EPA-600/7-80-111
May 1980

BITUMINOUS COAL COMBUSTION
AP-42 Section 1.1
Reference Number
31

EPA

Emissions of Reactive Volatile Organic Compounds from Utility Boilers

Interagency Energy/Environment R&D Program Report

(Note: March 1993 VOC data before and after venturi scrubbers is given on p 36 of Ref 28)

Note: Not specified if VOC data are before or after controls. It seems they are after controls, generally cyclones + ESPs, but some scrubbers. Ref 28, p36, indicates a scrubber may reduce VOC.

Utility Boilers	C_2-C_{16}, ng/J (range)	C_2-C_{16} lb/ton, avg.	CH_4, ng/J (range)	CH_4 lb/ton, avg.
Pulverized Dry Bottom				
Site 205-1	.309-1.896	.062	0-.318	.008
Site 205-2	.466-2.072	.071	0-.321	.009
Site 154	1.635-2.263	.11	1.567	.087
Pulverized Wet Bottom				
Site 206	.81-1.28	.058		
Site 212	.066-.230	.008	.616	.034
Site 213	.161-.293	.013	2.374	.132
Site 336	.465-1.028	.042	.308	.017
Site 338	1.073-1.659	.076	.439	.024
Site 218	.067-.688	.021	.595	.033
Cyclone				
Site 134	.655-1.853	.07	.787	.044
Site 207	.151-.363	.014	0-.042	.001
Site 209	.079-.218	.006	0-.027	.0008
Site 330	4.12-4.95	.25	.080	.004
Site 331	3.07-4.46	.21	.560	.002
Stoker				
Site 137	.124-.310	.012	.403	.022
Site 204	.380-2.197	.071	0-.363	.010
Site 332	.55-1.83	.067	.57	.032
AVERAGE		0.068		0.029

Reference: EPA-600/7-80-111 (TRW, May 1980)

VOC from all pulverized, cyclone and stoker units

EPA-600/7-80-111
May 1980

Emissions of Reactive Volatile Organic Compounds from Utility Boilers

by

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ABSTRACT

The report gives results of the measurement of emission factors for reactive volatile organic compounds (VOC) from 43 utility boilers firing bituminous coal, lignite, oil, and natural gas. The boilers ranged in size from 9 to 910 MW. The median reactive VOC emission factors were determined to be between 0.47 and 1.85 ng/J for coal- and lignite-fired sources (excluding stoker data); between 0.03 and 1.48 ng/J for residual-oil-fired sources; and between 0.01 and 1.00 ng/J for gas-fired sources. Approximately 50% of the coal- and lignite-fired plants and a majority of the oil- and gas-fired plants were emitting reactive VOC below the 100-ton per year level.

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1. INTRODUCTION

This report was prepared under the Conventional Combustion Environmental Assessment program, to support the requirements of the Monitoring and Data Analysis Division (MDAD) of the Office of Air Quality Planning and Standards (OAQPS), for the development of reactive volatile organic compound (VOC) emission factors for utility power plants. The emission factors developed by TRW were derived from stack sampling tests conducted by TRW and its subcontractor, GCA, at a number of bituminous coal-, lignite-, oil- and gas-fired utility boilers throughout the United States, as part of the "Emissions Assessment of Conventional Stationary Combustion Systems" (EACCS) program under EPA Contract No. 68-02-2197. The sampling and analysis procedures employed in the EACCS program were an integral part of the phased environmental assessment approach and applied primarily to Level I. The results obtained were intended to provide the basis for establishing the priorities of streams, components, and classes of materials for further testing by more stringent Level II techniques and procedures. As such, the results of the sampling and analysis procedures were designed to be quantitative within a factor of ± 2 to 3. A detailed discussion of the sampling and analysis methods used to determine VOC emissions could be found in the Methods and Procedures Manual for Sampling and Analysis prepared specifically for the EACCS program (1). In the preparation of this manual, the IERL Procedures Manual - Level 1, Environmental Assessment (2) was used as the guideline and made an integral part of it.

VOC's, as defined in the EACCS program, cover compounds that range in boiling point from -160 to 300°C. This parallels the boiling range of n-alkanes from methane (C_1) through n-hexadecane (C_{16}). Total VOC emissions include C_1 to C_{16} hydrocarbons. However, only the reactive hydrocarbons, C_2 to C_{16}, are of regulatory interest to the EPA at this point. Methane has been excluded from the reactive VOC emission factors calculated in this study. Although it is obvious that most of the C_1's are methane, it is not known from the TRW/GCA data the quantity of other specific organic compounds present. This is because of the nature of the Level I procedures utilized by TRW and GCA in the sampling and analysis of utility boiler flue gases, for which no detailed attempt was made to routinely identify individual organic compounds. Reactive VOC emission data presented in this report, therefore, include all organic emissions in the C_2 to C_{16} n-alkane boiling range. The emission values presented are conservative, since limited data acquired by Rockwell have shown that most of the C_2 compounds emitted are in the form of ethane, and ethane is classified as non-reactive per the EPA July 8, 1977 VOC designation (3). If the Rockwell data were substantiated, the C_2 fraction of VOC's could be subtracted from the emission factors, resulting in lower reactive VOC emission estimates.

2. SUMMARY

A number of utility boilers were tested for stack VOC emissions. Samples were taken and analyzed in the field for C_1 to C_6's, and in the laboratory for C_7 to C_{16}'s. Fuel heating values, fuel analysis results, and stack gas oxygen concentrations were used to compute emission factors on a mass per unit heat input basis. Numbers calculated from laboratory analyses were on a mass per standard gas volume basis (1 atmosphere, 20^{o}C). Data for a total of 43 sites have been analyzed in this report. The breakdown of utilities tested by boiler type was:

- 3 pulverized bituminous coal-fired, dry bottom
- 6 pulverized bituminous coal-fired, wet bottom
- 6 cyclone bituminous coal-fired
- 3 stoker bituminous coal-fired
- 3 pulverized lignite-fired, dry bottom
- 2 cyclone, lignite
- 2 stoker lignite-fired
- 5 tangentially-fired oil
- 6 wall-fired oil
- 3 tangentially-fired gas
- 4 wall-fired gas

The breakdown by fuel type was:

- 18 bituminous coal-fired
- 7 lignite-fired
- 11 residual oil-fired
- 7 gas-fired

The size of utility boilers tested ranged from a small lignite-fired boiler of 9 MW to a large bituminous coal-fired unit of 910 MW.

Data were summarized in tabular form by site, fuel, and boiler type. Summations were made for each of the following C_1 to C_{16} individual alkane equivalents:

- C_2 to C_6 (-100 to 90°C boiling range)
- C_7 to C_{16} (90 to 300°C boiling range)
- C_2 to C_{16} (reactive VOC's, -100 to 300°C boiling range)
- C_1 to C_{16} (-160 to 300°C boiling range)

C_1 to C_6's were determined in the field; C_7 to C_{16}'s in the laboratory. Means and standard deviations were calculated for each fuel and boiler type.

Emission data were analyzed by plotting reactive VOC emission values versus the cumulative frequency in the population sampled. Based on equivalent alkane groups, the median reactive VOC emission factors were determined to be between 0.47 and 1.85 ng/J for coal- and lignite-fired sources (when stoker data were excluded), between 0.03 and 1.48 ng/J for residual oil-fired sources, and between 0.01 and 1.00 ng/J for gas-fired sources. The range of emission estimates represents different interpretations of the emission data and whether upper detection limits were used in the computation of emission factors.

For a 1000 MW power plant operating at 33 percent efficiency and a load factor of 60 percent, an emission factor of approximately 1.58 ng/J is required in order for the power plant to exceed 100 tons reactive VOC's per year. Analysis of the emission data indicated that approximately half of the coal- and lignite-fired plants, and the majority of residual oil- and gas-fired plants are emitting reactive VOC's below this level.

3. SAMPLING AND ANALYSIS PROCEDURES

Stack gas emissions from a number of utility boilers were sampled in the "Emissions Assessment of Conventional Stationary Combustion Systems" (EACCS) program. In the analysis of samples, a gas chromatograph (GC) was calibrated and the results tabulated as total hydrocarbon mass corresponding to the various alkanes. These alkanes, their boiling points and the reporting ranges are shown in Table 1. Most saturated and aromatic hydrocarbons are relatively nonpolar and thus eluted at retention times corresponding to their boiling points on the GC columns chosen for the EACCS program. Possible hydrocarbons in each reported boiling range could be tentatively established. However, polar compounds with functional groups do not always follow the same bp-retention time relationships as the hydrocarbons. For example, a C_2 organic acid, bp 119°C, may or may not elute in the boiling range 110-140°C. The scope of the EACCS program did not include specific identification of individual compounds.

Sampling and analysis of VOC's were performed in two distinct parts (1). In part 1, the C_1-C_6 materials were collected on site in Tedlar bags utilizing EPA Method 3. This bag sample was then analyzed immediately on site using a dual column FID gas chromatograph with 6 ft. (1.8 m) x 1/8 inch (3.2 mm) stainless steel columns packed with Poropak Q. The instrument was calibrated with a C_1-C_6 standard accurate to ± 15-20%. During the early testing phase of the EACCS program, however, erratic electrical fields at most power plant sites have precluded use of the maximum sensitivity of the instrument.

During the EACCS program, TRW was directed to attempt an increase in the GC sensitivity by a factor of approximately 10 to achieve a new sensitivity of about 0.1 ppm. This was done by using a larger sample size and by installing a special electrical isolation transformer.

In the second part of the sampling and analysis methodology, the C_7 to C_{16} materials were collected in the field using a porous polymer resin (XAD-2) mounted downstream of the filter in the particulate sampling portion of the SASS

TABLE 1. REPORTING RANGES FOR VOC ANALYSIS

	Boiling Point ^{o}C	Reporting Range, ^{o}C	Reported As
Methane	-161	-160 to -100	C_1
Ethane	- 88	-100 to - 50	C_2
n-Propane	- 42	- 50 to 0	C_3
n-Butane	0	0 to 30	C_4
n-Pentane	36	30 to 60	C_5
n-Hexane	69	60 to 90	C_6
n-Heptane	98	90 to 110	C_7
n-Octane	126	110 to 140	C_8
n-Nomane	151	140 to 160	C_9
n-Decane	174	160 to 180	C_{10}
n-Undecane	196	180 to 200	C_{11}
n-Docane	216	200 to 220	C_{12}
n-Tridecane	234	220 to 240	C_{13}
n-Tetradecane	252	240 to 260	C_{14}
n-Pentadecane	270	260 to 280	C_{15}
n-Hexadecane	288	280 to 300	C_{16}

train. Some VOC's might have also been adsorbed on the collected particulate or condensed in the train. Organic material collected on the resin and on the particulate catch was then extracted with methylene chloride in Soxhlet extractors in the laboratory. Condensed material was analyzed using a dual column FID gas chromatograph with 6 ft. x 1/8 inch (1.8 m x 3.2 mm) stainless steel column packed with 1.5% SE-30A OV-101 on Gas Chrom Q. These results were reported separately.

It must be realized that less than 100% VOC sample collection efficiency (in the field) or sample recovery efficiency (in the laboratory) may have introduced error in the reported C_7-C_{16} values. Arthur D. Little, Inc., is presently documenting collection efficiency, while experiments at TRW indicate that substantial (≥50%) losses of C_7 materials are observed in the Level I analysis preparation procedure.

In analyzing C_7 to C_{16}'s, gas chromatography was used to determine the quantity of lower boiling hydrocarbons (boiling points between 90° and 300°C) in the concentrates of all organic solvent rinses and XAD-2 resin fractions encountered in Level 1 environmental sample analyses. Typically, this procedure generated analytical results based on the sum of C_7 to C_{16} total chromatographable organic (TCO) contributions from each part of the SASS sample train. However, TCO analyses of particulate extracts and probe and cyclone rinses were eliminated after March, 1978, by an official EPA change to Level I. This change was subsequently incorporated into the EACCS analysis procedures, as contributions to TCO's from these components were found to be negligible. Filter catches and XAD-2 module condensate contributions to TCO's were analyzed.

The conditions under which TCO analyses were conducted provided a lower detection limit equivalent to a hydrocarbon concentration of 2×10^{-4} mg/m^3 in 30 m^3 of sample gas (the quantity of gas required in these tests).

In contrast to C_7 to C_{16} analyses, which were quantitatively determined due to low detection limits, many C_1 to C_6 analyses were reported as less than 0.1 ppm, or less than 1.0 ppm, based on methane. Thus, a reported value of less than 1 ppm for any C_1 to C_6 implies an actual value anywhere between 0 and 667 μg/m^3. Alternatively, a reported value of 1 ppm was defined as 1251 μg/m^3 for C_2's, 3585 μg/m^3 for C_6's, etc.

4. RESULTS AND DISCUSSION

The rated capacity, age, and pollution control method for the 43 sites tested are presented in Tables 2 to 5. The operating load and fuel feed rates for these sites at the time of testing are presented in Tables 6 to 9. These data are provided to associate the test results with site characteristics.

Table 10 provides a detailed tabulation of C_1 to C_{16} organics for each bituminous coal-fired utility boiler tested. The analyses are grouped by boiler type - pulverized coal, dry bottom, wet bottom, cyclone, and stoker. All values are listed opposite their equivalent C_1 to C_{16} alkane group in $\mu g/m^3$. In addition, total values for C_2 to C_6, C_7 to C_{16}, C_2 to C_{16}, and C_1 to C_{16} are summed for each site at the bottom of each column. These totals are given in both $\mu g/m^3$ and ng/J.

To convert from $\mu g/m^3$ to n/J required computation of site specific factors from boiler operating parameters, including oxygen percent in the outlet flue gas, fuel composition, and fuel heating values. Specifically, the number of gm moles of flue gas per gm of fuel was first computed using the fuel composition analysis and effluent O_2 concentration:

$$n_{FG} = \frac{4.762\ (n_C + n_S + 0.5\ n_N) + .9405\ n_H - 3.762\ n_{O_2}}{1 - 4.762\ (O_2/100)}$$

where: n_{FG} = gm moles of dry effluent/gm of fuel under actual operating conditions.

n_j = gm moles of element j in fuel per gm of fuel.

O_2 = volumetric O_2 concentration in percent.

The emission factor expressed as ng/J was then computed from emission concentration expressed as $\mu g/m^3$ using the following equation:

$$\begin{Bmatrix}\text{Emission}\\ \text{Factor}\end{Bmatrix} (\text{ng/J}) = \frac{\begin{Bmatrix}\text{Mass}\\ \text{Concentration}\end{Bmatrix}_s (\mu g/m^3) \times n_{FG} \times 24.04}{\begin{Bmatrix}\text{Fuel}\\ \text{Heating Value}\end{Bmatrix} (\text{kJ/kg fuel})}$$

TABLE 2. CHARACTERISTICS OF BITUMINOUS COAL-FIRED UTILITY BOILERS SELECTED FOR TESTING

Combustion Source Type	Site No.	Rated Capacity, MW	Age as of 1979, Years	Pollution Control Device*
Pulverized Dry Bottom	154	358	4	Wet scrubber utilizing lime/alkaline fly ash with tested efficiencies of 99.5% for particulate removal and 70-75% for SO_2 removal.
	205-1	91	22	Mechanical precipitator of 20% design efficiency in series with ESP. Combined design efficiency: 90-99.5%. Combined tested efficiency: 98.6%.
	205-2	77	21	Mechanical precipitator of 20% design efficiency in series with ESP. Combined design efficiency: 90-99.5%. Combined tested efficiency: 98.6%.
Pulverized Wet Bottom	206	128	17	Mechanical precipitator of 83.5-84% design efficiency in series with ESP. Combined design efficiency: 99.6%. Combined estimated efficiency: 99.6%.
	212	145	21	ESP with 99.9% design and 99.9% estimated efficiency.
	213	137	21	ESP with 99.9% design and 99.9% estimated efficiency.
	218	825	3	Venturi wet scrubbing system utilizing thiosorbic lime, with 99.9% tested particulate removal efficiency and 95.0% tested SO_2 removal efficiency.
	336	360	9-10	ESP with 99.0% design and 94.5% tested efficiency.
	338	360	9	ESP with 99.0% design and 94.5% tested efficiency.
Cyclone	134	874	10	Wet scrubber utilizing limestone with design efficiency of 98.75% for particulate removal and 76.0% for SO_2 removal; tested efficiency 98.2% for particulate removal and 76.2-80.14% for SO_2 removal.
	207	643	11	ESP with 98% design and 94.30% tested efficiency.
	208	360	16	ESP with 96.0-98.0% design and 96.70-98.70% tested efficiency.
	209	643	12	ESP with 98% design and 94.30% tested efficiency.
	330	135	24	ESP with 99.65% design and 96.08% tested efficiency.
	331	135	20	ESP with 99.65% design and 98.55% tested efficiency.
Stoker	137	12.65	22	Baghouses with 99.92% tested efficiency.
	204	12.65	18	Mechanical precipitator with 94.9% design and 85.5-85.6% tested efficiency.
	332	7.5	21	Multiclone with 92% design and 75.0-83.5% tested efficiency.

*Efficiencies apply to particulate removal unless otherwise stated.

TABLE 3. CHARACTERISTICS OF LIGNITE-FIRED UTILITY BOILERS SELECTED FOR TESTING

Combustion Source Type	Site No.	Rated Capacity, MW	Age as of 1979, Years	Pollution Control Device*
Pulverized Dry Bottom (Front-fired)	314	20	29	Multiclones with 84% design efficiency.
	315	20	27	Multiclones with 84% design efficiency.
	318	66	15	ESP with 98.5% design efficiency.
Cyclone	155	437	4	ESP with 98.8% design and 99.8% test efficiency.
	316	440	6	ESP with 99.05% design and 99.53% test efficiency.
Spreader Stoker	317	8	31	Multiclones with 89.5% design efficiency.
	319	15	30	ESP with 99.82% design efficiency.

*Listed efficiencies are for particulate removal.

TABLE 4. CHARACTERISTICS OF RESIDUAL OIL-FIRED UTILITY BOILERS SELECTED FOR TESTING

Combustion Source Type	Site No.	Rated Capacity, MW	Age as of 1979, Years	Pollution Control Device*
Tangentially Fired	210	75	24	Mechanical precipitators.
	211	158	14	ESP.
	322	637	7	Cyclone separators with 85% design efficiency.
	323	40	26	None.
Wall Fired	105	44	21	None.
	109	170	24	None.
	118	750	11	Off-stoichiometric firing and flue gas recirculation for NO_x control.
	119	345	17	None.
	141-144	350	14	Off-stoichiometric firing/flue gas recirculation for NO_x control.
	305	560	11	ESP with 99% design efficiency.
	324	40	29	None.

*Efficiencies listed are for particulate removal. Particulate removal efficiencies for the control devices associated with Sites 210 and 211 are not available. For Sites 322 and 305, the stated design efficiencies for particulate removal may be for coal firing and not for oil firing.

TABLE 5. CHARACTERISTICS OF GAS-FIRED UTILITY BOILERS SELECTED FOR TESTING

Combustion Source Type	Site No.	Rated Capacity, MW	Age as of 1979, Years	Pollution Control Device
Tangentially Fired	113	113.6	13	None.
	114	80	23	None.
	115	180	15	None.
Wall Fired	106	42	21	None.
	108	170	24	None.
	116	50	19	Overfire air for NO_x control.
	117	75	17	Overfire air for NO_x control.

TABLE 6. OPERATING LOAD AND FUEL FEED RATES OF BITUMINOUS COAL-FIRED UTILITY BOILERS

Combustion Source Type	Site No.	Operating Load, MW	% of Base Load	Fuel Feed Rate, kg/hr	Energy Input GJ/hr
Pulverized Dry Bottom	154	282	79	159,500	3,175
	205-1	91	100	33,680	930
	205-2	77	100	25,630	710
Pulverized Wet Bottom	206	110	86	47,000	1,300
	212	135	99	38,520	1,050
	213	130	95	37,100	1,030
	218	830	100	240,360	7,120
	336	356	99	126,550	3,790
	338	324	90	129,500	3,900
Cyclone	134	690	79	295,000	7,090
	207	440	68	213,000	5,000
	208	310	86	126,530	2,900
	209	450	70	210,000	5,120
	330	119	85	60,200	1,540
	331	119	85	53,928	1,330
Stoker	137	11.2	89	5,800	166
	204	9.9	78	5,570	148
	332	6.5	87	4,060	10

TABLE 7. OPERATING LOAD AND FUEL FEED RATES OF LIGNITE-FIRED UTILITY BOILERS

Combustion Source Type	Site No.	Operating Load, MW	% of Base Load	Fuel Feed Rate, kg/hr	Energy Input GJ/hr
Pulverized Dry Bottom (Front fired)	314	20	100	19,200	292
	315	20	100	17,700	290
	318	68	103	54,000	855
Cyclone	155	420	96	336,500	4,780
	316	383	87	372,900	5,420
Spreader Stoker	317	7.5	94	8,230	91
	319	12.3	82	13,000	187

TABLE 8. OPERATING LOAD AND FUEL FEED RATES OF RESIDUAL OIL-FIRED UTILITY BOILERS

Combustion Source Type	Site No.	Operating Load, MW	% of Base Load	Fuel Feed Rate, kg/hr	Energy Input GJ/hr
Tangentially Fired	210	79	105	18,500	860
	211	152	96	35,600	1,650
	322	548	86	111,800	4,780
	323	42	105	12,200	520
Wall Fired	105	44	100	13,000	580
	109	171	100	40,800	1,830
	118	702	94	165,100	7,010
	119	281	81	61,700	2,920
	141	330	94	69,000	3,030
	142	218	62	54,900	2,410
	143	325	93	66,300	2,920
	305	560	100	116,100	5,100
	324	43	108	12,500	530

TABLE 9. OPERATING LOAD AND FUEL FEED RATES OF NATURAL GAS-FIRED UTILITY BOILERS

Combustion Source Type	Site No.	Operating Load, MW	% of Base Load	Fuel Feed Rate, m^3/hr	Energy Input GJ/hr
Tangentially Fired	113	90	79	22,710	870
	114	76	95	22,650	870
	115	193	107	50,970	1,950
Wall Fired	106	36	82	13,310	510
	107	19.5	65	7,500	290
	108	162	95	40,210	1,540
	116	48	96	14,050	540
	117	70	93	20,400	780

TABLE 10. BITUMINOUS COAL-FIRED UTILITY BOILER VOC EMISSIONS

Boiler Type	Pulverized coal, dry bottom ($\mu g/m^3$)					
Site No.	205-1		205-2		154	
C_1	<667		<667		3337	
C_2	<667		<667		<334	
C_3	<667		<667		<334	
C_4	<667		<667		<334	
C_5	<667		<667		3301	
C_6	<667		<667		<334	
C_7	38.1		17.0		22	
C_8	206.8		133.0		68	
C_9	69.9		72.9		44	
C_{10}	75.2		306.7		4	
C_{11}	<1.0		41.5		16	
C_{12}	205.4		192.3		6	
C_{13}	32.0		73.0		8	
C_{14}	13.6		45.8		4	
C_{15}	2.5		82.8		8	
C_{16}	4.6		4.1		0	
Add'l C_7-C_{16}	0		0		0	
TOTALS	$\mu g/m^3$	ng/J	$\mu g/m^3$	ng/J	$\mu g/m^3$	ng/J
C_2-C_6	0-3335	0-1.587	0-3335	0-1.605	3301-4637	1.551-2.178
C_7-C_{16}	648-649	0.309	969	0.466	180	0.085
C_2-C_{16}	648-3984	0.309-1.896	967-4304	0.466-2.072	3481-4817	1.635-2.263
C_1-C_{16}	648-4651	0.309-2.214	967-4971	0.466-2.393	6818-8154	3.203-3.830
%CH_4 -		0 – 14%		0 – 13%		51–57%

NOTE: For conversions from metric to English units:

$6.243 \times 10^{-11} \times \mu g/m^3 = lb/ft^3$

$2.326 \times 10^{-9} \times ng/J = lb/Btu$

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TABLE 10. (Continued)

Boiler Type	Pulverized coal, wet bottom (µg/m³)											
Site No.	206		212		213		336		338		218	
C_1	10,544		1268		4872		734		1001		1602	
C_2	838		<67		250		876		1626		<334	
C_3	<334		<67		<67		<334		<334		<334	
C_4	<334		<67		<67		<334		<334		<334	
C_5	34,305		<67		<67		<334		<334		<334	
C_6	<334		<67		<67		<334		<334		<334	
C_7	75.7		<0.2		3.2		- <1		104		21	
C_8	106		77.1		31.4		98		203		41	
C_9	81.9		43.0		39.9		<1		3		39	
C_{10}	77.7		<0.4		<0.4		96		272		0	
C_{11}	<0.8		1.1		<0.4		9		8		18	
C_{12}	447.2		5.0		2.1		<1		126		39	
C_{13}	19.6		6.7		3.3		<1		52		0	
C_{14}	13.6		3.8		<0.4		18		14		12	
C_{15}	25.9		0.9		1.6		<1		4		0	
C_{16}	37.0		<0.4		<0.4		12		35		9	
Add'l C_7-C_{16}	0		0		0		0		0		0	
TOTALS	µg/m³	ng/J	µg/m³	ng/J	µg/m³	ng/J	µg/m³	ng/J	µg/m³	ng/J	µg/m³	ng/J
C_2-C_6	35,143-36,145	16.508-16.978	0-335	0-.163	250-518	.122-.252	876-2212	.367-.928	1626-2962	.713-1.299	0-1670	0-.621
C_7-C_{16}	871.8-875.4	.410-.411	136.0-138.6	.066-.067	79.9-83.1	.039-.040	233-238	0.098-0.100	821	.360	179	.067
C_2-C_{16}	36,015-37,020	16.917-17.389	136-474	.066-.230	330-601	.161-.293	1109-2450	.465-1.028	2447-3783	1.073-1.659	179-1849	.067-.688
C_1-C_{16}	46,559-47,564	21.870-22.342	1404-1742	.682-.846	5202-5473	2.535-2.667	1843-3184	.773-1.335	3448-4784	1.512-2.098	1781-3451	.662-1.283
% C_1 (CH_4)	23-22		73-9[illegible]		89-94%		25-40%		21-29%		46-90%	

TABLE 10. (Continued)

Boiler Type	Cyclone (µg/m³)					
Site No.	134	207	208	209	330	331
C_1	1800	<67	NO DATA	<67	187	1068
C_2	<667	<67	NO DATA	<67	<667	<667
C_3	<667	<67	NO DATA	<67	<667	<667
C_4	<740	<67	NO DATA	<67	9865	<667
C_5	<667	<67	NO DATA	<67	<667	<667
C_6	<667	<67	NO DATA	<67	56,711	12,403
C_7	<0.2	31.0	<0.4	10.0	28	1080
C_8	50	43.0	<0.2	26.0	<1	2290
C_9	13	12.5	<0.2	26.7	<1	83
C_{10}	260	27.8	0.9	52.4	2	1127
C_{11}	300	4.0	<0.4	5.1	24	70
C_{12}	71	108.4	5.0	35.4	31	2
C_{13}	7.4	7.4	2.3	12.1	<1	50
C_{14}	2.4	3.9	<0.4	8.8	<1	110
C_{15}	27	0.6	<0.4	0.4	<1	319
C_{16}	42	1.3	<0.4	19.8	3	794
Add'l C_7-C_{16}	0	0	0	0	3	0

TOTALS	134 µg/m³	134 ng/J	207 µg/m³	207 ng/J	208 µg/m³	208 ng/J	209 µg/m³	209 ng/J	330 µg/m³	330 ng/J	331 µg/m³	331 ng/J
C_2-C_6	704-3408	.312-1.510	0-335	0-.212	-	-	0-335	0-.137	66,576-68,577	27.56-28.38	12,403-15,071	6.434-7.819
C_7-C_{16}	773.0	.343	237.1-239.9	.151	7.0-10.6	.0037-.0055	193.3-196.7	.081	91-96	.038-.040	5925	3.074
C_2-C_{16}	1477-4181	.655-1.853	237-575	.151-.363	-	-	193-532	.079-.218	66,667-68,673	27.59-28.42	18,328-20,996	9.508-10.89
C_1-C_{16}	3277-5981	1.452-2.651	237-642	.151-.405	-	-	193-599	.079-.245	66,859-68,860	27.67-28.50	19,396-22,064	10.06-11.45
% C_1 (CH_4)	30-55%		0-10%				0-10%		0%		5%	

Avg CH_4 (for tubular boilers) 30%

TABLE 10. (Continued)

Boiler Type	Stoker (µg/m³)					
Site No.	137		204		332	
C_1	734		<667		1201	
C_2	<67		<667		11,508	
C_3	<67		<667		<667	
C_4	<67		<667		<667	
C_5	<67		<667		<667	
C_6	<67		<667		<667	
C_7	4.3		76		14,776	
C_8	160.0		32		400	
C_9	5.1		1		47	
C_{10}	33.0		305		330	
C_{11}	0.4		2		214	
C_{12}	0.4		31		42	
C_{13}	10.1		4		43	
C_{14}	3.2		127		57	
C_{15}	0.4		27		10	
C_{16}	11.7		93		20	
Add'l C_7-C_{16}	0		0		0	
TOTALS	µg/m³	ng/J	µg/m³	ng/J	µg/m³	ng/J
C_2-C_6	0-335	0-.184	0-3335	0-1.817	11,508-14,176	5.487-6.759
C_7-C_{16}	225.4-228.6	.126	698	.380	15,939	7.600
C_2-C_{16}	225-564	.124-.310	698-4033	.380-2.197	27,447-30,115	13.09-14.36
C_1-C_{16}	959-1298	.527-.713	698-4700	.380-2.560	28,648-31,316	13.66-14.93

The final row of data, before totals and immediately following C_{16}'s is identified as additional C_7 to C_{16}'s. This number takes into account components in the SASS train (such as probe rinse, cyclone rinse, etc.) which contained less than the minimum sample quantity required for individual analyses by alkane group.

Tables 11, 12, and 13 provide the same type of data as shown in Table 10, but for lignite, residual oil, and gas-fired utility boilers, respectively.

Table 14 presents a summary of totaled data from Tables 10 to 13 in both SI units (ng/J) and English units (lb/10^9 Btu). Data are presented for each site tested by feed type (coal, lignite, residual oil, and gas) and boiler type (pulverized dry bottom, pulverized wet bottom, cyclone, stoker, tangentially-fired, and wall-fired).

Means, $\bar{x}$, and standard deviations of the mean, $s(\bar{x})$, have been calculated for each group of data in Tables 10 to 14 corresponding to a common fuel and boiler type. These statistical parameters have been tabulated in Table 15 for each of the four totals (C_2 to C_6, C_7 to C_{16}, C_2 to C_{16}, and C_1 to C_{16}) by fuel and boiler type.

The standard deviation calculated in this report is based on a limited sample size and is designated as $s(\bar{x})$. $s(\bar{x})$ differs from the estimate of the population standard deviation, $s(x)$. $s(x)$ is based on the sample $x_1, x_2 \dots x_n$ and is calculated by the following formula (4):

$$s(x) = \sqrt{\frac{\Sigma (x-\bar{x})^2}{n-1}}$$

The use of n-1 in the denominator offsets the bias due to calculating the deviations of x from $\bar{x}$, the sample mean, rather than from the unknown true population means.

$s(\bar{x})$ designates the estimated standard deviation of the means of samples of size n drawn from the populaton which is estimated to have a standard deviation of $s(x)$. These two quantities are related in the following way:

$$s(\bar{x}) = \frac{s(x)}{\sqrt{n}}$$

TABLE 11. LIGNITE-FIRED UTILITY BOILER VOC EMISSIONS

Boiler Type	Pulverized, dry bottom (µg/m³)						Cyclone (µg/m³)				Stoker (µg/m³)			
Site No.	314		315		318		316		155		317		319	
C_1	1,335		5,339		1,034		10,677		2,202		1,782			
C_2	<667		<667		1,751		<667		<334		<667			
C_3	<667		<667		1,211		<667		<334		<667		NO DATA	
C_4	<667		<667		<667		<667		<334		<667			
C_5	9,004		<667		<667		<667		5,102		<667			
C_6	32,263		<667		<667		<667		<334		<667			
C_7	<0.2		<0.2		4.8		<0.2		14		<0.2		<0.2	
C_8	<1.0		<0.2		<1.0		<0.2		29		<1.0		<1.0	
C_9	13.8		4.0		71.0		0		30		0		16.3	
C_{10}	82.3		73.5		56.2		143		23		164		60.1	
C_{11}	37.3		133.3		<0.2		0		5		202		0 0	
C_{12}	132.0		96.8		94.0		75		10		104		67.6	
C_{13}	0		313.8		43.1		0		6		0		33.7	
C_{14}	1.94		3.2		63.5		3		6		22.5		37.0	
C_{15}	14.8		291.0		35.9		.2		8		12.3		12.1	
C_{16}	40.4		6.7		32.9		123		7		34.5		19.0	
Add'l C_7-C_{16}	106.0		14.0		18.0		2		0		104		23.2	
TOTALS	µg/m³	ng/J	µg/m³	ng/J	µg/m³	ng/J	µg/m³	ng/J	µg/m³	ng/J	µg/m³	ng/J	µg/m³	ng/J
C_2-C_6	41,267-43,268	14.21-14.90	0-3335	0-1.125	2,962-4,963	1.820-3.049	0-3335	0-1.308	5102-6438	2.065-2.605	0-3335	0-1.839	--	--
C_7-C_{16}	428.5-429.7	.148	936.2-936.6	.316	419.4-420.6	.258	382.4-382.6	.150	138	.056	643.3-644.5	.355	269.0 270.2	.148
C_2-C_{16}	41,696-43,698	14.36-15.05	936-4,272	.316-1.441	3,381-5,384	2.077-3.308	382-3718	.150-1.458	5240-6576	2.121-2.661	643-3980	.355-2.195	--	--
C_1-C_{16}	43,031-45,033	14.82-15.51	6,279-9,611	2.116-3.241	4,415-6,418	2.712-3.943	11,059-14,395	4.336-5.645	7442-8778	3.012-3.552	2425-5762	1.337-3.178	--	--

TABLE 12. RESIDUAL OIL-FIRED UTILITY BOILER VOC EMISSIONS

Boiler Type	Tangentially-fired ($\mu g/m^3$)							
Site No.	210		211		322		323	
C_1	<667		734		2,469		2,669	
C_2	<667		<67		<667		<667	
C_3	<667		<67		<667		<667	
C_4	<667		<67		<667		24,903	
C_5	3,301		<67		<667		<667	
C_6	<667		<67		<667		<667	
C_7	17.5		22.8		<1		<1	
C_8	62.5		0.8		44		16	
C_9	13.4		0.9		36		<1	
C_{10}	3.4		45.7		0		0	
C_{11}	0.3		<0.4		0		0	
C_{12}	2.9		5.1		59		0	
C_{13}	2.2		15.8		47		1	
C_{14}	0.6		5.6		0		0	
C_{15}	0.6		0.8		0		0	
C_{16}	2.0		2.8		0		0	
Add'l C_7-C_{16}	0		0		0		0	
TOTALS	$\mu g/m^3$	ng/J	$\mu g/m^3$	ng/J	$\mu g/m^3$	ng/J	$\mu g/m^3$	ng/J
C_2-C_6	3301-5969	1.438-2.601	0-335	0-.135	0-3335	0-1.264	24,903-27,571	11.82-13.09
C_7-C_{16}	103.2-105.4	.056	98.1-100.7	.041	187	.071	19	.009
C_2-C_{16}	3404-6074	1.483-2.647	98-436	.039-.176	187-3522	.071 1.335	24,922-27,590	11.83-13.10
C_1-C_{16}	3404-6741	1.483-2.819	832-1170	.335-.471	2656 5991	1.007 2.271	27,591 30,259	13.10 14.37

TABLE 12. (Continued)

Boiler Type	Wall-fired (µg/m³)								
Site No.	105	109	118	119	305	324	141	142	143
C_1	16,684	NO DATA	<667	<667	22,423	400	981	<850	<327
C_2	<667	NO DATA	2502	<667	<667	<667	< 67	< 67	< 67
C_3	<667	NO DATA	<667	<667	<667	<667	<267	<133	< 67
C_4	<667	NO DATA	<667	<667	<667	<667	<133	< 67	< 67
C_5	<667	NO DATA	<667	<667	<667	<667	< 67	< 67	< 67
C_6	<667	NO DATA	<667	<667	<667	<667	< 67	< 67	< 67
C_7	<100	300	8.6	10.6	<0.2	<1	No Data	<1.0	1.1
C_8	3400	800	17.7	20	<0.2	95	No Data	27.3	29.1
C_9	2400	200	4.8	10.9	0.56	62	No Data	8.7	10.7
C_{10}	4900	4	18.7	<0.8	15.1	<1	No Data	3.5	3.7
C_{11}	8500	400	1.1	6.1	4.8	<1	No Data	7.9	8.4
C_{12}	4200	1800	4.8	12.4	11.6	<1	No Data	14.7	1.0
C_{13}	5500	0	1.6	<0.8	2.9	<1	No Data	2.9	3.4
C_{14}	800	200	4.4	1.4	0	<1	No Data	1.2	3.8
C_{15}	<1	200	6.4	2.8	2.7	<1	No Data	1.2	1.0
C_{16}	<1	800	5.4	<0.8	<0.2	<1	No Data	1.5	1.1
Add'l C_7-C_{16}	0	0	0	0	13.7	0	No Data	0	0

TOTALS	105 µg/m³	105 ng/J	109 µg/m³	109 ng/J	118 µg/m³	118 ng/J	119 µg/m³	119 ng/J	305 µg/m³	305 ng/J	324 µg/m³	324 ng/J	Average for 141,142,143* µg/m³	Average for 141,142,143* ng/J
C_2-C_6	0-3335	0-1.213	--	--	2502-5170	.799-1.651	0-3335	0-1.683	0-3335	0-1.435	0-3335	0-1.334	0-446	0-.151
C_7-C_{16}	29,700-29,802	10.80-10.84	4704	1.889	68.5-73.5	.023	66.6	.034	51.2-52.0	.022	157-165	.063-.066	57.9-66.6	.023
C_2-C_{16}	29,700 33,137	10.80 12.05	--	--	2571-5244	.821-1.675	67-3402	.034 1.716	51-3387	.022-1.457	157 3500	.063 1.400	58-435	.020-.147
C_1-C_{16}	46,384 49,821	16.87 18.12	--	--	2571-5911	.821-1.888	67-4069	.034 2.053	22,474-25,810	9.668-11.103	557-3900	.223-1.560	58-1023	.020-.347

*Site Nos. 141, 142, 143 are 3 sets of data acquired from the same boiler.

TABLE 13. GAS-FIRED UTILITY BOILER VOC EMISSIONS

Boiler Type	Tangentially-fired (µg/m^3)						Wall-fired (µg/m^3)							
Site No.	113		114		115		106		108		116		117	
C_1	<334		<667		<667		24,692		NO DATA		<667		<667	
C_2	<334		<667		<667		9,669				<667		<667	
C_3	<334		<667		<667		<667				<667		<667	
C_4	<334		<667		<667		<667				<667		<667	
C_5	<334		<667		<667		<667				18,000		<334	
C_6	<334		<667		<667		<667				<667		<334	
C_7	3.2		<0.8		12.6		<1		<1		1.3		3.5	
C_8	18.0		17.2		32.4		396		199		37.5		30.0	
C_9	11.7		5.3		5.1		1,288		99		1.2		<0.6	
C_{10}	<0.2		11.3		22.6		891		298		14.7		2.2	
C_{11}	<0.2		<0.4		35.9		23,900		1,192		562.4		1.6	
C_{12}	<0.2		<0.4		16.5		1,800		1,093		252.5		<0.6	
C_{13}	<0.6		<0.4		34.2		2,971		1,490		156.5		11.5	
C_{14}	3.2		1.2		57.1		1,684		994		166.6		0.3	
C_{15}	2.1		2.5		107.8		<1		1,292		207.7		6.1	
C_{16}	<0.6		<0.6		98.6		<1		1,590		304.9		1.0	
Add'l C_7-C_{16}	0		0		0		0		0		0		0	
TOTALS	µg/m^3	ng/J	µg/m^3	ng/J	µg/m^3	ng/J	µg/m^3	ng/J	µg/m^3	ng/J	µg/m^3	ng/J	µg/m^3	ng/J
C_2-C_6	0-1670	0-0.50	0-3335	0-.987	0-3335	0-1.309	9,669-12,337	3.095-3.949	--	--	18,000-20,668	6.651-7.640	0-2669	0-.891
C_7-C_{16}	37.0-40.0	.012	36.5-40.1	.012	419.2-422.8	.166	32,930	10.54	8248	3.356	1702.9-1705.3	.694	53.8-57.4	.019
C_2-C_{16}	37-1710	.012-0.51	37-3375	.012-.999	419-3758	.166-1.475	42,599-45,267	13.64-14.49	--	--	19,703-22,373	7.284-8.271	54-2726	.019-.910
C_1-C_{16}	37-2044	.012-0.61	37-4042	.012-1.197	419-4425	.166-1.736	67,291-69,959	21.54-22.40	--	--	19,703-23,040	7.284-8.517	54-3393	.019-1.133

TABLE 14. TOTAL VOLATILE ORGANIC COMPOUND EMISSIONS

Boiler Code*	Site	C_2-C_6 ng/J	C_2-C_6 lb/10^9 Btu	C_7-C_{16} ng/J	C_7-C_{16} lb/10^9 Btu	C_2-C_{16} ng/J	C_2-C_{16} lb/10^9 Btu	C_1-C_{16} ng/J	C_1-C_{16} lb/10^9 Btu
C, PDB	205-1	0-1.587	0-3.7	.309	.7	.309-1.896	.7-4.4	.309-2.214	.7-5.2
	205-2	0-1.605	0-3.7	.466	1.1	.466-2.072	1.1-4.8	.466-2.393	1.1-5.6
	154	1.551-2.178	3.6-5.1	.085	.2	1.635-2.263	3.8-5.3	3.203-3.830	7.5-8.9
C, PWB	206	16.508-16.978	38.4-39.5	.411	1.0	16.917-17.389	39.3-40.4	21.870-22.342	50.9-52.0
	212	0- .163	0- .4	.067	.2	.066- .230	.2- .5	.682- .846	1.6- 2.0
	213	.122- .252	.3- .6	.040	.1	.161- .293	.4- .7	2.535- 2.667	5.9- 6.2
	336	.367- .928	.8- 2.2	.100	.2	.465 1.028	1.1- 2.4	.773- 1.335	1.8- 3.1
	338	.713- 1.299	1.7- 3.0	.360	.8	1.073 1.659	2.5- 3.9	1.512- 2.098	3.5- 4.9
	218	0- .621	0- 1.4	.067	.2	.067- .688	.2- 1.6	.662- 1.283	1.5- 3.0
C, CC	134	.312- 1.510	.7- 3.5	.343	.8	.655- 1.853	1.5- 4.3	1.452- 2.651	3.4- 6.2
	207	0- .212	0- .5	.151	.4	.150- .363	.3- .8	.150- .405	.3- .9
	208	--	--	.0055	.01	--	--	--	--
	209	0- .137	0- .3	.081	.2	.079- .218	.2- .5	.079- .245	.2- .6
	330	27.56 -28.38	64.1-66.0	.040	.0007	27.59 - 28.42	64.2-66.1	27.67 - 28.50	64.4-66.3
	331	6.434- 7.819	15.0-18.2	3.074	.01	9.508-10.89	22.1-25.3	10.06 - 11.45	23.4-26.6
C, S	137	0- .184	0- .4	.126	.3	.124- .310	.3- .7	.527- .713	1.2- 1.7
	204	0- 1.817	0- 4.2	.380	.9	.380- 2.197	.9- 5.1	.380- 2.560	.9- 6.0
	332	5.487- 6.759	12.8-15.7	7.600	17.7	13.09 -14.36	30.4-33.4	13.66 -14.93	31.8-34.7
L, PDB	314	14.21 -14.90	33.1-34.7	.148	.3	14.36 -15.05	33.4-35.0	14.82 -15.51	34.5-36.1
	315	0- 1.125	0- 2.6	.316	.7	.316- 1.441	.7- 3.4	2.116- 3.241	4.9- 7.5
	318	1.820- 3.049	4.2- 7.1	.258	.6	2.077- 3.308	4.8- 7.7	2.712- 3.943	6.3- 9.2
L, CC	316	0- 1.308	0- 3.0	.150	.3	.150- 1.458	.3- 3.4	4.336- 5.645	10.1-13.1
	155	2.065- 2.605	4.8- 6.1	.056	.1	2.121- 2.661	4.9- 6.2	3.012- 3.552	7.0- 8.3

*The first letter refers to feed type: C (coal); L (lignite); O (oil); and, G (gas). The second group of letters refer to boiler type: PDB (pulverized dry bottom; PWB (pulverized wet bottom; CC (cyclone); S (stoker); TF (tangentially-fired); and, WF (wall-fired).

TABLE 14. (Continued)

Boiler Code	Site	C_2-C_6 ng/J	C_2-C_6 lb/10^9 Btu	C_7-C_{16} ng/J	C_7-C_{16} lb/10^9 Btu	C_2-C_{16} ng/J	C_2-C_{16} lb/10^9 Btu	C_1-C_{16} ng/J	C_1-C_{16} lb/10^9 Btu
L,S	317	0 - 1.839	0 - 4.3	.355	.8	.355- 2.195	.8 - 5.1	1.337- 3.178	3.1 - 7.4
	319	-	-	.148	.3	-	-	-	-
O,TF	210	1.438- 2.601	3.3- 6.0	.056	.1	1.483- 2.647	3.4 - 6.2	1.483- 2.819	3.5 - 6.6
	211	0 - .135	0 - .3	.041	.1	.039- .176	.1 - .4	.335- .471	.8 - 1.1
	322	0 - 1.264	0 - 2.9	.071-	.2	.071- 1.335	.2 - 3.1	1.007- 2.271	2.3 - 5.3
	323	11.82 -13.09	27.5-30.4	.009	.02	11.83- 13.10	27.5 -30.5	13.10- 14.37	30.5 -33.4
O,WF	105	0 - 1.213	0 - 2.8	10.84	25.2	10.80- 12.05	25.1 -28.0	16.87- 18.12	39.2 -42.1
	109	--	--	1.889	4.4	--	-	-	-
	118	.799- 1.651	1.9- 3.8	.023	.05	.821- 1.675	1.9 - 3.9	.827- 1.888	1.9 - 4.4
	119	0 - 1.683	0 - 3.9	.034-	.08	.034- 1.716	.08 - 4.0	.034- 2.053	.08- 4.8
	305	0 - 1.435	0 - 3.3	.022	.05	.022- 1.457	.05- 3.4	9.668-11.103	22.5 -25.8
	324	0 - 1.334	0 - 3.1	.066	.2	.063- 1.400	.1 - 3.3	.223- 1.560	.5 - 3.6
	141-3	0 - .151	0 - .4	.023	.05	.020- .147	.05- .3	.020- .347	.05- .8
G,TF	113	0 - 0.50	0 - 1.2	.012	.03	.011- .51	.03- 1.2	.011- .61	.03- 1.4
	114	0 - .987	0 - 2.3	.012	.03	.011- .999	.03- 2.3	.011- 1.197	.03- 2.8
	115	0 - 1.309	0 - 3.0	.166	.4	.164- 1.475	.4 - 3.4	.164- 1.736	.4 - 4.0
G,WF	106	3.095- 3.949	7.2- 9.2	10.54	24.52	13.64 -14.49	31.7 -33.7	21.54 -22.40	50.1 -52.1
	108	-	-	3.356	7.8	-	-	-	-
	116	6.651- 7.640	15.5-17.8	.694	1.6	7.284- 8.271	16.9 -19.2	7.284- 8.517	16.9 -19.8
	117	0 - .891	0 - 2.1	.019	.04	.018- .910	.04- 2.1	.018- 1.133	.04- 2.6

*The first letter refers to feed type: C (coal); L (lignite); O (oil); and, G (gas). The second group of letters refer to boiler type: PDB (pulverized dry bottom; PWB (pulverized wet bottom; CC (cyclone); S (stoker); TF (tangentially-fired); and, WF (wall-fired).

TABLE 15. AVERAGED VOLATILE ORGANIC COMPOUND EMISSIONS

Fuel*	Boiler† Type	Alkane Group	$\bar{x}$ µg/m^3	$\bar{x}$ lb/10^9 SCF	$\bar{x}$ ng/J	$\bar{x}$ lb/10^9 Btu	$s(\bar{x})$ ng/J	$s(\bar{x})$ lb/10^9 Btu
C	PDB	C_2-C_6	1,100- 3,769	69- 235	.52-1.80	1.2- 4.2	.19	.4
		C_7-C_{16}	599	37	.29	.7	.11	.3
		C_2-C_{16}	1,696- 4,368	106- 273	.80-2.08	1.9- 4.8	.11	.3
		C_1-C_{16}	2,808- 5,925	175- 370	1.32-2.81	3.1- 6.5	.51	1.2
C	PWB	C_2-C_6	6,316- 7,307	394- 456	2.95-3.37	6.9- 7.8	2.73	6.3
		C_7-C_{16}	339	21.2	.174	.4	.067	.2
		C_2-C_{16}	6703- 7696	418- 480	3.12-3.55	7.3- 8.3	1.45	3.4
		C_1-C_{16}	10,040-11,033	627- 689	4.67-5.10	10.9-11.9	3.46	8.0
C	CC	C_2-C_6	15,937-17,545	995-1095	6.86-7.61	16.0-17.7	5.38	12.5
		C_7-C_{16}	1207	75	.62	1.4	.49	1.1
		C_2-C_{16}	17,380-18,991	1085-1186	7.60- 8.35	17.7-19.4	5.39	12.5
		C_1-C_{16}	17,991-19,629	1123-1225	7.88- 8.65	18.3-20.1	5.37	12.5
C	S	C_2-C_6	3,836- 5,949	239- 371	1.83-2.92	4.3- 6.8	1.98	4.6
		C_7-C_{16}	5,622	351	2.70	6.3	2.45	5.7
		C_2-C_{16}	9,457-11,571	591- 723	4.53- 5.62	10.5-13.1	4.40	10.2
		C_1-C_{16}	10,100-12,438	631- 777	4.86- 6.07	11.3-14.1	4.46	10.4
L	PDB	C_2-C_6	14,743-17,189	920-1073	5.34-6.36	12.4-14.8	4.31	10.0
		C_7-C_{16}	596	37	.24	.6	.05	.1
		C_2-C_{16}	15,338-17,785	958-1110	5.58-6.60	13.0-15.4	4.26	9.9
		C_1-C_{16}	17,907-20,354	1118-1271	6.55-7.56	15.2-17.6	3.98	9.3

*C, L, O, and G refer to coal, lignite, residual oil, and gas, respectively.

†PDB means pulverized dry bottom, PWB - pulverized wet bottom; CC - cyclone; S - stoker; TF - Tangentially-fired; and, WF - wall-fired.

TABLE 15. (Continued)

Fuel	Boiler Type	Alkane Group	$\bar{x}$ μg/m³	$\bar{x}$ lb/10⁹ SCF	$\bar{x}$ ng/J	$\bar{x}$ lb/10⁹ Btu	$s(\bar{x})$ ng/J	$s(\bar{x})$ lb/10⁹ Btu
L	CC	C_2-C_6	2,551- 4,887	159-305	1.03-1.96	2.4- 4.6	.65	1.5
		C_7-C_{16}	260	16	.10	.2	.05	.1
		C_2-C_{16}	2,811- 5,147	175-321	1.14-2.06	2.7- 4.8	.60	1.4
		C_1-C_{16}	9,251-11,587	578-723	3.67-4.60	8.5-10.7	1.05	2.4
L	S	C_2-C_6	0- 3,335*	0-208	0-1.84	0- 4.3	--	--
		C_7-C_{16}	457	29	.252	.6	.10	.2
		C_2-C_{16}	643- 3,980	40-248	.36-2.20	.8- 5.1	--	--
		C_1-C_{16}	2,425- 5,762	151-360	1.34-3.18	3.1- 7.4	--	--
O	TF	C_2-C_6	7,051- 9,303	440-581	3.31-4.27	7.7- 9.9	2.98	6.9
		C_7-C_{16}	102	6.4	.044	.1	.01	.02
		C_2-C_{16}	7,153- 9.406	447-587	3.36-4.31	7.8-10.0	2.97	6.9
		C_1-C_{16}	8,621-11,040	538-689	3.98-4.98	9.3-11.6	3.17	7.4
O	WF	C_2-C_6	500- 3,124	31-195	.16-1.25	.4- 2.9	.28	.7
		C_7-C_{16}	82	5	0.033	0.077	.008	0.02
		C_2-C_{16}	581- 3,194	36-199	0.19-1.28	0.4- 3.0	0.29	0.7
		C_1-C_{16}	5,145- 8,142	321-508	2.15-3.39	5.0- 7.9	1.95	4.5
G	TF	C_2-C_6	0- 2,780	0-173	0-0.93	0- 2.2	.24	.6
		C_7-C_{16}	168	10	.033	.1	.05	.1
		C_2-C_{16}	164- 2,948	10-184	.06- .99	.1- 2.3	.28	0.7
		C_1-C_{16}	164- 3,504	10-219	.06-1.18	.1- 2.7	.33	.8
G	WF	C_2-C_6	9,000-11,669	562-728	3.32-4.27	7.7- 9.9	3.37	7.8
		C_7-C_{16}	880	55	0.36	0.8	0.34	0.8
		C_2-C_{16}	9,880-12,550	617-783	3.65-4.59	8.5-10.7	3.68	8.6
		C_1-C_{16}	9,880-13,216	617-825	3.65-4.83	8.5-11.2	3.69	8.6

*Data based on only one site.

Examination of the data presented indicated unusually high C_2-C_{16} emissions from bituminous coal-fired sites 206, 330, 331, and 332, lignite-fired site 314, residual oil-fired sites 105 and 323, and gas-fired sites 106 and 116. For sites 105 and 106, the extremely high levels of organic materials in the blanks for the XAD-2 resin and in the solvent blanks have rendered the organic emission data unusable. Data from these two sites are, therefore, not included in the determination of emission factors. For the remaining sites associated with high C_2-C_{16} emissions, however, examination of the field and laboratory operation data revealed no indication that these high values are artifacts. A possible explanation for these higher emissions is that in source testing of the EACCS program, no special readjustments of burners at any of the sites were ever made. Therefore, some of the boilers tested may be in poor operating condition with inefficient mixing between air and fuel, and resulted in high organic emissions. Nevertheless, because of the existence of a few high emission values which cannot be discarded as outliers, the calculated average emission factors presented in Table 15 are "biased" and not representative of VOC emissions from typical power plants*. Another method of data analysis was, therefore, used in determining representative VOC emission factors.

In Figures 1 to 5, the reactive VOC emission data from Table 14 are summarized in graphical form for each fuel type by plotting reactive VOC emissions versus the cumulative frequency in the population sampled. Both the maximum and minimum reactive VOC emission data are presented in the same diagram. These minimum and maximum values are based on the detection limits of the procedures employed. The minimum emission values were computed by assuming all "less than" values in reported data as zero, whereas the maximum emission values were computed by assuming upper limit values for all "less than" values. Thus, the range in emission values represents data uncertainty due to the low sensitivity of the field gas chromatograph used in determining C_1-C_6 emissions. The true value is expected to lie between the minimum and

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*These average emission factors, however, are useful in determining total emissions from all sources, which include both typical and atypical plants.

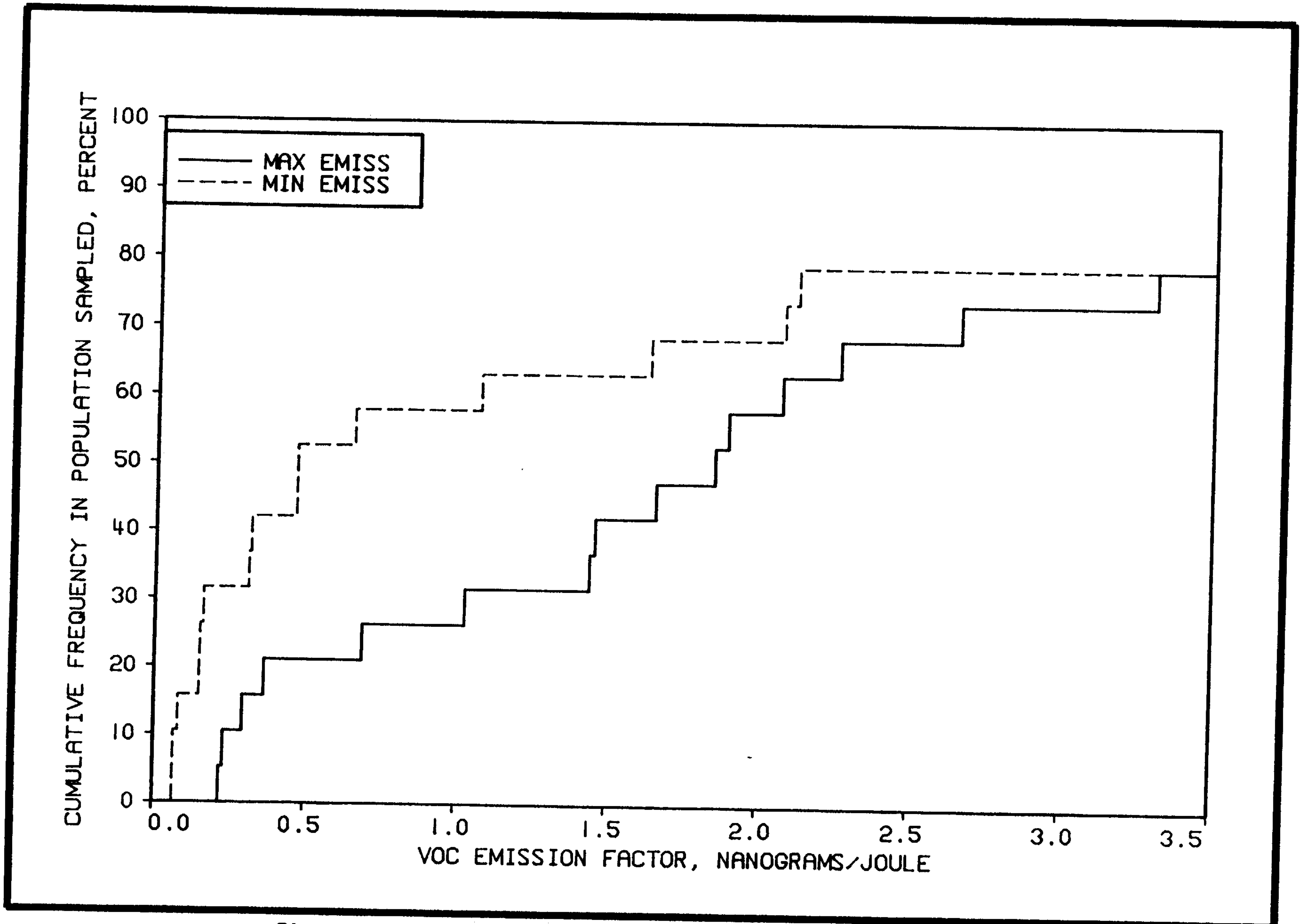

Figure 1. Cumulative graph of VOC data for bituminous coal and lignite-fired units with pulverized or cyclone firing.

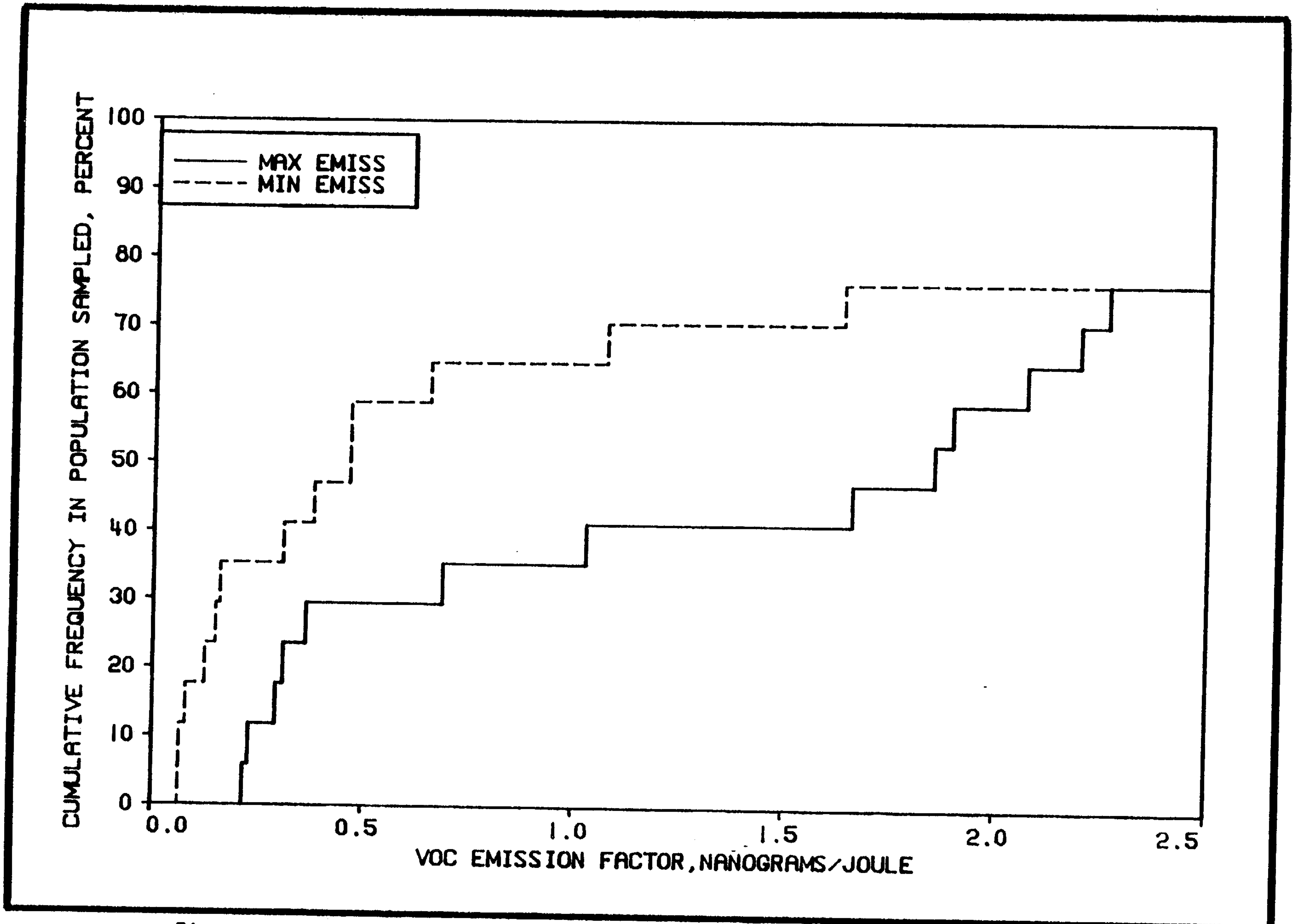

Figure 2. Cumulative graph of VOC data for bituminous coal-fired boilers.

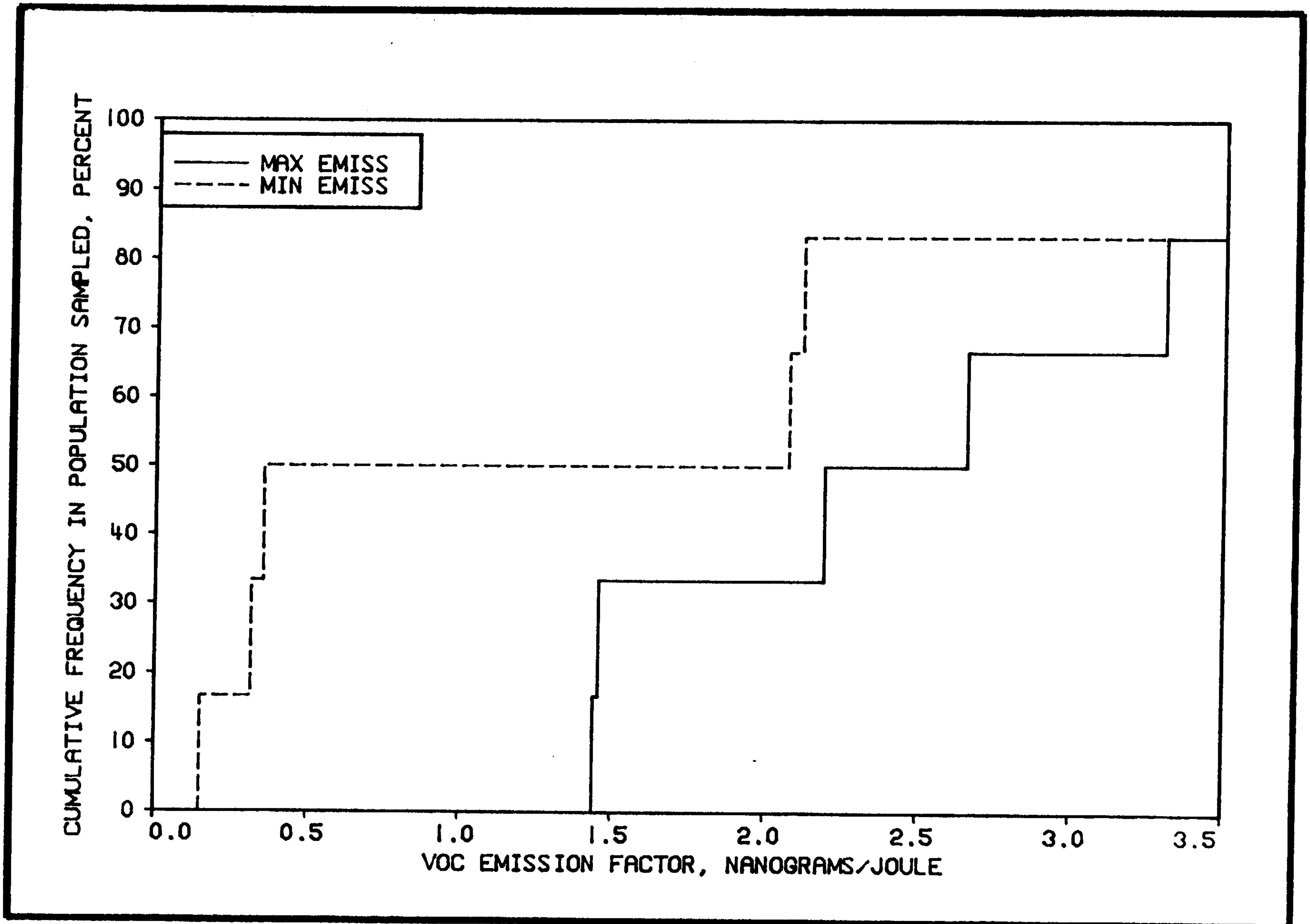

Figure 3. Cumulative graph of VOC data for lignite-fired boilers.

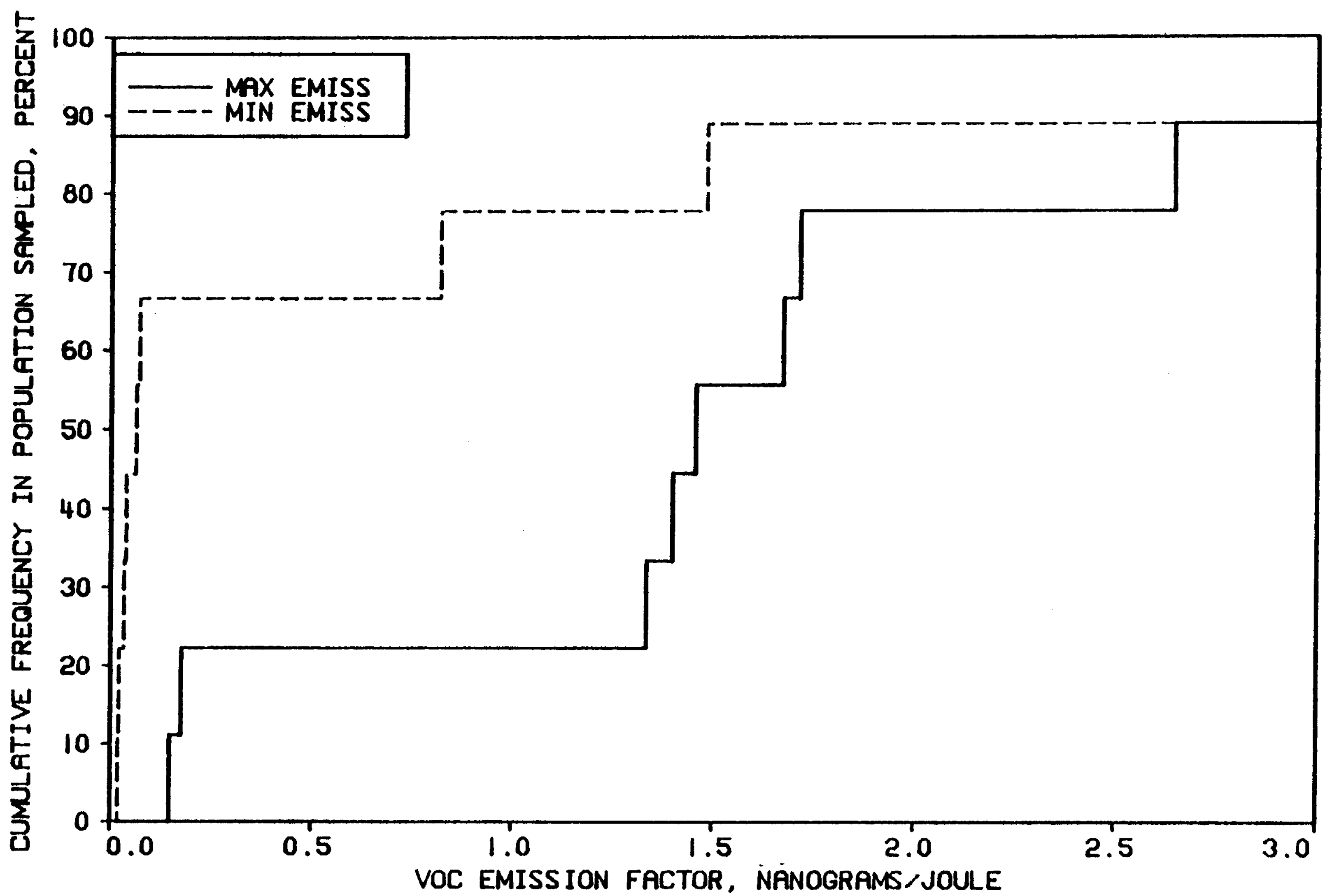

Figure 4. Cumulative graph of VOC data for oil-fired boilers.

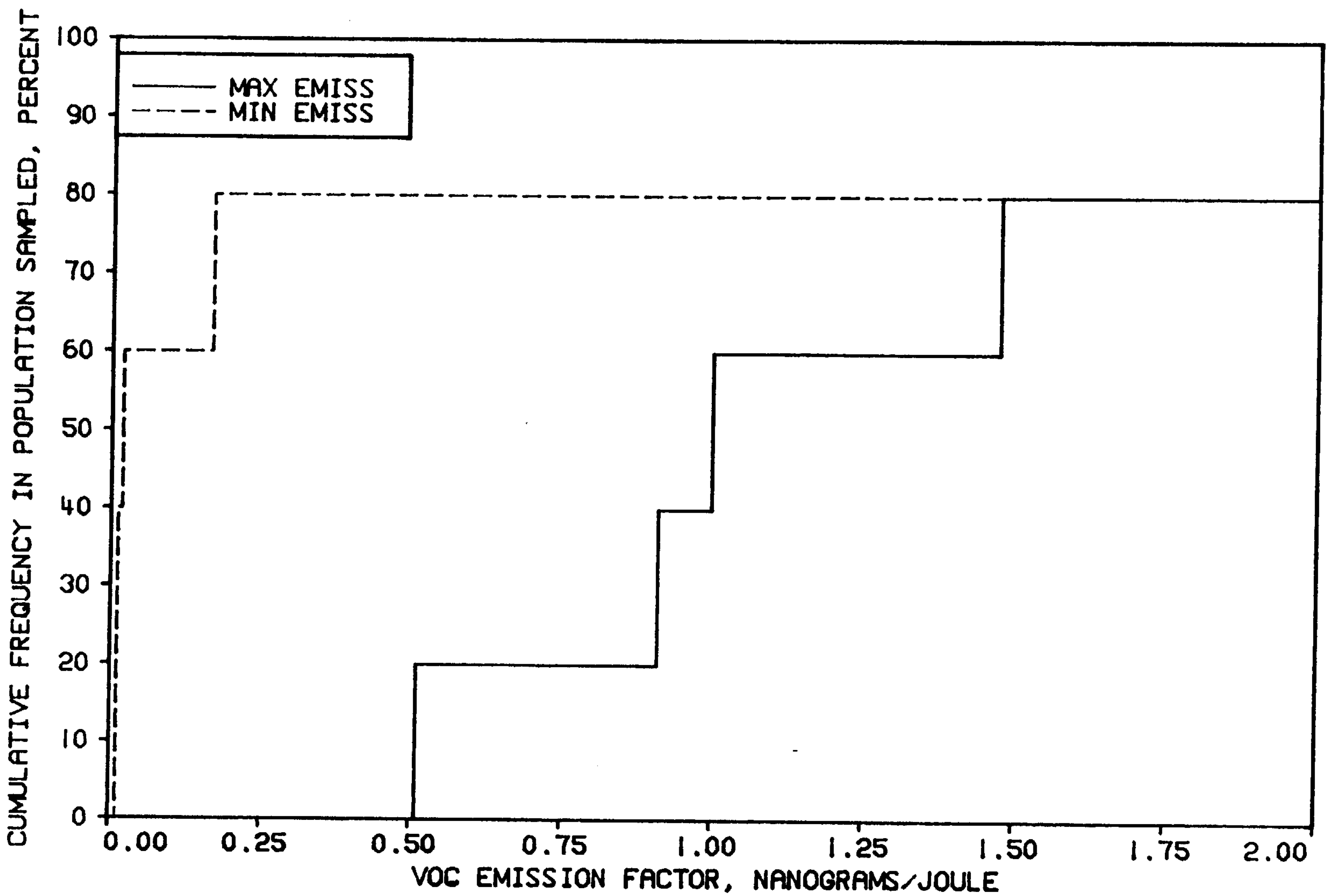

Figure 5. Cumulative graph of VOC data for gas-fired boilers.

maximum values. For example, the plot in Figure 1 shows that between 42 and 63 percent of all bituminous coal-fired and lignite-fired pulverized and cyclone boilers tested had reactive VOC emissions less than 1.58 ng/J (equivalent to less than 100 tons/year). The same plot also shows that the median value of the reactive VOC emission factor for these types of boilers is between 0.47 and 1.85 ng/J. Similar information can be obtained from Figures 2, 3, 4, and 5 for bituminous coal-fired, lignite-fired, oil-fired, and gas-fired utility boilers, respectively.

Data presented in Figures 1 to 5 were used to determine total quantities of reactive VOC's emitted annually from hypothetical 1000 MW power plants fired with each type of fuel. The following assumptions were used:

- Each power plant has a maximum rated capacity of 1000 MW.
- Each power plant operates year-round at a load factor of 60%.
- Overall efficiency is 33 percent for each power plant, regardless of fuel type.
- Median values of reactive VOC emission factors are representative of reactive VOC emissions from typical power plants.

On the above basis, the calculated reactive VOC emissions from typical 1000 MW power plants are as follows:

Fuel Type	Median Emission Factor (ng/J)	Annual Reactive VOC Emissions (Tons/year)
Coal and Lignite*	0.47-1.85	30-117
Coal	0.47-1.85	30-117
Lignite	0.38-2.65	24-168
Residual Oil	0.03-1.48	2-94
Gas	0.01-1.00	1-63

*Based on data from Figure 1, these are combined test data from bituminous coal-fired and lignite-fired utility boilers, with the exception that all stoker test data have been excluded.

The percentage of hypothetical 1000 MW power plants with annual reactive VOC emissions less than 100 tons/year can also be obtained from Figures 1 to 5. It was determined that 42 to 63 percent of coal- and lignite-fired plants*, 55 to 89 percent of residual oil-fired plants, and 80 percent of gas-fired plants emit less than 100 tons/year of reactive VOC's.

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*Based on data from Figure 1, these are combined test data from bituminous coal-fired and lignite-fired utility boilers, with the exception that all stoker test data have been excluded.

5. CONCLUSIONS AND RECOMMENDATIONS

Based on the emission data collected and analyzed by TRW and GCA at 43 coal-, lignite-, residual oil-, and gas-fired utility boilers, the following conclusions can be reached:

- Median values of reactive VOC emissions ranged between 0.47 and 1.85 ng/J for coal- and lignite-fired utility boilers, between 0.03 and 1.48 ng/J for residual oil-fired utility boilers, and between 0.01 and 1.00 ng/J for gas-fired utility boilers. The ranges in emission values represent data uncertainty due to the low sensitivity of field gas chromatograph used in determining C_1-C_6 emissions. Comparison of these median emission values indicates that reactive VOC emissions are highest for coal- and lignite-fired sources, and lowest for gas-fired sources.

- Five of the boilers sampled had reactive VOC emissions above 10 ng/J. These higher emissions were probably due to burner maladjustment with inefficient mixing between air and fuel, and demonstrate the importance of proper maintenance.

- The percentage of hypothetical 1000 MW power plants with annual reactive VOC emissions less than 100 tons/year was 42 to 63 percent for coal- and lignite-fired sources, 55 to 89 percent for residual oil-fired sources, and 80 percent for gas-fired sources.

The Level I organic analysis procedure used provided data on emissions of gaseous organics (C_1-C_6), volatile organics (C_7-C_{16}), and nonvolatile organics ($>C_{16}$). The gas chromatographic (GC) analyses performed were used to obtain information on the quantity of organic material boiling within discrete ranges corresponding to the boiling points of the n-alkanes. Organic emissions were classified solely on the basis of their retention time relative to n-alkanes and were quantitated as n-alkanes. Thus, any oxygenated hydrocarbons emitted were included in the reported C_2-C_{16} and $>C_{16}$ values as n-alkane equivalents, although separate, quantitative determinations of the oxygenated hydrocarbons were not made.

According to the Level I procedure, further organic analysis is conducted only if the total organic concentration in the stack gas exceeds 500 $\mu g/m^3$.

The additional analysis includes a class fractionation by liquid chromatography (LC), followed by gas chromatography (GC) and infrared (IR) analysis. For LC fractions containing substantial quantities of organics (>500 $\mu g/m^3$), low resolution mass spectrometric (LRMS) analysis to determine compound types was also performed. Examination of IR and LRMS analysis results obtained in the EACCS program has indicated the presence of aldehydes/ketones, carboxylic acids, alcohols, phenols, ethers, and esters in stack emissions from utility boilers. However, these analysis techniques only provide qualitative determination of the oxygenated hydrocarbons. If more refinements in the current reactive VOC emission data base are desired, additional work in the following areas are recommended:

- Quantitative identification of oxygenated hydrocarbons using specially designed Level II sampling and analysis procedures.
- Monitoring of C_1-C_6 emissions with high sensitivity gas chromatograph in the field, so that emission data can be reported as exact values and not "less than" values due to detection limit problems. This would result in more accurate estimates of VOC emission factors.
- Evaluation of the effects of boiler types and boiler operating parameters on VOC emissions by a statistically designed experimental matrix. This would result in the subgrouping of VOC emission data and lead to better estimates of VOC emission factors for each fuel/boiler subcategory.

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16. ABSTRACT The report gives results of the measurement of emission factors for reactive volatile organic compounds (VOC) from 43 utility boilers firing bituminous coal, lignite, oil, and natural gas. The boilers ranged in size from 9 to 910 MW. The median reactive VOC emission factors were determined to be between 0.47 and 1.85 ng/J for coal- and lignite-fired sources (excluding stoker data); between 0.03 and 1.48 ng/J for residual-oil-fired sources; and between 0.01 and 1.00 ng/J for gas-fired sources. Approximately 50% of the coal- and lignite-fired plants and a majority of the oil- and gas-fired plants were emitting reactive VOC below the 100-ton per year level.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Boilers	Stationary Sources	13A
Utilities	Reactive Volatile Organic Compounds	
Emission		14G
Organic Compounds		07C
Volatility		20M
Fossil Fuels		21D

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