dotted line - high preheat
52-54	Line follows trend of normal higher preheat - second line not drawn to avoid confusion
55-60	Line drawn follows trend of mid air/load range. Other lines not drawn to avoid confusion although separate trends are observed.
61-72	Normal trends for mid air, mid load, and high preheat ranges
73	Dotted line sets off an area of possible NO reduction bounded by "zero" line and dotted line. Scatter in data makes true reduction unknown.
74-76	Single line seems to describe all data equally well
77	Composite curves - solid - coal dotted - gas dash/dot - oil
78	No single line would suffice for all data
79	Solid line - describes front slot staging Dotted line - side slot staging Hatched line - substoichiometric
80	No single line describes all data

Graph #'s	Comments
81	Solid line - staging (front slots) Dotted line - staging with burner flue gas recirculation Dash/dot line - staging with port flue gas recirculation Hatched line - substoichiometric
82	No single line drawn through all data
83	All front slot data represented by one line
84	Solid - coal Dotted - gas Dash/dot - oil

FIGURE D-2
COAL - MID LOAD

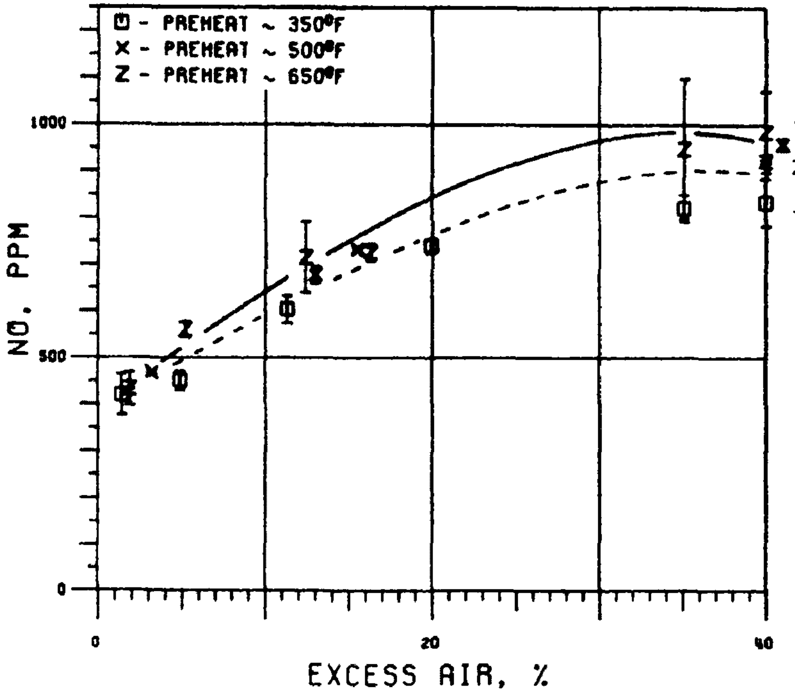


FIGURE D-4
COAL - LOW EXCESS AIR

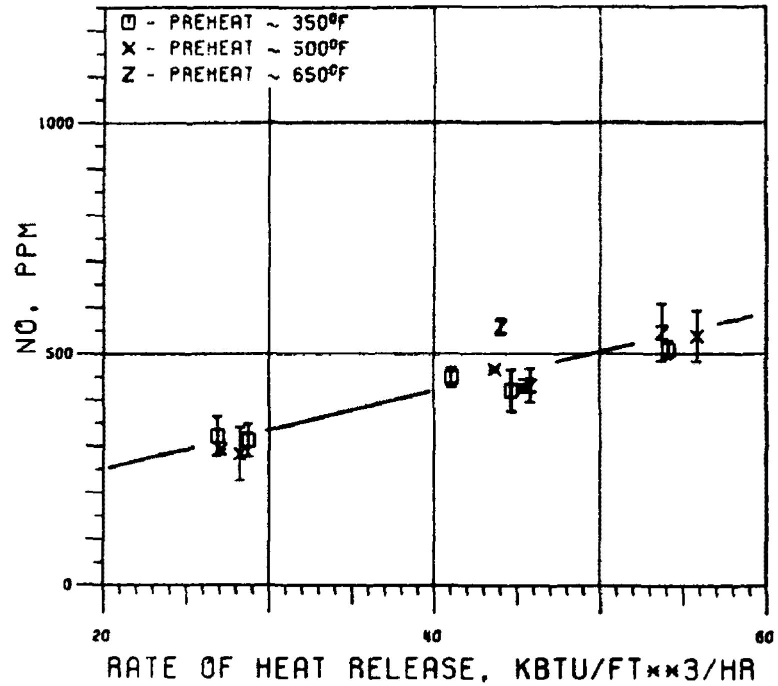


FIGURE D-1
COAL - LOW LOAD

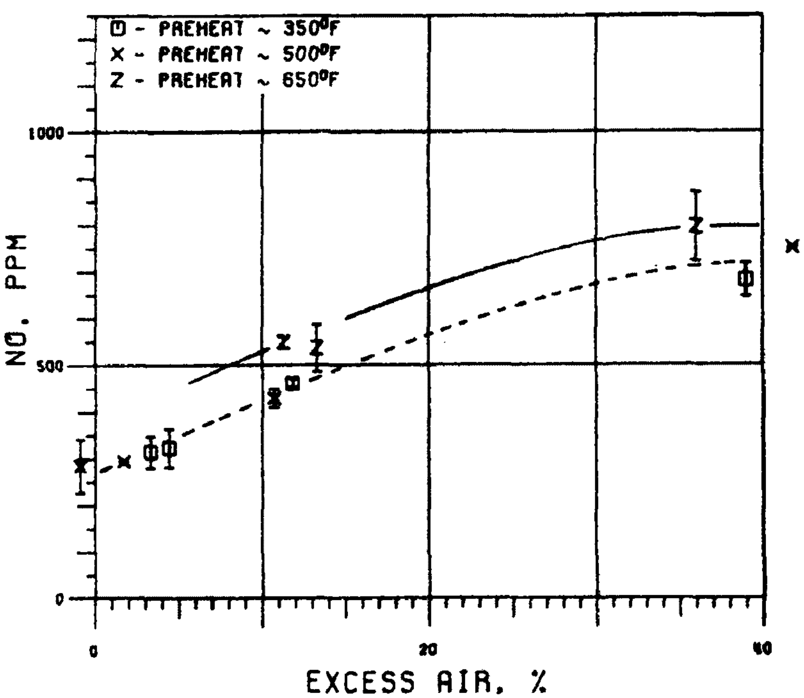


FIGURE D-3
COAL - HIGH LOAD

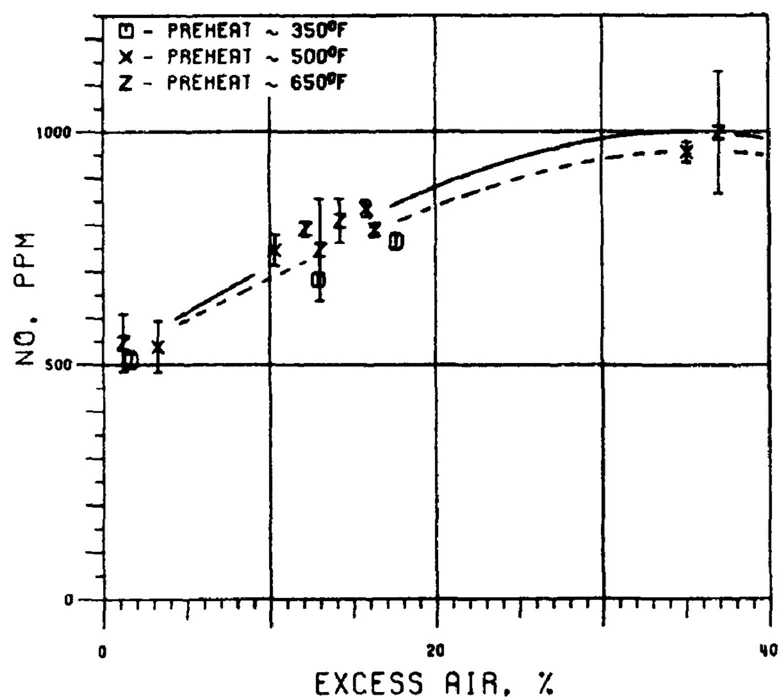


FIGURE D-6
COAL - HIGH EXCESS AIR

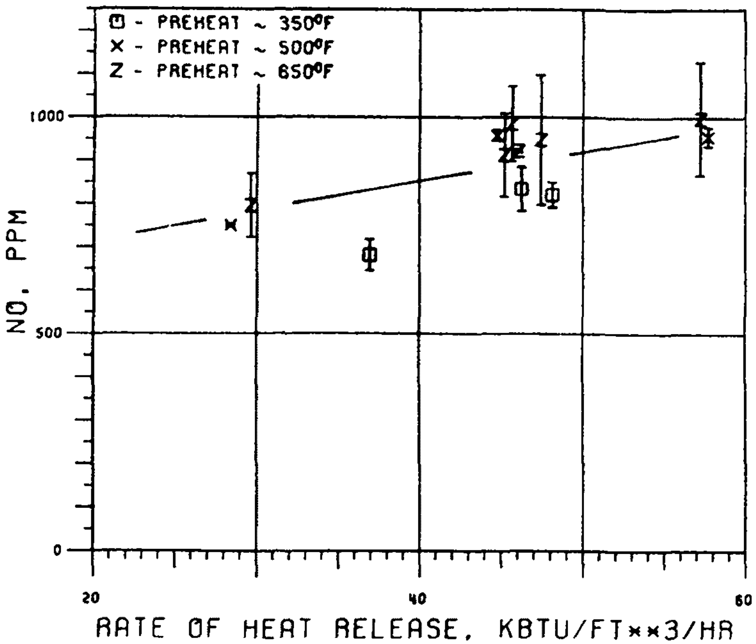


FIGURE D-8
COAL - MID LOAD

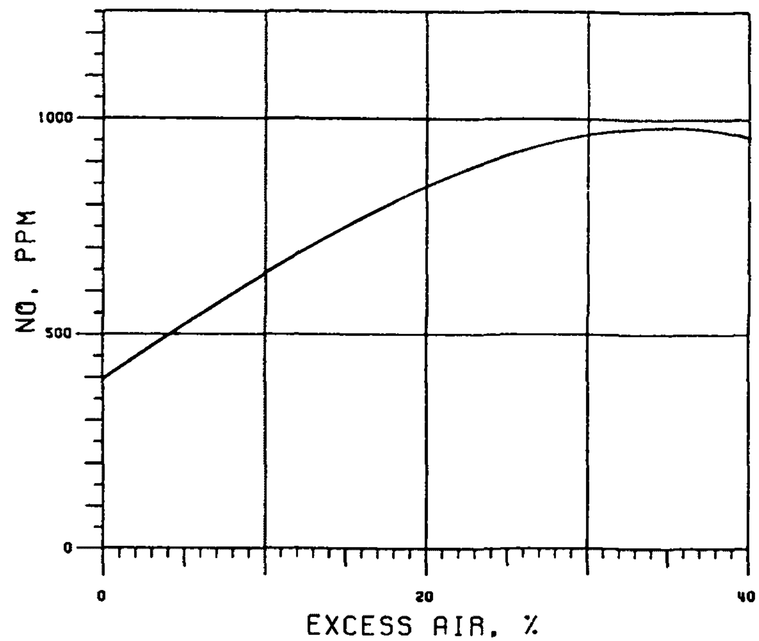


FIGURE D-5
COAL - MID EXCESS AIR

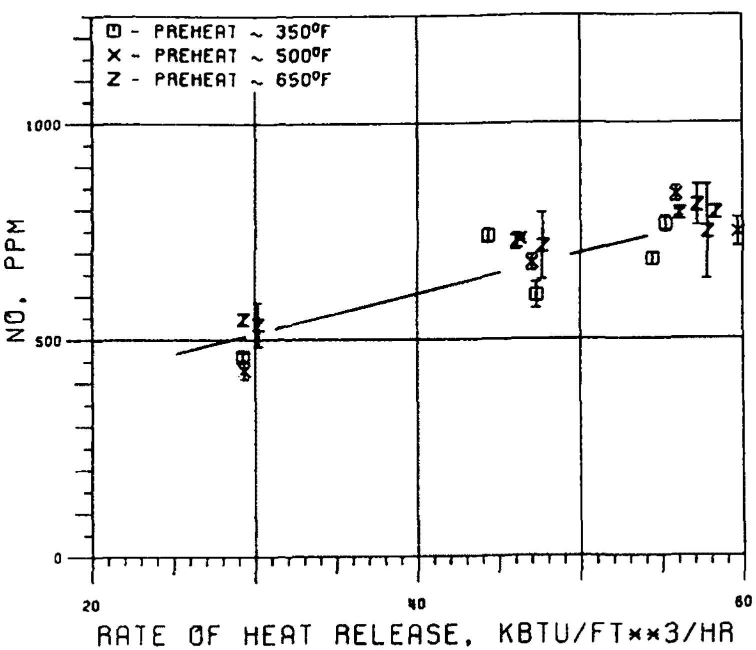


FIGURE D-7
COAL - LOW LOAD

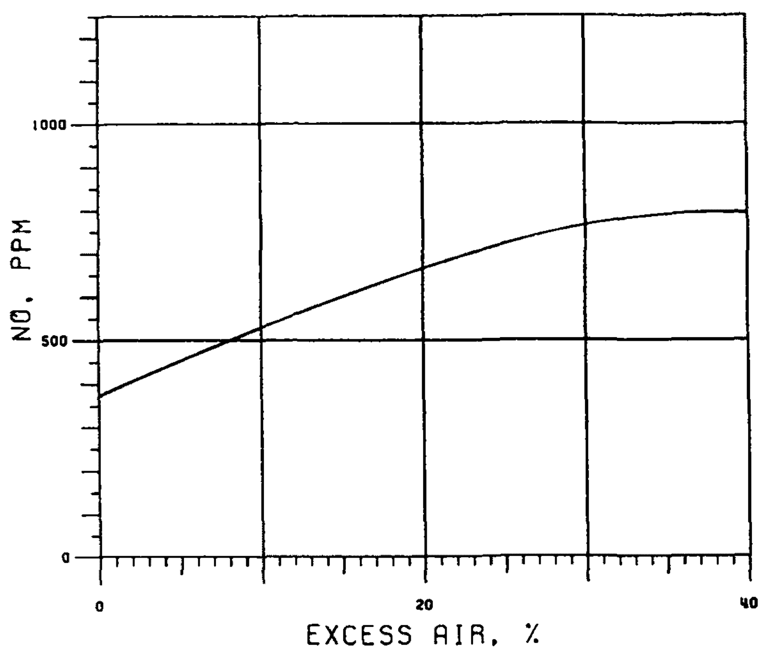


FIGURE D-10
COAL - LOW EXCESS AIR

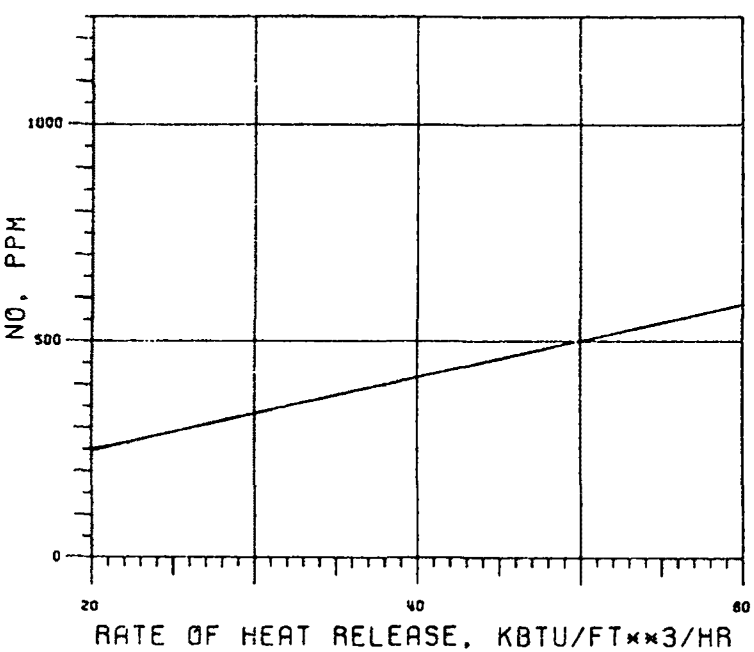


FIGURE D-12
COAL - HIGH EXCESS AIR

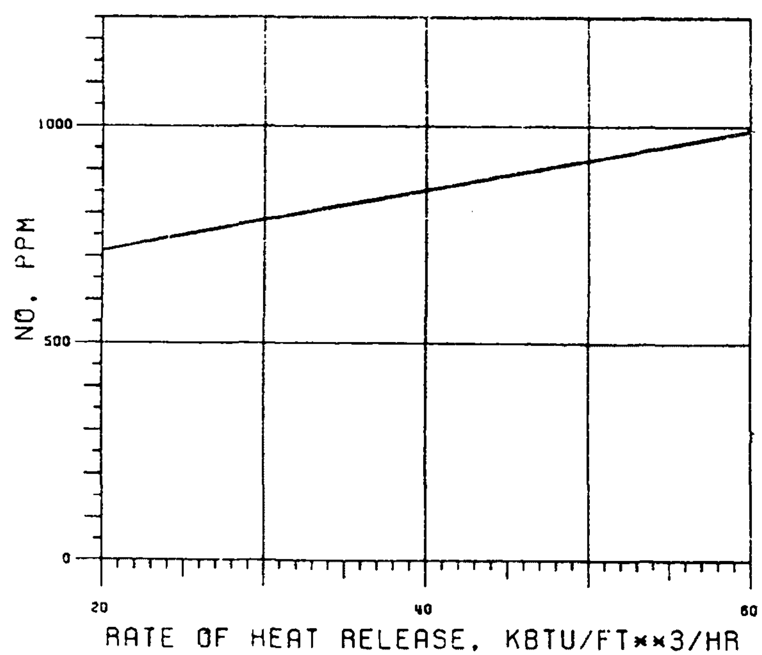


FIGURE D- 9
COAL - HIGH LOAD

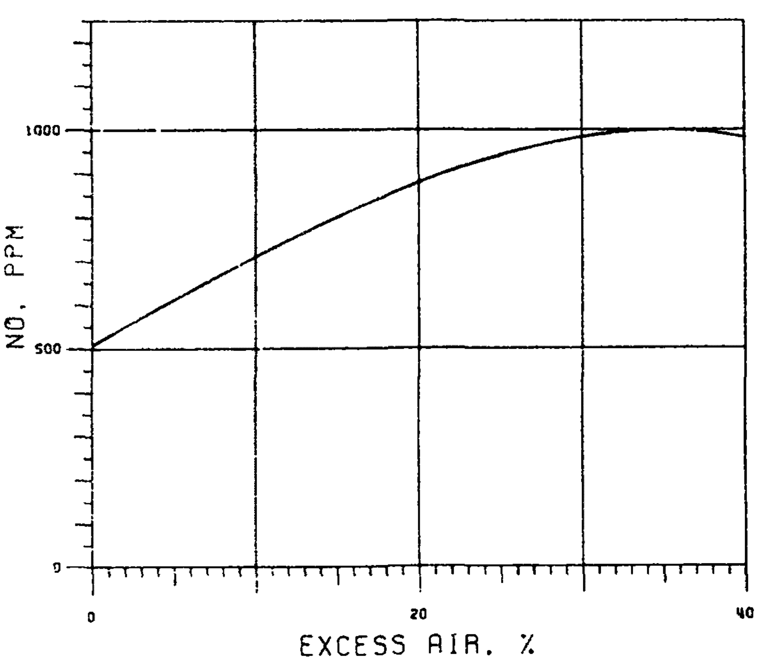
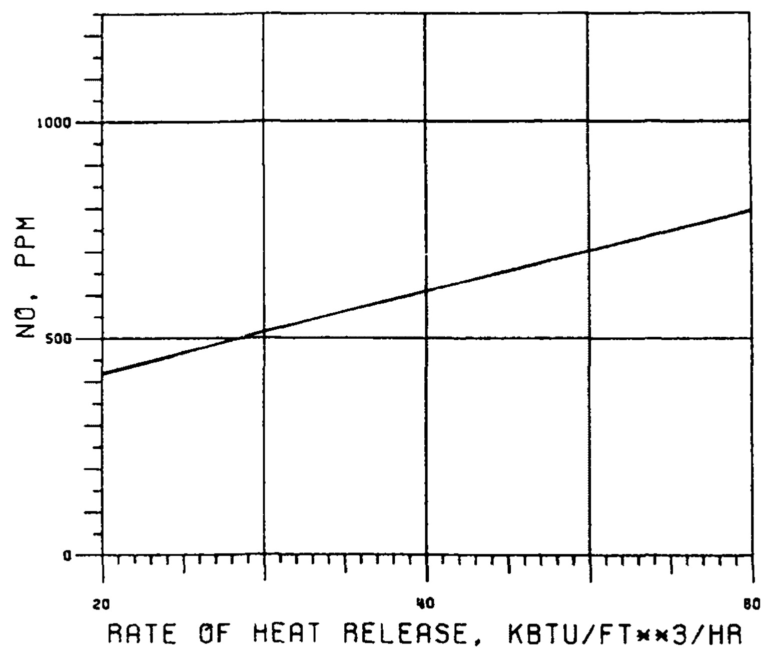


FIGURE D-11
COAL - MID EXCESS AIR



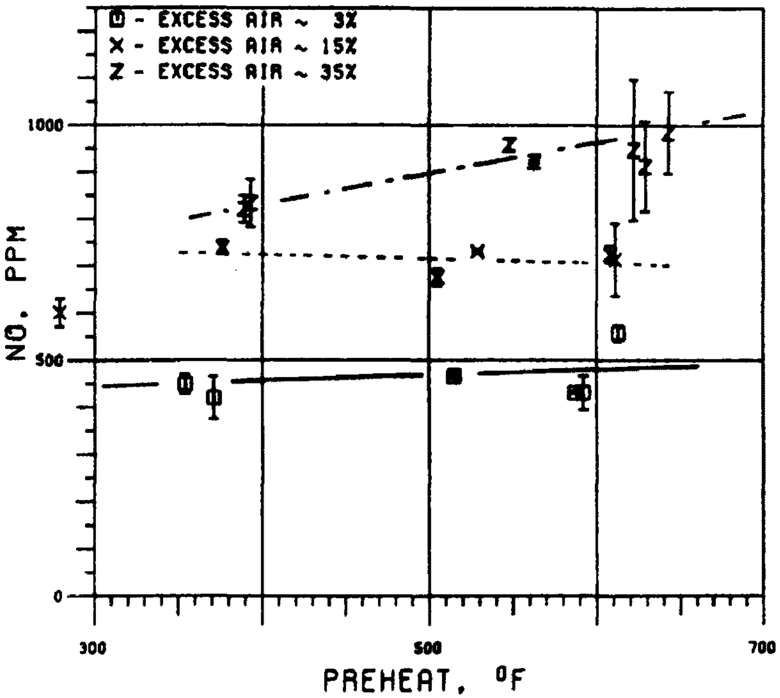


FIGURE D-14
COAL - MID LOAD

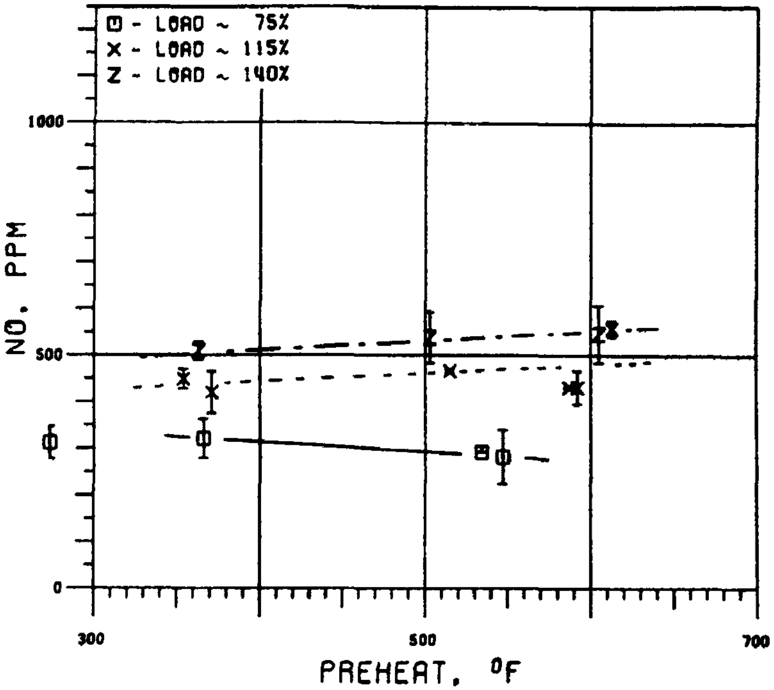


FIGURE D-16
COAL - LOW EXCESS AIR

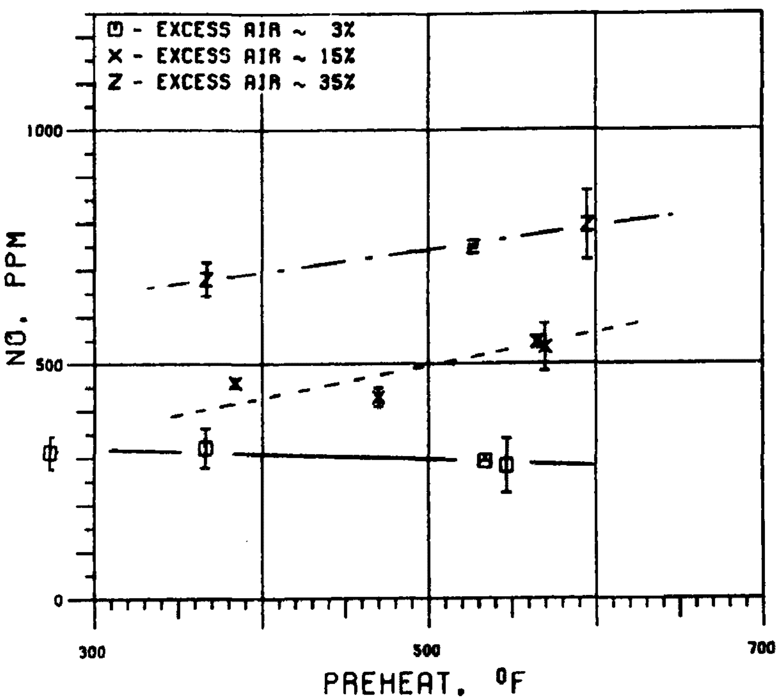


FIGURE D-13
COAL - LOW LOAD

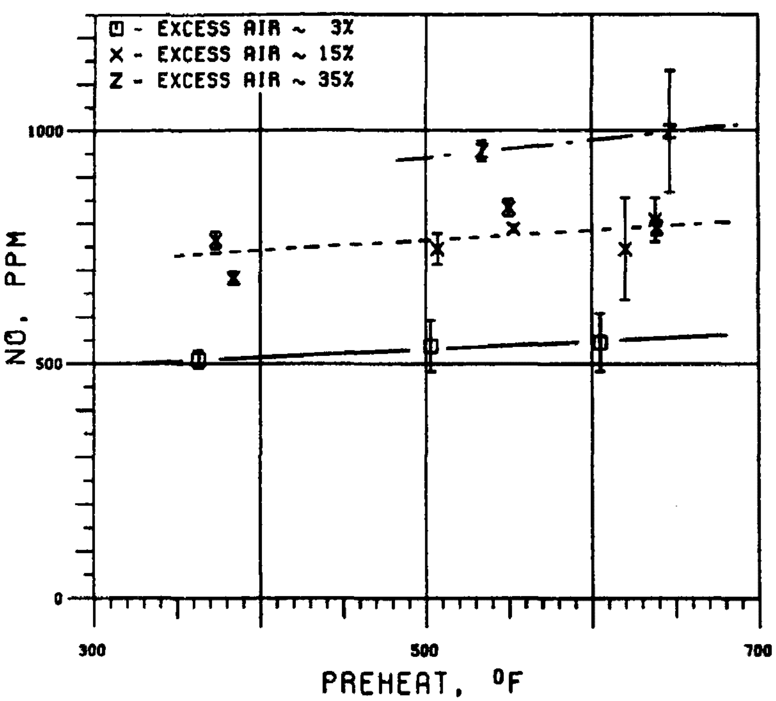


FIGURE D-15
COAL - HIGH LOAD

FIGURE D-18
COAL - HIGH EXCESS AIR

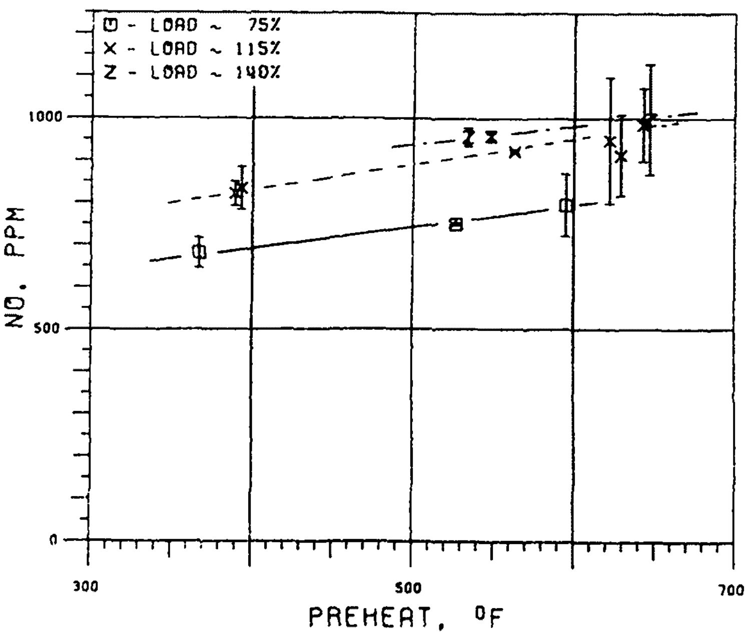


FIGURE D-20
COAL - MID LOAD

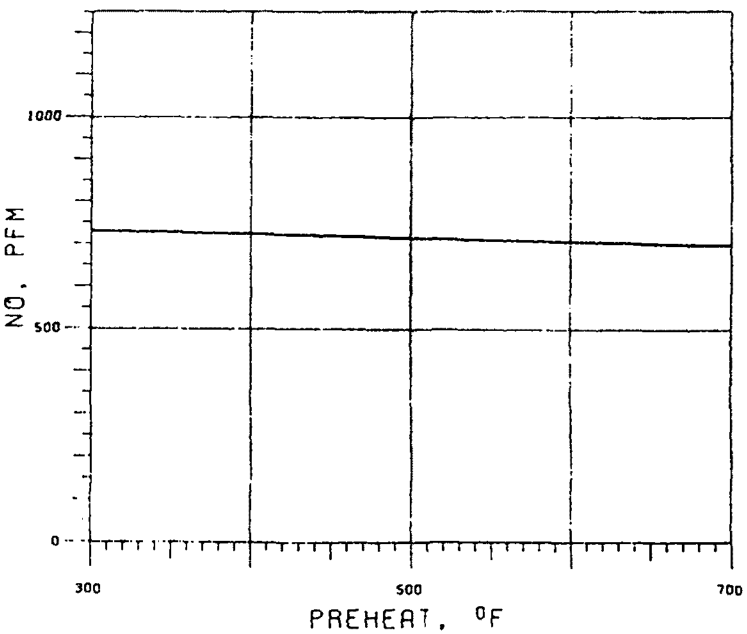


FIGURE D-17
COAL - MID EXCESS AIR

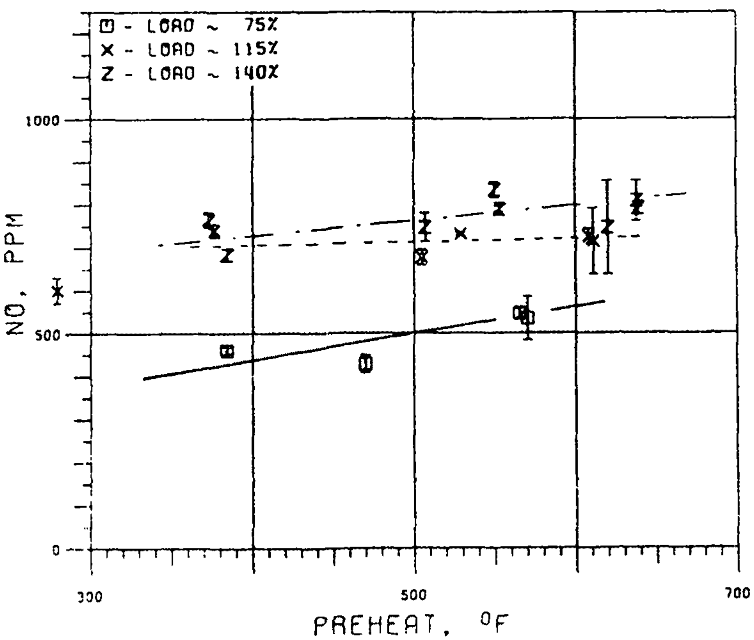
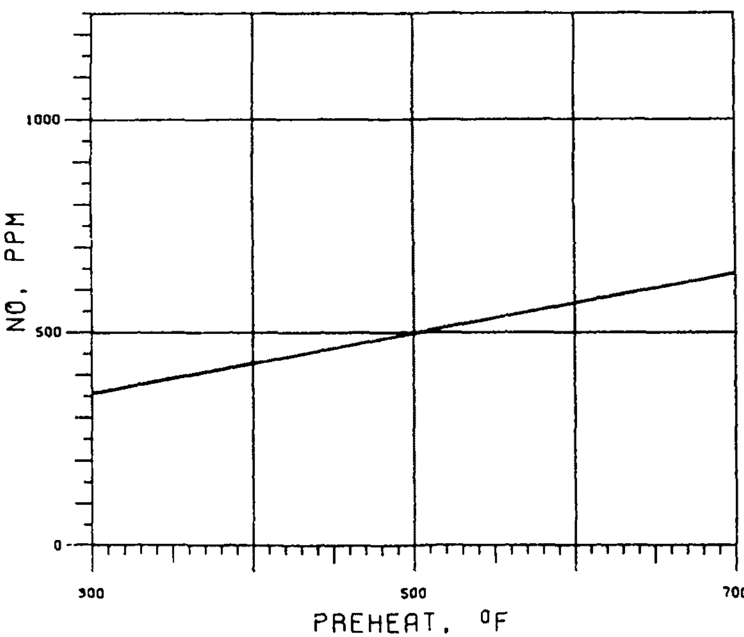


FIGURE D-19
COAL - LOW LOAD



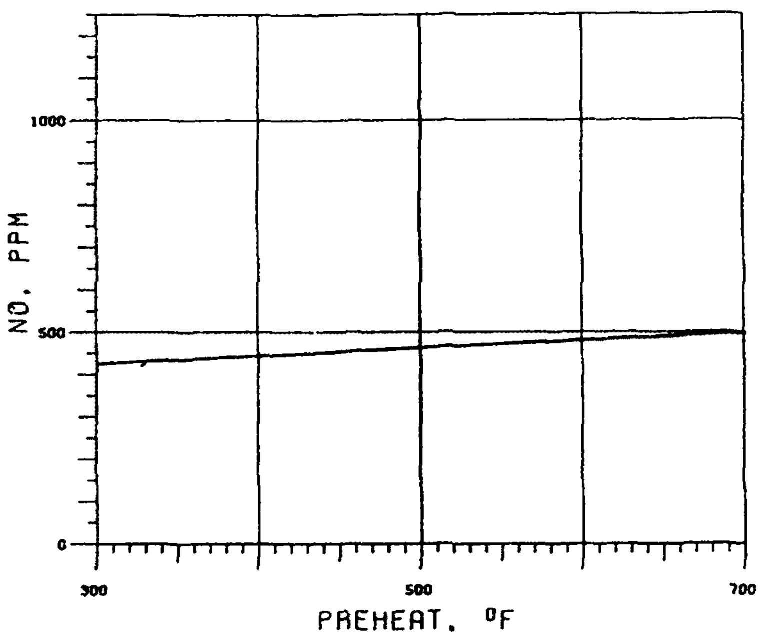


FIGURE D-22
COAL - LOW EXCESS AIR

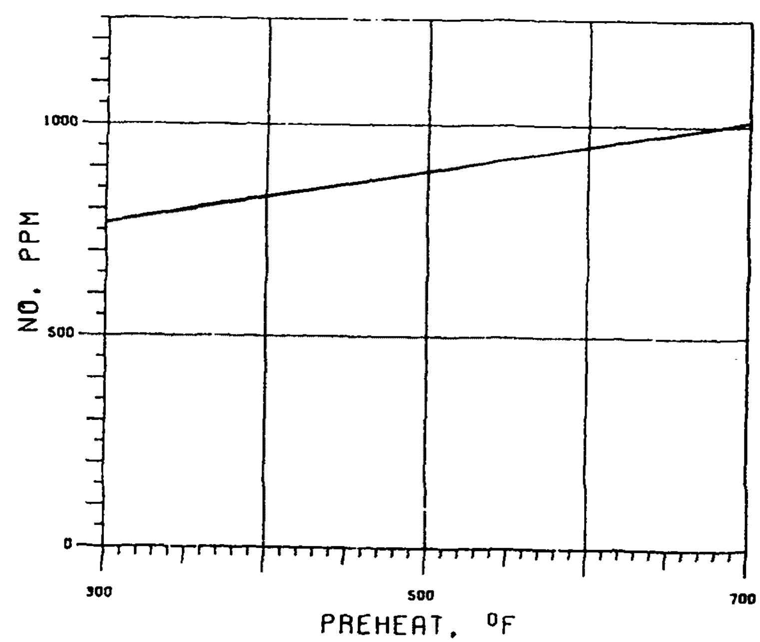


FIGURE D-24
COAL - HIGH EXCESS AIR

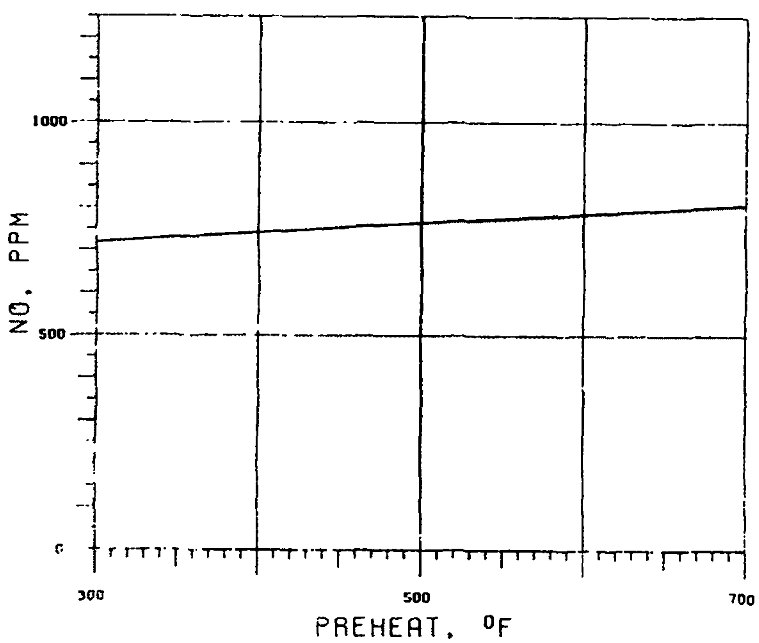


FIGURE D-21
COAL - HIGH LOAD

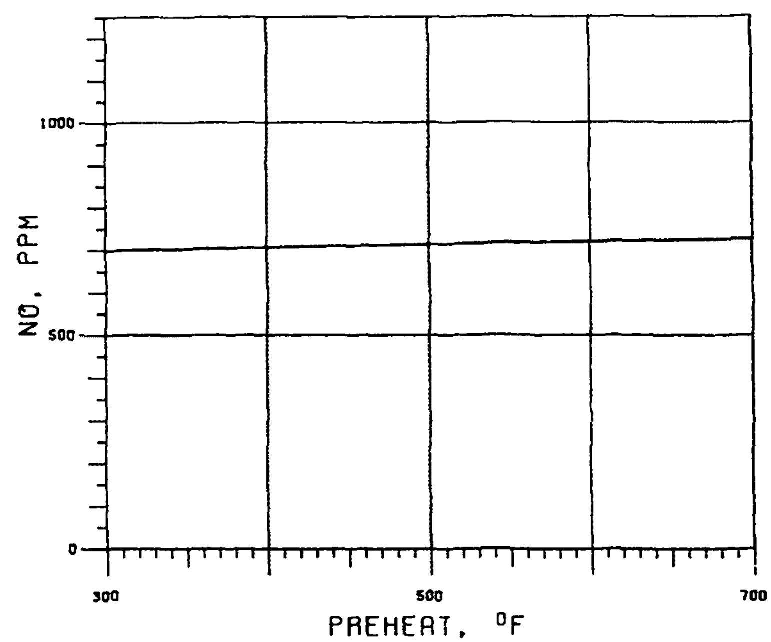


FIGURE D-23
COAL - MID EXCESS AIR

FIGURE D-26
GAS - MID LOAD

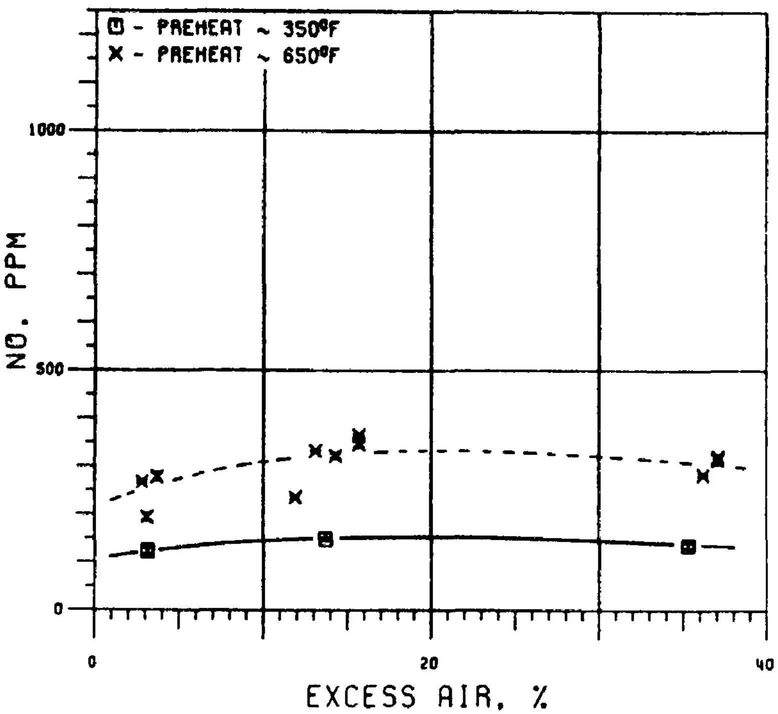


FIGURE D-28
GAS - LOW EXCESS AIR

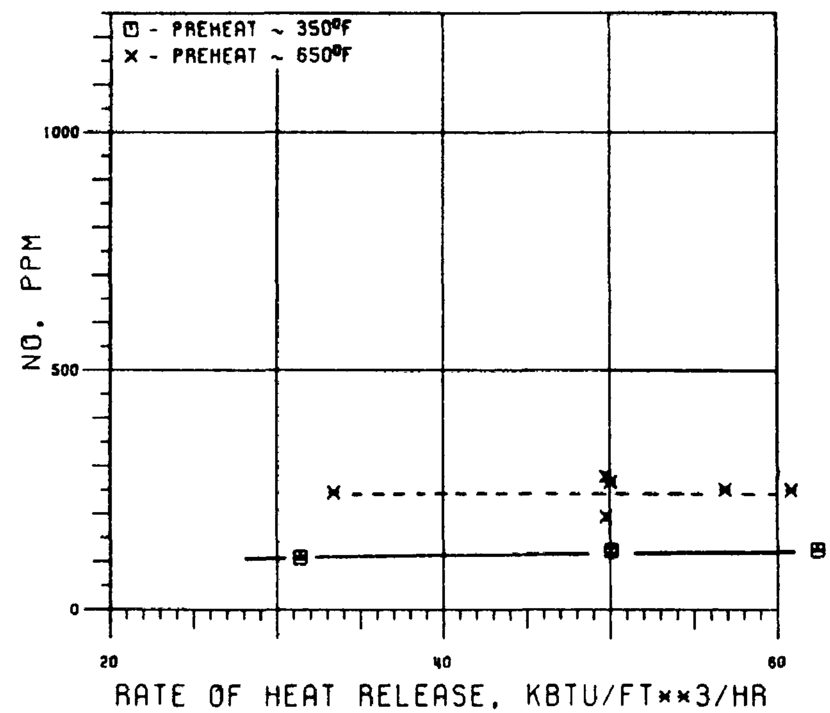


FIGURE D-25
GAS - LOW LOAD

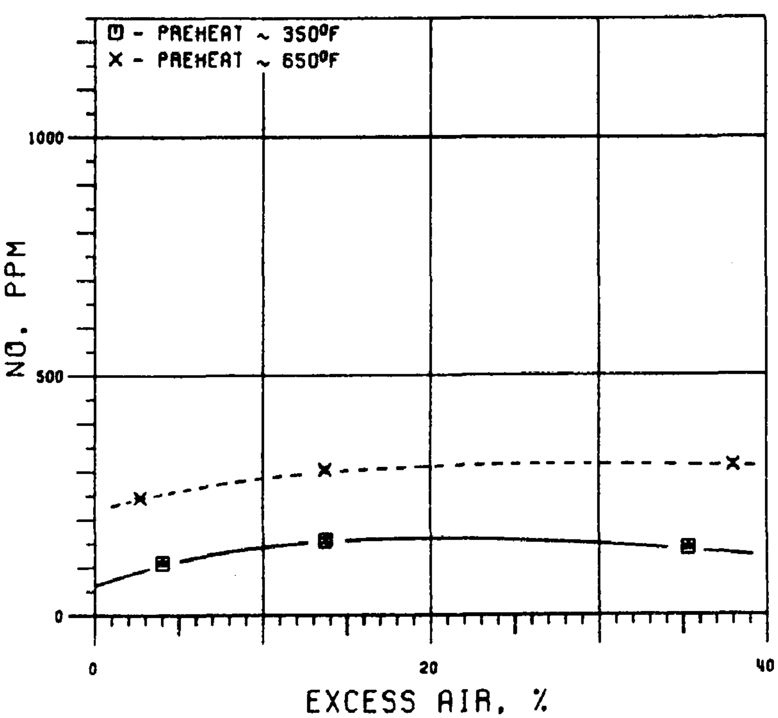
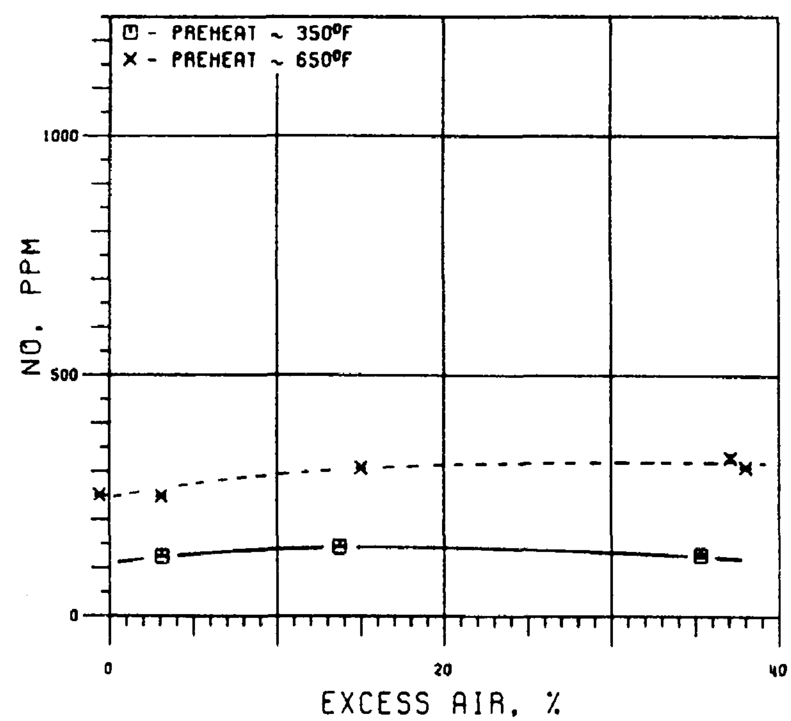


FIGURE D-27
GAS - HIGH LOAD



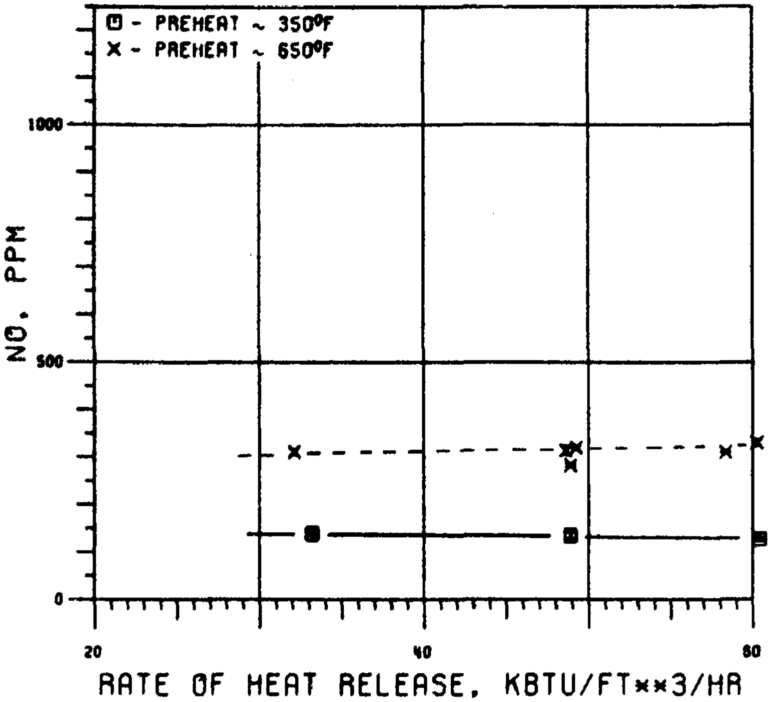


FIGURE D-30
GAS - HIGH EXCESS AIR

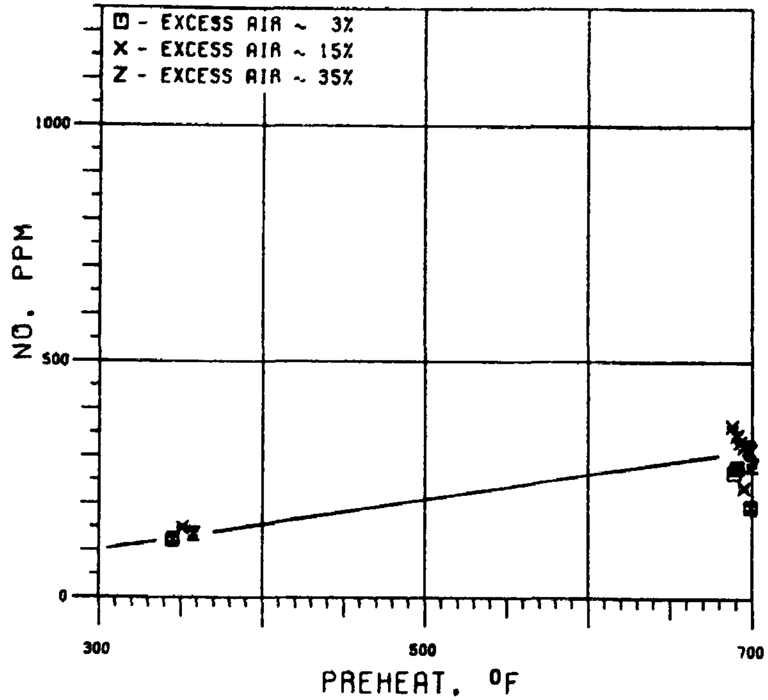


FIGURE D-32
GAS - MID LOAD

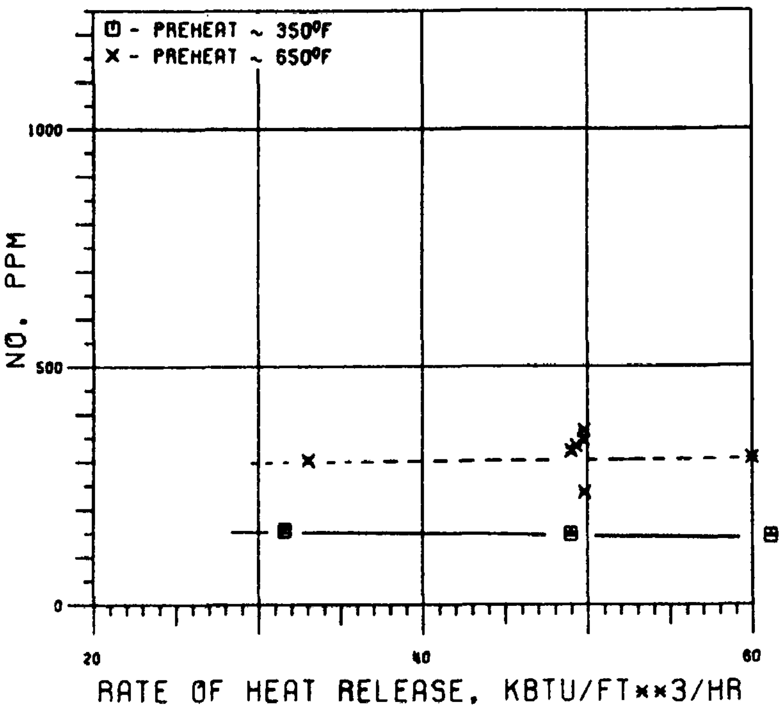


FIGURE D-29
GAS - MID EXCESS AIR

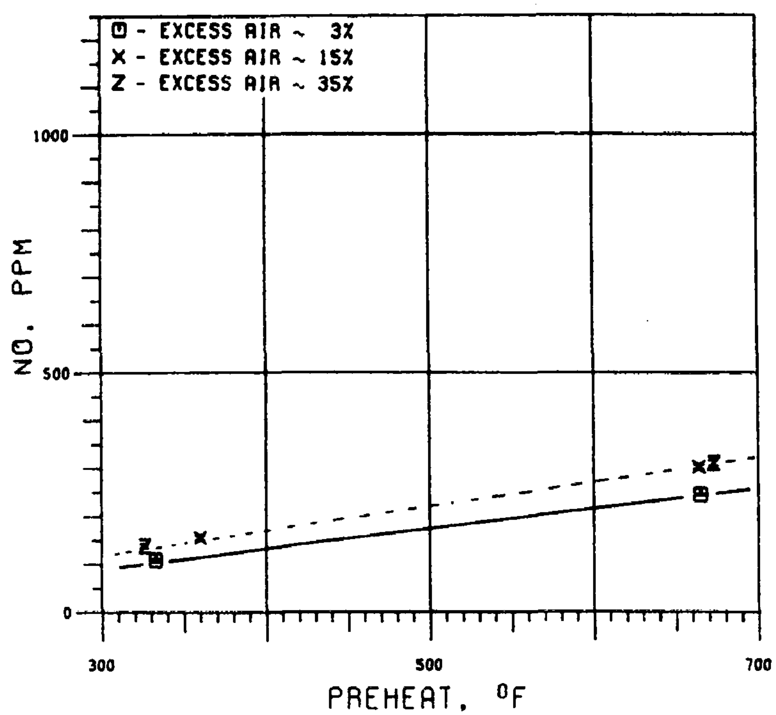


FIGURE D-31
GAS - LOW LOAD

FIGURE D-34
GAS - LOW EXCESS AIR

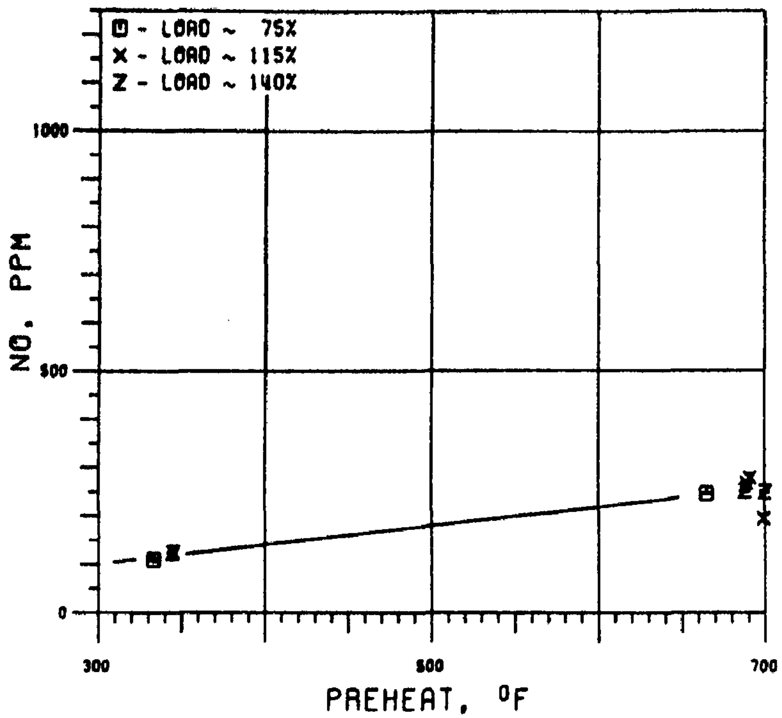


FIGURE D-36
GAS - HIGH EXCESS AIR

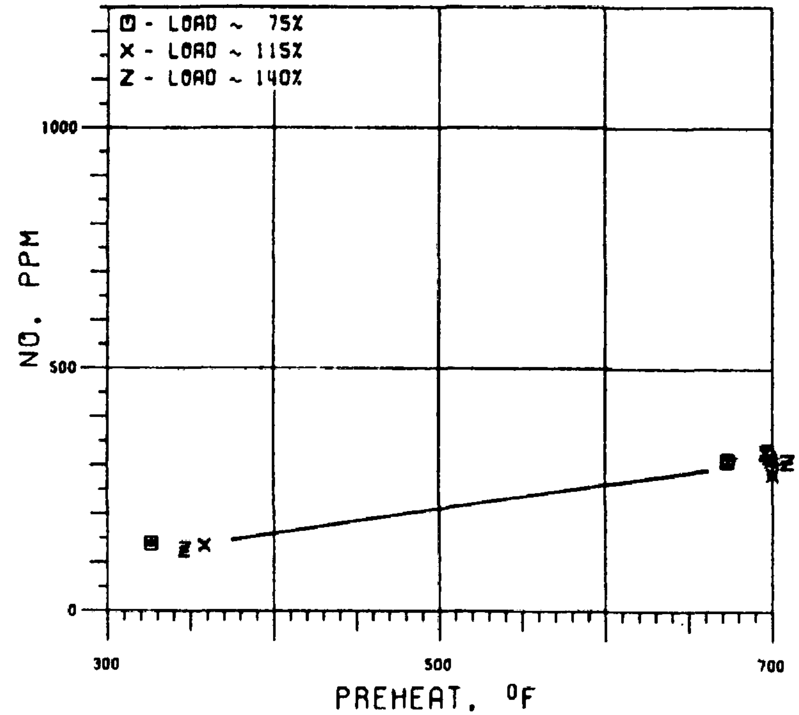


FIGURE D-33
GAS - HIGH LOAD

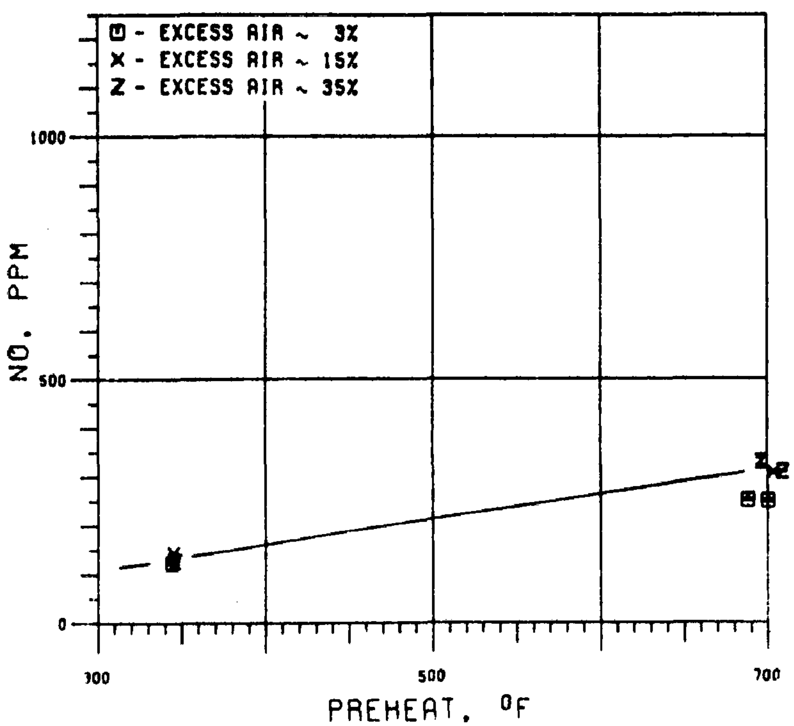
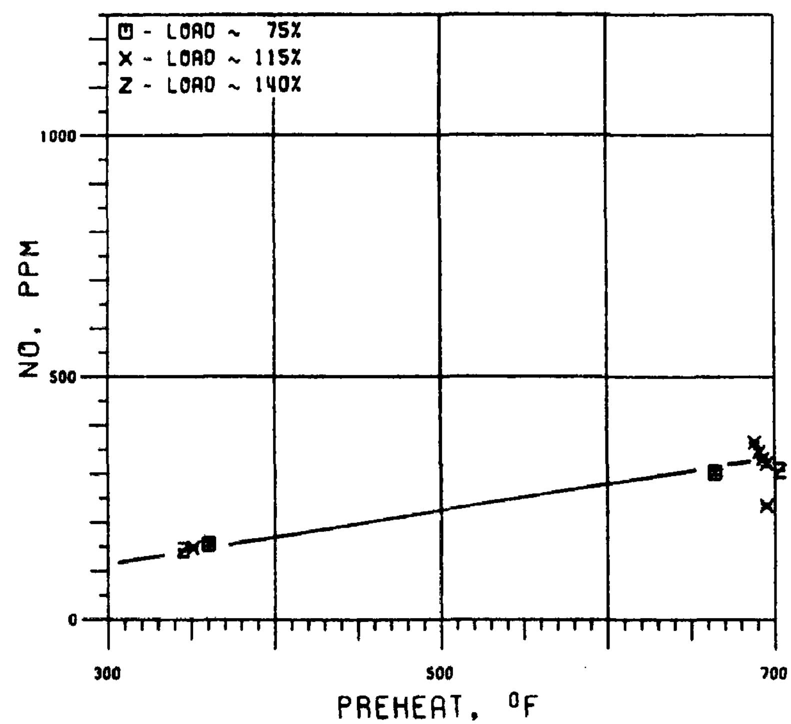


FIGURE D-35
GAS - MID EXCESS AIR



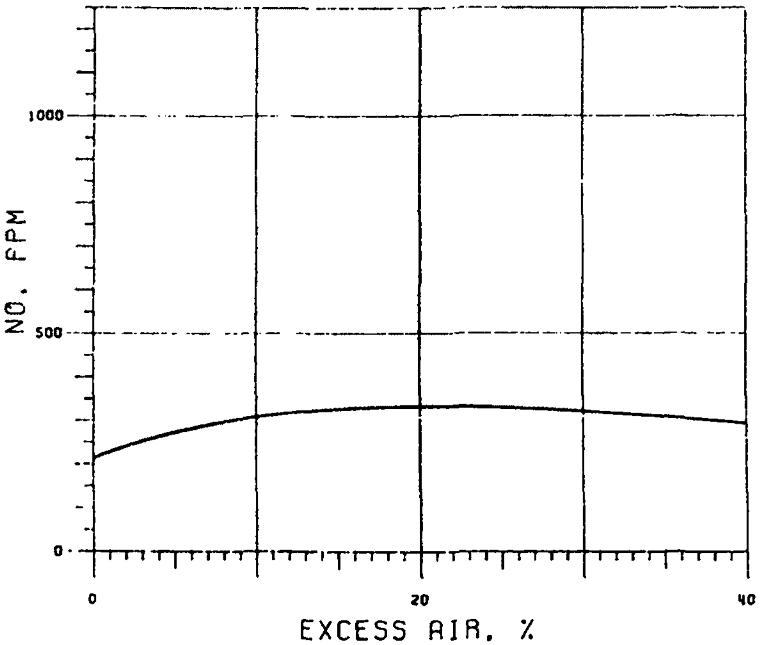


FIGURE D-38
GAS - MID LOAD

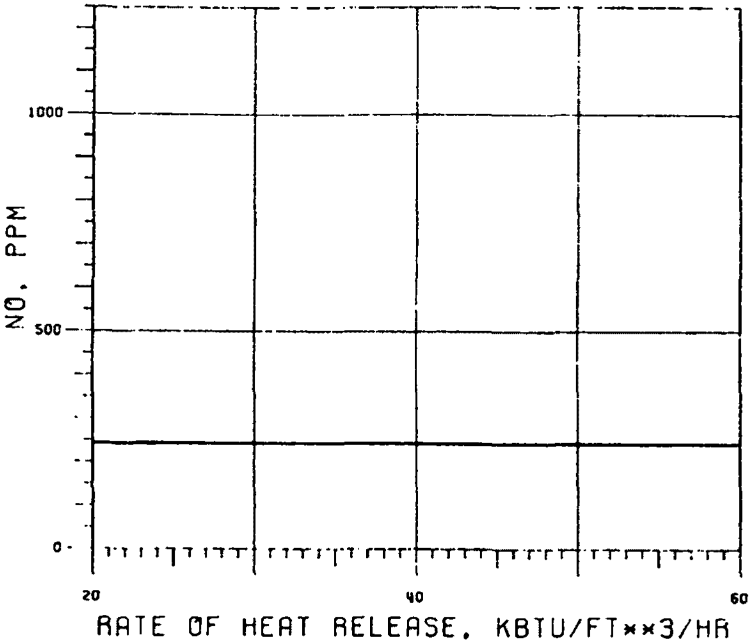


FIGURE D-40
GAS - LOW EXCESS AIR

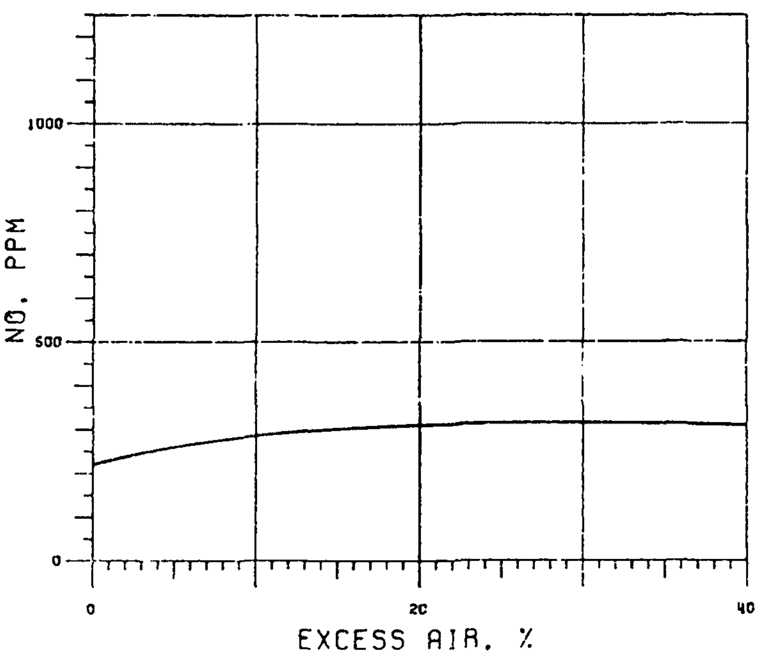


FIGURE D-37
GAS - LOW LOAD

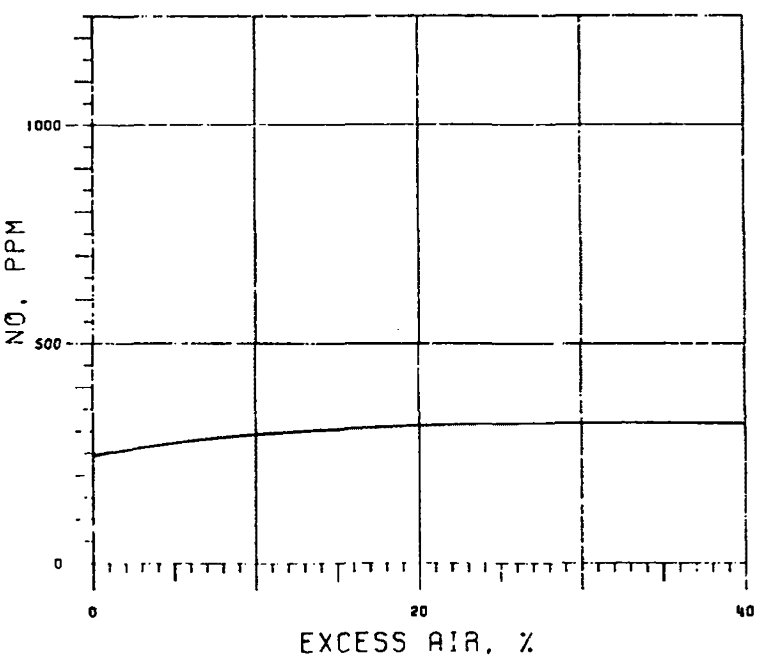


FIGURE D-39
GAS - HIGH LOAD

FIGURE D-41
GAS - MID EXCESS AIR

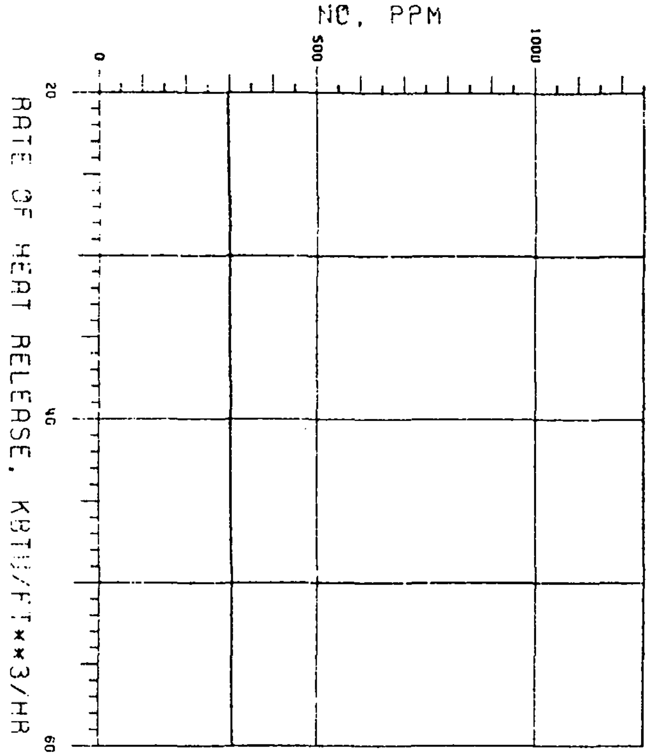


FIGURE D-42
GAS - HIGH EXCESS AIR

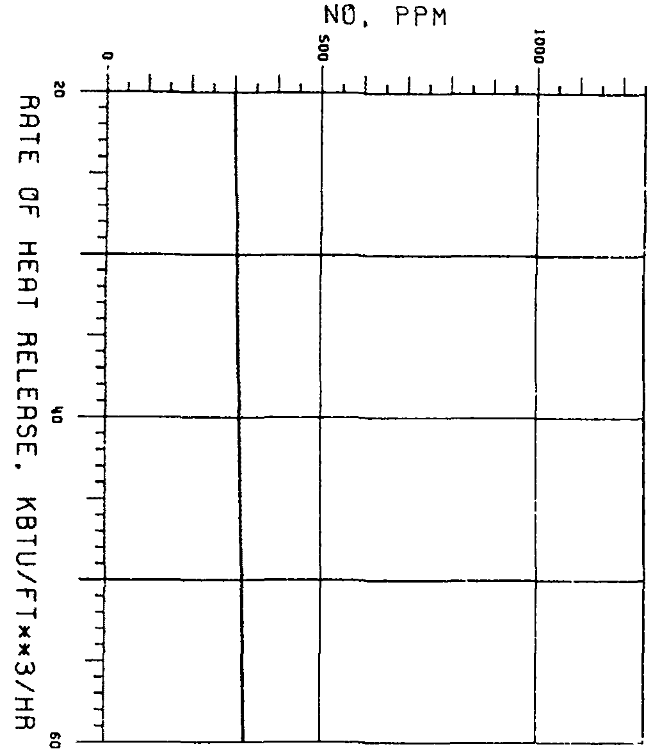


FIGURE D-43
GAS - LOW LOAD

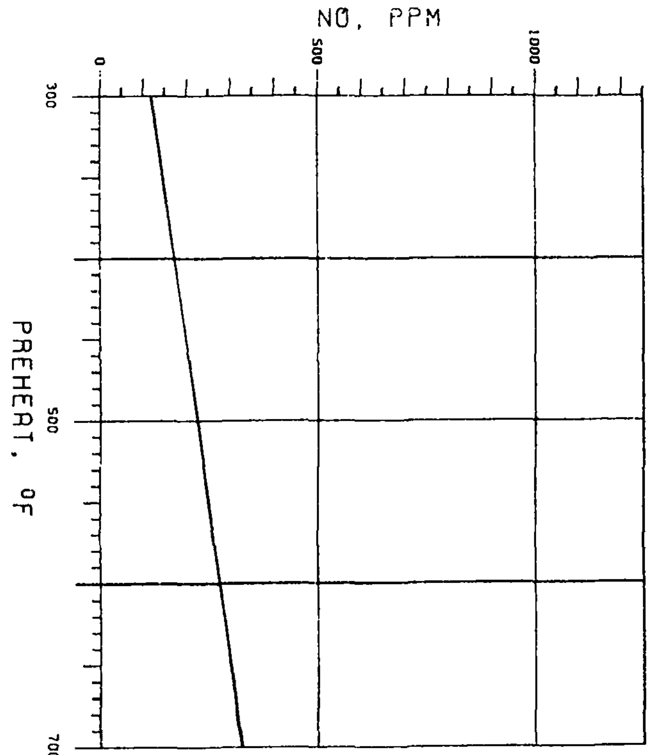
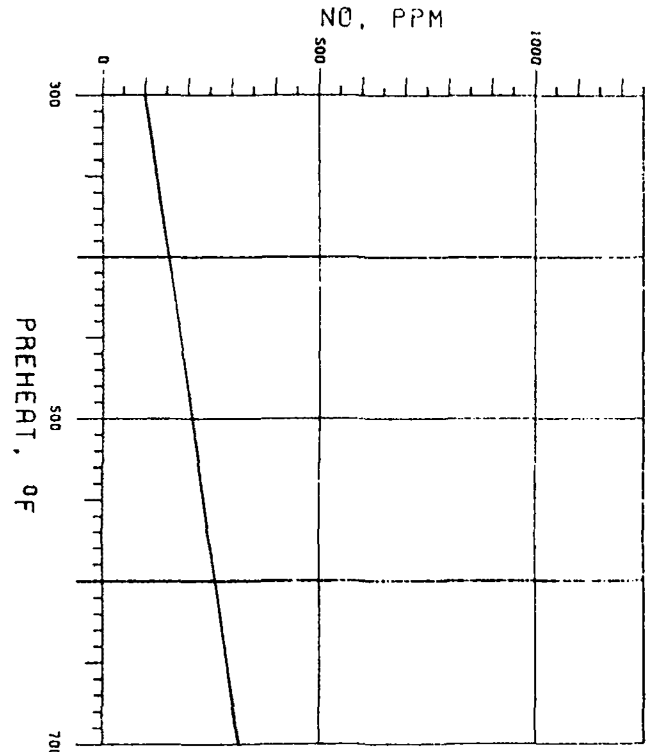


FIGURE D-44
GAS - MID LOAD



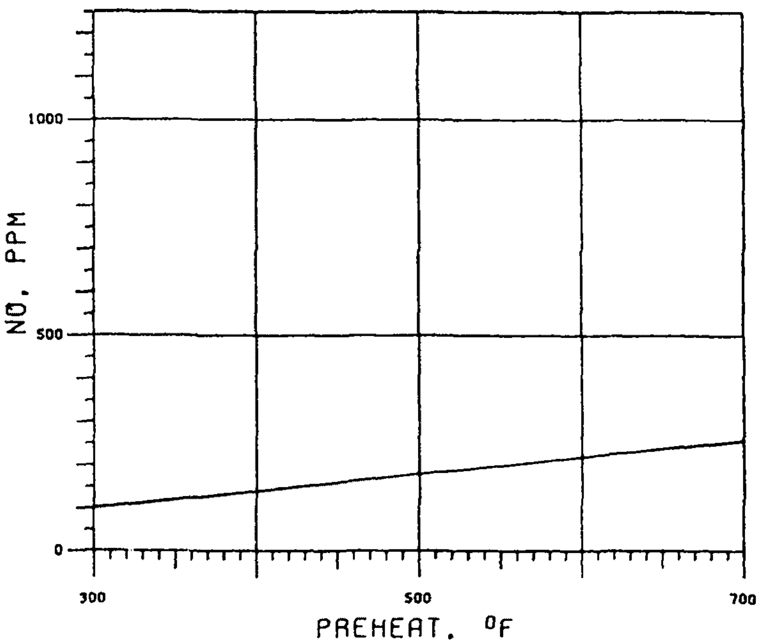


FIGURE D-46
GAS - LOW EXCESS AIR

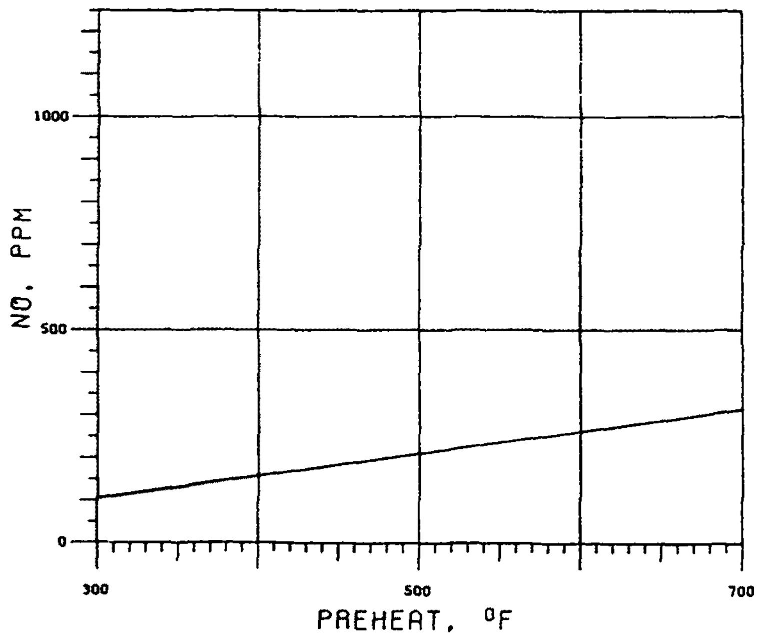


FIGURE D-48
GAS - HIGH EXCESS AIR

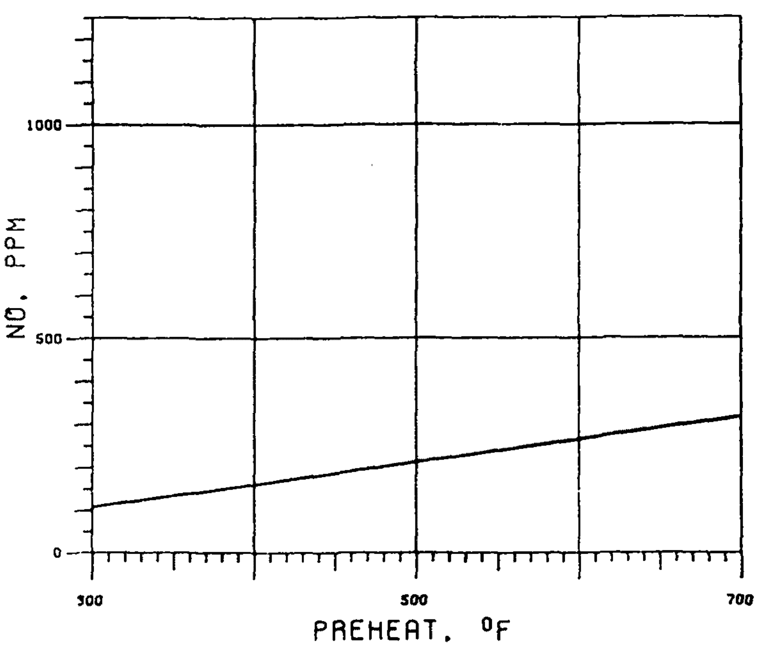


FIGURE D-45
GAS - HIGH LOAD

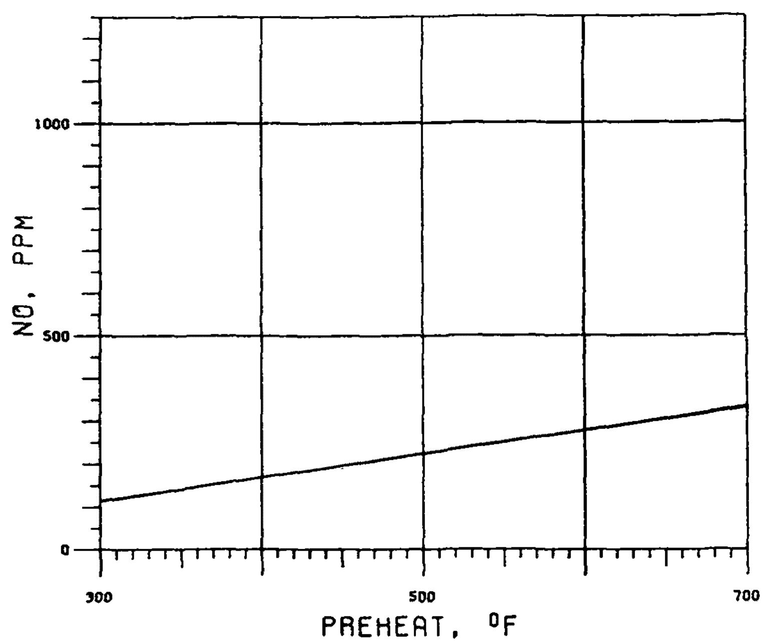


FIGURE D-47
GAS - MID EXCESS AIR

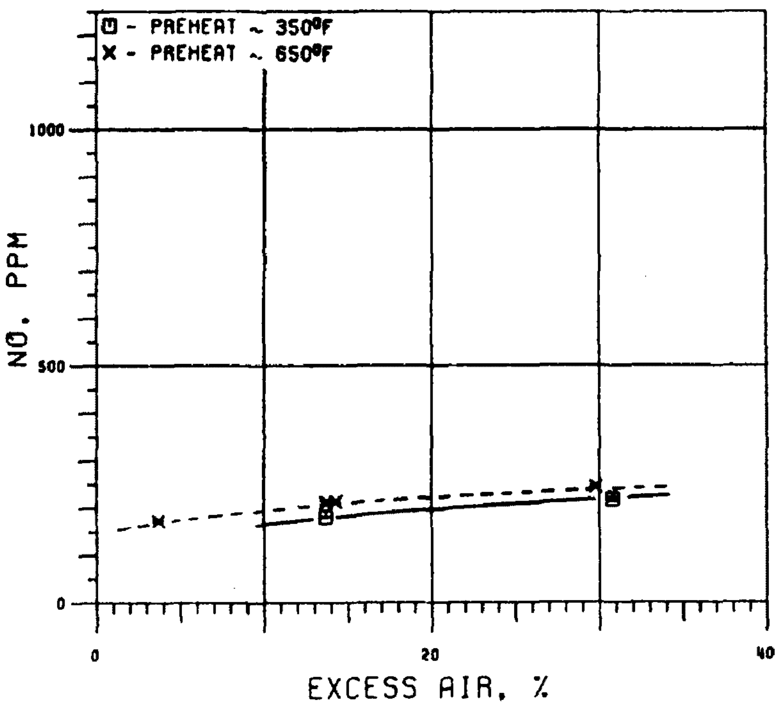


FIGURE D-49
OIL - LOW LOAD

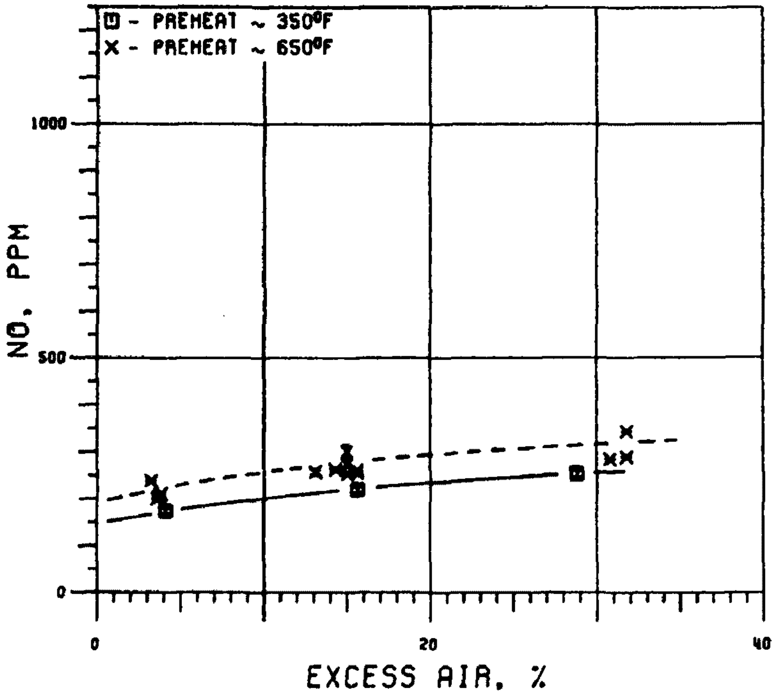


FIGURE D-50
OIL - MID LOAD

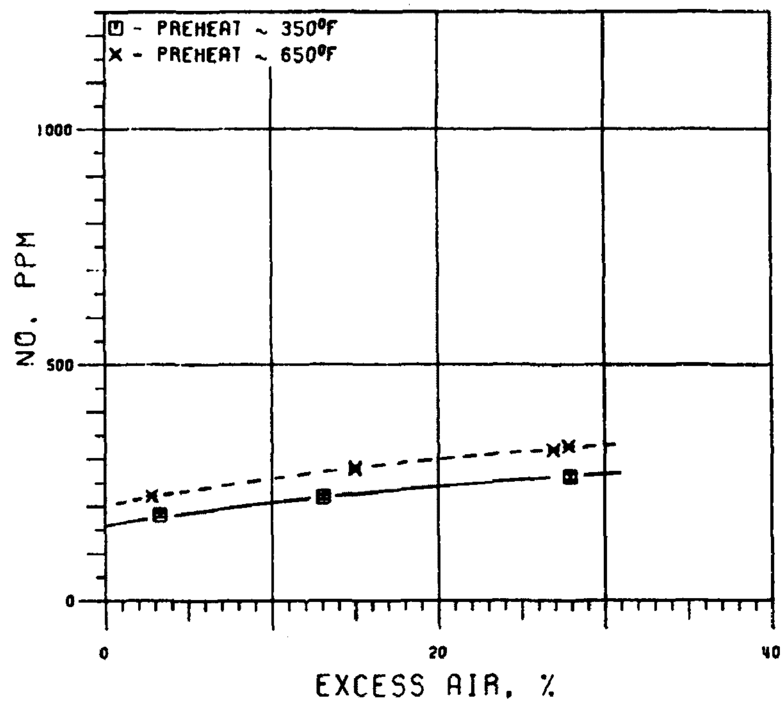


FIGURE D-51
OIL - HIGH LOAD

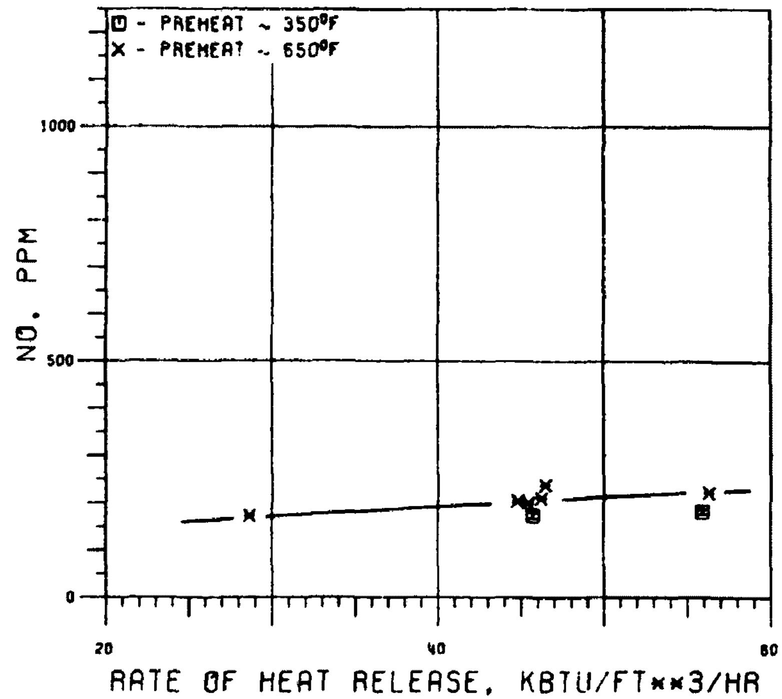


FIGURE D-52
OIL - LOW EXCESS AIR

FIGURE D-53
OIL - MID EXCESS AIR

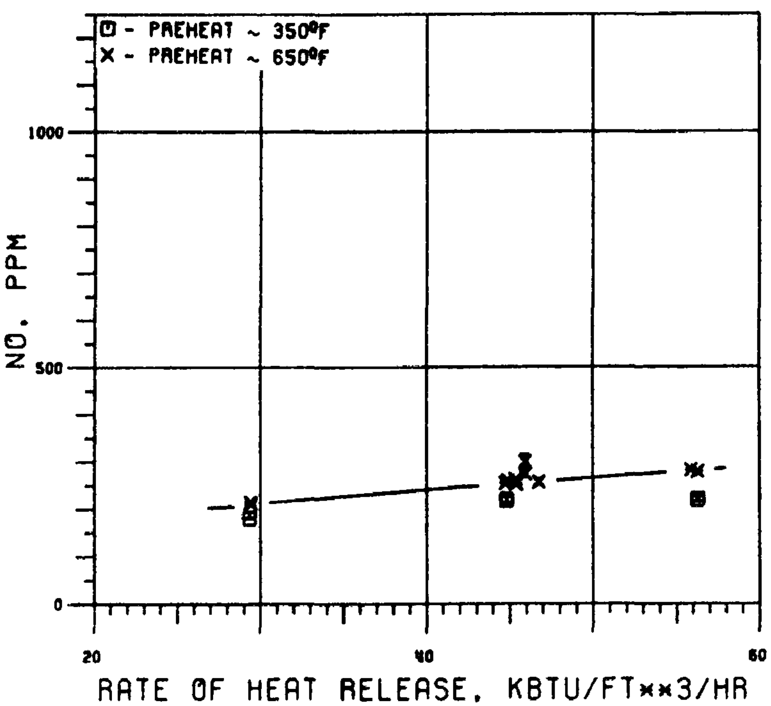


FIGURE D-54
OIL - HIGH EXCESS AIR

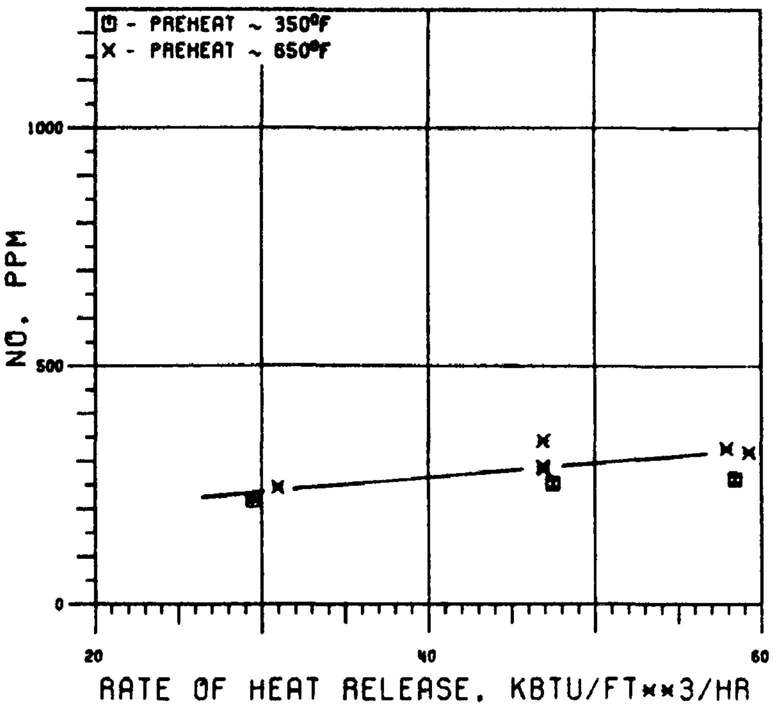


FIGURE D-55
OIL - LOW LOAD

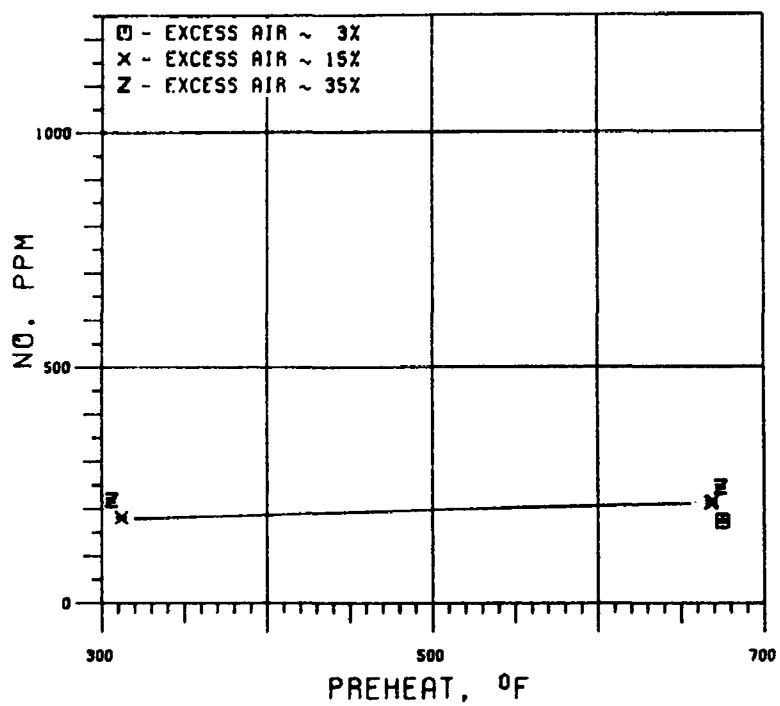


FIGURE D-56
OIL - MID LOAD

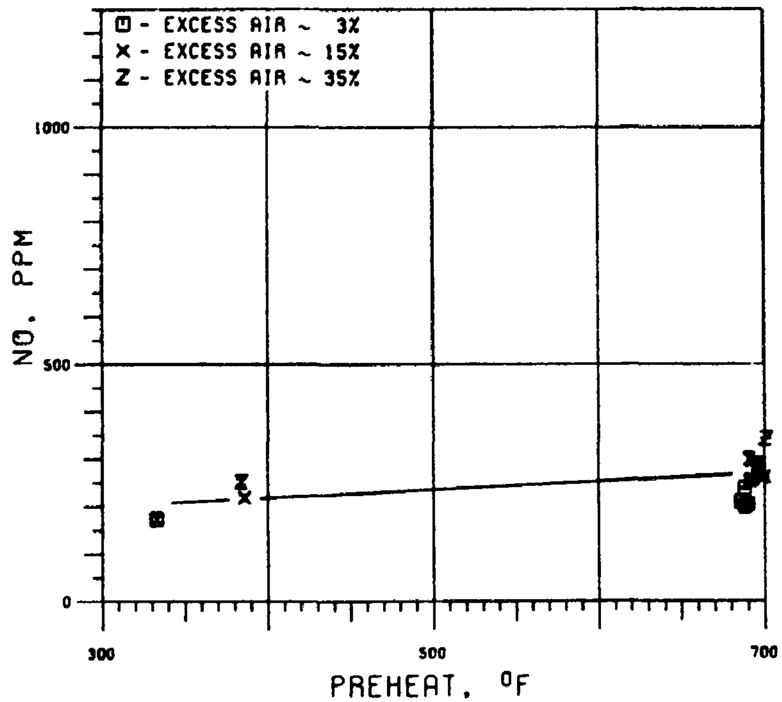


FIGURE D-58
OIL - LOW EXCESS AIR

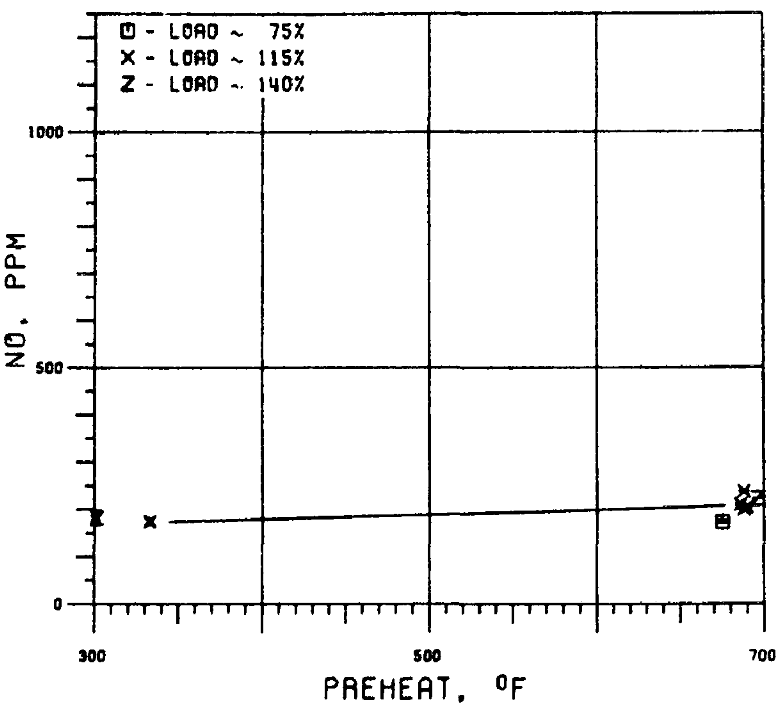


FIGURE D-60
OIL - HIGH EXCESS AIR

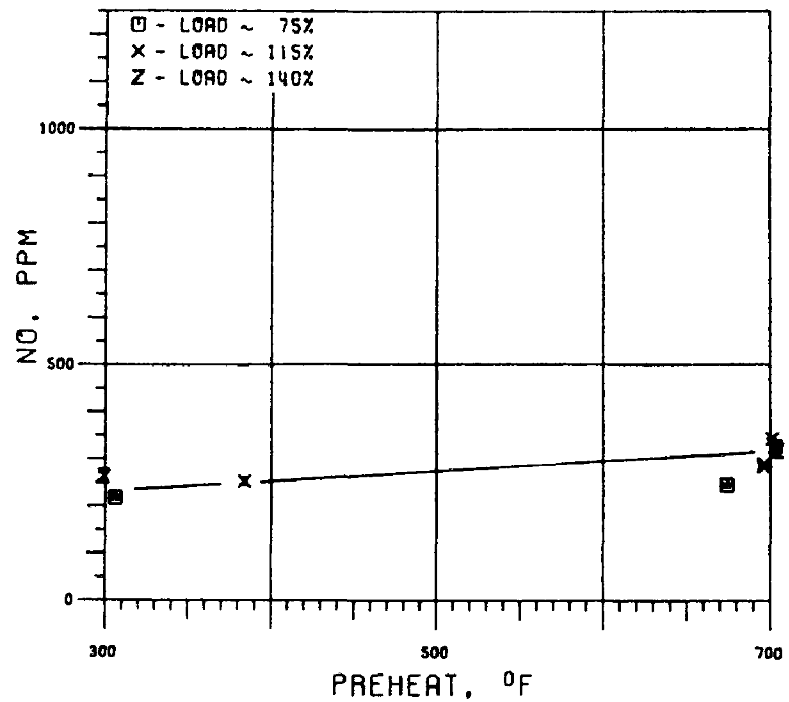


FIGURE D-57
OIL - HIGH LOAD

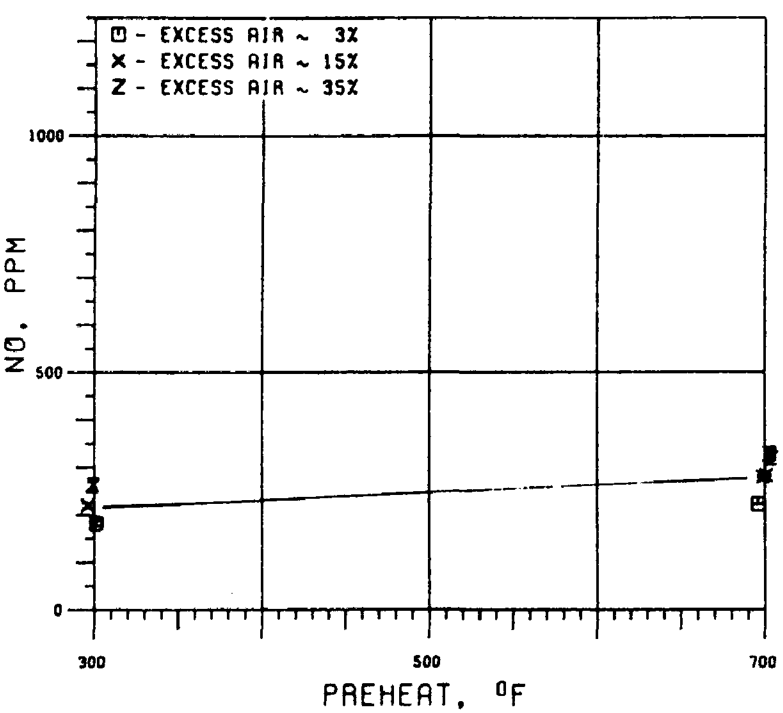
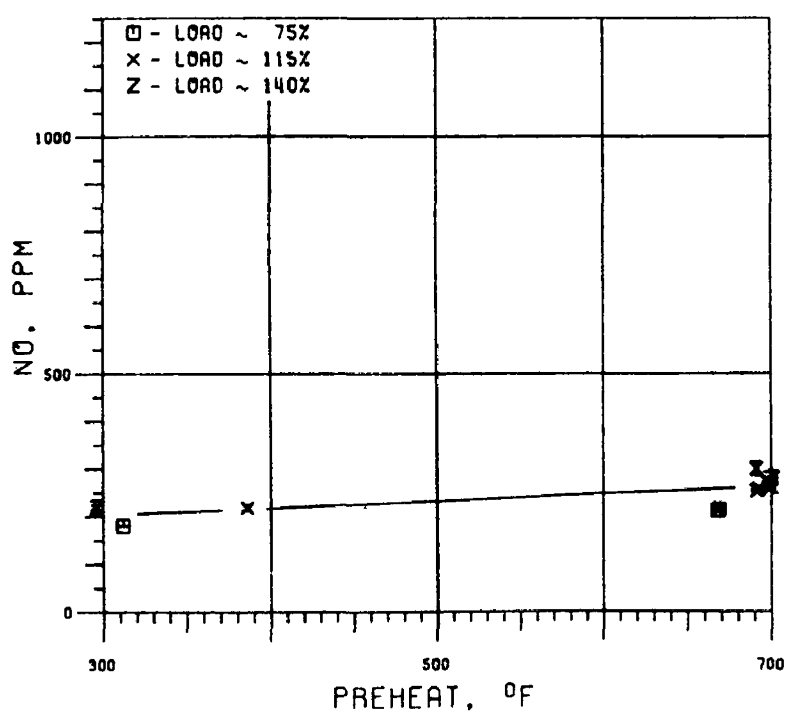


FIGURE D-59
OIL - MID EXCESS AIR



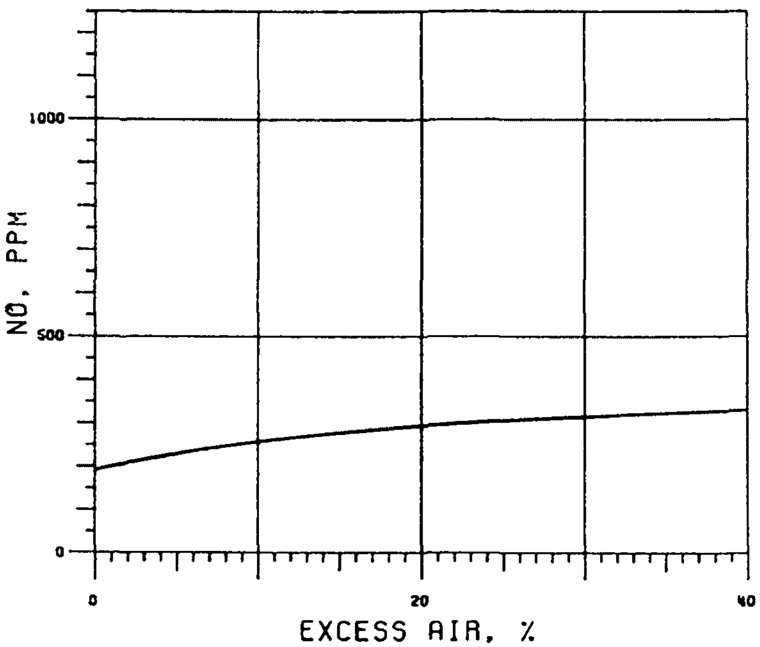


FIGURE D-62
OIL - MID LOAD

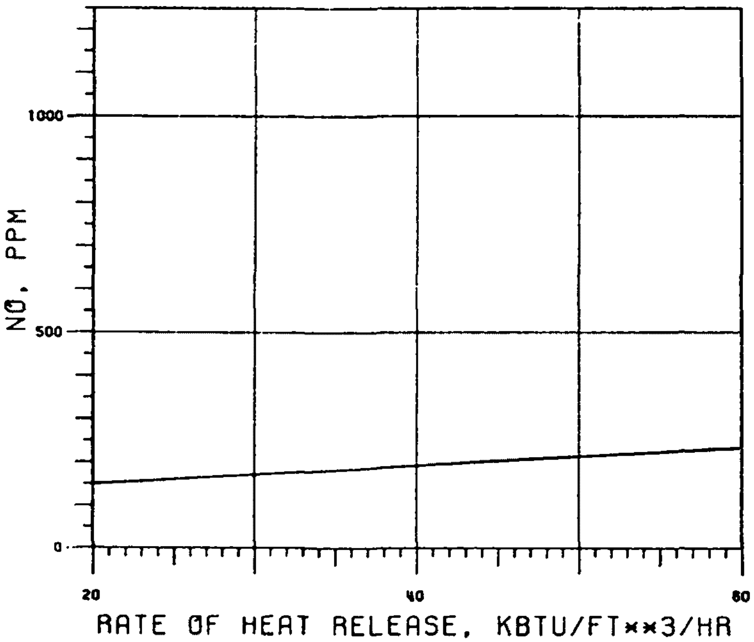


FIGURE D-64
OIL - LOW EXCESS AIR

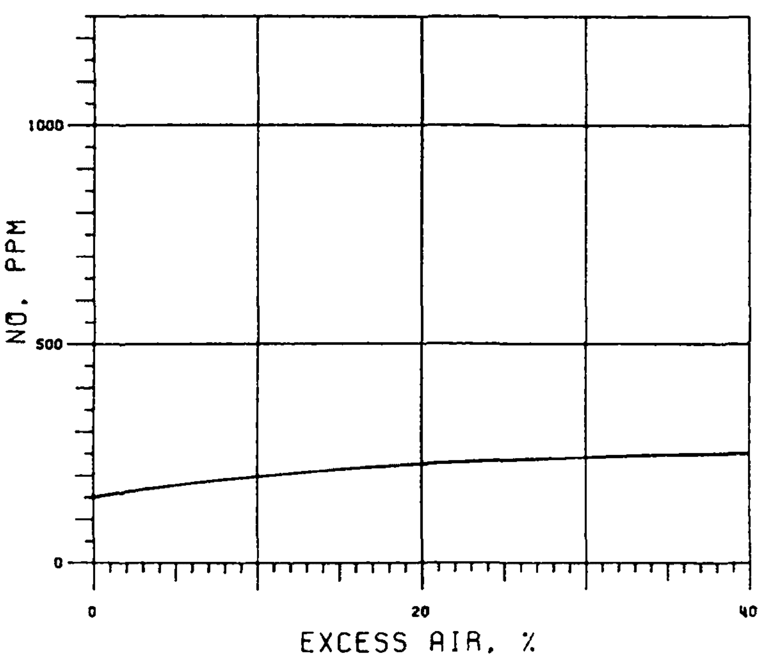


FIGURE D-61
OIL - LOW LOAD

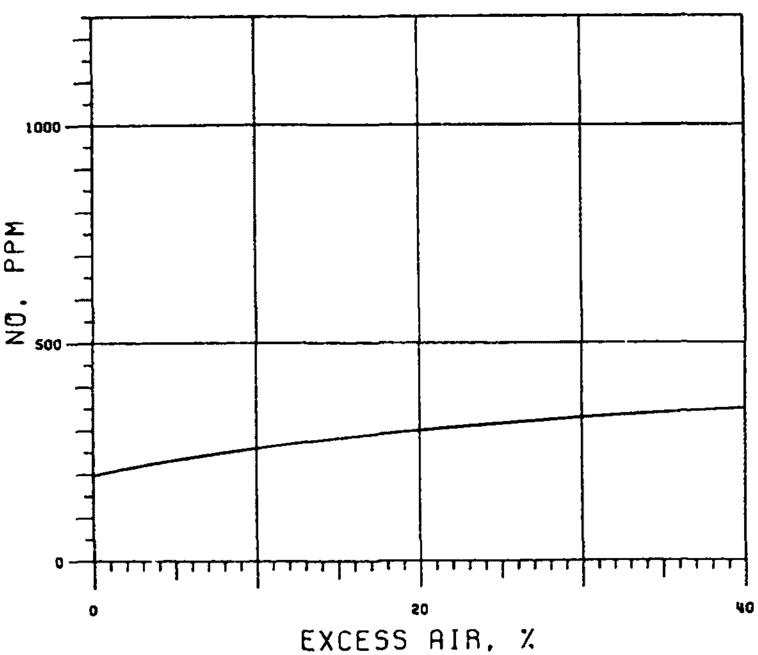


FIGURE D-63
OIL - HIGH LOAD

FIGURE D-66
OIL - HIGH EXCESS AIR

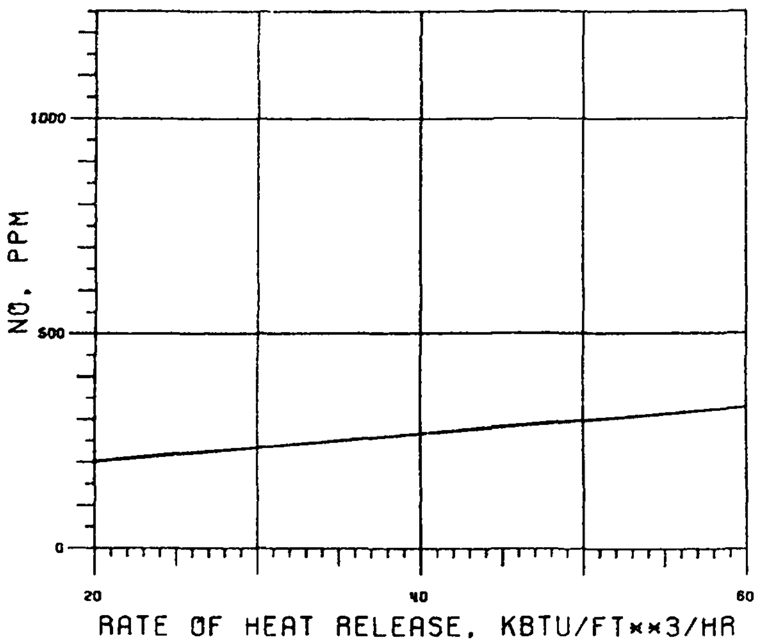


FIGURE D-68
OIL - MID LOAD

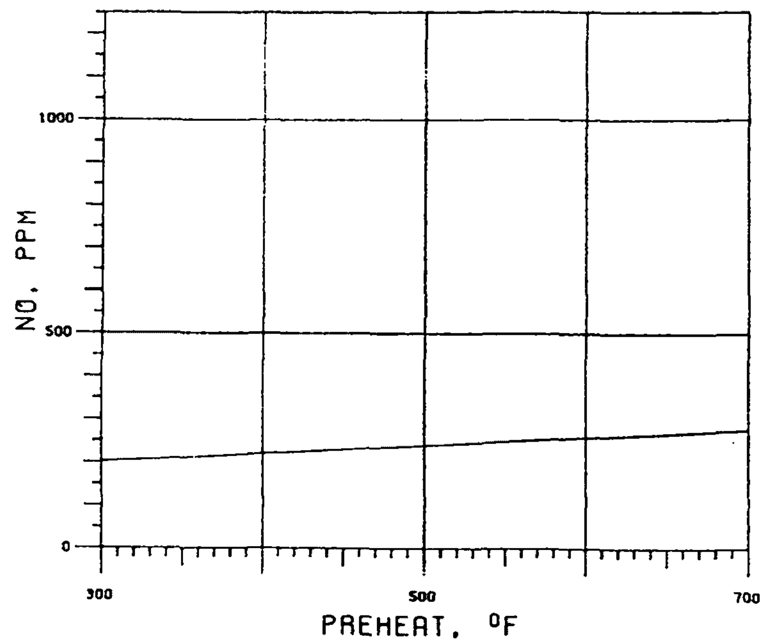


FIGURE D-65
OIL - MID EXCESS AIR

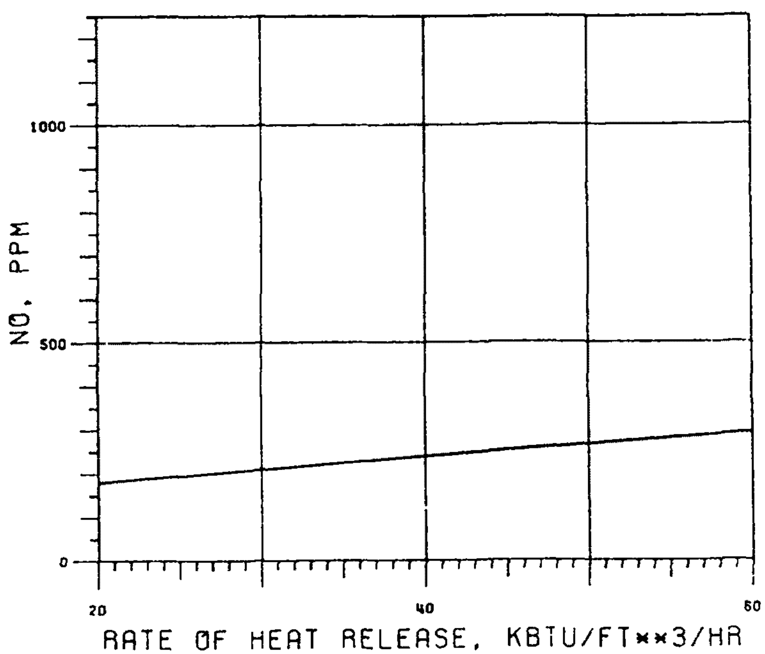


FIGURE D-67
OIL - LOW LOAD

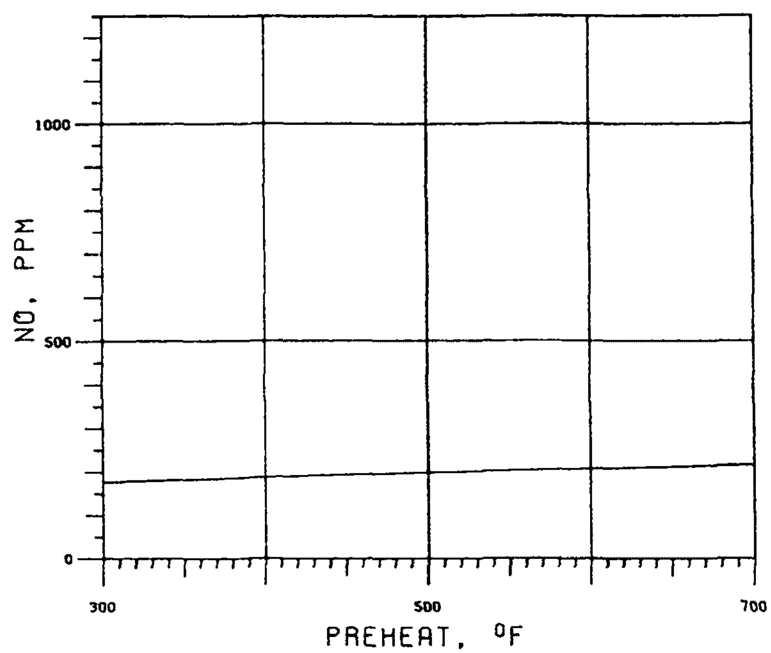


FIGURE D-69
OIL - HIGH LOAD

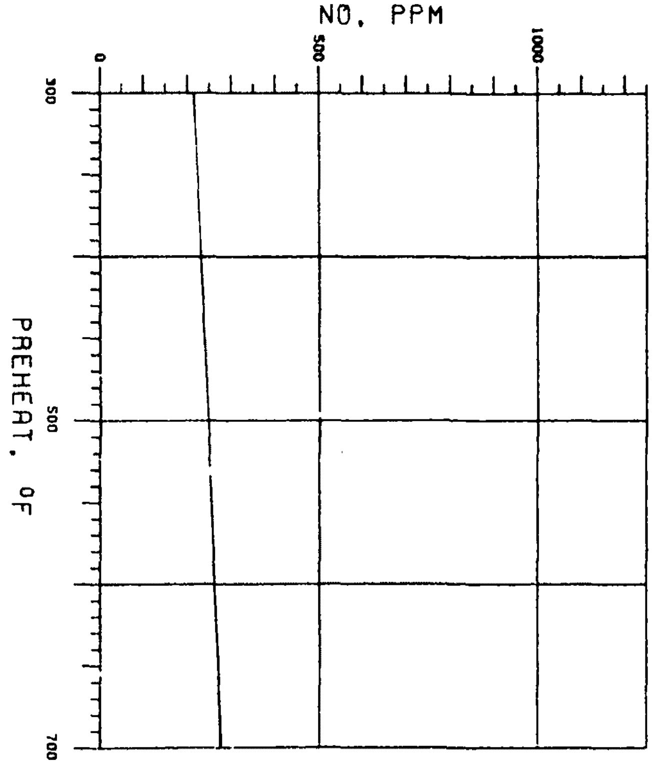


FIGURE D-70
OIL - LOW EXCESS AIR

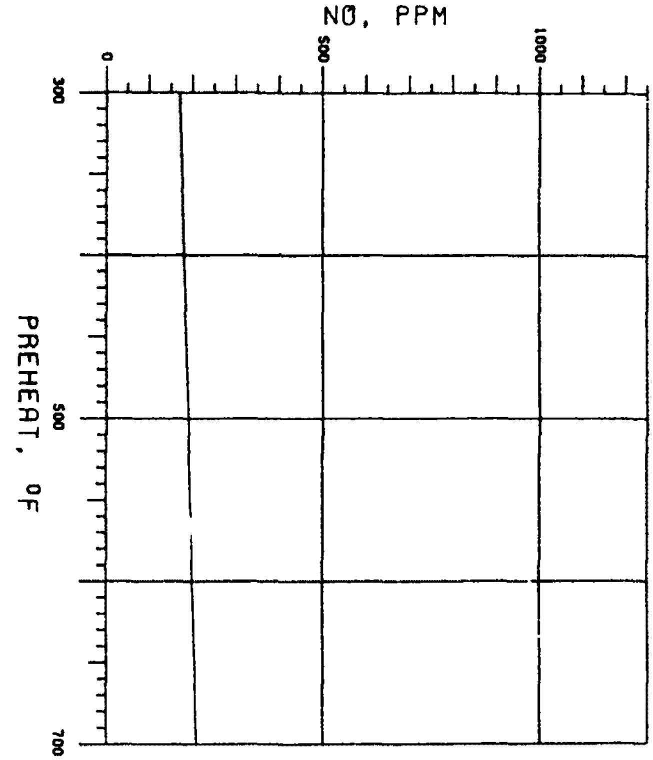


FIGURE D-71
OIL - MID EXCESS AIR

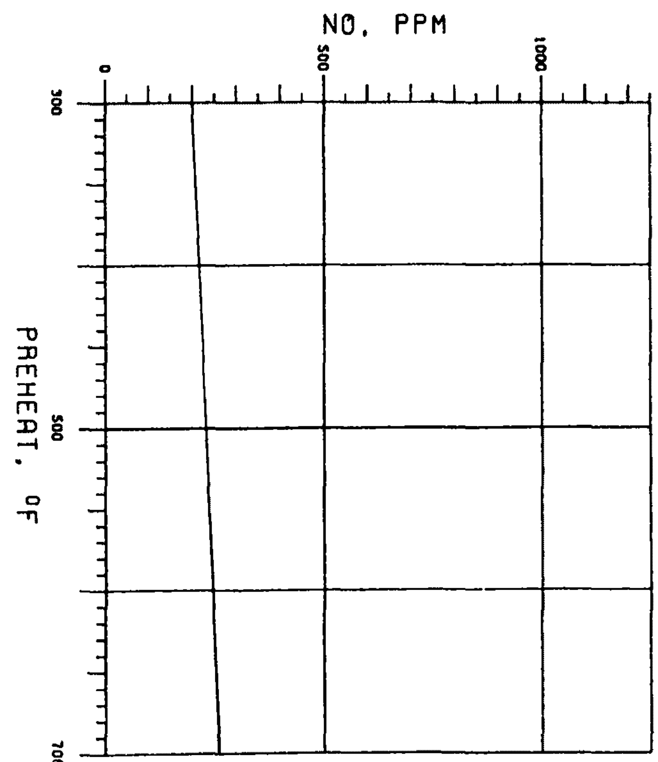
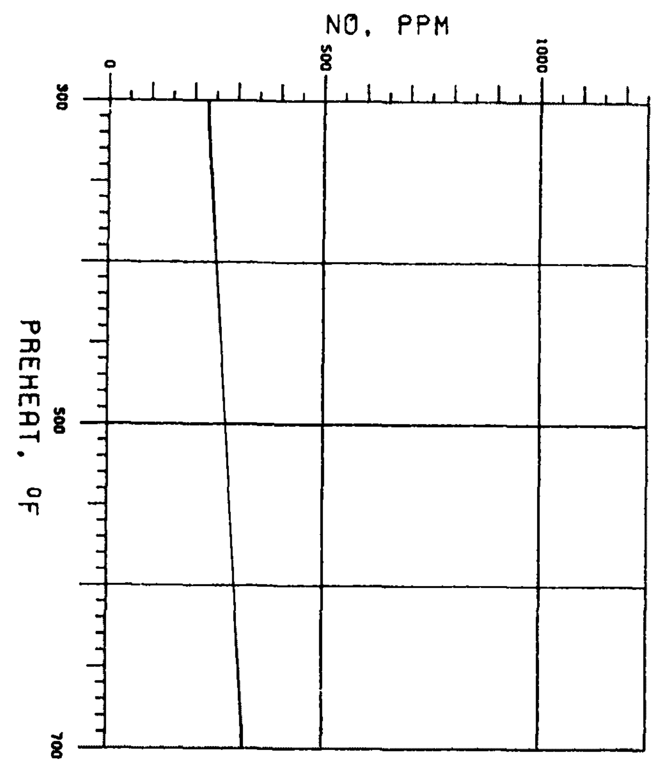


FIGURE D-72
OIL - HIGH EXCESS AIR



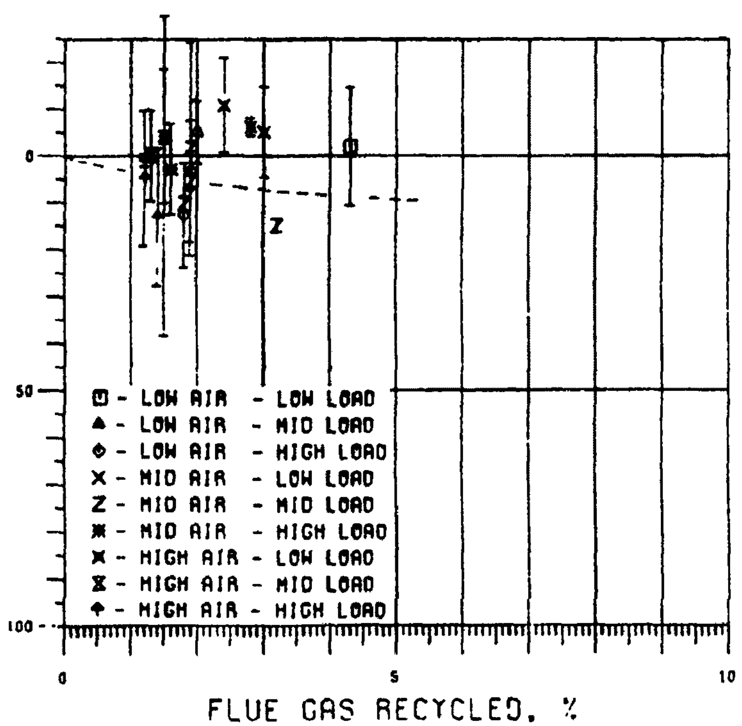


FIGURE D-73
PRIMARY FLUE GAS RECIRC.

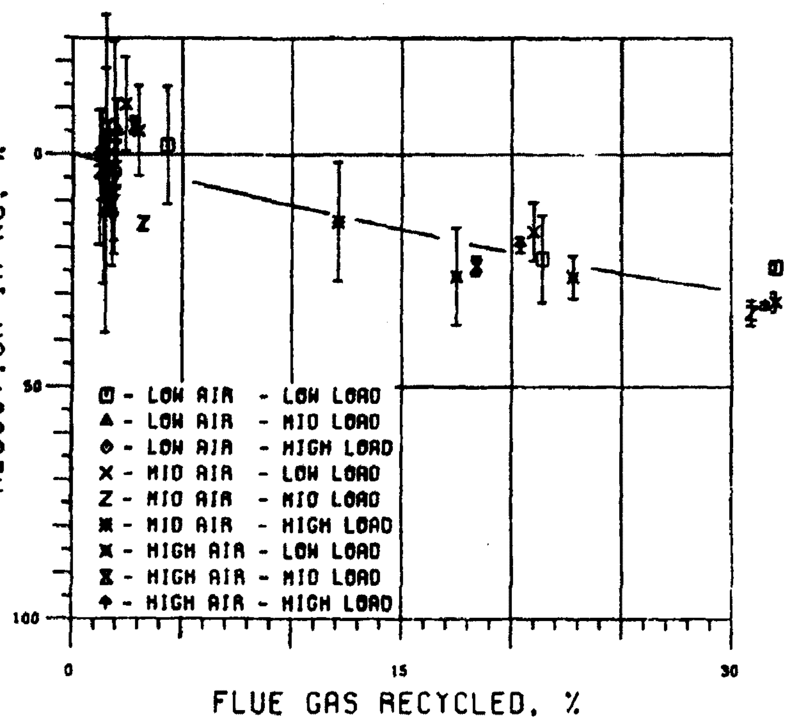


FIGURE D-74
FLUE GAS RECIRC. - COAL

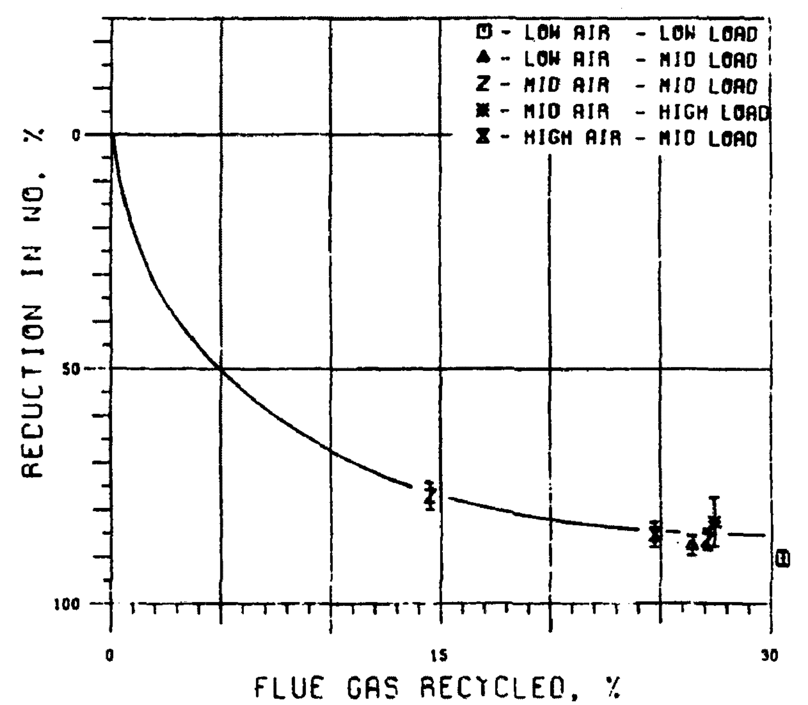


FIGURE D-75
FLUE GAS RECIRC. - GAS

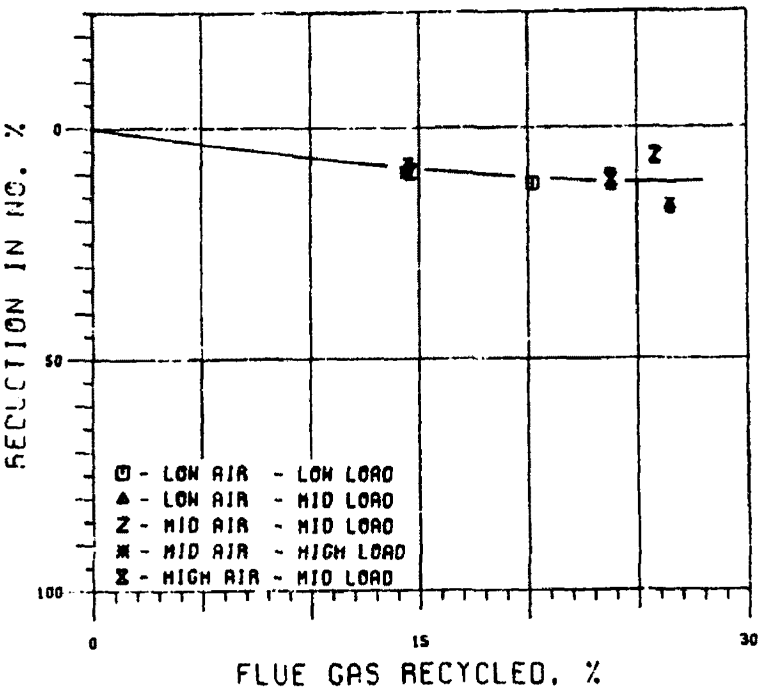


FIGURE D-76
FLUE GAS RECIRC. - OIL

FIGURE D-78
2 STAGE COMBUSTION COAL

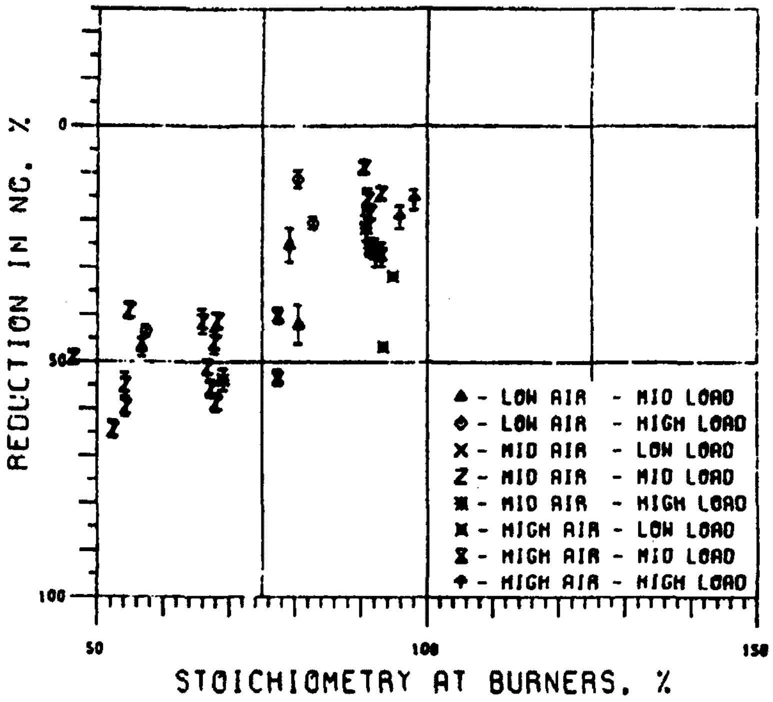


FIGURE D-80
2 STAGE COMBUSTION, GAS

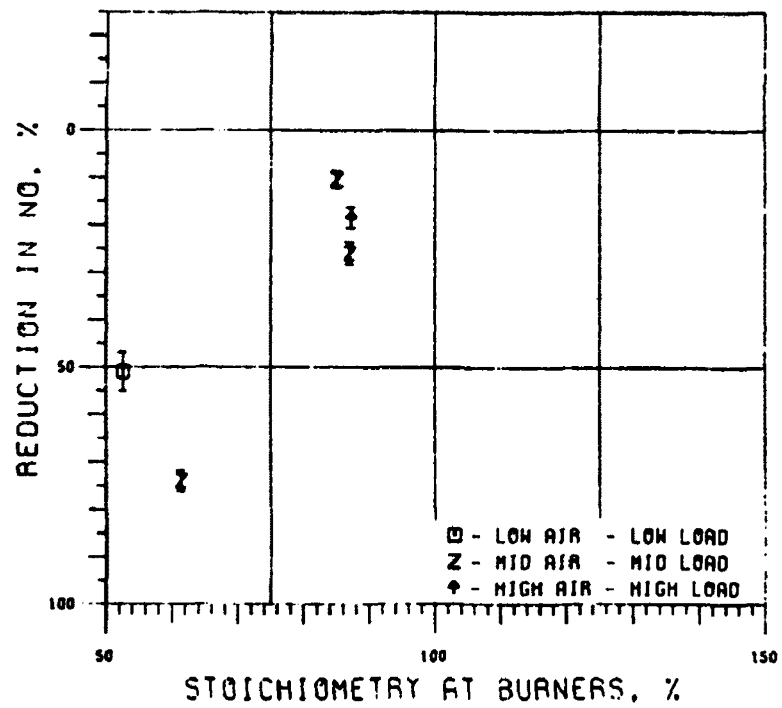


FIGURE D-77
FLUE GAS RECIRCULATION

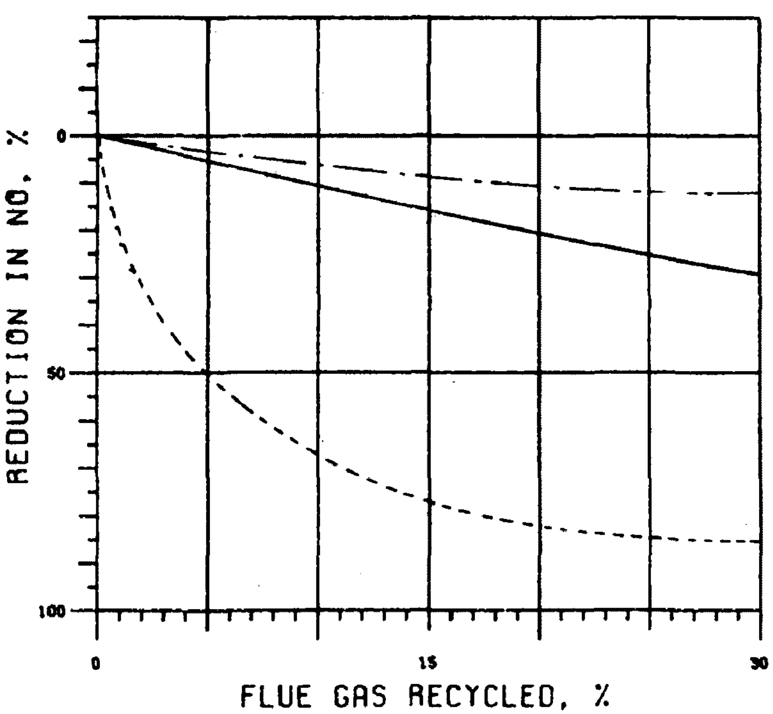
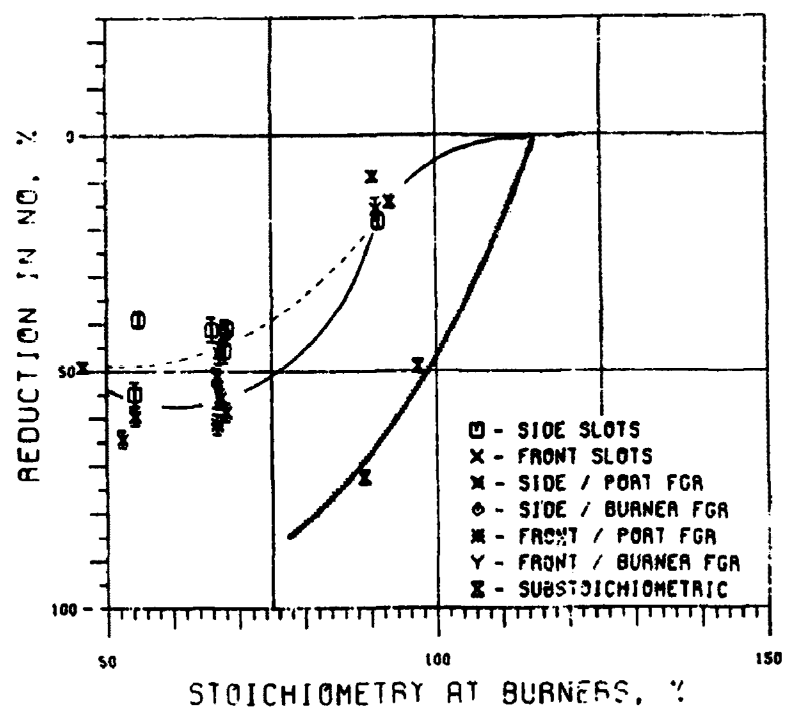


FIGURE D-79
TWO STAGE - MID AIR/LOAD



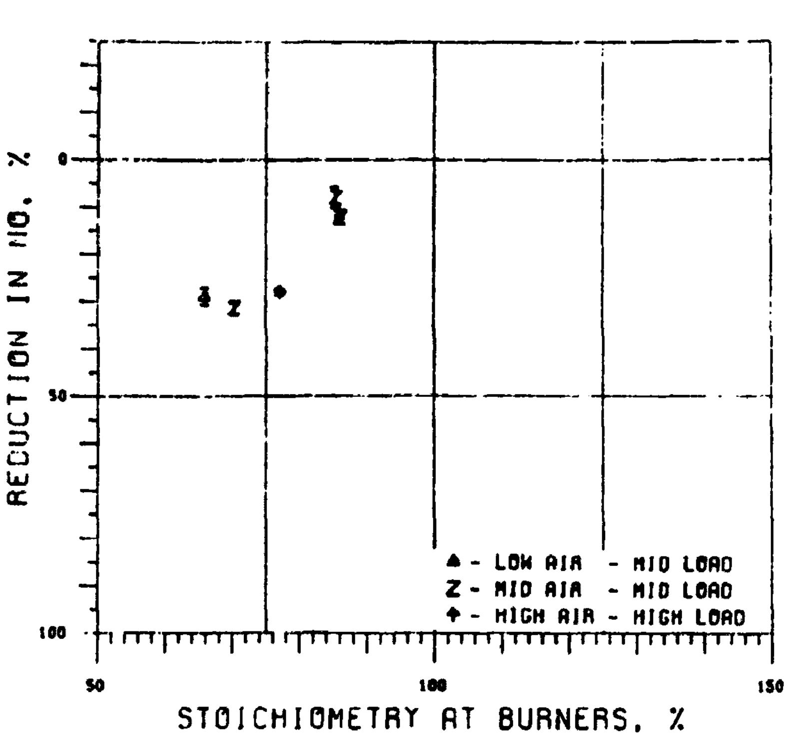


FIGURE D-82
2 STAGE COMBUSTION, OIL

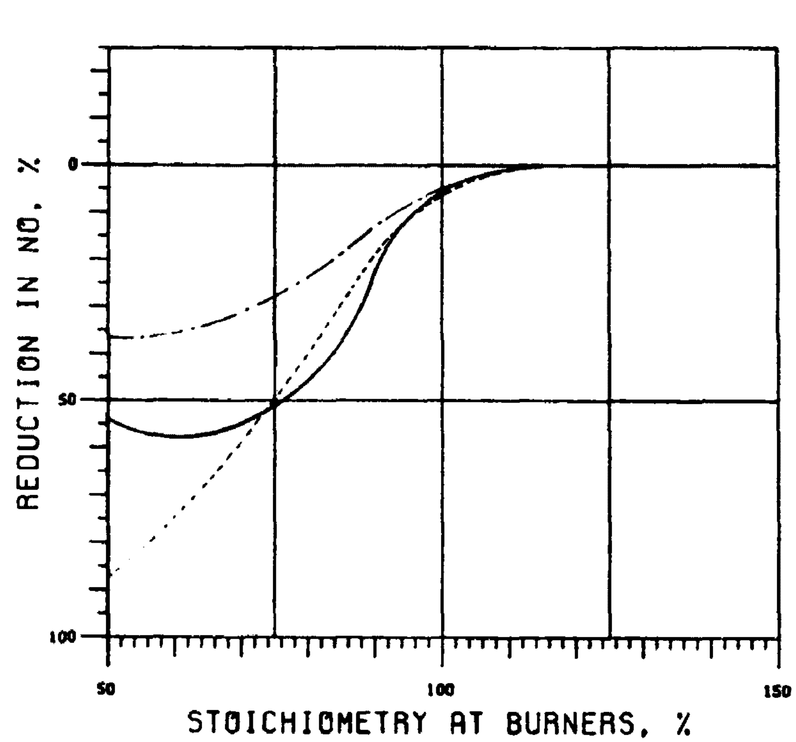


FIGURE D-84
TWO STAGE - MID AIR/LOAD

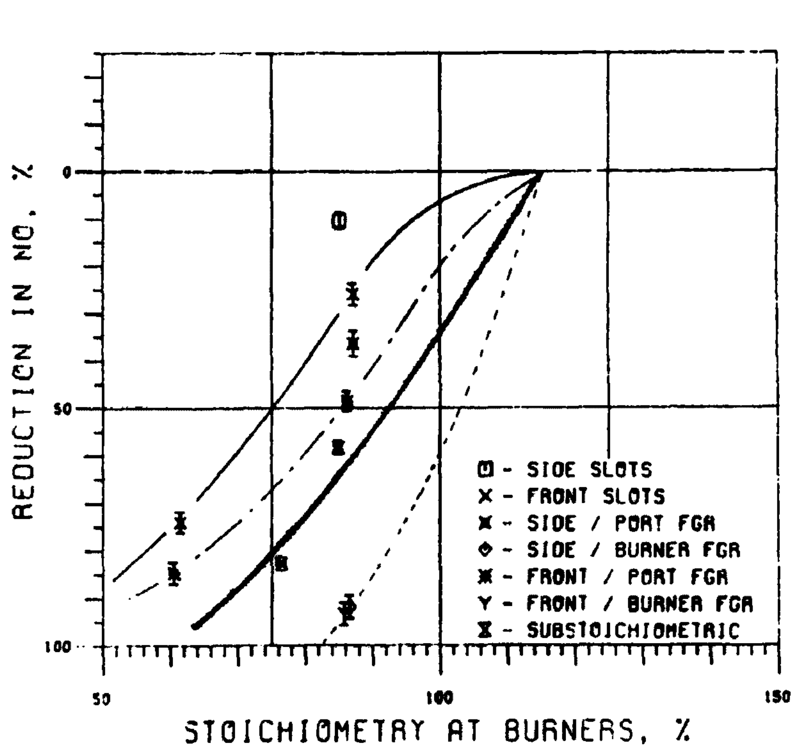


FIGURE D-81
TWO STAGE - MID AIR/LOAD

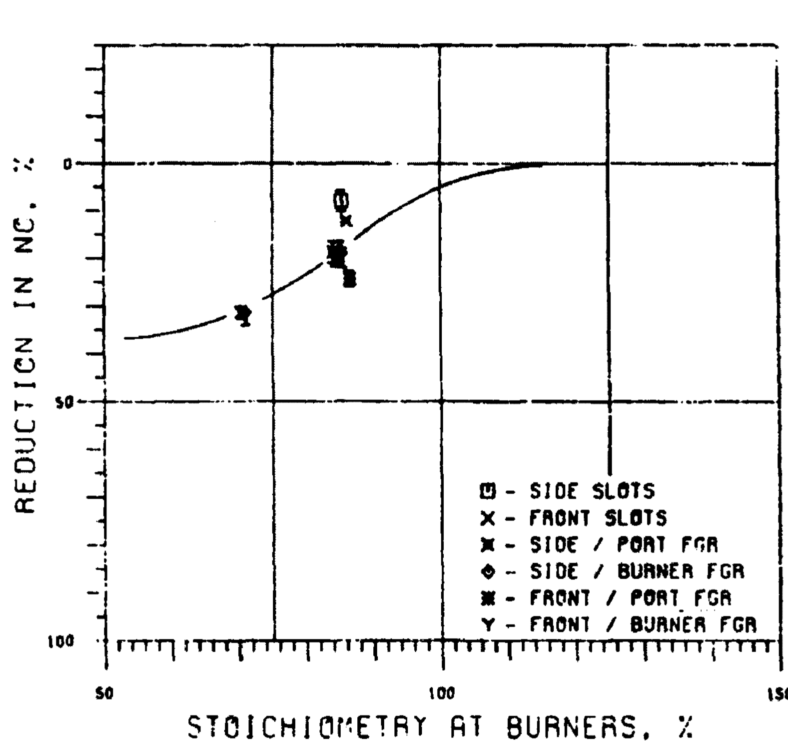


FIGURE D-83
TWO STAGE - MID AIR/LOAD

APPENDIX E

MATHEMATICAL DERIVATIONS AND CALCULATIONS

Initial calculations are done by computer and yield 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 is calculated. For large amounts of combustibles (>3%) in the flue gas during sub-stoichiometric tests, a gas chromatographic sample is analyzed for CO and H_2 (and CH_4) for coal fired tests to determine equivalent combustibles as CO; and for natural gas tests, the equivalent CO is hand calculated since both fuel and air are metered. (The equivalent CO for combustibles assumes all combustible is present as CO for ease of excess air calculations - H_2 and CO both require 1/2 O_2 and no other combustibles are found in the flue gas except solid carbon in coal tests. Since the unburned carbon in all coal tests is relatively constant, it is ignored in these excess air calculations.)

The flue gas recirculation is 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 is 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 are applied to the NO_x instrument readings for CO_2 and H_2O. The following series of constants are used:

Constant Used		Coal	Gas*	Oil
$\frac{\text{Wt of stoich. air}}{\text{Wt of fuel}}$		8.588	16.48	13.71
Wt of moisture/ 100 lb fuel		6.13	0.0	0.0
MF	MFI	0.6298	0.6315	0.6298
	MFR	0.3154	0.6315	0.5028
MA	MAI	0.5694	0.5709	0.5694
	MAR	0.2976	0.5709	0.4752
MM	MMI	0.1192	0.1197	0.1192
	MMR	0.02549	0.1197	0.05506
MC	MCI	0.06135	0.06138	0.06135
	MCR	0.05405	0.06138	0.07259

The equations are thus given as:

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

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

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

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

* Gas analysis used for coal and oil igniter firing is slightly different from latest used for gas firing. Difference in final calculations using old gas analysis for igniter is insignificant.

MMF = 0.0613 lb H_2O/lb coal (only for 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)

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 three equations, one for each fuel:

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

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

Oil: $BTU = 23855 \times W_{NI} + 18620 \times W_f$

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 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 - $\sim$127 ft^3 (8 ft long, 4.5 ft diameter)

2) 100% load $\equiv$ 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

$$L_1 \pm L_1'$$

and

$$L_2 \pm L_2'$$

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 yet include conversion to the SI/metric system. It is intended that these conversions will be made during the later contract work when required by EPA.

APPENDIX F

PRELIMINARY ECONOMICS ON FIELD UNIT MODIFICATION OR CONTROL

Reduction of NO_x by Field Unit Modification or Control utilizing the data from this report would have to be discussed on a preliminary basis only. Although the trends from the single burner test unit are useful, the magnitude of these trends might not hold on large field units with many burners. The limit of control used on the basic combustion unit may also be outside the practical range of large field units. Preliminary economical analyses are included for the best methods of proposed NO_x control:

1) Control of excess air - Pulverized coal fired units normally operate in the range of 15% to 30% excess air for control reasons. Operation at low excess air may present difficulties. Problems which need to be solved are, for example, the slagging from Eastern coals or excessive carbon loss.

2) Load/Rating - There is this capability in existing units. The cost of adding lower efficient units must be considered as the cost for making up for the loss of electricity from reduction of load on the operating units.

3) Preheat - This must be balanced against the combustion efficiency since carbon and stack losses in the field increase as preheat decreases. In addition, burner stability for safe operation may limit the amount of preheat reduction which is permissible.

4) Flue gas recirculation - The greatest problem appears to be the needed capacity for moving this flue gas around. Increased capital costs and operating costs are unavoidable. In addition, erosion may be accelerated.

5) Staged combustion - Two problems immediately evident are slagging and potential corrosion in the reducing/oxidizing boundary zone. The progressive mixing concept might hold greater promise as a compromise means of staging so that reducing gas would be kept off of the metal surfaces.

APPENDIX G

PHASE II - WORK PLAN

Future Work Plan for Phase II

I. Task I Data Correlation/Further Firing Tests

A. Data Correlations (NO_x and combustibles)

1) Computer analysis of data - preliminary
2) Firing tests to fill data gaps
3) Correlation to find quantitative trends
4) Further testing where uncertainty exists or for further information such as substoichiometric firing, etc.

B. Further Testing

1) Optimize most important trends from A - Detailed data correlation
2) Test two additional coals with different fuel bound nitrogen
3) Further quantifying tests as time permits, e.g., fuel bound nitrogen conversion, etc.
4) Prepare a preliminary operator's guide manual for application of technology to existing units

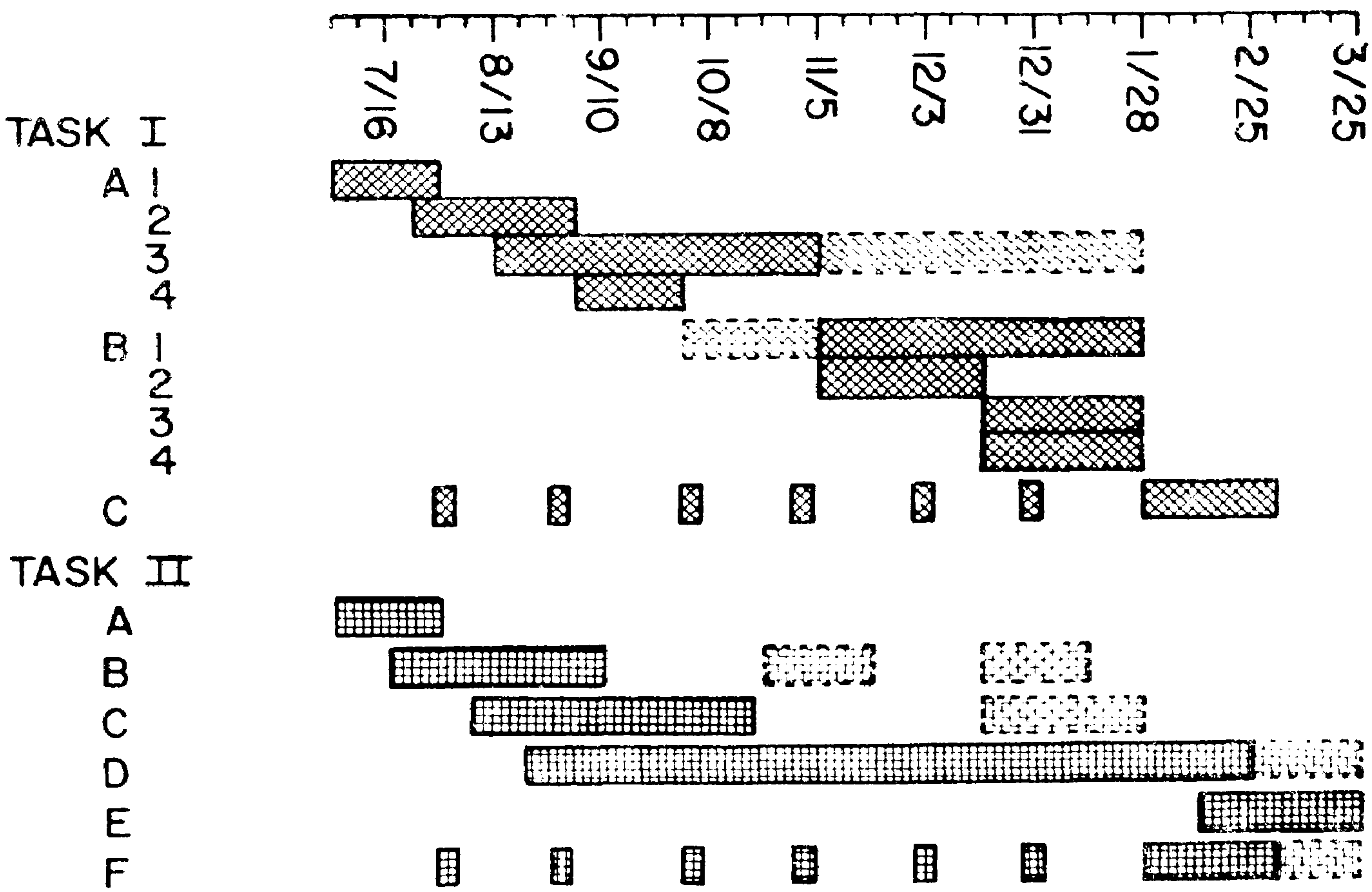
C. Reporting, Monthly, and Final

II. Task II Construction of New Multiburner Unit

A. Justification Report
B. Design
C. Purchase of Materials
D. Construction and Site Preparation
E. Preliminary Testing
F. Reporting, Monthly, and Final

FIGURE G.1

TIME SCHEDULE FOR PHASE II



BIBLIOGRAPHIC DATA SHEET	1. Report No. EPA-650/2-74-002a	2.	3. Recipient's Accession No.

4. Title and Subtitle
Effects of Design and Operating Variables on NOx from Coal-Fired Furnaces -- Phase I

5. Report Date
January 1974

6.

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13. Type of Report & Period Covered
Phase I, Final

14.

15. Supplementary Notes

16. Abstracts The report gives results of Phase I of an investigation of combustion modification techniques for controlling NOx emissions from pulverized-coal-fired utility boilers. The techniques--studied on a 5-million Btu/hr single-burner pilot unit--included: excess air; air preheat; rating; flue gas recirculation; staged combustion; quench; and swirl. The study showed that NOx reductions of up to 50% are possible either using staged combustion or by lowering excess air levels from 30 to zero %. Flue gas recirculation yielded only moderate NOx reductions. Fuel-bound nitrogen conversion increased with increasing excess air level and decreasing temperature. At substoichiometric conditions, the final precursors for NO formation from either fuel-bound nitrogen or thermal atmospheric fixation appeared identical. For existing units, control of excess air promises to be the best method for NOx reduction; however, for new units, staging (with physical separation of the two stages) appears to be the most promising.

17. Key Words and Document Analysis. 17a. Descriptors
Air Pollution
Nitrogen Oxides
Combustion Control
Coal
Combustion Chambers
Flue Gases

17b. Identifiers/Open-Ended Terms
Air Pollution Control
Stationary Sources
NOx Reduction
Staged Combustion
Flue Gas Recirculation
Air Preheat
Excess Air
Quench
Swirl
Fuel Nitrogen

17c. COSATI Field/Group 13B, 20M, 21B

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