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A review of recent NOx test data was performed, and summaries of emission factors presented for various types of stationary source combustion and for various fossil fuels. The effects of combustion modifications on NOx emissions are quantified. Background data are given to help the user determine the reliability of each factor in particular applications.

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Publication No. EPA-450/4-79-021

TABLE OF CONTENTS

TABLE OF CONTENTS (Concluded)

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF TABLES (Concluded)

SECTION 1

INTRODUCTION

In order for EPA, states, and local agenices to compile reliable emission inventories of nitrogen oxides, it is important to have accurate and precise NO_x emission factors. The two major source categories responsible for the bulk of all manmade NO_x emissions are mobile sources and stationary source combustion. The Monitoring and Data Analysis Division (MDAD) of The Office of Air Quality Planning and Standards is responsible for determining the NO_x emission factors for the latter area. Hence, it is periodically necessary that MDAD critically review the existing emission factors for the major stationary sources of NO_x and update those factors for which newer and more comprehensive data exist.

To assist MDAD in this task, The Energy and Environmental Division of Acurex has compiled and reviewed the NO_x source test data that have been generated over the last several years on the major stationary combustion sources. This compilation includes external combustion of coals, oils and gas in boilers as well as internal combustion in reciprocating and turbine engines.

Stationary external combustion units are covered in the next three sections of this report. For the purposes of this report, they are broken into four categories:

- Utility boilers -- >29 MW (>100 x 10^6 Btu/hr) input
- Industrial boilers -- 2.9 to 29 MW (10 to 100 x 10^6 Btu/hr) input
- Commercial boilers -- 150 kW to 2.9 MW (5 x 10^5 to 10 x 10^6 Btu/yr) input
- Residential furnaces and boilers -- <150 kw (<5 x 10^5 Btu/yr) input

Within each size category, the boilers are further classified according to design and fuel. Section 2 is devoted to utility boilers alone. Section 3 covers industrial boilers and Section 4, commercial and residential units. In support of the NO_x emission factor tables, each section also contains population-NO_x emission histograms, percentage NO in NO_x and, for utility boilers, a section on state-of-the-art control techniques and their effectiveness.

The last two sections cover stationary reciprocating engines and turbines, respectively. The breakdown within each section is based on size, number of strokes per combustion cycle and fuel for reciprocating engines and size, type of cycle and fuel for turbines.

In assessing the data reviewed in this study, it was mandatory that the following information, in addition to that needed to calculate the NO_x emission factors, be known:

- The type of boiler or engine -- e.g., tangential, four stroke
- Boiler operating condition: "baseline"/state-of-the-art NO_x control techniques -- This was particularly important for utility sized boilers and turbines; all other sources had no NO_x control technique applied unless they were specifically operated under a control evaluation program.

This report is concerned with emissions at the "baseline," or as-found condition. Thus, baseline emissions are those measured generally in the absence of any NO_x control techniques. For utility and industrial boilers, baseline measurements were included if they were made at 60 to 110 percent load. All data reported without the type of boiler delineated were rejected; data reported on utility boilers, turbines, etc. with NO_x control techniques specified e.g., BOOS, FGR, water injection, etc. were included in the section on control effectiveness.

Table 1-1 includes thermal equivalents for fuels discussed in this report. Since the emission factor tables are expressed both in terms of lb/fuel unit and ng/J, these factors were used for conversions when the data was reported in only one set of units.

TABLE 1-1. CONVERSION FACTORS

To Obtain	From	Multiply By
ng/J	$lb/10^6$ Btu	430
ng/J NO_x (as NO_2)	NO_x ppm @ 3% O_2 dry	0.510 (natural gas)*
ng/J NO_x (as NO_2)	NO_x ppm @ 3% O_2 dry	0.561 (oil)*
ng/J NO_x (as NO_2)	NO_x ppm @ 3% O_2 dry	0.611 (coal)*
NO_x ppm @ 3% O_2 dry	NO_x ppm dry	$\left(\frac{17.9}{20.9 - \%\ O_2\ dry}\right)$

Thermal Equivalents*

Fuel	Heating Value (Gross)
Bituminous coal	10,000 - 14,000 Btu/lb* (used 12,000 Btu/lb)
Lignite coal	8,000 Btu/lb*
Residual oil	150,000 Btu/gal*
Distillate oil	140,500 Btu/gal*
Natural gas	1,050 Btu/ft^3

*These factors used only when data were otherwise insufficient.

Sources:

Maloney, K. L., et al., "systems Evaluation of the Use of Low-Sulfur Western Coal in Existing Small and Intermediate-Sized Boilers," KVB Inc., EPA-600/7-78-153a, July 1978.

U.S. Environmental Protection Agency, "Compilation of Air Pollutant Emission Factors," Third Edition, AP-42, August 1977.

SECTION 2

UTILITY BOILERS

For the purposes of this study, utility boilers are defined as field-erected watertube boilers with a heat input greater than 29 MW (100×10^6 Btu/hr) used for generation of electricity. This category includes the vast majority of field-erected boilers used for utility or industrial electric power generation via steam production. The major fuels fired are coal, oil, and natural gas. Within this definition, the utility boiler population is divided into nine major boiler types and further subdivided into seven fuel categories. Firing of subbituminous coal is included in the bituminous category.

2.1 NO_x EMISSION FACTORS FOR UTILITY BOILERS

Tables 2-1 and 2-2 contain the NO_x emission factors for utility boilers.* The first table is in English units and the emission factors are based on the amount of fuel consumed. The second table is in SI units and the emission factors are given as weight per energy unit released (ng/J).

A considerable body of data were collected for horizontally opposed units firing bituminous coal, oil and natural gas. These data were abstracted from several different sources (References 2-1, 2-2, 2-3, 2-4, 2-5, 2-6 and 2-7). Major differences between the new averages and the existing AP-42 values occur in the oil- and the bituminous coal-fired units. In the former, the NO_x average emission factor was 35 percent lower and in the latter 50 percent higher. Because of the number of data

*The factors reported in the tables as well as the text are in terms of NO_x emissions as NO_2 except as noted.

TABLE 2-1. NO_x EMISSION FACTORS SURVEY OF UTILITY BOILERS (ENGLISH UNITS)

Type Boiler	Baseline NO_x Emissions as a Function of Fuel[a]						
	Coal (lb/ton burned)			Oil (lb/10^3 Gal oil burned)		Gas (lb/10^6 SCF gas)	
	Anthracite	Bituminous	Lignite	Residual	Distillate	Natural	Process
Tangential		18[b] 14[c] (27[d]) -22%[e]	8 7 (2) -12%	50 42 (2) -16%		300 200 (3) -33%	
Horizontally Opposed		18 27 (8) +50%	14	105 68 (9) -35%		700 570 (10) -19%	
Single Wall		18 20 (11) +11%	14 13 (1) -7%	105 65 (36) -38%	-- 28 (3)	700 340 (39) -51%	-- 790 (8)
Vertical[b]	18	18	14	105		700	
Cyclone		55 36 (7) -35%	17 12 (3) -29%	105 87 (4) -17%		700 660 (2) -6%	
Wet Bottom[f]		30 48 (2) +60%	14				
Spreader Stoker		15 15 (8) 0%					
Overfeed Stoker		5.4 (2)					

[a]NO_x values reported in terms of NO_2 EE-T-118

[b]Old AP-42 value

[c]Recommended replacement number based on new or revised data base

[d]Number of boilers tested

[e]Percent change in emissions factor

[f]Includes one vertical and one horizontally-opposed unit

TABLE 2-2. NO_x EMISSION FACTORS SURVEY OF UTILITY BOILERS (SI UNITS)

Type Boiler	Baseline NO_x Emissions (ng/J) as a Function of Fuel[a]						
	Coal			Oil		Gas	
	Anthracite	Bituminous	Lignite	Residual	Distillate	Natural	Process
Tangential		320[b] 250[c] (27[d]) -22%[e]	215 190 (2) -12%	140 120 (2) -14%		120 80 (3) -33%	
Horizontally Opposed		320 480 (8) +50%	380	300 200 (9) -33%		290 230 (10) -21%	
Single Wall		320 360 (11) +12%	380 350 (1) -8%	300 190 (36) -37%	-- 86 (3)	290 140 (39) -52%	-- 320 (8)
Vertical[b]	310	320	380	300		290	
Cyclone		980 650 (7) -34%	460 320 (3) -30%	300 250 (4) -17%		290 270 (2) -7%	
Wet Bottom[f]		540 860 (2) +57%	380				
Spreader Stoker		270 270 (8) 0%					
Overfeed Stoker		100 (2)					

EE-T-119

[a] NO_x values reported in terms of NO_2

[b] Old AP-42 value

[c] Recommended replacement number based on new or revised data base

[d] Number of boilers tested

[e] Percent change in emissions factor

[f] Includes one vertical and one horizontally-opposed unit

points and the variety of sources, the new numbers appear to be more justifiable than the old.

Data were also obtained for tangential units firing bituminous coal (References 2-8, 2-1, 2-2, 2-9, 2-10, 2-11, 2-12, 2-13, and 2-14). The NO_x emission factor obtained from averaging these baseline test numbers was 22 percent less than the existing AP-42 value.

A considerable body of data were also obtained for single wall units firing bituminous coal (References 2-8, 2-2, 2-6, 2-11 through 2-17, 2-18, 2-19, 2-20, and 2-13), oil (References 2-1, 2-2 and 2-15), natural gas (References 2-1, 2-3, 2-4, 2-5 and 2-15) and process gas (Reference 2-16). All NO_x emission factors were less than those given in AP-42 except for bituminous coal which showed a slight increase. The decreases for the oil-fired units (38 percent) and the gas-fired units (51 percent) give values consistent with expected results when these units are compared with horizontally opposed units and single wall, large industrial boilers burning the same fuels. Consistent with the other average values obtained for single wall and horizontally opposed boilers, it is recommended that the average value for lignite-fired, single wall boilers be reduced from 14 lb/ton (380 ng/J) to 13 lb/ton (350 ng/J). The eight process gas-fired utility boilers show an average NO_x emission factor of 790 lb/10^6 scf (330 ng/J).

All of the cyclone boiler data came from a recent compilation of previous tests (Reference 2-21). These data show less NO_x emission than the initial AP-42 numbers in all fuel categories. In particular, NO_x emissions for bituminous coal-fired cyclone boilers were 34 percent less than the initial AP-42 value. The new data are probably more accurate as they are based on the average of seven different cyclone boilers. Some cyclone boilers may have been better classified as large industrial units but were included in the utility section to provide a better data base.

No new data were obtained for vertical units and only two new data points were obtained for wet bottom units. Both of these were in the bituminous coal category (References 2-8 and 2-1). These data suggest that wet bottom, coal-fired boilers should have their NO_x emission factors increased by some 60 percent. In comparison to cyclone units, the original wet bottom boiler NO_x emission data seem unusually low; the new data, especially in light of the recent cyclone boiler data, would seem more reasonable for such units.

The remaining category for which new information is now available is for spreader stoker units firing bituminous coal. New data on six units are included (References 2-15, 2-16, 2-22, 2-23, 2-24, and 2-25). The average NO_x emission value, 15 lb/ton (270 ng/J) is a good representative value for these units, agreeing well with the industrial boiler NO_x emission factor for the same category.

Although wet bottom boilers are not mutually exclusive from the other categories, in this report they are treated separately because of their very high NO_x emission rates.

2.2 HISTOGRAMS OF NO_x EMISSIONS FOR UTILITY BOILERS

Figures 2-1, 2-2, 2-3 and 2-4 are bar graphs of baseline NO_x emission factors versus number of units tested within each boiler type/fuel category. Figure 2-1 covers bituminous coal-, oil- and gas-fired horizontally opposed units; Figure 2-2 covers bituminous coal-, oil- and gas-fired single wall units. Figure 2-3 covers bituminous coal- and oil-fired cyclone units and Figure 2-4 covers bituminous coal-fired tangential units. Since there were only two data points for natural gas-fired cyclone units, no histogram was constructed. With few exceptions, the data fall quite close together considering the numbers of variables involved. Two boilers, one a gas-fired, single wall unit and the other an oil-fired, single wall unit, were too far from the average based on Chauvenet's criterion and, were excluded from the data presented in Tables 2-1 and 2-2.

The variation within each boiler and fuel category may be due to load (not all baselines were run at 80 percent load), air preheat, burner type, furnace dimensions, differences in fuel nitrogen, amount of excess air, errors in measurement, to name a few. Because of the number of variables, the data are presented to only two significant figures.

2.3 EFFECT OF CONTROLS ON NO_x EMISSIONS FOR UTILITY BOILERS

There are several NO_x control techniques currently in use with utility boilers. These include:

- Low Excess Air (LEA) -- The excess amount of combustion air supplied is reduced

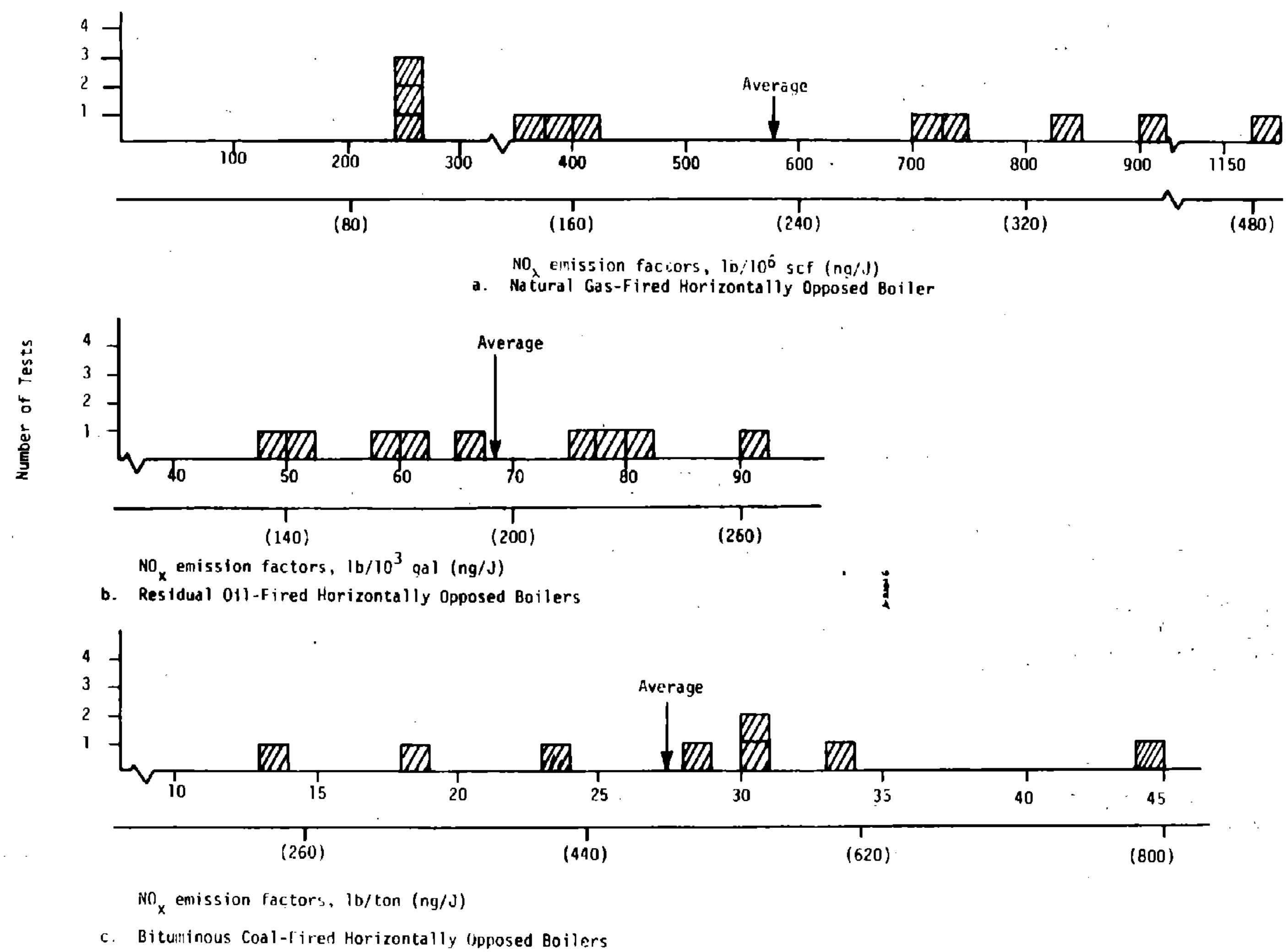
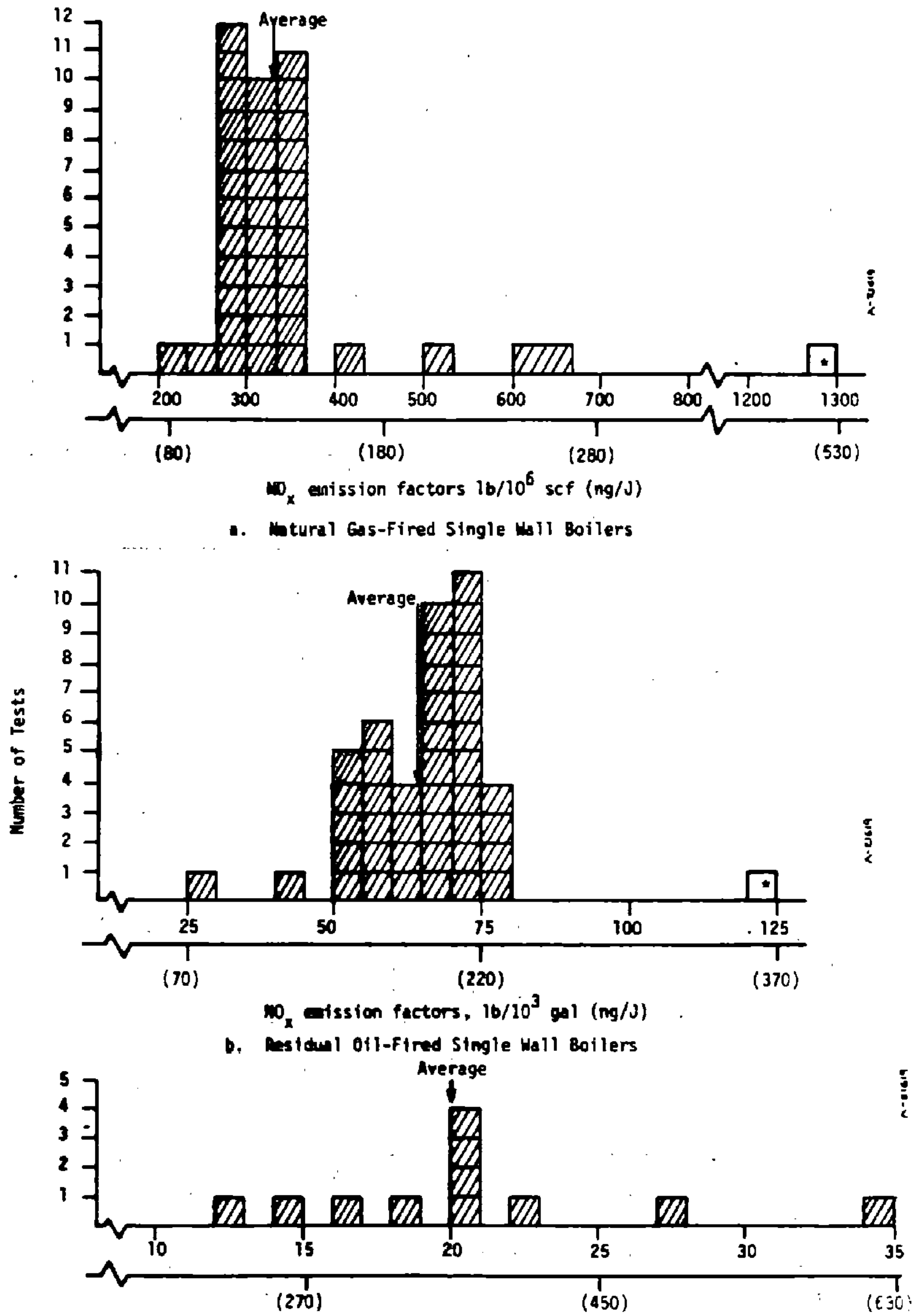


Figure 2-1. Population histograms of NO_x emission factors for horizontally opposed utility boilers.



a. Natural Gas-Fired Single Wall Boilers

b. Residual Oil-Fired Single Wall Boilers

c. Bituminous Coal-Fired Single Wall Boilers

*after a statistical analysis these tests were not considered representative of the boiler population, and therefore not included in the replacement emission factor.

Figure 2-2. Population histograms of NO_x emission factors for single wall utility boilers.

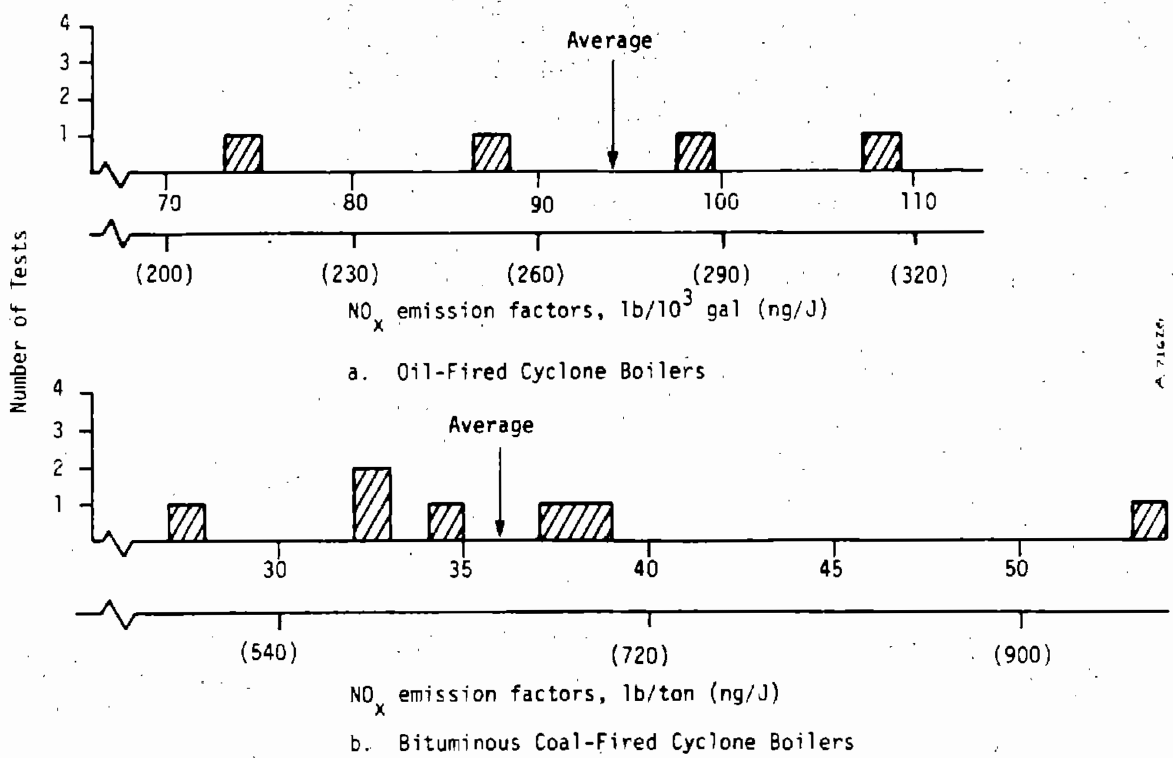


Figure 2-3. Population histograms of NO_x emission factors for cyclone utility boilers.

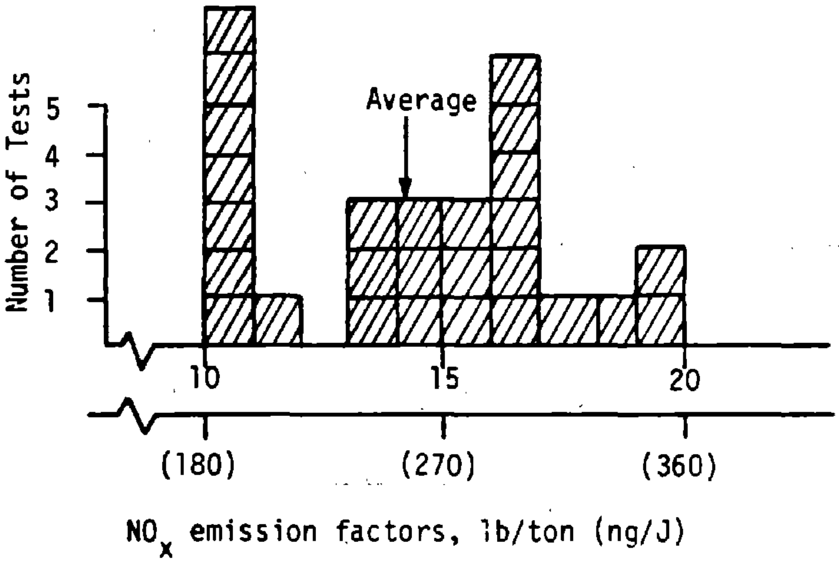


Figure 2-4. Population histograms of NO_x emission factors for bituminous coal-fired tangential utility boilers.

- Off-Stoichiometric Combustion (OSC) -- Some burners fire a fuel-rich mixture and combustion is completed by injection of additional air or lean mixture downstream
- Flue Gas Recirculation (FGR) -- A portion of the flue gas is recycled to the firebox
- Load Reduction (LR) -- The boiler is fired at less than capacity
- Combinations of two or more of the above
- Low NO_x Burner (LNB)

Much of the data on these controls have previously been analyzed by Acurex (Reference 2-26). In addition to this review, a section of the cyclone boiler report (Reference 2-21) considers the applicability of many NO_x control techniques to this boiler type. The Standards Support and Environmental Impact Statement report on lignite-fired boilers (Reference 2-27) also dwells on certain of the NO_x controls. Table 2-3 indicates the percent reduction one can expect by applying particular NO_x control techniques to each boiler/fuel category.

TABLE 2-3. AVERAGE PERCENT REDUCTION OF NO_x EMISSION FACTORS BY STATE-OF-THE-ART CONTROL TECHNIQUES FOR UTILITY BOILERS (ENGLISH UNITS)

T-1431

Type Boiler Control Techniques	NO_x Emissions (lb NO_2/unit fuel consumed) as a Function of Fuel							
	Coal				Residual Oil		Natural Gas	
	Bituminous		Lignite					
	NO_x (lb/ton)	% Reduction	NO_x (lb/ton)	% Reduction	NO_x (lb/10^3 gal)	% Reduction	NO_x (lb/10^6 SCF)	(% Reduction)
Tangential								
Baseline	15	--	8	--	50	--	300	--
LEA	12	20	6	20	[40]	[20]	210	30
OSC	9	40	5	38	[40]	[20]	300	0
FGR		*		*	[35]	[30]	120	60
LR	13	15	7	12	[45]	[10]	300	0
OSC + FGR		*		*	[20]	[60]	[90]	[70]
OSC + LR	8	45	4	45	[35]	[30]	[270]	[10]
OSC + LR + FGR		*		*	[35]	[30]	[60]	[70]
Horizontally Opposed								
Baseline	25	--	14	--	70	--	700	--
LEA	22	10	11	20	56	20	600	15
OSC	20	20	11	20	45	35	300	60
FGR	20	20	11	20	60	13	[350]	[60]
LR	22	10	13	10	50	30	300	60
OSC + FGR	15	40	[8]	[40]	56	20	[175]	[75]
OSC + LR	19	25	10	25	35	50	140	80
OSC + LR + FGR		*		*	28	60	100	85
LNB	15	40						

*Indicates that no data is available and technique may result in severe corrosion and/or slagging problems
[ ] Indicates engineering estimate

TABLE 2-3. Concluded

T-1431

Type Boiler Control Techniques	NO_x Emissions (lb NO_2/unit fuel consumed) as a Function of Fuel							
	Coals				Residual Oil		Natural Gas	
	Bituminous		Lignite					
	NO_x (lb/ton)	% Reduction	NO_x (lb/ton)	% Reduction	NO_x (lb/10^3 gal)	% Reduction	NO_x (lb/10^6 SCF)	(% Reduction)
Single Wall								
Baseline	19	--	[11]	--	50	--	410	--
LEA	16	15	[9]	[20]	38	25	350	15
OSC	13	30	[8]	[30]	30	40	210	50
FGR		*		*	[35]	[30]	270	35
LR	14	25	[8]	[25]	35	30	125	70
OSC + FGR		*		*	22	55	105	75
OSC + LR	10	45	[6]	[45]	28	45	80	80
LR + OSC + FGR		*		*	22	55	165	60
LNB	11	40						
Cyclone								
Baseline	36	--	13	--	87	--	660	--
LEA		*		*	78	10	[560]	[15]
OSC		*		*		*		*
FGR		*		*	[61]	[30]	330	50
LR	25	30	9	30	70	20	[330]	[50]
OSC + FGR		*		*		*		*
OSC + LR		*		*		*		*
OSC + LR + FGR		*		*		*		*

*Indicates that no data is available and technique may result in severe corrosion and/or slagging problems
[ ] Indicates engineering estimate

It should be noted that off-stoichiometric combustion (OSC), also known as two-staged combustion, can be accomplished by one of the following:

- Burners-Out-Of-Service (BOOS) -- Lower burners fire a fuel-rich mixture, while upper burners supply only combustion air
- Biased Burner Firing (BBF) -- Lower burners simply fire a richer fuel-air mixture than upper burners
- Overfire Air (OFA) -- All burners fire a richer mixture, then additional combustion air is supplied above the firebox

The first two are generally used in a retrofit situation while the last is principally a new boiler feature.

2.4 NITRIC OXIDE AS PERCENT CONSTITUENT OF TOTAL NO_x EMISSIONS

Some data, principally from KVB (Reference 2-10 and 2-11) and the cyclone boiler report (Reference 2-21) indicate that NO is the principal constituent of NO_x. Of the four boiler categories for which either NO or NO_2 were measured along with NO_x, NO constituted at least 95 percent of the NO_x emissions. These data are presented in Table 2-4.

TABLE 2-4. NITRIC OXIDE AS A CONSTITUENT OF TOTAL NO_x EMISSIONS OF UTILITY BOILERS

Type Boiler	NO/NO_x as a Function of Fuel[a]		
	Bituminous Coal	Residual Oil	Natural Gas
Single wall	96% (3)[b]	98% (1)	95% (2)
Cyclone	99% (6)		

[a]Weight percentage, NO reported as NO_2
[b]Numbers in parentheses refers to number of boilers tested.

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SECTION 3

INDUSTRIAL BOILERS

Industrial boilers, for the purposes of this study, are defined as coal-, oil-, or gas-fired steam generators with rated heat input capacities ranging from 2.9 to 29 MW (10 to 100 x 10^6 Btu/hr). These units are generally packaged boilers, including small, stoker, coal-fired units as well as oil (residual and distillate) or gas burning firetube and watertube boilers. As in Section 2, subbituminous coal is included in the bituminous category.

As with all general definitions, there are exceptions. In fact, nearly 14 percent of the industrial boiler population have input capacities greater than 73 MW and nearly 26 percent have input capacities smaller than 2.9 MW (Reference 3-1). For purposes of this report those industrial boilers which have rated heat input capacities greater then 29 MW were incorporated with the previous utility boiler review, and those of less than 2.9 MW were designated as residential-commercial types, Section 4.

3.1 NO_x EMISSION FACTORS FOR INDUSTRIAL BOILERS

Industrial boilers burning oil and natural gas have been divided into two boiler types, watertube and firetube. A considerable quantity of data -- much of it from the KVB reports -- were amassed for each category (Tables 3-1 and 3-2). As before, Table 3-1 is presented in English units and Table 3-2 contains the same data presented in SI units. Since existing AP-42 emission factors for natural gas combustion are expressed as a range, suggested replacement factors are expressed in the same manner. Besides these results, the data also include Ultrasystems data for a watertube and a firetube boiler tested with both natural gas and residual oil (References 3-2 and 3-3) and Battelle data for a watertube

TABLE 3-1. NO_x EMISSION FACTORS SURVEY OF INDUSTRIAL BOILERS (10 to 100 x 10^6 Btu/hr) (ENGLISH UNITS)

Type Boiler	Baseline NO_x Emissions as a Function of Fuel[a]					
	Coal (lb/ton burned)			Oil (lb/10^3 gal)		Natural Gas (lb/10^6 SCF)
	Anthracite	Bituminous	Lignite	Residual	Distillate	
Watertube				60[b] 60[c] (14)[d] 0%[g]	22 19 (5) -14%	120-230 150 (13) 70-310[e]
Firetube				60 37 (6) -38%	22 21 (7) -4%	120-230 110 (9) 65-150
Spreader Stoker[f]		15 14 (3) 7%	6.0 9 [h]			
Underfeed Stoker[f]		15 9.5 (4) -37%	6.0			
Overfeed Stoker[f]	16	15 7.8 (3) -50%	6.0			

EE-T-120

[a] NO_x values reported in terms of NO_2
[b] Old AP-42 value
[c] Recommended replacement number based on new or revised data base
[d] Number of boilers tested
[e] Range found for boilers tested
[f] Stokers may be of either watertube or firetube construction
[g] Percent change in emission factor
[h] [ ] Engineering estimate

TABLE 3-2. NO_x EMISSION FACTORS SURVEY OF INDUSTRIAL BOILERS (2.9 to 29 MW) (SI UNITS)

Type Boiler	Baseline NO_x Emissions (ng/J) as a Function of Fuel[a]					
	Coal			Oil		Natural Gas
	Anthracite	Bituminous	Lignite	Residual	Distillate	
Watertube				170[b] 170[c] (14)[d] -6%[g]	67 58 (5) -18%	49-94 60 (13) 30-130[e]
Firetube				170 110 (6) -35%	67 64 (7) -3%	49-94 45 (9) 28-60
Spreader Stoker[f]		270 250 (3) 7%	160 240 h			
Underfeed Stoker[f]		270 170 (4) -37%	160			
Overfeed Stoker[f]	270	270 140 (3) -50%	160			

EE-T-121

[a]NO_x values reported in terms of NO_2

[b]Old AP-42 value

[c]Recommended replacement number based on new or revised data base

[d]Number of boilers tested

[e]Range found for boilers tested

[f]Stokers may be of either watertube or firetube construction

[g]Percent change in emission factor

[h][ ] Engineering estimate

and firetube boiler tested with natural gas, distillate oil and residual oil (Reference 3-4).

Coal-fired industrial boilers are generally of the stoker design. Pulverized coal units are limited to 29 MW (100×10^6 Btu/hr) as a minimum size because of efficiency considerations (Reference 3-5). The KVB data contain two spreader stokers, four underfeed stokers and one overfeed stoker. A third spreader stoker and two overfeed units were tested by Rockwell (Reference 3-6). These data for spreader stokers are consistent with utility boilers of the same category. The averages for the underfeed and overfeed units appear reasonable. Based on the bituminous coal NO_x emission factors for both spreader and underfeed stokers, a value of 9 lb/ton (240 ng/J) is suggested rather than the 6 lb/ton (160 ng/J) currently employed. The underfeed stoker lignite value, however, should be retained. Also there are not enough data for lignite coal-fired spreader stokers to improve on the existing overfeed stoker NO_x emission value for lignite.

3.2 HISTOGRAMS OF NO_x EMISSIONS FOR INDUSTRIAL BOILERS

Figure 3-1 shows bar graphs of baseline emission values versus class of boiler for those classes in which more than two NO_x emission numbers were gathered. The variation within each boiler and fuel category may be due to load (not all baselines were run at 80 percent load), air preheat, burner type, furnace dimensions, differences in fuel nitrogen, amount of excess air, errors in measurement, to name a few. Because of the number of variables, the data are presented to only two significant figures. All baseline data found were included.

3.3 NITRIC OXIDE AS PERCENT CONSTITUENT OF TOTAL NO_x EMISSIONS

The total nitrogen oxides (NO_x) emissions consist primarily of two components: Nitrogen dioxide (NO_2) and nitric oxide. Thus, if the concentration of two are known, the third can be determined to some degree of accuracy.

KVB determined NO and NO_x on almost all boilers tested during its two field investigations. Table 3-3 contains this data reduced to percent NO in NO_x. As can be seen, the average percent NO in NO_x is at least 94. The ratio of NO to NO_x does not seem to be affected by fuel type or boiler type or size.

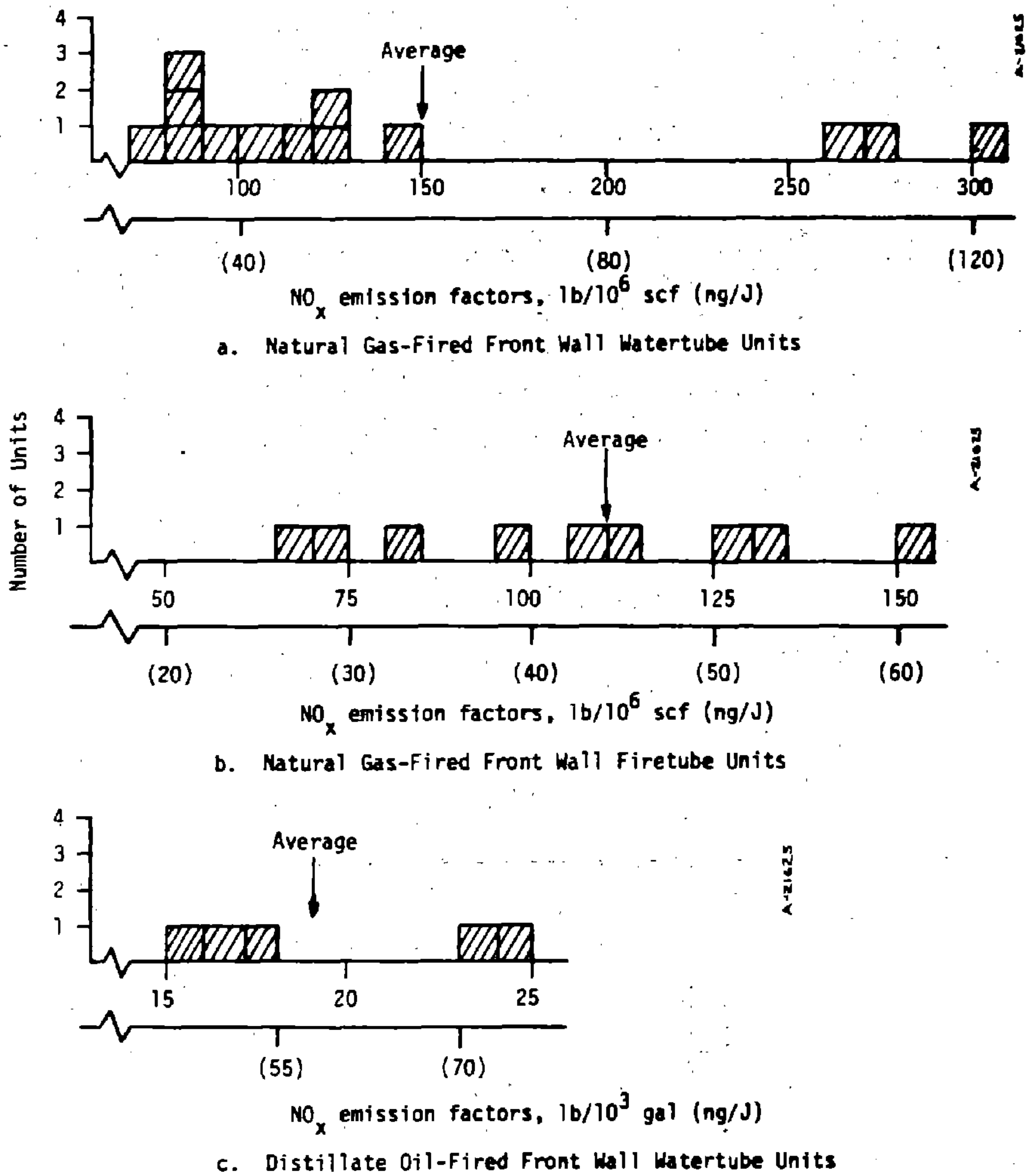
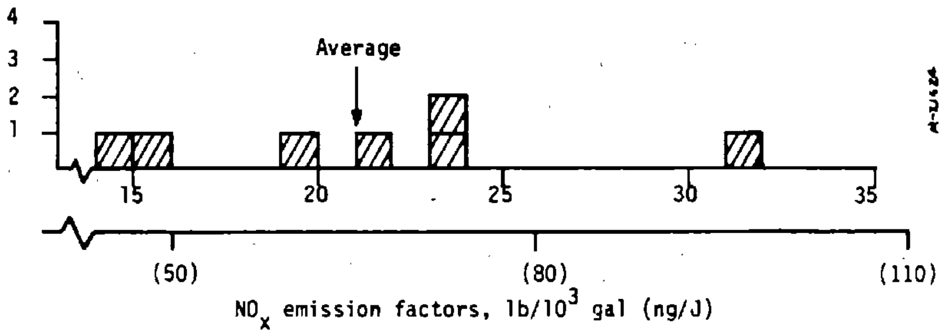
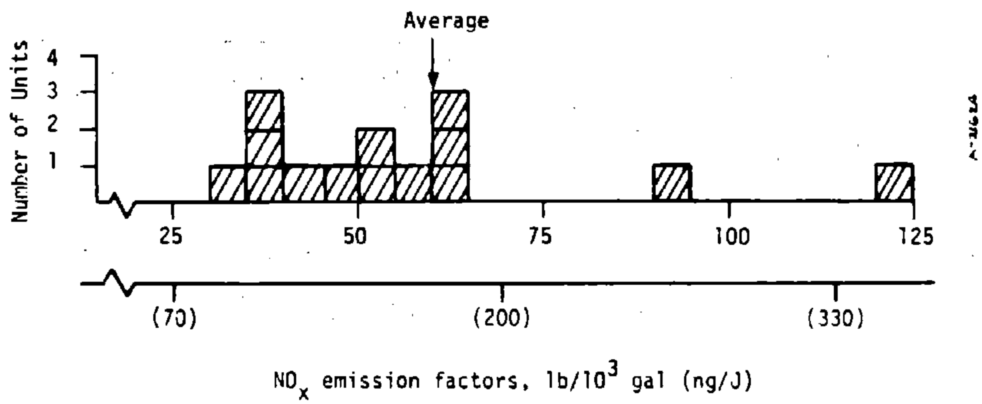


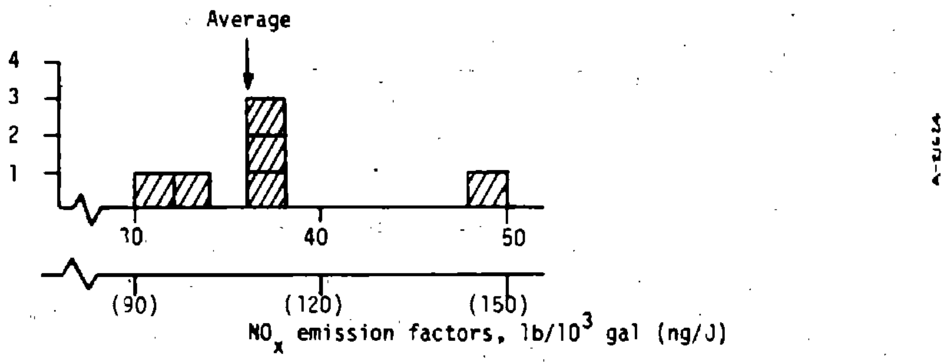
Figure 3-1. Population histograms of NO_x emission factors for industrial boilers.



d. Distillate Oil-Fired Front Wall Firetube Units

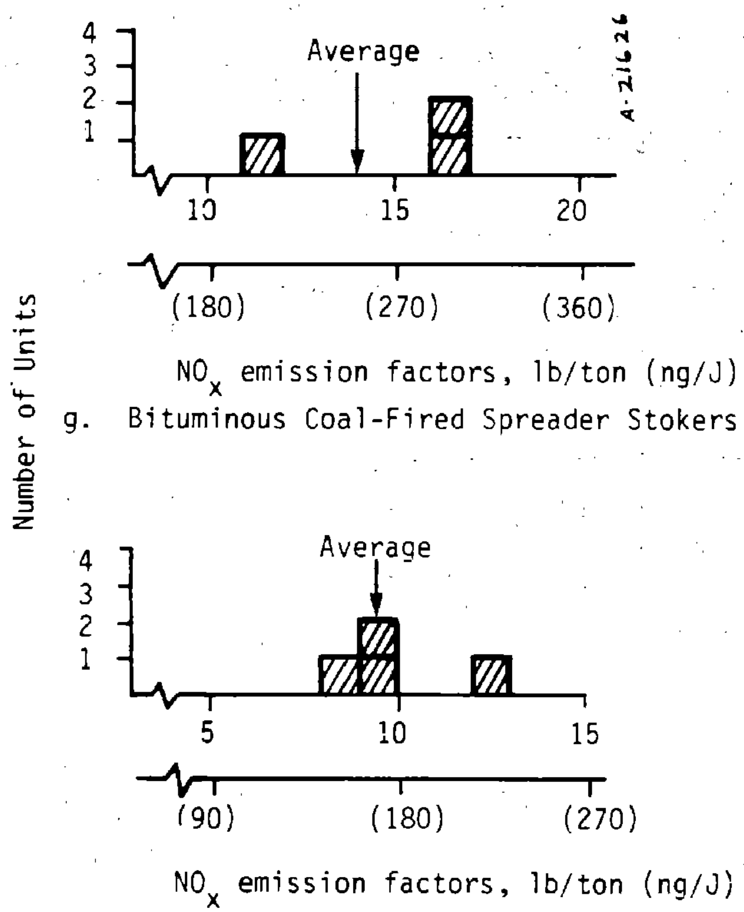


e. Residual Oil-Fired Front Wall Watertube Units



f. Residual Oil-Fired Front Wall Firetube Units

Figure 3-1. Continued.



g. Bituminous Coal-Fired Spreader Stokers

h. Bituminous Coal-Fired Underfeed Stokers

Figure 3-1. Concluded.

TABLE 3-3. NITRIC OXIDE AS A CONSTITUENT OF TOTAL NO_x EMISSIONS OF INDUSTRIAL BOILERS

Type Boiler	NO/NO_x as a Function of Fuel[a]			
	Bituminous Coal	Residual Oil	Distillate Oil	Natural Gas
Watertube		99% (12)[a]	97% (3)	95% (8)
Firetube		98% (4)	95% (5)	94% (9)
Spreader Stoker	98% (2)			
Underfeed Stoker	98% (4)			

[a]Weight percentage, NO reported as NO_2
[b]Numbers in parentheses refers to number of boilers tested

3.4 EFFECT OF CONTROLS ON NO_x EMISSIONS FOR INDUSTRIAL BOILERS

No long term testing of state-of-the-art NO_x emission controls has yet been undertaken for industrial boilers. Because of this, it is difficult to say whether the NO_x control techniques developed for utility boilers will be equally effective for industrial boilers. Short term tests by KVB and others do indicate, however, that combustion modification control techniques are effective in reducing NO_x (References 3-7, 3-8, 3-2 and 3-3). It is not yet recommended that these limited controlled emissions data be published in AP-42.

3.5 OTHER DATA

One data source for coal-fired boilers which met the requirements for inclusion in the survey was that of Ferrari (3-9). However, the data are presented separately for two reasons:

- The source of the data is Australia and, although the boilers may be basically the same, some may be different in design.
- Where the data overlaps the data in this study; they are quite different and generally do not follow the expected trend with unit size.

Table 3-4 lists Ferrari's values and compares them with averages for all of the boiler types for which the design is specified. Ferrari also reported on pulverized coal units but failed to indicate the type of units tested. However, his results for pulverized coal are considerably lower than the averages for tangential, single wall and horizontally opposed boilers in the utility category.

TABLE 3-4. COMPARISON OF DATA FROM FERRARI et al. WITH CALCULATED AVERAGES FOR SAME BOILER TYPE AND SIZE

Type Unit	NO_x emission factors (ng/J) as function of boiler size	
	Utility	Industrial
Chain Grate Stokers (overfeed)	141 (4)[a]	187 (2)[b]
	--	110[c] (3)
Spreader Stokers	166	192 (2)
	260 (5)	250 (3)

[a]Top row Ferrari's values.

[b]Numbers in parentheses refer to number of boilers tested.

[c]Bottom row, NO_x emissions update averages.

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SECTION 4

COMMERCIAL AND RESIDENTIAL UNITS

This section not only covers all stationary steam generating sources whose rated heat input capacity is less than 2.9 MW ($<10 \times 10^6$ Btu/hr) but also residential hot water, steam and forced air heaters. The arbitrary dividing line between commercial and residential units is set at 150 kW (5×10^5 Btu/hr). As noted previously in the introduction to industrial boilers, nearly 26 percent of the boilers used in industry have input capacities less than 2.9 MW. Thus, some commercial boiler data were obtained from industrial boiler reports.

4.1 NO_x EMISSION FACTORS FOR COMMERCIAL SIZED BOILERS

Commercial boilers fall into three categories: stoker fed coal-fired, hand fed coal-fired, and oil- or gas-fired units generally of a firetube design. Many are used as a source of hot water rather than a source of steam or electricity. Tables 4-1 and 4-2 contain information on those units whose NO_x emissions have been measured.

The initial KVB boiler survey (Reference 4-1) contains data on two firetube boilers with heat input capacities of 2.1 MW (7×10^6 Btu/hr) and 2.4 MW (8×10^6 Btu/hr). One of these units was run with two grades of residual oil, distillate oil and natural gas. The other was run with natural gas only. The oil data have previously been incorporated into AP-42, supplement 6 (Reference 4-2). The natural gas data are 22 percent lower than the existing AP-42 number which is composed solely of the results from seven boilers tested by Battelle (References 4-3 and 4-10). However, two of these Battelle units were industrial size and the data have been recalculated to reflect this. Thus, the new value is the arithmetic average of the remaining five units plus the two KVB results.

TABLE 4-1. NO_x EMISSION FACTORS SURVEY OF COMMERCIAL STATIONARY STEAM AND HOT WATER GENERATING UNITS (0.5 to 10 x 10^6 Btu/hr) (ENGLISH UNITS)

Type Boiler	Baseline NO_x Emissions as a Function of Fuel[a]					
	Coal (lb/ton)			Oil (lb/10^3 gal)		Natural Gas (lb/10^6 SCF)
	Anthracite	Bituminous	Lignite	Residual	Distillate	
Firetube				60[b] 61[c] (8)[d] 2[e]	22 19 (7) -14%	120 92 (7) -22%
Commercial Stokers	2.2-3.2[f] (1)	6.0	6.0			
Commercial Hand-Fired Units	3	3.0				

[a] NO_x values reported in terms of NO_2

[b] Old AP-42 value

[c] Recommended replacement number based on new or revised data base

[d] Number of boilers tested

[e] Percent change in emissions factor

[f] Range as reported in literature, best available information (Reference 4-5)

TABLE 4-2. NO_x EMISSION FACTORS SURVEY OF COMMERCIAL STATIONARY STEAM AND HOT WATER GENERATING UNITS (0.15 to 2.9 MW) (SI UNITS)

Type Boiler	Basline NO_x Emissions (ng/J) as Function of Fuel[a]					
	Coal			Oil		Natural Gas
	Anthracite	Bituminous	Lignite	Residual	Distillate	
Firetube				172[b] 180[c] (8)[d] 2[e]	67 58 (7) -15%	49 38 (7) -22%
Commercial Stokers	37-55(1)[f]	110	160			
Commercial Hand-Fired Units	51	54				

EE-T-119

[a]NO_x values reported in terms of NO_2
[b]Old AP-42 value
[c]Recommended replacement number based on new or revised data base
[d]Number of boilers tested
[e]Percent change in emissions factor
[f]Range as reported in literature, best available information (Reference 4-5)

Battelle (Reference 4-3) has also tested a 200 kW commercial boiler fitted with both bituminous and anthracite stokers. This unit was operated at extremely low loads for most of the test sequences in an attempt to achieve smokeless results. The NO_x emission factors reported here for anthracite were run at 74 percent load and the bituminous at 49 percent load. Because of the low load and large excess air conditions, incorporation of the bituminous coal data in AP-42 is not recommended and have not been included in the reported average.

4.2 NO_x EMISSION FACTORS FOR RESIDENTIAL FURNACES AND BOILERS

Residential units fall into the same broad categories as the commercial boilers, above. NO_x emission data for residential units are contained in Tables 4-3 and 4-4, in English units and SI units, respectively.

Monsanto (Reference 4-6) has recently published information on a 200,000 Btu/hr furnace and a 200,000 Btu/hr boiler. Both units are supplied by underfeed stokers and fired with western subbituminous coal. Average baseline NO_x for the two units is 8.5 lb/ton (152 ng/J). The NO_x emission factors were approximately twice as great for the furnace as for the boiler using the same coal. This suggests that design features may play an important part in NO_x emission factors for these units.

Several recent sources of data on NO_x emissions for natural gas-fired residential units have been abstracted (References 4-7, 4-8, and 4-9). The most extensive results, conducted by The American Gas Association (AGA) Laboratories (Reference 4-7) cover 38 gas-fired, forced air furnaces manufactured by 29 different companies with heat input rates ranging from 75×10^3 to 180×10^3 Btu/hr. The average NO_x emission factors for these units are 103 lb $NO_2/10^6$ scf (42.1 ng NO_2/J) and they ranged from 18.8 to 128.1 lb $NO_2/10^6$ scf (7.7 to 52.5 ng NO_2/J). The lowest number was considered outside of acceptable limits and was discarded for the final average. The data for the blue flame, high O_2 condition, were considered as baseline. A second, low excess air (yellow flame adjustment) testing sequence showed an average 10 percent decrease in NO_x emissions for this control technique.

Hall (Reference 4-8) reports on the testing of two gas-fired furnaces and one gas-fired boiler. In these tests NO measurements averaged 60.5 lb $NO/10^6$ scf (24.8 ng NO/J). If one assumes that at

TABLE 4-3. NO_x EMISSION FACTORS SURVEY OF RESIDENTIAL STEAM AND HOT WATER GENERATING UNITS (<500,000 Btu/hr) (ENGLISH UNITS)

Type Boiler	Baseline NO_x Emissions as a Function of Fuel[a]					
	Coal (lb/ton)			Oil (lb/10^3 gal)		Natural Gas (lb/10^6 SCF)
	Anthracite	Bituminous	Lignite	Residual	Distillate	
Residential Heating					18	80[b] 102[c] (44)[d] +28%[e]
Stoker Units	6.0 8.5 (2) 42%	6.0				
Hand-Fired Units	3.0[b]					

EE-T-122

[a]NO_x values reported in terms of NO_2

[b]Old AP-42 value

[c]Recommended replacement number based on new or revised data base

[d]Number of boilers tested

[e]Percent change in emissions factor

TABLE 4-4. NO_x EMISSION FACTORS SURVEY OF RESIDENTIAL (<0.15 MW) STEAM AND HOT WATER GENERATING UNITS (SI UNITS)

Type Boiler	Baseline NO_x Emissions (ng/J) as a Function of Fuel[a]				
	Coal		Oil		Natural Gas
	Bituminous	Lignite	Residual	Distillate	
Residential Heating				55[b]	33[b] 42[c] (44)[d] +28%[e]
Stoker Units	107 152 (2) 42%	160			
Hand-Fired Units	54[b]				

[a] NO_x values reported in terms of NO_2

[b] Old AP-42 value

[c] Recommended replacement number based on new or revised data base

[d] Number of boilers tested

[e] Percent change in emissions factor

least 90 percent of NO_x is NO then the NO_x concentration (measured in terms of NO_2) is 102 lb $NO_2/10^6$ scf (41.8 ng NO_2/J). The units tested by Hall were "as is." Those by the AGA were tuned (blue flame). In both cases, the tests were considered baseline. Similar lack of effects of boiler tuning on NO_x emissions were shown by KVB for industrial boilers (Reference 4-10).

Finally, Rocketdyne (Reference 4-9), prior to testing various modifications on the unit, procured and tested a Lennox 011-140 warm air furnace equipped with a stock Lennox Burner. A baseline run on the unit gave 98 lb $NO/10^6$ scf (40 ng NO/J). This is equivalent to 167 lb $NO_2/10^6$ scf (68 ng NO_2/J) of NO_x measured as NO_2 if the NO as measured previously accounted for 90 percent of the NO_x.

Summation of these 41 individual boilers with the two units previously averaged in AP-42 Supplement 3 (Reference 4-11) gave 102 lb $NO_2/10^6$ scf (42.0 ng/J) as the overall average.

4.3 NO_x EMISSION FACTORS FOR PILOT LIGHTS

Most residential, gas-fired waterheaters and forced air furnaces contain pilot burners. Fuel input ranged from 828 to 1570 Btu/hr for the seven pilot lights examined by the AGA (Reference 4-7). The average NO_x emission factor for these pilots is 71.3 lb/10^6 scf (29.2 ng/J), roughly 75 percent of that for the burners.

4.4 HISTOGRAMS OF NO_x EMISSIONS FOR COMMERCIAL AND RESIDENTIAL UNITS

Population NO_x emission histograms are drawn for gas-fired commercial boilers, residential heating units and pilot lights. These histograms are shown in Figure 4-1. All data are within acceptable limits except the 7.7 ng/J residential unit reported by Thrasher and Dewerth (Reference 4-7).

4.5 NITRIC OXIDE AS PERCENT CONSTITUTENT OF TOTAL NO_x EMISSIONS

Much of the data reviewed was reported in terms of either NO and NO_2 or NO and NO_x. These data are presented in Table 4-5. A trend in the data seems to indicate that the smaller the source, the greater the fraction of NO in the NO_x emissions. The pilot light data and 38 data points for gas-fired residential units were reported by the American Gas Association Report (Reference 4-7). The remaining NO/NO_2 data were taken from two older Battelle documents (Reference 4-3 and 4-4). Data for commercial units were reported by Battelle (Reference 4-3) and KVB (Reference 4-1).

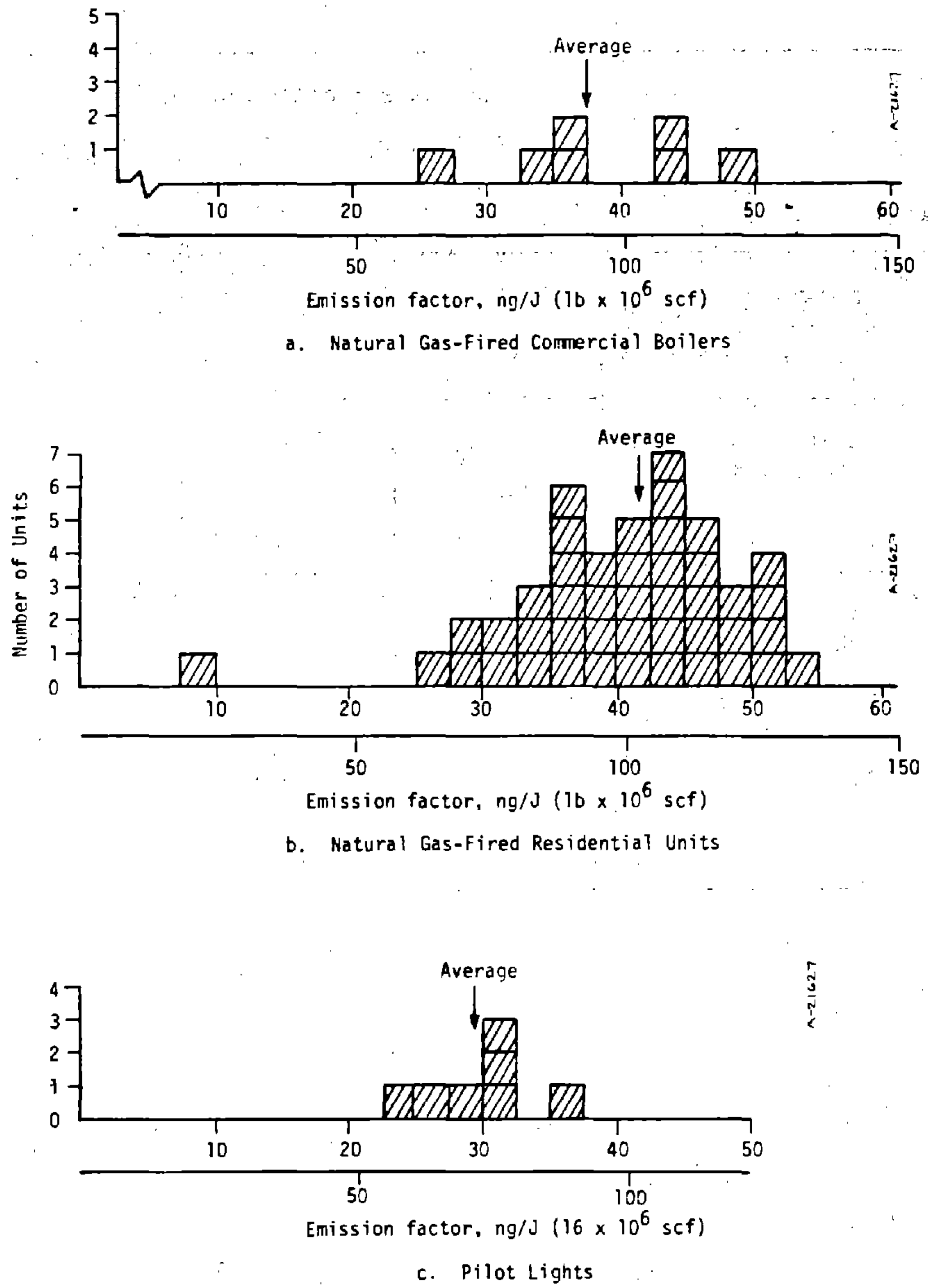

Figure 4-1. Population histograms of NO_x emission factors for natural gas-fired commercial boilers, residential units, and pilot lights.

TABLE 4-5. NITRIC OXIDE AS A CONSTITUENT OF TOTAL NO_x EMISSIONS OF COMMERCIAL AND RESIDENTIAL BOILERS AND HEATING UNITS AND PILOT LIGHTS

Type Boiler	NO/NO_x as a Function of Fuel[a]		
	Natural Gas	Distillate Oil	Residual Oil
Commercial 0.5 to 10 x 10^6 Btu/hr	97 (8)[b]	99 (7)	99 (7)
Residential 2 to 500 x 10^3 Btu/hr	As found 79 (2) Tuned 95 (38)	75 (32)	
Pilot Light <2000 Btu/hr	55 (7)		

[a]Weight percentage, NO reported as NO_2

[b]Numbers in parentheses refers to number of boilers tested.

REFERENCES FOR SECTION 4

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SECTION 5

STATIONARY RECIPROCATING ENGINES

Reciprocating engines consist of two major subclasses, compression ignition (CI) and spark ignition (SI). Each subclass is divided into two-stroke and four-stroke engine cycle categories (Reference 5-1). Further division by engine use has also been customary (Reference 5-2 and 5-3); however, because engine type and size are constantly changing within each use category, the substitution of rated power output is recommended.

5.1 NO_x EMISSION FACTORS FOR COMPRESSION IGNITION ENGINES

These engines are divided into three power output categories; large (>75 kW/cyl), medium (75 kW/cyl to 75 kW/engine), and small (<75 kW/engine). Further division is by fuel type and by engine cycle. Two fuel types are characteristic of compression ignition engines; diesel engines, burning diesel oil fuel, and dual fuel engines, burning a mixture of diesel oil and gas (natural and synthetic) consisting of anywhere from >95:5 to <5:95 parts by weight of the two fuels. Some dual fuel engines also have the capability of burning each fuel separately.

Table 5-1 gives the emission factors in 3 different units. To convert from output specific units, e.g., gm/hp-hr, to input specific units, e.g., ng/J and Kg/10^3 liter or lb/10^3 gal, heat rates for compression ignition engines were estimated. These are presented in Table 5-2.

The nitrogen oxides emissions factors for large and medium CI engines were reported in the Standards Support Document (Reference 5-1) and Hare and Springer (Reference 5-4). NO_x emission factors for small engines were found in Marshall and Fleming (Reference 5-5) in addition to Hare and Springer.

TABLE 5-1. BASELINE NO_x EMISSION FACTORS SURVEY OF RECIPROCATING COMPRESSION IGNITION (CI) ENGINES

Engine Size	Units	NO_x Emissions as a Function of Stroke and Fuel[a]			
		Diesel oil		Dual Fuel	
		2 Stroke	4 Stroke	2 Stroke	4 Stroke
arge 75 kW/cyl.	ng/J[b] g/hp-hr lb/10^3 gal[b] No. Engines	1800 13.3 600 (14)	1200 8.8 400 (19)	1520 10.4 --[c] (3)	1260 8.6 --[c] (6)
edium 75 kW/eng. 75 kW/cyl.	ng/J[b] g/hp-hr lb/10^3 gal[b] No. Engines	1980 16.1 660 (23)	1100 9.0 360 (66)		
mall 75 kW/eng.	ng/J[b] g/hp-hr lb/10^3 gal[b] No. Engines	-- -- -- --	1300 10.5 430 (15)		

NO_x values reported in terms of NO_2

Input Specific

Constituent ratio of dual fuel unknown

TABLE 5-2. HEAT RATES FOR COMPRESSION IGNITION ENGINES

Engine Size	Fuel	Heat Rate (Btu/hp-hr)
Large	Diesel	7000 (Reference 5-1)
	Dual	6500 (Reference 5-1)
Medium and Small	Diesel	7680 (Reference 5-3)

AP-42, Supplement 4 previously lists Hare and Springer data without differentiation as to size or number of strokes per firing cycle.

5.2 NO_x EMISSION FACTORS FOR SPARK IGNITION ENGINES

Spark ignition (SI) engines are divided into four categories of power output; large (>75 kW/cyl), medium (75 kW/cyl to 75 kW/engine), small (15-75 kW/engine) and very small (<15 kW/engine). Like compression ignition engines, these engines are further divided by engine cycle and fuel type. The principal fuels for spark ignition engines are gasoline and natural gas. Table 5-3 contains the average NO_x emissions factors for these engines.

A substantial body of data was acquired for natural gas-fired large and medium sized, stationary, spark ignited (SI) engines (References 5-1, 5-6, 5-7, and 5-8). The current emission factors are 20 percent higher for two-stroke engines and 40 percent higher for four-stroke engines than those in AP-42, which are based on Urban and Springer and Dietzman and Springer alone (Reference 5-6 and 5-7). The best data available were considered to be that of Dietzman and Springer which were repeated in Urban and Springer. These were used in the averages in Table 5-3. These data agreed well with that abstracted from References 5-1 and 5-6.

Data for gasoline fired SI engines were obtained for all categories except large engines (References 5-4, 5-9, 5-10, and 5-11). Numbers for the small and very small engine categories are from Hare and Springer (Reference 5-4). They have previously been abstracted into AP-42 under "industrial equipment", Section 3.3.3, and "small, general utility engines", Section 3.2.5. There are no additional data in these categories, but a minor adjustment was necessary. The values reported

TABLE 5-3. BASELINE NO_x EMISSION FACTORS SURVEY OF RECIPROCATING SPARK IGNITION (SI) ENGINES

Engine Size	Units	NO_x Emissions as a Function of Stroke and Fuel[a]		
		Gasoline	Natural Gas	
		4 Stroke	2 Stroke	4 Stroke
Large >75 kW/cyl.	ng/J[b] g/hp-hr lb/10^3 gal[b] lb/10^b SCF[b] No. Engines		1660 13.2 -- 4000 55	1960 15.5 -- 4800 24
Medium 75 kW/eng. -75 kW/cyl.	ng/J[b] g/hp-hr lb/10^3 gal[b] lb/10^b SCF[b] No. Engines	740 10.8 260 -- 9		1600 12.7 -- 3900 23
Small 15-75 kW/eng.	ng/J[b] g/hp-hr lb/10^3 gal[b] No. Engines	310 5.4 110 3		
Very Small <15 kW/eng.	ng/J[b] g/hp-hr lb/10^3 gal[b] No. Engines	198 5.0 69 5		

[a] NO_x values reported in terms of NO_2

[b] Input specific values, all others are output specific

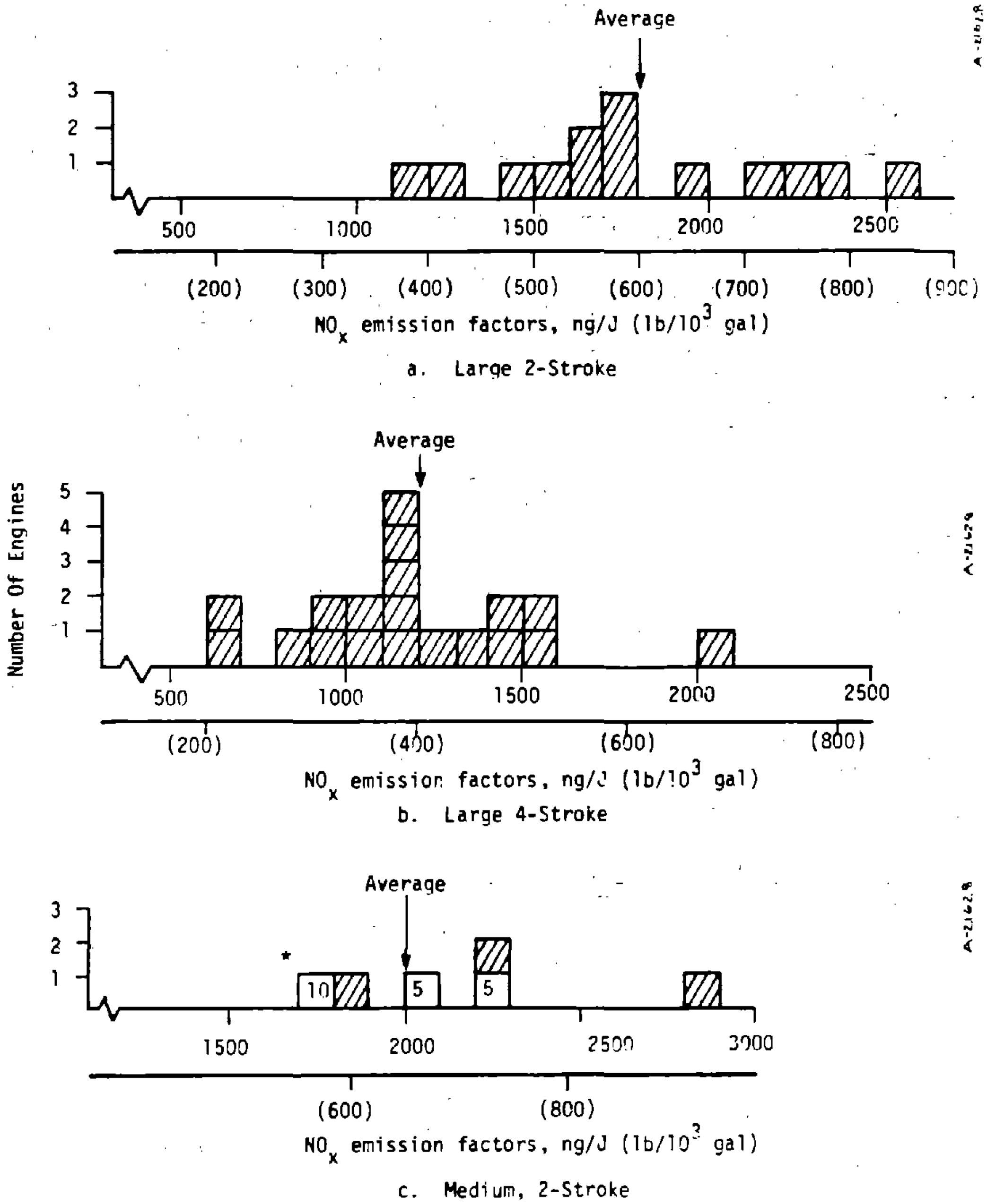
herein are computed on an evenly weighted average and one engine that was not tested at baseline was deleted.

5.3 HISTOGRAMS OF NO_x EMISSIONS FOR RECIPROCATING ENGINES

Population versus NO_x emission factor histograms were drawn for all of the categories of SI and CI engines for which data were obtained. They appear in Figure 5-1 through 5-4. Two of the histograms contain blocks with numbers superimposed on them. These blocks represent averages of a particular number of engines as reported in the literature; values for the individivual tests were not given. Abscissae of these plots are marked in both English and SI units where possible.

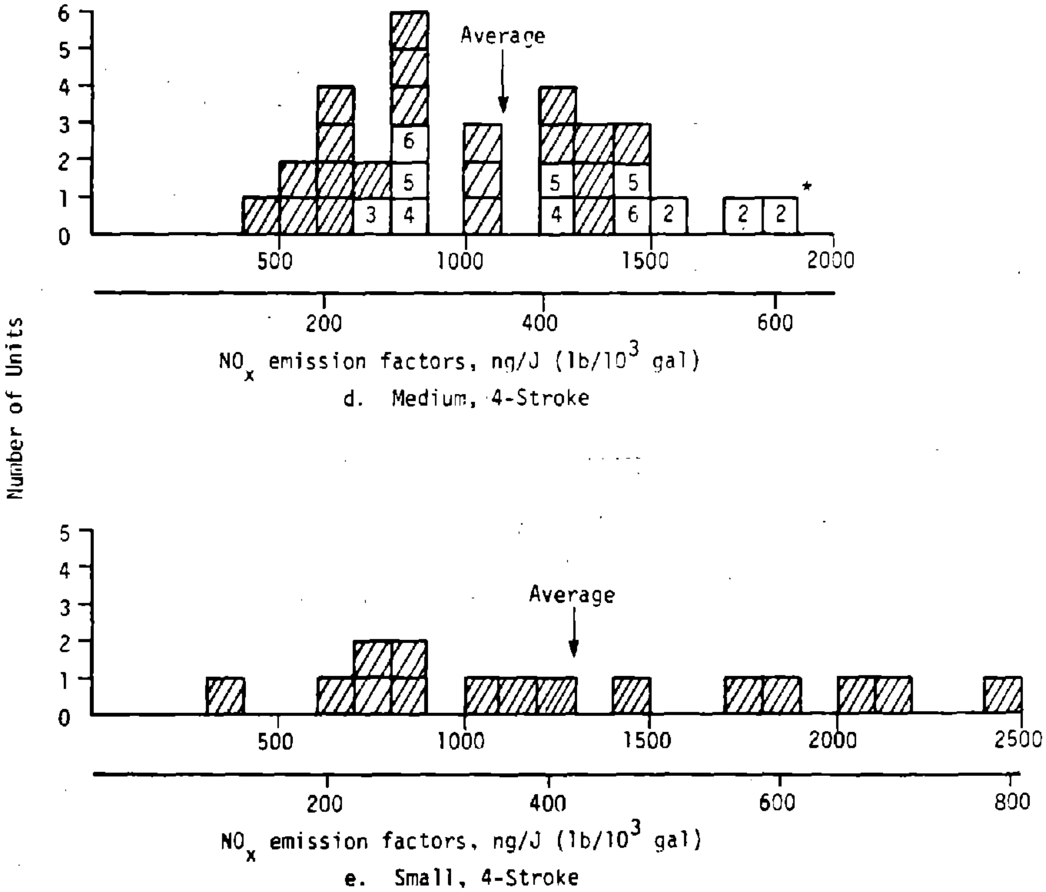
5.4 NITRIC OXIDE AS PERCENT CONSTITUTENT OF TOTAL NO_x EMISSIONS

Data for percent NO in total NO_x were taken from Hare and Springer, Dewerth, and Dietzman and Springer (References 5-4, 5-6, and 5-8). It is presented by engine subclass and category in Table 5-4.



*Numbers in blocks indicate averages of this number of engines as reported in the literature. Shaded blocks indicate individual engines.

Figure 5-1. Population histograms of NO_x emission factors for compression ignition engines firing diesel fuel.



*Numbers in blocks indicate averages of this number of engines as reported in the literature. Shaded blocks indicate individual engines.

Figure 5-1. Concluded.

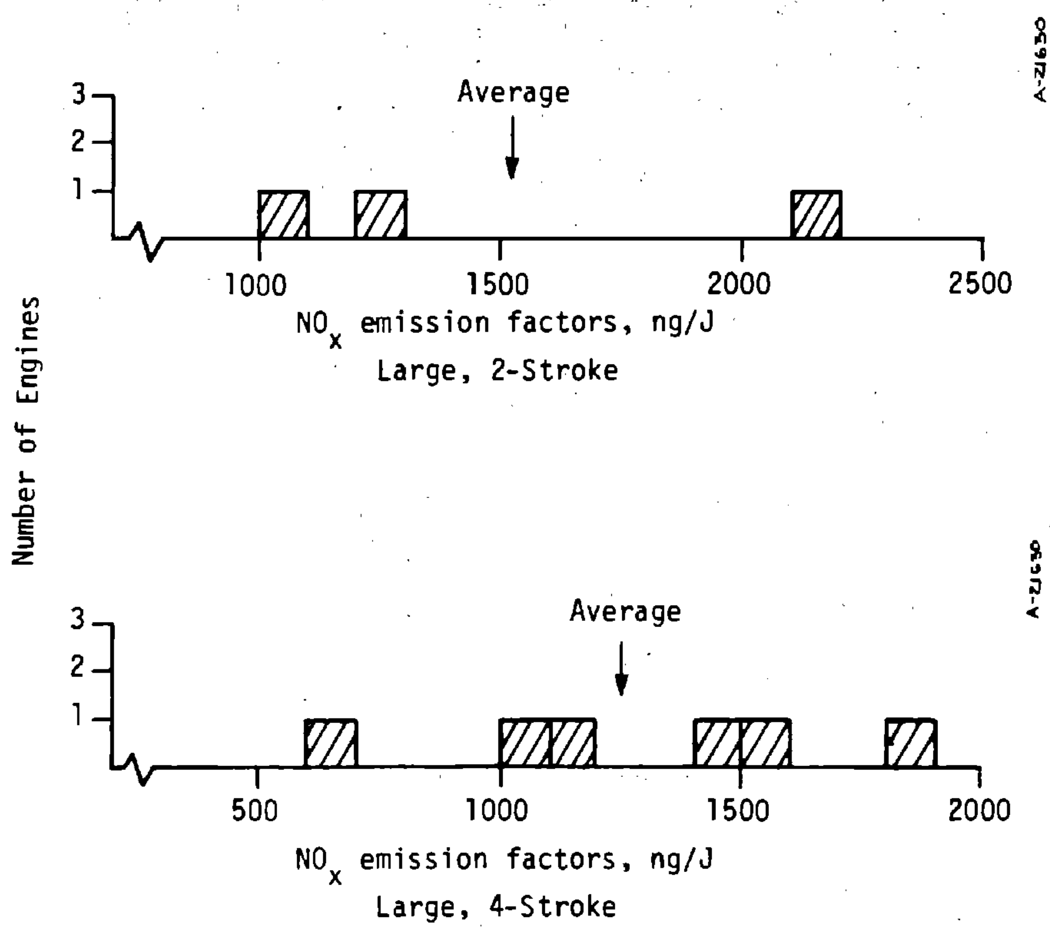


Figure 5-2. Population histograms of NO_x emission factors for compression ignition engines firing dual fuels.

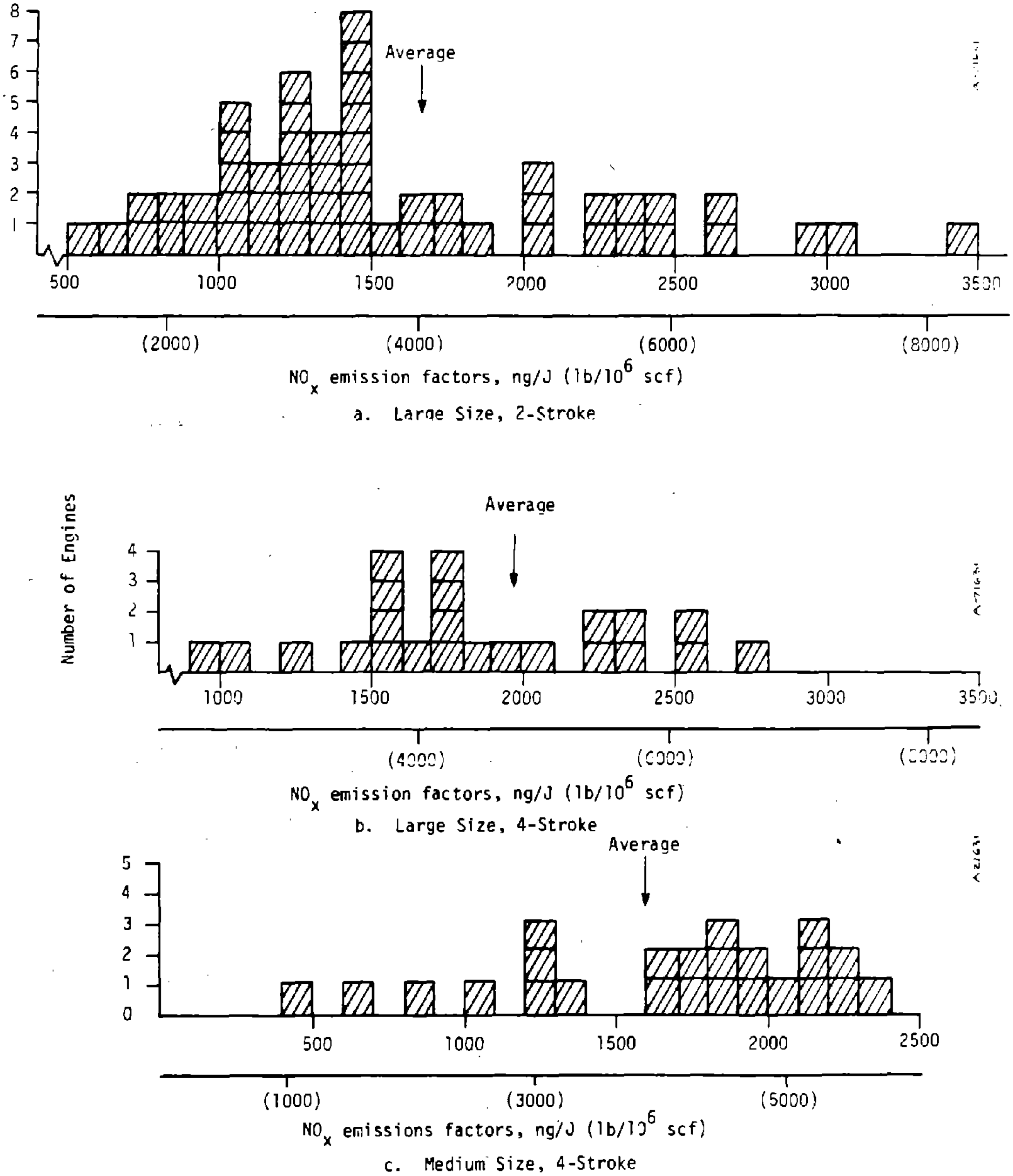


Figure 5-3. Population histograms of NO_x emission factors for stationary reciprocating, natural gas firing SI engines.

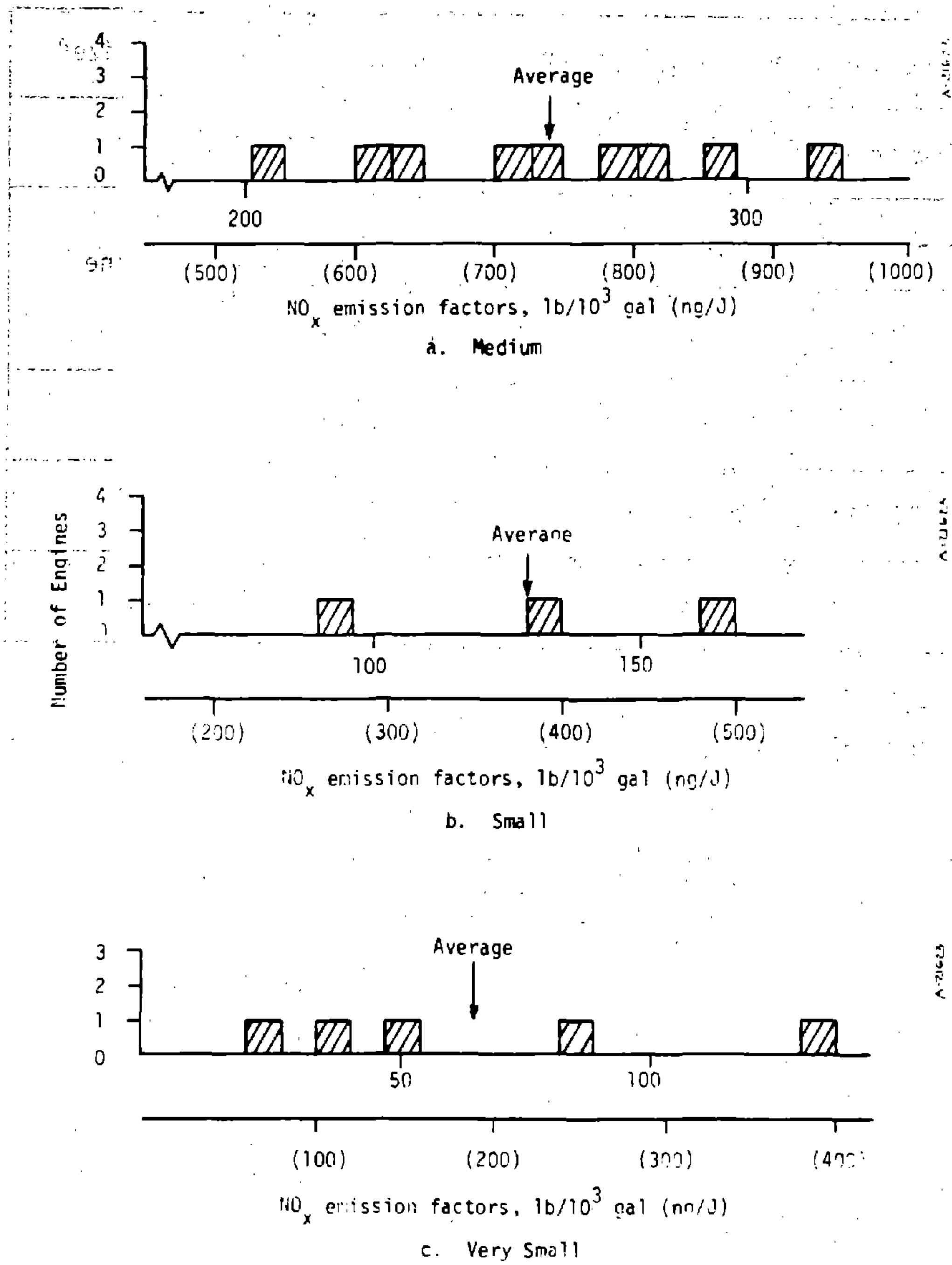


Figure 5-4. Population histograms of NO_x emission factors for stationary reciprocating gasoline fired Spark Ignition engines.

TABLE 5-4. NITRIC OXIDE AS A CONSTITUENT OF TOTAL NO_x EMISSIONS OF RECIPROCATING ENGINES

Engine Size	NO_x Emissions as a Function of Type, Stroke, Fuel and Size[a]				
	Compression Ignition		Spark Ignition		
	Diesel Fuel		Natural Gas		Gasoline
	2 Stroke	4 Stroke	2 Stroke	4 Stroke	
Large	--	--	88 (42)[b]	83 (9)	
Medium	93 (1)	96 (4)	--	96 (15)	
Small	--	98 (3)			98 (3)

[a]Weight percentage, NO reported as NO_2

[b]Number in parentheses refers to number of engines tested

REFERENCES FOR SECTION 5

5-1 Youngblood, S. B. et al., "Standards Support and Environmental Impact Statement for Reciprocating Internal Combustion Engines," Acurex Draft Report TR-78-99, March 1978.

5-2 Anon, "Compilation of Air Pollution Emission Factors," U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Publication AP-42, April 1973 and Supplements.

5-3 Shimizu, A. B., et al., "NO_x Combustion Control Methods and Costs for Stationary Sources -- Summary Study," EPA 600/2-75-046, September 1975.

5-4 Hare, C. T. and K. J. Springer, "Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines, Final Report -- Part 5, Heavy-Duty Farm, Construction and Industrial Engines," Southwest Research Institute, San Antonio, Texas, AR-898, October 1973.

5-5 Marshall, W. F. and R. D. Fleming, "Diesel Emissions Reinventoried," Report of Investigations No. 7530 by the U.S. Department of the Interior, Bureau of Mines, 1972.

5-6 Dietzmann, H. E., and K. J. Springer, "Exhaust Emissions from Piston and Gas Turbine Engines Used in Natural Gas Transmission," Southwest Research Institute, San Antonio, Texas, prepared for American Gas Association, Arlington, VA, January 1974.

5-7. Urban, C. M. and K. J. Springer, "Study of Exhaust Emissions from Natural Gas Pipeline Compressor Engines," Southwest Research Institute, San Antonio, Texas, prepared for American Gas Association, Arlington, VA, February 1975.

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5-9 Hare, C. T. and K. J. Springer, "Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines, Final Report, Part 4, Small Air-Cooled Spark Ignition Utility Engines," U.S. Environmental Protection Agency, APTD-1493, May 1973.

5-10 Fleming, R. D. and F. R. French, "Durability of Advanced Emission Controls for Heavy Duty Diesel and Gasoline Fueled Engines," EPA 460/3-73-010, September 1973.

5-11 Springer, K. J., "Baseline Characterization and Emissions Control Technology Assessment of Heavy-Duty Gasoline Engines," Final Report Southwest Research Institute, San Antonio, Texas, AF-844, November 1972.

SECTION 6

GAS TURBINES

6.1 NO_x EMISSION FACTORS FOR VARIOUS TYPES AND SIZES OF GAS TURBINE ENGINES

For the purpose of this study, gas turbines have been divided into three sizes: large >15 MW (>20,000 hp), medium, 4 to 15 MW (5300 hp to 20,000 hp) and small, <4 MW (<5300 hp). The units were further divided into simple and regenerative cycle* and subsequently classified as to fuel. As no distinction could be made between the various types of oil burned, all of these were combined into liquid fuel. The liquid fuel category does not contain derived fuels such as methanol but does include heavy distillates and crudes when reported.

Table 6-1 contains a summation of the data extracted. Much of the information was obtained from the Standard Support Document (Reference 6-1). Other sources include Dietzman and Springer (which has already been incorporated into Supplement 6 of AP-42) (Reference 6-2), Dewerth (Reference 6-3), Wasser (Reference 6-4), Crawford, et al., (Reference 6-5) and Acurex (Reference 6-6). Much of the data contained heat rates for the units tested so that it was possible to determine input specific (lb/MBtu, ng/J, lb/10^6 scf or lb/10^3 gal) as well as output specific (ppm at 15 percent O_2, lb/MWH, g/hp-hr) NO_x emission terms.

6.2 HISTOGRAMS OF NO_x EMISSIONS FOR GAS TURBINE ENGINES

Figure 6-1 shows population NO_x emission factor histograms for the six classes of gas turbine engines in which data on more than two units were found. The graphs for the small turbine category show numbers

*Regenerative units use exhaust gases to preheat combustion air.

TABLE 6-1. NO_x EMISSION FACTORS SURVEY OF SIMPLE AND REGENERATIVE CYCLE GAS ENGINES

Turbine Size	Units	Baseline NO_x Emissions as a Function of Cycle and Fuel[a]			
		Simple Cycle		Regenerative Cycle	
		Natural Gas	Liquid Fuel	Natural Gas	Liquid Fuel
Large ≥15 MW (≥20,000 hp)	No. Engines	4	16	--	2
	ppm @ 15% O_2[b]	98	188	--	340
	lb/MWH[b]	4.1	10.2[d]	--	12.0
	g/hp-hr[b]	1.4	3.5[d]	--	4.1
	ng/J[c]	140	360	--	650
	lb/MBtu[c]	0.32	0.85	--	1.51
	lb/MSCF[c]	350	--	--	--
	or lb/10^3 gal	--	120	--	220
Medium 4 to 15 MW (5,300 to 20,000 hp)	No. Engines	8	3	--	--
	ppm @ 15% O_2[b]	80	108	--	--
	lb/MWH[b]	3.8	6.1	--	--
	g/hp-hr[b]	1.3	2.1	--	--
	ng/J[c]	120	210	--	--
	lb/MBtu[c]	0.29	0.48	--	--
	lb/MSCF[c]	300	--	--	--
	or lb/10^3 gal	--	70	--	--
Small <4 MW (<5,300 hp)	No. Engines	30	58	1	1
	ppm @ 15% O_2[b]	78	93	--	--
	lb/MWH[b]	4.9	5.6	6.2	11.4
	g/hp-hr[b]	1.7	1.9	2.1	3.8
	ng/J[c]	120	180	180	360
	lb/MBtu[c]	0.28	0.41	0.42	0.84
	lb/MSCF[c]	300	--	440	--
	or lb/10^3 gal	--	47	--	120

[a] NO_x values reported in terms of NO_2
[b] Output specific values
[c] Input specific values
[d] Average of 14 units only

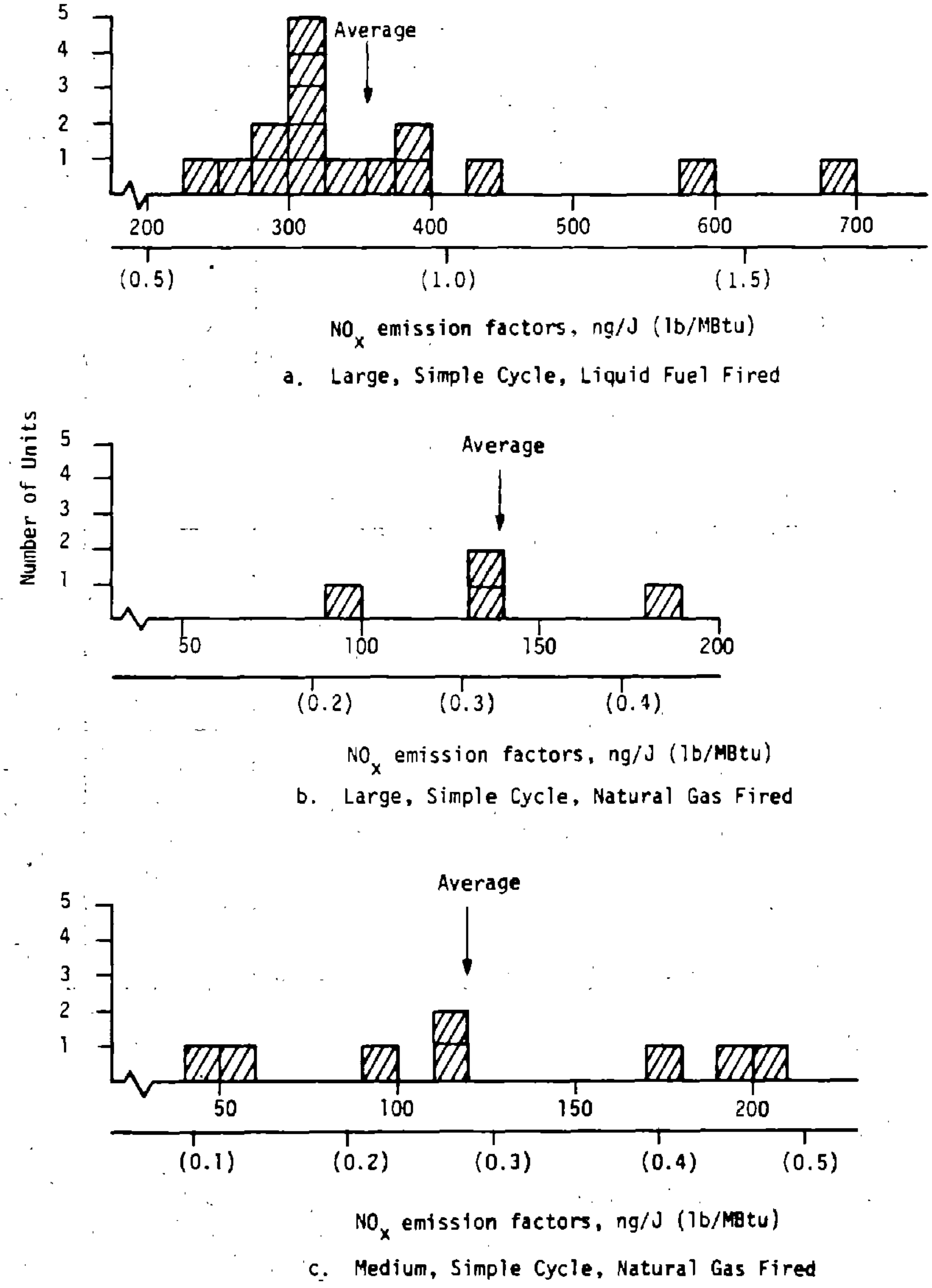

Figure 6-1. Population histograms of NO_x emission factors for gas turbine engines.

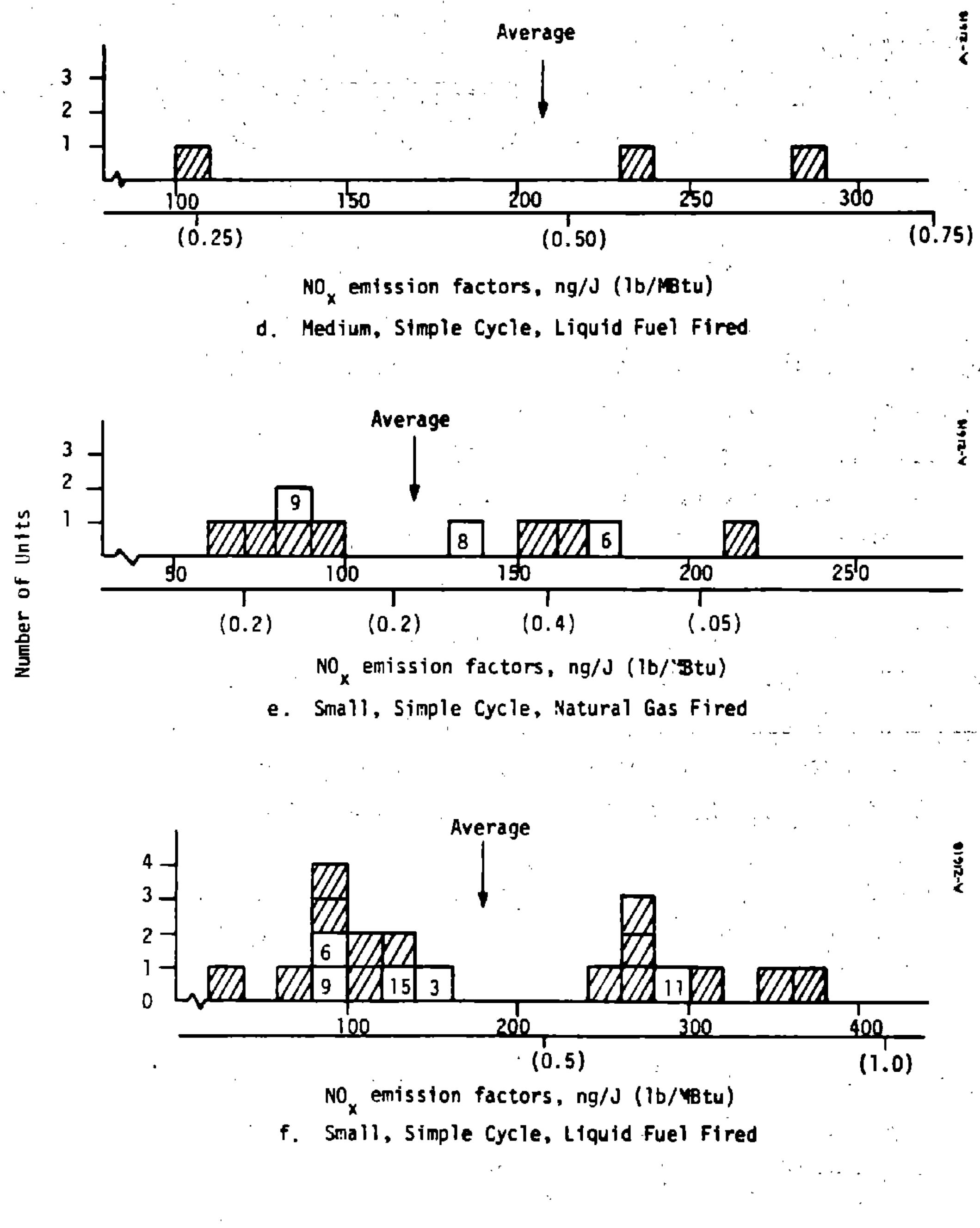

Figure 6-1. Concluded.

in some of the boxed squares. These numbers represent averages of NO_x emission values as they were presented in the literature; individual values were not presented. The small liquid fuel fired turbine histogram appears to be bimodal in appearance. This characteristic does not appear to be related to turbine size or to fuel as all four fuels, Jet A., kerosene, and No. 1 and No. 2 fuel oils appear in both modes. It may be related to the make of turbine or to the method of testing.

6.3 STATE-OF-THE-ART CONTROL TECHNIQUES FOR NO_x EMISSIONS -- WATER INJECTION

Water injection into the combustion zone in either as a liquid or as steam has been used to increase efficiency since 1961 with NO_x control being a fringe benefit. Not until 1971 was it primarily used to meet NO_x regulations (Reference 6-1). A water/fuel ratio of 0.5 generally provides a NO_x reduction of 50 percent and for a water/fuel ratio of 1.0, 80 percent. Steam appears to be less effective as the energy for vaporization is no longer supplied by the combustion process of the turbine. Figure 6-2 illustrates the effect of increasing the water/fuel ratio in reducing the overall NO_x concentration. Steam/water injection appears to work equally well for natural gas and distillate oils.

6.4 NITRIC OXIDE AS PERCENT CONSTITUTENT OF TOTAL NO_x EMISSIONS

Dietzman and Springer (Reference 6-2) have reported NO as a percentage of NO_x for one turbine firing natural gas in the 4 to 15 MW range. The average of the tests run was 87 percent. Nitric oxide (NO) was not measured on any of the other turbines examined during this test program. Dewerth (Reference 6-3) analyzed two 400 hp turbines at 60 percent load for both NO and NO_x and obtained an 86 percent average of NO.

Previously, Tuttle, et al., (Reference 6-7) reviewed much of the data prior to 1974 and found that it was clearly contradictory as to whether NO_2 (and inversely NO) is a small or large fraction of total NO_x emissions for gas turbine engines. Recently Johnson and Smith (Reference 6-8) varied a 45 MW gas turbine from idle (15 MW) to full load. NO as a percentage of NO_x increased from 0 to 78 percent as shown in Figure 6-3. This is roughly collaborated by a second test run by Wasser (Reference 6-4) on a 0.125 MW turbine at an EPA facility as shown in Figure 6-4; however, results at low loads indicate a considerable

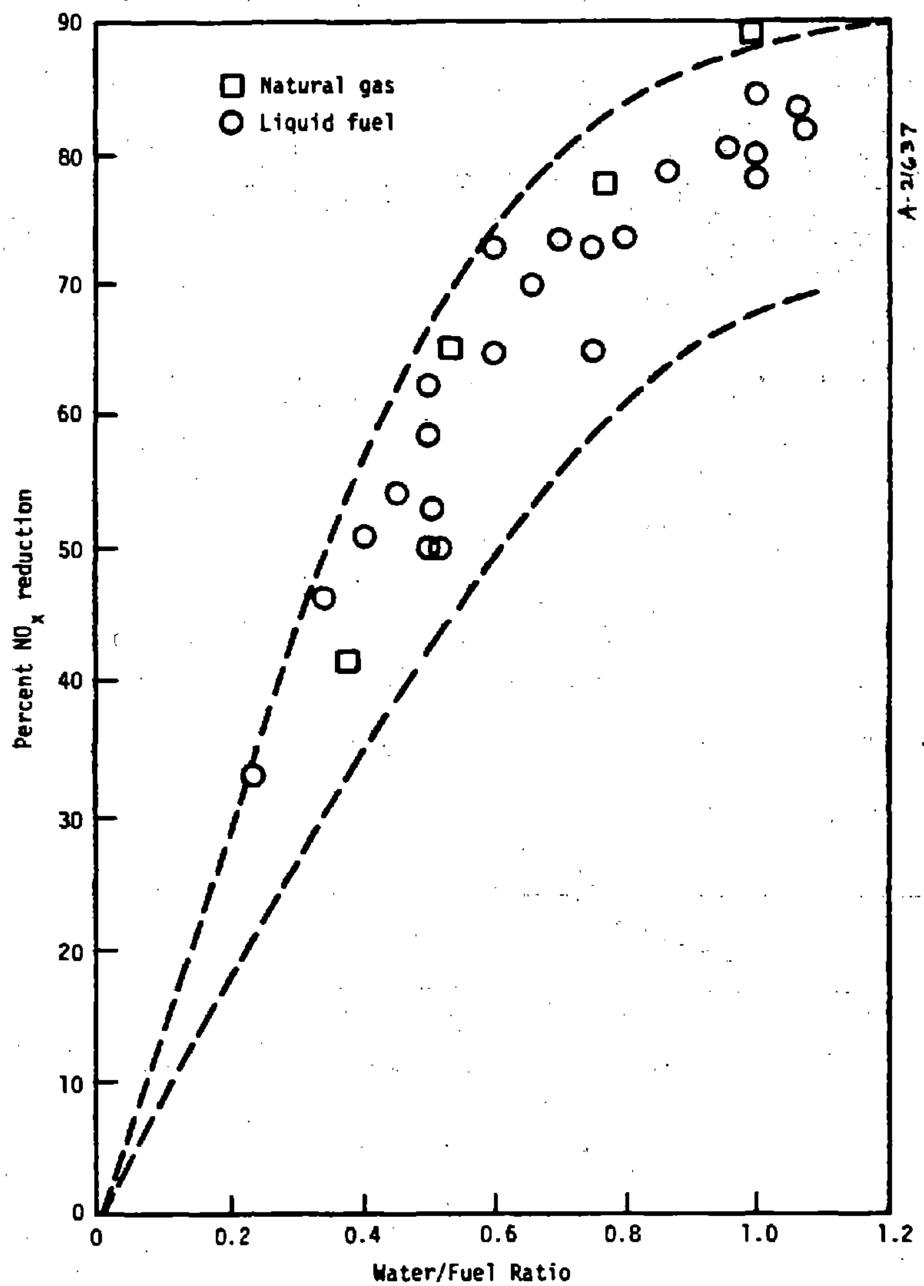

Figure 6-2. Effectiveness of water/steam injection in reducing NO_x emissions (Reference 5-1).

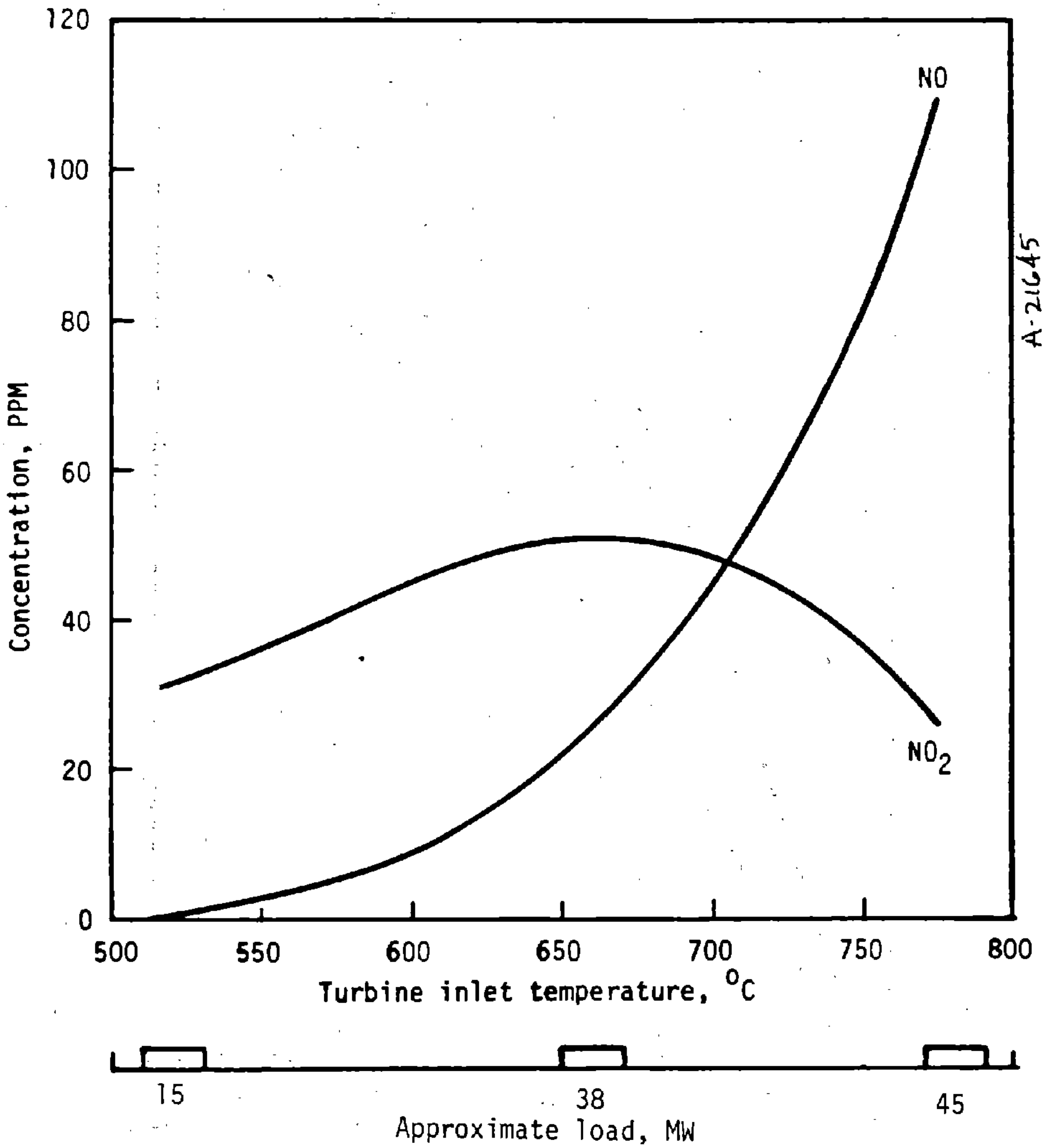

Figure 6-3. NO and NO_2 concentrations at base of No. 3 stack for various turbine loads, i.e., turbine inlet temperature (Reference 6-7).

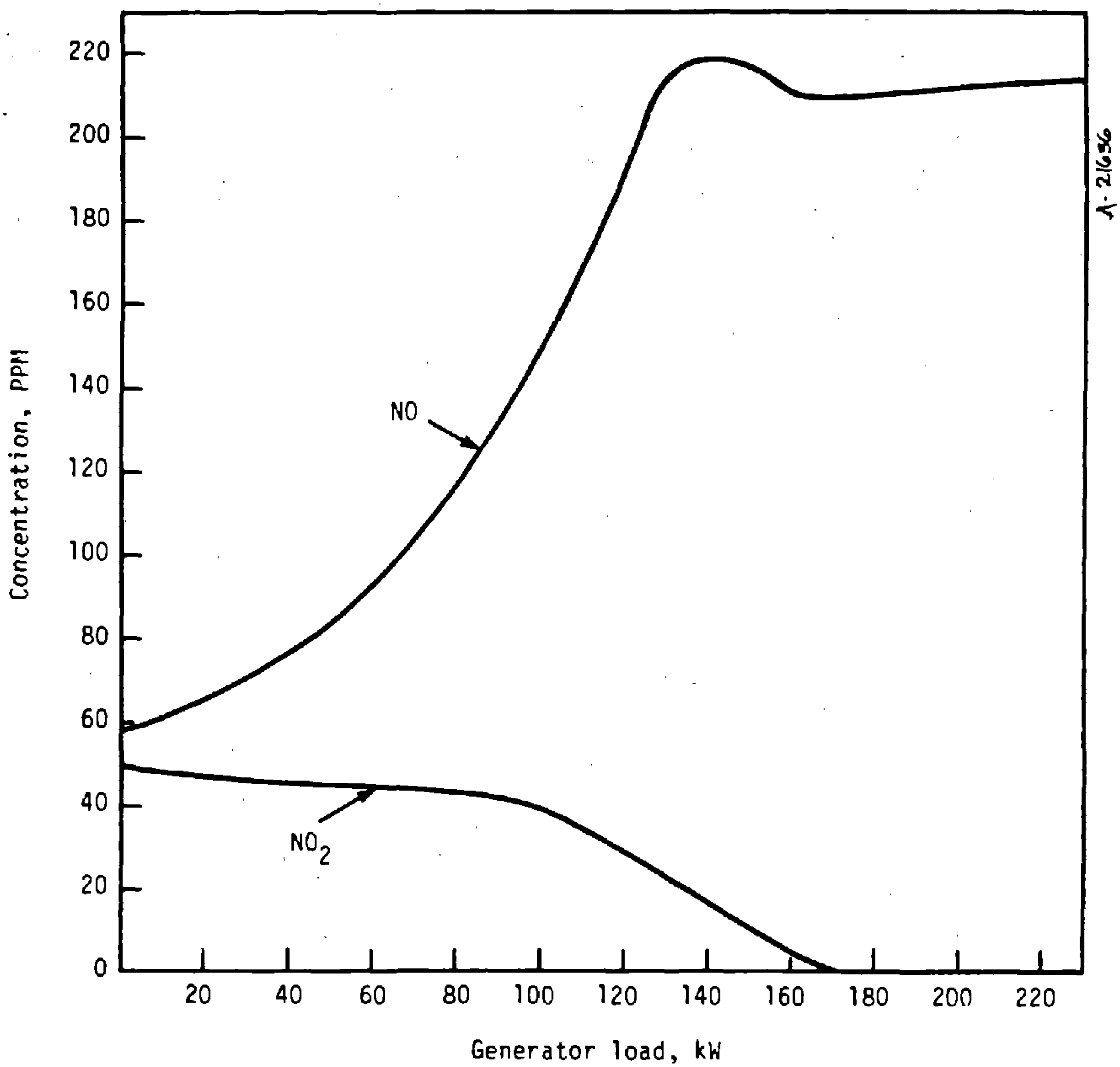

Figure 6-4. NO and NO_x concentrations of a small turbine at various loads firing No. 2 oil (Reference 6-4).

quantity of NO in the EPA turbine exhaust and virtually none reported by Johnson and Smith. Also indicated is a dropoff of NO_2 directly from the low load value for the EPA unit whereas the Johnson and Smith unit shows an increase prior to dropping off. Much of this difference may be due to the difference in fuels, type and size of the turbine and operating parameters.

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6-2. Dietzmann, H. E., and K. J. Springer, "Exhaust Emissions from Piston and Gas Turbine Engines Used in Natural Gas Transmission," Southwest Research Institute, San Antonio, Texas. Prepared for American Gas Association, Arlington, VA, January 1974.

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6-8. Johnson, G. M. and M. Y. Smith, "Nitrogen Dioxide Emissions from a Gas Turbine Power Station," International Clean Air Conference, The Clean Air Society of Australia and New Zealand, Brisbane, Australia, May 15-19, 1978.