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COMBUSTION CONTROL OF POLLUTANTS FROM MULTI-BURNER COAL-FIRED SYSTEMS

by

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The report gives results of an investigation, utilizing an experimental 500-lb/hr multi-burner pulverized-coal-fired furnace, to determine the effects of several combustion modifications on nitrogen oxide (NOx) emissions. Techniques investigated were: reduced excess air, staged combustion, flue gas recirculation to both primary and secondary combustion air streams, and combinations of all techniques. Reducing excess air from 20 to 2 percent reduced NOx emissions by about 70 percent; however, the NOx reduction was accompanied by a significant decrease in carbon conversion at the lower excess air levels. Staged combustion reduced NOx emissions by about 50 percent, with little increase in carbon loss over conventional combustion. Using 30 percent flue gas recirculation also reduced NOx emissions by about 50 percent, but was accompanied by a significant reduction in carbon combustion efficiency, similar to that experienced in the low excess air tests. Various combinations of the individual NOx reduction techniques were tested but, since the effects were not cumulative, they did not offer any advantage.

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Combustion	Combustion Modification	21B
Coal	Reduced Excess Air	21D
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ABSTRACT

An experimental 500 lb/hr multi-burner pulverized-coal fired furnace was utilized to determine the effects of several combustion modifications on nitrogen oxides emissions. Techniques investigated were reduced excess air, staged combustion, flue gas recirculation to both primary and secondary combustion air streams, and combinations of all techniques.

Reduction of about 70% in NO_x emissions were achieved by reduction of excess air from 20% to 2%, however, the NO_x reduction was accompanied by a significant decrease in carbon conversion at the lower excess air levels.

Staged combustion resulted in about a 50% reduction in NO_x emissions, with little increase in carbon loss over conventional combustion.

Thirty percent flue gas recirculation also resulted in an NO_x reduction of about 50%, but was accompanied by a significant reduction in carbon combustion efficiency similar to that experienced in the low excess air tests. Various combinations of the individual NO_x reduction techniques were tested but they did not offer any advantage as the effects were not cumulative.

This report was submitted in fulfillment of Interagency Agreement Number EPA-IAG-020(D) by the U.S. Bureau of Mines under the sponsorship of the Environmental Protection Agency. Work was completed as of February 1, 1974.

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I. INTRODUCTION

It is generally known that coal-fired utility boilers are the largest stationary source contributor of nitrogen oxides (NO_x) in the U.S. Compounding the NO_x problem from coal are a variety of industrial applications where coal is the fuel. Recent estimates indicate that about 42% of the total NO_x emissions from stationary sources result from coal combustion.

Combustion modification techniques offer the most promising cost-effective short-term approach to control of NO_x from stationary combustion sources regardless of fuel. This study, however, deals with techniques applicable to multi-burner coal-fired combustion systems. The techniques studied will have the greatest beneficial impact on utility and industrial size boilers.

The purpose of the study was to investigate in further detail the effects of specific combustion modification techniques and assess the impact that they have on NO_x and combustion-related pollutants, C, CO, and hydrocarbons. Additionally the study provided an insight into the impact that combustion modifications have on combustion efficiency as measured by carbon losses.

The experimental studies should provide more definitive guidance as to the merits and limitations of these techniques for subsequent application to field units.

II. DESCRIPTION OF FACILITY

Combustion tests were conducted in an experimental, pulverized-coal-fired furnace designed to simulate the performance of an industrial steam generating unit used in power generating plants. The wall-fired, dry-bottom furnace is capable of burning 500 pounds of coal per hour, with an exit gas temperature of 2000°F. Heat release rate is about 16,000 Btu/hr.-cu.ft. A photograph of the combustor is shown in Figure 1. The furnace has water-cooled walls with refractory applied in the burner zone to provide flame stability and to prevent excessive heat transfer to the walls in the vicinity of the burners. Coal is burned in a direct-fired system through four burners in the front wall of the 7 ft. wide, 12 ft. high and 5 ft. deep rectangular furnace. A simplified flowsheet of the combustion system is shown in Figure 2. Provision has been made to preheat secondary air and to vary distribution of combustion air between the primary and secondary streams. Variations in coal feed rate can result in pockets deficient in either fuel or oxygen, producing fluctuations in fuel-air ratio. Consequently a recycle loop was provided in the primary air-coal transport line to obtain a more uniform coal feed rate and thus minimize these fluctuations. Figure 3 shows the principal components of the combustion system in half section. Shown are the combustor, the convective heat-transfer section, a duct designed for emission measurements, and the recuperative air preheater. Combustion products flow through the convective heat transfer section decreasing the gas temperature to 1000°F; through the air heater, used to preheat secondary air; then through a mechanical dust

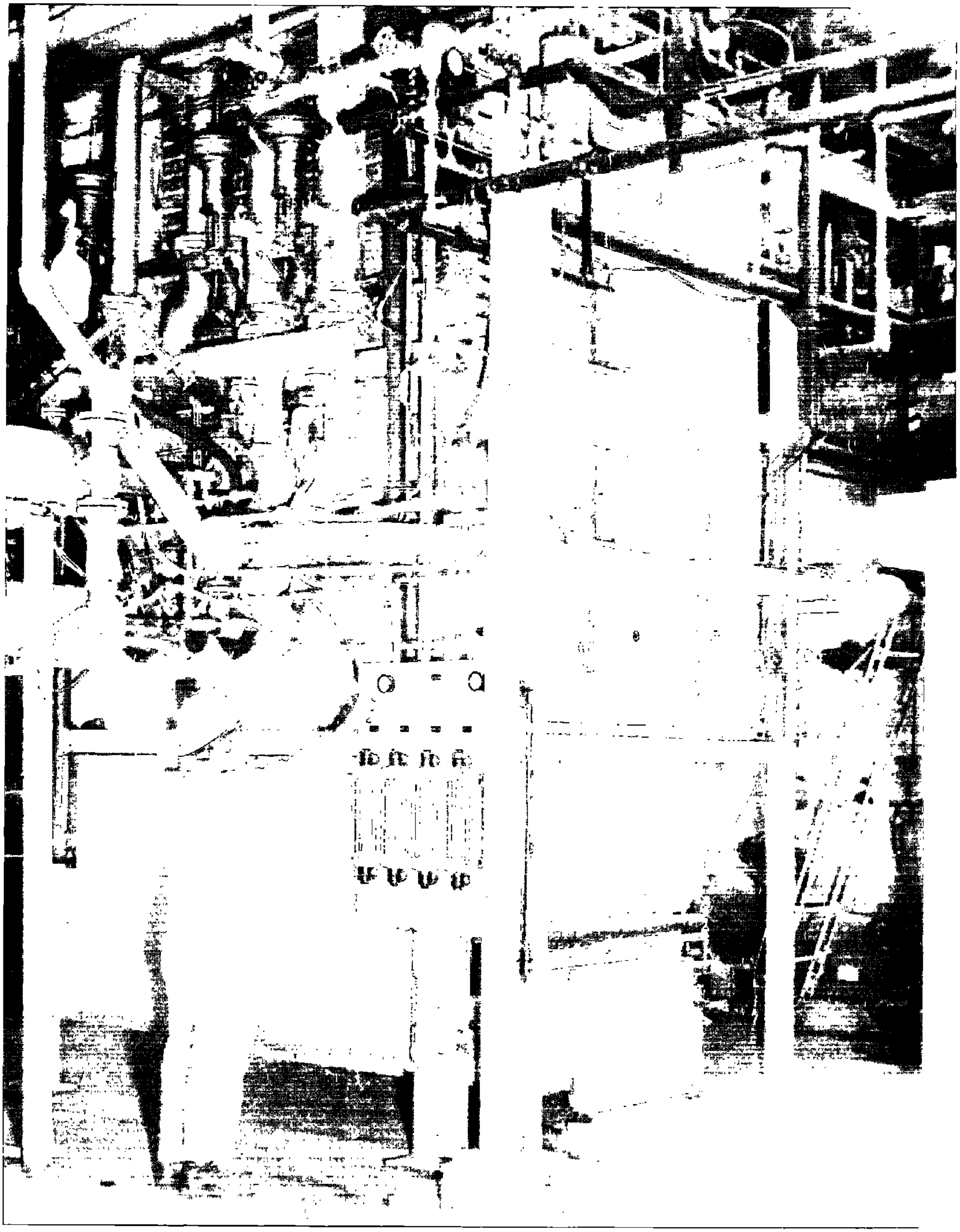

Figure 1. View of 500 lb/hr coal-fired furnace.

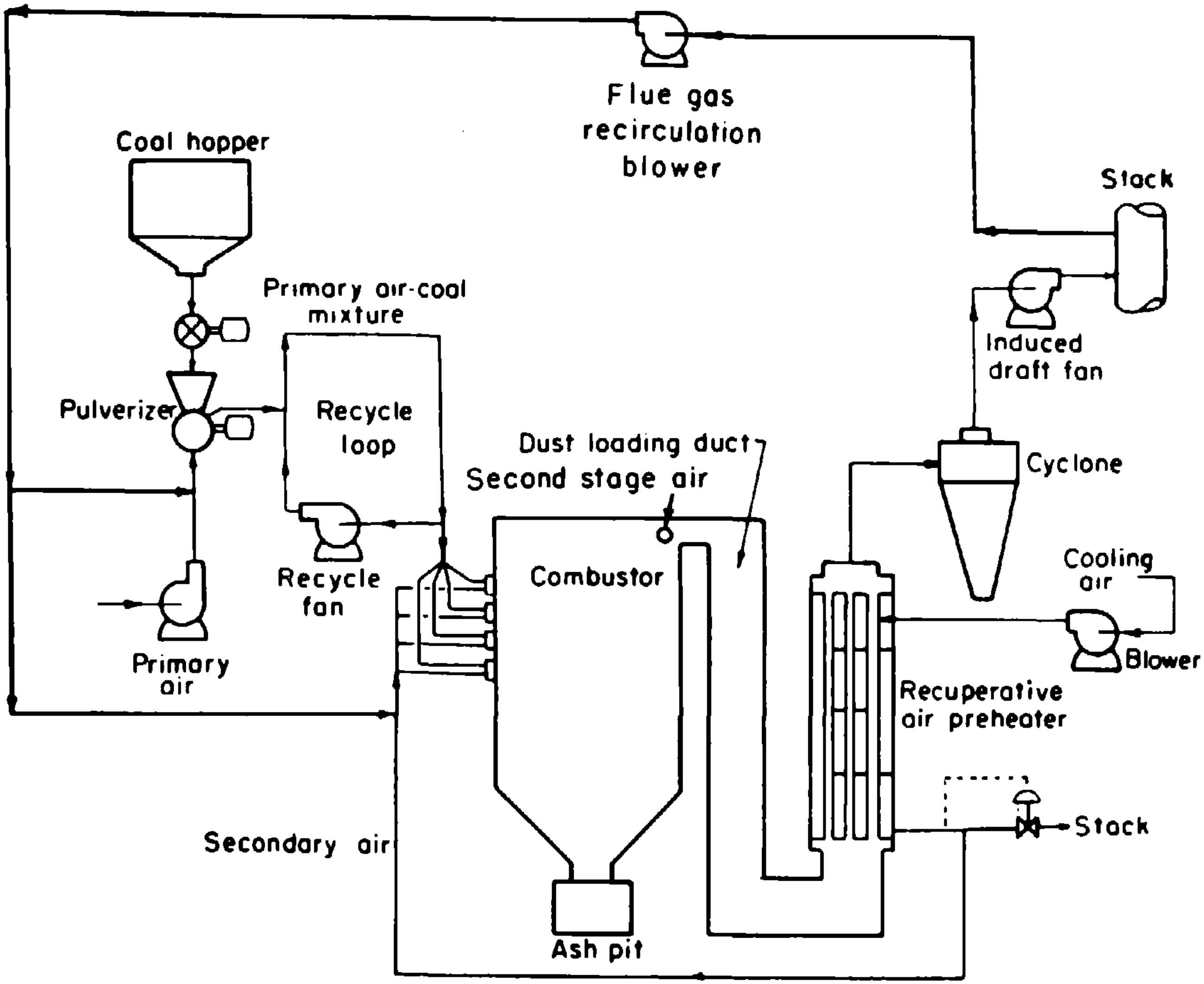

Figure 2. Flowsheet of pulverized coal-fired facility.

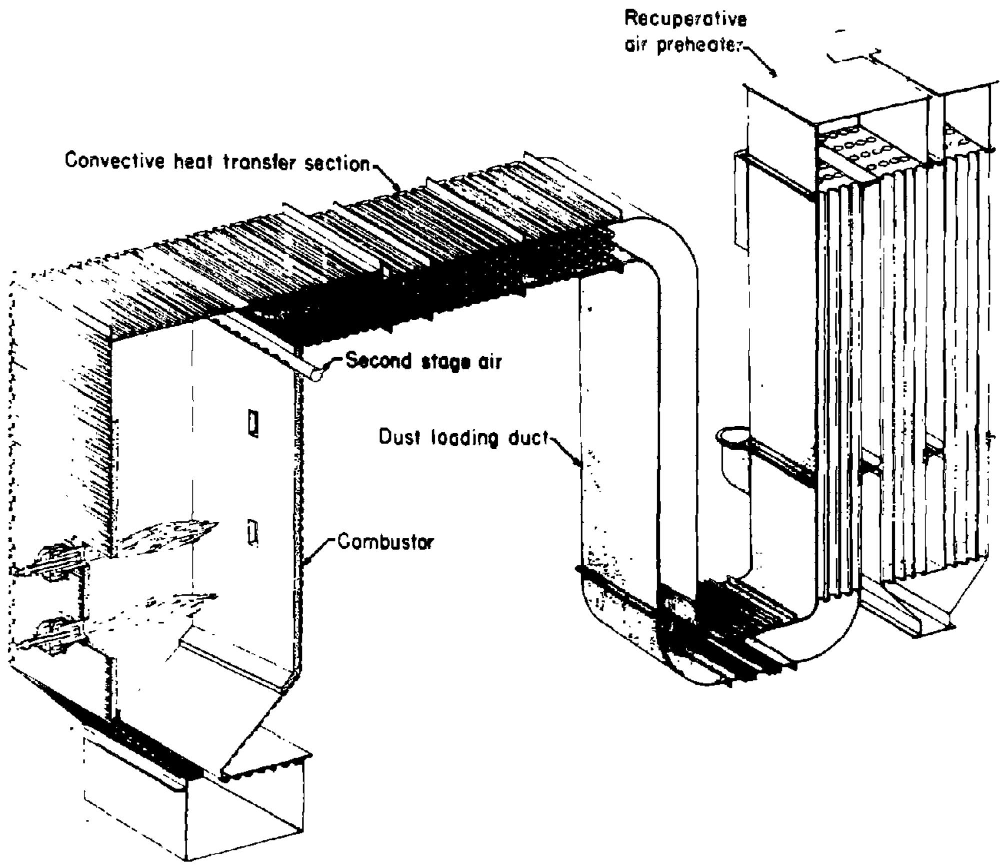

Figure 3. Half section view of principal components of the combustion system.

collector. The cross section of a multi-fuel burner is shown in Figure 4. The burners were designed to impart swirl in both primary and secondary air streams. The flame profile can be continuously varied from a short, bushy pattern to a relatively long, narrow pattern by adjustment of swirl induced in the secondary air stream.

The four front-wall burners were designed to fire natural gas and/or pulverized solid fuel. Prior to each test period, the experimental furnace was fired with natural gas to preheat the refractory and to provide a source of preheat for secondary air. During this period combustion air flows were established and necessary secondary air swirl adjustments were made to provide flames that were attached to the burners, but not drawn into the burner tubes. Preheating was then continued until secondary air temperature reached 550°F. Natural gas flow to each burner was then reduced by 50%, and pulverized coal feed was started at a rate of about 250 lb/hr. From this point oxygen content of the flue gas was used as a guide in the fuel changeover. As coal feed rate was increased, natural gas input was decreased to maintain a constant oxygen level. When the desired coal feed rate was reached, all natural gas input was eliminated, and the unit was allowed to reach thermal equilibrium.

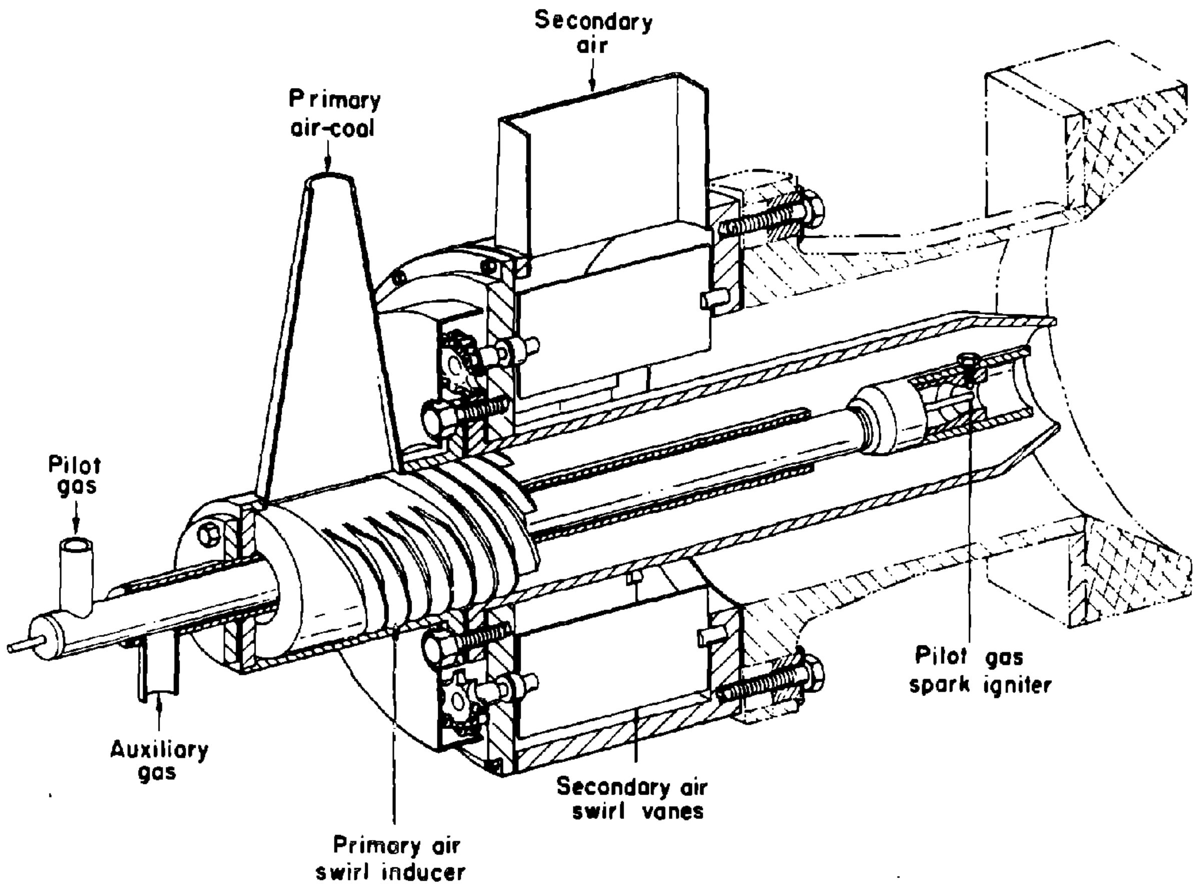

Figure 4. Multi-fuel burner assembly.

During the course of the experimental program, the coal-firing rate was maintained at 500 lb/hr, coal fineness at 75% through 200 mesh, and secondary air temperature at 600°F. Table 1 shows proximate and ultimate analyses of the coal fired. Sufficient coal was obtained to minimize variations in analysis. As a result, nitrogen content of 1.4% was maintained throughout the program.

TABLE 1.- TYPICAL ANALYSIS OF COAL FIRED

	As received, wt-%
Proximate	
Moisture	2.2
Volatile matter	36.5
Fixed carbon	51.5
Ash	9.8
Ultimate	
Hydrogen	5.3
Carbon	73.0
Nitrogen	1.4
Oxygen	8.4
Sulfur	2.1
Ash	9.8

Heating value -------- 13,060 Btu/lb

Emission measurements were made during each test period, using instrumented methods where possible. Samples were taken from the dust loading duct for analysis of gaseous components and carbon content of the fly ash. Gaseous species and the instrumentation used for their measurement were:

Oxygen	Catalytic combustion Polarographic electro-chemical
Carbon Dioxide	Non-dispersive infrared
Carbon Monoxide	Non-dispersive infrared
Nitric Oxide (NO)	Non-dispersive infrared
NO/NO_x	Chemiluminescent
Sulfur Dioxide	Electro-chemical
Hydrocarbons	Flame ionization

Throughout this report, NO_x emissions are expressed either as ppm corrected to 0% O_2 or as g $NO_2/10^6$ cal heat input. This latter method is consistent with requirements of the Federal Register, Vol. 36, No. 247-Thursday, December 23, 1971. To convert from g $NO_2/10^6$ cal to lb $NO_2/10^6$ Btu, divide by 1.8.

To minimize sample time lag, a massive sample was taken from the duct, passed through glass wool filters to remove particulate, than cooled in ice baths. From this stream proportional samples were fed to each instrument using the shortest possible conductor length. Excess gas in the major stream was vented to the atmosphere. The ice baths were designed to provide limited gas-liquid contact. In addition, spot samples were obtained for wet chemical analysis. For NO_x, the EPA-recommended phenoldisulphonic acid technique was used, while the Shell technique was used for sulfur oxides.

Samples for particulate determination were obtained using apparatus manufactured to Environmental Protection Agency specifications.

III. RESULTS AND DISCUSSION

A. Baseline Tests

Prior to initiating the experimental study of combustion modifications, a baseline NO_x emission level was established for the combustion unit. This study was conducted firing at rated capacity, 500 lb/hr, with 20% excess air and secondary air preheated to 600°F, representing a situation somewhat typical of those encountered in commercial practice. These conditions served as a basis to define the process conditions and modifications used in later phases of the program. Tests at baseline conditions were repeated several times throughout the program with excellent reproducibility. Nitrogen oxides emissions were 1.46 g $NO_2/10^6$ cal. Oxides of sulfur were on the order of 1600 ppm. Concentration of hydrocarbons in the flue gas were typically about 1 ppm.

B. Low Excess Air Tests

The initial phase of the study of combustion modifications dealt with variations in excess air level. Results of the tests are shown in Table 2. As indicated, excess air was reduced from a 20% baseline condition, to as low as 2%, with resulting nitrogen oxide reduction from 1.46 g $NO_2/10^6$ cal to about 0.5 g $NO_2/10^6$ cal. These results are shown in Figure 5. Sulfur oxides emissions appeared to be a function only of the sulfur content of the coal. About 2.5% of the total sulfur in the coal was found in the ash, the remainder being in the effluent gas. Variations in sulfur oxide concentration, shown in Table 2, are mainly the result of dilution by excess air.

Also shown in Table 2 is the effect of reduced excess air on carbon conversion. At 20% excess air, 99.5% of the carbon in the coal was burned, while at 2% excess air carbon combustion efficiency was reduced to 96.2%. The effect of reduced excess air on carbon combustion efficiency is shown in Figure 6.

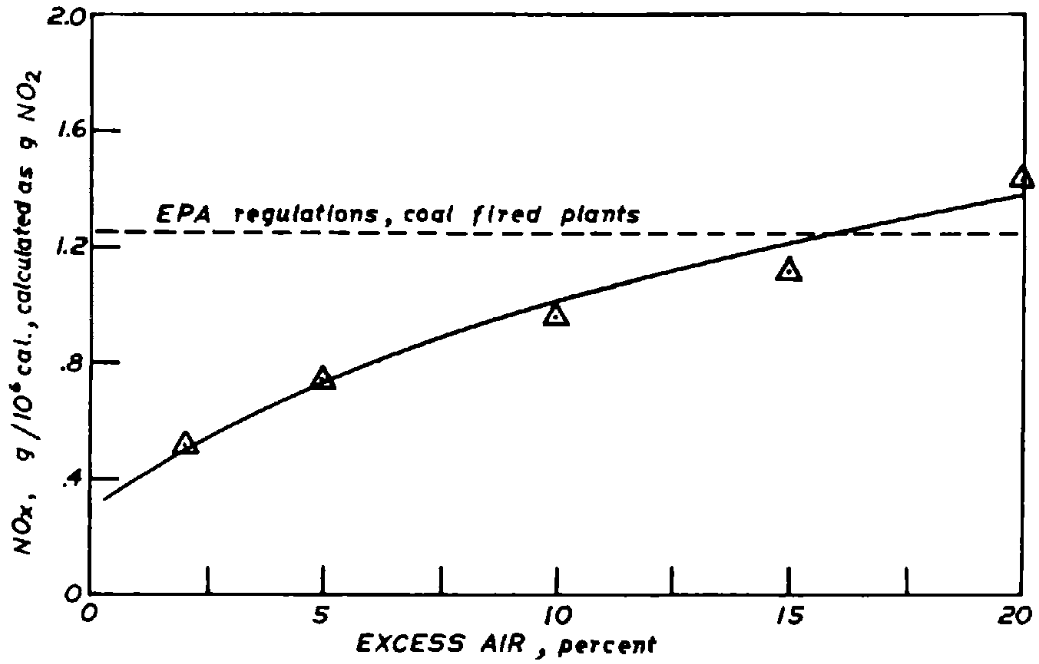

FIGURE 5. NO_x Formation as a function of excess air.

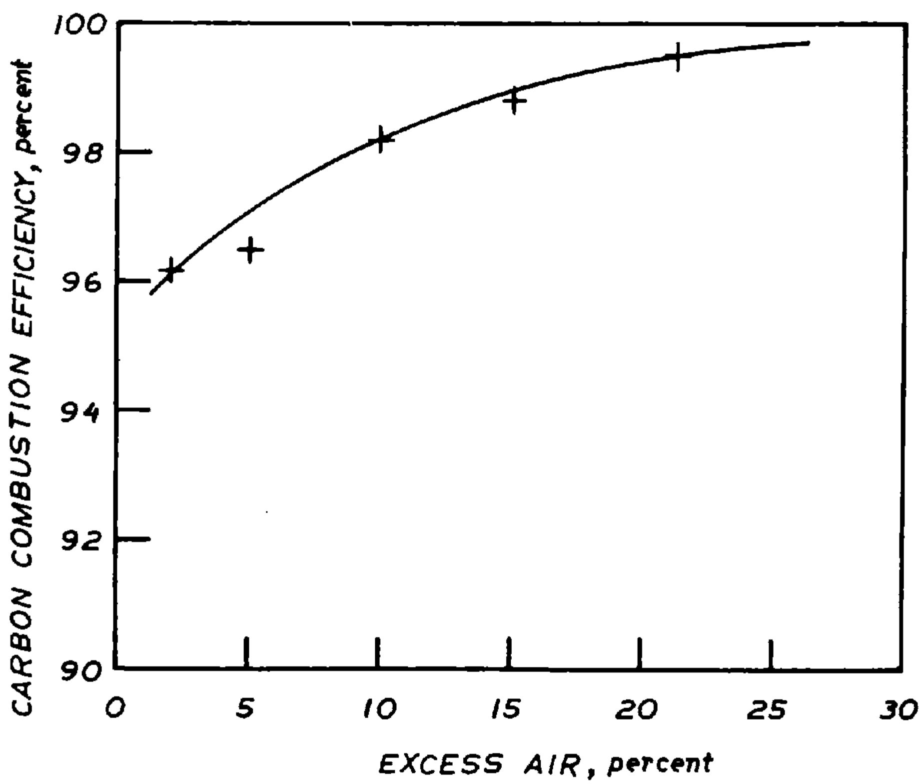

FIGURE 6. Carbon combustion efficiency as a function of excess air.

TABLE 2. - SUMMARY OF TESTS AT VARIOUS EXCESS AIR LEVELS

Excess air, %	NO_x, as g $NO_2/10^6$ cal	NO_x, as ppm corrected to 0% O_2	CO, ppm	SO_2, ppm	Carbon combustion efficiency, %	Furnace outlet temperature, °F
20	1.46	694	30	1620	99.5	2025
15	1.17	560	60	1770	98.8	2040
10	0.97	466	100	2030	98.2	2060
5	0.74	327	1000	2150	96.5	2075
2	0.52	253	5000	-	96.2	2100

C. Two-Stage Combustion Tests

A water-cooled second-stage air injector that could be installed at various positions in the furnace was constructed for the two-stage combustion studies. As shown in Figure 7 it was equipped with 14 equally spaced nozzles to provide uniform distribution of second stage air over the entire width of the furnace. Initially the injector was located at the furnace outlet, point A in Figure 8. The nozzles were aimed toward the burner wall at a 45° angle from the horizontal. Results of tests with second stage air introduced in this manner are shown in Table 3 and Figure 9. Air to the first combustion stage (burners) was varied from 105 to 80% of the stoichiometric requirement. Overall excess air as measured in the sampling duct was maintained at 20% in all tests. Nitrogen oxides emissions were 1.1 g $NO_2/10^6$ cal with 105% to the first stage and 0.77 g $NO_2/10^6$ cal with 80% of stoichiometric supplied to the first stage. These values

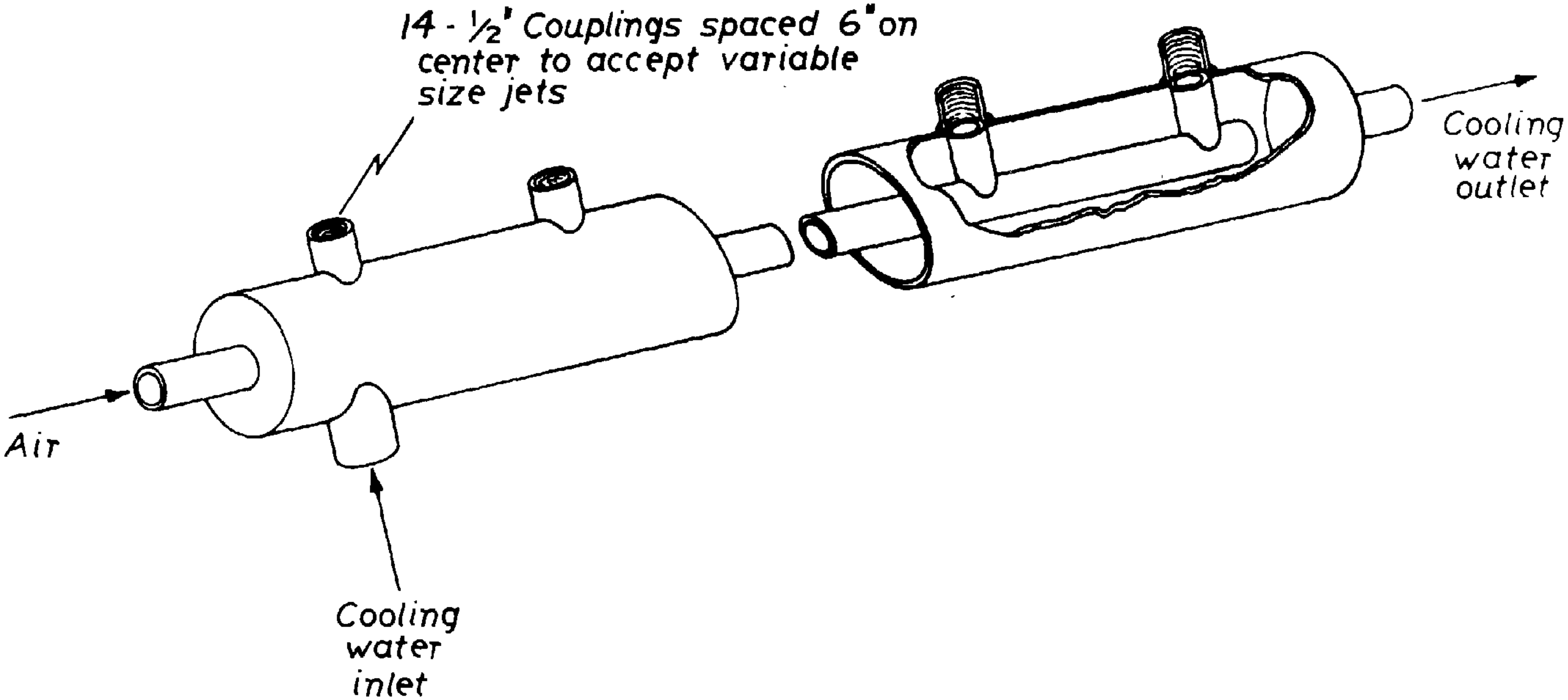

Figure 7. Water-cooled second stage air injector.

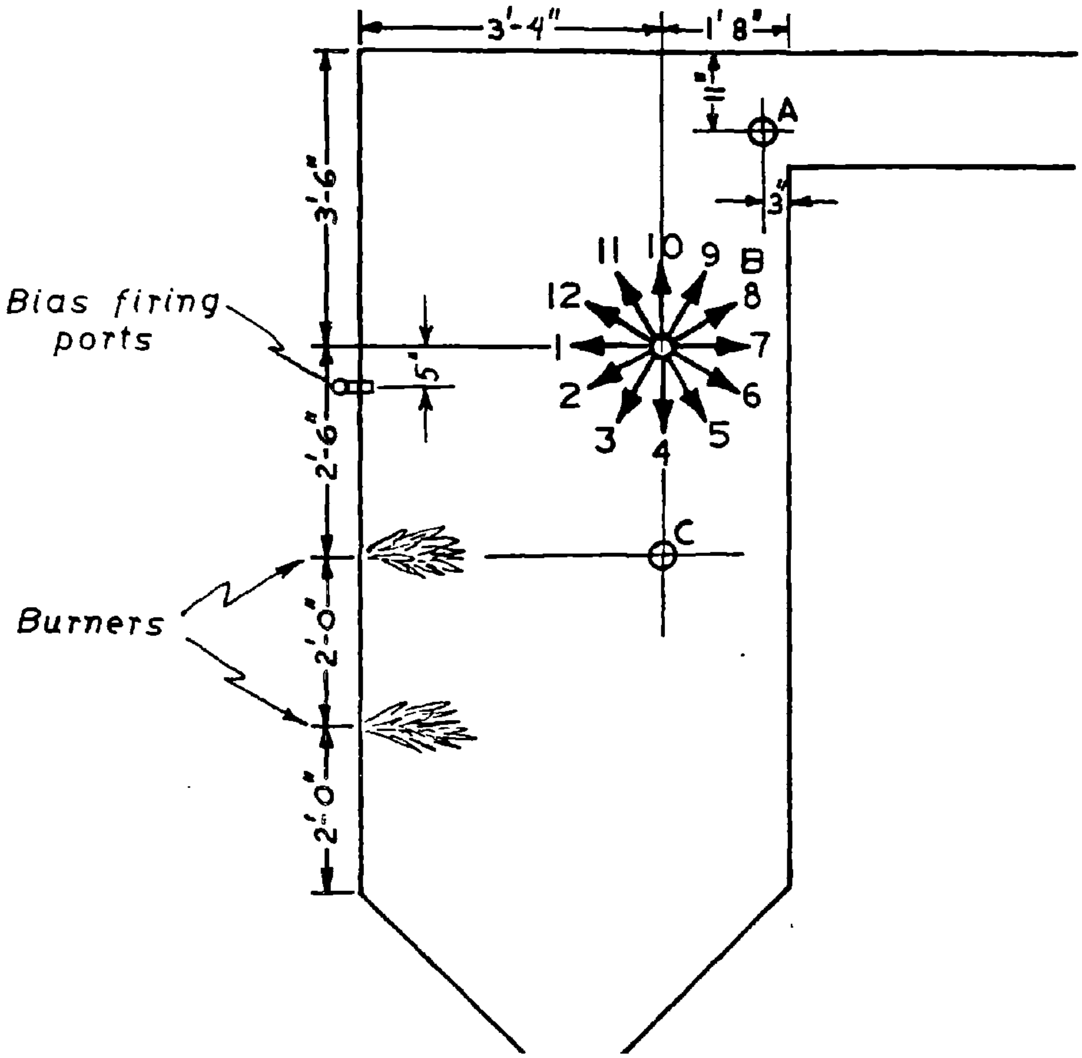

Figure 8. Points of second stage air introduction (A, B and C) and bias firing ports.

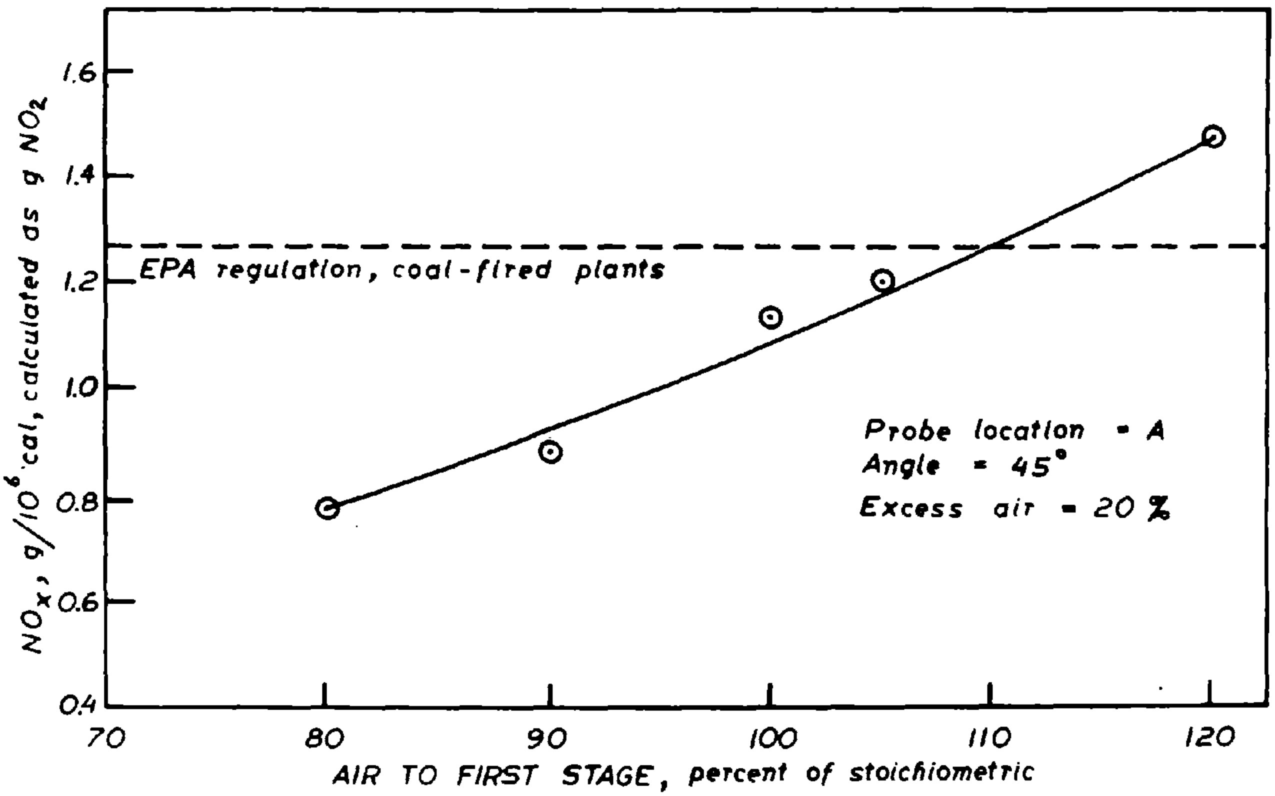

Figure 9. NO_x formation with two-stage combustion.

TABLE 3.- RESULTS OF TWO-STAGE COMBUSTION TESTS

(Second stage air introduced at furnace outlet)

Air to first stage, % of stoichiometric	NO_x, as g $NO_2/10^6$ cal	NO_x, as ppm corrected to 0% O_2	CO, ppm	Hydrocarbon, ppm	SO_2, ppm	Carbon combustion efficiency, %	Furnace outlet temperature, °F
105	1.20	581	140	1.3	1490	98.9	2050
100	1.13	548	180	0.4	1470	99.0	2050
90	0.88	426	160	0.6	1480	99.0	1970
80	0.77	374	180	0.8	1480	98.8	1950

must be compared with 1.46 g $NO_2/10^6$ cal, emission from conventional combustion. Thus, two-stage combustion with 80% of stoichiometric air supplied to the first stage resulted in about 47% reduction in NO_x emissions. Furthermore, this reduction was accomplished with carbon combustion efficiency of nearly 99%, just slightly lower than that obtained under conventional combustion conditions in the experimental furnace.

To investigate the effect of position and angle of air introduction, the probe was rotated on its axis at each point of introduction. These points (A, B and C) and angles of air introduction are shown in Figure 8. Since the provision of 80% of stoichiometric air to the first stage resulted in the most effective NO_x reduction in the initial tests, this level was used to study the effect of position and angle of second stage air introduction. The probe was installed at points A, B and C, Figure 8, and rotated on its axis through angles corresponding to positions 1 through 12. Overall excess air was 20%. Results of the combustion tests are given in Table 4. Stable combustion could not be maintained at several angles. Table 4 therefore contains no data for these points. Although several positions in Table 4 indicate NO_x reductions greater than those obtained in the initial staged combustion tests, these reductions were achieved only with a sacrifice in carbon combustion efficiency. The data suggest that the original point of air introduction (A) was probably the most favorable for optimizing both NO_x reduction and combustion efficiency.

Observations of the flames were made during the course of these tests. When second stage air was introduced at an angle at which the air penetrated the primary combustion zone, combustion intensity increased, resulting in high NO_x emissions. Additionally, the flames were forced down along the front sloping wall, resulting in overheating of the lower furnace section. When the probe was rotated such that the second stage air was directed toward the rear wall, some combustion air short circuited to the furnace outlet, resulting in high carbon loss.

TABLE 4.- SUMMARY OF DATA: TWO-STAGE COMBUSTION

Point of introduction of 2nd stage air	Position	NO_x, as g $NO_2/10^6$ cal	NO_x, as ppm corrected to 0% O_2	CO, ppm	Hydrocarbons, ppm	Carbon combustion efficiency, %
A	1	0.72	350	100	0.8	96
	2	0.67	332	100		
	2½	0.76	359	120	0.8	98.8
	3	0.74	353	140	0.8	
	4	0.81	400	200		
	5	0.74	353	220		
	11	0.61	296	360	0.8	
	12	0.63	302	360	0.8	94.6
B	1	0.64	302	220	0.7	
	2	0.94	453	200	0.4	
	3	0.94	362	210	0.6	98.4
	4	0.79	386	180	0.6	97
	5	0.86	416	180	0.5	
	6	0.74	356	220	0.7	
	7	0.70	326	240	1.0	96.7
	8	0.52	253	200	1.2	
	9	0.40	193	400	1.3	95
	10	0.45	217	320	0.9	
	11	0.60	278	260	0.8	
	12	0.60	278	260	0.75	
C	1	0.77	374	340	0.7	
	2	0.74	362	340	0.7	
	3	0.67	326	280	0.65	
	4	0.77	374	260	0.6	
	5	0.76	368	340	0.6	
	6	0.79	386	240	0.9	
	7	0.70	338	360	0.65	
	8	0.54	266	400	0.85	
	9	0.54	260	420	0.9	94
	10	0.59	290	360	0.8	
	11	0.59	290	380	0.8	
	12	0.77	374	440	0.8	

D. Bias Firing Tests

It would probably be difficult to adapt the method of second stage air distribution used in the 500 lb/hr furnace to large commercial units. As a result the combination of combustion modifications study was duplicated, substituting bias firing for staged combustion with second stage air introduced at the furnace outlet. For these tests an air supply system was installed above the burners to simulate an additional row of burners. The location of this air supply is shown in Figure 8.

Thus, for bias firing tests, the top row of "burners" was operated with air only, and the two lower rows of burners were operated fuel rich. Table 5 and Figure 10 present the results of this combustion modification for two levels of overall excess air. The NO_x levels were nearly identical to those obtained in the two-stage combustion tests.

TABLE 5.- RESULTS OF BIAS FIRING TESTS

Excess air, %	Bias firing[1]	NOx, as g $NO_2/10^6$ cal
20	80	0.68
5	80	0.63
20	100	1.19
5	100	0.98

1 Percent of stoichiometric air supplied in first combustion stage.

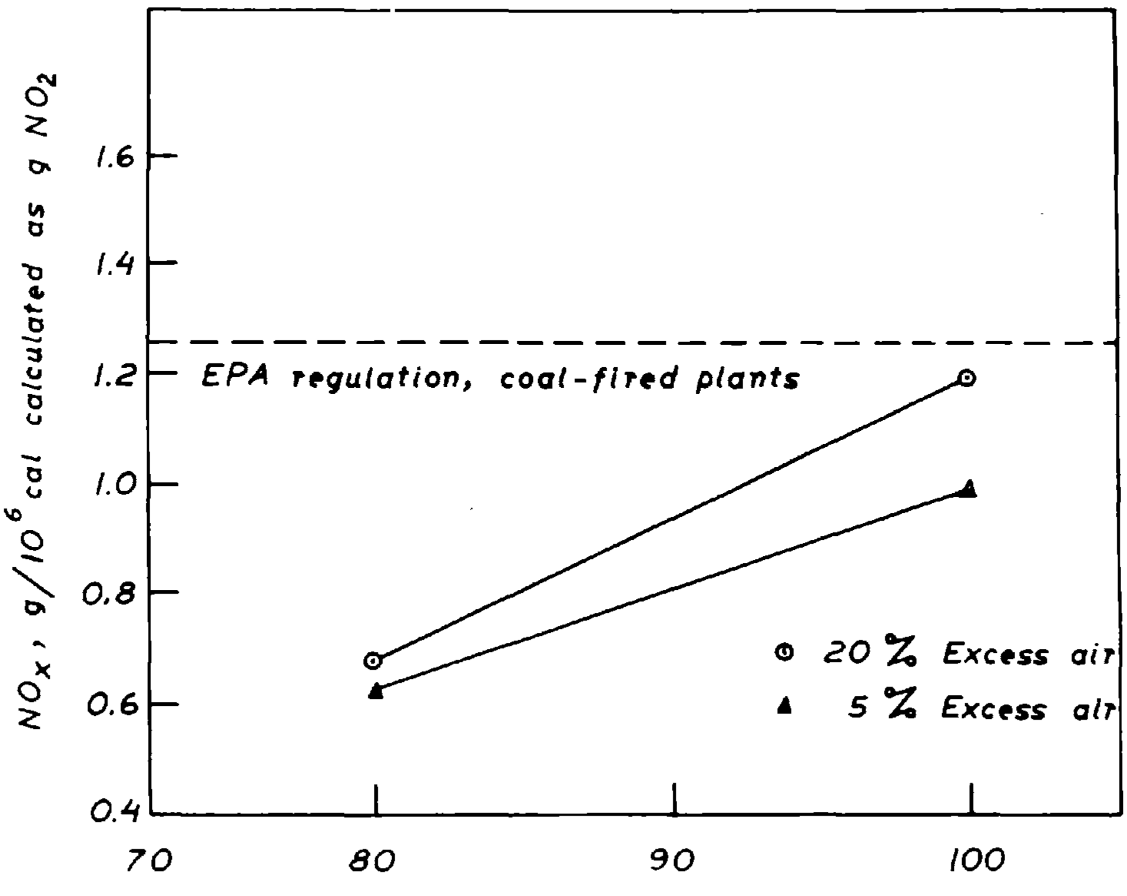

Figure 10. NO_x formation with bias firing.

E. Flue Gas Recirculation Tests

1. Recirculation to Secondary Air

The furnace was provided with a piping system which allowed equal distribution of recirculated flue gas to the four secondary air supplies just before entry into the burners.

Results of combustion tests with various percentages of flue gas recirculation (FGR) supplied to the secondary air are given in Table 6. Percent FGR is defined as:

$$\% \text{ FGR} = 100 \times \frac{W_{fg}}{Wa' + W_f}$$

where W_{fg} = wet mass of flue gas taken from the flue and recirculated

Wa = mass of inlet air (corrected to 80°F and 60% relative humidity)

W_f = mass of fuel burned.

TABLE 6.- FLUE GAS RECIRCULATION TO SECONDARY AIR

Percent FGR	NO_x, as g $NO_2/10^6$ cal	NO_x, as ppm corrected to 0% O_2	CO, ppm	Hydro-carbon ppm	Carbon combustion efficiency, %	Furnace outlet temperature, °F
0	1.46	694	30	-	99.5	2025
10	1.26	585	140	-	98.8	2020
15	1.19	543	160	0.6	98.2	2005
20	1.00	482	180	0.75	98.2	1980
23	0.91	446	200	0.9	96.2	1950
24.3	0.86	422	200	0.9	96.2	1930
28	0.87	422	210	1.1	96.0	1870
31	0.81	398	240	-	95.9	-
31	0.79	386	260	1.2	-	-

The temperature of the recirculated flue gas was about 300°F. Furnace outlet temperature decreased with increased FGR. Figure 11, a plot of NO_x concentration vs flue gas recirculation to secondary air, indicates that NO_x reduction is directly proportional to the % FGR, and that about 45% NO_x reduction was obtained with 30% FGR. However, as can be seen in Table 6, carbon combustion efficiency was significantly reduced. With reduced excess air, reductions of NO_x on the order of 70% were also achieved with similar carbon loss. It should also be pointed out that the reduction obtained from FGR to secondary air must be weighed against increased blower requirement and wear on recirculation components.

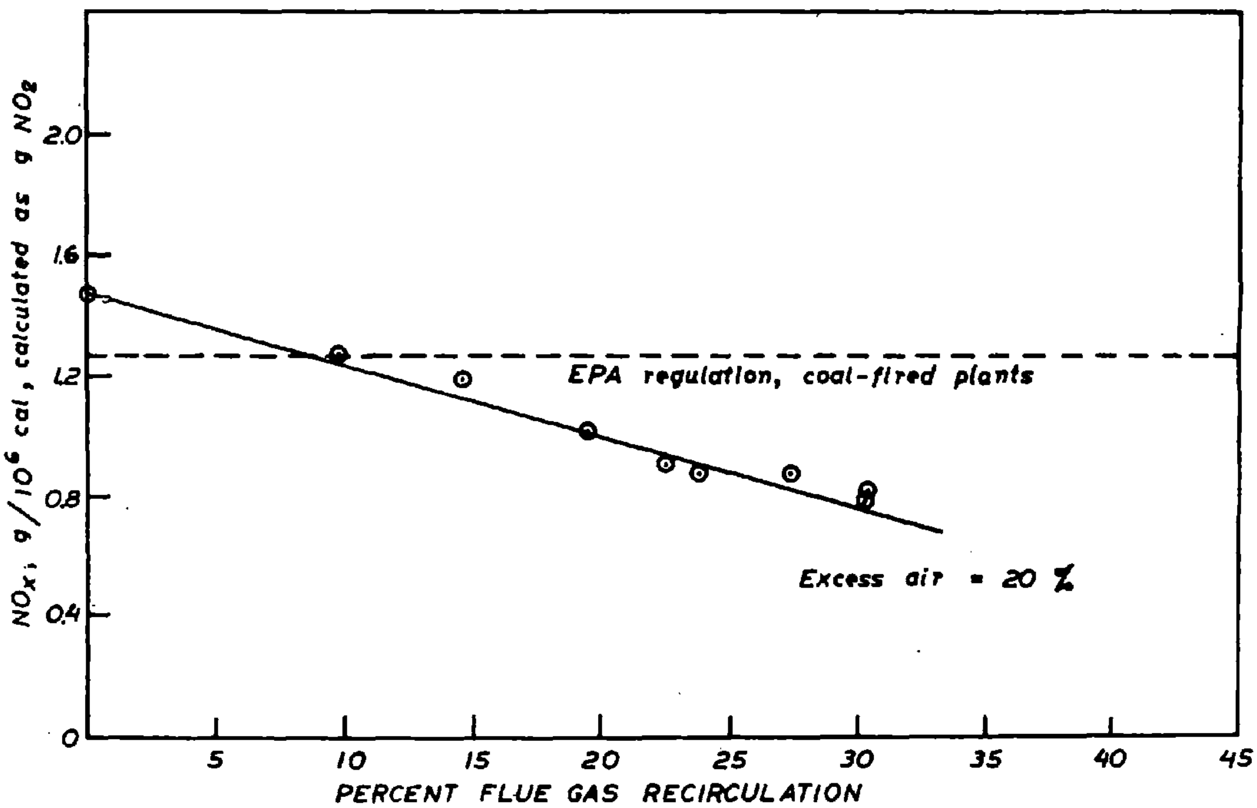

Figure 11. NO_x formation with flue gas recirculation to secondary air.

2. Recirculation to Primary Air

Various amounts of flue gas, together with primary air were used to sweep the pulverizer. Percent FGR was as previously defined. With conventional combustion in the furnace, about 15% of total air was supplied as primary air. For the modification studies, the levels of FGR used were about 6, 9, and 12%.

Air displaced by flue gas in the primary stream was added to the secondary air stream, so that the total standard cubic feet of the primary stream remained constant over the range of FGR studied. Overall excess air was maintained at 20% in all cases. Experimental results of the tests are shown in Table 7 and Figure 12. The data indicate that FGR to primary air

TABLE 7.- FLUE GAS RECIRCULATION TO PRIMARY AIR

Percent FGR	NO_x, as g $NO_2/10^6$ cal	CO, ppm	Hydro-carbons, ppm	Carbon combustion efficiency, %	Furnace outlet temperature, °F
0	1.46	30	-	99.5	2050
6.6	1.35	90	0.4	99.1	1970
9.3	1.33	90	0.4	99.1	1940
12	1.17	120	0.9	98.4	1950

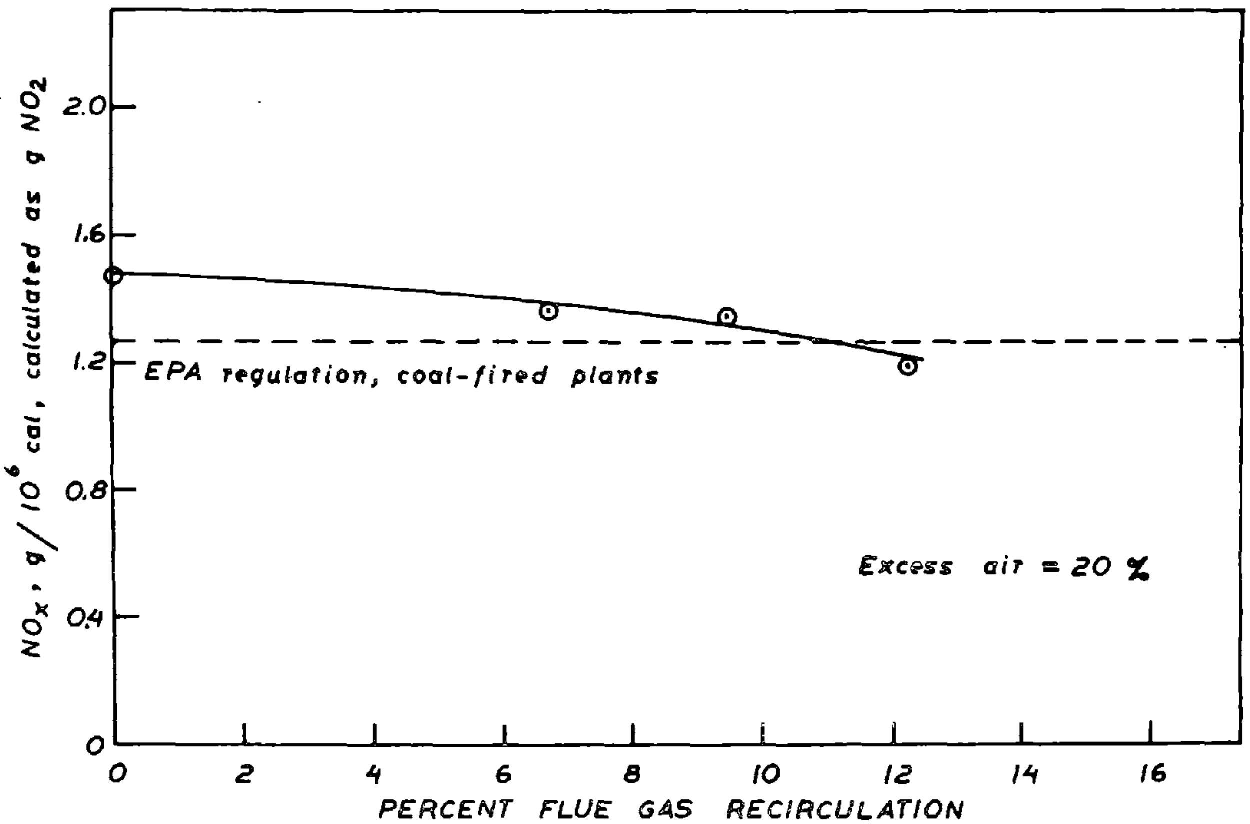

Figure 12. NO_x formation with flue gas recirculation to primary air.

provided about the same degree of NO_x reduction as FGR to secondary air. However, 12% was the highest primary FGR obtainable in the 500 lb/hr furnace. Attempts to exceed 12% resulted in flame instability. There are two probable causes: (1) lack of sufficient oxygen, since that level of FGR produced a primary stream containing nearly 85% flue gas by volume, and (2) the huge proportion of hot flue gas increased the temperature of the primary stream and the expanded volume caused excessive burner port velocities.

F. Combinations of Combustion Modifications

An extensive investigation was conducted on the effects of combinations of combustion modifications on emissions. The study included all possible combinations of the modifications investigated earlier in the program. Experience gained in the earlier phases of the program was used to determine ranges of excess air level, and distribution of air for two stage combustion. The parameters and their ranges are:

Excess air ----------------------	5 and 20%
Two-stage combustion ------------	80 and 100% of stoichiometric to the first stage
Flue gas recirculation to primary air --------------------	0 and 6%
Flue gas recirculation to secondary air ------------------	0 and 20%

The values used for FGR to primary and secondary were selected since their total was approximately equal to the maximum volume capability of the FGR blowers. Combustion appeared stable under all combustion conditions. Experimental results of combination tests, with second stage air supplied at the furnace outlet, are given in Table 8. Reduced excess air provided further NO_x reduction when used in combination with two-stage combustion. Again, however, the reduction was accompanied by a decrease in carbon combustion efficiency. Flue gas recirculation provided little further NO_x reduction when used in combination with staged combustion and excess air variation.

TABLE 8.- COMBINATIONS OF TECHNIQUES WITH TWO-STAGE COMBUSTION

(Second stage air introduced at furnace outlet)[1]

Excess air, %	Two-stage firing[2]	Flue-gas recycle, primary air[3]	Flue gas recycle secondary air[3]	NOx, as g $NO_2/10^6$ cal	NO_x, as ppm corrected to 0% O_2	Hydro-carbons, ppm	CO, ppm	Carbon combustion efficiency, %	Furnace outlet temperature, °F
20	80	0	0	0.77	359	0.95	200	98.8	1950
5	80	0	0	0.63	261	0.70	160	93.0	1940
20	100	0	0	1.13	532	0.95	190	99.0	2050
5	100	0	0	1.10	463	0.45	130	97.8	2070
20	80	6	0	0.85	410	0.50	70	98.9	-
5	80	6	0	0.63	263	-	-	-	-
20	100	6	0	1.10	527	0.70	450	97.8	1980
5	100	6	0	1.07	448	0.40	200	95.6	-
20	80	0	20	0.75	353	0.98	340	93.5[4]	1830
5	80	0	20	0.70	290	0.63	240	91.6	1970
20	100	0	20	0.96	468	1.65	400	93.9[4]	1860
5	100	0	20	0.76	318	0.60	480	92.0	1880
20	80	6	20	0.74	358	1.00	190	97.1	1830
5	80	6	20	0.59	245	1.70	525	90.4	-
20	100	6	20	1.01	478	-	125	98.9	1800
5	100	6	20	0.83	347	2.40	510	97.2	1900

[1]Second stage air introduced at an angle of 45° from horizontal.
[2]Percent of stoichiometric air supplied in first combustion stage.
[3]Weight percent of recirculated flue gas to total input products.
[4]C.C.E. values appear low, probably due to instability while ash samples were obtained.

The investigation of combinations of combustion modifications was repeated using bias firing in place of the two-stage combustion mode previously used since the bias firing techniques was somewhat more representative of what could be employed on a commercial unit. Experimental results of these combination tests are given in Table 9.

Examination of the data in Tables 8 and 9 indicate that bias firing or two-stage combustion used in combination with other techniques are equally effective. However, there appears to be no advantage to combining bias firing or two-stage combustion with FGR.

Comparing Tables 8 and 9, it may be noted that some discrepancies appear in the carbon combustion efficiencies. For example, the efficiency obtained with bias-firing at 5% excess air and 20% flue gas recycle to secondary air is significantly lower than that obtained with two stage combustion and the same conditions. It must be assumed that the ash samples taken for these determinations were in error, and that the efficiency is actually nearer the higher value, since other values obtained are nearly identical. The tests were not repeated because the carbon-combustion efficiency data were not required to evaluate the tests.

TABLE 9.- COMBINATIONS OF TECHNIQUES WITH BIAS FIRING

Excess air, %	Bias firing[1]	Flue-gas recycle, primary air[2]	Flue gas recycle secondary air[2]	NO_x, as g $NO_2/10^6$ cal	NO_x, as ppm corrected to 0% O_2	Hydro-carbons, ppm	CO, ppm	Carbon combustion efficiency, %	Furnace outlet temperature, °F
20	80	0	0	0.68	324	0.30	80	98.6	1930
5	80	0	0	0.63	260	0.30	-	93.4	1870
20	100	0	0	1.19	567	0.30	55	98.7	1930
5	100	0	0	0.98	405	0.30	130	97.3	1930
20	80	6	0	0.83	396	0.70	120	97.9	-
5	80	6	0	0.65	273	0.35	170	96.8	-
20	100	6	0	1.29	618	0.60	80	98.8	-
5	100	6	0	1.02	421	0.30	170	98.1	-
20	80	0	20	0.71	340	0.90	-	95.8	1830
5	80	0	20	0.66	275	-	540	92.1	1910
20	100	0	20	1.05	507	1.25	690	97.3	1860
5	100	0	20	0.80	328	0.55	250	84.9[3]	1840
20	80	6	20	0.72	341	1.00	230	96.9	1830
5	80	6	20	0.53	222	1.75	345	91.7	1880
20	100	6	20	1.04	494	-	350	98.2	1850
5	100	6	20	0.80	333	1.95	250	94.7[3]	1940

[1]Percent of stoichiometric air supplied in first combustion stage.
[2]Weight percent of recirculated flue gas to total input products.
[3]C.C.E. values appear low, probably due to instability while ash samples were obtained.

IV. CONCLUSIONS

Combustion modifications of the type studied in this program should be adaptable to many existing combustion systems, and could be incorporated into the design of new units.

Environmental Protection Agency New Source Performance Standards for new coal-fired steam generating units of over 250 million Btu/hr limit NO_x emissions to 1.26 g $NO_2/10^6$ cal. Conventional firing in the experimental furnace produced NO_x emissions of 1.46 g $NO_2/10^6$ cal.

Operation at low excess air would be satisfactory where a relatively small reduction is required to meet regulations, i.e., operation at 15% excess air rather than 20%, result in a 20% reduction in NO_x with a 0.7% loss in carbon combustion efficiency from normal operation. If higher reductions of NO_x are required, they can be achieved via staged combustion or bias firing.

Two-stage combustion or bias firing reduced NO_x emissions to 0.77 g $NO_2/10^6$ cal and 0.68 g $NO_2/10^6$ cal respectively with an overall excess air of 20%. This corresponded to reductions of 47% and 53% with little effect on carbon combustion efficiency. When used in combination with reduced excess air (5%) two-stage combustion and bias firing both resulted in NO_x reductions of 57%. However, at this reduced excess air level, carbon combustion efficiency was adversely affected.

The indication that bias firing produced NO_x emission reductions comparable to that of staged firing with second stage air supplied at the furnace outlet is significant. Bias firing would probably be more easily achieved in many existing combustion units (although some load reduction could occur because of limiting pulverizer capacity).

Flue gas recirculation to primary and secondary air streams was effective in reducing NO_x emissions, but increased carbon loss also resulted. It did not offer any advantage over low excess air firing. In addition, the effectiveness of flue gas recirculation as an NO_x control modification must be weighed against increased blower requirements and wear on the recirculation system.

Combination of combustion modifications do not appear to offer any significant advantage over staged combustion or bias firing. Apparently the advantages of individual techniques are not cumulative.

Throughout the program, NO_2 was about 5 to 7% of the total nitrogen oxides emission.

Sulfur oxides emissions were not influenced by combustion modifications, except by dilution with excess air. Approximately 2.5% of the total sulfur in the coal remained in the fly ash, the balance was emitted in the flue gas.

Carbon monoxide levels were generally on the order of 30 to 60 ppm for conventional combustion tests, and did not exceed 250 ppm for staged combustion tests. However, with 5% excess air, CO increased to 1000 ppm and with 2% excess air increased further to 5000 ppm.

Total hydrocarbons emissions were generally low over the entire test program, on the order of 0.5 to 0.8 ppm in tests conducted at 20% excess air. Highest values, 2 to 5 ppm, were detected at reduced excess air levels.

Effects of combustion modifications on slagging and conditions arising due to local reducing atmospheres are difficult to ascertain because of the relatively short period of operation at a given test condition. It is recommended that, if possible, these evaluations be made on a large combustion unit where the unit could be operated for an extended time period.