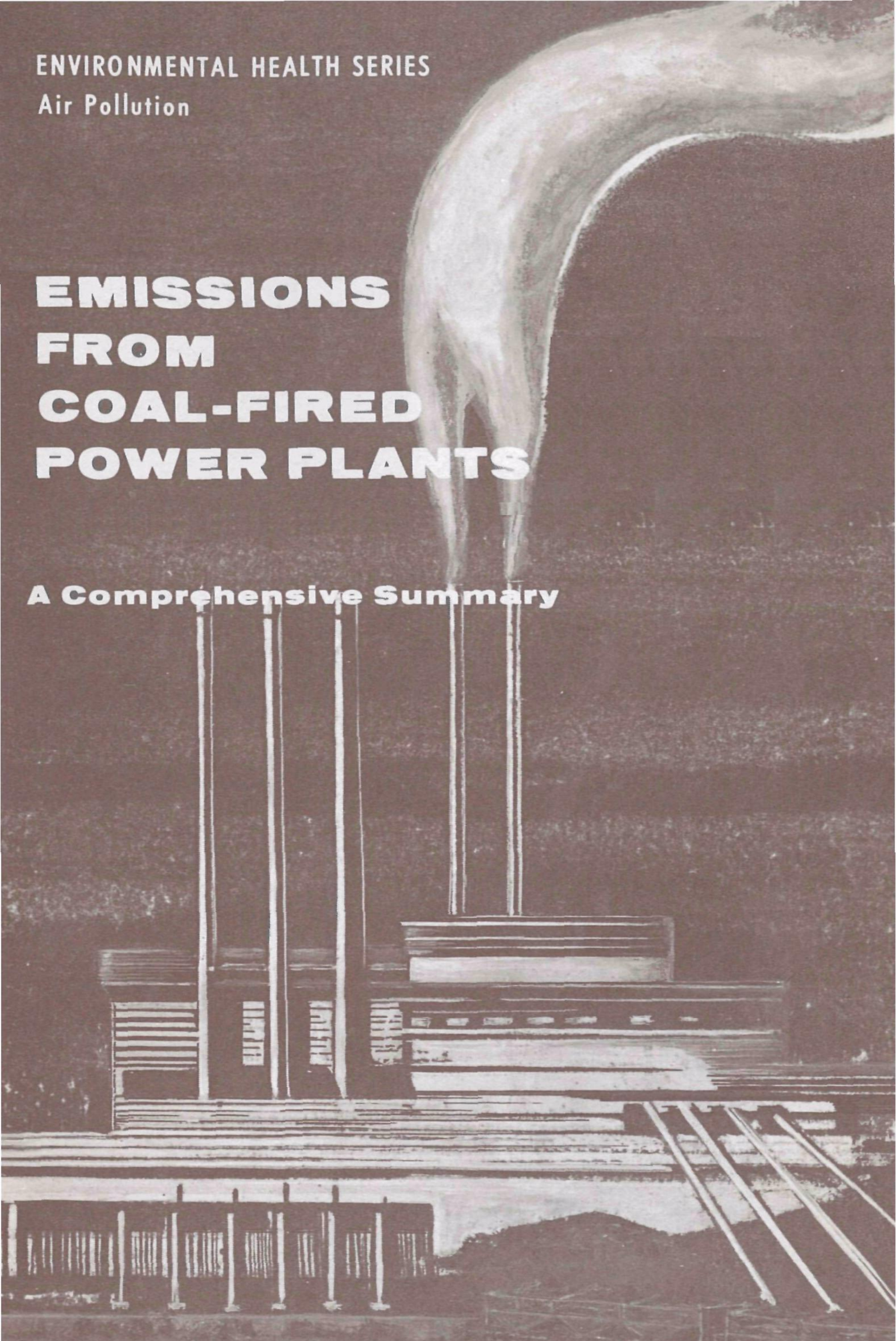
ENVIRONMENTAL HEALTH SERIES

Air Pollution

EMISSIONS FROM COAL-FIRED POWER PLANTS

A Comprehensive Summary



U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE

Public Health Service

EMISSIONS FROM COAL-FIRED POWER PLANTS: A COMPREHENSIVE SUMMARY

Stanley T. Cuffe
and
Richard W. Gerstle
National Center for Air Pollution Control

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Bureau of Disease Prevention and Environmental Control

Cincinnati, Ohio

1967

The ENVIRONMENTAL HEALTH SERIES of reports was established to report the results of scientific and engineering studies of man's environment: The community, whether urban, suburban, or rural, where he lives, works, and plays; the air, water, and earth he uses and reuses; and the wastes he produces and must dispose of in a way that preserves these natural resources. This SERIES of reports provides for professional users a central source of information on the intramural research activities of programs and Centers within the Public Health Service, and on their cooperative activities with State and local agencies, research institutions, and industrial organizations. The general subject area of each report is indicated by the two letters that appear in the publication number; the indicators are

AP Air Pollution

AH - Arctic Health

EE - Environmental Engineering

FP - Food Protection

OH - Occupational Health

RH - Radiological Health

WP Water Supply
and Pollution Control

Triplicate tear-out abstract cards are provided with reports in the SERIES to facilitate information retrieval. Space is provided on the cards for the user's accession number and key words.

Reports in the SERIES will be distributed to requesters, as supplies permit. Requests should be directed to the Center identified on the title page, or to 5555 Ridge Avenue, Cincinnati, Ohio 45213.

Public Health Service Publication No. 999-AP-35

CONTENTS

ABSTRACT

The Public Health Service and the Bureau of Mines conducted a study of air pollutant emissions from the six main types of coal-burning power plants. The components tested include sulfur oxides, nitrogen oxides, polynuclear hydrocarbons, total gaseous hydrocarbons, solid particulates, formaldehyde, organic acids, arsenic, trace metals, and carbon monoxide. This report relates the effects of variables such as method of operation, type of boiler furnace and auxiliaries, reinjection of fly ash, and type of coal burned to the concentrations of gaseous and particulate pollutants in the products of combustion.

EMISSIONS FROM COAL-FIRED POWER PLANTS:

A COMPREHENSIVE SUMMARY

INTRODUCTION

Total requirements for power plant energy from the combustion of coal are expected to increase from 211,000,000 tons per year in 1963 to over 600,000,000 tons per year in 2000.[1] This 300 percent expansion is expected in spite of the increased use of nuclear and petroleum fuels.

Most of this coal will be burned in large power plants with steam capacities in excess of 1 million pounds per hour. In 1962, over 60 percent of the steam generators sold in the United States had capacities of 2 million pounds of steam per hour; this trend toward large-capacity generators is expected to continue as the need for more economical power production increases.

To assess the contribution of coal-fired power plants to the overall air pollution burden, the Public Health Service and the Bureau of Mines conducted a joint study to determine atmospheric emissions from the main types of coal-fired power plants. The objective of the study was the assessment of a number of flue-gas-stream components of interest in air pollution. The components determined were sulfur oxides, nitrogen oxides, polynuclear hydrocarbons, total gaseous hydrocarbons, solid particulates, formaldehyde, trace metals, carbon monoxide, carbon dioxide, and oxygen. When possible, the effects of variables such as method of operation, type of boiler furnace, type of coal burned, and reinjection of fly ash were related to the type and amount of pollutant emitted.

The six typical designs of coal-fired steam generators tested were vertically fired; corner-fired; front-wall horizontally fired; horizontally opposed fired, wet-bottom; cyclone-fired wet-bottom; and traveling-grate spreader-stoker fired. Results of tests on the first four designs have been published.[2,3] This report presents comparative data for all six types of boilers.

SAMPLING AND ANALYTICAL TECHNIQUES

Summarized descriptions of flue-gas sampling and analytical techniques used for the power plant study have been published.[2,3,4] Standard methods were used for sulfur oxides,[5,6] nitrogen oxides,[7] polynuclear hydrocarbons,[8,9,10] total gaseous hydrocarbons, solid particulate, formaldehyde,[11] arsenic,[12] trace metals, carbon monoxide, carbon dioxide, and oxygen.

Solid particulate was collected by simultaneously traversing the inlet and outlet ducts of the fly-ash collector with the sample train illustrated in Figure 1. Isokinetic sampling rates were maintained by continually measuring the velocity with a pitot tube attached to the probe. Particulate obtained from the cyclone and filters, in addition to that obtained by brushing the train and filtering the bubbler and wash water, was used for determining total particulate weight after drying at 105°C.

Samples of coal entering the furnaces were collected hourly during the test periods. Proximate and sulfur analyses were made on each sample, and ultimate analyses were made on composite samples (Table 1).

DESCRIPTION OF UNITS

Boiler operating conditions and flue-gas data for all six types of boilers at both full and partial load are given in Table 2.

Vertically Fired Unit   The vertically fired dry-bottom unit (Figure 2) is rated at 1,100,000 pounds of steam per hour at 1,900 psig and 1,000°F. Coal, pulverized in two ball mills, is conveyed to 16 sets of burner ports by four exhausters. Combustion air is supplied by two 210,000-cfm forced-draft fans. The air enters the furnace through the burner ports

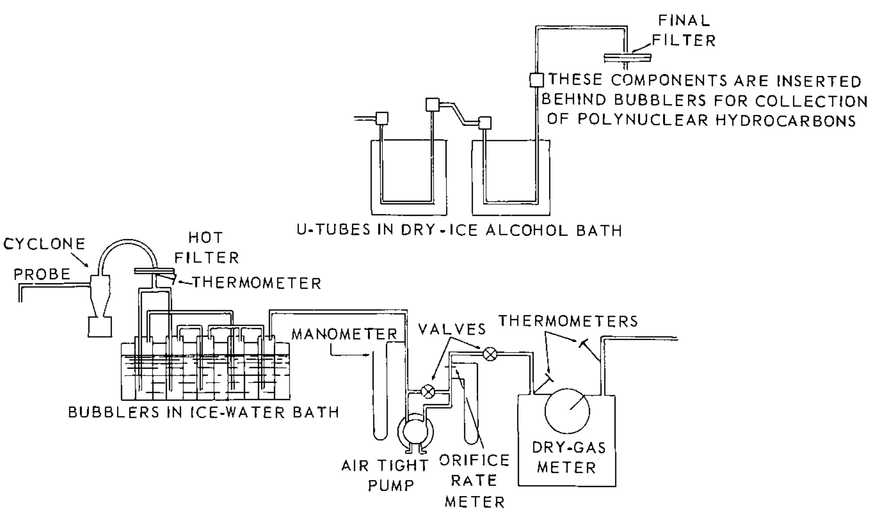


Figure 1. Particulate sampling train.

Table 1. ANALYSES OF COALS BURNED

Component	Vertical	Corner		Front-wall		Spreader stoker	Cyclone	Horizontally opposed
	Pa.	Ohio	W. Va. District 8	Ky. Strip	W. Va. Deep Mine	Ill.	Pa.	Ill.
Proximate Analysis (as-fired), %								
Moisture	1.1	2.8	1.8	2.3	1.2	4.1	1.1	2.0
Volatile matter	30.8	37.2	32.9	38.3	36.2	42.9	37.0	36.5
Fixed carbon	48.3	44.0	53.6	49.6	54.5	44.8	54.5	53.6
Ash	19.8	16.0	11.7	9.8	8.1	8.2	7.4	7.9
Ultimate analysis (as-fired), %								
Hydrogen	4.6	5.0	4.8	5.1	5.1	5.5	5.2	5.1
Carbon	65.8	64.2	72.1	70.9	75.9	70.0	77.4	73.7
Nitrogen	1.4	1.3	1.4	1.5	1.5	1.4	1.4	1.6
Oxygen	6.1	11.8	9.0	10.4	8.2	12.4	6.1	9.4
Sulfur	2.3	1.8	1.0	2.3	1.2	2.5	2.4	2.3
Ash	19.8	16.0	11.7	9.8	8.1	8.2	7.5	7.9
Heating value, Btu/lb	11,820	11,480	12,645	12,640	13,540	12,650	13,910	13,195

Table 2. SUMMARY OF BOILER AND FLUE GAS DATA

Type of boiler firing	Boiler conditions		Flue-gas volume, mscfm		Average flue-gas temp, °F		Moisture, %		CO_2, %		O_2, %		Excess air,[b] %	
	Steam rate, lb/hr	Coal rate, ton/hr	B[e]	A[e]	B[e]	A[f]	B[e]	A[f]	B[e]	A[f]	B[e]	A[f]	B[e]	A[f]
Full-load tests[c]														
Vertical	1,100,000	65.6	397.4	409.9	258	268	6.4	5.7	12.6	12.2	6.2	6.4	41.0	45.3
Corner	960,000	56.1	362.9	351.0	283	275	7.0	8.1	14.4[a]	14.3[a]	4.7	4.8	28.6	29.1
Front-wall	920,000	52.2	329.0	328.0	257	255	5.9	6.3	13.6	13.0	5.3	5.6	32.9	35.5
Spreader-stoker	150,000	9.2	53.9	59.6	426	328	7.8	7.5	12.1	11.8	6.6	7.0	44.5	44.8
Cyclone	1,332,000	64.4	557.6	500.8	279	256	6.3	5.9	12.8	12.7	6.4	6.3	42.6	42.0
Horizontally opposed	149,000	9.6	62.2	62.2	315	310	6.8	6.5	13.2	13.0	5.9	6.1	38.6	40.7
Partial-load tests[d]														
Vertical	815,000	41.1	297.2	303.8	245	235	6.4	6.6	12.5	12.2	6.6	7.0	45.0	48.8
Corner	696,500	40.8	283.8	264.2	253	252	8.0	7.4	14.9[a]	14.7[a]	4.2	4.4	24.2	25.6
Front-wall	628,000	38.8	254.0	256.0	244	244	5.9	6.0	13.3	13.0	5.6	5.8	35.0	37.7
Spreader-stoker	119,500	6.9	44.0	46.7	396	327	7.4	7.0	12.1	12.0	6.9	7.2	47.8	51.1
Cyclone	1,022,000	41.3	443.5	404.1	265	240	6.6	6.4	12.0	12.2	6.8	6.8	46.0	46.2
Horizontally opposed	108,000	6.6	43.8	44.6	314	308	6.6	6.6	12.8	12.4	6.0	6.5	38.4	43.7

[a] Calculated values, based on oxygen values and fuel analysis.
[b] Measured at fly-ash collectors.
[c] Average values for three or four tests at each unit under normal steam load conditions.
[d] Average values for two tests at each unit.
[e] B: Before fly-ash collector.
[f] A: After fly-ash collector.

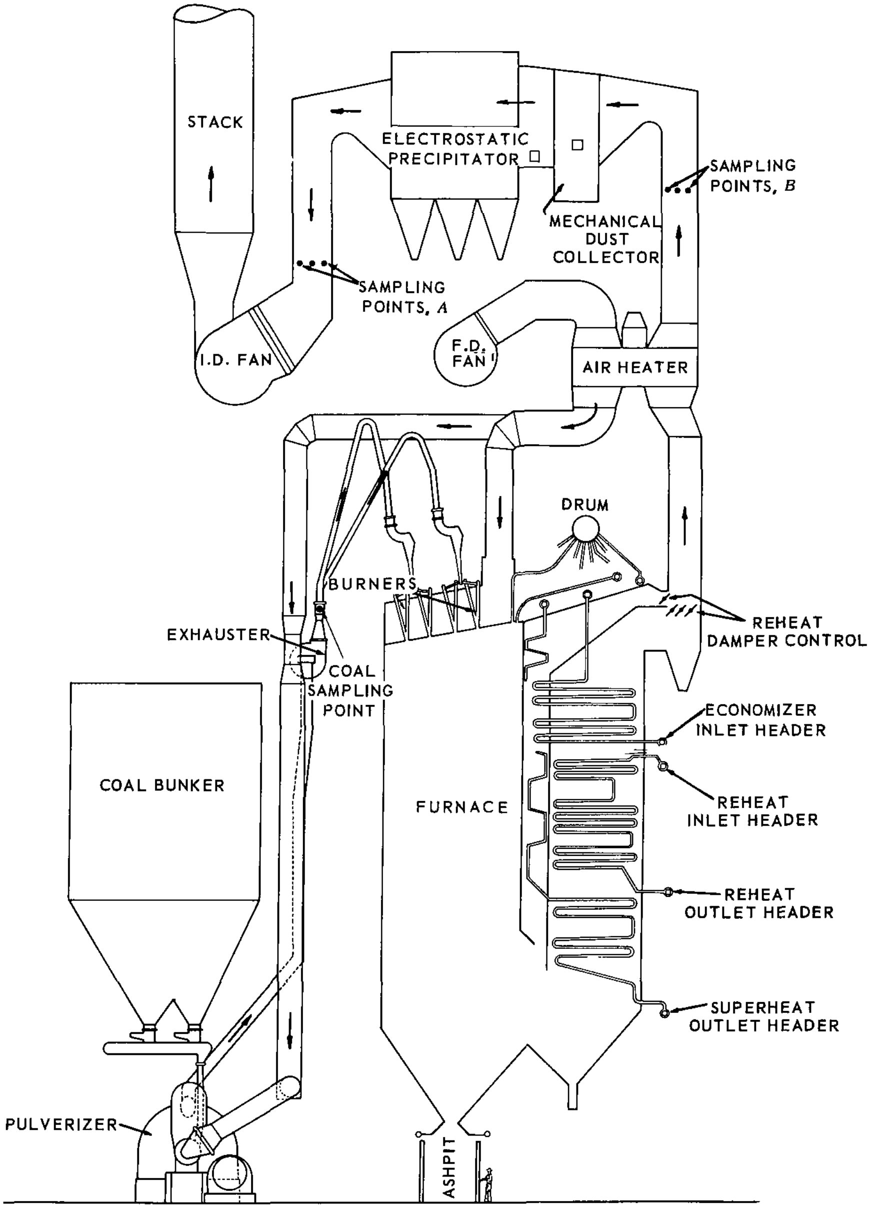


Figure 2. Boiler outline for vertically-fired unit showing sampling positions.

with the coal and through additional ports interspersed between the burner ports. The steam generator consists of a water-wall furnace section, a combined radiant and convection superheater, a reheater, an economizer, and an air heater. Flue gas, after passing through the regenerative air heaters, is divided into two parallel ducts and drawn through the fly-ash collector by two 300,000-cfm induced-draft fans. The clean gas is then discharged through a brick-lined steel stack. The fly-ash control system includes a cyclone-type separator followed by an electrostatic precipitator.

A high-volatile bituminous coal from Pennsylvania was burned in the vertically fired unit. Three tests were run at full load and two at three-quarter load.

Corner-fired Unit The corner-fired dry-bottom boiler is of the mono-tube type, i.e., without a steam drum (Figure 3). It is completely water-cooled and rated at 960,000 pounds per hour steam at 2,565 psig and 1,050°F. The 16 tangential corner-mounted burners receive pulverized coal from 4 ball mills. Two 185,000-cfm forced-draft fans supply combustion air. The flue gas leaving the boiler is carried through two regenerative-type air preheaters, fly-ash collectors, a low-level heat economizer, and two 275,000-cfm induced-draft fans before it is discharged through a stack to the atmosphere. The fly-ash collector consists of a cyclone-type separator in series with an electrostatic precipitator.

The high-volatile bituminous coals burned in the corner-fired unit were obtained from West Virginia and Ohio (Table 1). Normal amounts of excess air were used during three tests at full boiler load and two tests at three-quarter load.

Front-Wall Horizontally Fired Unit The front-wall-fired dry-bottom unit is illustrated in Figure 4. At full load, the unit produces 920,000 pounds of steam per hour at 1,000°F and 1,900 psig. Coal is pulverized in 4 rotary mills and conveyed to 24 front-wall burners. Combustion air from the regenerative preheaters enters the furnace as primary air with the coal and as secondary air through the annular ports of each burner. Hot gas recirculates from the economizer outlet to the bottom of the furnace. The convection heat-transfer section of the water-cooled furnace includes superheater, reheater, and economizer units. Flue gas from the two air heaters enters two parallel electrostatic precipitators for collection of fly ash.

The coals burned in this unit were supplied from a Kentucky strip mine and a West Virginia deep mine. Three full-load tests and two partial-load tests were conducted at normal excess air conditions.

Horizontally Opposed Fired Unit The turbo-fired wet-bottom unit (Figure 5) burns either pulverized coal or gas and is designed to re-inject all fly-ash. Steam production is rated at 150,000 pounds per hour at 1,000 psig and 835°F. The water-cooled furnace is designed for continuous drip removal of slag. The fly-ash collector consists of

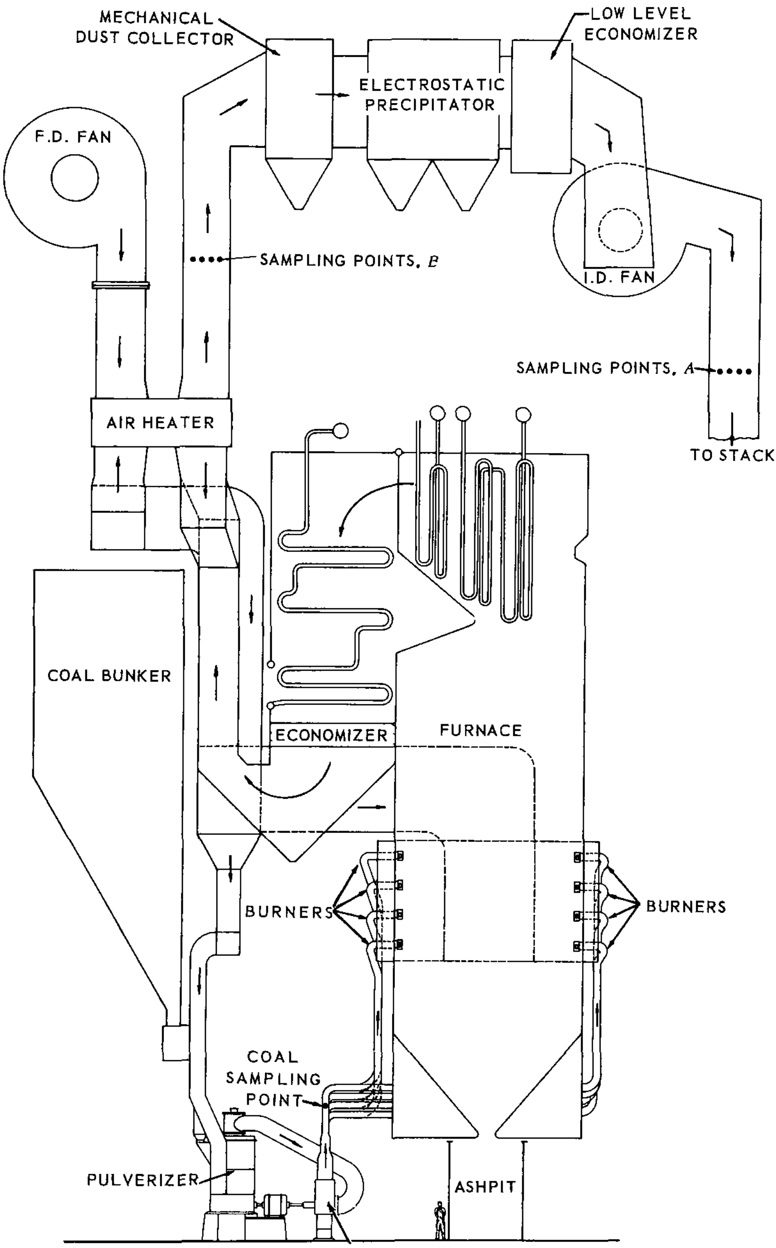


Figure 3. Boiler outline for corner-fired unit showing sampling positions.

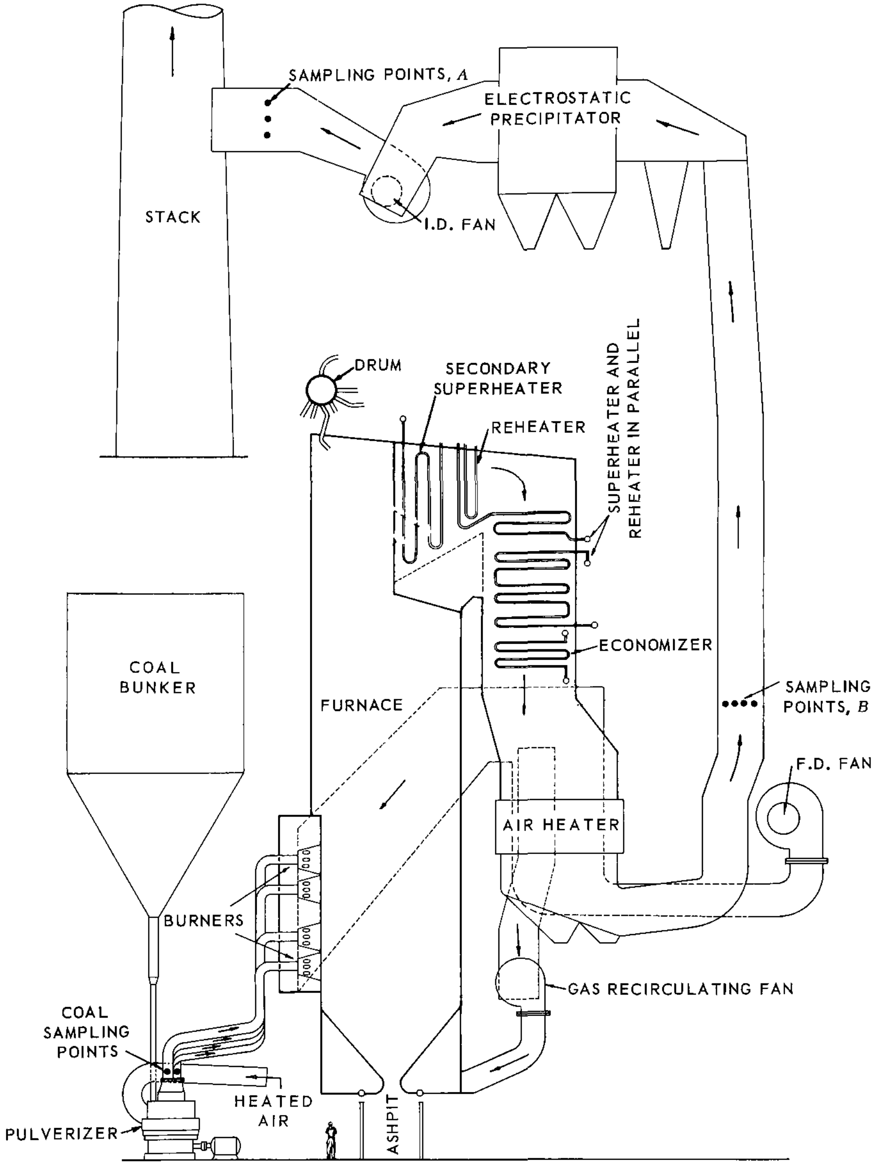


Figure 4. Boiler outline for front-wall fired unit showing sampling positions.

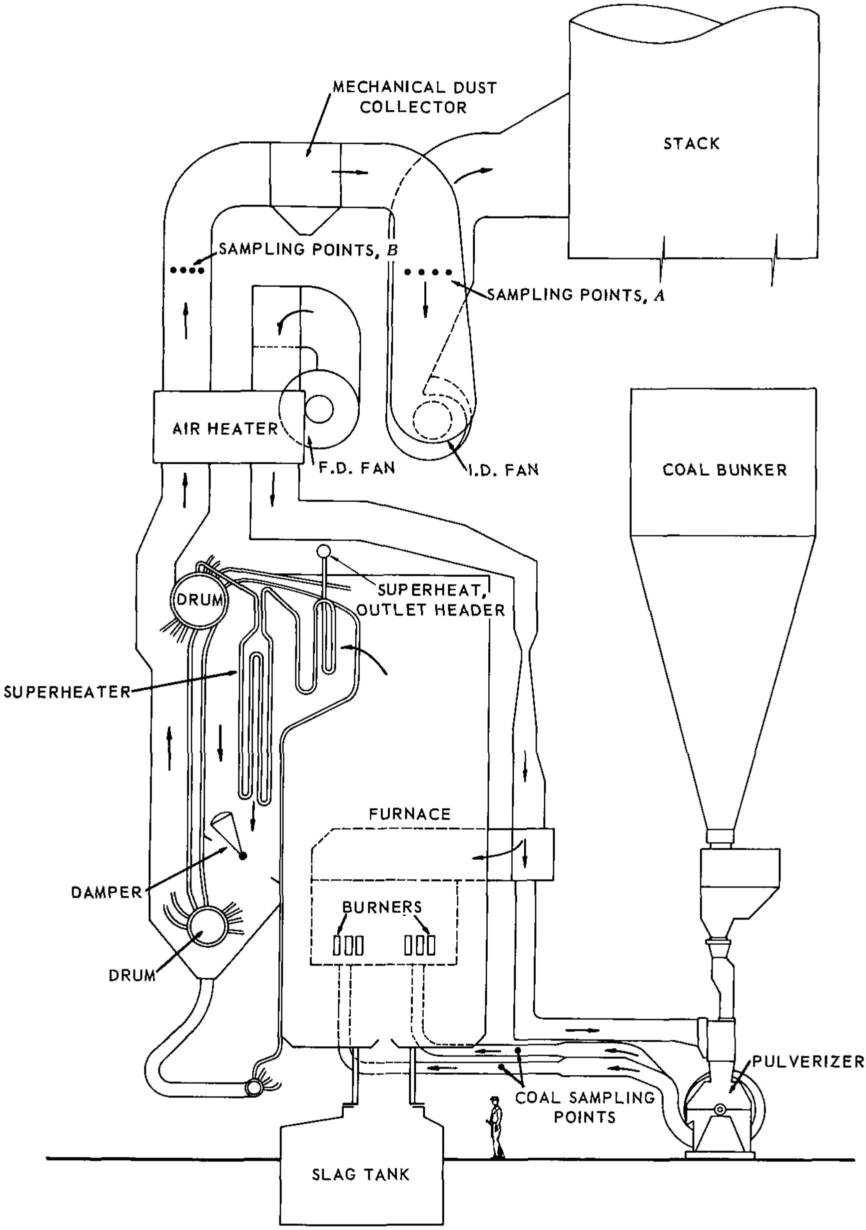


Figure 5. Boiler outline for horizontally-opposed firing unit showing sampling positions.

a cyclone-type separator with facilities for storage or reinjection of fly ash. Six tests were run on the turbo-fired unit to evaluate emissions at full and three-quarter load both with and without fly-ash reinjection. A high-volatile bituminous coal from Illinois was burned during all tests.

Cyclone-Fired Unit In the cyclone-type furnace, a mixture of crushed coal and air is injected tangentially into a horizontal, cylindrical combustion chamber. Essentially all of the combustion takes place in this

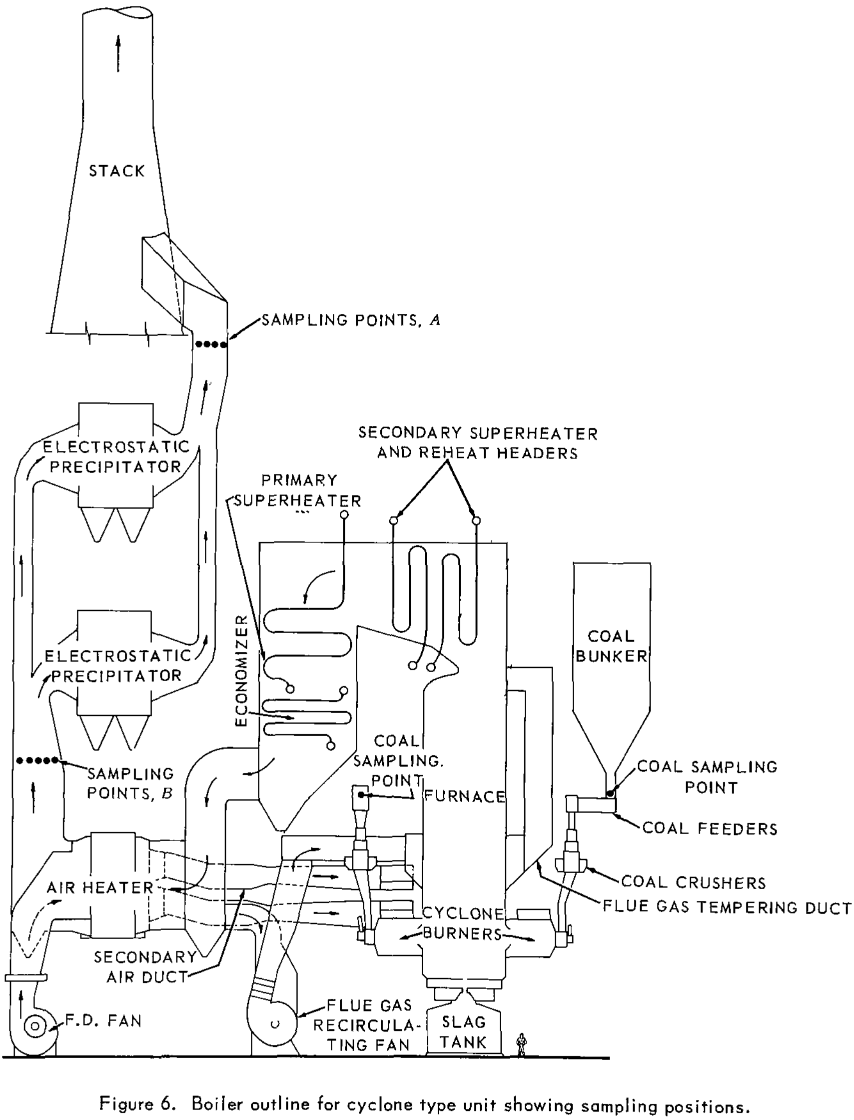


Figure 6. Boiler outline for cyclone type unit showing sampling positions.

water-cooled chamber. A substantial amount of ash is melted in the cyclone and removed from the furnace as slag. This boiler is rated at 1,360,000 pounds of steam per hour at 2,400 psig and 1,050^{O}F.

Two forced-draft fans with a capacity of 370,000 scfm supply combustion air to the furnace and maintain positive pressure throughout the furnace-boiler system. Flue gas leaving the boiler passes through secondary and primary superheater sections, an economizer, an air preheater, and finally a fly-ash collector, as shown in Figure 6. The fly-ash collectors include two parallel electrostatic precipitators. Collected fly ash is normally reinjected into the furnace.

A single type of high-volatile bituminous coal from Pennsylvania was burned during all tests. Three tests were run at approximately full load, two of which included fly-ash reinjection. Two additional tests were run at three-quarter load, both with fly-ash reinjection. All tests were conducted with normal amounts of excess air.

Spreader-Stoker Fired Unit In this traveling-grate type of spreader stoker, as shown in Figure 7, crushed coal is gravity-fed to rotating blades which distribute the coal over a slowly revolving continuous grate. Collected fly ash is also reinjected at the rear of the grate.

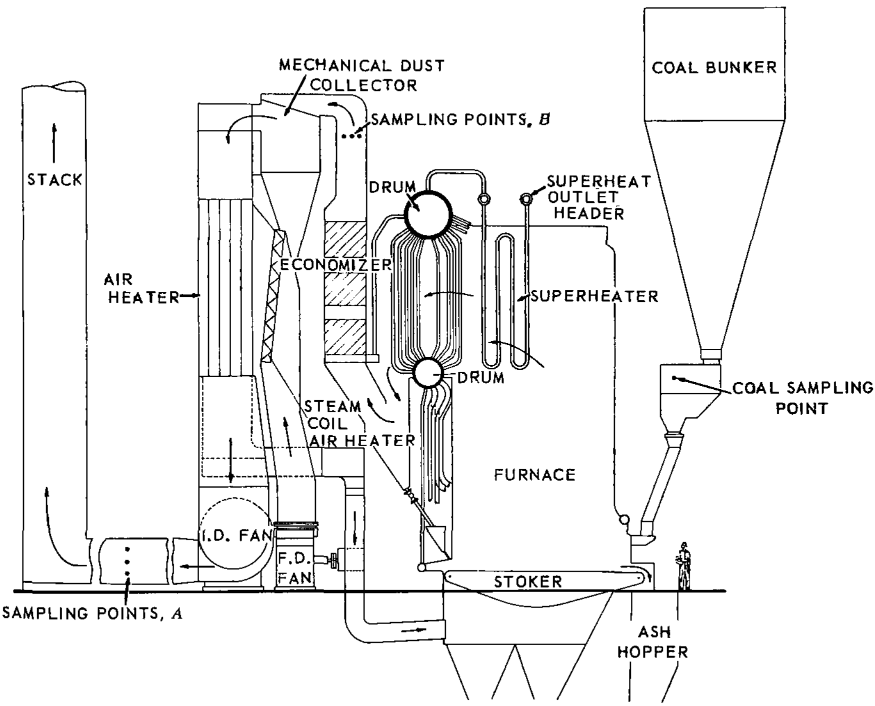


Figure 7. Boiler outline for spreader stoker unit showing sampling positions.

The coal passes slowly through the combustion zone where it is burned, and the remaining ash is discharged from the opposite end of the revolving grate into an ash hopper. The grate has an effective area of 362 square feet and serves a boiler with a nominal capacity of 220,000 pounds of steam per hour at 875 psig and 760°F.

Combustion air is supplied by both forced-draft fans and overfire-air fans. Flue gases leaving the grate pass up through a water-cooled boiler-furnace section, superheater, economizer, cyclone-type fly-ash collector, air preheater, and induced-draft fan before entering the stack.

A high-volatile bituminous mixed coal from Illinois was burned during all tests.

DISCUSSION OF RESULTS

1. Oxides of Sulfur

The average sulfur content of coals used for electric-power production in the United States is about 2.5 percent. The sulfur content of the coals burned in the six units during testing varied from 1.6 to 2.9 percent (Table 3), with an average of 2.4 percent.

The sulfur in the coal appears mainly as sulfur dioxide in the flue gas. The balance of the residual sulfur in the fuel appears as sulfur trioxide, sulfuric acid mist, or as other compounds in the fly ash or bottom slag. The sulfur content of either the fly ash or slag from five power plants tested was normally 0.1 to 0.2 percent. Since the average ash content of the coal from these units was about 10 to 12 percent, less than 1 percent of the sulfur in the coal appeared in the ash. The spreader stoker had approximately 1.0 percent sulfur in the reinjected particulate and 0.25 percent in the grate ash; this accounted for about 2 percent of the sulfur in the coal. The remainder of the sulfur should therefore appear as sulfur oxides in the flue gas. Other investigators have estimated that between 90 and 100 percent of sulfur entering the boiler in the coal would be expected to appear as sulfur oxides in the flue gas. [13]

The concentrations of sulfur dioxide in the flue gas leaving the fly-ash collector varied from 1,000 to 1,730 ppm for all six units (Table 3). No significant changes in concentrations of sulfur dioxide were noted in full- and partial-load operation. Material balances for conversion of sulfur in the coal to sulfur dioxide in the flue gas showed conversions ranging from 91 to 105 percent. Since sulfur conversion must be below 100 percent, the errors involved in calculating theoretical emissions and in sampling and analysis for sulfur oxides become apparent. The change in sulfur content of coals during the sampling runs, non-uniform mixing of flue gases, and slight inaccuracies in sampling and analysis could account for errors of 5 to 10 percent. The range of conversions does not include concentrations of sulfur dioxide from the front-wall-fired unit, which averaged 120 percent of theoretical. These high values for sulfur dioxide were due probably to interference

Table 3. TEST CONDITIONS AND MAJOR POLLUTANT EMISSIONS

Type of boiler firing	Coal		Emissions							
			gr/scf[e]		ppm by volume, dry basis					
	Sulfur,[c] %	Ash,[d] %	Fly-ash		Nitrogen oxides[f]		Sulfur dioxide		Sulfur trioxide	
			B[g]	A[h]	B[g]	A[h]	B[g]	A[h]	B[g]	A[h]
Full-load tests[a]										
Vertical	2.9	20.2	4.8	0.18	221	310	1450	1730	66	9
Corner	1.7	14.9	3.7	0.23	526	413	1150	1130	8	12
Front-wall	2.3	10.3	2.5	0.44	416	606	2120	1680	11	7
Spreader-stoker	2.8	8.4	2.3	0.38	431	437	1380	1570	58	76
Cyclone	2.4	7.7	1.5	0.39	1204	1160	1350	1360	21	31
Horizontally opposed	2.4	8.2	4.9	0.68	393	350	1560	1380	10	9
Partial-load tests[b]										
Vertical	2.8	19.0	4.7	0.11	161	171	1700	1640	46	10
Corner	1.6	13.5	2.9	0.13	393	325	1120	1000	10	12
Front-wall	1.8	9.2	2.4	0.22	500	453	1080	1460	3	20
Spreader-stoker	2.5	8.7	1.5	0.19	430	390	1280	1240	52	69
Cyclone	2.4	7.4	1.8	0.22	742	784	1380	1370	13	22
Horizontally opposed	2.9	7.8	2.9	0.61	395	328	1780	1680	6	8

[a]Average values from three or four tests.
[b]Average values from two tests.
[c]Moisture- and ash-free basis.
[d]Moisture-free basis.
[e]Corrected to 12% CO_2, dry basis.
[f]Reported as NO_2.
[g]Before fly-ash collector.
[h]After fly-ash collector.

from organic acids and/or other trace mineral acids before the analytical technique was modified to preclude this interference.

It was theorized that the percentage conversion of sulfur in the coal to sulfur dioxide in the flue gas would be considerably lower in wet-bottom units. This theory was based on the assumptions that (1) some of the sulfur in the coal would contact the furnace bottom slag and form molten iron sulfide, particularly with low excess air, or (2) the iron content of recirculated fly ash would catalytically oxidize the sulfur dioxide in the flue gas to sulfur trioxide. Results did not substantiate this theory. Between 95 and 100 percent of the sulfur that entered in the coal appeared as sulfur dioxide in the stack gases in the wet-bottom units.

The concentrations of sulfur trioxide in the flue gas leaving the fly-ash collector varied between 7 and 76 ppm for all six units. The average outlet concentration of sulfur trioxide at both full and three-quarter load was 24 ppm. The total gaseous sulfur oxides found to be sulfur trioxide varied from 0.3 to 4.4 percent for measurements at the fly-ash collector inlet; the arithmetic mean was 1.7 percent. Under conditions of thermodynamic equilibrium, the percentage of sulfur trioxide should have been negligible at flame temperatures, and over 99 percent of the sulfur oxides after the air heater.[14] The measured concentrations, however, correspond to equilibrium values for conditions of gas temperature and oxygen content near the furnace outlet. The rapid cooling of gases in the convective-heat-transfer system near the furnace outlet appears to quench further oxidation of sulfur dioxide to sulfur trioxide.

In the vertically fired unit, which produced the highest concentrations of sulfur oxides, the sulfur trioxide concentration was reduced appreciably in passage through the fly-ash collector (Table 3). It was initially theorized that cooling of flue gases in the fly-ash collector at points of influent air leakage could result in condensation of sulfur trioxide and formation of sulfuric acid mist. The acid mist could then be adsorbed on the fly-ash particles and their removal effected by the collection of fly ash. This theory does not appear valid in all cases, because none of the other units realized significant reductions of sulfur trioxide in passage through the fly-ash collector.

2. Oxides of Nitrogen

Oxides of nitrogen are formed largely by high-temperature oxidation of atmospheric nitrogen during combustion. Nitric oxide (NO) is the primary combustion product resulting from nitrogen fixation in the furnace. Theoretical equilibrium concentrations of nitric oxide may be as high as 1,000 ppm at 2,500°F and as low as 1 ppm or less at the lower temperatures (250-300°F) of the fly-ash collector.[15]

Concentrations of nitrogen oxides measured at the inlet of the fly-ash collectors in all units except the cyclone-fired furnace ranged from 221 to 526 ppm at full load and from 161 to 500 ppm at three-quarter load (Table 4). These concentrations were generally equilibrium levels for temperatures near the furnace outlet. The nitrogen oxides tended to decompose as the gases cooled. Apparently, the concentrations of nitrogen oxides are determined by flame temperature, incomplete decomposition as the gases flow from the flame to the furnace outlet, and rapid quenching of the decomposition reaction as the gases cool in the convective heat-transfer system.

The higher temperatures encountered in the cyclone-fired furnace resulted in expected higher levels of nitrogen oxides at the fly-ash collector inlet -- 1,204 ppm at full load and 742 ppm at three-quarter load (Table 4). The wet-bottom turbo-fired furnace, which also operated with higher temperatures in the slagging zone, was also expected to produce higher concentrations of nitrogen oxides than the 395 ppm measured at the inlet of the fly-ash collector (Table 4). By concentration of combustion in the slagging zone at the bottom of the

Table 4. NITROGEN OXIDE CONCENTRATIONS

Full-load tests[a]				
	ppm[b]		$Lb/10^6 Btu$	
Type of boiler firing	B[d]	A[e]	B[d]	A[e]
Vertical	221	310	0.38	0.55
Corner	526	413	0.95	0.71
Front-wall	416	606	0.68	0.95
Spreader-stoker	431	437	0.65	0.76
Cyclone	1204	1160	2.5	2.2
Horizontally opposed	393	350	0.65	0.59
Partial-load tests[c]				
	ppm[b]		$Lb/10^6 Btu$	
Type of boiler firing	B[d]	A[e]	B[d]	A[e]
Vertical	161	171	0.28	0.31
Corner	393	325	0.73	0.57
Front-wall	500	453	0.82	0.74
Spreader-stoker	430	390	0.73	0.68
Cyclone	742	784	1.9	1.8
Horizontally opposed	395	328	0.66	0.56

[a]Average values for three or four tests at each unit.
[b]Reported as NO_2, at stack conditions.
[c]Average values for two tests at each unit.
[d]B: Before fly-ash collector.
[e]A: After fly-ash collector.

furnace, however, a relatively long and gradual cooling of combustion products was provided in the upper part of the furnace and probably accounted for the decomposition of the nitrogen oxides. The result was a lower concentration of nitrogen oxides than would have been expected on the basis of combustion temperature alone.

In two of the four units equipped with electrostatic-type fly-ash collectors (the vertically-fired and front-wall-fired units), the concentrations of nitrogen oxides measured at the outlet of the fly-ash collectors were 40 to 45 percent higher than those measured at the inlet during full-load tests. This increase may be attributed to formation of ozone and atomic oxygen in the corona discharge of the electrostatic precipitator and their subsequent reaction with nitrogen to form additional nitrogen oxides. No increase in nitrogen oxide levels was found, however, at reduced loads for the vertically-fired and front-wall-fired units or at either load condition for the corner-fired or cyclone-fired boilers in passage through the electrostatic precipitators. Since the literature gives little information on this subject, additional studies are required to explain this phenomenon.

3. Solid Particulate

Efficient fly-ash-control equipment has enabled operators of the modern coal-burning power plant to reduce particulate emissions considerably. Fly-ash collection efficiencies of over 95 percent are not uncommon today.

The three pulverized-coal-burning units, i.e., the vertically fired, the corner-fired, and the front-wall-fired boilers are operated with bituminous coals having ash contents ranging from approximately 10 to 20 percent. It has been estimated that over 75 percent of the ash in dry-bottom pulverized-coal-burning power plants leaves the furnace with the flue gas. The average grain loadings at the fly-ash collector inlet for these three units during full-load operation were 4.8, 3.7, and 2.5 grains per standard cubic foot respectively (Table 5). Ash leaving the furnace and entering the fly-ash collector amounted to about 60 percent for the vertically-fired unit, 80 percent for the corner-fired unit, and 75 percent for the front-wall-fired unit. A vertically-fired unit would be expected to retain more fly ash than a corner- or horizontally-fired unit because of the downward direction of flow resulting in fly-ash impaction on the bottom of the furnace. This condition would allow more fly ash to settle in the furnace. The lower ash retention for the corner-fired and front-wall-fired units would also be expected because their horizontal firing arrangement hinders ash dropout to the furnace floor.

The combination mechanical-electrostatic fly-ash collectors for both the vertically- and corner-fired units effected average collection efficiencies of 96.4 and 93.9 percent, respectively, at full load (Table 5). The average collection efficiencies at three-quarter load increased to 97.5 percent for the vertically-fired unit and 95.7 percent for the corner-fired unit. The electrostatic fly-ash collector for the front-wall-

Table 5. FLY-ASH CONCENTRATIONS AND COLLECTION EFFICIENCIES

Type of boiler firing	Ash in coal,[a] %	Concentrations				Type of fly-ash collector[d]	Collector efficiency, %
		gr/scf[b]		lbs/1000 lb[c] dry flue gas			
		B[g]	A[h]	B[g]	A[h]		
Full-load tests[e]							
Vertical	20.2	4.8	0.18	8.8	0.27	C, E	96.4
Corner	14.9	3.7	0.23	6.9	0.42	C, E	93.9
Front-wall	10.3	2.5	0.44	4.6	0.82	E	83.1
Spreader-stoker	8.4	2.3	0.38	4.2	0.66	C	83.9
Cyclone	7.7	1.5	0.39	2.8	0.62	E	74.5
Horizontally opposed	8.2	4.9	0.68	8.9	1.27	C	83.9
Partial-load tests[f]							
Vertical	19.0	4.7	0.11	8.7	0.21	C, E	97.5
Corner	13.5	2.9	0.13	5.5	0.21	C, E	95.7
Front-wall	9.2	2.4	0.22	4.4	0.41	E	91.3
Spreader-stoker	8.7	1.5	0.19	2.8	0.35	C	87.3
Cyclone	7.4	1.8	0.22	3.1	0.36	E	86.3
Horizontally opposed	7.8	2.9	0.61	5.1	1.1	C	77.7

[a]Moisture-free basis.
[b]Corrected to 12 percent CO_2, dry volume basis.
[c]1000 pounds of dry flue gas corrected to 50 percent excess air.
[d]C designates cyclone; E designates electrostatic precipitator.
[e]Average values for either three or four tests of each unit.
[f]Average values for two tests at each unit.
[g]Before fly-ash collector.
[h]After fly-ash collector.

fired unit operated with an average collection efficiency of 83.1 percent at full load and 91.3 percent at three-quarter load. Although good reproducibility for fly-ash collection efficiency was obtained for both the vertically- and the corner-fired units, the collection efficiency varied appreciably at full-load operation of the front-wall and cyclone-fired units. No reason was apparent for this variation.

The spreader-stoker unit was fired with crushed coal having an average ash content of 8.2 percent. The average grain loading at the inlet to the mechanical fly-ash collector during normal-load operation was 2.3 grains per standard cubic foot, which represents about 47 percent of the particulate entering the boiler as ash in the coal and as reinjected material. Average collection efficiency of the mechanical fly-ash collector was 83.9 percent at normal load and 87.3 percent at partial load.

The cyclone-fired unit and the horizontally opposed, downward-inclined fired unit are both wet-bottom boilers that normally operate with fly-ash reinjection. Both were fired with bituminous coals having ash contents ranging from about 7 to 8 percent. The average grain loadings at the inlet to the fly-ash collector during full-load operation were 1.5 grains per standard cubic foot for the cyclone unit and 4.9 grains per standard cubic foot for the horizontally opposed fired unit (Table 5). The amounts of ash leaving the boiler and entering the fly-ash collector were about 50 percent for the cyclone-fired unit and 70 percent for the horizontally opposed fired unit.

The electrostatic fly-ash collector for the cyclone-fired unit operated with average collection efficiencies of 74.5 percent at full load and 87.8 percent at three-quarter load. The mechanical fly-ash collector for the horizontally opposed fired unit effected average collection efficiencies of 83.9 percent at full load and 77.7 percent at three-quarter load. Particulate emissions from the electrostatic precipitators of the three pulverized-coal-burning units and of the cyclone unit would meet the old American Society of Mechanical Engineers standard of 0.85 pound particulate per 1,000 pounds of dry flue gas corrected to 50 percent excess air.[16] Particulate emissions from the mechanical collectors of the horizontally opposed fired unit would not meet this standard.

Average fly-ash collector efficiencies of plants in operation a number of years were lower than those originally guaranteed by the manufacturer.

Table 6 lists the guaranteed fly-ash collector efficiencies and the actual efficiencies measured during the tests.

In general, operation at partial load showed higher fly-ash collector efficiencies. This indicated an over-loaded condition during normal operation. Decreases in fly-ash collector efficiencies were largely due to blockage of air passage with dust, which increased velocities; breakage and corrosion of electrostatic precipitator

Table 6. COMPARISON OF FLY-ASH COLLECTOR EFFICIENCIES

Type of firing	Type of collector[a]	Fly-ash collector efficiency, %		
		Guaranteed by manufacturer	Obtained in tests	
			Normal load	Partial load
Vertical	C & E	98.2	96.4	97.5
Corner	C & E	97.5	93.9	95.7
Front-wall	E	95.0	83.1	91.3
Spreader-stoker	C	93.1	83.9	87.3
Cyclone	E	95.0	74.6[b]	86.3[b]
Horizontally opposed	C	89.7	88.5[b]	78.0[b]

[a]C denotes a cyclone type collector;
E denotes an electrostatic precipitator.
[b]Includes only tests with fly-ash reinjection, which was normal operating procedure at these plants.

electrodes; and changes in fly-ash characteristics due to variations of coal or boiler operation, or both.

The amount and composition of mineral matter in the coal largely determines the concentrations of trace metals in the fly ash. Seventeen common trace metals were determined in fly-ash samples from each of the six units (Table 7) during full-load operation. The estimated accuracy of these values is ± 50 percent of the measured value. The spectrographic analyses of fly-ash samples were intended to determine any significant difference in collector efficiency for individual minerals as indicated by the content of the various metals. The average collector efficiencies of trace metals for any of the six power plants were nearly the same as the fly-ash collection efficiencies for each unit; for the spreader-stoker unit, however, metal collection efficiency was only 47 percent.

4. Polynuclear Hydrocarbons

Although polynuclear hydrocarbons normally occur in minute concentrations, these compounds are of interest from an air pollution standpoint because several of them have exhibited carcinogenic properties in animal studies.[17, 18] Previous work has shown that polynuclear hydrocarbons result from the incomplete combustion of organic fuels;[19] thus, when a combustion process is poorly controlled, emissions of polynuclears may be high. Since combustion control in power plants was generally good and fuel-burning methods efficient, emissions of polynuclear hydrocarbons were low. The results are

Table 7. METALS ANALYSIS FOR FULL-LOAD TESTS (grains/scf x 10-4)[a]

Type of boiler firing	Avg. coll. eff., %	Sampling point	Cd	Ba	Be	Fe	Pb	Cr	Cu	Sn	Sb	Mn	Ni	Mo	V	Ti	Zn	Co	As
Vertical	89	B[b]	T[d]	9.5	0.24	480	3.6	0.95	9.5	T[d]	T[d]	7.2	4.8	0.95	9.5	95	T[d]	0.48	
		A[c]	T[d]	0.34	0.02	17	1.1	0.08	0.87	0.04	T[d]	0.26	1.1	0.17	0.88	3.4	0.34	0.06	
Corner	94	B[b]	<0.42	20.8	0.42	1900	4.2	8.3	25	<0.42	<4.2	4.2	8.8	<1.22	24.8	420	12.2	1.22	1.4
		A[c]	<0.024	1.4	0.024	102	0.24	0.58	1.1	<0.22	<0.24	0.44	0.58	0.10	1.4	22	<0.72	0.082	0.11
Front-wall	86	B[b]	0.73	20.4	0.60	480	12.5	4.8	3.6	<0.26	<0.8	17.0	12.5	3.8	24	460	<24	2.0	
		A[c]	0.26	3.4	0.11	58	1.2	0.68	0.88	0.26	<0.8	1.6	0.76	0.58	2.4	48	<2.8	0.37	
Spreader-stoker	47	B[b]	T[d]	3.65	0.20	1100	4.8	1.95	1.9	T[d]	<2.4	6.1	3.6	0.73	6.1	48	<7.3	<0.73	2.6
		A[c]	T[d]	0.94	0.06	380	7.4	1.52	1.1	0.17	<0.4	1.3	1.5	0.37	1.5	17	3.0	0.21	1.6
Cyclone	69	B[b]	0.30	27.2	0.28	1360	11.4	8.2	3.2	0.65	<1.4	5.7	10.3	1.14	13.6	136	<4.2	2.2	0.66
		A[c]	0.12	7.5	0.08	380	3.8	2.2	0.8	0.26	<0.4	1.2	2.2	0.38	4.7	38	<1.2	0.8	0.30
Horizontally opposed	84	B[b]	<0.97	6.8	0.94	6800	68	9.7	20	<0.68	<6.7	10.6	20	10.6	42	540	42	5.1	4.0
		A[c]	0.58	1.1	0.14	730	14	1.8	4.4	0.32	<0.8	0.73	3.0	2.2	6.6	73	14	0.66	0.54

[a]Based on particulate grain loading. Each value is the average of at least two tests.
[b]Before fly-ash collector.
[c]After fly-ash collector.
[d]Trace; blank indicates no data.

shown in Table 8. Figure 8 and Table 8 compare concentrations of seven polynuclears for which the analytical technique was most accurate. Concentrations of polynuclears are shown for the fly-ash-collector outlet only because early tests showed significant recovery of polynuclears by the fly-ash collectors. The levels of polynuclear hydrocarbon emissions for all units were well below the levels that result from the firing of coal in smaller furnaces with less precise control of the combustion process. Benzo(a)pyrene emissions from small furnaces varied from 3,800 to 400,000 micrograms per million Btu heat input; [19] average benzo(a)pyrene emission from six plants ranged from 19 to 223 micrograms per million Btu.

5. Emissions of Trace Contaminants

Concentrations of carbon monoxide and gaseous hydrocarbons were low for all six units (Table 9). These low values indicated a high degree of combustion efficiency. Concentrations of these gases did not change significantly in any unit during operation at full and partial load, nor did passage of the flue gas through the fly-ash collector affect the concentrations.

Formaldehyde concentrations from all units were very low, ranging between 0.03 and 0.25 ppm. The fly-ash collector reduced formaldehyde concentrations in five of the six units, with an average reduction of 45 percent. Removal of formaldehyde in the fly-ash collectors indicated adsorption of this compound by the fly-ash particles that were removed. The slight increase indicated for formaldehyde in the spreader-stoker test was probably due to an excessive amount of particulate in the outlet sampling train. No

Table 8. POLYNUCLEAR HYDROCARBON CONCENTRATIONS[a]
(micrograms/10^6 Btu heat input)

	Type of boiler firing					
Compound	Vertical	Corner	Front-wall	Spreader stoker	Cyclone	Horizontally opposed
Fluoranthene	200	390	80	50	79	188
Pyrene	155	140	180	105	1025	91
Benzo(a)pyrene	19	140	19	< 20	223	81
Benzo(e)pyrene		86	23	30	395	265
Benzo(ghi)perylene		150	7		198	645
Coronene		7		5	6	56
Perylene		71			17	

[a]After fly-ash collector during full-load operation. Average values for two tests at each unit. A blank indicates that the compound was not detected.

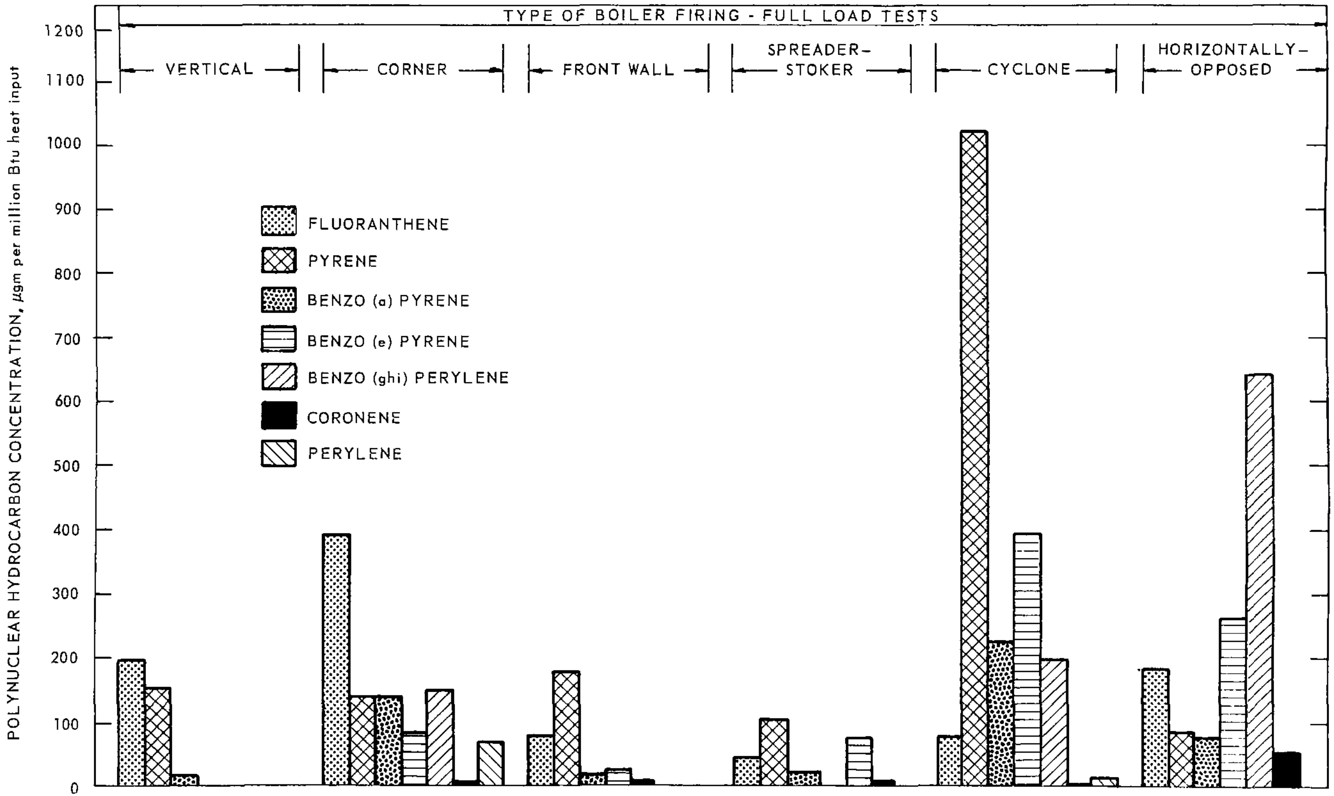


Figure 8. Polynuclear hydrocarbon concentrations at fly-ash collector outlet.

Table 9. SUMMARY OF TRACE GASEOUS EMISSIONS
(ppm by volume, dry basis)

Full-load tests[a]

Type of boiler firing	Carbon monoxide		Hydrocarbons[b]		Formaldehyde	
	B[d]	A[e]	B[d]	A[e]	B[d]	A[e]
Vertical	17	11	17	14	0.25	0.12
Corner	11	16	7	9	0.17	
Front-wall	5	6	18	6	0.14	0.12
Spreader-stoker	29	32	15	8	0.06	0.08
Cyclone	f	f	0	0	0.17	0.10
Horizontally opposed	44	51	2	0	0.10	0.07

Partial-load tests[c]

Type of boiler	Carbon monoxide		Hydrocarbons[b]		Formaldehyde	
	B[d]	A[e]	B[d]	A[e]	B[d]	A[e]
Vertical	13	19	17	14	0.26	0.07
Corner	39	33	6	6	0.11	0.04
Front-wall	12	5	10	7	0.14	0.06
Spreader-stoker	13	17	3	2	0.03	0.06
Cyclone	15	10	0	0	0.15	0.11
Horizontally opposed	69	64	6	6	0.11	0.09

[a]Average values for three or four tests at each unit.
[b]Gaseous hydrocarbons at room temperature expressed as a single carbon atom hydrocarbon.
[c]Average values for two tests at each unit.
[d]Before fly-ash collector.
[e]After fly-ash collector.
[f]No data.

significant changes in concentrations of any of these trace contaminants resulted from operation at either full or partial load.

SUMMARY

A series of tests of six coal-burning power plants was conducted to determine certain stack-gas components of interest in atmospheric pollution. The six units tested included three dry-bottom pulverized-coal-burning units, two wet-bottom units, and a large spreader-stoker traveling-grate unit.

Measurements of sulfur oxides indicated that essentially 90 to 100 percent of the sulfur in the coal appeared as sulfur oxides in the stack gas. Of this amount 1 to 2 percent was in the form of sulfur trioxide and the balance was sulfur dioxide. Neither the type of furnace, the conditions of firing, nor the reinjection of fly ash affected sulfur oxide emissions significantly. Thus, concentrations of sulfur oxides are essentially determined by the amount of sulfur in the coal entering the furnace.

Concentrations of nitrogen oxides varied widely, ranging from 221 ppm for the vertically fired unit to 1,204 ppm for the cyclone-type furnace. Concentrations of nitrogen oxides apparently are determined by initial flame temperatures in the firebox, decomposition in the high-temperature region of the furnace, and quenching of the decomposition reaction as the gases are cooled in the boiler section of the furnace.

Control of particulate emissions varied considerably in coal-fired power plants. Combination cyclone and electrostatic-precipitator-type fly-ash collectors gave collection efficiencies of about 96 percent and an outlet grain loading of 0.20 grain per standard cubic foot at full load. Electrostatic precipitators and mechanical cyclone collectors, when used separately, gave average collection efficiencies ranging from 75 to 85 percent, with loadings at the fly-ash collector outlet varying from 0.19 to 0.68 grain per standard cubic foot.

Other emissions were determined including polynuclear hydrocarbons, carbon monoxide, gaseous hydrocarbons, formaldehyde, and trace metals. None of these components were found in appreciable quantities during normal furnace-operating conditions.

REFERENCES

1. Rohrman, F. A., B. J. Steigerwald. Some Potential Air Pollution Problems of the Future. Unpublished report. Division of Air Pollution, U.S. Public Health Service, R. A. Taft Sanitary Engineering Center, Cincinnati, Ohio (April 1965).

2. Cuffe, S. T., R. W. Gerstle, A. A. Orning, C. H. Schwartz. Air Pollutant Emissions from Coal-Fired Power Plants; Report No. 1. J. Air Pollution Control Assoc. 10:9 353-363 (Sept. 1964).

3. Gerstle, R. W., S. T. Cuffe, A. A. Orning, C. H. Schwartz. Air Pollutant Emissions from Coal-Fired Power Plants; Report No. 2. J. Air Pollution Control Assoc. 15:2 59-64 (Feb. 1965).

4. Cuffe, S. T. Techniques for Evaluating Air Pollutants from Power Plants. Arch. Environ. Health. 6:422-427 (March 1963).

5. Determination of Sulfur Dioxide and Sulfur Trioxide in Stack Gases. Emeryville Method Series 4S16/59a, Shell Development Company Analytical Department, Emeryville, California (1959).

6. Berk, A. A., L. R. Burdick. A Method of Test for SO_2 and SO_3 in Flue Gases. Bureau of Mines Report of Investigations 4618 (Jan. 1950).

7. Beatty, R. L., L. B. Berger, and H. H. Schrenk. Determination of the Oxides of Nitrogen by the Phenoldisulfonic Acid Method. Bureau of Mines Report of Investigations 3687 (Feb. 1943).

8. Stenburg, R. L., D. J. Von Lehmden, and R. P. Hangebrauck. Sample Collection Techniques for Combustion Sources -- Benzopyrene Determination. Amer. Ind. Hyg. Assoc. J. 22: 271-275 (Aug. 1961).

9. Commins, B. T., P. J. Lawther. Volatility of 3, 4 Benzpyrene in Relation to the Collection of Smoke Samples. Brit. J. Cancer 12: 351-354 (Sept. 1958).

10. Sawicki, E., T. W. Stanley, T. R. Hauser, and F. T. Fox. The Detection and Determination of Polynuclear Hydrocarbons in Urban Airborne Particulates -- 1, The Benzopyrene Fraction. Intern. J. Air Pollution 2: 273-282 (1960).

11. Altshuller, A. P., D. L. Miller, and S. F. Sleva. Determination of Formaldehyde in Gas Mixtures by the Chromotropic Acid Method. Anal. Chem. 33: 621 (Apr. 1961).

12. The Silver Diethyldithiocarbamate Method of Arsenic Determination. Technical Data 142, Fisher Scientific Co. (Feb. 1960).

13. Committee on Air Pollution, Interim Report. Cmd. 9011, Her Majesty's Stationery Office, London (1953).

14. Orning, A. A., C. H. Schwartz, J. F. Smith. Minor Products of Combustion in Large Coal-Fired Steam Generators. Presented at the Winter Annual Meeting of the Am. Soc. Mech. Engrs., New York, New York (Nov. 29 Dec. 4, 1964) Paper No. 64-WA/FU-2.

15. Orning, A. A. Air Pollutants from Coal-Fired Electric Power Plants. National Conference on Air Pollution, Washington, D. C. PHS Publication No. 654, 159-160 (Nov. 1958).

16. Stern, A. C. Air Pollution. Academic Press, New York and London. Vol II, Chapter 37 (1962).

17. Sawicki, E., K. Cassel, (ed.). Analysis of Carcinogenic Air Pollutants. Natl. Cancer Inst. Monograph No. 9 (Aug. 1962).

18. Hartwell, I. L. Survey of Compounds Which Have Been Tested for Carcinogenic Activity. Second Edition, Public Health Service Publication No. 149 (1951).

19. Hangebrauck, R. P., D. J. Von Lehmden, J. E. Meeker. Emissions of Polynuclear Hydrocarbons and Other Pollutants from Heat-Generation and Incineration Processes. J. Air Pollution Control Assoc. 14: 7 267-278 (July 1964).

BIBLIOGRAPHIC: Cuffe, S. T. and Gerstle, R. W. Emissions from coal-fired power plants: a comprehensive summary. PHS Publ. No. 999-AP-35. 1967. 26 pp.

ACCESSION NO.

KEY WORDS:

ABSTRACT: The Public Health Service and the Bureau of Mines conducted a study of air pollutant emissions from the six main types of coal-burning power plants. The components tested include sulfur oxides, nitrogen oxides, polynuclear hydrocarbons, total gaseous hydrocarbons, solid particulates, formaldehyde, organic acids, arsenic, trace metals, and carbon monoxide. This report relates the effects of variables such as method of operation, type of boiler furnace and auxiliaries, reinjection of fly ash, and type of coal burned to the concentrations of gaseous and particulate pollutants in the products of combustion.

BIBLIOGRAPHIC: Cuffe, S. T. and Gerstle, R. W. Emissions from coal-fired power plants: a comprehensive summary. PHS Publ. No. 999-AP-35. 1967. 26 pp.

ACCESSION NO.

KEY WORDS:

ABSTRACT: The Public Health Service and the Bureau of Mines conducted a study of air pollutant emissions from the six main types of coal-burning power plants. The components tested include sulfur oxides, nitrogen oxides, polynuclear hydrocarbons, total gaseous hydrocarbons, solid particulates, formaldehyde, organic acids, arsenic, trace metals, and carbon monoxide. This report relates the effects of variables such as method of operation, type of boiler furnace and auxiliaries, reinjection of fly ash, and type of coal burned to the concentrations of gaseous and particulate pollutants in the products of combustion.

BIBLIOGRAPHIC: Cuffe, S. T. and Gerstle, R. W. Emissions from coal-fired power plants: a comprehensive summary. PHS Publ. No. 999-AP-35. 1967. 26 pp.

ACCESSION NO.

KEY WORDS:

ABSTRACT: The Public Health Service and the Bureau of Mines conducted a study of air pollutant emissions from the six main types of coal-burning power plants. The components tested include sulfur oxides, nitrogen oxides, polynuclear hydrocarbons, total gaseous hydrocarbons, solid particulates, formaldehyde, organic acids, arsenic, trace metals, and carbon monoxide. This report relates the effects of variables such as method of operation, type of boiler furnace and auxiliaries, reinjection of fly ash, and type of coal burned to the concentrations of gaseous and particulate pollutants in the products of combustion.