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EVALUATION OF THE POLLUTANT EMISSIONS FROM GAS-FIRED FORCED AIR FURNACES

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AMERICAN GAS ASSOCIATION LABORATORIES

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EVALUATION OF THE POLLUTANT EMISSIONS FROM GAS-FIRED FORCED AIR FURNACES

by

W. H. THRASHER

and

D. W. DEWERTH

PROJECT EP-1-23

ANALYSIS OF FLUE PRODUCTS FROM GAS-FIRED APPLIANCES

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AMERICAN GAS ASSOCIATION

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I. SUMMARY

The emissions from 38 different forced air furnaces of 29 different manufacturers were analyzed for CO, NO, NO_2, CH_4, C_2H_4 and total aliphatic aledhydes with well-adjusted and poorly-adjusted new appliances. All measurements were made in a Laboratory, using a dispersive type infrared spectrophotometer. Table 1 presents results for each unit studied and Table 3 presents a summary and averages of the emissions. This latter table shows that the overall average emissions under well adjusted conditions were 8.1 ppm CO, 88.8 ppm NO, 4.7 ppm NO_2 and 0.18 ppm aliphatic aledhydes (all on an air free basis). The NO_X emission factor was 0.098 lbs NO_X (as NO_2) per 10^6 Btu burned. The CH_4 and SO_2 emissions were negligible from an air pollution standpoint.

This study showed that burner type, burner aeration, and heat exchanger design affect the NO_X emission of a forced air furnace. Single port burners emitted slightly less NO_X than the multiport burners (statistically significant at the 95% confidence level). The multiport burners provide more sites for near stoichiometric flame fronts with maximum flame temperature conditions favoring NO_X production. In most cases the yellow flame conditions, which represented the poorly-adjusted flames sometimes encountered after lengthy field use, showed higher CO, NO_2, and aldehyde emissions and a decrease in the NO and NO_X emission factor. The yellow flame conditions result in lower peak flame temperature favoring higher CO emission and lower NO formation.

Emission measurements were made for nine different burner pilots. The average NO_2 emission rate was higher than that measured for the main burners. This higher NO_2 emission is due to the large amounts of excess air available when the pilot operates alone and the extremely low flame intensity both of which cause a low temperature condition which favors NO_2 formation. The NO_X emission factor of the pilots, however, was 0.068 lbs NO_X (as NO_2) per 10^6 Btu which is lower than that measured for the main burners.

This report discusses some burner modifications which can be employed to reduce the NO_X emission levels of forced air furnaces without materially affecting the heat transfer characteristics or sacrificing system efficiency. For single port burners a secondary air shield, which controls the ingress of secondary air to the hottest flame zones, can reduce NO_X emission by 35 percent. For multiport burners a modification that included the addition of screens above the burner ports is described. When the burner is in operation these screens become radiant, cool the flame and reduce the NO_X emission by as much as 58 percent.

TABLE 1

FORCED AIR FURNACE EMISSIONS

FAF #	Input Rate, Btu/Hr *	Blue Flame Adjustment: Sample, Percent CO_2	Blue: Percent Primary Air	Blue: (1) Δt °F	Blue: Flue Gas Concentration PPM, Air Free (2) *** CO	Blue: NO	Blue: NO_2	Blue: -CHO	Blue: NO_x ** Emission Factor, (E.F.) lbs/10^6 Btu	Yellow Flame Adjustment: Sample, Percent CO_2	Yellow: Percent Primary Air	Yellow: (1) Δt °F	Yellow: Flue Gas Concentration PPM, Air Free (2) *** CO	Yellow: NO	Yellow: NO_2	Yellow: -CHO	Yellow: NO_x ** Emission Factor, (E.F) lbs/10^6 Btu	Burner: Multi-port	Burner: Single Port Up-shot	Burner: Single Port In-shot	Burner: Other	Heat Exchanger: Sectional	Heat Exchanger: Drum	Heat Exchanger: Other	FAF #
1	103,000	6.90	45	66	5.4	78.38	5.65	---	0.090	7.15	39	66	450	69.30	10.94	---	0.084			X		X			1
2	102,500	5.75	69	82	30	95.52	6.26	---	0.109	5.80	48	82	715	82.76	5.48	---	0.094	X				X			2
3	134,000	6.90	49	85	17	86.37	7.86	---	0.098	7.00	39	87	264	74.38	9.17	---	0.087	X I				X			3
4	82,500	6.85	62	68	75	85.86	12.89	---	0.102	7.00	42	68	236	72.05	12.81	---	0.088	X				X			4
5	103,000	6.50	59	82	18	98.14	4.32	---	0.106	6.80	39	84	284	89.56	6.51	---	0.099	X				X			5
6	98,000	4.95	57	90	12	102.91	2.16	---	0.108	5.05	30	86	252	89.39	10.55	---	0.103	X				X			6
7	103,000	5.20	45	60	12	111.69	3.58	0.12	0.119	5.50	23	60	183	81.97	11.26	0.44	0.096	X				X			7
8	99,500	6.00	46	.63	16	111.18	6.94	0.33	0.122	6.10	23	61	283	88.62	9.82	---	0.101	X				X			8
9	98,900	5.10	53	74	12	81.04	1.65	0.43	0.085	5.30	15	72	512	39.35	14.11	1.13	0.055		X				X		9
10	103,000	5.45	51	67	11	64.53	4.21	0.10	0.071	5.70	33	65	467	54.46	11.14	0.53	0.068			X		X			10
11	179,400	4.25	49	55	14	105.46	3.61	0.08	0.113	4.25	22	56	133	97.53	8.47	0.56	0.109	X				X			11
12	121,500	6.20	50	89	6	89.36	3.39	0.12	0.099	6.40	31	89	469	55.93	11.44	0.83	0.072		X I				X		12
13	101,500	5.70	59	83	17	89.52	2.46	0.30	0.099	5.90	25	80	39	92.26	5.37	0.60	0.105	X				X			13
14	103,000	5.90	63	74	20	76.12	2.79	0.53	0.080	5.65	20	77	255	74.78	12.36	3.07	0.091	X I				X			14
15	137,000	3.75	55	88	22	76.51	2.78	0.05	0.086	4.20	25	93	529	32.74	21.46	1.02	0.058			X I			X I		15
16	126,600	5.40	39	55	1.0	58.71	2.40	0.07	0.064	6.05	18	61	20	66.39	7.00	0.17	0.079				X I(3)		X		16
17	104,600	5.45	51	63	2.8	107.63	4.34	0.13	0.118	5.45	14	67	315	82.92	9.49	1.06	0.098	X				X			17
18	102,000	8.40	50	85	31.7	72.17	1.77	0.29	0.078	8.50	42	85	613	64.33	2.85	0.39	0.071	X				X			18
19	96,900	5.05	62	67	5.5	96.81	3.80	0.21	0.105	5.10	29	71	379	74.75	10.64	1.40	0.091	X				X			19
20	85,300	6.80	64	93	6.4	90.60	4.02	0.19	0.101	6.85	43	97	1156	68.36	8.69	0.46	0.082	X				X			20
21	157,500	5.10	46	78	12.0	76.12	3.53	0.04	0.085	5.10	16	82	41.2	56.75	4.66	0.10	0.065		X I				X		21
22	116,200	6.60	76	47	8.4	97.89	7.33	0.23	0.113	6.20	23	45	248	71.86	10.05	0.94	0.087	X				X			22
23	103,900	5.40	59	78	1.4	107.44	2.47	0.27	0.118	5.90	23	60	89	72.81	5.49	0.23	0.084	X				X			23
24	122,000	6.05	67	96	2.8	107.05	3.00	0.01	0.118	6.35	23	99	4.4	97.76	4.06	0.16	0.110	X				X			24
25	106,000	5.20	62	56	3.1	84.00	3.05	0.04	0.092	5.25	25	64	42	78.45	8.37	0.13	0.091	X				X			25
26	81,600	8.80	--	54	95	9.30	7.70	0.10	0.018												X (4)			X (5)	26
27	75,000	7.40	--	54	1.9	75.13	3.58	---	0.083	7.60	-	54	3.3	93.02	4.41	---	0.102		X				X		27
28	102,100	4.70	51	74	10.7	55.86	9.11	0.07	0.068	4.85	20	76	309	62.65	10.94	0.56	0.077			X		X			28
29	98,100	5.95	72	55	3.4	104.75	6.86	---	0.116	6.00	27	59	62	94.08	9.92	---	0.108	X				X			29
30	113,500	5.60	66	87	4.7	89.74	6.47	---	0.100	6.15	42	89	1046	75.00	10.93	---	0.089	X				X			30
31	98,400	5.70	74	74	3.8	84.86	5.92	---	0.095	5.80	54	77	215	73.88	10.47	---	0.088	X				X			31
32	96,000	6.90	56	40	3.3	77.06	4.66	---	0.086	7.05	21	38	213	78.71	8.92	---	0.092	X				X			32
33	104,200	8.70	--	79	5.1	97.39	2.59	---	0.107	11.80	--	86	75	82.29	4.16	---	0.093				X (6)			X (7)	33
34	95,000	5.10	65	76	127	80.56	5.93	---	0.093	5.10	43	72	668	79.41	9.79	---	0.096	X				X			34
35	98,500	5.10	58	50	4.5	77.95	5.46	---	0.090	5.20	34	55	1299	48.05	20.01	---	0.073			X I		X			35
36	86,000	4.70	59	62	2.0	92.58	3.57	---	0.103	4.70	34	65	429	62.14	10.57	---	0.078	X				X			36
37	100,000	3.80	45	60	12.9	79.20	7.83	---	0.090	5.00	30	59	43	69.65	10.70	---	0.083			X		X			37
38	90,500	3.30	36	85	8.0	48.58	6.72	---	0.058	3.35	--	87	93	16.26	24.36	---	0.042				X (8)		X		38

TABLE 1 (Continued)

NOTES:

* Actual input rate measured at time of sampling

** NO_x emission factor - $lbs/10^6$ Btu, sum of NO and NO_2 calculated as NO_2

$$NO_x\ (lbs/10^6\ Btu) = \frac{NO_x\ (ppm\ air\ free) \times 10^6\ Btu \times P \times d(NO_2)}{10^6 \times HV}$$

where:

HV = heating value of gas in Btu/ft^3

P = ft^3 combustion products per ft^3 gas burned (60 F, 30" Hg)

d = density of gas in lbs/ft^3 (60 F, 30" Hg)

NO_2 (P x d) = 1.061

*** Total aliphatic aldehydes expressed as formaldehyde

(1) Circulating air temperature rise

(2) $(\text{Air Free Concentration}) = \frac{\text{Ultimate } CO_2}{\text{Sample } CO_2} \times (\text{Sample Conc.})$

(3) Two rectangular ribbon blocks

(4) & (5) Powered burner and unique heat exchanger

(6) & (7) Powered burner with tubes in drum heat exchanger

(8) Multiport shaped to look like two logs

I Cast iron burner construction

II. INTRODUCTION

At present, gas-fired appliances are not considered to be a major source of air pollution. It has been estimated that air pollution from residential and commercial heating sources accounts only for approximately 10 percent of the total air pollution (primarily CO and NO_X pollution[1]). However, since pollutants are emitted by these sources near the ground level and in highly populated areas, heating appliance emissions may be more important than is indicated by the 10 percent value. The gas industry is sponsoring A.G.A. Research Project EP-1-23, "Analysis of Flue Products from Gas-Fired Appliances," at the A.G.A. Laboratories to study the emissions from gas-fired appliances.

The project objectives are: (1) to determine the composition of the effluents from gas-fired appliances and the contribution of such effluents to air pollution, and (2) to develop appliance designs and recommendations for minimizing air pollutants from these appliances. This information is needed by the gas industry, regulatory agencies and others interested in environmental protection to assess the overall contribution of gas appliances to pollution. This information also provides a basis from which further development work can proceed to minimize gas appliance emissions.

This report on the emission of 38 different gas-fired forced air furnaces (from 29 different manufacturers) is the third publication of this project. A.G.A. Laboratories' Report No. 1488, "A Review of Instrumentation and Methods for the Measurement of Air Pollutants," March 1973, reviewed instrumentation and sampling techniques that could be used to measure pollutant emissions. Report No. 1492, "Gas-Fired Range Emission Studies," Sept., 1974, covered studies of emissions from gas-fired ranges.

III. DISCUSSION OF RESULTS

A. Forced Air Furnace Emission Results

1. Overall Emission Results from Forced Air Furnaces

Table 1 presents the CO_2, CO, nitrogen oxide and aliphatic aldehyde emissions measured with 38 different gas-fired forced air furnaces. All samples were taken downstream of the appliance draft hood thus accounting for the low CO_2 values. This sample point is representative of what is emitted to the ambient air. Burner and heat exchanger type data for those furnaces are also shown in this table. As mentioned previously, CH_4, C_2H_4 and SO_2 measurements indicated that these pollutants generally were present in amounts that are insignificant with regard to ambient air pollution.

All concentrations of CO, NO, NO_2 and aldehydes are in ppm (parts per million) by volume on an air-free basis. The air-free factor is calculated from the measured sample concentration and ultimate CO_2 content of the Cleveland area natural gas used throughout these studies which is very close to 12.0 percent.

Air free value
= meas. value (12.0/meas. CO_2)

The NO_X emission factor (EF) in lbs/10^6 Btu is the sum of NO and NO_2 calculated as NO_2. This emission factor can be used for strict comparison of one appliance to another. The notes of Table 1 show how the emission factor is calculated. Δt is the circulating air temperature rise in degrees F.

Table 2 presents a summary of the burner and heat exchanger design data for all the furnaces studied. The table shows that 63.2 percent of the furnaces studied had tubular multiport burners, 26.3 percent had single port burners and 10.5 percent had burners of other designs. Sectional heat exchangers were installed in 76.3 percent of the units, drum heat exchangers in 18.4 percent and 5.3 percent had heat exchangers of other designs. The most common combination of tubular multiport burner with sectional heat exchanger was installed in 23 units, or 60.5 percent of all the furnaces studied.

To present the results of this study in the most meaningful manner, the data were analyzed by a statistician consultant, Dr. John B. Neuhardt of the Ohio State University. Results of his analysis have been presented in the following data.

Figures 1 and 2 present frequency-distribution histograms for the oxides of nitrogen emissions of 33 gas-fired forced air furnaces operated under well adjusted blue flame conditions. This was the number of furnaces for which data were analyzed after omitting the special appliances described in subsection 2. Since these histograms roughly follow a normal distribution the simple mean and standard deviation is a valid method for presenting the NO_X results. The percentage of times a value was obtained within a particular interval is noted at the bottom of each frequency interval rectangle. The sum of the percentages may not add up to 100 percent because of rounding off. The mean value of each item is listed at the top of the histogram and its relative location is indicated by the dashed vertical line. For example: In Figure 1(a) eight out of 33 atmospheric injection furnaces tested emitted between 90 and 100 ppm total NO_X(NO + NO_2). These eight units represent 24.2 percent of the total of 33. The mean total NO_X emission is 93.5 ppm.

In the case of CO emissions the assumption of symmetric errors seemed unreasonable because of the large standard deviation of error-to-average ratio. The CO emissions were therefore transformed to logarithm-emissions. Figure 3 shows the normal distribution and log-normal distribution histograms which verify the use of the log-normal analysis for CO emissions.

TABLE 2

SUMMARY OF BURNER AND HEAT EXCHANGER TYP IN EMISSIONS MEASUREMENT STUDY

Type	Material of Construction	Number
	BURNERS	
Multiport	Cast Iron	3
Multiport	Steel, Stamped or Tube	21
		24 (Total)
Single Port Upshot	Cast Iron	2
Single Port Upshot	Steel	2
Inshot	Cast Iron	2
Inshot	Steel	4
		10 (Total)
Other		4 (Total
	HEAT EXCHANGER	
Sectional	Stamped Steel	29
Drum	Steel	6
Drum	Cast Iron	1
Other		2

FIGURE 1

FREQUENCY–DISTRIBUTION HISTOGRAMS FOR NO_x EMISSION OF 33 GAS-FIRED FORCED AIR FURNACES OPERATED UNDER WELL ADJUSTED BLUE FLAME CONDITIONS

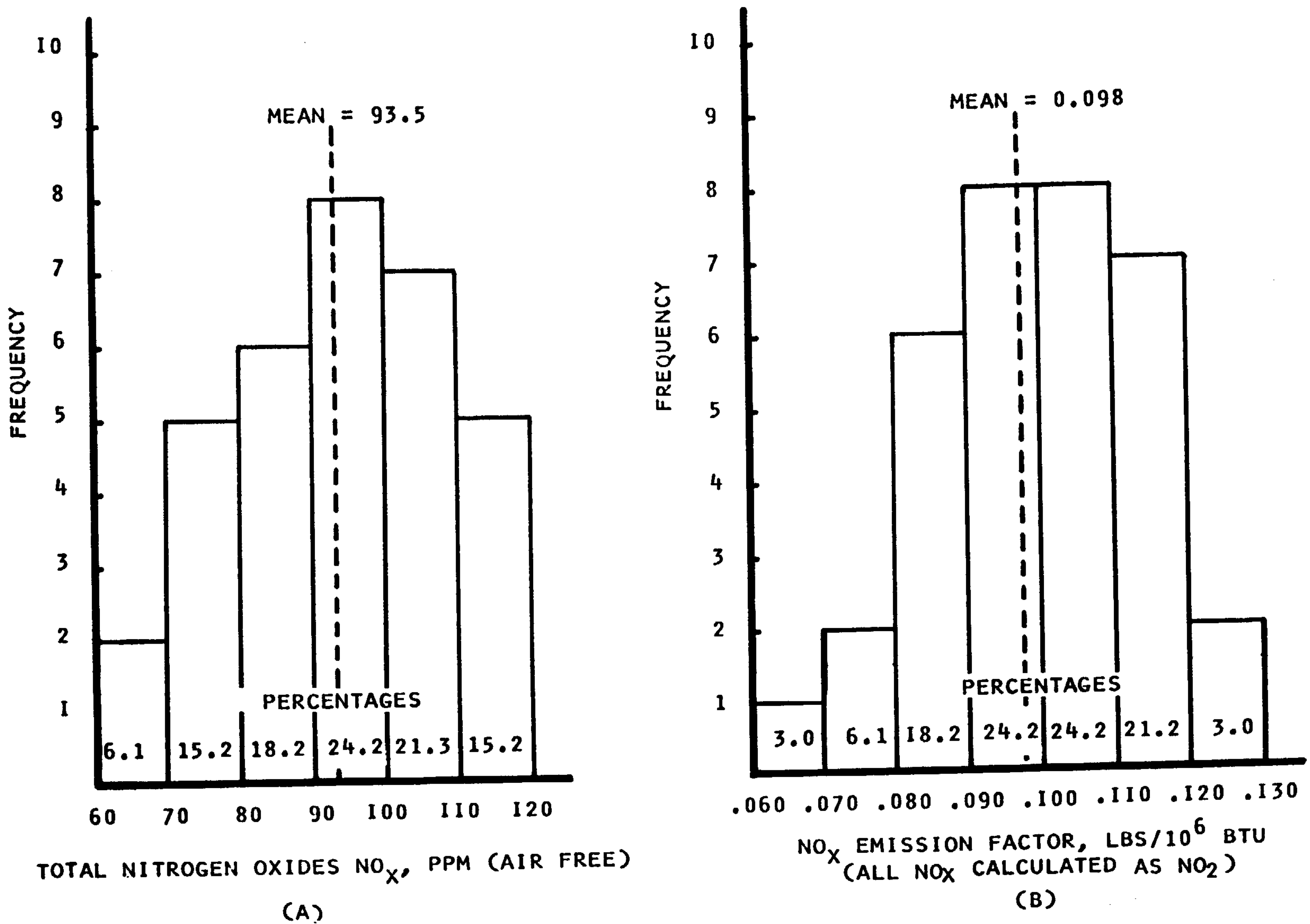
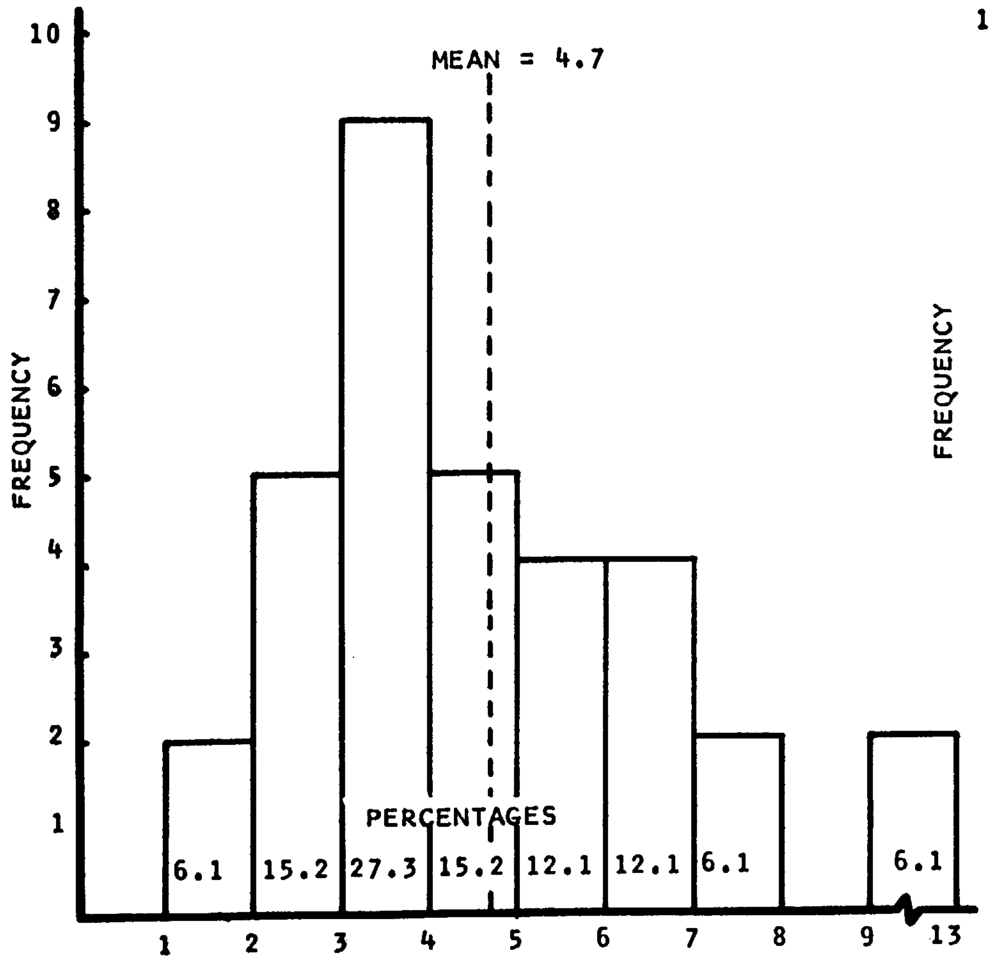
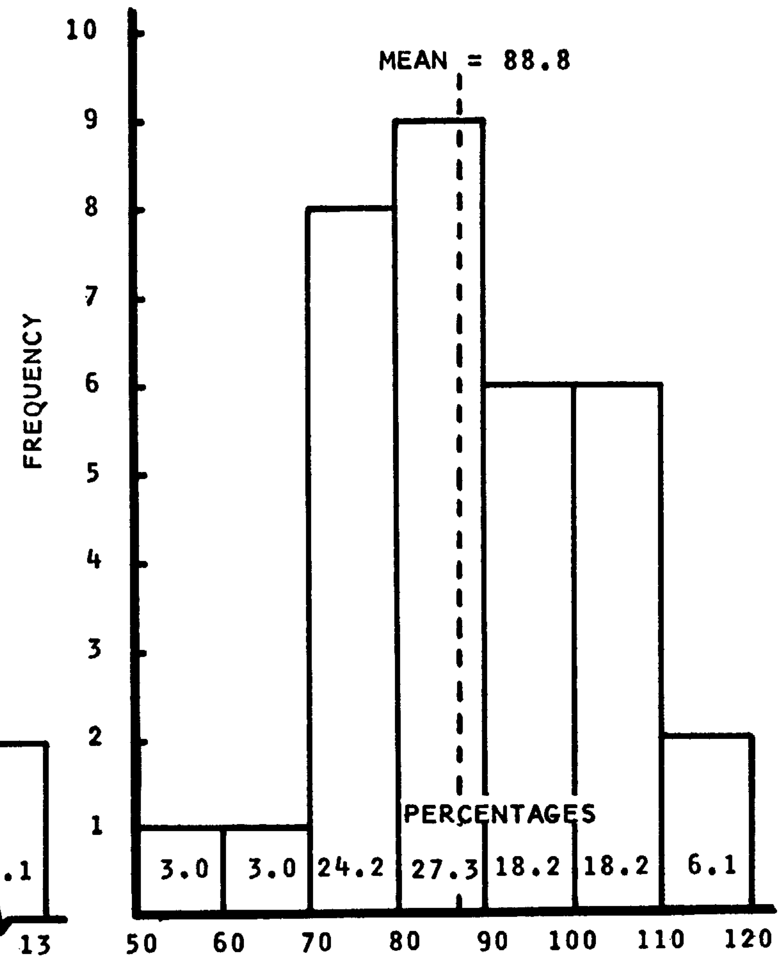


FIGURE 2

FREQUENCY–DISTRIBUTION HISTOGRAMS FOR NO AND NO_2 EMISSIONS OF 33 GAS-FIRED FORCED AIR FURNACES OPERATED UNDER WELL ADJUSTED BLUE FLAME CONDITIONS



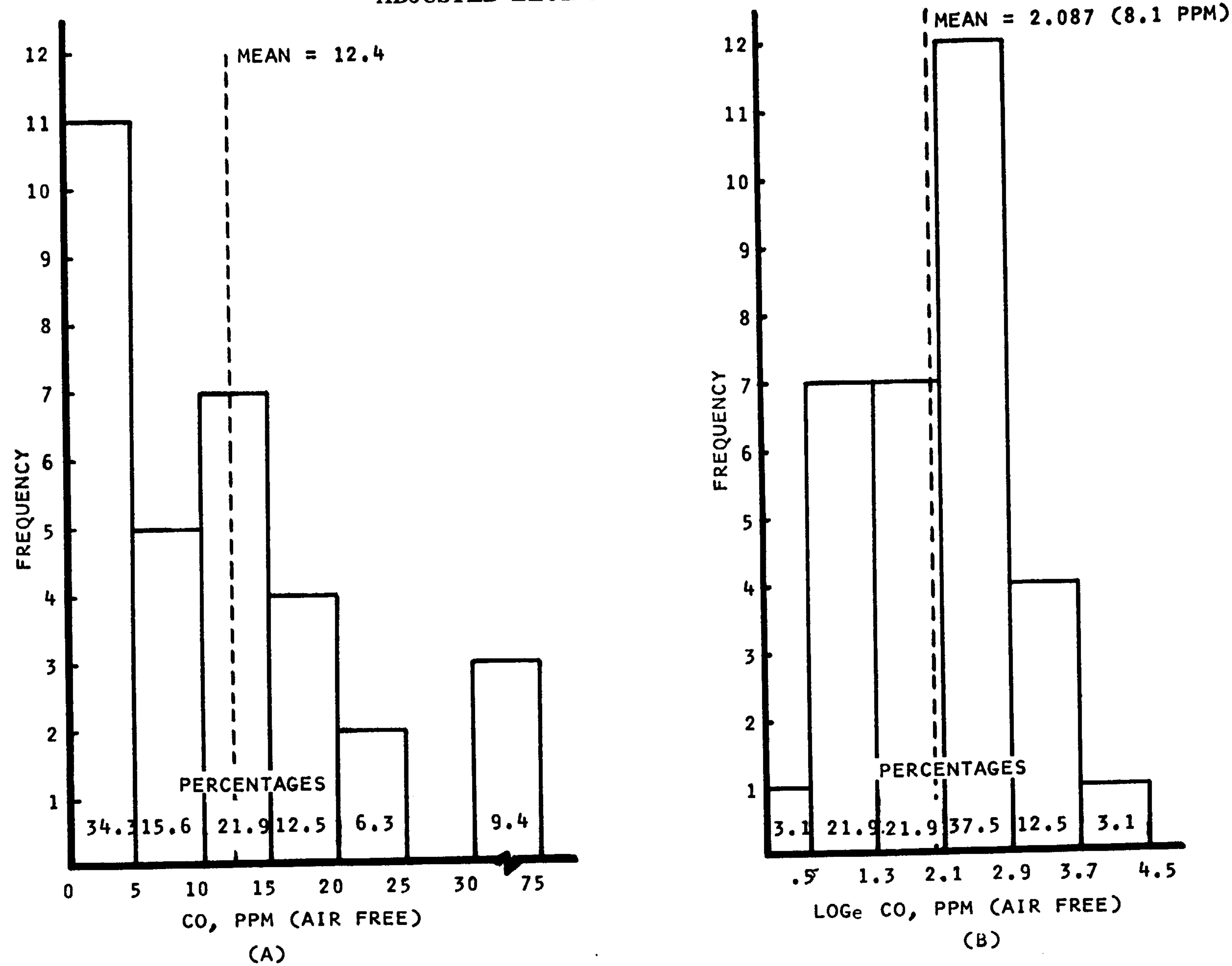
(A)



(B)

FIGURE 3

FREQUENCY–DISTRIBUTION HISTOGRAMS OF CO EMISSIONS OF 32 GAS-FIRED FORCED AIR FURNACES OPERATED UNDER WELL ADJUSTED BLUE FLAME CONDITIONS



2. Average Emission Results

Table 3 presents the average emissions of the atmospheric injection furnaces. The overall average is further subdivided into averages for single port and multiport burners. The CO_2 values presented are the means of all the atmospheric injection furnaces tested. The CO values exclude FAF 34 because its CO data is "out of control," and FAF 16 since it is neither single nor multiport. The NO_X values exclude FAF 16 for the same reason. FAF 38 was not included in the overall average because of its unusual design (decorative fireplace and furnace). FAF 37 was not included because it was received after the statistical analysis was completed.

In most cases the yellow flame results, which represent a poorly-adjusted flame, showed higher CO, NO_2 and aliphatic aldehyde levels while showing a decrease in NO and NO_X emission levels, when compared to the well-adjusted blue flame results. In adjusting the yellow flame conditions the burner air shutters were fully closed or closed until carbon production seemed imminent. The flames were usually highly luminous. The yellow flame adjustment, it was felt, would simulate long field use under minimum maintenance conditions or burner maladjustment. The lower flame temperature associated with yellow flames results in poorer CO burnout (higher emissions) and less NO production.

Table 4 presents results of the statistical analysis of the data. Yellow flame emissions were compared to blue flame emissions, and single port with multiport burners. This analysis showed that (with 95 percent confidence) the blue flame CO emissions are significantly lower than the yellow flame CO emissions and that the blue flame NO_X emission factor is significantly higher than the yellow flame NO_X emission factor. These significant differences occur when data from each type of burner are analyzed separately, or when the data from both types of burners are combined and analyzed together. The maladjusted yellow flames decreased the NO_X emission factor by an average of from 0.006 to 0.015 lbs NO_X per 10^6 Btu, with 95 percent confidence. The CO emission under yellow flame conditions, however, increased by a factor of between 15 and 42 ppm, with 95 percent confidence.

In comparing single port burners with multiport burners the NO_X emission factor is significantly lower for single port burners by a factor of from 0.010 to 0.029 lbs NO_X per 10^6 Btu with 95 percent confidence when operated in blue flame conditions and by a factor of from 0.012 to 0.030 lbs NO_X per 10^6 Btu, with 95 percent confidence, when operated in yellow flame conditions. The variability in CO results in very large confidence limits and no significant difference exists.

In interpreting the significant differences assume that each furnace of each design (single or multiport) has a long term average emission due to:

M = model (given the design),

F = differences in furnaces for a given model, and

E = measurement error, including short time variation (minute to minute)

Since there was only one furnace to represent a particular model, the variation in observed emissions are made up of factors F and E. The significant difference is stated for the average of M (for the furnaces observed).

Before initiating our systematic sampling of forced air furnaces we determined the time needed to reach emission steady state, the emission level stability and the reproducibility of a typical furnace. This information was used to determine proper statistical procedures. The typical time concentration data shown in Tables 5 and 6 indicate that emission level steady state is achieved after about 5-10 minutes of operation—very close to the time that temperature steady state occurred. All flue gas samples from furnaces

TABLE 3

AVERAGE EMISSIONS OF ATMOSPHERIC INJECTION FORCED AIR FURNACES

Average	Flame	Sample, Percent CO_2	Flue Gas Concentration, ppm, Air Free				NO_x Emission Factor lbs/10^6 Btu*
			CO	NO	NO_2	HCHO**	
Overall	Blue	5.8 ± 1.0	8.1 ± 2.6	88.8 ± 14.0	4.7 ± 2.4	0.18 ± 0.14	0.098 ± 0.015
	Yellow	6.0 ± 1.0	208 ± 4	73.6 ± 16.0	9.7 ± 3.9	0.60 ± 0.39	0.088 ± 0.014
Multiport Burner	Blue	5.9 ± 0.9	8.2 ± 2.8	94.0 ± 11.7	4.8 ± 2.5	0.20 ± 0.14	0.104 ± 0.012
	Yellow	6.0 ± 0.9	201 ± 3	80.0 ± 10.0	8.8 ± 2.6	0.62 ± 0.40	0.093 ± 0.010
Single Port Burner	Blue	5.5 ± 1.1	7.8 ± 2.1	75.0 ± 9.6	4.4 ± 2.2	0.14 ± 0.15	0.084 ± 0.010
	Yellow	5.8 ± 1.1	225 ± 6	56.9 ± 17.6	12.1 ± 5.8	0.60 ± 0.40	0.073 ± 0.014

0.090 lb/10^6 Btu

NOTES:

* Sum of NO and NO_2 calculated as NO_2

** Total aliphatic aldehydes expressed as formaldehyde (HCHO)

The ± value is the standard deviation of the average shown

$\frac{0.09 \text{ lb}}{10^6 \text{ Btu}} \times \frac{1050 \text{ Btu}}{\text{std ft}^3} = 94.5 \frac{\text{lb}}{10^6 \text{ std ft}^3}$

TABLE 4

FORCED AIR FURNACE STATISTICAL ANALYSIS RESULTS

Effect	Mean of Difference	95% Conf. Limits of Mean	Remarks
YELLOW MINUS BLUE			
DEF, Multiport	-0.0106	-0.015, -0.006	Significant
DEF, Single port	-0.0114	-0.025, +0.003	Significant
DEF, Single port and Multiport Combined	-0.0108	-0.015, -0.0063	Significant
DLCO, Multiport	3.203	2.62, 3.78	Significant
DLCO, Single port	3.364	2.14, 4.58	Significant
DLCO, Single port and Multiport Combined	3.249	2.75, 3.75 (15.6, 42.5 ppm)	Significant
SINGLE MINUS MULTIPORT			
DEF, Blue Flame		-0.010, -0.029	Significant
DEF, Yellow Flame		-0.012, -0.030	Significant
DLCO, Blue Flame		-0.81, +0.71	
DLCO, Yellow Flame		-1.11, +0.89 (.33, 2.4 ppm)	

NOTE: DEF = Difference in NO_x Emission Factor Value, Yellow Flame Minus Blue Flame or Single Port Minus Multiport

DLCO = Difference in CO Emission Level With the CO Expressed as LOG_e (LOG_e CO Yellow - LOG_e CO Blue) or (LOG_e CO single port - LOG_e CO multiport)

TABLE 5

FORCED AIR FURNACE REPRODUCIBILITY

Run No.	Fuel Input Rate Btu/hr	Sample Percent CO_2	Flue Gas Concentration ppm, Air Free CO	NO	NO	NO_x	NO_x Emission Factor* lbs/10^6 Btu
			a. FAF 25 - Constant On				
1	100,500	5.50	13	81.5	0.7	82.2	0.086
2	99,900	5.50	11	80.7	2.4	83.1	0.087
3	99,900	5.45	11	82.2	2.7	84.9	0.088
4	99,900	5.40	13	81.3	2.7	84.0	0.087
5	99,300	5.35	11	84.4	1.4	85.8	0.089
6	99,300	5.35	11	84.0	2.0	86.0	0.090
7	99,300	5.30	11	84.8	2.0	86.8	0.090
8	99,300	5.30	14	85.4	2.0	87.5	0.091
Mean			12	83.0	2.0	85.0	0.089
Standard Deviation			1.1	1.8	0.7	1.8	0.002
Relative Standard Dev. Percent			9.2	2.2	35.0	2.1	2.2
			b. FAF 25 - Cold Start Runs				
1	101,600	5.25	16	81.5	1.8	83.3	0.087
2	101,600	5.20	12	85.0	1.8	86.8	0.090
3	100,700	5.10	12	86.1	2.3	88.4	0.092
4	100,700	5.05	12	88.1	2.1	90.2	0.094
5	100,700	5.00	12	89.1	2.2	91.3	0.095
6	100,700	5.05	12	88.9	2.4	91.3	0.095
7	100,700	5.00	12	89.5	2.2	91.7	0.095
8	100,200	5.00	12	92.3	1.4	93.7	0.097
Mean			12	92.3	2.0	89.6	0.093
Standard Deviation			1.5	3.3	0.3	3.3	0.003
Relative Standard Dev. Percent			2.1	3.8	15.0	3.7	3.2

* Sum of NO and NO_2 Calculated as NO_2

TABLE 6

EFFECT OF BURNER-ON TIME ON THE EMISSIONS OF FAF 25

Time Mins.	Sample CO_2, Percent	Flue Gas Concentration ppm, Air Free CO	NO	NO_2	NO_x	NO_x Emission Factor, * lbs/10^6 Btu	Flue Temp. °F
1	5.60	---	65.3	4.3	69.6	0.072	290
2	5.60	15	70.5	3.2	73.7	0.077	363
3	5.50	18	72.5	2.6	75.1	0.078	396
4	5.45	18	73.9	2.0	75.9	0.079	415
5	5.45	18	75.2	1.1	76.3	0.079	420
10	5.40	16	76.6	0.9	77.5	0.081	432
15	5.40	25	76.9	0.2	77.1	0.080	433
20	5.35	27	76.8	0.9	77.7	0.081	433
25	5.35	25	77.6	0.2	77.8	0.081	432
30	5.30	25	77.5	0.9	78.4	0.082	432

* Sum of NO and NO_2 calculated as NO_2

were taken after at least 30 minutes of operation to insure that emission steady state conditions prevailed.

Table 5 shows the reproducibility of FAF 25, which was considered a typical forced air furnace from the standpoint of fuel input and design. These data indicated the emission level stability and the ability of a furnace burner to reproduce results. The constant-on data represent measurements taken one after the other while the furnace was operating at steady state. The cold start runs were made by allowing the entire unit and sampling system to cool to room temperature between samples. The relative standard deviations show that a furnace is very stable with regard to CO and NO_X emission while operating at steady state and after allowing the unit to cool off and re-establish steady state. The high relative standard deviation for the NO_2 emission is insignificant from a practical standpoint because of the overall low level of NO_2 emission which varied from 1.4 to 2.4 ppm air free. These reproducibility data showed that a single sample taken over a 6 minute period would be statistically representative.

While the small difference in emission factor between multiport and single port burners is statistically significant, and small differences exist for the other emission levels, they may or may not be practically significant. It is felt the difference in NO_X emission factor is due to:

1) Multiport burners provide more sites for near stoichiometric flame fronts with attendant maximum flame temperatures which cause higher NO_X production,

2) Single port burners generally have larger flame volumes with fewer regions of high intensity which lowers the potential for optimum NO_X production, and

3) The longer flames of single port burners allow more time for NO_X decay.

Yellow flames have been shown to have statistically significant different emission levels with regard to the NO_X emission factor and CO emission. Yellow flames are cooler than blue flames and this results in the overall decrease in NO_X levels. The NO_2 emission levels of the maladjusted yellow flames increased because of the lower flame temperature conditions which favor NO_2 formation and because more secondary air is available at the flame front. Since these yellow flames are relatively fuel rich, as compared to blue flames, less complete combustion results with a corresponding increase in CO and aldehyde emission levels.

The mean fuel input rate for the atmospheric injection furnaces tested was 107,500 Btu/hr with a standard deviation of 20,500 Btu/hr. Two of the units studied fell outside the 95 percent confidence limits for these values. These two furnaces, FAF 11 and FAF 21, can be used to indicate whether the increased fuel input rate has any effect on the emission levels. Since most units are modularly constructed, large units are made up of smaller ones thus there would not appear to be any size effects on emissions. Table 1 data verify this point for it can be seen that all of the emission values for these two units fell within the 95 percent confidence limits of the emissions listed in Table 3. Further study on larger drum-type forced air furnaces would be needed to determine if there is any affect with this type of design since one size drum may be used for more than one input rate.

FAF 37 results were obtained too late to be included in the overall statistical analysis. This unit was equipped with two single port inshot type burners in two clam type heat exchanger sections. Emission results for this unit were within the 95 percent confidence limits obtained for all single port type burners.

FAF 38 was of an unusual design and its emission results were not included in the averages. This unit was a combination decorative fireplace and forced air furnace. It was equipped with a multiport burner shaped like two logs. Pieces of asbestos were attached to the burner surface to achieve some radiation and provide a pleasing appearance to the eye. A drum type heat exchanger system was mounted above the burner to achieve an overall appliance heat transfer efficiency of at least 75 percent. There are several reasons why the NO_X emissions of this design were so low (see Table 1). First, the burner was designed with many widely spaced ports spread out over a relatively large surface area. The fuel input rate per unit of mass of this burner was low compared to contemporary multiport designs. The large burner mass acted as a heat sink cooling the flames on each port and, thus, minimizing NO_X emission. Second, the burner design was such that the burner operated at 36 percent primary aeration under best adjustment. The low primary air, in conjunction with the fact that the entire system was designed so that it operated at minimum levels of excess air which controlled the ingress of N_2 and O_2 to the burner flames resulted in a condition which minimizes NO_X emissions.

3. Pilot Burner Emission Results

A representative sample of the types of pilots currently in use was determined from a review of the furnaces used for this study. Representative pilots with safety shutoff device, were removed from the units and analyzed for emissions in a controlled system. In situ samples were not obtained because of the large amounts of excess air which could not be controlled without affecting the pilot performance. Since changing airflow patterns affect the pilot flame stability and, therefore, the emissions level, analysis of the pilots while operating within a closed system was felt to be the preferable way to measure the pilots. In the controlled system the pilots were mounted identical to the mountings used in the furnace, including flame sensor and burner impingement, if any. The results are presented in Table 7 and show a higher CO and NO_2 emission level and a lower NO_X emission factor than main burners.

Nine pilots representing five different manufacturers were tested. All of the pilots except No. 6 were nonprimary aerated. One of the pilots (No. 7) had a bimetal switch acting as a flame sensing device. All of the others had a portion of the flame impinging on a thermocouple to activate an automatic pilot safety device in the main gas valve.

Fuel input rates of the pilot burners ranged from 828 to 1570 Btu/hr, with an average of 1023 Btu/hr, and are much higher than range pilot burner fuel inputs. The NO_2 emission level is much higher than that measured for the main burner, and on the average represents 45 percent of the NO_X ($NO + NO_2$) emitted by pilot burners. The high NO_2 levels are due to the lower flame intensity and flame temperature caused by the low flame intensity and the fact that all but one pilot was non-primary aerated. The average NO_X emission factor of 0.068 lbs $NO_X/10^6$ Btu burned, however, is not out of line with results obtained for the main burners of furnaces. It appears that a relationship between the input rate and the emission factor may exist, but due to the limited data available no definite correlation can be made.

B. Performance Factors Influencing Forced Air Furnace Emission Levels

1. Burner-On Time

FAF's 25 and 38 were used to show the effect of appliance-on time on furnace emissions levels, starting from a cold start. FAF 25 was equipped with 3 slotted port tubular burners and 3 stamped sheet metal heat exchanger sections. FAF 38 was equipped with a large multiported burner, shaped to look like two logs, and a drum shaped heat exchanger positioned above and away from the burner. The results for the two units are presented in Figures 4 and 5.

Figure 4 shows FAF 25 reached an essentially steady state emission level after about 5 minutes of operation with respect to CO_2, CO and the oxides of nitrogen. Based on experience with the 38 furnaces, this time

TABLE 7

FORCED AIR FURNACE PILOT EMISSION DATA

Pilot Burner Number	FAF Number	Input Rate Btu/Hr	Flue Gas Concentration ppm, Air Free				NO_x Emission Factor* lbs/10^6 Btu
			CO_2	CO	NO	NO_2	
1	34	1005	1.55	116	41.0	24.4	.068
2A	35	828	1.30	231	27.2	23.5	.053
2B	18	1020	1.45	166	32.7	26.9	.062
3	14	890	1.20	250	28.0	42.5	.073
4A	7	1020	1.90	126	38.5	24.6	.065
4B	10	1150	2.00	240	28.8	30.0	.061
5	31	875	1.95	92	48.0	21.2	.072
6**	6	1570	3.20	112	43.1	39.0	.085
7	20	850	1.75	240	38.4	33.6	.075
AVERAGE		1023		175	36.2	29.5	.068
STANDARD DEVIATION		230		65	7.4	7.4	.009

* Sum of NO and NO_2 calculated as NO_2.

** Primary aerated

A & B are identical models from the same manufacturer.

FIGURE 4

EMISSION CONCENTRATION VS. TIME FROM COLD START FOR FAF 25 WHEN OPERATING UNDER BLUE FLAME CONDITIONS

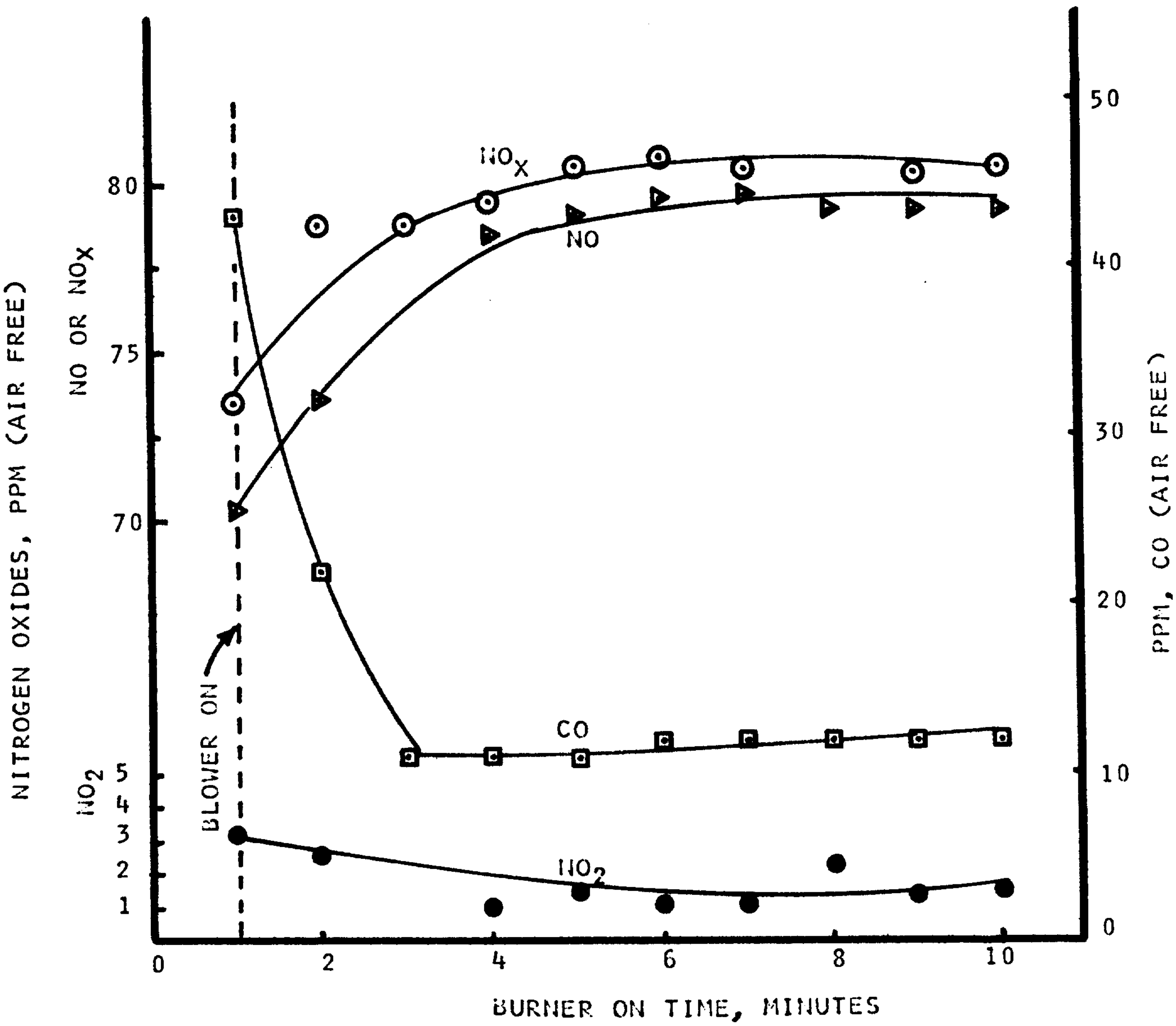
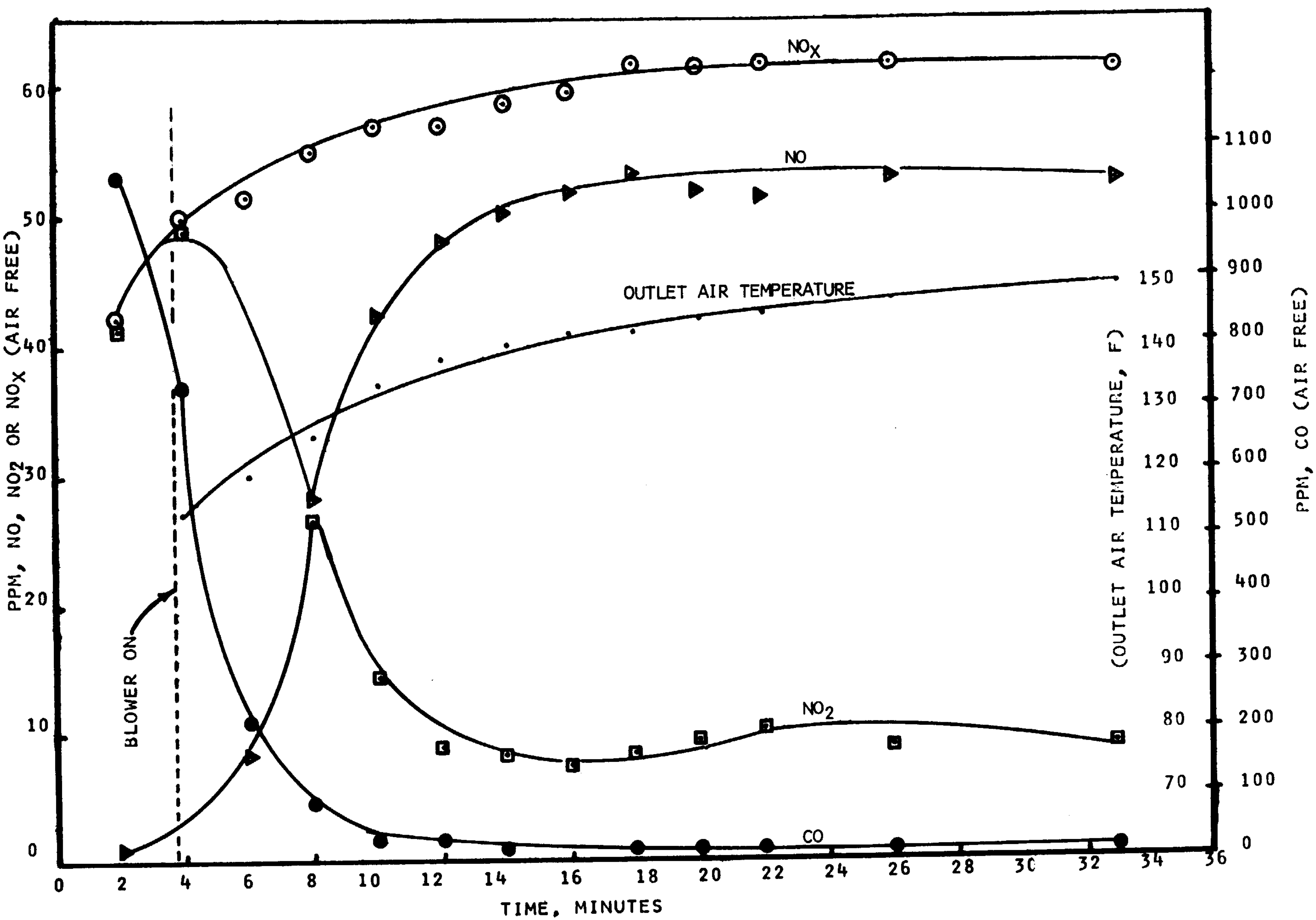


FIGURE 5

EMISSION CONCENTRATION VS. TIME FROM COLD START FOR FAF 38
WHEN OPERATING UNDER BLUE FLAME CONDITIONS



appears to be representative of typical forced air furnaces. Prior to the five minute mark, the NO_2, CO_2 and CO levels reached peaks at under 1 minute and thereafter decreased while the NO and total NO_X levels slowly increased.

This relatively short time needed to reach emission stability is not unexpected since the heat exchangers are air backed and temperatures quickly stabilize throughout the furnace combustion system. Thus, the emission levels of the various pollutants reach an equilibrium quickly.

Figure 5 shows that FAF 38 required about 16 minutes to reach an essentially steady operating state with respect to its emissions level and outlet air temperature. Prior to the 16 minutes the NO and total NO_X levels increased, the NO_2 concentration first increased and then decreased, and the CO concentration decreased.

FAF 38 required longer time to reach emission stability because it required longer for the system to reach temperature equilibrium. The separation of the burner from the heat exchanger and the larger mass and volume of the heat exchanger are responsible for the relatively long time needed to reach temperature equilibrium.

The equilibrium times for these 2 furnaces compare to a time of about 20 minutes needed by a range top burner to reach emission equilibrium.

2. Varying the Circulating Air Temperature Rise

The circulating air temperature rise of two furnaces were varied to determine the effects on the emission levels. FAF 10 which has 3 single port inshot burners, and FAF 22 which has 4 tubular multiport burners, were chosen to give a comparison between two different types of burner systems. Changing the air temperature rise was accomplished by varying the size of the warm air outlet of the furnace plenum. This resulted in various mass air flows passing through the furnace. The results are presented in Figure 6.

Increasing the circulating air temperature rise of both furnaces, as shown in Figure 6, caused a small, insignificant from a practical standpoint, change in the CO emission, an increase in both NO and total NO_X levels and a decrease in the NO_2 concentration. The percent change in emission levels from the lowest to highest air temperature rise of the single port burner furnace is greater than that of the multiport burner furnace. With the air temperature rise increasing from 53 to 113 F, the single port burner furnace NO_X emission increased by 22 percent, the NO by 28 percent and the NO_2 decreased by 100 percent. Increasing the air temperature rise of the multiport burner furnace from 45 to 109 F increased the NO_X emission by 1 percent, the NO by 6 percent and reduced the NO_2 by 65 percent.

The thermal efficiency of both units was highest at the lowest circulating air temperature rise and decreased as the air temperature rise increased (FAF 10 thermal effiency decreased from 78.4 to 74.1 percent and FAF 22 thermal efficiency decreased from 77.1 to 75.0 percent). The higher efficiency means that more heat is being removed from the flame and combustion system thus resulting in lower flame temperatures and, therefore, lower NO and total NO_X levels. This lower flame temperature also favors increased NO_2 levels. Decreasing the airflow through the furnaces resulted in higher outlet air temperatures, lower thermal efficiencies and higher flame temperatures thus accounting for the higher NO and NO_X levels and the lower NO_2 levels.

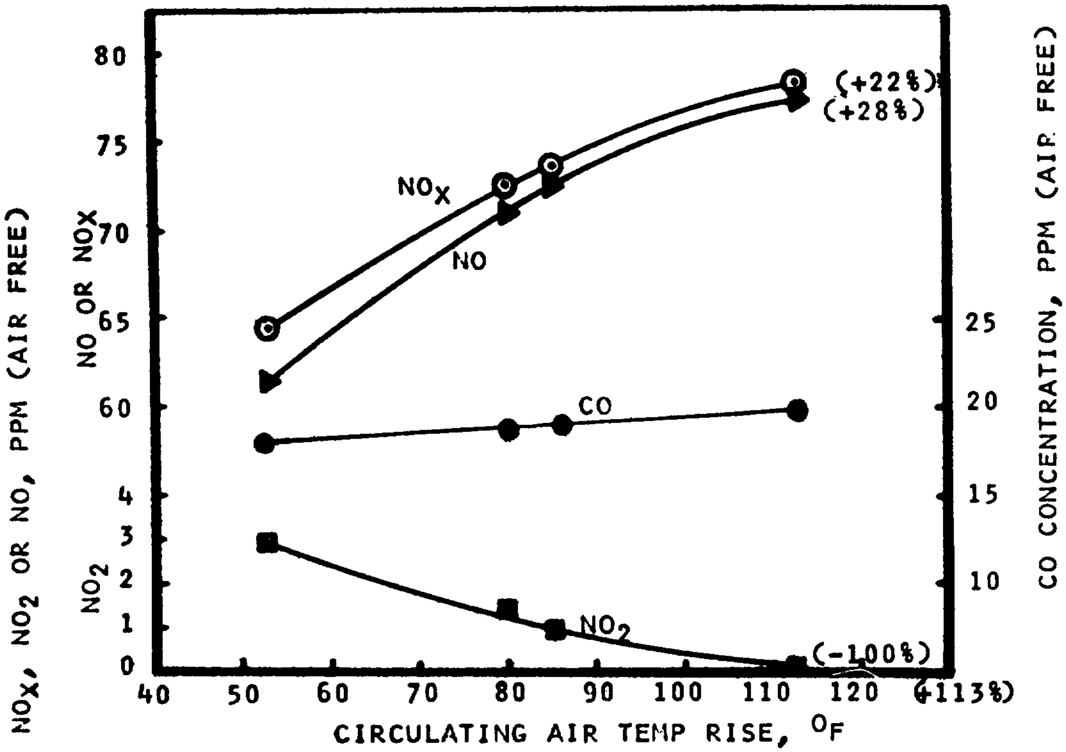
3. Varying Fuel Input Rate

The fuel input rates were varied and emission analyses made of six different atmospheric injection forced air furnaces. One of the furnaces was tested with two different types of burners. The results obtained with these furnaces are presented in Table 8. The data shown in this table were taken with no

FIGURE 6

EFFECT OF OUTLET AIR TEMPERATURE ON NO_x EMISSION

FAF 10 (BLUE FLAME) SINGLE PORT INSHOT BURNER



FAF 22 (BLUE FLAME) TUBULAR MULTIPORT BURNER

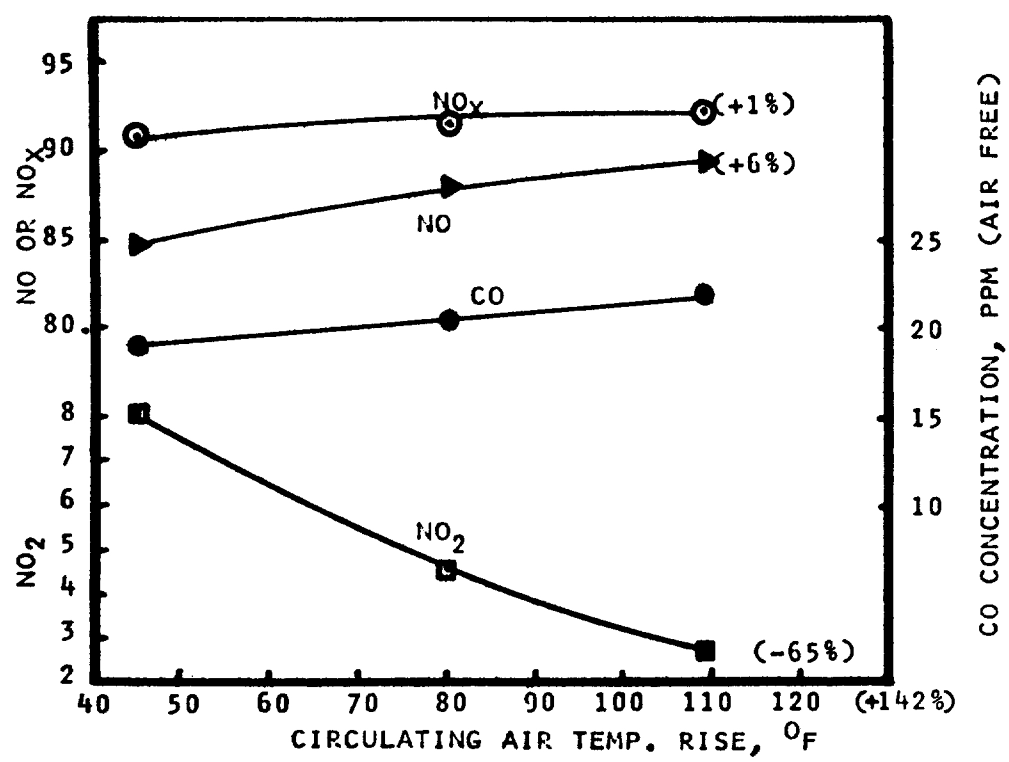


TABLE 8

EFFECTS OF VARYING FUEL INPUT RATE ON EMISSION LEVELS OF SIX ATMOSPHERIC INJECTION FORCED AIR FURNACES

FAF No.	Burner Type	Input Rate Btu/Hr	Percent Rated Input	Sample CO_2, Percent	Flue Gas Concentration ppm, Air Free			
					CO	NO	NO_2	NO_x
4	Multiport Slots	90,000	110	7.7	1169	68.9	12.1	81.0
		81,500	100	7.0	69	72.3	8.6	80.9
		42,500	52	3.6	118	42.3	21.9	64.2
7	Multiport Slot	114,500	112	5.9	20	98.4	0	98.4
		102,500	100	5.3	23	94.6	0	94.6
		52,100	51	2.8	43	61.3	15.0	76.3
12	Single Port Circular Slot (Cast Iron)	120,000	100	6.3	29	75.5	1.5	77.0
		109,000	91	4.7	26	97.3	0.5	97.8
		82,800	69	4.5	13	77.3	0	77.3
14	Multiport Slot (Cast Iron)	130,000	124	7.6	32	85.7	1.9	87.6
		104,500	100	6.0	20	75.2	2.8	78.0
		50,500	48	3.0	80	30.4	20.0	50.4
23	Multiport Slot	116,200	111	6.1	20	92.5	0	92.5
		105,000	100	5.5	17	92.7	0	92.7
		89,300	85	4.8	20	91.0	1.0	92.0
		72,600	69	4.0	15	79.0	5.2	84.2
		51,600	49	2.9	60	51.7	19.5	71.2
36	Multiport Slot (Cast Iron)	84,000	100	4.7	13	91.1	3.4	94.5
		51,000	61	3.0	61	36.6	18.7	53.3
		32,700	39	1.9	221	12.6	29.7	42.3
	Single Port Inshot (Cast Iron)	84,600	100	4.7	26	55.1	6.7	61.8
		51,000	60	2.9	41	50.5	9.9	60.4
		32,900	39	1.9	158	29.7	29.7	59.4

effort made to control the excess aeration. Thus, while the input was reduced the excess aeration increased as shown by the CO_2 values of Table 8. Typically, except for FAF 12, as the fuel input rate was decreased the CO and NO_2 levels increased while the NO and total NO_X levels decreased. The NO and total NO_X levels decreased because of a decrease in the flame intensity and volume as the total input rate was reduced. The NO_2 increased because of the added excess air available for reaction around the flame front and the lower flame temperature conditions which favor NO_2 formation; the CO increased due to a reduction in primary air injection and cooling of the flame. FAF 36 with the single port inshot burners behave typically with regard to CO, NO and NO_2, however, the total NO_X decreased only slightly with a decrease in the input rate. This was due to the flame maintaining a relatively constant intensity, regardless of the input rate, because of the single ported burner design.

The results of FAF 12 shown in Table 8 are significantly different from results expected of a typical unit under varying inputs. This unit was equipped with a circular-slotted-port cast iron burner with a drum heat exchanger. Measurements show that the burner primary air increased as the input rate was increased from the low to the middle input values, but dropped off at the normal input rate. Thus it appears the burner was slightly under designed and the reduced aeration at the full rated input may have affected the results. At 110 percent of rated input FAF 4 also showed untypical performance. The burner injection at this high rate was still good, but the heat exchanger probably was overloaded, thus causing unstable combustion conditions and erratic emission results.

FAF 36 was tested with two completely different burner systems. It was originally equipped and studied with standard cast iron multiport burners and also, was studied with cast iron single port inshot burners. Each set of burners was designed to operate at the same fuel input rate. The results in Table 8 verify that at the full rated input the single port inshot burners emitted less NO_X than the multiported burners.

FAF 36 was also equipped with an electronic control system to automatically modulate the fuel input rate and blower speed as a function of the home heating demand. The data for this unit shown in Table 8, include results with changing air flow and reduced input. The results show that the air flow changes did not appear to overshadow the rate effect on the emissions levels.

The data of Table 9 show the effect of reduced input and excess aeration on the NO_X emissions level. For each of the reduced inputs measurements were made with the unmodified unit (lower line of data) and with the furnace flue outlet restricted (upper line of data). This table shows a significant reduction in NO_X emission with reduced input, but an insignificant change with increased excess aeration at each reduced input rate. Based on these results it appears that the reduced rate effect has overshadowed any effects of higher excess aeration. This demonstrates again the importance of the temperature on NO_X generation. The reduced input must have a more significant influence on the flame temperature than increasing excess air.

Figure 7 graphically represents the results of reducing the fuel input rate of FAF 23, a typical unit. This figure shows that as the fuel input is reduced and the flame intensity diminished the NO and NO_X decrease, while the NO_2 and CO increase due to the lower flame temperature.

4. Powered Burners

Emissions from two furnaces equipped with powered burners (FAF's 26 and 33) were compared with those from the atmospheric injection burner furnaces.

The powered burner of FAF 33 was similar to an atmospheric injection single port inshot burner except that all of the combustion air

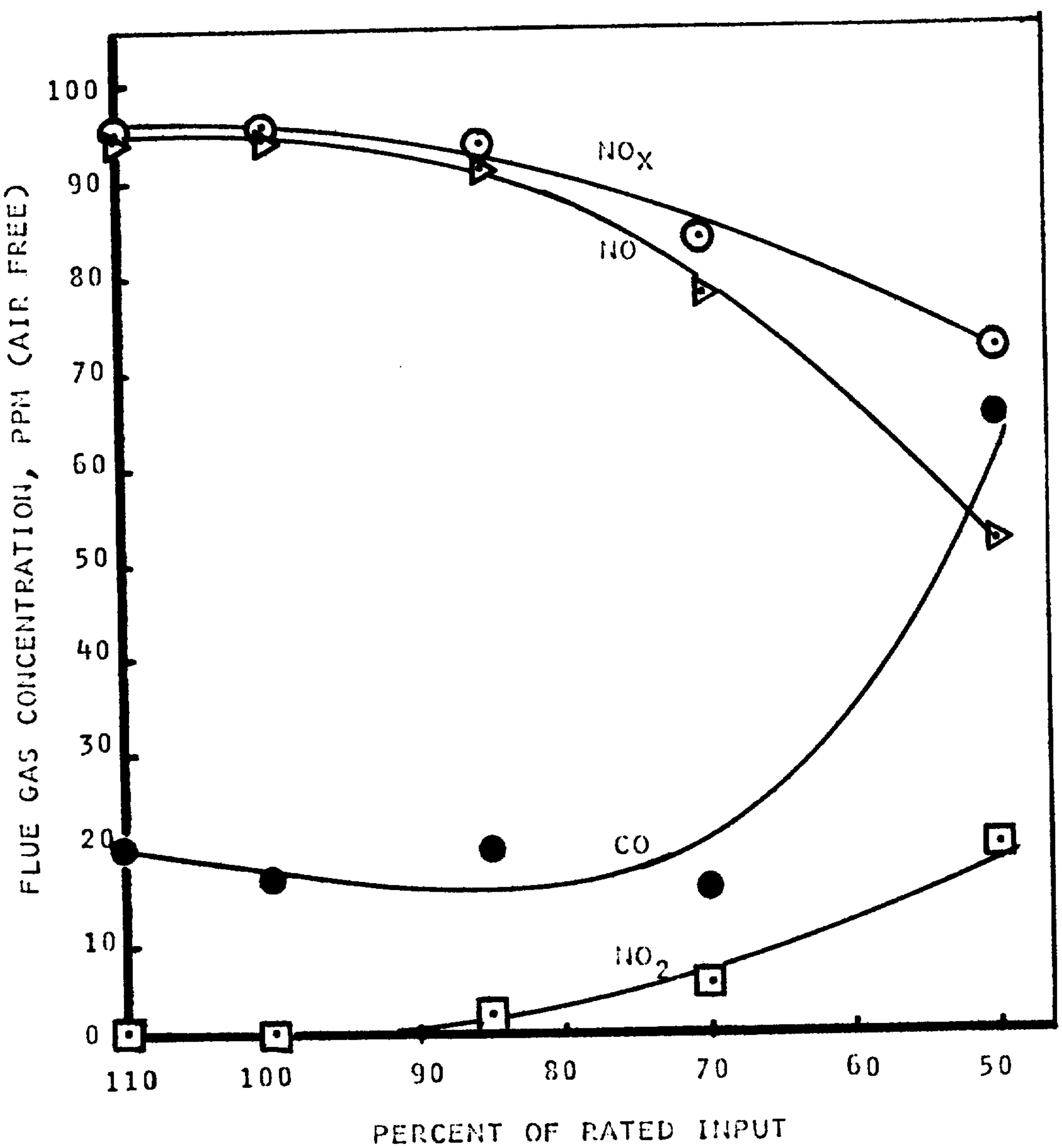
TABLE 9

EFFECT OF CHANGES IN FUEL INPUT RATE AND EXCESS AIR ON CO AND NO_x EMISSION OF FORCED AIR FURNACE 25

Rate, Btu/Hr	Percent Rated Input	Excess Air Percent	Sample CO_2, Percent	Flue Gas Concentration ppm, Air Free			
				CO	NO	NO_2	NO_x
105,700	100	114	5.20	23	80.2	1.6	81.8
85,700	81	113	5.25	11	74.5	3.2	77.7
		163	4.20	14	76.3	2.0	78.3
63,500	60	143	4.55	21	66.2	4.7	70.9
		253	3.10	19	65.8	5.4	71.2
54,600	52	182	3.90	25	60.9	7.4	68.3
		303	2.70	22	60.0	8.4	68.4

FIGURE 7

EFFECT ON EMISSIONS OF FUEL INPUT RATE FOR FAF 23 WHEN OPERATING UNDER BLUE FLAME CONDITIONS



was forced into the sealed combustion chamber system by a squirrel cage blower. The heat exchanger was of a shell-and-tube design with circulating air passing through the tubes. The emissions of this unit, as shown in Table 1, were within the 95 percent confidence limits of the average values determined for the furnaces equipped with atmospheric burners.

FAF 26 had a powered system that forced the air-gas mixture through a screen, causing the flame to consist of many tiny cones. The hot flue gases then passed through a heat exchanger matrix made up of small diameter steel balls, through which a fluid passed for heat transfer. This unit had an electronic system for choosing between two different fuel input rates dependent upon the home heating demand.

At the lower fuel input rate the total NO_X emission for FAF 26 was lower than that measured for any other unit. The NO_2 emission level was slightly higher than the average, but its NO level was only a fraction of the average. This low NO concentration is responsible for lowering the NO_X emission factor to 0.018 lbs/10^6 Btu. The CO concentration is higher than average, however, it does not exceed any value set by standards (See Table 1). Increasing the fuel input rate to its high rate of 120,000 Btu/hr caused an increase in CO, from 95 ppm air free at the low rate to 130 ppm air free, while reducing the NO_X emission factor from 0.018 to 0.013 lbs/10^6 Btu.

The predominant design factors of FAF 26 responsible for the low NO_X emission are: 1) the precise control of the air available for reaction in the flame which minimizes the NO level through a decrease in oxygen available in the NO formation zone of the flame, and 2) a high rate of cooling of the combustion products as they flow away from the flame front. The temperature of these combustion products is quickly lowered to below 2800 F where the NO formation reactions are essentially stopped.

The design of FAF 26 provides a method of significantly reducing the NO_X emissions of a furnace, however, the unit design is more complex and probably more costly to manufacture.

C. Furnace Emission Reduction Experiments

The peak temperatures of flames are the primary factor that determines the level of production of the oxides of nitrogen. Harris, et. al.[3] have presented general principles to be applied to gas appliance design to reduce the emission levels of carbon monoxide and the oxides of nitrogen. Three of these design factors are: 1) reduce peak flame temperatures to below 3050 F, 2) initiate rapid cooling to temperatures below 3050 F if peak temperatures are above 3050 F, and 3) speed up the oxidation of CO and simultaneously oppose the formation of NO_X by lowering local flame temperatures through the rapid introduction of secondary air into the primary and secondary combustion zones of flames. A final general rule for minimizing NO_X emission is to limit the availability of O_2 and N_2 to the combustion zone.

Table 10 summarizes the relative effects of flame or combustion temperature on NO_X formation. Above 3050 F $\pm$100 F the highest concentrations of NO_X occur and the peak concentrations of NO_X for lean and stoichiometric flames show a marked decrease with decreasing flame temperature. Below 3050 F the emission of NO_X is significantly reduced and the formation of NO_X in the secondary combustion zone essentially ceases. Practically no further formation of NO_X occurs in the short time available in a gas appliance. NO_X decomposition occurs below this temperature. At a temperature of 2140 F $\pm$ 300 F the decomposition rate of NO_X is too slow for a significant reaction to occur and the NO_X level is effectively frozen.

Thus, to reduce the nitrogen oxide level in the typical furnace flame the peak flame temperature must be kept below 3050 F, the flue gas temperature should be slowly cooled

TABLE 10

EFFECTS OF TEMPERATURE ON NITROGEN OXIDE FORMATION

Temperature ↑	
	• Highest concentration of nitrogen oxides occur • Peak concentrations of nitrogen oxides for lean and stoichiometric flames show a marked decrease with decreasing temperature
3050 F ± 100	
	• Emission of nitrogen oxides significantly reduced • Formation of nitrogen oxides in the secondary combustion zone essentially ceases • Nitrogen oxide decomposition occurs • Practically no further formation of nitrogen oxides occurs in the short time available in a gas appliance
2140 F ± 300	
	• Decomposition rate is too slow for a significant reaction to occur

Paraphrased from: "Reduction of Air Pollutants From Gas Burners Including Related Reaction Kinetics" by Margaret E. Harris, et. al., U. S. Bureau of Mines, Bulletin 653, U. S. Department of Interior, Washington, D.C., 1970.

to 2140 F to cause NO_X decomposition, and the availability of excess O_2 and N_2 to the high temperature flame region should be minimized.

One method of reducing peak flame temperature is to radiate heat away from the flame as it is produced by using a radiating screen placed into the flame. A second method is by the use of a secondary air baffle to provide a semi-closed system in which the flame can burn and slightly cool before combustion is completed at the top of the baffle. The following two sections describe these two methods in greater detail.

1. Radiant Screens

It was established in other work at the Laboratories[2] and also by Roessler[4] that an infrared type burner was a low emitter of pollutants. The cooler flames produced by placing radiating screens in the flames of a range top burner produced less NO_X. Similar screen arrangements were placed in the flames of forced air furnace burners to decrease the flame temperature and to minimize NO_X formation.

These studies showed that the judicious placement of a screen in the flame does in fact reduce the NO_X emissions, while not adversely affecting the CO level. The optimum position and shape for the screen is such that the screen is in as much of the flame as possible and becomes incandescent, radiating heat away from the flame while still keeping the flame temperature high enough to provide for complete combustion. Generally this location is just downstream from the inner cone of the flame at what is generally considered to be the flame hot spot.

Initially single burners were modified on FAF's 23 and 25. Each of these units had a differently designed tubular shaped multiport slotted port burner. The screens (6 x 6 mesh Inconel® with .042 inch wire) were shaped into an inverted "V" (see Figure 8a) and were placed along the entire length of the burner just above the inner cone of the flame as shown in Figure 8b. In both cases there were no appreciable changes in the CO and NO_2 levels but there were significant decreases in the NO and total NO_X levels (see Table 11).

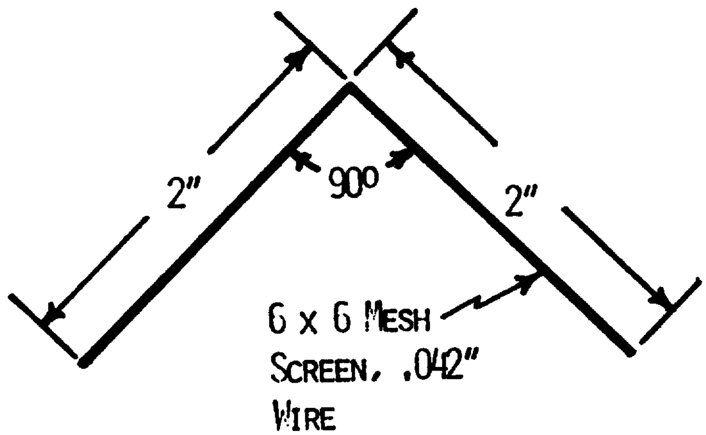
FAF 9, which had a single port upshot burner with a 3-1/2 inch diameter flame spreader 1 inch above the burner port, was modified (see Figure 9) by the addition of a screen around the burner. The screen was a 5-3/4 inch diameter cylindrically-shaped screen 4-1/2 inches high located with its bottom edge just below the burner port. The flame from the burner passed through the screen and caused it to become incandescent. The CO and NO_2 levels increased slightly while the NO and total NO_X levels decreased by 39 percent and 36 percent respectively (see Table 11).

Table 12 is a description of the performance of two furnaces (FAF's 23 and 25) both before and after complete modification of all burners with radiant screens. Data were taken with the furnace operating in its normal configuration followed by a similar set of data with the radiant screens in place. The units were allowed to come to temperature equilibrium before each set of data were taken. Significant changes were noted in all emission levels. The NO_2 levels increased while the NO and total NO_X levels decreased substantially. The CO levels increased, but not enough to be significant from a practical standpoint. The average NO_X decrease for the two modified units was 58 percent representing a significant reduction with a relatively simple burner modification.

A significant result of these measurements is the fact that this modification not only can reduce NO_X emission but can increase the thermal efficiency of the appliance. The higher efficiency results from increased flame and burner radiation.

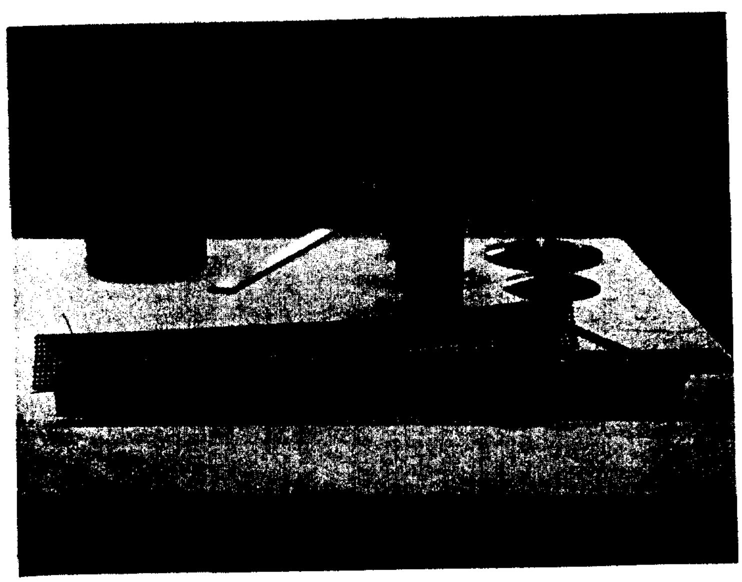
The results of both tests with radiant screens showed substantial increases in burner temperature, and heat exchanger

FIGURE 8



(a)

END VIEW OF INVERTED "V" SCREEN

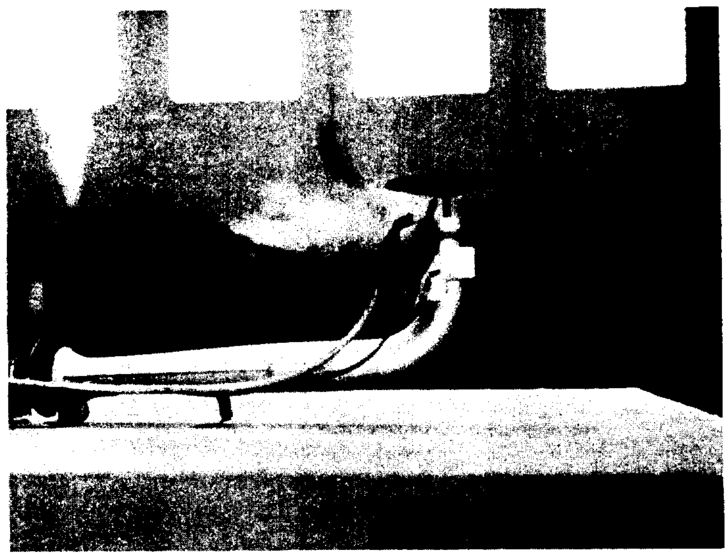


(b)

VIEW OF RADIANT SCREEN APPLIED TO MULTIPORT TYPE BURNER

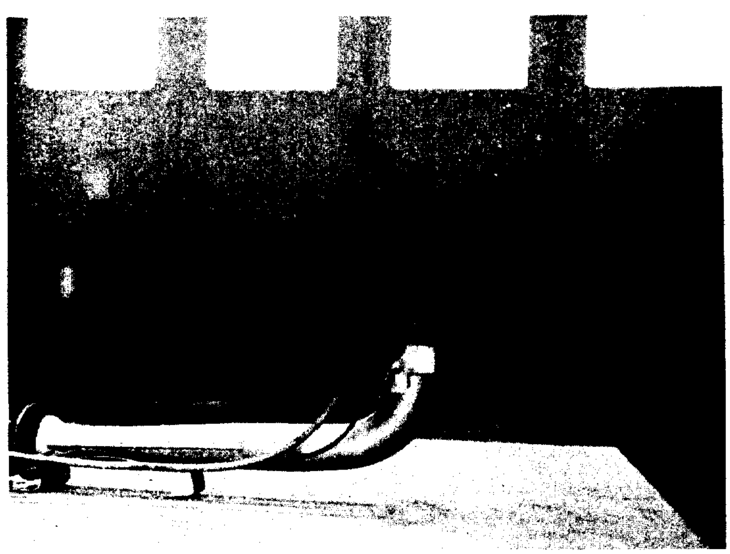
FIGURE 9

VIEWS OF SINGLE PORT TYPE BURNER BEFORE AND AFTER MODIFICATION WITH RADIANT SCREEN TO MINIMIZE NO_x EMISSIONS LEVEL



(a)

UNMODIFIED SINGLE PORT UPSHOT BURNER WITH FLAME SPREADER (FAF 9) RATED AT 100,000 BTU/HR



(b)

ABOVE BURNER MODIFIED WITH RADIANT SCREEN

TABLE 11

EFFECT ON CO AND NO_x EMISSION OF PLACING RADIANT SCREEN IN BURNER FLAME

Unit	Sample CO_2, Percent	Flue Gas Concentration ppm, Air Free				NO_x Percent Change
		CO	NO	NO_2	NO_x	
FAF 23 - Tubular Multiport						
No screen	8.50	14	104.9	0	104.9	
Screen	8.30	15	23.4	1.6	25.0	-76%
FAF 25 - Tubular Multiport						
No screen	7.70	8	76.7	3.7	80.5	
Screen	7.75	11	21.5	3.4	24.9	-69%
FAF 9 - Single Port Upshot with Flame Spreader						
No screen	4.05	15	61.3	1.6	62.9	
Screen	4.05	44	37.3	3.0	40.3	-36%

TABLE 12

EFFECT OF RADIANT SCREENS ON FORCED AIR FURNACE PERFORMANCE AND EMISSION LEVELS

Unit	FAF 23		FAF 24	
	Normal	Modified	Normal	Modified
Burner Temperature, °F (Average)				
(1) Top	791	1096		
Side			385	678
Flue Gas Temperature, °F	300	291	440	416
Heat Exchanger Temperature				
Top	290°F	277°F	410°F	371°F
Bottom	165°F	253°F	207°F	322°F
Side 6" from bottom			224°F	365°F
Flue Loss	20.1%	19.7%	26.6%	25.4%
CO_2 (Sample)	4.4%	4.4%	4.60%	4.65%
CO (Air Free), ppm	14	27	13	26
NO (Air Free), ppm	76.1	26.4	84.5	33.0
NO_2 (Air Free), ppm	≤ 0.1	4.4	≤ 0.1	4.4
NO_x (Air Free), ppm	76.1	30.8	84.5	37.4
Percent NO_x Decrease		60%		56%

NOTE: (1) The burner temperature reported is the average temperature of these burners with thermocouples located on each burner to give a representative temperature.

temperature in the vicinity of the burner. The higher burner temperatures may require the use of a different material in burner construction, but the increased heat exchanger temperature will require no changes in heat exchanger material. This increase in heat exchanger temperature adjacent to the burners is not high enough to cause any problems with the maximum allowable surface temperature. However, this increase in heat exchanger temperature in the vicinity of the burner in one case raised the air temperature between two adjacent heat exchanger sections to the point where the furnace limit control reached its upper limit and turned the burner off. This problem may occur in other furnaces and could be solved by a relocation of the limit control to some point in the furnace where it is less susceptable to the high temperatures present during start-up.

Radiant screen modifications also were made on single port inshot type burners (see Table 13a). With an inverted "V" shaped screen in its optimum position in relation to the burner the total NO_X emission decreased by 51 percent. There was a small increase in CO emission and no significant increase in burner or heat exchanger temperature. When using a flat screen in its optimum position a 41 percent decrease in NO_X was noted.

Radiant screens show much promise in reducing emission levels while at the same time increasing appliance thermal efficiency, however, work is needed to fully develop the technique; and some life studies are needed in regard to screen deterioration, deformation, and the effects of these possible changes on combustion.

2. Secondary Air Baffles

The effect on emissions of controlling the secondary air ingress to the flame was studied with single port inshot and upshot burners. This approach seems more readily applicable to these types of burners.

FAF 9 was one of the two furnaces used for the secondary air baffle studies and was equipped with a single port upshot burner with a drum type heat exchanger. FAF 26 was equipped with 3 single port inshot burners and a sectional heat exchanger.

Carefully controlling the ingress of secondary air to a flame causes a decrease in the NO_X levels with essentially no increase in CO concentration. The decreased amount of oxygen available for reaction at the flame front is responsible for the decrease in NO_X levels. However, restricting too much secondary air will cause incomplete combustion and high CO levels.

Cylindrically shaped secondary air baffles of various diameters and heights were designed and applied to the upshot burner of FAF 9, and the effects on the emissions level were measured. The design criteria was to produce a baffle such that a stable flame burned within the baffle using the controlled secondary air available to it. The remainder of the combustion would occur at the top of the baffle and would use uncontrolled secondary air. The flame of this burner was designed to be cooler and of longer duration than the flame of the original burner configuration. These two conditions are favorable to lower NO_X production.

The baffle diameters were all larger than the diameter of the burner and the bottom of the baffles extended slightly below the top of the burner head. The flame spreader was positioned at various distances above the top of the baffle. Figure 10 illustrates a typical secondary air baffle application to a single port upshot type burner. The addition of the baffle to the burner resulted in an overall increase in the burner height which should cause no problems.

Generally, baffles with smaller diameters caused the flame to burn only at the baffle outlet, thus defeating its purpose of secondary air control. Larger diameter baffles that caused the flame to burn inside and at the

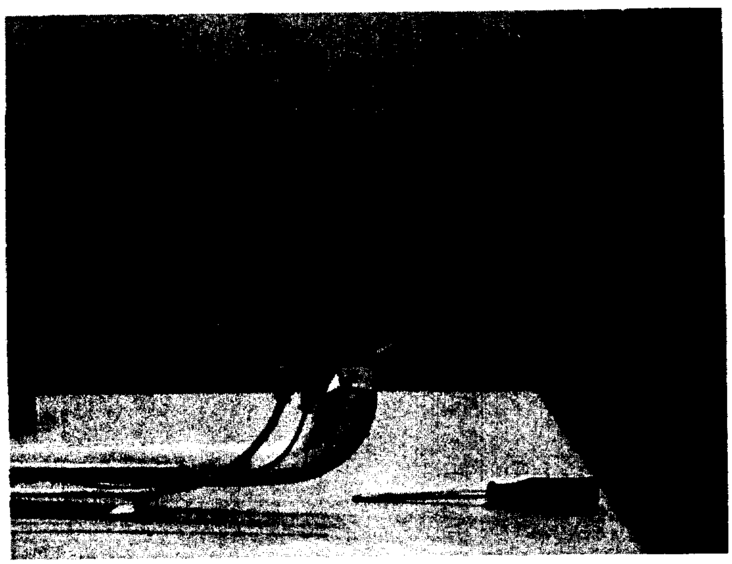
TABLE 13

EMISSION REDUCTION EXPERIMENTS ON SINGLE PORT INSHOT BURNER IN SINGLE HEAT EXCHANGER SECTION

Burner Configuration	Sample Percent CO_2	Flue Gas Concentration ppm, Air Free CO	NO	NO_2	NO_x	NO_x Percent Change
Unmodified	6.25	19	56.8	2.1	58.9	
		a. Radiant Screens				
Inverted "V" Shaped Screen	6.85	82	22.4	6.5	28.9	-51%
Flat Screen	6.80	26	30.0	4.6	34.6	-41%
		b. Secondary Air Baffles				
Cylinder 6 inches Long by 2-1/2 inch Diameter	7.0	>2000				
Cylinder 6 inches Long by 3 inch Diameter	7.3	1100	3.3	30.4	33.7	-43%
Same as above with added air holes	7.1	338	17.8	19.4	37.2	-37%

FIGURE 10

TYPICAL CYLINDRICAL SECONDARY AIR BAFFLE ARRANGEMENT FOR FORCED AIR FURNACE MOUNTED SINGLE-PORT UPSHOT BURNER



top of the baffle reduced the NO_X level. The smaller diameter baffles can be modified to cause the flame to burn within the baffle by the addition of air holes near the base of the flame.

The placement of the flame spreader above the baffle also is a critical dimension. If it is placed too low burning occurs only at the annulus formed between the baffle and the flame spreader. If placed too high, it loses effect as a flame spreader and in one case caused an increase in the NO_X level (see Table 14).

Table 14 also shows that with baffle height and flame spreader placement (in relation to the baffle) remaining constant, increasing the baffle diameter results in an increase in NO_X levels. The NO_X increases because of the increased secondary air passing through the area between the flame front and the inside baffle wall. Increasing the height of the baffle, with the baffle diameter and flame spreader placement (in relation to the baffle) remaining constant, results in a decrease in NO_X levels. The NO_X decreases because of an increased volume of flame burning the controlled sciondary air. Increasing the baffle height causes more of the fuel to be consumed under the conditions of controlled air.

In these tests, the optimum configuration of baffle diameter, height and flame spreader placement reduced the total NO_X by 37 percent with a small increase in CO.

Cylindrical baffles were also adapted for use with an inshot burner of FAF 28. This modification, however, was not as successful as those on the upshot burner (see Table 13b). The NO_X level was lowered 43 percent by using a baffle 6 inches long by 3 inches diameter, but the CO concentration was 1100 ppm. The addition of numerous air holes in the bottom of the baffle resulted in a 37 percent NO_X reduction but the CO concentration remained questionably high. The high CO levels probably could be lowered with further burner development. As shown in Table 14 this modification had very little effect on the appliance thermal efficiency. If any trend is shown it is toward a small increase in efficiency.

While these approaches decreased the NO_X emissions, with varying increases in CO emissions, none were as effective as a radiant screen. They may work in combination with the screens but this was not tried. The baffle method of reducing emissions has some promise, but further development would be needed to produce a suitable design. More advanced designs could use the secondary air baffle as an integral part of the burner or the heat exchanger. Further, it is important that the baffle maintain its shape and it must not warp or change shape as a result of heating and cooling.

TABLE 14

EFFECT OF SECONDARY AIR BAFFLES ON EMISSION LEVELS OF A SINGLE PORT UPSHOT BURNER

Burner Configuration			Sample Percent CO_2	Flue Gas Concentration ppm, Air Free: CO	Flue Gas Concentration ppm, Air Free: NO_x	NO_x Percent Change	Flue Loss, Percent
Original Burner			4.05	15	62.9		22.8
With Secondary Air Baffle							
Height	Diameter	Flame Spreader Height *					
3 inches	2-1/2 inches	1/2 inch	4.10	14	54.7	-13%	22.6
3 inches	2-3/4 inches	1/2 inch	4.20	14	56.0	-11%	22.2
6 inches	2-1/2 inches	1/2 inch	4.25	28	44.8	-29%	22.0
6 inches	2-1/2 inches	3/4 inch	4.25	28	48.0	-24%	22.0
6 inches	2-5/16 inches	1/2 inch	4.25	28	53.4	-15%	22.5
** 8 inches	2-1/2 inches	1/2 inch	4.40	177	41.5	-34%	21.9
** 8 inches	2-1/2 inches	3/4 inch	4.40	68	39.8	-37%	----

Baffle Height Comparison (bracket linking NO_x values 54.7, 44.8, 41.5)

Baffle Diameter Comparison (brackets linking NO_x values 54.7–56.0 and 44.8–53.4)

* Height of lowest point of flame spreader above the secondary air baffle.

** Four air holes at bottom of baffle.

IV. INSTRUMENTATION AND METHODS OF ANALYSIS

A. CO_2 and CO

A Mine Safety Appliance Co. (MSA) Model 300 Lira non-dispersive type infrared analyzer was used for analysis of CO_2 and CO. The full scale CO_2 reading was 0-12 percent and the full scale CO readings were either 0-200 ppm or 0-1000 ppm. A Beckman Model IR-9 dispersive type infrared spectrophotometer also was used to monitor these gases. The Beckman IR-9 is a dispersive, double-beamed instrument capable of very high resolution through a prism-grating optical system incorporating a double monochromator. This instrument was fitted with a gas cell which provided optical path lengths from 10 cm. to 10 meters.

The Beckman IR-9 was used periodically to check the CO_2 measurements of the Lira and was the primary instrument used for the analysis of CO. CO analysis in the sub part per-million range are possible with this instrument.

B. NO and NO_2

The oxides of nitrogen were measured with both the Beckman IR-9 and a Thermo Electron Corp. (TECO) Model 12A chemiluminescent gas analyzer. The Beckman IR-9 was the primary instrument used for the NO_X analysis of furnace flue gas samples. This instrumentation setup and calibration technique have been described in detail in a previous technical paper.[5] The TECO 12A is capable of full scale readings from 0.01 ppm to 2500 ppm and was the primary instrument of analysis for the pilot samples. Due to its fast response time, the TECO 12A also was used to study the effectiveness of various factors influencing the emission levels of the units studied.

C. CH_4 and C_2H_4

Methane and ethylene were analyzed using the Beckman IR-9. Concentrations of these gases in the sub part-per-million range can be determined using this instrument.

D. Aliphatic Aldehydes

The MBTH method, as outlined in Public Health Service Publication No. 999-AP-11 "Selected Methods for the Measurement of Air Pollutants," was used to determine the total water-soluble aliphatic aldehydes (measured as formaldehyde) in flue gas samples. Determinations in the parts-per-billion range are possible with this method. The method is recommended for the analysis of ambient air, but it is felt that it is applicable to flue gas samples since the average measured concentration was well under one part-per-million.

E. SO_2

Sulfur dioxide emissions from forced air furnaces were not measured because it was previously determined that the possibility of obtaining SO_2 concentrations of greater than 0.1 ppm by burning Cleveland area natural gas is very small. This possibility exists only if the supplied natural gas contains considerable amounts of sulfur compounds as odorants. The concentration of SO_2 in flue products could then be calculated from the concentration of sulfur in the natural gas and the quantity of gas burned.

Earlier in this project SO_2 was measured in the flue gases of other appliances using both the West & Gaeke wet chemical method and the Beckman IR-9. The amounts measured were in trace quantities and insignificant from an air pollution standpoint, and thus support the contention that further measurements of SO_2 in the flue products is not necessary.

Previously published studies have shown that excellent correlation exists between the infrared and standard wet chemical methods of analysis.[5] These publications also detail more completely the infrared techniques used and describe the accuracy and sensitivity of the method.

V. MEASUREMENT TECHNIQUES

A. Forced Air Furnaces

Each forced air furnace tested in this study was set up to operate in as near a normal manner as possible. Each unit was operated at its normal fuel input rate and was equipped with a plenum which was adjusted to operate the unit within the normal temperature rise and static pressures as specified by the manufacturer. Each unit was equipped with enough stack attached to the top of the draft hood to prevent draft hood spillage.

The units were tested in both a well adjusted (blue flame) and a poorly adjusted (yellow flame) condition. The yellow flame condition was obtained by closing the air shutter(s) to a point just short of where carbon was produced and where the flame was highly luminous.

A small flue gas sampling hole was placed in the stack sections at a point one foot above the draft hood to provide a sampling point. It was felt that this point was representative of the gases exiting the home chimney into the ambient air. An 8 mm O.D. L-shaped quartz sampling probe was inserted into the gas sampling hole and adjusted so that the inlet of the probe was centered in the stack and facing the flow of the flue products. The quartz probe was connected to a freezeout trap by means of a 1/4 inch O.D. Teflon® tube. The freezeout trap, maintained at -60 C, was used to remove as much water as possible from flue gas samples because of the major interferences presented by water vapor when measuring trace components of flue products with dispersive infrared instruments. From the freezeout trap, the sample was then transferred to the 10 m gas cell. A stainless steel tee was placed in the sample line immediately before the freezeout trap to provide a location from which to draw a portion of the sample for CO_2 and CO analysis.

In taking a typical flue gas sample a furnace was turned on and allowed to come to a steady state condition (usually the appliance was in operation approximately one hour). The non-dispersive infrared analyzer and the TECO 12A were used to assure that a steady state condition had been reached based on the CO_2 and NO_X concentrations. At this point the CO_2 and CO concentrations were noted and the flue gas sample was passed through the freezeout trap and then into the gas cell for further analysis.

B. Pilot Emissions Measurement

Forced air furnace pilots were tested in a standard controlled system rather than in their respective furnaces in order to obtain more comparative results. This system insured each pilot could be tested separately without the outside interferences that would have been present in the furnace environment.

The pilot was placed in the center of a quartz collector funnel 11 inches in diameter at the base and 4 inches in diameter at the top. The quartz probe, of the sampling system previously discussed, was inserted into the top of the quartz funnel and the top of the funnel was then restricted to increase the CO_2 concentration of the products of combustion to a level which made the air free correction factor reasonable in magnitude. Part of the flue products went directly to CO_2 and CO analysis, while part went through the freezeout trap and then into the TECO 12A for NO_X analysis.

REFERENCES

(1) Bartok, W., et. al., *Systems Study of Nitrogen Oxide Control Methods for Stationary Sources,* Interim Status Report Under Contract PH - 22 - 68 - 55 for National Air Pollution Control Administration, May 1, 1974.

(2) Himmel, R. L. and DeWerth, D. W., *Evaluation of the Pollutant Emmissions from Gas Fired Ranges,* A.G.A. Laboratories Research Report No. 1492, Cleveland, Ohio, September, 1974.

(3) Harris, M. E., et. al., *Reduction of Air Pollutants from Gas Burners and Related Reaction Kinetics,* U.S. Bureau of Mines Bulletin G53, 1970.

(4) Roessler, W., et. al., *Investigation of Surface Combustion Concepts for NO_X Control in Utility Boilers and Stationary Gas Turbines,* Aerospace Corp. Report to E.P.A., No. EPA-650/2-73-014, August 1973.

(5) DeWerth, D. W., *Infrared Spectrophotometric Measurement of Air Pollutants in the Flue Gases of Gas-Fired Appliances,* 1971 Conference on Natural Gas Research & Technology, Chicago, Illinois, 1971.

SOURCE CATEGORY: Natural Gas

EXCLUSION CRITERIA CHECKLIST

REFERENCE #21 "Evaluation of the Pollutant Emissions from Gas-fired Forced Air Furnaces" (1975) Thrasher, DeWerth

CRITERIA	YES	NO
1. Test series averages are reported in units that can be converted to the selected reporting units?	X	
2. Test series respresent compatible test methods?	X	
3. In tests in which emission control devices were used, the control devices are fully specified?	X	
4. Is the source process clearly identified and described?	X	
5. Is it clear whether or not the emissions were controlled (or not controlled)?	X	

Form filled out by [signature]

Date 3/17/92

INDICATE WHETHER ANSWER IS YES OR NO WITH AN "X" IN APPROPRIATE BOX.

IF ALL ANSWERS ARE "YES" PROCEED TO METHODOLOGY/DETAIL CRITERIA CHECKLIST.

Factors: CH_4, aliphatic aldehydes, CO_2

SOURCE CATEGORY: *Natural Gas*

METHODOLOGY/DETAIL CRITERIA CHECKLIST

REFERENCE *#21 "Evaluation of the Pollutant Emissions from Gas-Fired ....."*

CRITERIA	YES	NO	COMMENTS
1. Is the manner in which the source was operated well documented in the report?	X		
Was the source operating within typical parameters during the test?		X	*there were some tests of modifications to reduce NOx emissions.*
2. Did sampling procedures deviate from standard methods?		X	
If so, were the deviations well documented?			
Were the deviations appropriate?			
Comment on how any alterations in sampling procedure may have influenced the results.			
3. Were there wide variations in the results?		X	
If yes, can the variations be adequately explained by information in the report?			
If the variations are not well explained, should the data be considered of poor quality?			
4. Do the test reports contain original raw data sheets?		X	
Are the nomenclature and equations used equivalent to those specified by the EPA?	X		
Comment on the consistency amd completeness of the results.			[illegible]

Form filled out by *[signature]*

Date *3/19/92*

INDICATE WHETHER ANSWER IS YES OR NO WITH AN "X" IN APPROPRIATE BOX. FILL IN COMMENTS.

IF ,BASED ON ABOVE ANSWERS, IT IS DETERMINED THAT SOURCE REPORTS PROVIDE ADEQUATE DETAIL AND DEMONSTRATE A SOUND METHODOLOGY, PROCEED TO RATING THE DATA IN THE RATING CRITERIA CHECKLIST.

[illegible], aliphatic aldehydes, CO_2

SOURCE CATEGORY: Natural Gas

RATING CRITERIA CHECKLIST

REFERENCE #21 "Evaluation of the Pollutant Emissions from Gas-Fired..."

RATING	CRITERIA	YES	NO
A	Tests performed by a sound methodology and reported in enough detail for adequate validation?		X
B	Tests were performed by a generally sound methodology, but not enough detail for adequate validation?	X	
C	Were tests based on untested or new methodology that lacks significant amount of background data?		X
D	Were tests based on generally unacceptable methods, but may provide order-of-magnitude values for the source?		X

COMMENTS

Conditions were [illegible] in order to determine the effect of changes in burner [illegible] on [illegible] NO_x [illegible]. The effects of these [illegible] on CO_2, CH_4 and aliphatic aldehydes [illegible] were not as thoroughly analyzed.

Form filled out by [signature]

Date 3/19/92

BASED ON ANSWERS TO ABOVE, AND COMMENTS, ASSIGN A RANK TO THIS LITERATURE SOURCE:

B

RANK ASSIGNED TO EMISSION SOURCE DATA

for CO_2

CH_4

aliphatic aldehydes (HCHO)

Ref # 21

EPA [illegible]
25 May 92

Evaluation of the Pollutant Emissions From Gas-Fired Forced Air Furnaces
Cleveland Laboratories, May 1975

"Air free concentration" equivalent to 15% CO_2 concentration.

"Yellow flame conditions" = poorly adjusted flames sometimes encountered after lengthy field use.

- "Blue-flame condition" = well adjusted [illegible]
- Burner types included:
  - Multiport
  - Single port - upshot
  - Inshot
  - [illegible]

75,000 - [illegible] Btu/hr heat input

- Heat exchangers included
  - Sectional
  - Drum
  - Other

- Standard conditions for measurements
  - 60 °F, 30" Hg.

- CH_4, C_2H_4, and SO_2 pollutants present at "insignificant" levels

CO_2: 124,845 $\frac{lb}{10^6 scf}$

Average 124,845 $\frac{lb}{10^6 scf}$

Overall Averages - Blue flame and Yellow flame conditions

Pollutant	EF, lb/10^6 scf Blue Flame	Yellow Flame	Average	lb/10^6 Btu Average
CO	5.36	[illegible]	[illegible]	[illegible]
NO	[illegible]	57.6	[illegible] ✓	0.057
NO_2	[illegible]	7.5	6.2 ✓	[illegible]
Total NO_x [illegible]		[illegible]	[illegible] ✓	[illegible]
[illegible] Aldehydes [illegible]	[illegible]	0.78	[illegible]	[illegible]
CO_2	124,845	124,845	124,845 ✓	110.9

- From Table 3, p. 11, Overall average

for blue flame conditions:

CO = 8.1 ppm.

$$\frac{8.1 \text{ lbmole CO}}{10^6 \text{ lbmole FG}} \times \frac{1 \text{ lbmole}}{385 \text{ scf @ } 68°F} \times \frac{1040 \text{ scf @ } 68°F}{10^6 \text{ Btu}} \times \frac{100\%}{10\%} \times \frac{28 \text{ lb}}{\text{lbmole CO}}$$

$$= 5.105E\text{-}3 \frac{\text{lb}}{10^6 \text{ Btu}} \times \frac{1050 \text{ Btu}}{\text{scf}} = 5.36 \frac{\text{lb CO}}{10^6 \text{ scf}}$$

NO = 88.8 ppm

$$\frac{88.8}{10^6} \times \frac{1}{385} \times \frac{1040}{10^6} \times \frac{100}{10} \times 30$$

$$= 0.0600 \frac{\text{lb}}{10^6 \text{ Btu}} \times \frac{1050 \text{ Btu}}{\text{scf}} = \frac{63.0 \text{ lb NO}}{10^6 \text{ scf}}$$

NO_2 = 4.7 ppm

$$\frac{4.7}{10^6} \times \frac{1}{385} \times \frac{1040}{10^6} \times \frac{100}{10} \times 44$$

$$= 4.66E\text{-}3 \frac{\text{lb}}{10^6 \text{ Btu}} \times \frac{1050 \text{ Btu}}{\text{Scf}} = 4.9 \frac{\text{lb } NO_2}{10^6 \text{ scf}}$$

$HCHO = 0.18\ ppm$ (Aliphatic aldehydes)

$$\frac{0.18}{10^6} \times \frac{1}{385} \times \frac{1040}{10^6} \times \frac{100}{12} \times \frac{30\ lb}{lb\text{-}mole}$$

$$= 1.22E\text{-}4\ \frac{lb}{10^6 Btu} \times 1050\ \frac{Btu}{scf} = 0.128\ \frac{lb}{10^6 scf}$$

$CO_2 = 5.8\ \% = 58,000\ ppm$

$$\frac{58,000}{10^6} \times \frac{1}{385} \times \frac{1040}{10^6} \times \frac{100}{5.8} \times 44$$

$$= 118.9\ \frac{lb}{10^6 Btu} \times 1050\ \frac{Btu}{scf} = 124,845\ \frac{lb}{10^6 scf}$$

For Yellow Flame Condition

	For Yellow Flame Condition	Average Blue Flame Condition ($lb/10^6 scf$)
CO:	$\frac{[illegible]}{[illegible].1} \times 5.[illegible] = 127.6\ \frac{lb}{10^6 scf}$	→ 71.5
NO:	$\frac{72.6}{88.8} \times 63.0 = 52.2\ \frac{lb}{10^6 scf}$	57.6
N_2:	$\frac{9.7}{4.7} \times 4.9 = 10.1\ \frac{lb}{10^6 scf}$	7.5
HCHO:	$\frac{0.60}{0.18} \times 0.128 = 0.427\ \frac{lb}{10^6 scf}$	0.28