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EPA U.S. Environmental Protection Agency, Office of Research and Development, Industrial Environmental Research Laboratory, Research Triangle Park NC 27711

EPA-600/7-79-237a
November 1979

Field Tests of Industrial Stoker Coal-fired Boilers for Emissions Control and Efficiency Improvement – Site D

Interagency Energy/Environment R&D Program Report

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by

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IAG/Contract Nos. IAG-D7-E681 (EPA), EF-77-C-01-2609 (DoE)
Program Element No. EHE624

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Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

U.S. DEPARTMENT OF ENERGY
Division of Power Systems/Energy Technology Branch
Washington, DC 20545

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ACKNOWLEDGEMENTS

The authors wish to express their appreciation for the assistance and direction given the program by project monitors W. T. (Bill) Harvey of the United States Department of Energy (DOE) and R. E. (Bob) Hall of the United States Environmental Protection Agency (EPA). Thanks are due to their agencies, DOE and EPA, for co-funding the program.

We would also like to thank the American Boiler Manufacturers Association, ABMA Executive Director, W. H. (Bill) Axtman, ABMA Assistant Executive Director, R. N. (Russ) Mosher, ABMA's Project Manager, B. C. (Ben) Severs, and the members of the ABMA Stoker Technical Committee chaired by W. B. (Willard) McBurney of the McBurney Corporation for providing support through their time and travel to manage and review the program. The participating committee members listed alphabetically are as follows:

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We would also like to recognize the KVB engineers and technicians who spent much time in the field, often under adverse conditions, testing the boilers and gathering data for this program. Those involved at Site D were Jim Burlingame, Russ Parker, Mike Jackson, and Jim Demont.

Finally, our gratitude goes to the host boiler facilities which invited us to test their boiler. At their request, the facilities will remain anonymous to protect their own interests. Without their cooperation and assistance this program would not have been possible.

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1.0 INTRODUCTION

The principal objective of the test program described in this report, one of several reports in a series, is to produce information which will increase the ability of boiler manufacturers to design and fabricate stoker boilers that are an economical and environmentally satisfactory alternative to oil-fired units. Further objectives of the program are to: provide information to stoker boiler operators concerning the efficient operation of their boilers; provide assistance to stoker boiler operators in planning their coal supply contracts; refine application of existing pollution control equipment with special emphasis on performance; and contribute to the design of new pollution control equipment.

In order to meet these objectives, it is necessary to define stoker boiler designs which will provide efficient operation and minimum gaseous and particulate emissions, and define what those emissions are in order to facilitate preparation of attainable national emission standards for industrial size, coal-fired boilers. To do this, boiler emissions and efficiency must be measured as a function of coal analysis and sizing, rate of flyash reinjection, overfire air admission, ash handling, grate size, and other variables for different boiler, furnace, and stoker designs.

A field test program designed to address the objectives outlined above was awarded to the American Boiler Manufacturers Association (ABMA), sponsored by the United States Department of Energy (DOE) under contract number EF-77-C-01-2609, and co-sponsored by the United States Environmental Protection Agency (EPA) under inter-agency agreement number IAG-D7-E681. The program is directed by an ABMA Stoker Technical Committee which, in turn, has subcontracted the field test portion to KVB, Inc., of Minneapolis, Minnesota.

This report is the Final Technical Report for the fourth of eleven boilers to be tested under the ABMA program. It contains a description of the facility tested, the coals fired, the test equipment and procedures, and the results and observations of testing. There is also a data supplement to this report containing the "raw" data sheets from the tests conducted. The data

supplement has the same EPA report number as this report except that it is followed by "b" rather than "a". As a compilation of all data obtained at this test site, the supplement acts as a research tool for further data reduction and analysis as new areas of interest are uncovered in subsequent testing.

At the completion of this program, a Final Technical Report will combine and correlate the test results from all sites tested. This final report will provide the technical basis for the ABMA publication on "Design and Operating Guidelines for Industrial Stoker Firing," and will be available to interested parties through the ABMA, EPA, or DOE. A separate report covering trace species data will also be written at the completion of this program. It, too, will be available to interested parties through the ABMA, EPA, or DOE.

Although it is EPA policy to use S.I. units in all EPA sponsored reports, an exception has been made herein because English units have been conventionally used to describe boiler design and operation. Conversion tables are provided in the Appendix for those who prefer S.I. units.

To protect the interests of the host boiler facilities, each test site in this program has been given a letter designation. As the fourth site tested, this is the Final Technical Report for Test Site D under the program entitled "A Testing Program to Update Equipment Specifications and Design Criteria for Stoker Fired Boilers."

2.0 EXECUTIVE SUMMARY

A mass fed vibrating grate stoker rated at 90,000 lbs steam/hour was extensively tested for emissions and efficiency between July 28 and September 15, 1978. Steam loading on this unit was limited to 88% of its design rating due to draft losses associated with a retrofitted multiclone dust collector. For consistency with other reports in this series, steam loading will be presented as percent of design steam capacity. It should be understood, however, that the unit was tested at its maximum derated load whenever the reported load is in the range of 86 to 89% of design capacity. This section summarizes the results of all tests performed at Site D and provides references to supporting Figures, Tables and commentary found in the main text of the report.

UNIT TESTED: Described in Section 3.0, pages 9-12

- Babcock & Wilcox Boiler

  Built 1964
  Type FP -- two-drum Stirling
  90,000 lb/hr rated capacity
  200 psig operating steam pressure
  Saturated steam
  Economizer

- Detroit Vibragrate Stoker

  Mass fed
  Vibrating inclined grate
  No flyash reinjection
  Two rows OFA on front water wall

COALS TESTED: Individual coal analysis results given in Tables 5-7, 5-8, 5-9 and 5-10, pages 72-75. Commentary in Section 3.0, pages 12-15.

- Perfect 8 Coal

  13,003 Btu/lb
  8.71% Ash
  2.60% Sulfur
  3.23% Moisture
  2050°F initial ash deformation temperature

0 Century Coal

13,629 Btu/lb
5.86% Ash
1.23% Sulfur
2.68% Moisture
2680°F initial ash deformation temperature

0 Victoria Coal

13,405 Btu/lb
6.72% Ash
1.11% Sulfur
3.11% Moisture
2590°F initial ash deformation temperature

OVERFIRE AIR TEST RESULTS: Overfire air pressure was varied over its operating range of 5" to 15" H_2O, at low, medium and high boiler loadings (Section 5.1, pages 35-48).

0 Particulate Loading

Mixed results were obtained. On Perfect 8 coal, particulate loading increased with increasing OFA pressure. On Century coal, particulate loading decreased with increasing overfire air pressure. There was insufficient data on Victoria coal to draw any conclusions. (Section 5.1.1, page 37; Figures 5-2 and 5-3, pages 38, 39; Tables 5-1 and 5-2, pages 40, 41.)

0 Nitric Oxide

Nitric oxide concentrations increased an average ten percent when overfire air pressure was increased from 5" to 15" H_2O (Section 5.1.2, page 42; Table 5-3, page 44; Figure 5-4, page 43).

0 Carbon Monoxide

At high loads, 13" to 15" H_2O were necessary to control carbon monoxide. At low loads, carbon monoxide concentrations remained insignificant over the full operating range of the overfire air system (Section 5.1.3, page 45; Table 5-4, page 47; Figure 5-5, page 46).

0 Boiler Efficiency

The data indicate that maximum overfire air pressure will minimize the heat loss due to combustibles in the flyash. Combustible heat loss reductions of up to 0.47% were measured (Section 5.1.4, page 45; Table 5-5, page 48).

BOILER EMISSION PROFILES: Boiler emissions were measured over the load range 45-89% of design capacity which corresponds to a grate heat release range of 141,000 to 359,000 Btu/hr-ft^2. Measured oxygen levels ranged from 7.3 to 12.5% (Section 5.2, pages 49-71).

0 Excess Oxygen Operating Levels

The excess oxygen operating level was highly dependent on boiler load at Site D. As load increased, O_2 decreased. At maximum obtainable load (about 88% of design capacity) the lowest obtainable O_2 was 7.3%.* Extrapolation of the data trend to 100% capacity would give an O_2 of 6.4%. The boiler's design operating level is 31% excess air, or about 5% O_2 (Section 5.2.1, pages 49, 51; Figures 5-6 and 5-7, pages 50, 52)

*This lower O_2 limit was a function of control limitations and/or operator's reluctance to lower O_2 further. Definitive O_2 limits were not established on this boiler.

0 Particulate Loading

At maximum load the particulate loading averaged 1.03$\pm$.19 lb/10^{6}Btu at the boiler outlet and 0.55$\pm$.14 lb/10^{6}Btu after the multiclone dust collector. The particulate loadings dropped more than 20% at loads below a grate heat release of 300,000 Btu/hr-ft^2 (Section 5.2.2, pages 51, 54; Figures 5-8, and 5-9, pages 51, 53).

0 Nitric Oxide

At maximum load the nitric oxide emissions averaged 0.28 lb/10^6 Btu. NO emissions increased sharply as load decreased due to the resulting increase in O_2. Maximum measured NO was 0.46 lb/10^{6}Btu at an operating level of 12.5% O_2 (Section 5.2.3, pages 54, 57; Figures 5-10 through 5-15, pages 56, 58-62).

0 Carbon Monoxide

Carbon monoxide was found in significant concentrations only at loads which resulted in a grate heat release above 300,000 Btu/hr-ft^2. At these loads it could be controlled by supplying overfire air pressures greater than 13" H_2O (Section 5.2.4, page 63; Figures 5-16 through 5-18, pages 64-66).

0 Combustibles in Ash

Combustibles in the boiler outlet flyash were greatest under high load, low O_2 conditions where they ranged in value from 22 to 40% by weight. At lower loads they ranged from 14 to 35% by weight. Combustibles in the bottom ash ranged in value from 8 to 36% by weight (Section 5.2.5, pages 63, 68; Figures 5-19 and 5-20, pages 67, 69).

BOILER EFFICIENCY: Boiler efficiency was determined for 15 tests using the ASTM heat loss method. Boiler efficiency averaged 83.3% and did not vary with boiler load (Section 5.2.6, page 68; Figure 5-20, page 69; Table 5-6, page 71).

COAL PROPERTIES: Emissions and boiler efficiency were studied to determine any effects which could be related to differences in the properties of the three coals fired (Section 5.3, pages 71-77).

0 Sulfur Dioxide

Sulfur dioxide emissions were proportional to sulfur content of the coals. Sulfur retention in the ash averaged two percent of the fuel sulfur (Section 5.3.3, page 77; Table 5-13, page 82).

0 Combustibles in Bottom Ash

Combustibles in the bottom ash were highest for the two Victoria coal tests (Figure 5-20, page 69).

0 Boiler Efficiency

Boiler efficiency was highest while burning Century coal. This was due in part to a low dry gas loss and a low combustible loss. Victoria coal showed the lowest boiler efficiency's due to high combustible heat losses (Table 5-6, page 71; Figure 5-21, page 70).

0 Multiclone Collection Efficiency

Multiclone collection efficiency was highest while burning Century coal, and was low for the single Victoria coal test. Particle size distribution data helps explain this difference. Century coal had 39% of its flyash below 20 micrometers in diameter. This high percentage of fine particulate matter helps explain the low collection efficiencies (Section 5.5, page 88; Table 5-16, page 89; Figure 5-28, page 90).

0 Other Emissions

Boiler outlet particulate loading, nitric oxide, carbon monoxide and flyash combustible levels were all unaffected by the differences in the three coals tested.

SMOKE SPOT: A Bacharach smoke spot tester was used at the multiclone outlet and one, two or three pumps were taken instead of the specified ten pumps used in oil fired units.

- Results

  The results did not correlate well with stack opacity or particulate loading (Section 5.6, page 88; Table 5-17, page 91; Figures 5-29, 5-30, pages 92, 93).

SOURCE ASSESSMENT SAMPLING SYSTEM: Flue gas was sampled for polynuclear aromatic hydrocarbons and trace elements during one test on Victoria coal. Data will be presented in a separate report at completion of test program (Section 5.7, page 94; Table 5-18, page 94).

The emissions data are summarized in Table 2-1 on the following page. Other data tables are included at the end of Section 5.0, Test Results and Observations. For reference, a Data Supplement containing all the unreduced data obtained at Site D is available under separate cover but with the same title followed by the words "Data Supplement," and having the same EPA document number followed by the letter "b" rather than "a". Copies of this report and the Data Supplement are available through EPA and NTIS.

TABLE 2-1

EMISSION DATA SUMMARY - TEST SITE D

Test No.	Date	% Design* Capacity	Coal**	Test Description	O_2 % dry	CO_2 % dry	CO ppm dry	Excess Air %	NO ppm dry	NO*** lb/10^6Btu	NO_2 lb/10^6Btu	Part. Blr Out lb/10^6Btu	Part. D.C. Out lb/10^6Btu	Stack† Opacity %
1	7/27/78	67	P	Med Load - 6" OFA	8.5	10.9	112	63	183	0.249				
2	7/28/78	73	P	Med Load - 6" OFA	9.0	10.2	--	69	206	0.280				
3	8/03/78	69	P	Med Load - 6" OFA	10.1	9.3	108	75	225	0.306			0.355	
4	8/15/78	64	P	Med Load - 6" OFA	9.3	9.8	24	74	235	0.321		0.664	0.557	30
5	8/16/78	86	P	High Load - 10" OFA	7.9	11.2	89	55	222	0.302		0.832	0.574	23
6	8/18/78	65	P	Med Load - 5" OFA	8.7	10.9	87	65	184	0.250	0.001	0.694	0.372	12
7	8/22/78	63	P	Med Load - 15" OFA	10.2	9.9	29	88	255	0.346	-0.008	0.793	0.488	12
8	8/23/78	66	P	Med Load - 10" OFA	9.7	10.0	57	80	226	0.306	-0.023	0.788	0.328	12
9	8/29/78	45	P	Low Load - 10" OFA	11.5	8.5	56	114	262	0.353	0.000	0.732	0.456	7
10	8/31/78	63	P	Med Load - 10" OFA	9.9	10.3	61	83	233	0.317		0.707	0.354	12
11A	8/31/78	52	P	Low Load - 10" OFA	11.3	8.5	65	112	278	0.378				
11B	8/31/78	52	P	Low Load - 5" OFA	10.5	9.2	126	96	241	0.328				
11C	8/31/78	52	P	Low Load - 15" OFA	12.5	7.8	85	143	341	0.464				
11D	8/31/78	52	P	Low Load - 10" OFA	11.0	8.8	72	106	298	0.405				
11E	8/31/78	52	P	Low Load - 5" OFA	10.8	9.0	129	102	282	0.383				
11F	8/31/78	52	P	Low Load - 15" OFA	12.0	8.2	80	129	332	0.451				
12	9/06/78	87	P	High Load - 10" OFA	8.4	11.4	321	61	188	0.253	0.000	1.097	0.667	19
13A	9/08/78	89	P	High Load - 5" OFA	7.8	11.9	2345	54	172	0.232				
13B	9/08/78	89	P	High Load - 7" OFA	7.4	12.1	640	49	200	0.269	0.003	0.837	0.490	29
13C	9/08/78	89	P	High Load - 15" OFA	7.6	12.0	73	52	202	0.276				
13D	9/08/78	89	P	High Load - 10" OFA	7.6	12.0	378	52	199	0.272				
14	9/12/78	87	C	High Load - 7" OFA	7.5	12.2	618	51	226	0.307	-0.001	1.336	0.754	35
15	9/12/78	88	C	High Load - 15" OFA	7.8	11.6	39	54	217	0.294	0.000	1.000	0.424	19
16	9/13/78	64	C	Med Load - 10" OFA	8.7	10.8	25	65	234	0.314	0.000	0.798	0.319	12
17	9/14/78	87	C	High Load - 10" OFA	7.3	12.0	885	48	199	0.269	0.000	1.072	0.393	32
18††	9/15/78	79	C	SOx - Normal Conditions	8.1	11.2	34	58	230	0.312	-0.010	0.969	0.421	19
19	9/15/78		C	NOx (PDS Flask) - 12" OFA	9.0	10.4	32	70	154	0.313				
20	9/15/78		C	NOx (PDS Flask) - 9" OFA	10.5	9.5	25	94	147	0.343				
21	9/15/78		C	NOx (PDS Flask) - 15" OFA	11.5	8.5	24	115	155	0.400				
22††	9/21/78	59	V	SASS & SOx - Normal Conditions	10.2	10.0	29	89	243	0.327				
23	9/22/78	61	V	Med Load - 13" OFA	10.4	9.9	19	92	260	0.352		0.762	0.595	11

* The maximum obtainable load was 89% of the design capacity of 90,000 lb stm/hr due to draft losses from a retrofit dust collector.

** P - Perfect 8 Coal; C - Century Coal; V - Victoria Coal

*** Expressed as NO_2

† Stack opacity data based on transmissometer readings

†† SOx data was as follows: Test 18 SO_2 - 2.402, SO_3 - 0.000 lb/10^6Btu
Test 22 SO_2 - 2.425, SO_3 - 0.019 lb/10^6Btu

3.0 DESCRIPTION OF FACILITY TESTED AND COALS FIRED

This section discusses the general physical layout and operational characteristics of the boiler tested at Test Site D. The coals utilized in this test series are also discussed.

3.1 BOILER D DESCRIPTION

Boiler D is a Babcock & Wilcox type FP-18 No. 52 Integral Furnace Boiler Unit, designed for 700 psig, and capable of a maximum continuous capacity of 90,000 pounds of steam per hour at 200 psig and saturated temperature using feedwater at 250°F. The unit has a Detroit Stoker Company Vibragrate stoker, with water-cooled vibrating continuous ash discharge grate. Coal is mass fed to the upper end of the vibrating grate and is shaken toward the ash discharge end by the grate's vibrating action. There is no suspension burning. Undergrate air can be controlled in five zones. Design data on the boiler and stoker are presented in Table 3-1. Predicted performance data and performance data from a 1964 acceptance test are given in Table 3-2.

The boiler is equipped with a UOP multiclone dust collector. There is no flyash reinjection.

3.2 OVERFIRE AIR SYSTEM

The overfire air system on Boiler D consists of two rows of air jets on the front wall. The nozzles are 1-1/4" in diameter and there are sixteen nozzles in each row. The overfire air was found to be operating at about 10" H_2O. At maximum flow the pressure is about 15" H_2O. The overfire air is supplied by an independent fan, having a 4000 CFM capacity.

TABLE 3-1

DESIGN DATA
TEST SITE D

BOILER:	Manufacturer	Babcock & Wilcox Company
	Type	Two-drum FP-18 Integral Furnace Boiler
	Boiler Heating Surface	7706 ft^2
	Design Pressure	700 psig
	Tube Diameter	2"
ECONOMIZER:	Type	Continuous Tube
	Heating Surface	4275 ft^2
	Design Pressure	750 psig
	Tube Diameter	2"
FURNACE:	Volume	3520 ft^3
	Projected Area of Water Cooled Furnace Walls	737 ft^2
STOKER:	Manufacturer	Detroit Stoker Company
	Type	Vibra-Grate
	Width	15'6"
	Length	16'6.5"
	Effective Grate Area	256.3 ft^2
HEAT RATES:	Steam Flow	90,000 lbs/hr
	Input to Furnace	102.8×10^6 Btu/hr
	Furnace Width Heat Release	6.63×10^6 Btu/ft furnace width-hr
	Grate Heat Release	401×10^3 Btu/ft^2-hr
	Furnace Liberation	29.7×10^3 Btu/ft^3-hr

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TABLE 3-2

PREDICTED PERFORMANCE AND ACCEPTANCE TEST
TEST SITE D

	Predicted	Acceptance Test 2/20/64
Steam Flow	90,000 lbs/hr	88,389
Fuel	Western Kentucky Coal	--
Excess Air Leaving Boiler	31%	31%
Coal Flow	8,090 lbs/hr	7,060 lbs/hr
Flue Gas Leaving Boiler	112,500 lbs/hr	--
Air Leaving F.D. Fan	94,200 lbs/hr	--
Steam Pressure at Boiler Outlet	200 psig	218 psig
Economizer to Drum Pressure Drop	10 psig	--
Temp. Flue Gas Leaving Boiler	673°F	677°F
Temp. Flue Gas Leaving Economizer	370°F	398°F
Temp. Water Entering Economizer	250°F	262°F
Temp. Water Leaving Economizer	342°F	342°F
Temp. Air Entering F.D. Fan	80°F	67°F
Furnace Draft Loss	0.1"H_2O	0.08
Boiler Draft Loss	1.5"H_2O	1.04
Economizer Draft Loss	1.0"H_2O	1.58
Damper and Flue Draft Loss	1.1"H_2O	--
Total Draft Loss	3.7"H_2O	--
Dry Gas Heat Loss	7.0%	--
H_2O and H_2 in Fuel Heat Loss	4.6%	--
Moisture in Air Heat Loss	0.2%	--
Unburned Combustible Heat Loss	1.6%	--
Radiation Heat Loss	0.5%	--
Unaccounted for and Manufacturers Margin	1.5%	--
Total Heat Loss	15.4%	--
Efficiency of Unit	84.6%	86.7%

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3.3 PARTICULATE COLLECTION EQUIPMENT

The boiler is equipped with a UOP multiclone dust collector. Some of the tubes have been blanked off in order to increase the velocity through the remaining cyclones and so improve the efficiency of the collector.

3.4 TEST PORT LOCATIONS

Emissions measurements were made at two locations -- at the boiler outlet (before the multiclone dust collector) and at the stack outlet. The locations of these sample sites are shown in Figure 3-1. Their geometry is shown in Figure 3-2.

Whenever particulate loading was measured it was measured simultaneously at both locations using 24-point sample traverses. Gaseous measurements of O_2, CO_2, CO, and NO were obtained by pulling samples individually and compositely from six probes distributed along the width of the boiler outlet duct. SOx measurements and SASS samples for organic and trace element determinations were each obtained from single points within the boiler outlet duct. For these measurements a heated sample line was attached to one of the middle gaseous probes at the boiler outlet. Its purpose was to eliminate losses due to condensation when measuring NO_2 and unburned hydrocarbons.

3.5 COALS UTILIZED

Three coals were test fired at Test Site D. These were Perfect 8 coal, Century coal, and Victoria coal. Coal samples were taken for each test involving particulate or SASS sampling. Most of the test data were obtained on Perfect 8 coal, the primary coal at this site. Eight tests were run on Century coal and only two tests on Victoria coal. Certain sections in this report do not discuss Victoria coal because the data was insufficient to draw meaningful conclusions. The average analyses obtained from these samples are presented in Table 3-3. They show significant differences in moisture, sulfur and Btu content. Individual analyses for each coal sample are presented in Section 5.0, Test Results and Observations, Tables 5-7 through 5-11.

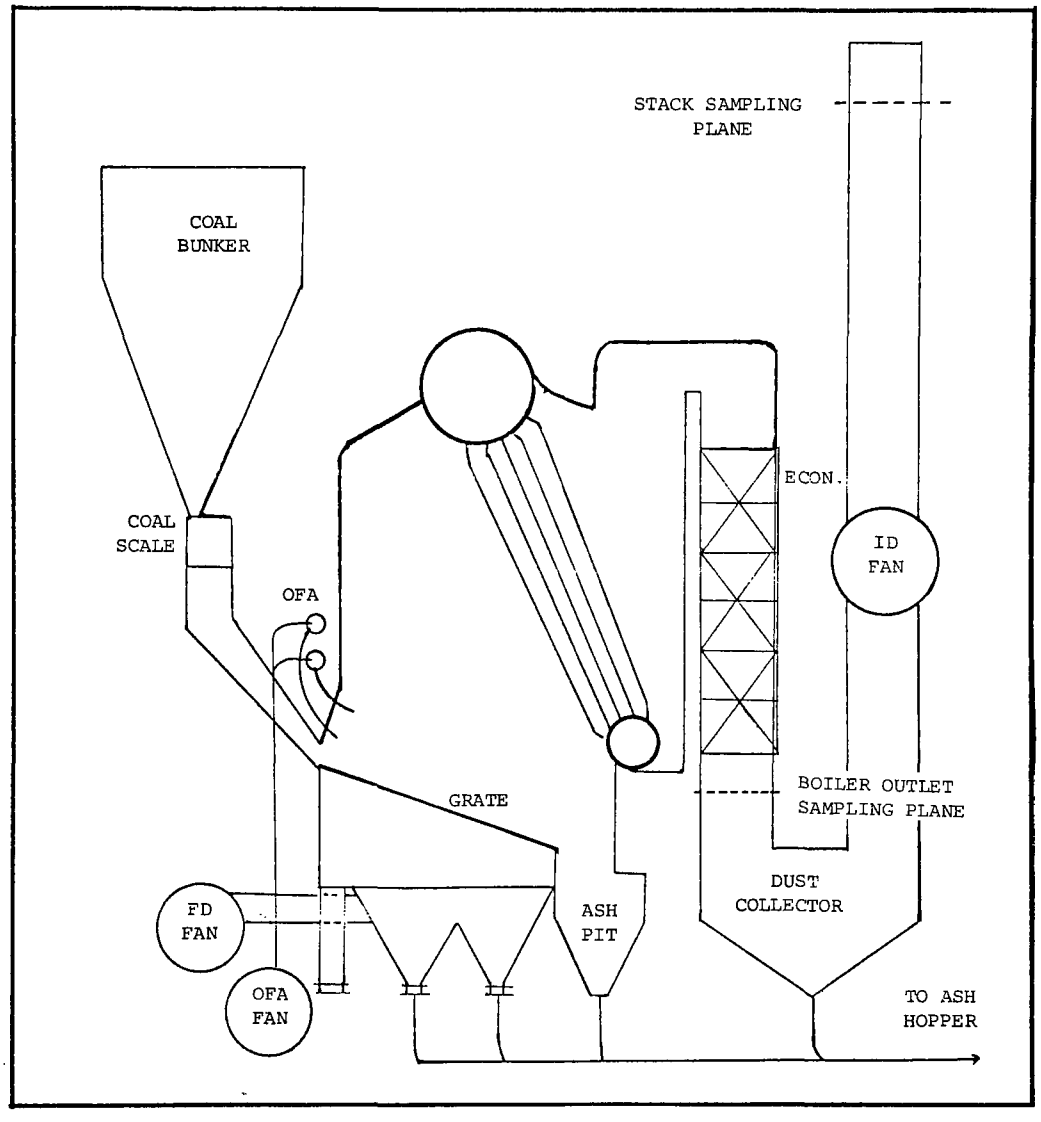

FIGURE 3-1. BOILER D SCHEMATIC

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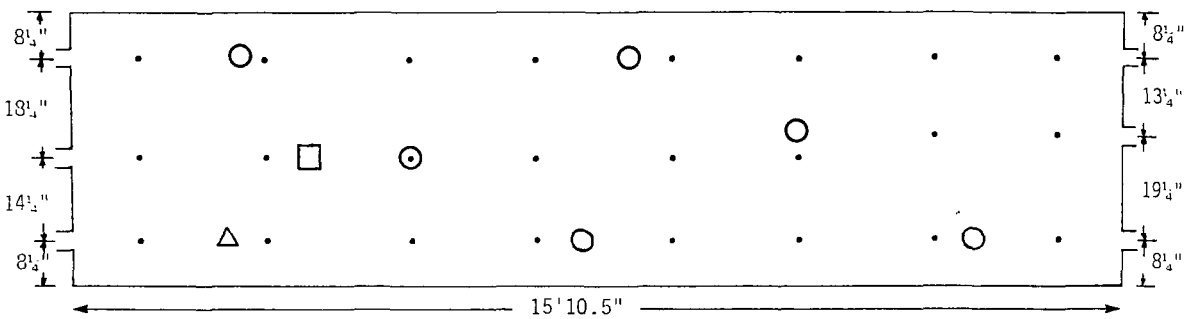
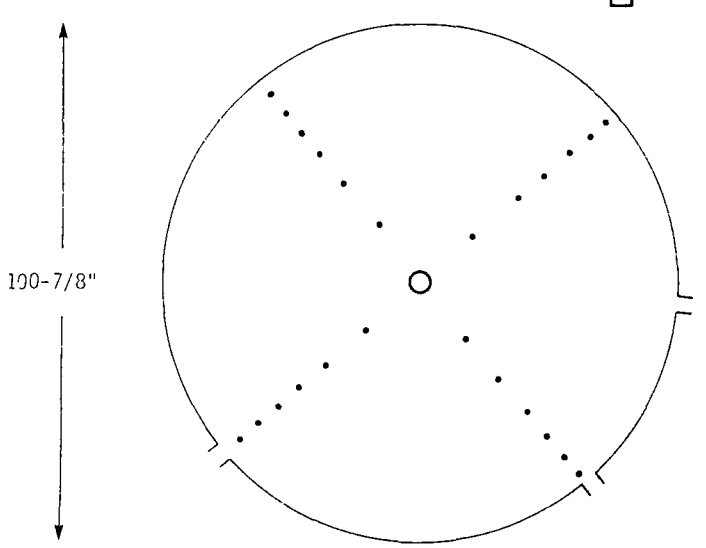
Boiler Outlet Sampling Plane
Cross Sectional Area = 64.82 ft^2





Stack Sampling Plane
Cross Sectional Area = 55.5 ft^2

FIGURE 3-2. BOILER D SAMPLE PLANE GEOMETRY

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TABLE 3-3

AVERAGE COAL ANALYSIS
TEST SITE D

	Century Coal	Perfect 8 Coal	Victoria Coal
PROXIMATE (As Rec'd)			
% Moisture	2.68	3.23	3.11
% Ash	5.86	8.71	6.72
% Volatile	38.44	39.17	37.25
% Fixed Carbon	53.02	48.89	52.94
Btu/lb	13629	13003	13405
% Sulfur	1.23	2.60	1.11
ULTIMATE (As Rec'd)			
% Moisture	2.68	3.23	3.11
% Carbon	76.08	72.07	74.96
% Hydrogen	5.15	5.01	5.00
% Nitrogen	1.33	1.23	1.30
% Chlorine	0.13	0.12	0.07
% Sulfur	1.23	2.60	1.11
% Ash	5.86	8.71	6.72
% Oxygen (Diff)	7.54	7.03	7.76

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4.0 TEST EQUIPMENT AND PROCEDURES

This section details how specific emissions were measured and the sampling procedures followed to assure that accurate, reliable data were collected.

4.1 GASEOUS EMISSIONS MEASUREMENTS (NOx, CO, CO_2, O_2, HC)

A description is given below of the analytical instrumentation, related equipment, and the gas sampling and conditioning system, all of which are located in a mobile testing van owned and operated by KVB. The systems have been developed as a result of testing since 1970, and are operational and fully checked out.

4.1.1 Analytical Instruments and Related Equipment

The analytical system consists of five instruments and associated equipment for simultaneously measuring the constituents of flue gas. The analyzers, recorders, valves, controls, and manifolds are mounted on a panel in the vehicle. The analyzers are shock mounted to prevent vibration damage. The flue gas constituents which are measured are oxides of nitrogen (NO, NOx), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and gaseous hydrocarbons (HC).

Listed below are the measurement parameters, the analyzer model furnished, and the range and accuracy of each parameter for the system. A detailed discussion of each analyzer follows:

Constituent:	Nitric Oxide/Total Oxides of Nitrogen (NO/NOx)
Analyzer:	Thermo Electron Model 10 Chemiluminescent Analyzer
Range:	0-2.5, 10, 25, 100, 250, 1000, 2500, 10,000 ppm NO
Accuracy:	±1% of full scale

Constituent:	Carbon Monoxide
Analyzer:	Beckman Model 315B NDIR Analyzer
Range:	0-500 and 0-2000 ppm CO
Accuracy:	±1% of full scale

Constituent:	Carbon Dioxide
Analyzer:	Beckman Model 864 NDIR Analyzer
Range:	0-5% and 0-20% CO_2
Accuracy:	±1% of full scale

Constituent:	Oxygen
Analyzer:	Teledyne Model 326A Fuel Cell Analyzer
Range:	0-5, 10 and 25% O_2 full scale
Accuracy:	±1% of full scale

Constituent:	Hydrocarbons
Analyzer:	Beckman Model 402 Flame Ionization Analyzer
Range:	5 ppm full scale to 10% full scale
Accuracy:	±1% of full scale

Oxides of nitrogen. The instrument used to monitor oxides of nitrogen is a Thermo Electron chemiluminescent nitric oxide analyzer. The instrument operates by measuring the chemiluminescent reaction of NO and O_3 to form NO_2. Light is emitted when electronically excited NO_2 molecules revert to their ground state. The resulting chemiluminescence is monitored through an optical filter by a high sensitivity photomultiplier, the output of which is linearly proportional to the NO concentration.

Air for the ozonator is drawn from ambient air through a dryer and a ten micrometer filter element. Flow control for the instrument is accomplished by means of a small bellows pump mounted on the vent of the instrument downstream of a separator that prevents water from collecting in the pump.

The basic analyzer is sensitive only to NO molecules. To measure NOx (i.e., $NO+NO_2$), the NO_2 is first converted to NO. This is accomplished by a converter which is included with the analyzer. The conversion occurs as the gas passes through a thermally insulated, resistance heated, stainless steel coil. With the application of heat, NO_2 molecules in the sample gas are reduced to NO molecules, and the analyzer now reads NOx. NO_2 is obtained by the difference in readings obtained with and without the converter in operation.

Specifications:
- Accuracy 1% of full scale
- Span stability ±1% of full scale in 24 hours
- Zero stability ±1 ppm in 24 hours
- Power requirements 115±10V, 60 Hz, 1000 watts
- Response 90% of full scale in 1 sec. (NOx mode), 0.7 sec. NO mode
- Output 4-20 ma

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Sensitivity 0.5 ppm
Linearity ±1% of full scale
Vacuum detector operation
Range: 2.5, 10, 25, 100, 250, 1000, 2500, 10,000 ppm full scale

Carbon monoxide. Carbon monoxide concentration is measured by a Beckman 315B non-dispersive infrared analyzer. This instrument measures the differential in infrared energy absorbed from energy beams passed through a reference cell (containing a gas selected to have minimal absorption of infrared energy in the wavelength absorbed by the gas component of interest) and a sample cell through which the sample gas flows continuously. The differential absorption appears as a reading on a scale from 0 to 100 and is then related to the concentration of the specie of interest by calibration curves supplied with the instrument. The operating ranges for the CO analyzer are 0-500 ppm and 0-2000 ppm.

Specifications: Span stability ±1% of full scale in 24 hours
Zero stability ±1% of full scale in 24 hours
Ambient temperature range 32°F to 120°F
Line voltage 115±15V rms
Response 90% of full scale in 0.5 or 2.5 sec.
Precision ±1% of full scale
Output 4-20 ma

Carbon dioxide. Carbon dioxide concentration is measured by a Beckman Model 864 short path-length, non-dispersive infrared analyzer. This instrument measures the differential in infrared energy absorbed from energy beams passed through a reference cell (containing a gas selected to have minimal absorption of infrared energy in the wavelength absorbed by the gas component of interest) and a sample cell through which the sample gas flows continuously. The differential absorption appears as a reading on a scale from 0 to 100 and is then related to the concentration of the specie of interest by calibration curves supplied with the instrument. The operating ranges for the CO_2 analyzer are 0-5% and 0-20%.

Specifications: Span stability ±1% of full scale in 24 hours
Zero stability ±1% of full scale in 24 hours
Ambient temperature range 32°F to 120°F
Line voltage 115±15V rms
Response 90% of full scale in 0.5 or 2.5 sec.
Precision ±1% of full scale
Output 4-20 ma

Oxygen. The oxygen content of the flue gas sample is automatically and continuously determined with a Teledyne Model 326A Oxygen analyzer. Oxygen in the flue gas diffuses through a Teflon membrane and is reduced on the surface of the cathode. A corresponding oxidation occurs at the anode internally and an electric current is produced that is proportional to the concentration of oxygen. This current is measured and conditioned by the instrument's electronic circuitry to give a final output in percent O_2 by volume for operating ranges of 0% to 5%, 0% to 10%, or 0% to 25%.

Specifications: Precision ±1% of full scale
Response 90% in less than 40 sec.
Sensitivity 1% of low range
Linearity ±1% of full scale
Ambient temperature range 32-125°F
Fuel cell life expectancy 40,000%-hours
Power requirement 115 VAC, 50-60 Hz, 100 watts
Output 4-20 ma

Hydrocarbons. Hydrocarbons are measured using a Beckman Model 402 hydrocarbon analyzer which utilizes the flame ionization method of detection. The sample is drawn to the analyzer through a heated line to prevent the loss of higher molecular weight hydrocarbons. It is then filtered and supplied to the burner by means of a pump and flow control system. The sensor, which is the burner, has its flame sustained by regulated flows of fuel (40% hydrogen plus 60% helium) and air. In the flame, the hydrocarbon components of the sample undergo a complete ionization that produces electrons and positive ions. Polarized electrodes collect these ions, causing a small current to flow through a circuit. This ionization current is proportional to the concentration of hydrocarbon atoms which enter the burner. The instrument is available with range selection from 5 ppm to 10% full scale as CH_4.

Specifications: Full scale sensitivity, adjustable from 5 ppm CH_4 to 10% CH_4
Ranges: Range multiplier switch has 8 positions: X1, X5, X10, X50, X100, X500, X1000, and X5000. In addition, span control provides continuously variable adjustment within a dynamic range of 10:1
Response time 90% full scale in 0.5 sec.
Precision ±1% of full scale
Electronic stability ±1% of full scale for successive identical samples

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Reproducibility ±1% of full scale for successive identical samples
Analysis temperature: ambient
Ambient temperature 32°F to 110°F
Output 4-20 ma
Air requirements 350 to 400 cc/min of clean, hydrocarbon-free air, supplied at 30 to 200 psig
Fuel gas requirements 75 to 80 cc/min of pre-mixed fuel consisting of 40% hydrogen and 60% nitrogen or helium, supplied at 30 to 200 psig
Electrical power requirements 120V, 60 Hz
Automatic flame-out indication and fuel shut-off valve

4.1.2 Recording Instruments

The output of the four analyzers is displayed on front panel meters and are simultaneously recorded on a Texas Instrument Model FLO4W6D four-pen strip chart recorder. The recorder specifications are as follows:

Chart size 9-3/4 inch
Accuracy ±0.25%
Linearity <0.1%
Line voltage 120V±10% at 60 Hz
Span step response: one second

4.1.3 Gas Sampling and Conditioning System

The gas sampling and conditioning system consists of probes, sample lines, valves, pumps, filters and other components necessary to deliver a representative, conditioned sample gas to the analytical instrumentation. The following sections describe the system and its components. The entire gas sampling and conditioning system shown schematically in Figure 4-1 is contained in the emission test vehicle.

4.1.4 Gaseous Emission Sampling Techniques

Boiler access points for gaseous sampling are selected in the same sample plane as are particulate sample points. Each probe consists of one-half inch 316 stainless steel heavy wall tubing. A 100 micrometer Mott Metallurgical Corporation sintered stainless steel filter is attached to each probe for removal of particulate material.

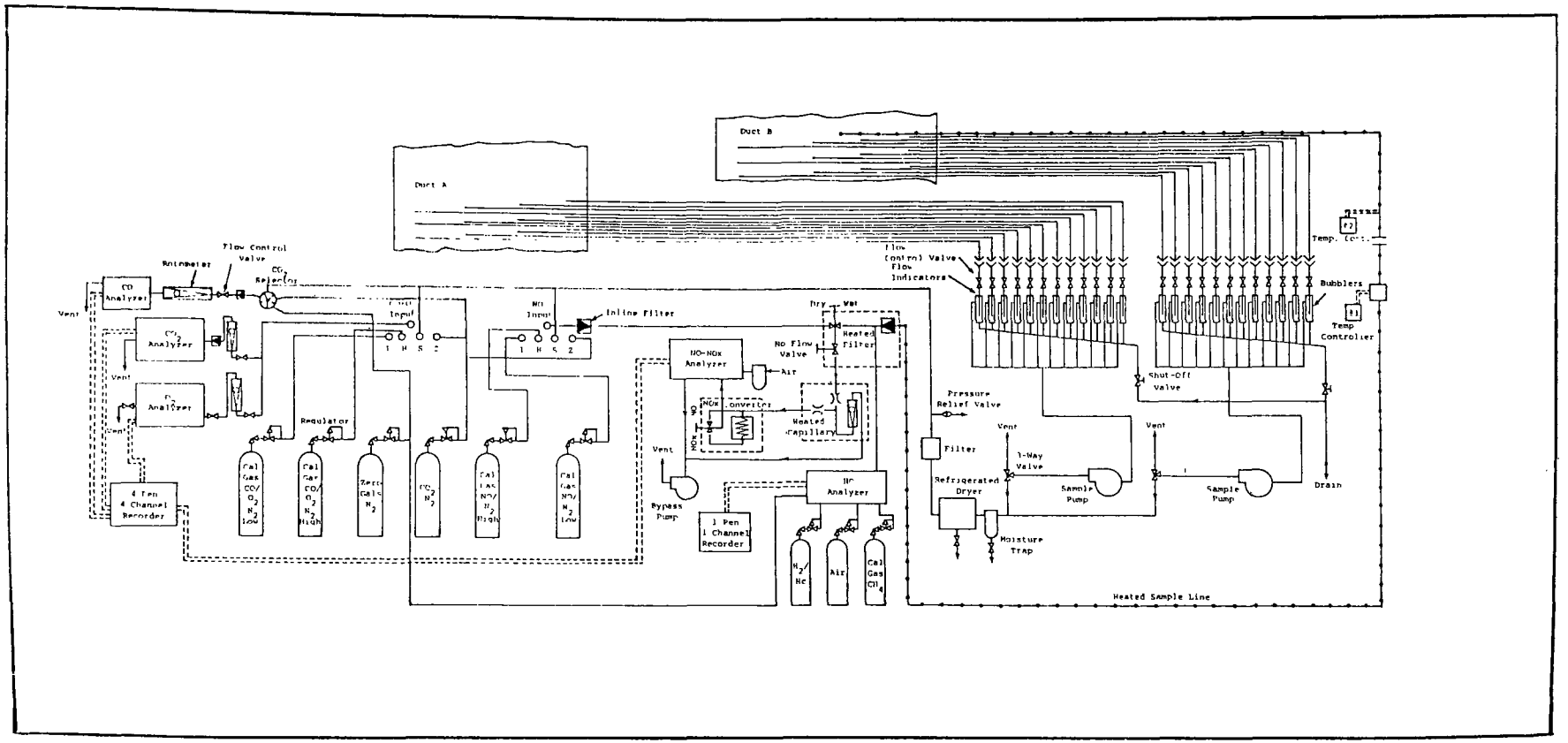

FIGURE 4-1. FLOW SCHEMATIC OF MOBILE FLUE GAS MONITORING LABORATORY

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Gas samples to be analyzed for O_2, CO_2, CO and NO are conveyed to the KVB mobile laboratory through 3/8 inch nylon sample lines. After passing through bubblers for flow control, the samples pass through a diaphragm pump and a refrigerated dryer to reduce the sample dew point temperature to 35°F. After the dryer, the sample gas is split between the various continuous gas monitors for analysis. Flow through each continuous monitor is accurately controlled with rotometers. Excess flow is vented to the outside. Gas samples are drawn both individually and compositely from all probes during each test. The average emission values are reported in this report.

4.2 SULFUR OXIDES (SOx) MEASUREMENT AND PROCEDURES

Measurement of SO_2 and SO_3 concentrations is made by wet chemical analysis using the "Shell-Emeryville" method. In this technique the gas sample is drawn from the stack through a glass probe (Figure 4-2), containing a quartz wool filter to remove particulate matter, into a system of three sintered glass plate absorbers (Figure 4-3). The first two absorbers contain aqueous isopropyl alcohol and remove the sulfur trioxide; the third contains aqueous hydrogen peroxide solution which absorbs the sulfur dioxide. Most of the sulfur trioxide is removed by the first absorber. The remainder, which passes through the absorber, is completely removed by the secondary absorber mounted above the first. After the gas sample has passed through the absorbers, the gas train is purged with nitrogen to transfer sulfur dioxide, which has dissolved in the first two absorbers, to the third absorber to complete the separation of the two components. The isopropyl alcohol is used to inhibit the oxidation of sulfur dioxide to sulfur trioxide before it gets to the third absorber.

The isopropyl alcohol absorber solutions are combined and the sulfate resulting from the sulfur trioxide absorption is titrated with standard lead perchlorate solution using Sulfonazo III indicator. In a similar manner, the hydrogen peroxide solution is titrated for the sulfate resulting from the sulfur dioxide absorption.

The gas sample is drawn from the flue by a single probe made of quartz glass inserted into the duct approximately one-third to one-half way.

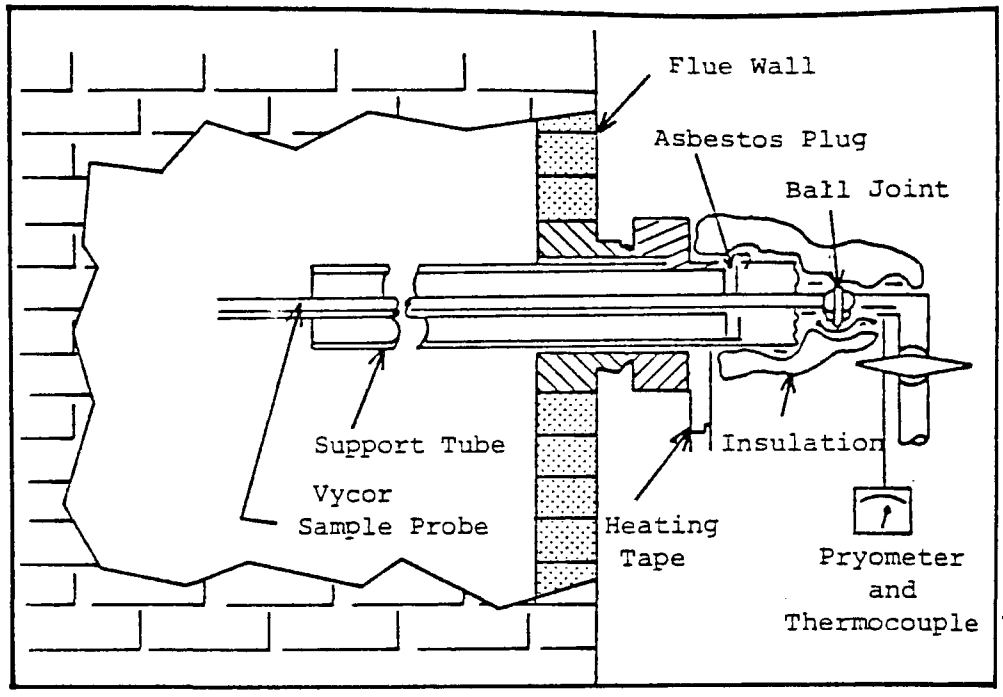

FIGURE 4-2. SOx SAMPLE PROBE CONSTRUCTION

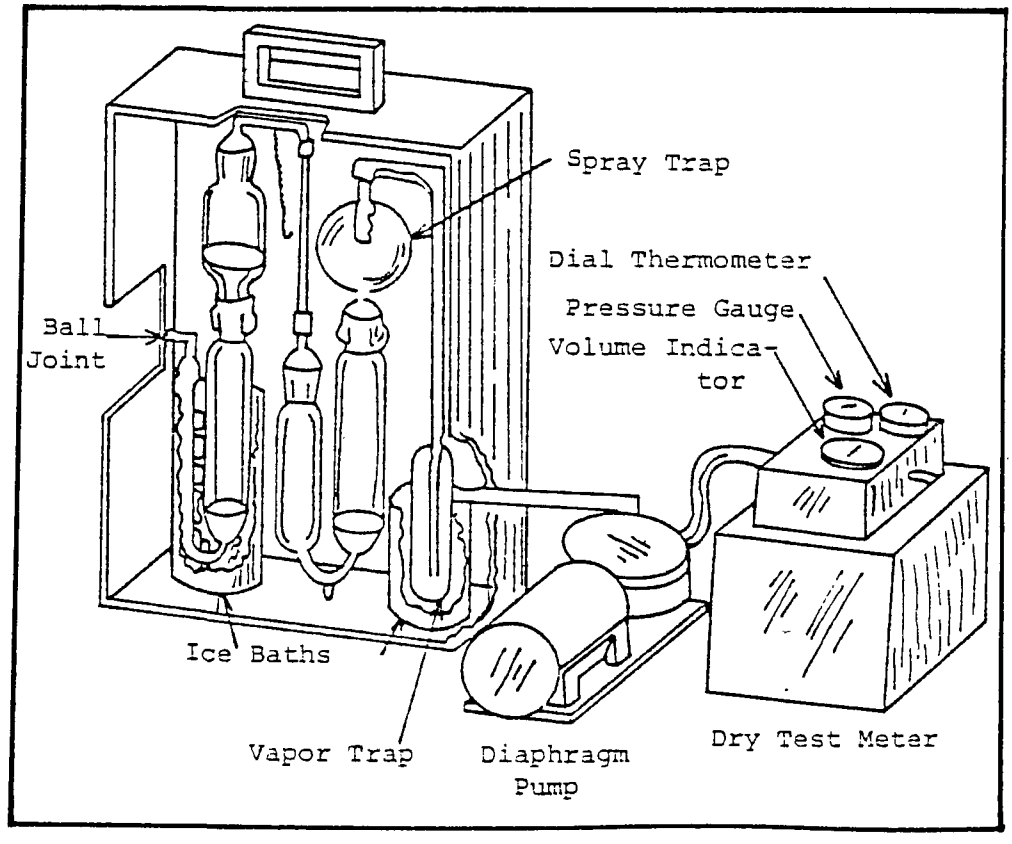

FIGURE 4-3. SULFUR OXIDES SAMPLING TRAIN

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The inlet end of the probe holds a quartz wool filter to remove particulate matter. It is important that the entire probe temperature be kept above the dew point of sulfuric acid during sampling (minimum temperature of 260°C). This is accomplished by wrapping the probe with a heating tape.

Three repetitions of SOx sampling are made at each test point.

4.3 PARTICULATE MEASUREMENT AND PROCEDURES

Particulate samples are taken at the same sample ports as the gaseous emission samples using a Joy Manufacturing Company portable effluent sampler (Figure 4-4). This system, which meets the EPA design specifications for Test Method 5, Determination of Particulate Emissions from Stationary Sources (Federal Register, Volume 36, No. 27, page 24888, December 23, 1971), is used to perform both the initial velocity traverse and the particulate sample collection. Dry particulates are collected in a heated case using first a cyclone to separate particles larger than five micrometers and a 100 mm glass fiber filter for retention of particles down to 0.3 micrometers. Condensible particulates are collected in a train of four Greenburg-Smith impingers in an ice water bath. The control unit includes a total gas meter and thermocouple indicator. A pitot tube system is provided for setting sample flows to obtain isokinetic sampling conditions.

All peripheral equipment is carried in the instrument van. This includes a scale (accurate to ±0.1 mg), hot plate, drying oven (212°F), high temperature oven, desiccator, and related glassware. A particulate analysis laboratory is set up in the vicinity of the boiler in a vibration-free area. Here filters are prepared, tare weighed and weighed again after particulate collection. Also, probe washes are evaporated and weighed in the lab.

4.4 PARTICLE SIZE DISTRIBUTION MEASUREMENT AND PROCEDURE

Particle size distribution is measured using several methods. These include the Brink Cascade Impactor, SASS cyclones, and the Bahco Classifier. Each of these particle sizing methods has its advantages and disadvantages.

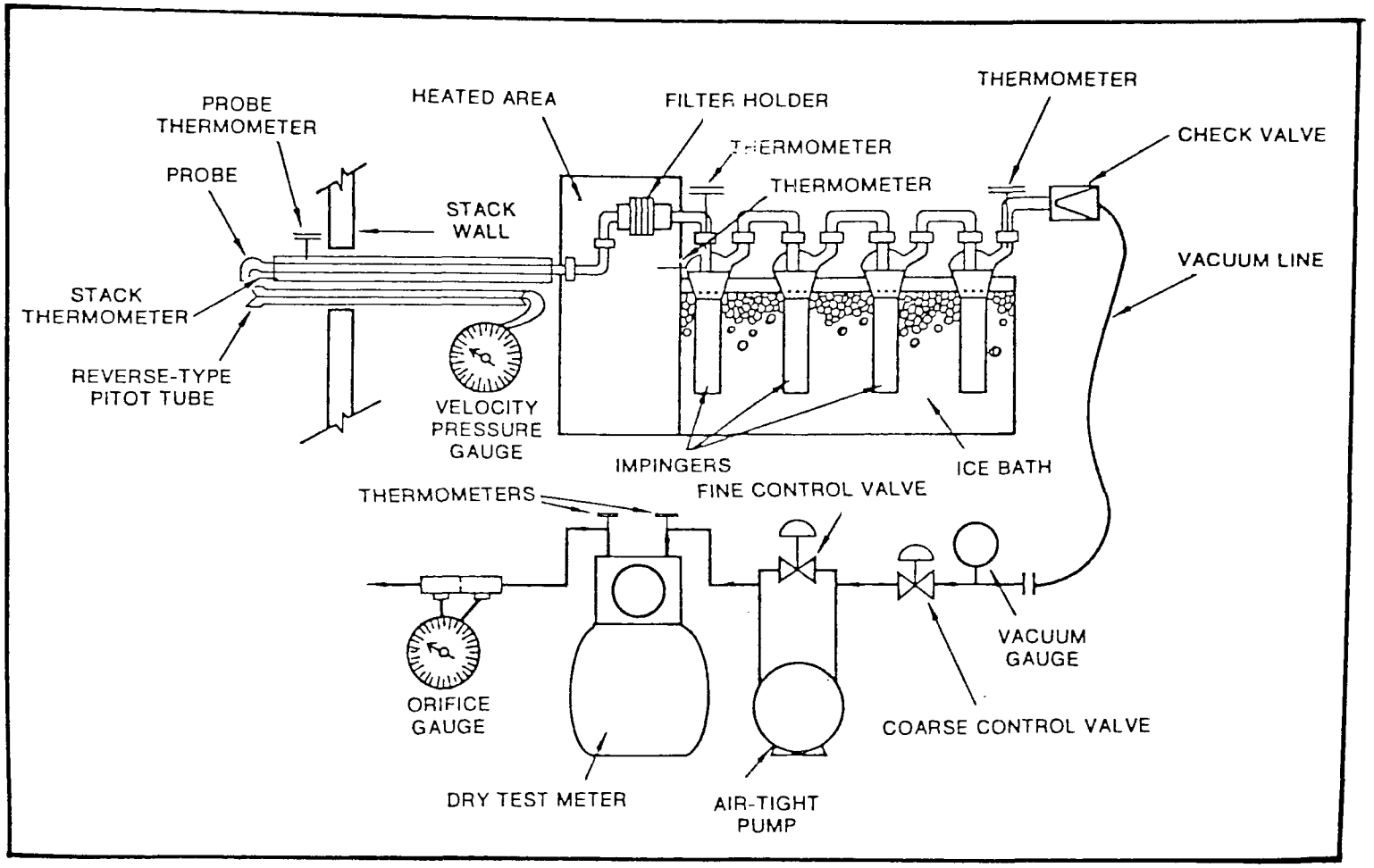

FIGURE 4-4. EPA METHOD 5 PARTICULATE SAMPLING TRAIN

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Brink. The Brink cascade impactor is an in situ particle sizing device which separates the particles into six size classifications. It has the advantage of collecting the entire sample. That is, everything down to the collection efficiency of the final filter is included in the analysis. It has, however, some disadvantages. If the particulate matter is spatially stratified within the duct, the single-point Brink sampler will yield erroneous results. Unfortunately, the particles at the outlets of stoker boilers may be considerably stratified. Another disadvantage is the instrument's small classification range (0.3 to 3.0 micrometers) and its small sample nozzle (1.5 to 2.0 mm maximum diameter). Both are inadequate for the job at hand. The particles being collected at the boiler outlet are often as large as the sample nozzle.

The sampling procedure is straight forward. First, the gas velocity at the sample point is determined using a calibrated S-type pitot tube. For this purpose a hand held particulate probe, inclined manometer, thermocouple and indicator are used. Second, a nozzle size is selected which will maintain isokinetic flow rates within the recommended .02-.07 ft^3/min rate at stack conditions. Having selected a nozzle and determined the required flow rate for isokinetics, the operating pressure drop across the impactor is determined from a calibration curve. This pressure drop is corrected for temperature, pressure and molecular weight of the gas to be sampled.

A sample is drawn at the predetermined ΔP for a time period which is dictated by mass loading and size distribution. To minimize weighing errors, it is desirable to collect several milligrams on each stage. However, to minimize reentrainment, a rule of thumb is that no stage should be loaded above 10 mg. A schematic of the Brink sampling train is shown in Figure 4-5.

Bahco. The Bahco classifier is described in Power Test Code 28. It is an acceptable particle sizing method in the power industry and is often used in specifying mechanical dust collector guarantees. Its main disadvantage is that it is only as accurate as the sample collected. Most Bahco samples are collected by cyclone separation; thus, particles below the cut point of the cyclone are lost. The Bahco samples collected at Test Site D came from the cyclone in the EPA Method 5 particulate train. These samples are spatially representative because they are taken from a 24-point sample matrix. However,

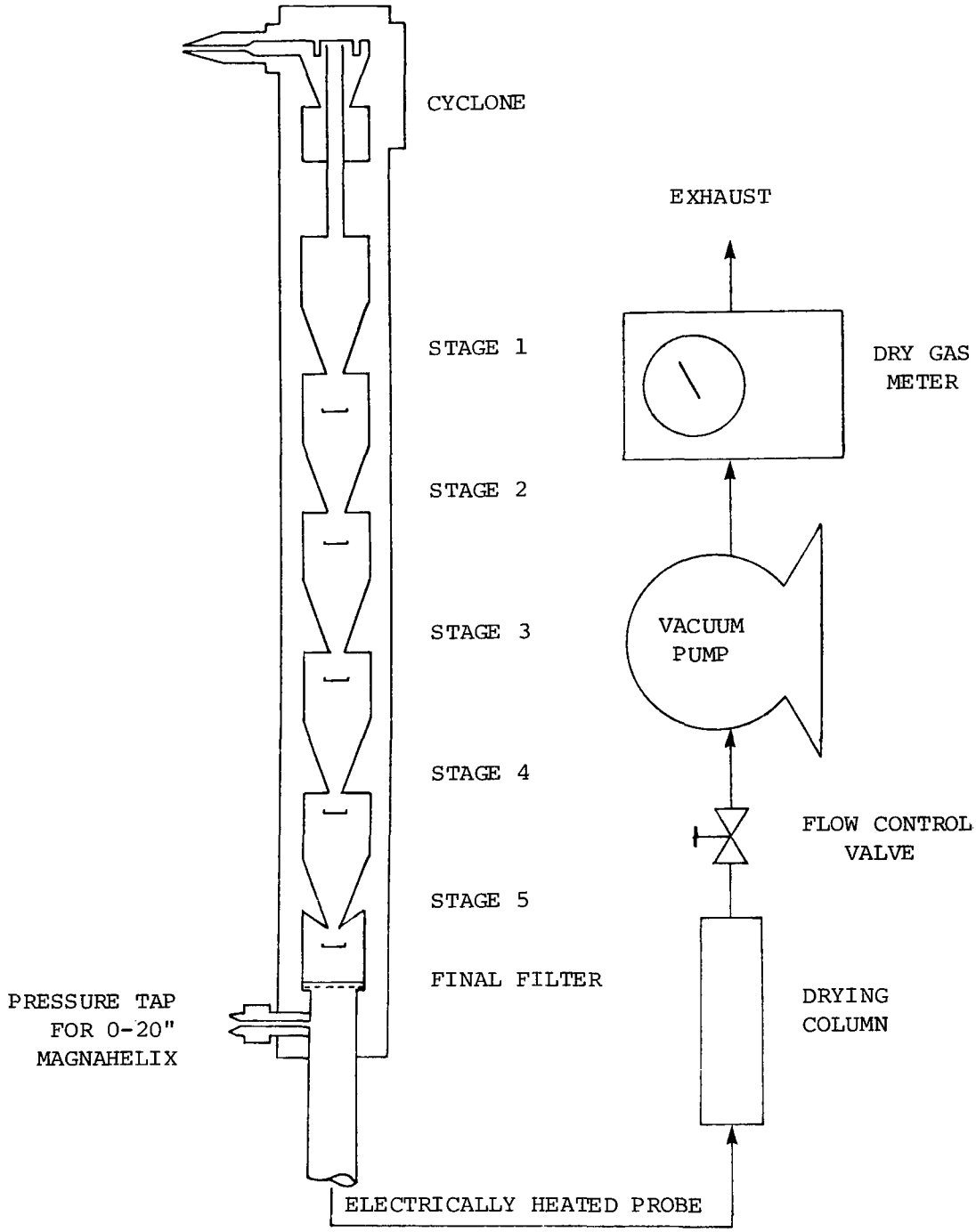

FIGURE 4-5. BRINK CASCADE IMPACTOR SAMPLING TRAIN SCHEMATIC

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much of the sample below about seven micrometers is lost to the filter. The Bahco test data are presented in combination with sieve analysis of the same sample. An attempt was made to correct for the lost portion of the sample.

SASS. The Source Assessment Sampling System (SASS) was not designed principally as a particle sizer but it includes three calibrated cyclones which can be used as such. The SASS train is a single point in-situ sampler. Thus, it is on a par with cascade impactors. Because it is a high volume sampler and samples are drawn through large nozzles (0.25 to 1.0 in.), it has an advantage over the Brink cascade impactor where large particles are involved. The cut points of the three cyclones are 10, 3 and 1 micrometers. A detailed description of the SASS train is presented in Section 4.9.

4.5 COAL SAMPLING AND ANALYSIS PROCEDURE

Coal samples at Test Site D were taken during each test from the unit's two coal scales. The samples were processed and analyzed for both size consistency and chemical composition. The use of the coal scale as a sampling station has two advantages. It is close enough to the furnace that the coal sampled simultaneously with testing is representative of the coal fired during the testing. Also, because of the construction of the coal scale, it is possible to collect a complete cut of coal off the scales' apron feeder thus insuring a representative size consistency.

In order to collect representative coal samples, a sampling tray having a twenty pound capacity was custom built. The tray has the same width as the apron feeder belt and can be moved directly under the belt's discharge end to catch all of the coal over a short increment of time (approximately five seconds).

The sampling procedure is as follows. At the start of testing one increment of sample is collected from each feeder. This is repeated twice more during the test (three to five hours duration) so that a six increment sample is obtained. The sample is then riffled using a Gilson Model SP-2 Porta Splitter until two representative twenty pound samples are obtained.

The sample to be used for sieve analysis is weighed, dried in an oven at 200°F for about four hours, and re-weighed. Drying of the coal is necessary for good separation of fines. If the coal is wet, fines cling to the larger pieces of coal and to each other. Once dry, the coal is sized using a six tray Gilson Model PS-3 Porta Screen. Screen sizes used are 1", 1/2", 1/4", #8 and #16 mesh. Screen area per tray is 14"x14". The coal in each tray is weighed on a triple beam balance to the nearest 0.1 gram.

The coal sample for chemical analysis is reduced to 2-3 pounds by further riffling and sealed in a plastic bag. All coal samples are sent to Commercial Testing and Engineering Company, South Holland, Illinois. Each sample associated with a particulate loading or particle sizing test is given a proximate analysis. In addition, composite samples consisting of one increment of coal for each test for each coal type receive ultimate analysis, ash fusion temperature, mineral analysis, Hardgrove grindability and free swelling index measurements.

4.6 ASH COLLECTION AND ANALYSIS FOR COMBUSTIBLES

The combustible content of flyash is determined in the field by KVB in accordance with ASTM D3173, "Moisture in the Analysis Sample of Coal and Coke" and ASTM D3174, "Ash in the Analysis Sample of Coal and Coke."

The flyash sample is collected by the EPA Method 5 particulate sample train while sampling for particulates. The cyclone catch is placed in a desiccated and tare-weighed ceramic crucible. The crucible with sample is heated in an oven at 230°F to remove its moisture. It is then desiccated to room temperature and weighed. The crucible with sample is then placed in an electric muffle furnace maintained at a temperature of 1400°F until ignition is complete and the sample has reached a constant weight. It is cooled in a desiccator over desiccant and weighed. Combustible content is calculated as the percent weight loss of the sample based on its post 230°F weight.

At Test Site D the bottom ash samples were collected in several increments from the stoker ash pit at completion of testing. These samples were mixed, quartered, and sent to Commercial Testing and Engineering Company for combustible determination. Multiclone ash samples were taken from ports near the base of the multiclone hopper. This sample, approximately two quarts in size, was sent to Commercial Testing and Engineering Company for combustible determination.

4.7 BOILER EFFICIENCY EVALUATION

Boiler efficiency is calculated using the ASME Test Form for Abbreviated Efficiency Test, Revised, September, 1965. The general approach to efficiency evaluation is based on the assessment of combustion losses. These losses can be grouped into three major categories: stack gas losses, combustible losses, and radiation losses. The first two groups of losses are measured directly. The third is estimated from the ABMA Standard Radiation Loss Chart.

Unlike the ASME test in which combustible losses are lumped into one category, combustible losses are calculated and reported separately for combustibles in the bottom ash, combustibles in the mechanically collected ash which is not reinjected, and combustibles in the flyash leaving the mechanical collector.

4.8 MODIFIED SMOKE SPOT NUMBER

Modified Bacharach smoke spot numbers are determined using a Bacharach field service type smoke tester. ASTM procedures for this measurement apply only to oil fired units. Therefore, KVB defined its own set of procedures, which differ from ASTM D2156-65 procedure in the number of strokes taken with the hand pump. At this test site, one, two and three strokes were taken at the multiclone outlet.

Smoke spot measurements are obtained by pulling a fixed volume of flue gas through a standard filter paper. The color (or shade) of the spot that is

produced is matched visually with a standard smoke spot scale. The result is a "smoke number" which is used to characterize the density of smoke in the flue gas.

The sampling device is a hand pump similar to the one shown in Figure 4-6. It is a commercially available item that with ten strokes can pass 2,250 ±100 cubic inches of gas at 60°F and one atmosphere pressure through an enclosed filter paper for each 1.0 square inch effective surface area of the filter paper.

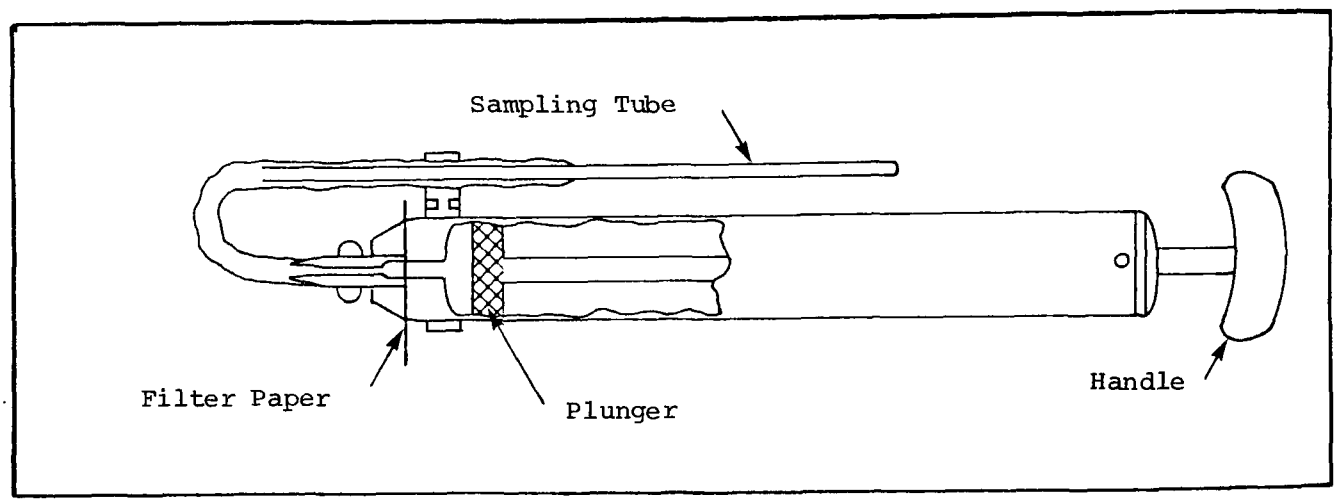

FIGURE 4-6. FIELD SERVICE TYPE SMOKE TESTER

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4.9 TRACE SPECIES MEASUREMENT

The EPA (IERL-RTP) has developed the Source Assessment Sampling System (SASS) train for the collection of particulate and volatile matter in addition to gaseous samples (Figure 4-7). The "catch" from the SASS train is analyzed for polynuclear aromatic hydrocarbons (PAH) and inorganic trace elements.

In this system, a stainless steel heated probe is connected to an oven module containing three cyclones and a filter. Size fractionation is accomplished in the series cyclone portion of the SASS train, which incorporates the cyclones in series to provide large quantities of particulate matter which are classified by size into three ranges:

A) >10 μm B) 3 μm to 10 μm C) 1 μm to 3 μm

Together with a filter, a fourth cut (<1 μm) is obtained. Volatile organic material is collected in an XAD-2 sorbent trap. The XAD-2 trap is an integral part of the gas treatment system which follows the oven containing the cyclone system. The gas treatment system is composed of four primary components: the gas conditioner, the XAD-2 organic sorbent trap, the aqueous condensate collector, and a temperature controller. The XAD-2 sorbent is a porous polymer resin with the capability of absorbing a broad range of organic species. Some trapping of volatile inorganic species is also anticipated as a result of simple impaction. Volatile inorganic elements are collected in a series of impingers. The pumping capacity is supplied by two 10 cfm high volume vacuum pumps, while required pressure, temperature, power and flow conditions are obtained from a main controller.

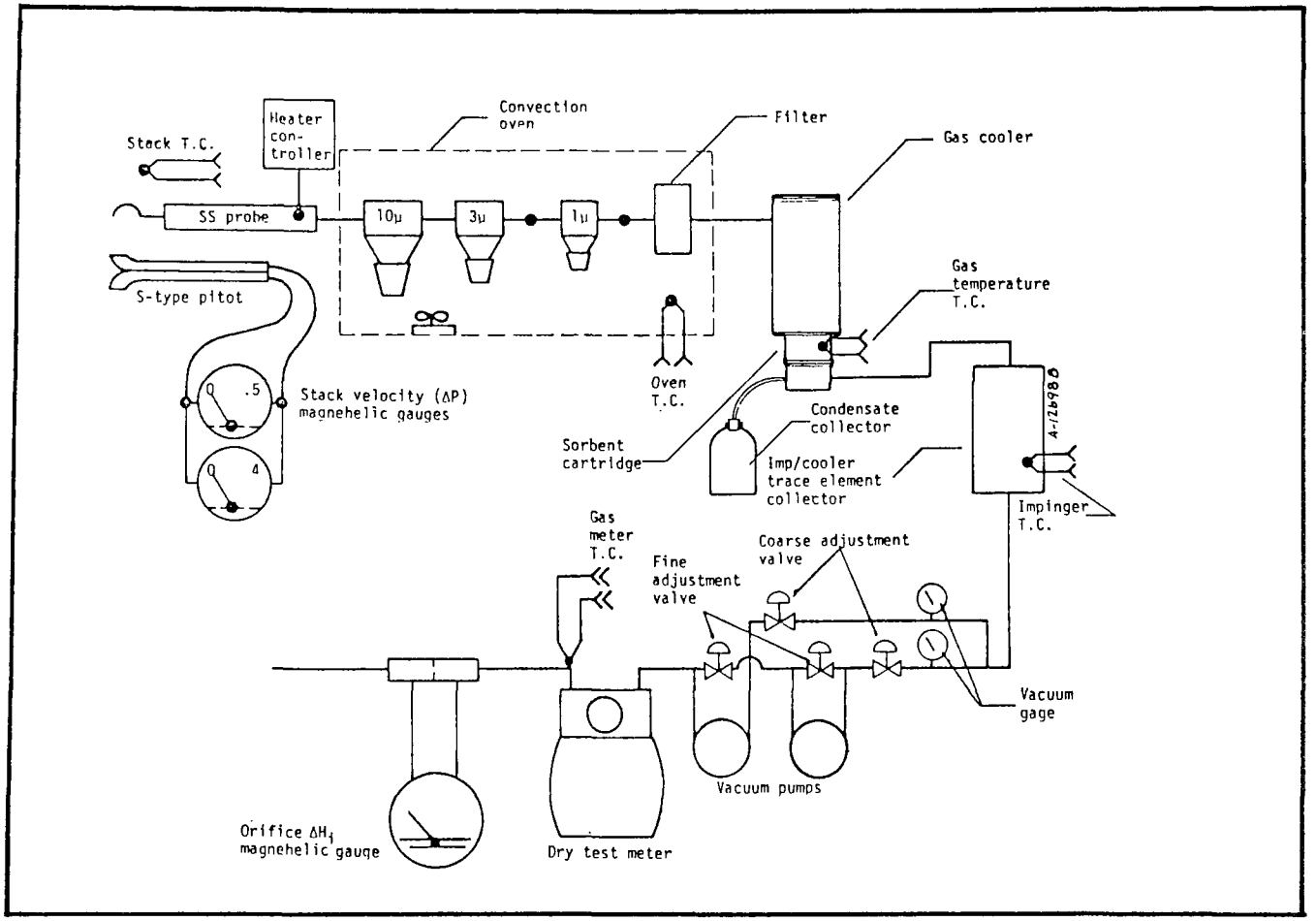

FIGURE 4-7. SOURCE ASSESSMENT SAMPLING (SASS) FLOW DIAGRAM

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5.0 TEST RESULTS AND OBSERVATIONS

This section presents the results of the tests performed on Boiler D. Observations are made regarding the influence on efficiency and gaseous and particulate emissions as the control parameters were varied. Twenty-three tests were conducted in a defined test matrix to develop this data. Data Tables 5-19 through 5-23 are included at the end of this section for reference.

5.1 OVERFIRE AIR

Boiler D had two rows of overfire air jets on the front water wall configured as shown in Figure 5-1. Several test series were run in which overfire air pressure (and thus overfire air flow) was the independent variable. Emissions and boiler efficiency were measured as the overfire air pressure was varied over its operating range of 5 to 15" H_2O static pressure. The purpose of these tests was to determine which overfire air pressure settings were optimum in terms of emissions and efficiency. Tests were run with both Perfect 8 coal and Century coal.

Perfect 8 coal exhibited increases in particulate loading and in nitric oxide concentrations as overfire air pressure was increased. Carbon carryover decreased only slightly with increasing overfire air, and boiler efficiency changes were negligible. At loads of 88% capacity, 13 to 15" H_2O pressure were required to control carbon monoxide levels. However, at lower loads -- in the range of 50 to 65% of capacity -- carbon monoxide emissions were negligible at all overfire air levels. The tests showed that 7 to 10" H_2O pressure would be best at low and medium loads because it would help minimize particulate and nitric oxide concentrations.

The test results for Century coal were largely the reverse of those for Perfect 8. Both particulate loading and nitric oxide concentrations decreased with increasing overfire air pressure at 88% of steam capacity. The heat loss due to combustibles in the flyash decreased nearly 0.5% as overfire

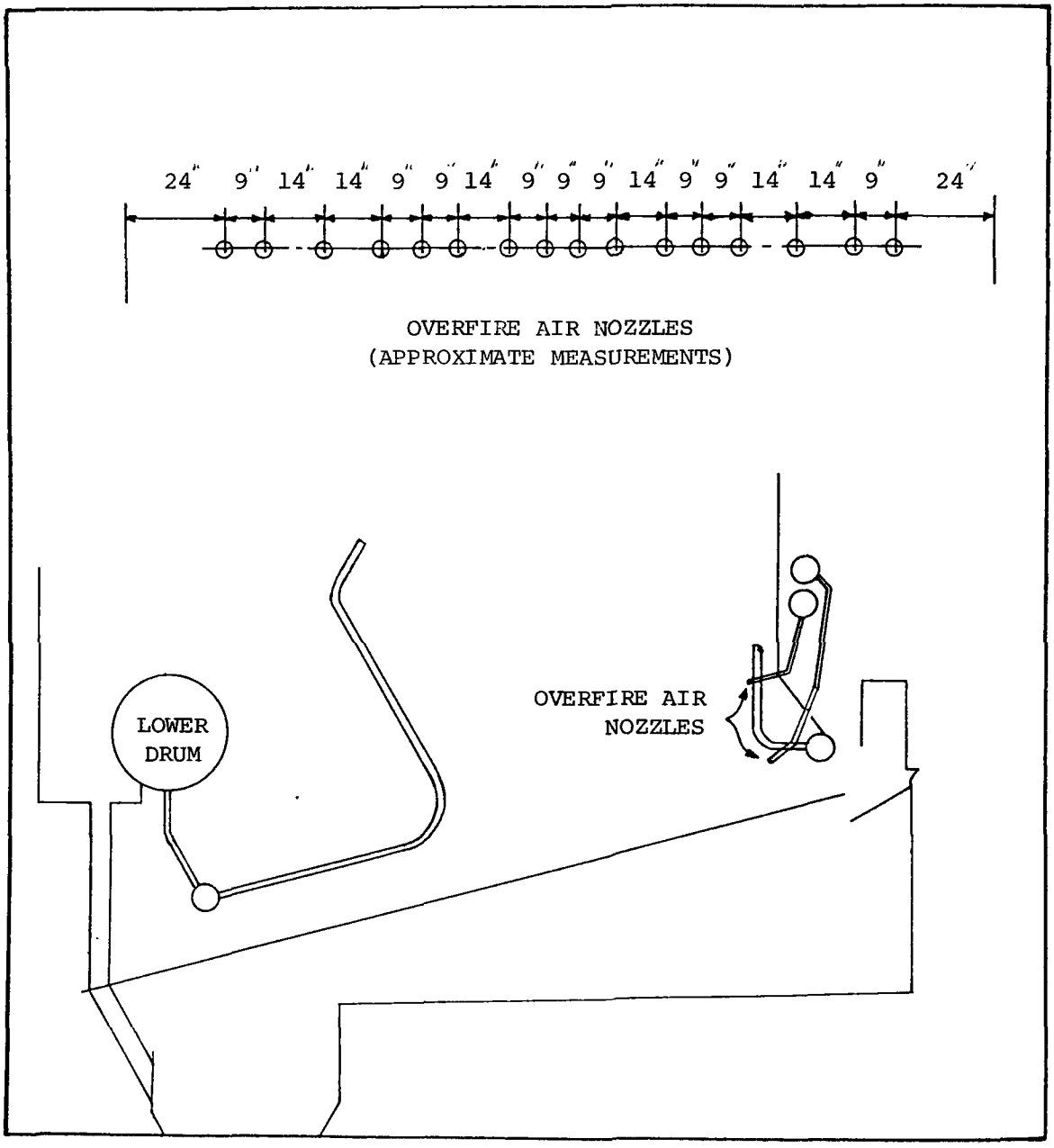

FIGURE 5-1. OVERFIRE AIR CONFIGURATION

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air was increased from 7 to 15 "H_2O pressure. Overfire air pressures of 13 to 15 "H_2O were again necessary to control carbon monoxide emissions at 88% steam capacity. Lower steam loadings were not tested.

These test results are discussed in greater detail in the following paragraphs.

5.1.1 Particulate Loadings vs Overfire Air

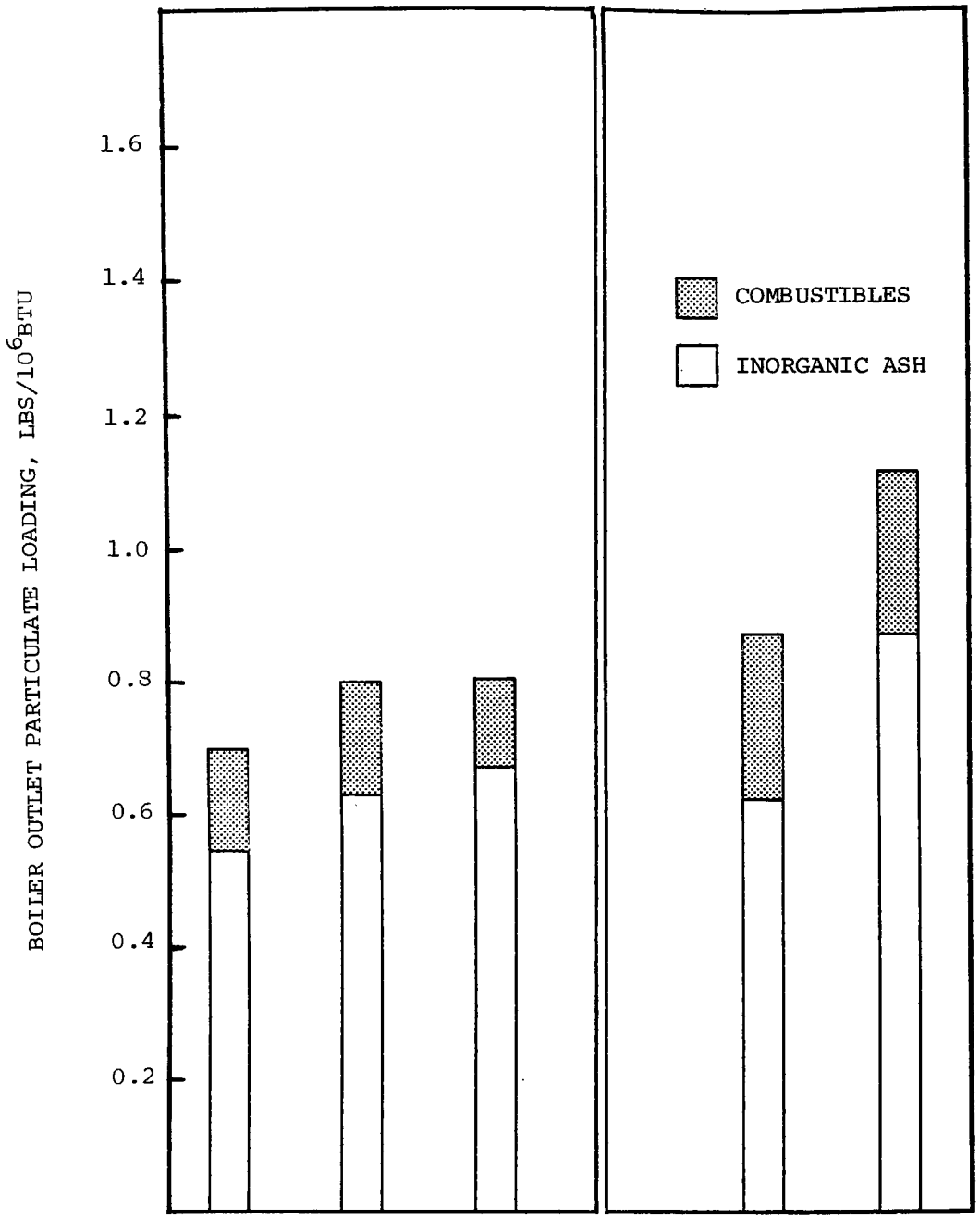
Five tests were run on Perfect 8 coal and four on Century coal to determine the effect of overfire air rates on particulate emissions. The results are shown in Figures 5-2 and 5-3 and in Tables 5-1 and 5-2.

For Perfect 8 coal the particulate loading at the boiler outlet tended to increase slightly with increasing overfire air flow. Most of this increase was in the inorganic fraction. Percent combustibles in the boiler outlet flyash decreased slightly with increasing overfire air flow.

For Century coal the particulate loading trend was just the reverse. For this coal the particulate loading at the boiler outlet tended to decrease with increasing overfire air flow. Most of this decrease was in the combustible fraction. Increasing overfire air pressure from 7 to 10 "H_2O pressure was very effective in reducing the combustibles from Century coal. This may be partly due to the fact that there was a significant concentration (40% in Test 14) of combustibles in the Century coal flyash at 7" overfire air pressure which could be reduced by additional overfire air. By comparison, the equivalent firing conditions on Perfect 8 coal (Test 13B) produced only 28% combustibles in the flyash. Overfire air increases above 10 "H_2O pressure had only a small effect on Century coal particulate loadings.

In general, the multiclone outlet particulate emissions followed the trends of the boiler outlet emissions. However, the multiclone outlet emissions were also affected by the multiclone collection efficiency, which varied between 38 and 63% during these tests.

In summary, the impact of overfire air on particulate emissions varied with the coal being fired. For both coals, combustible loadings decreased slightly with increasing overfire air flow. On the other hand, inorganic ash loading trends were in opposite directions for the two coals and were more



TEST NO.	6	8	7	13B	12
OFA PRES. "H_2O	5	9.8	15.5	7	10
OXYGEN (%)	8.7	9.7	10.2	7.5	8.4
LOAD (%)	65	66	63	89	87

FIGURE 5-2. PARTICULATE LOADING BREAKDOWN FOR PERFECT 8 COAL AS A FUNCTION OF OVERFIRE AIR

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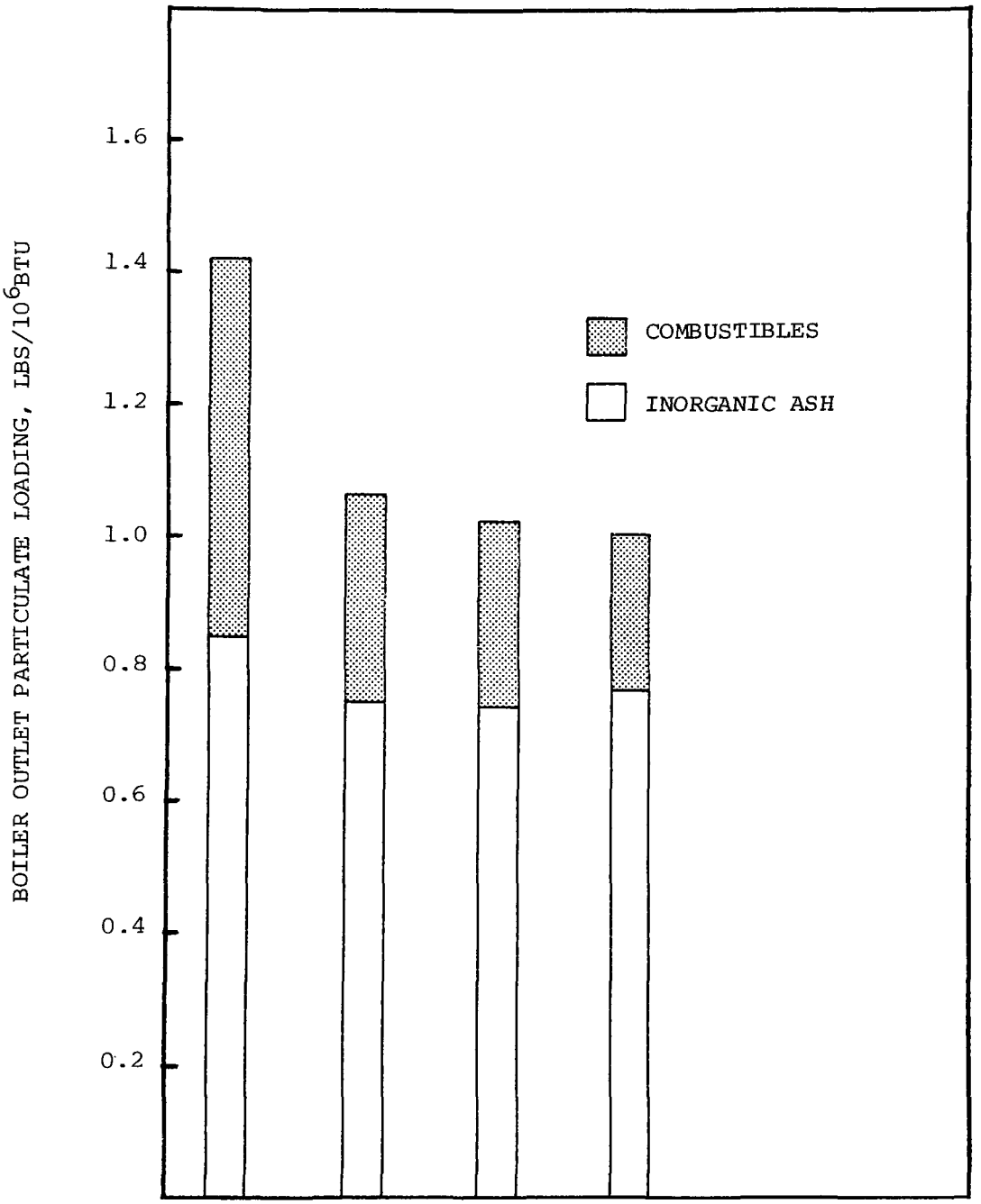

TEST NO.	14	17	18	15
OFA PRES. "H_2O	7	10	13	15.5
OXYGEN (%)	7.5	7.3	8.1	7.8
LOAD (%)	87	87	79	88

FIGURE 5-3. PARTICULATE LOADING BREAKDOWN FOR CENTURY COAL AS A FUNCTION OF OVERFIRE AIR

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TABLE 5-1

EFFECT OF OVERFIRE AIR ON EMISSIONS & EFFICIENCY
PERFECT 8 COAL - TEST SITE D

TEST NO. Description	6 Low OFA Med Load	8 Med OFA Med Load	7 High OFA Med Load	13B Low OFA High Load	12 Med OFA High Load
OVERFIRE AIR CONDITIONS					
Front Upper, "H_2O	5.0	10.0	15.5	7.0	10.0
Front Lower, "H_2O	5.3	9.5	15.5	7.0	10.0
FIRING CONDITIONS					
Load, % of Design Capacity*	65	66	63	89	87
Grate Heat Release, 10^3Btu/ft^2/hr	250	221	249	344	326
Coal Sizing, % Passing 1/4"	9	8	5	9	9
Excess Air, %	65	80	88	49	61
BOILER OUTLET EMISSIONS					
Particulate Loading, lb/10^6Btu	0.694	0.788	0.793	0.837	1.097
Combustible Loading, lb/10^6Btu	0.152	0.164	0.127	0.236	0.242
Inorganic Ash Loading, lb/10^6Btu	0.542	0.624	0.666	0.601	0.855
Combustibles in Flyash, %	21.9	20.8	16.0	28.2	22.1
O_2, % (dry)	8.7	9.7	10.2	7.5	8.4
CO, ppm (dry) @ 3% O_2	87	57	29	1225	321
NO, lb/10^6Btu	0.250	0.306	0.346	0.269	0.253
MULTICLONE OUTLET EMISSIONS					
Particulate Loading, lb/10^6Btu	0.372	0.328	0.488	0.490	0.667
Combustible Loading, lb/10^6Btu	0.051	0.029	0.052	0.043	0.059
Inorganic Ash Loading, lb/10^6Btu	0.321	0.299	0.436	0.447	0.608
Combustibles in Flyash, %	13.6	8.90	10.7	8.85	8.86
Multiclone Collection Efficiency, %	46.4	58.4	38.5	41.5	39.2
HEAT LOSSES, %					
Dry Gas Loss	8.20	9.20	8.80	7.25	8.10
Moisture in Fuel	0.28	0.27	0.30	0.30	0.32
H_2O from Combustion of H_2	4.03	4.03	4.05	4.01	4.02
Combustibles in Collected Flyash	0.10	0.12	0.14	0.09	0.05
Combustibles in Emitted Flyash	0.22	0.24	0.18	0.35	0.21
Combustibles in Bottom Ash	1.74	2.07	2.04	2.63	2.00
Radiation Loss	0.72	0.72	0.74	0.53	0.54
Unmeasured Losses	1.50	1.50	1.50	1.50	1.50
Total Losses	16.79	18.15	17.75	16.66	16.74
Boiler Efficiency	83.21	81.85	82.25	83.34	83.26

* Design capacity of 90,000 lb stm/hr was not met due to draft losses resulting from a retrofit dust collector.

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TABLE 5-2

EFFECT OF OVERFIRE AIR ON EMISSIONS & EFFICIENCY
CENTURY COAL - TEST SITE D

TEST NO.	14	17	18	15
Description	Low OFA High Load	Med OFA High Load	High OFA High Load	High OFA High Load
OVERFIRE AIR CONDITIONS				
Front Upper, "H_2O	7.0	10.0	13.0	15.0
Front Lower, "H_2O	7.0	10.0	13.0	16.0
FIRING CONDITIONS				
Load, % of Design Capacity*	87	87	79	88
Grate Heat Release, 10^3Btu/ft^2/hr	338	348	313	348
Coal Sizing, % Passing 1/4"	13.3	16.4	18.1	13.7
Excess Air, %	56	54	63	60
BOILER OUTLET EMISSIONS				
Particulate Loading, lb/10^6Btu	1.418	1.084	1.033	1.010
Combustible Loading, lb/10^6Btu	0.569	0.334	0.290	0.238
Inorganic Ash Loading, lb/10^6Btu	0.849	0.750	0.743	0.772
Combustibles in Flyash, %	40.1	30.8	28.1	23.6
O_2, % (dry)	7.5	7.3	8.1	7.8
CO, ppm (dry) @ 3% O_2	618	885	34	39
NO, ppm (dry) @ 3% O_2	226	199	230	217
NO, lb/10^6Btu	0.307	0.269	0.312	0.294
MULTICLONE OUTLET EMISSIONS				
Particulate Loading, lb/10^6Btu	0.759	0.397	0.425	0.429
Combustible Loading, lb/10^6Btu	0.087	--	0.063	0.070
Inorganic Ash Loading, lb/10^6Btu	0.672	--	0.362	0.359
Combustibles in Flyash, %	11.4	--	14.9	16.3
Multiclone Collection Efficiency, %	46.5	63.4	58.9	57.5
HEAT LOSSES, %				
Dry Gas Loss	7.84	7.63	7.76	8.11
Moisture in Fuel	0.27	0.22	0.20	0.23
H_2O From Combustion of H_2	4.00	3.97	3.98	4.03
Combustibles in Collected Flyash	0.11	0.02	0.27	0.09
Combustibles in Emitted Flyash	0.81	0.47	0.41	0.34
Combustibles in Bottom Ash	0.95	0.81	1.28	0.61
Radiation Loss	0.55	0.54	0.60	0.54
Unmeasured Losses	1.50	1.50	1.50	1.50
Total Losses	16.03	15.16	16.00	15.45
Boiler Efficiency	83.97	84.84	84.00	84.55

* Design capacity of 90,000 lb stm/hr was not met due to draft losses resulting from a retrofit dust collector.

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pronounced than the combustible loading trends. On the Perfect 8 coal, low overfire air flow gave lowest particulate emissions. On Century coal, high overfire air flow gave lowest particulate emissions.

5.1.2 Nitric Oxide vs Overfire Air

On Perfect 8 coal, increased overfire air flow tended to increase nitric oxide concentrations. On the single Century coal test series the reverse was true. The nitric oxide versus overfire air data is presented in Figure 5-4 and in Table 5-3.

In conducting these tests, the under grate air was held constant while the overfire air was varied. Therefore, the excess air increased with increasing overfire air flow. This procedure was adopted after unsuccessful attempts to maintain excess air constant while changing overfire air flows at constant load. It was characteristic of this boiler that changes in excess air upset the boiler loading. The length of time required for stabilization of load and excess air made fuel-air changes at constant load very difficult to perform.

To compensate for the changes in excess air, the nitric oxide concentrations were corrected to 9% O_2 by applying the established O_2-NO relationship: one percent O_2 increase = 0.041 lb/10^6 Btu NO increase.

Figure 5-4 plots the changes in nitric oxide concentration as a function of overfire air pressure for several test series. The three low and medium load test series demonstrate steady increases in NO concentration as overfire air pressure increases. The high load test series do not show a uniform NO concentration increase with OFA pressure. At high load, NO concentrations decreased as OFA pressure was increased from 7 to 10 "H_2O pressure. Above 13 "H_2O pressure at high load, NO concentrations increased slightly.

At maximum load (88% design capacity) and 5 "H_2O overfire air pressure, combustion was totally unsatisfactory. Opacity under these conditions averaged 40% and reached as high as 60%. Carbon monoxide concentrations were in excess of 2000 ppm uncorrected, which is the upper limit on the CO instrument. By increasing the overfire air from 5 to 7 "H_2O pressure, the opacity was dropped to around 20% and the carbon monoxide was dropped to around 500 ppm. Nitric oxide concentration increased, at the same time, from 0.281 to 0.334 lb/10^6Btu.

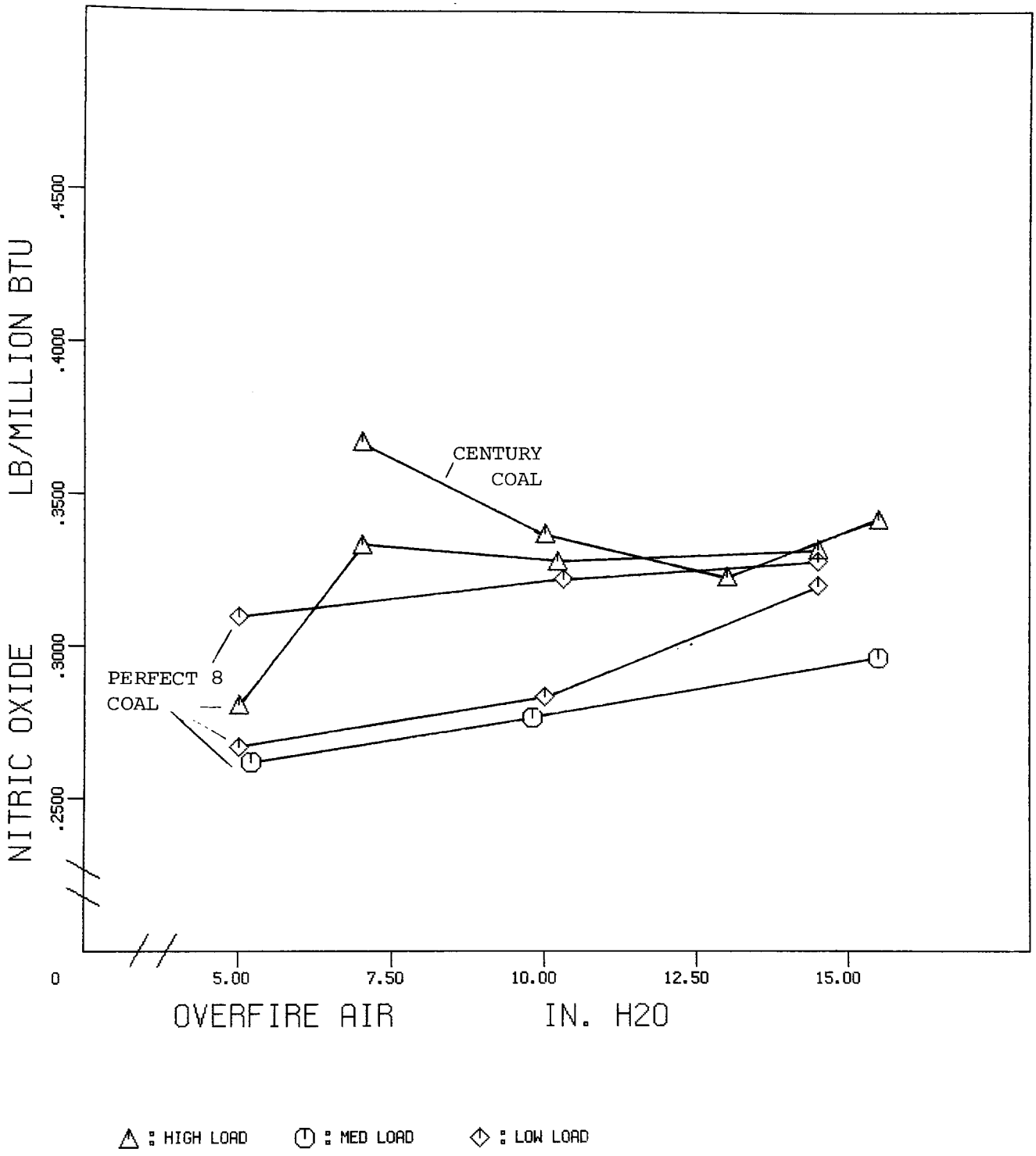

FIG. 5-4
NITRIC OXIDE VS. OVERFIRE AIR
TEST SITE D

EACH LINE REPRESENTS A UNIQUE SERIES OF TESTS PERFORMED IN SEQUENCE

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TABLE 5-3

NITRIC OXIDE EMISSIONS VS OVERFIRE AIR
TEST SITE D

Test No.	Coal	% Design Capacity*	O_2 %	OFA Pressure, "H_2O Upper	Lower	Nitric Oxide, lb/10^6Btu Corr**	Uncorr
13A	Perfect 8	89	7.8	5.0	5.0	0.281	0.232
13B	Perfect 8	89	7.4	7.0	7.0	0.334	0.269
13D	Perfect 8	89	7.6	10.3	10.0	0.329	0.272
13C	Perfect 8	89	7.6	15.0	14.0	0.333	0.276
14	Century	87	7.5	7.0	7.0	0.368	0.307
17	Century	87	7.3	10.0	10.0	0.338	0.269
18	Century	79	8.7	13.0	13.0	0.324	0.312
15	Century	88	7.8	15.0	16.0	0.343	0.294
6	Perfect 8	65	8.7	5.0	5.3	0.262	0.250
8	Perfect 8	66	9.7	10.0	9.5	0.277	0.306
7	Perfect 8	63	10.2	15.5	15.5	0.297	0.346
11B	Perfect 8	52	10.5	5.0	5.0	0.267	0.328
11A	Perfect 8	52	11.3	10.0	10.0	0.284	0.378
11C	Perfect 8	52	12.5	15.0	14.0	0.321	0.464
11E	Perfect 8	52	10.8	5.0	5.0	0.310	0.383
11D	Perfect 8	52	11.0	10.5	10.0	0.323	0.405
11F	Perfect 8	52	12.0	15.0	14.0	0.329	0.451

* Maximum obtainable load averaged 88% of design capacity due to draft losses resulting from a retrofit dust collector.

** Corrected to 9% O_2 by applying the established O_2-NO relationship: 1% O_2 increase = 0.041 lb/10^6Btu NO increase

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5.1.3 Carbon Monoxide vs Overfire Air

Carbon monoxide (CO) concentration was one of the parameters measured during the overfire air tests. The test data, presented in Figure 5-5 and Table 5-4, illustrate the need for increased overfire air flow at high loads to maintain high combustion efficiency and minimize carbon monoxide emissions.

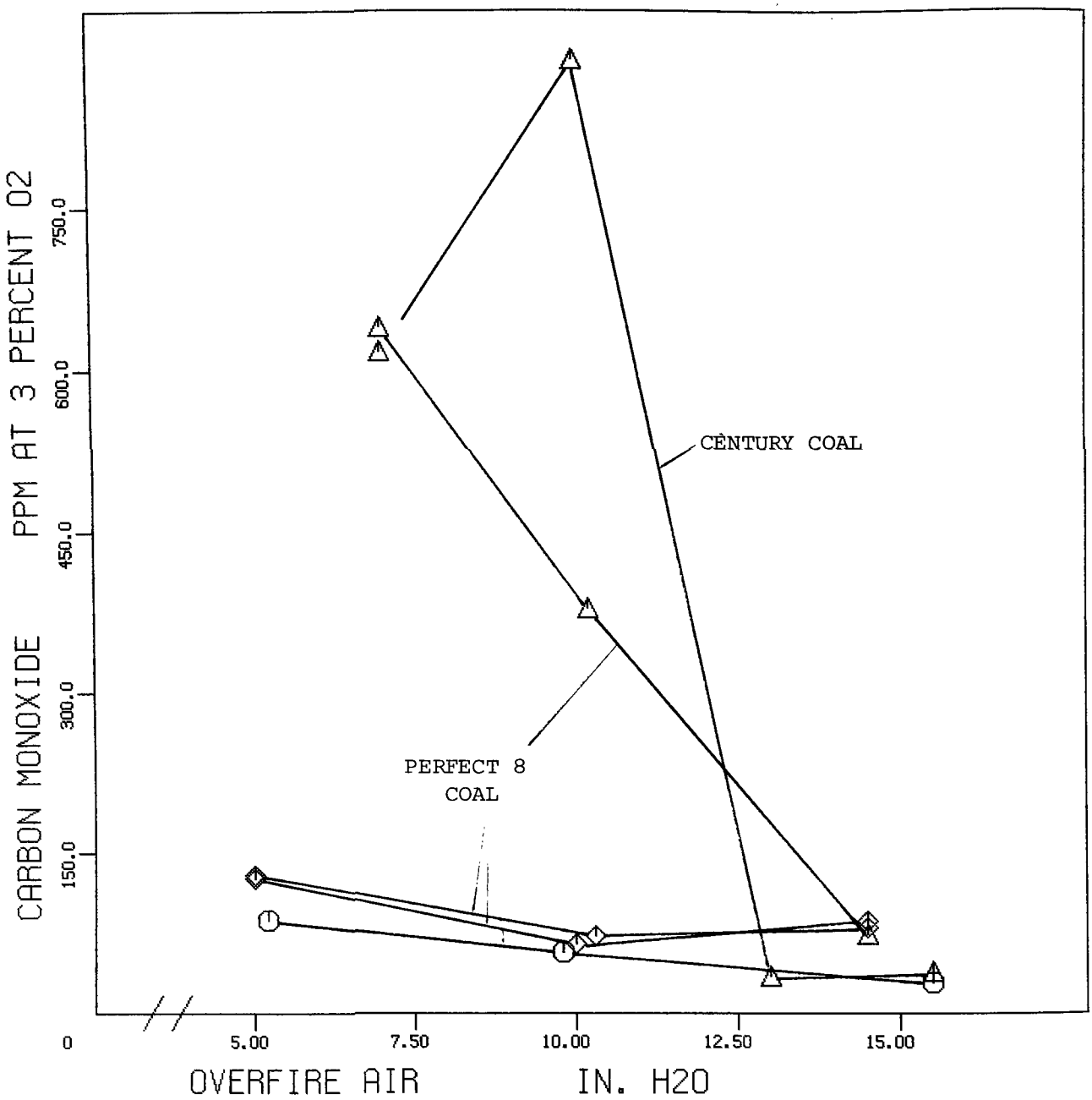
At high loads the carbon monoxide concentration increased rapidly as the overfire air flow was reduced. At 88% of design capacity, 12 "H_2O static pressure on the overfire air was required to maintain the CO concentration below 400 ppm (Figure 5-5). At reduced loads of 50-60% of design capacity, the carbon monoxide concentrations were below 130 ppm at all overfire air flow conditions examined, and showed only a slight tendency to decrease with increasing OFA flow.

These tests did not isolate the variable overfire air flow from the variable excess air. Grate air was held constant in each test series while overfire air was raised or lowered. As a result, excess air varied in direct proportion to the overfire air flow. Despite this fact, it is quite evident from the data that at boiler loads in the vicinity of 88% of design capacity overfire air pressures above 12 "H_2O were required to control CO emissions.

5.1.4 Boiler Efficiency vs Overfire Air

Boiler efficiency data are presented in Table 5-5 for three test sets in which overfire air was the variable. From this data it is clear that increasing overfire air pressure resulted in a decrease in the combustible fraction of the flyash leaving the boiler. The heat loss due to combustibles in the flyash was also reduced by up to 0.47% on a heat input basis. Boiler efficiency, on the other hand, does not show a direct correlation with overfire air pressure. Variations in other heat loss areas which are believed to be unrelated to the overfire air mask out the small changes in the flyash combustible heat loss.

The data indicate that maximum overfire air pressure will result in the lowest heat loss due to combustibles in the flyash.



△ : HIGH LOAD ⏲ : MED LOAD ◇ : LOW LOAD

FIG. 5-5
CARBON MONOXIDE VS. OVERFIRE AIR
TEST SITE D

EACH LINE REPRESENTS A UNIQUE SERIES OF TESTS
PERFORMED IN SEQUENCE

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TABLE 5-4

CARBON MONOXIDE EMISSIONS VS OVERFIRE AIR
TEST SITE D

Test No.	Coal	% Design Capacity*	O_2 %	OFA Pressure, "H_2O Upper	Lower	CO ppm @ 3% O_2
13A	Perfect 8	89	7.8	5.0	5.0	2345
13B	Perfect 8	89	7.4	7.0	7.0	640
13D	Perfect 8	89	7.6	10.3	10.0	378
13C	Perfect 8	89	7.6	15.0	14.0	73
14	Century	87	7.5	7.0	7.0	618
17	Century	87	7.3	10.0	10.0	885
18	Century	79	8.7	13.0	13.0	34
15	Century	88	7.8	15.0	16.0	39
6	Perfect 8	65	8.7	5.0	5.3	87
8	Perfect 8	66	9.7	10.0	9.5	57
7	Perfect 8	63	10.2	15.5	15.5	29
11B	Perfect 8	52	10.5	5.0	5.0	126
11A	Perfect 8	52	11.3	10.0	10.0	65
11C	Perfect 8	52	12.5	15.0	14.0	85
11E	Perfect 8	52	10.8	5.0	5.0	129
11D	Perfect 8	52	11.0	10.5	10.0	72
11F	Perfect 8	52	12.0	15.0	14.0	80

* Design capacity of 90,000 lb stm/hr not met due to draft loss from retrofit dust collector. Maximum obtainable load averaged 88% of design capacity.

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TABLE 5-5

BOILER EFFICIENCY VS OVERFIRE AIR
TEST SITE D

Test No.	% Design Capacity*	OFA Pressure "H_2O	Combustibles in Flyash, %	Heat Loss Due to Comb in Flyash, %	Boiler Efficiency, %
6	65	5	21.9	0.22	83.21
8	66	10	20.8	0.24	81.85
7	63	15	16.0	0.18	82.25
13B	89	7	28.2	0.35	83.34
12	87	10	22.1	0.21	83.26
14	87	7	40.1	0.81	83.97
17	87	10	30.8	0.47	84.84
18	79	13	28.1	0.41	84.00
15	88	15	23.6	0.34	84.55

* Design capacity of 90,000 lb stm/hr not met due to draft loss resulting from retrofit dust collector. Maximum obtainable load averaged 88% of design capacity.

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5.2 EXCESS OXYGEN AND GRATE HEAT RELEASE

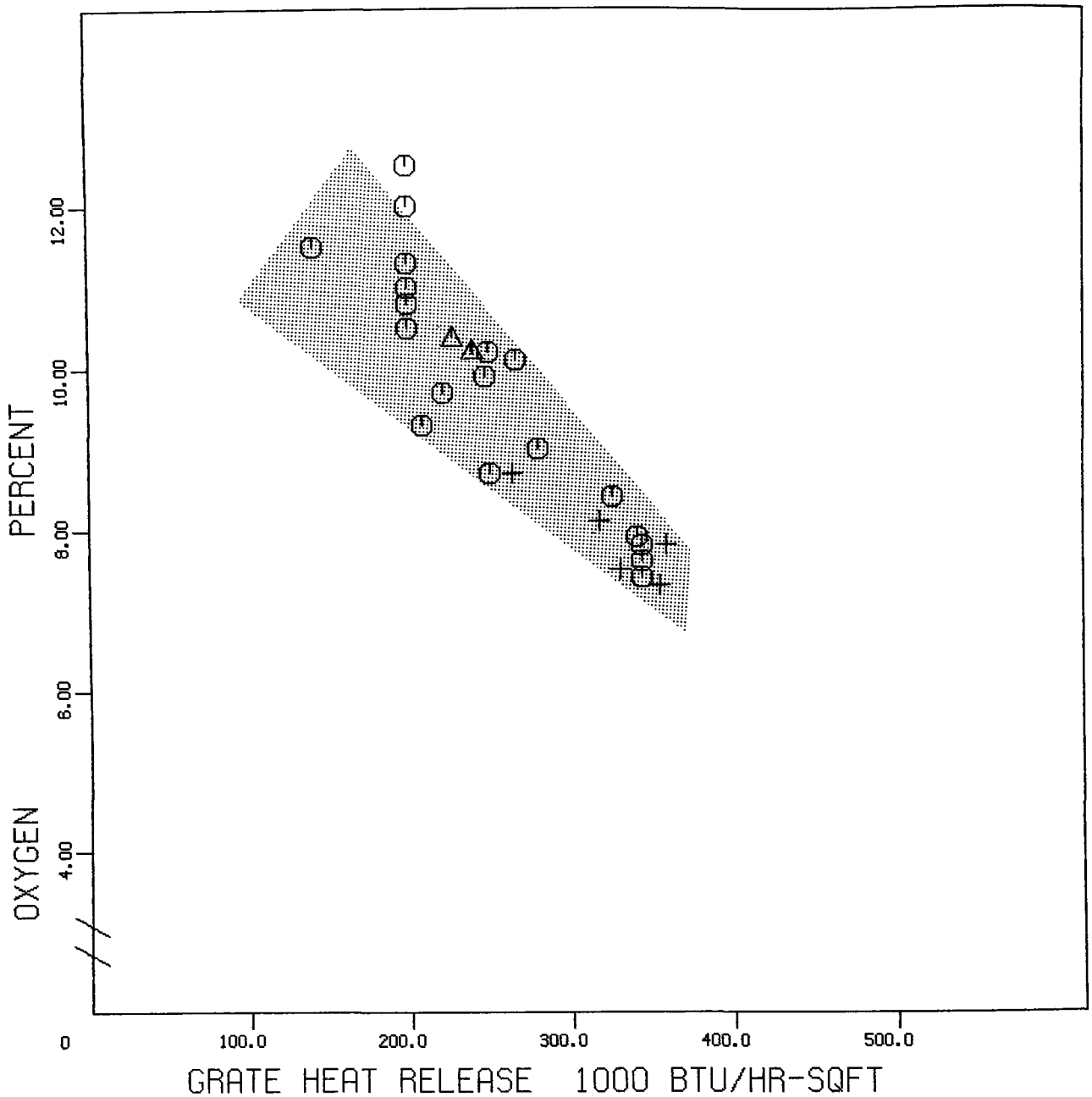
The boiler at Test Site D was tested for emissions and boiler efficiency over a wide range of loads and excess air conditions. This section presents the results of these emissions and efficiency tests as a function of load, expressed as grate heat release, and excess oxygen. Where other variables, such as coal properties, could influence test results, these variables were taken into account. Their influence on the performance of the boiler is also discussed below. The plots presented in this section, which are best characterized as emissions profiles, will be especially valuable when comparing the performance of boilers of different designs.

5.2.1 Excess Oxygen Operating Levels

Figure 5-6 depicts the various boiler loads, expressed as grate heat release, and oxygen levels at which tests were run on Boiler D. Different symbols are used to distinguish the three coals fired.

Design capacity was not achieved on this unit. The highest boiler load obtained during testing was 359×10^3 Btu/hr-ft^2 grate heat release. This is 90% of the design rating of 401×10^3 Btu/hr-ft^2. The load was limited to 90% by the ID fan. The unit was originally designed and installed without a multiclone dust collector. In its original configuration it was operated near design capacity. A larger ID fan was added to the unit when the multiclone dust collector was installed in order to handle the increased pressure drop. The new ID fan was too large and could not be effectively controlled. This necessitated that baffling be installed to reduce the air flow to the point where the automatic controls could effectively modulate the fan. It was as a result of this modification that the air flow was restricted to the point where design capacity could not be met.

The lowest oxygen level obtained was 7.3%, which represents 48% excess air. This compares to the design level of 31% excess air, or 5% O_2. Extrapolation of the O_2 - grate heat release relationship given in Figure 5-6 to the design capacity of 401×10^3 Btu/hr-ft^2 yields an oxygen level of no less than 6.4%. This indicates that the unit was being operated at a higher O_2 level than it was designed for. However, testing did not establish a lower O_2 limit on this unit and, therefore, there is no basis for assuming that the unit could not be operated at design O_2.



⊙ : PER & COAL + : CENT. COAL △ : VICT. COAL

FIG. 5-6
OXYGEN VS. GRATE HEAT RELEASE
TEST SITE D

CONDITIONS UNDER WHICH EMISSION TESTS WERE RUN

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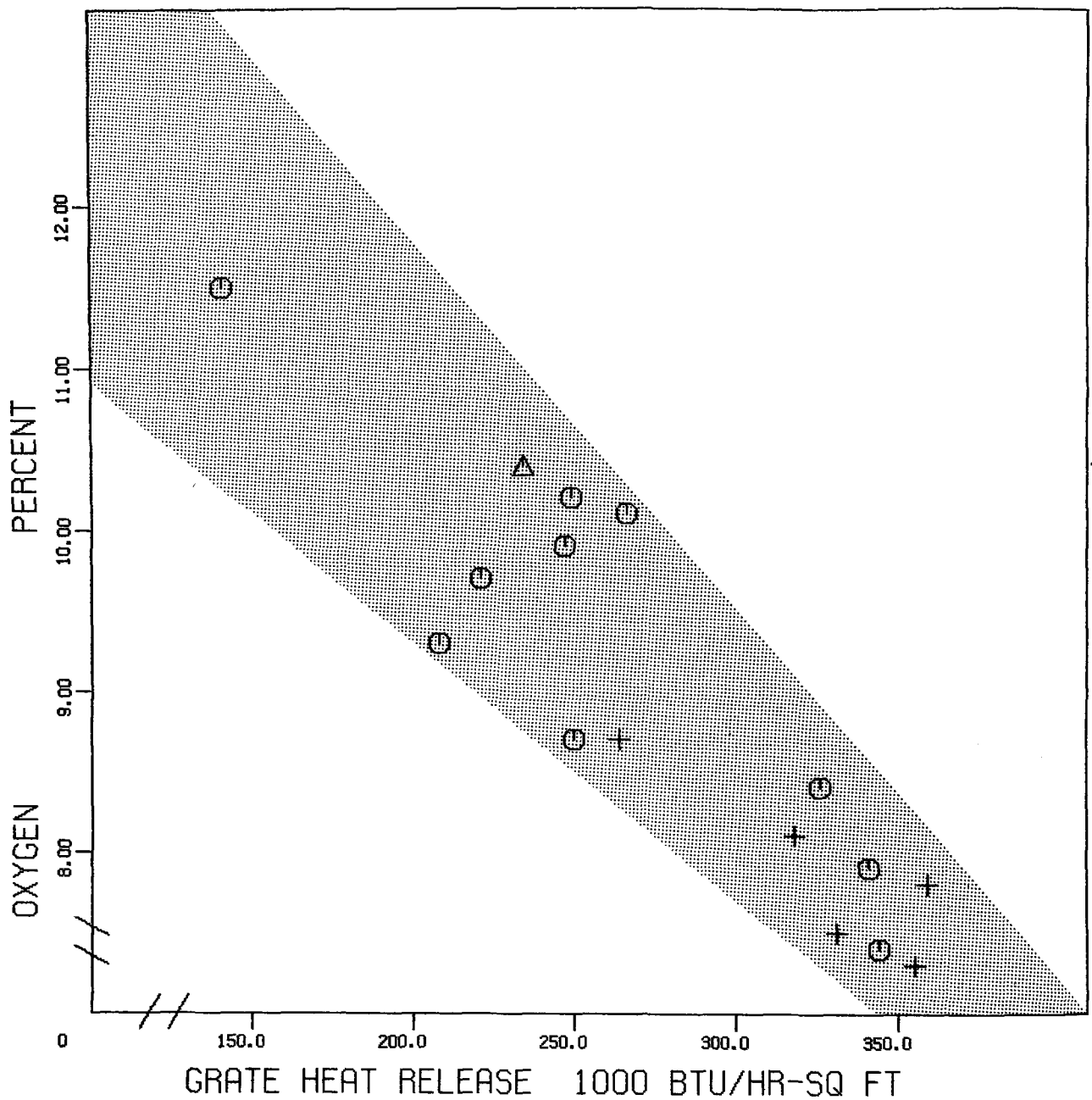
Figure 5-6 illustrates the conditions under which emission tests were run at Test Site D. At high load the measured oxygen spread was only 7.3 to 8.4%. Oxygen levels in the flue gas increased linearly as boiler loading decreased. At the lowest measured load of 141×10^3 Btu/hr-ft^2, the oxygen level was 11.5%. Coal properties did not appear to be a factor in the O_2 - grate heat release relationship: load-specific O_2 levels were similar for all three coals, as can be seen in Figure 5-6.

Because particulate loading tests are a principal part of this program, the oxygen and grate heat release conditions under which the particulate tests were conducted are given in Figure 5-7. In this plot, the scales are expanded to provide greater resolution. The data falls inside a band which is highly dependent on grate heat release and which is less than two percent O_2 wide.

5.2.2 Particulate Loading vs Oxygen and Grate Heat Release

Figure 5-8 profiles boiler outlet particulate loading as a function of grate heat release. The data points in this plot are keyed to coal type. The data shows a fairly well defined relationship between particulate loading and boiler load. Below 300×10^3 Btu/hr-ft^2 grate heat release the particulate loadings are not influenced by grate heat release and average 0.74 ± 0.05 lbs/10^6 Btu. Above 300×10^3 Btu/hr-ft^2 the particulate loadings average 1.02 ± 0.17 lbs/10^6 Btu, a 38% increase over particulate loadings below 300×10^3 Btu/hr-ft^2.

Coal ash did not play a role in the boiler outlet particulate loadings. As can be seen in Figure 5-8, particulate loadings at the boiler outlet were basically the same for all three coals. The Table on page 54 shows the amount of ash in the coal, and the amount of coal ash which was carried out of the boiler in the flyash. The data show that where the ash content of the coal was low, the percent carryover in the flyash was high, thus negating the potential benefits of firing a low ash coal to reduce particulates. This conclusion, however, only applies to the coals fired in these tests and to the boiler at Site D. The results should not be generalized to other coals or boilers.

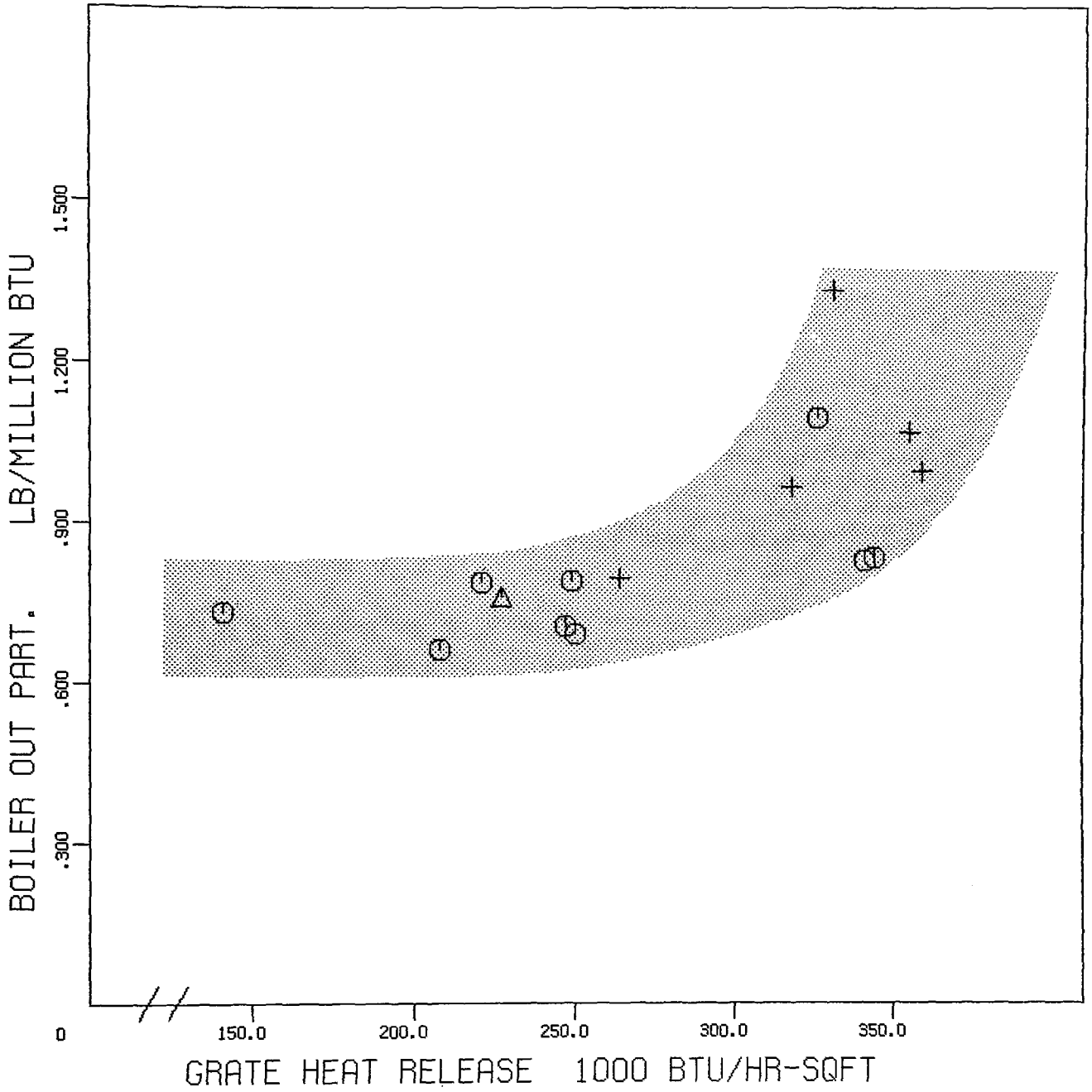


⊙ : PER 8 COAL + : CENT. COAL △ : VICT. COAL

FIG. 5-7
OXYGEN VS. GRATE HEAT RELEASE
TEST SITE D

CONDITIONS UNDER WHICH PARTICULATE TESTS WERE RUN

15900-529



⊙ : PER 8 COAL + : CENT. COAL △ : VICT. COAL

FIG. 5-8
BOILER OUT PART. VS. GRATE HEAT RELEASE
TEST SITE D

15900-529

ASH CARRYOVER VS COAL TYPE
TEST SITE D

Coal	Average Ash Content of Coal, lbs/10^6 Btu	Average Ash Content of Flyash, lbs/10^6 Btu	Average Ash Carryover, %
Perfect 8	6.73	0.627	9.3
Century	4.31	0.719	16.7
Victoria	5.19	0.560	10.8

Particulate measurements were made at the outlet of the multiclone dust collector simultaneously with the measurements made at the boiler outlet. Figure 5-9 plots the multiclone outlet particulate loadings as functions of grate heat release. Again, the data points are keyed to coal type.

There is more scatter in the data from this sample location than is the case with the test data from the boiler outlet. The scatter can be accounted for by variations in the collection efficiency of the dust collector. The dust collector was not operating at design efficiency. This problem will be discussed further in section 5.5.

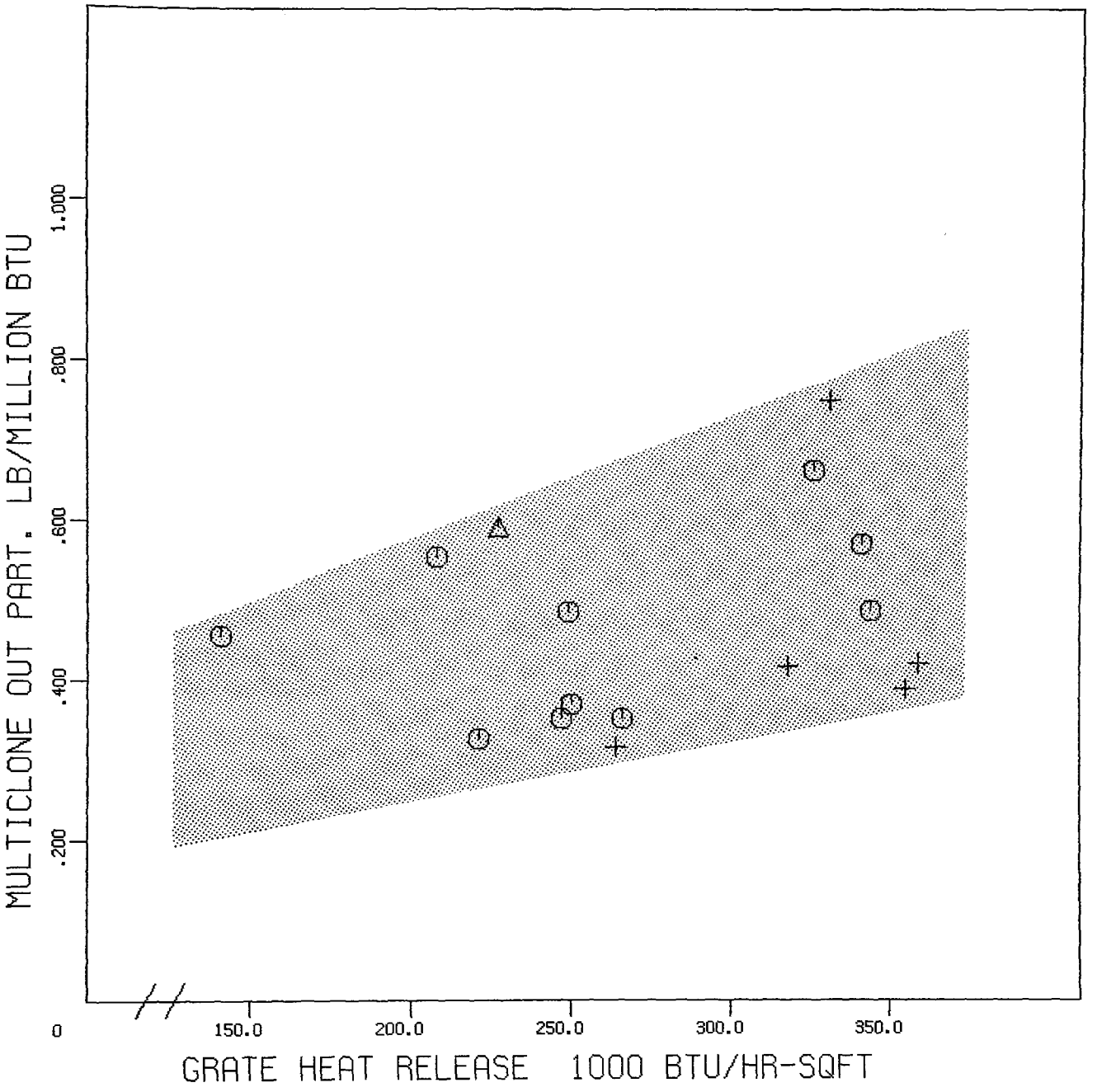
At the multiclone outlet, the particulate loading averaged 0.42 ± 0.10 lbs/10^6 Btu below 300×10^3 Btu/hr-ft^2 grate heat release, and 0.53 ± 0.14 lbs/10^6 Btu above this value. Thus, the average particulate loading was 26% greater at high load than at low load when measured after the multiclone.

It is evident from an examination of Figure 5-9 that coal type may be a factor in the particulate loadings after the multiclone. The apparent stratification by coal type may or may not be real. The scatter in the data makes it difficult to draw any conclusions about the effect of coal type.

5.2.3 Nitric Oxide vs Oxygen and Grate Heat Release

Nitric oxide (NO) concentration was measured during each test in units of parts per million (ppm). It is presented here in units of lbs/10^6 Btu to be more easily compared with existing and proposed emission standards. The parts per million values may be found in Table 2-1 of this report.

Figure 5-10 plots nitric oxide as a function of grate heat release, with coal type designated for each data point. The range in nitric oxide



⊙ : PER 8 COAL + : CENT. COAL △ : VICT. COAL

FIG. 5-9
MULTICLONE OUT PART. VS. GRATE HEAT RELEASE
TEST SITE D

15900-529

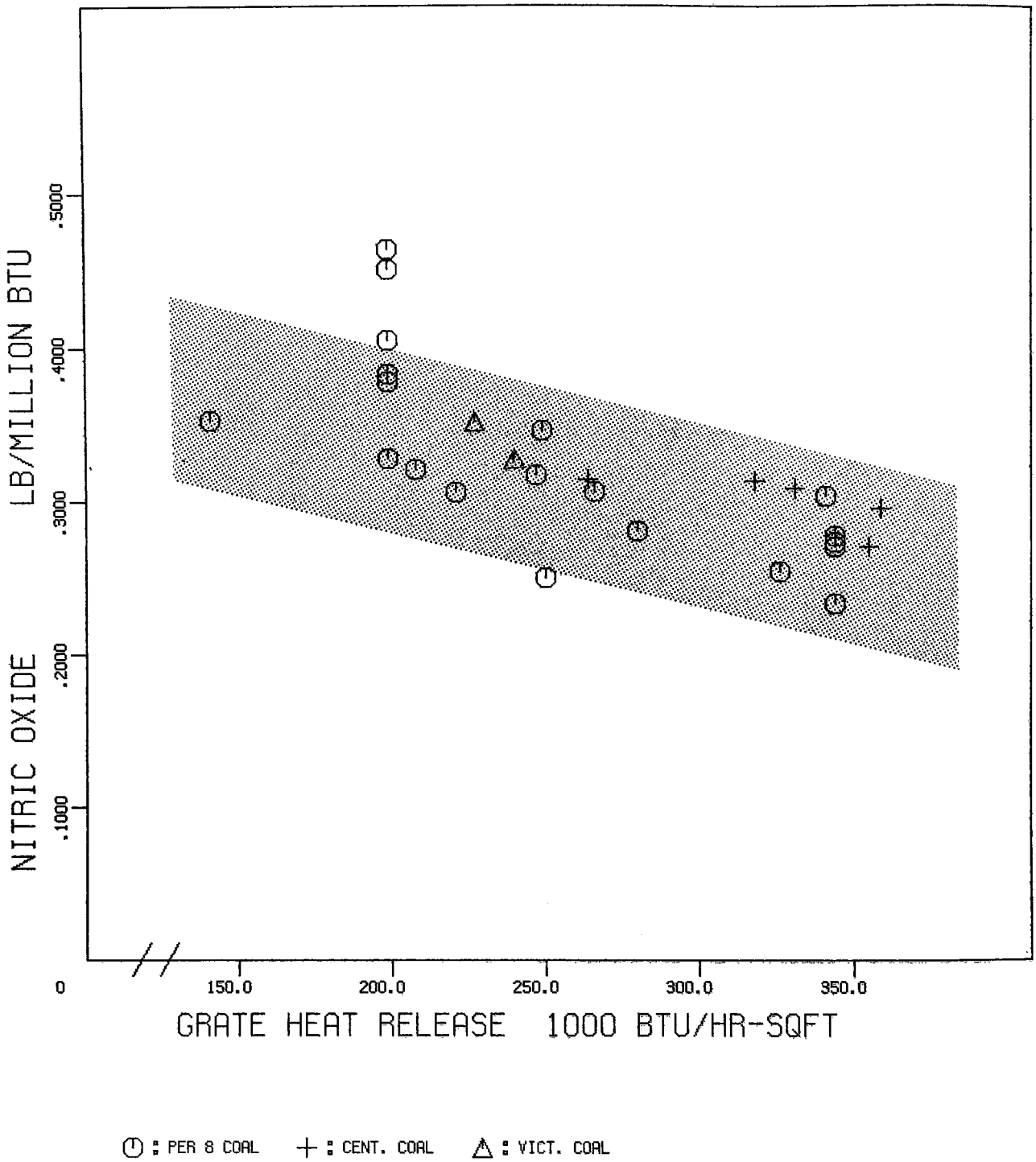


FIG. 5-10
NITRIC OXIDE VS. GRATE HEAT RELEASE
TEST SITE D

15900-529

loading at high load was 0.232 to 0.312 lbs/10^6 Btu. NO concentrations tended to increase slowly as load decreased. The maximum nitric oxide level of 0.464 lbs/10^6 Btu was created artificially by forcing the air up to 12.5% O_2 at low load. Under normal firing conditions on Boiler D, the upper limit on nitric oxide was about 0.35 lbs/10^6 Btu. Neither load nor coal type had a measurable influence on nitric oxide levels at Site D. Oxygen level, on the other hand, had a very strong influence on nitric oxide emissions. Figure 5-11 plots the nitric oxide data as a function of oxygen with the data points separated into these distinct grate heat release ranges. This plot clearly shows the strong relationship between NO and O_2 found at Test Site D.

Figures 5-12, 5-13 and 5-14 show the same data on expanded scales for each of the three grate heat release ranges. Through each data set a line that best "fits" the data has been drawn. The slopes of the lines were determined by means of linear regression analysis. The results of these tests can be interpreted as a flatening or leveling of the NO-O_2 relationship as O_2 declines. The data indicate that grate heat release does not have a significant effect on nitric oxide emissions on this boiler. Nitric oxide trend lines are being determined for each of the boilers tested under this program. Based on the data obtained at Test Site D, the nitric oxide trend line appears to be a function only of oxygen as shown in Figure 5-15.

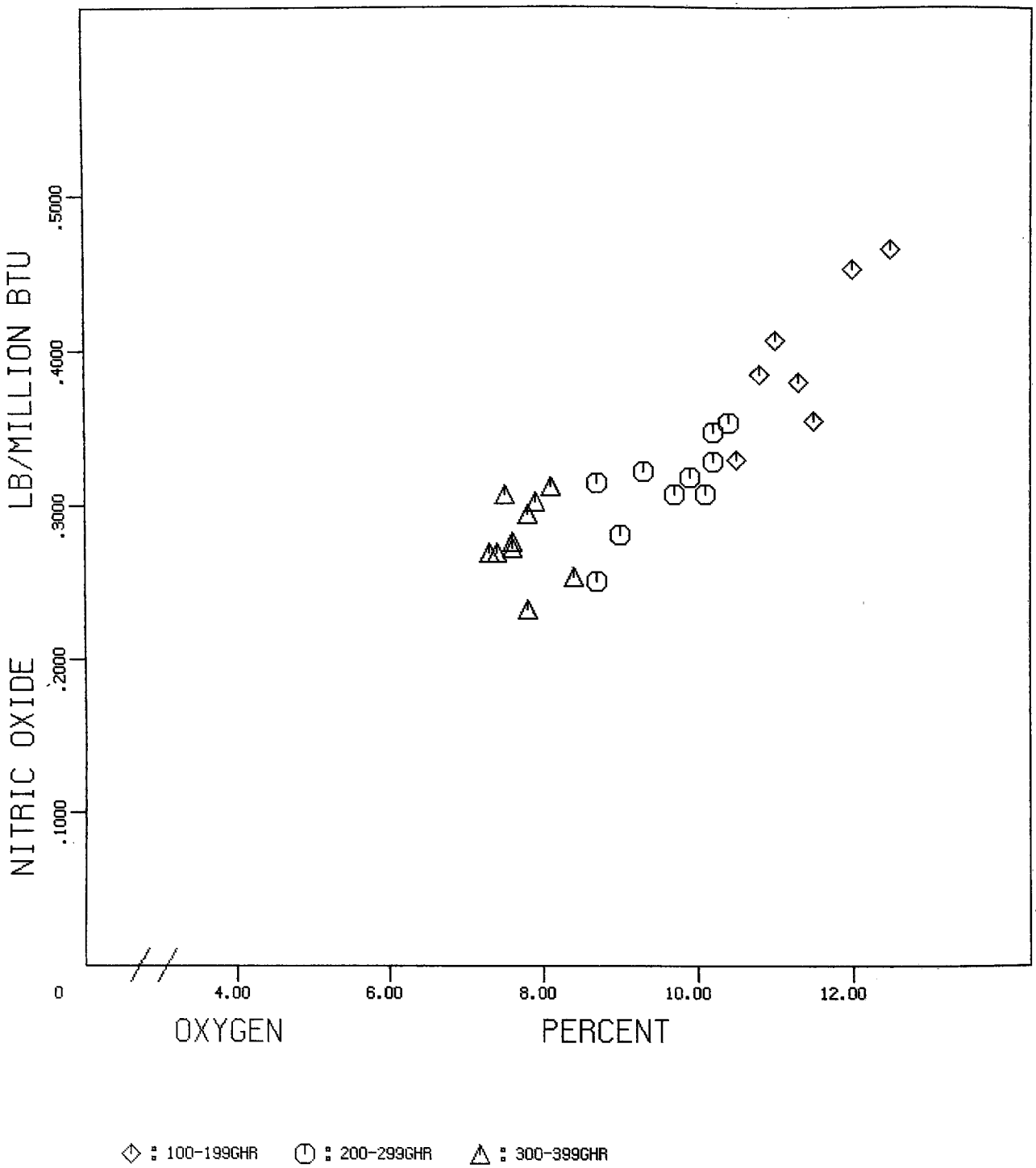
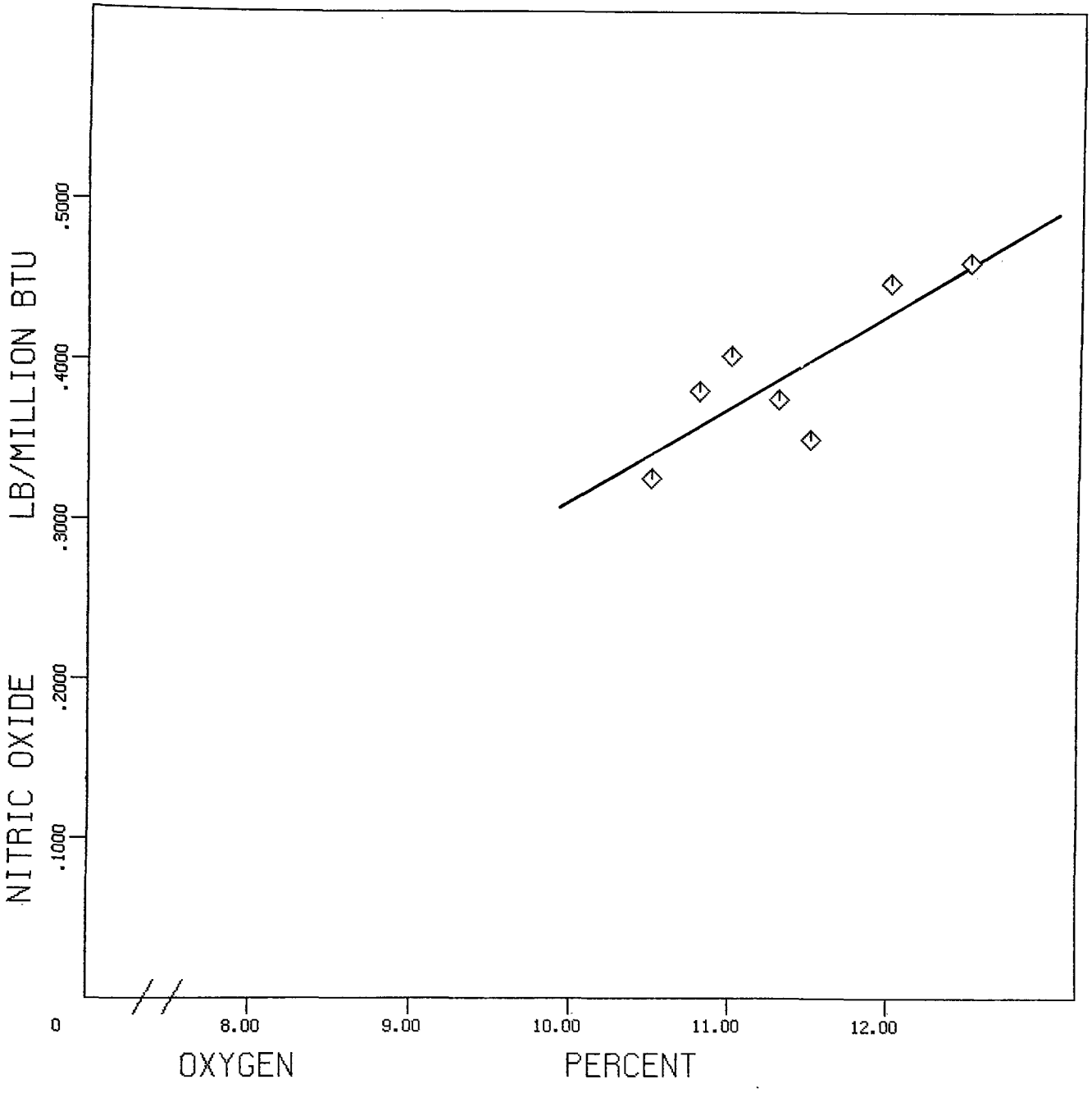


FIG. 5-11
NITRIC OXIDE VS. OXYGEN
TEST SITE D

15900-529

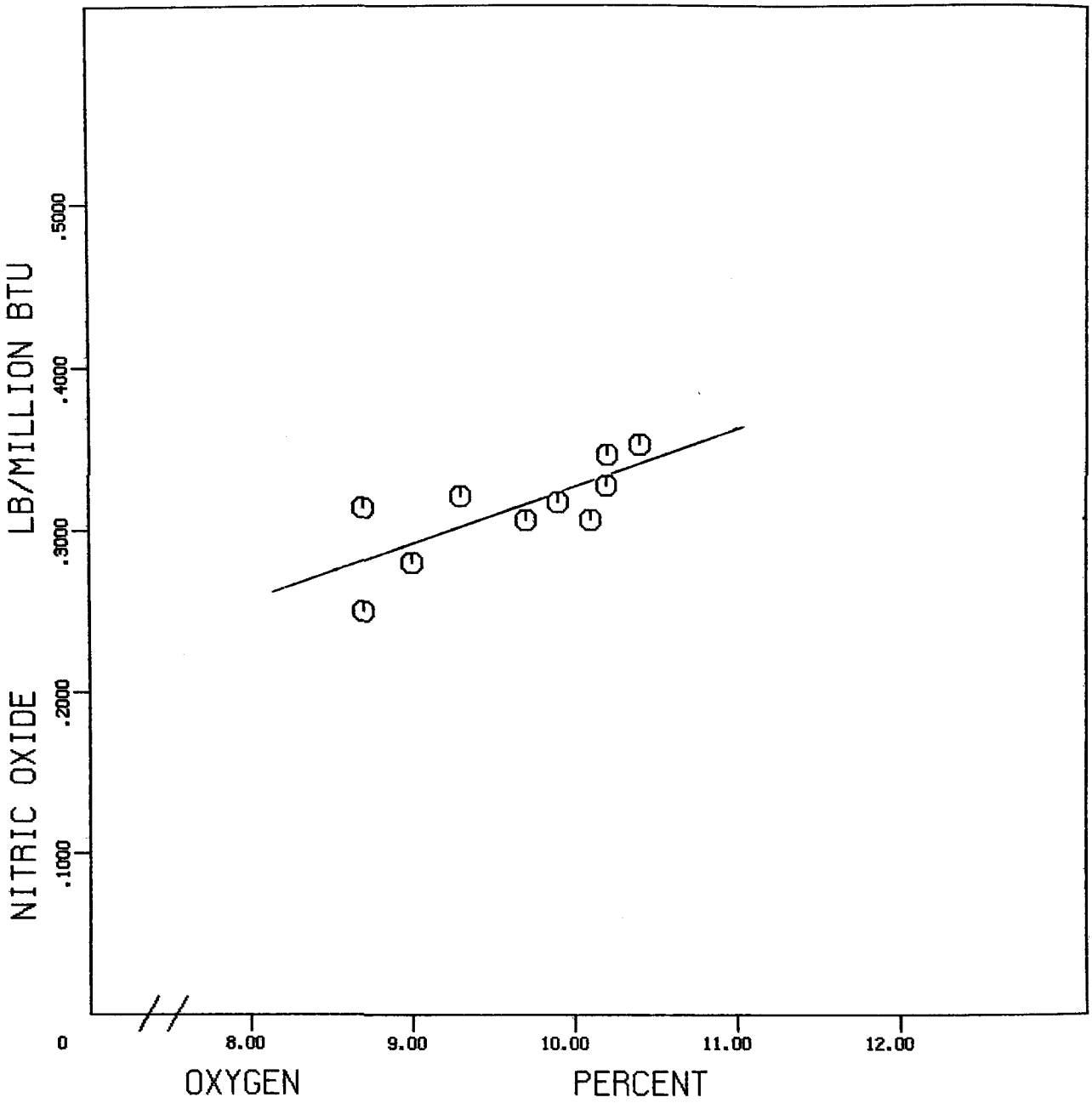


◇ : 100-199GHR

FIG. 5-12
NITRIC OXIDE VS. OXYGEN
TEST SITE D

LINEAR REGRESSION APPLIED BY METHOD OF LEAST SQUARES

15900-529

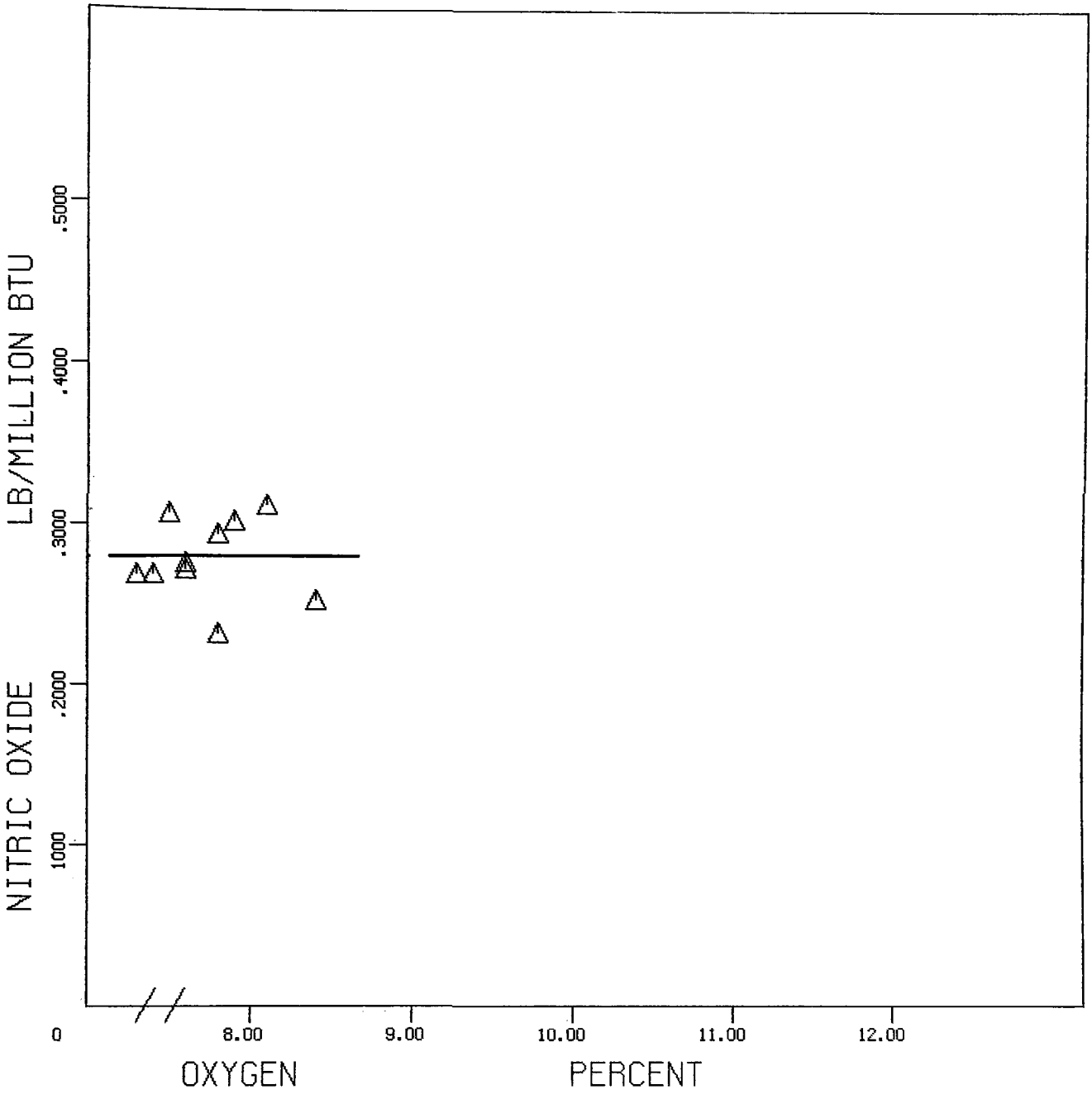


① : 200-299GHR

FIG. 5-13
NITRIC OXIDE VS. OXYGEN
TEST SITE D

LINEAR REGRESSION APPLIED BY METHOD OF LEAST SQUARES

15900-529



△ : 300-399GHR

FIG. 5-14
NITRIC OXIDE VS. OXYGEN
TEST SITE D

LINE INDICATES AVERAGE VALUE

15900-529

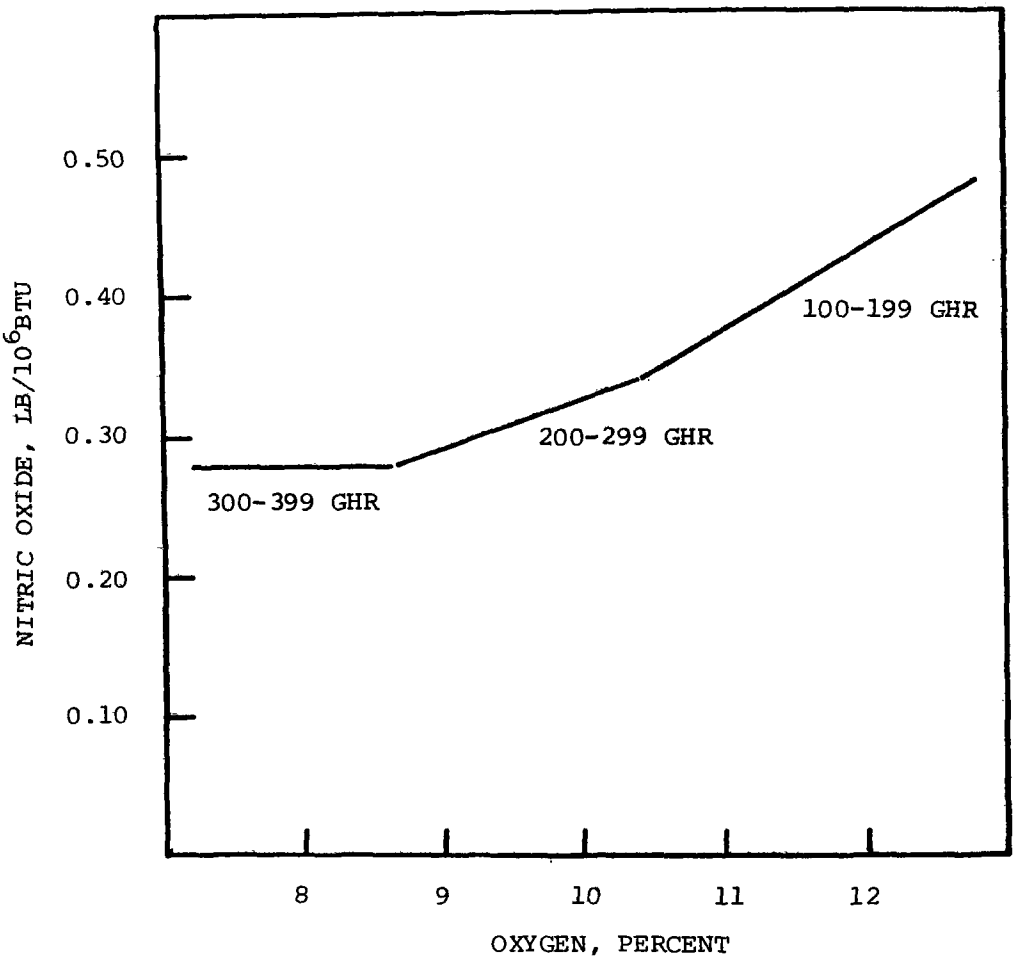


FIGURE 5-15. TREND IN NITRIC OXIDE EMISSIONS AS A FUNCTION OF OXYGEN AT SITE D

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5.2.4 Carbon Monoxide vs Oxygen and Grate Heat Release

Carbon monoxide (CO) was measured during each test and the data are presented here in units of parts-per-million (ppm) by volume on a dry basis, corrected to 3% O_2. Carbon monoxide is a by product of incomplete combustion, but if it is kept below 400 ppm it is considered insignificant for the purposes of this report. As a reference, 400 ppm CO is equivalent to 0.04% CO and represents a 0.20% heat loss in a coal fired boiler operating at 8% O_2.

Figure 5-16 presents the carbon monoxide data gathered under a variety of firing conditions and plotted as a function of grate heat release. Each data point is keyed to the coal type being fired. This plot shows that carbon monoxide was only found in significant concentrations at loadings above 300×10^3 Btu/hr-ft^2 grate heat release. Below 300×10^3 Btu/hr-ft^2 the concentrations were all below 130 ppm.

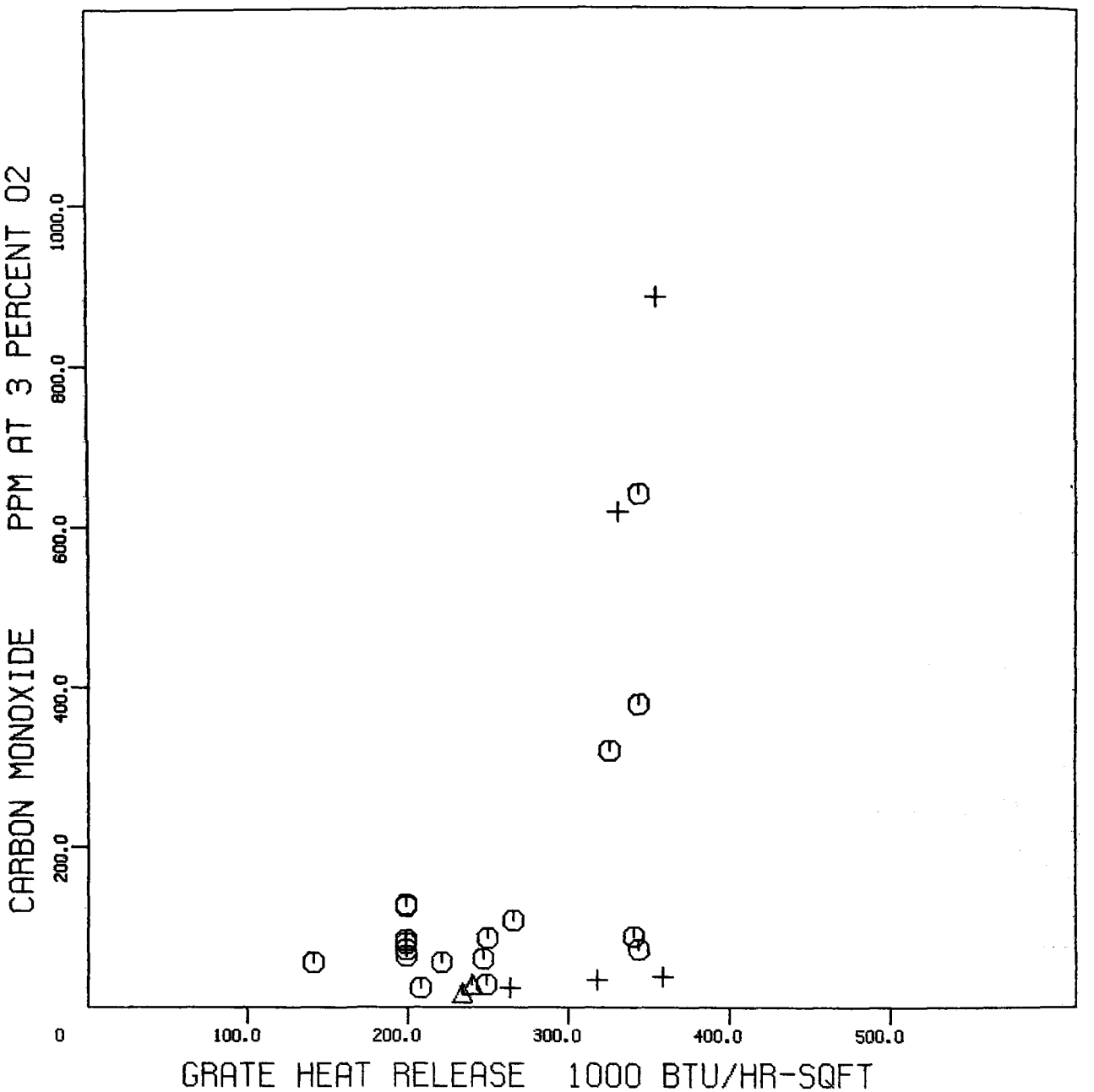
Figures 5-17 and 5-18 present the carbon monoxide concentrations as a function of oxygen for Perfect 8 coal and Century coal, respectively. Both plots show that carbon monoxide concentrations were significant only when firing at below 8% O_2. It must be kept in mind, however, that oxygen operating levels and grate heat release are closely related at this site so that it is not clear from this data whether the low O_2 or high grate heat release is responsible for the sudden increase in carbon monoxide at low O_2 levels.

Finally, the data show that coal properties did not significantly affect the carbon monoxide emission levels of Boiler D.

5.2.5 Combustibles vs Oxygen and Grate Heat Release

In this report the term "combustibles" refers only to the solid combustibles in the various ashes leaving the boiler. Combustibles are described here in terms of their percent by weight in the flyash at the boiler outlet and in the bottom ash collected from the ash pit.

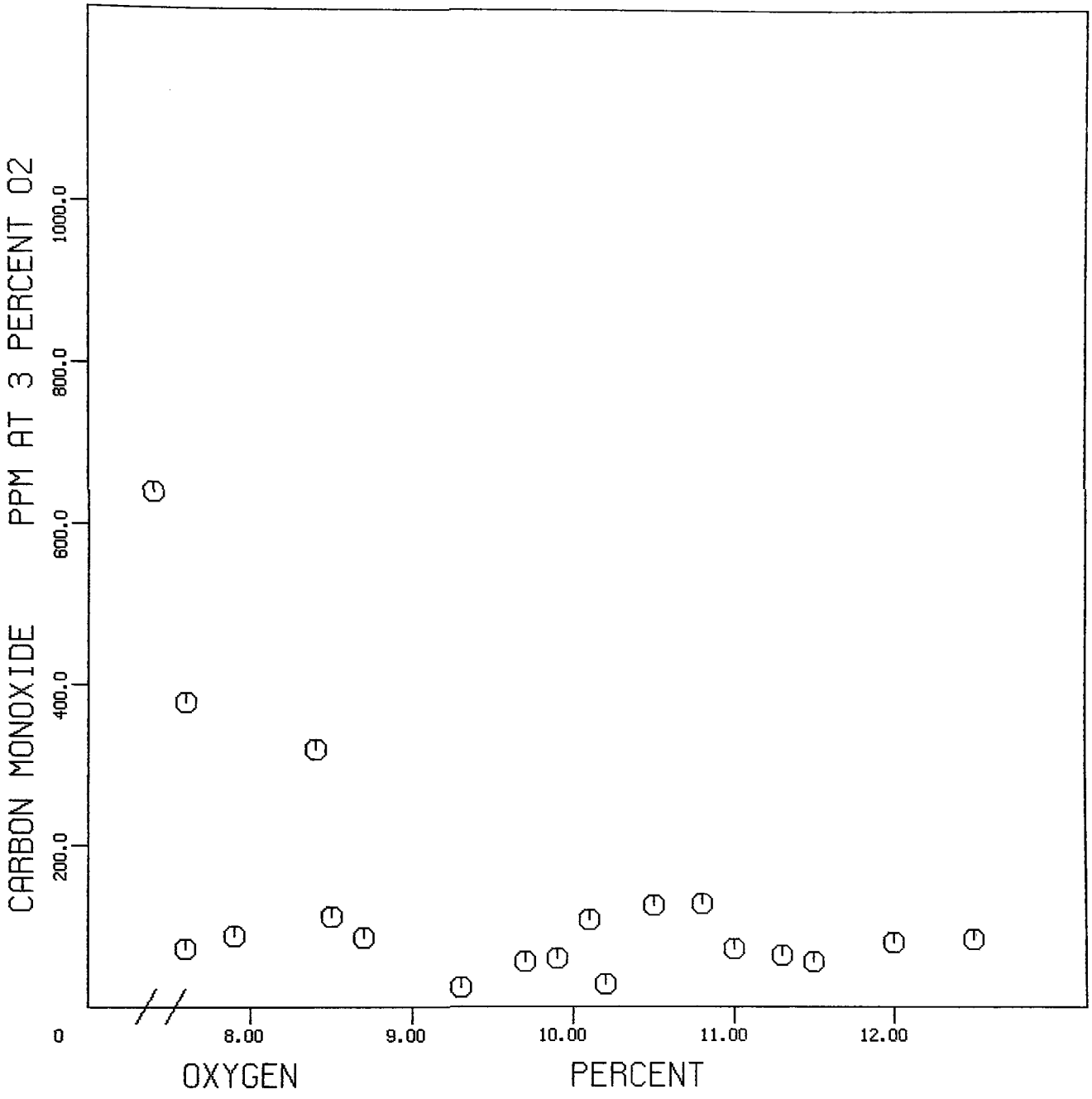
Figure 5-19 shows the combustibles in the boiler outlet flyash as a function of grate heat release. The data points are keyed to coal type. In these tests combustibles ranged between 14.4% and 40.1% with the Century



① : PER 8 COAL + : CENT. COAL △ : VICT. COAL

FIG. 5-16
CARBON MONOXIDE VS. GRATE HEAT RELEASE
TEST SITE D

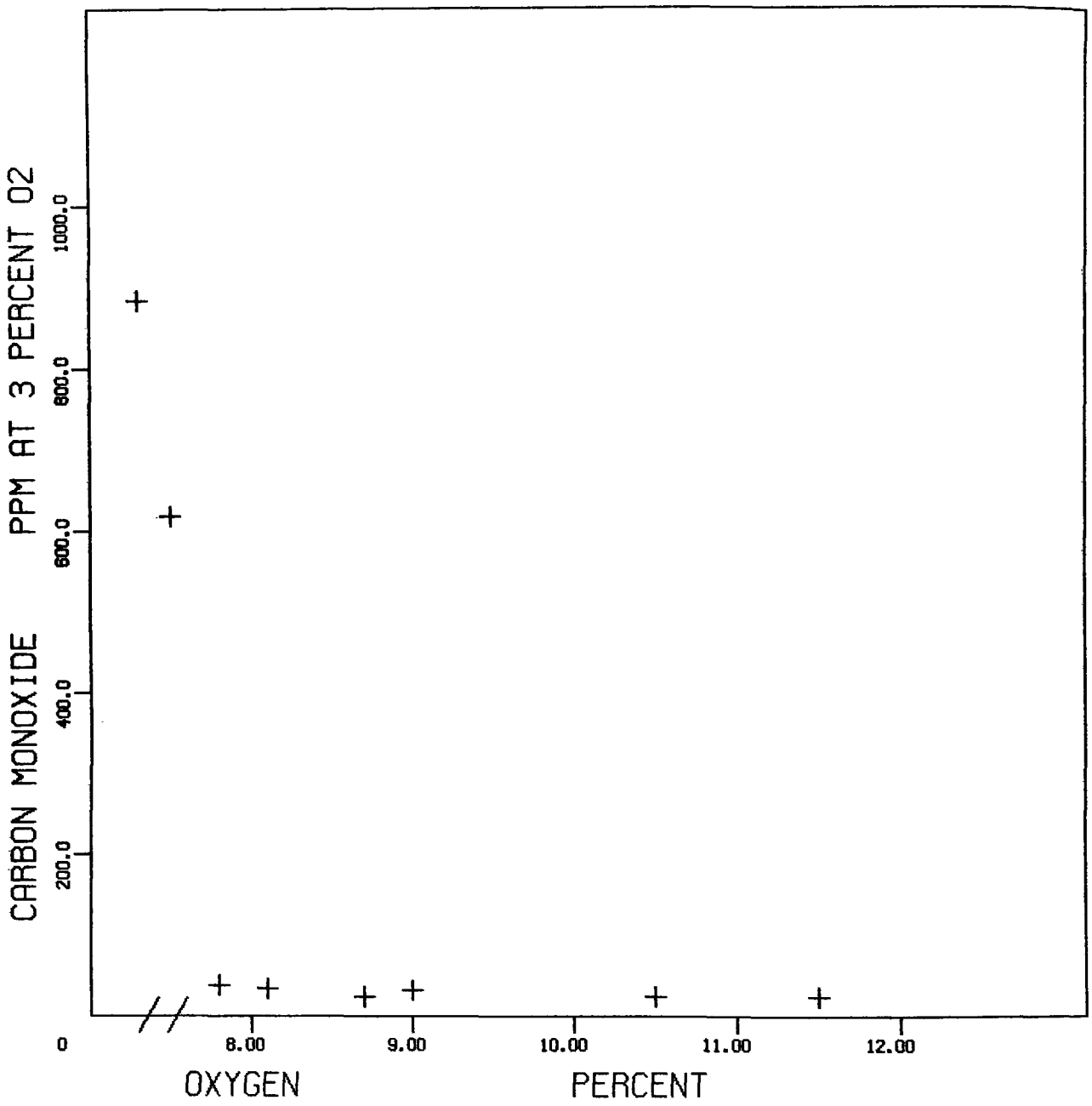
15900-529



(1) : PER 8 COAL

FIG. 5-17
CARBON MONOXIDE VS. OXYGEN
TEST SITE D

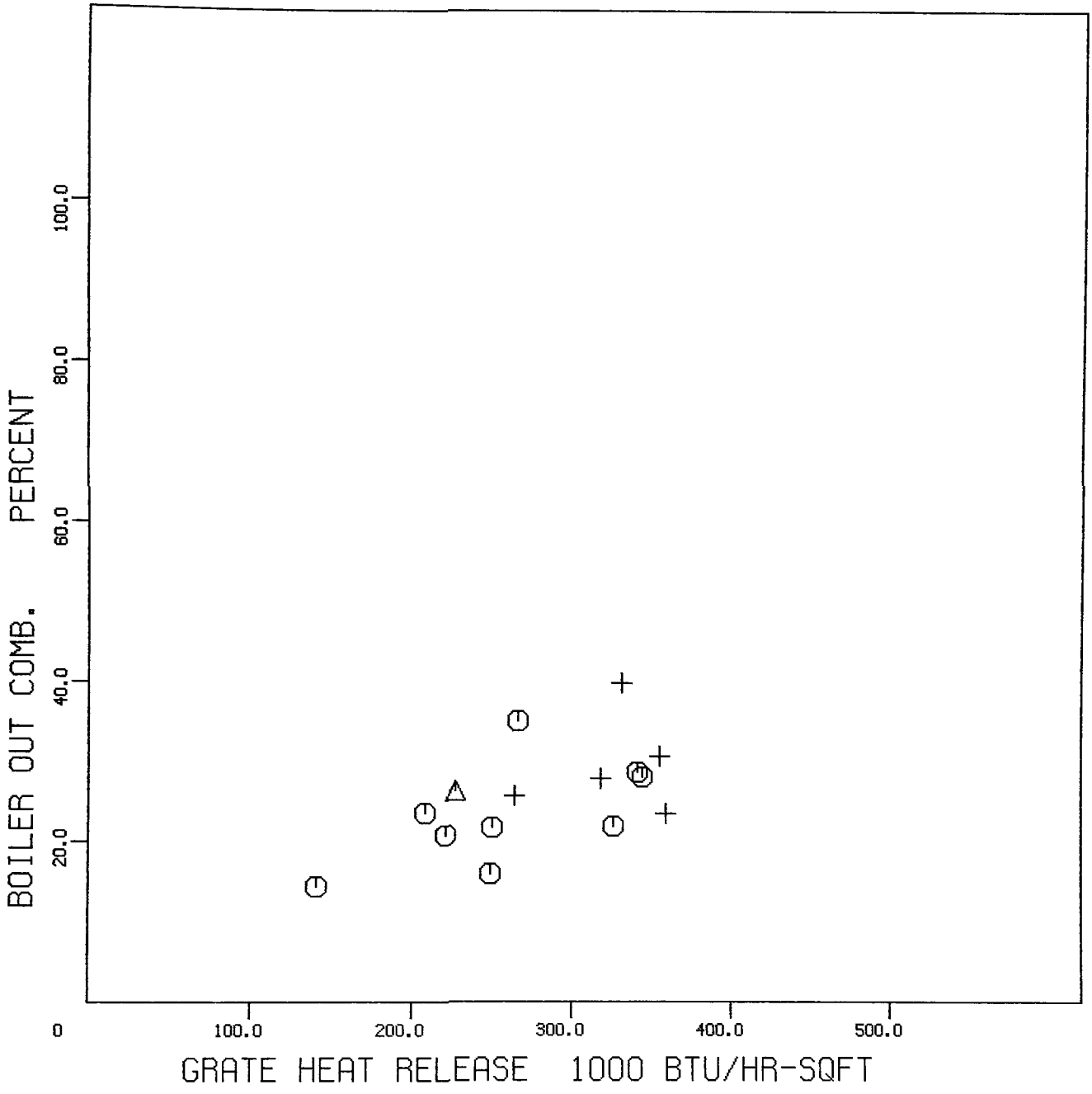
15900-529



+ : CENT. COAL

FIG. 5-18
CARBON MONOXIDE VS. OXYGEN
TEST SITE D

15900-529



⊕ : PER 8 COAL + : CENT. COAL △ : VICT. COAL

FIG. 5-19
BOILER OUT COMB. VS. GRATE HEAT RELEASE
TEST SITE D

15900-529

coal (average 29.7%), only slightly higher than the Perfect 8 coal (average 23.5%). The single Victoria coal data point (26.5%) falls between the averages for the other two coals. The average heat losses due to combustibles in the flyash at the boiler outlet were 0.24% for Perfect 8 coal, 0.47% for Century coal and 0.29% for the single Victoria coal test. These losses are relatively small and suggest that flyash reinjection, were it installed on this unit, would result in fairly insignificant energy savings.

Figure 5-20 describes combustibles in the bottom ash as a function of grate heat release. Again the data points are keyed to coal type. The absolute range of values was between 8.4% and 35.9%. Perfect 8 coal and Century coal showed similar results, averaging 18.4% and 16.4%, respectively. Victoria coal had the two highest measurements, averaging 34.8%.

The heat losses due to the bottom ash combustibles were higher than those due to the flyash combustibles. The average heat losses were 1.63%, 0.90%, and 3.51%, respectively, for Perfect 8, Century and Victoria coals. Grate heat release did not have a major influence on the levels of bottom ash combustibles.

5.2.6 Boiler Efficiency vs Oxygen and Grate Heat Release

Boiler efficiency was determined for each test that included a boiler outlet particulate loading measurement. The efficiency determinations were made by the ASTM heat loss method.

Figure 5-21 shows the calculated boiler efficiencies as a function of grate heat release. Data points are keyed to coal type. The efficiencies appear to be independent of grate heat release, but dependent upon coal type.

Table 5-6 shows the average heat loss differences between the coal types tested. This data is compared with the results of a 1964 performance acceptance test run at 370×10^3 Btu/hr-ft^2. The Table shows that boiler efficiency was highest with Century coal, but this may be explained in part by the fact that the tests with Century coal were run at high load and low O_2. The low efficiency of the single Victoria coal test was a result of its high combustibles heat loss. According to the boiler's predicted performance data, the guaranteed minimum efficiency is 84.6%.

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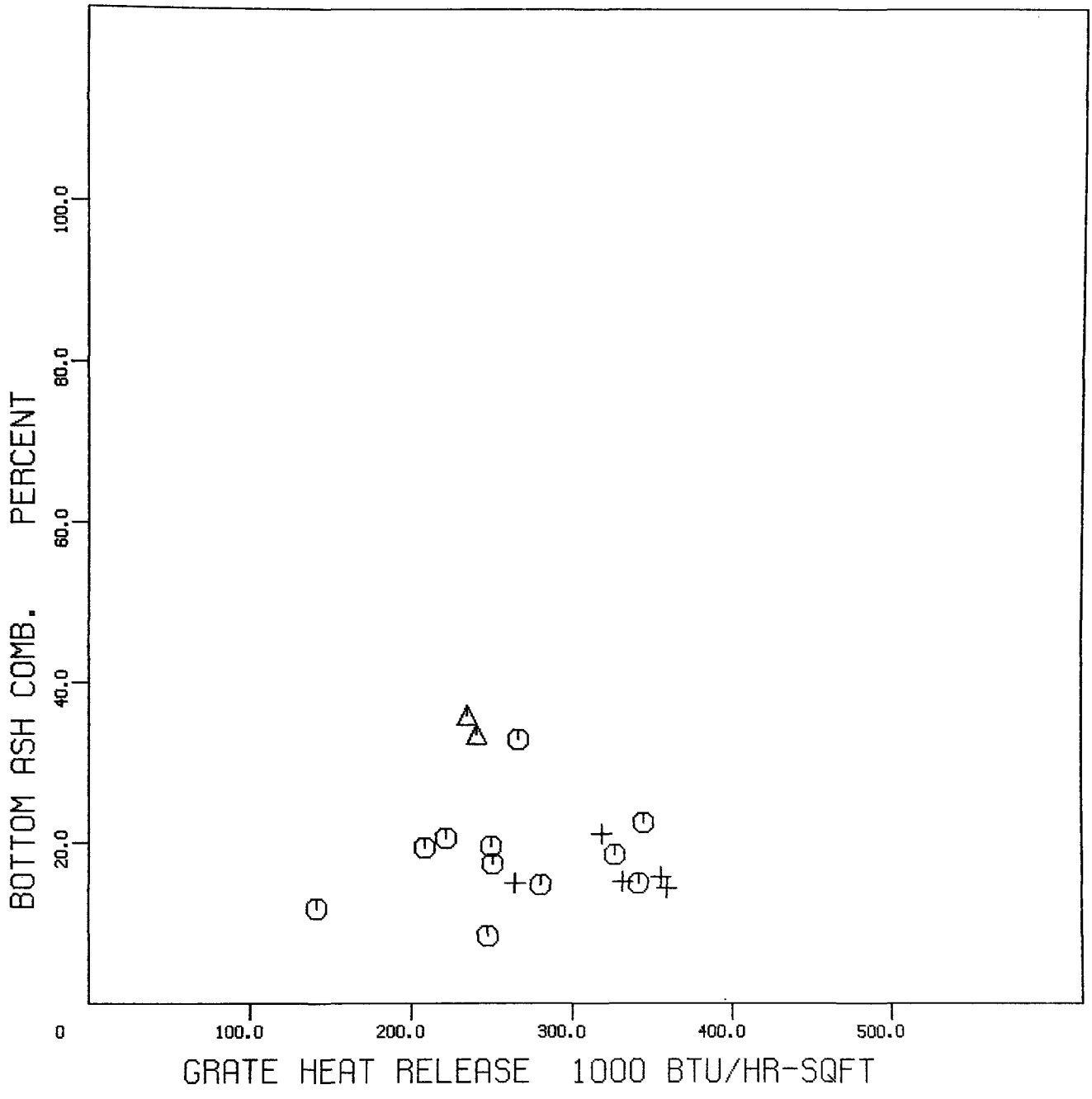

⊙ : PER 8 COAL + : CENT. COAL △ : VICT. COAL

FIG. 5-20
BOTTOM ASH COMB. VS. GRATE HEAT RELEASE
TEST SITE D

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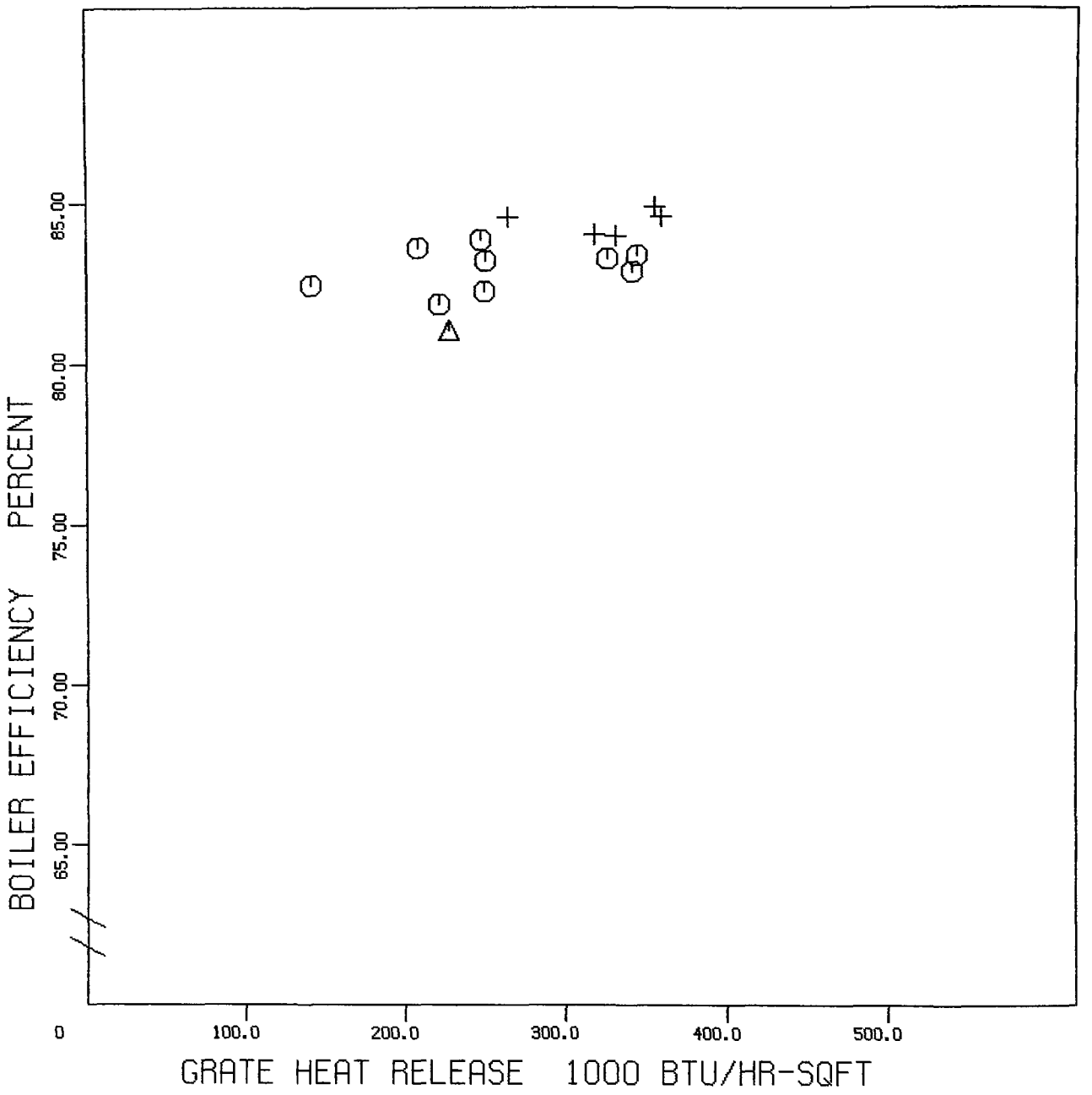

⊙ : PER 8 COAL + : CENT. COAL △ : VICT. COAL

FIG. 5-21
BOILER EFFICIENCY VS. GRATE HEAT RELEASE
TEST SITE D

15900-529

TABLE 5-6

AVERAGE HEAT LOSSES BY COAL TYPE

Coal	Dry Gas	Moisture in Fuel	H_2O From H_2 in Fuel	Total Combustibles	Radiation & Unmeasured	Total Losses	BOILER EFFICIENCY PERCENT
Perfect 8	8.53	0.29	4.05	1.96	2.20	17.04	82.96
Century	7.82	0.23	3.99	1.49	2.09	15.62	84.38
Victoria	8.58	0.28	3.97	3.85	2.27	18.95	81.05
Acceptance Test, 1964	7.76	0.39	4.13	0.21*	0.80**	13.29	86.71***

* Ash sample taken from "ash hopper" only and apparently does not include flyash
** This is radiation loss only and does not include unmeasured losses of 1.5%
*** Allowing for unmeasured losses of 1.5% and flyash combustible losses of 0.3% the acceptance test efficiency would be 84.91%.

5.3 COAL PROPERTIES

Coals from three different mines were tested in Boiler D. Representative coal samples were taken from the unit's two coal feeders during each test that included either a particulate measurement or SASS sample catch. These samples were analyzed for proximate analysis, ultimate analysis and size consistency. A composite sample consisting of increments from each test with each coal was also analyzed for ash fusion temperature, Hardgrove grindability index, free swelling index, and minerals in the ash. This section will bring into focus all of the coal related relationships which have been discussed in the previous two sections and will discuss the coal size consistency and sulfur balance data.

5.3.1 Chemical Composition of the Coals

The chemical analyses of each coal sample are grouped by coal and presented in Tables 5-7, 5-8, and 5-9. Coal ash analyses are given in Table 5-10. These Tables also show the average analysis for each coal and the standard deviation which is a measure of the variation in composition from sample to sample. From comparing these Tables, it is evident that all three coals were similar in makeup. However, some differences are notable.

TABLE 5-7

FUEL ANALYSIS - PERFECT 8 COAL
TEST SITE D

TEST NO.	2	3	4	5	6	7	8	9	10	12	13	COMP	AVG	STD DEV
PROXIMATE (As Rec'd)														
% Moisture	2.69	3.37	3.23	3.10	3.06	3.35	3.04	3.40	3.45	3.50	3.31	2.77	3.23	0.24
% Ash	8.44	9.26	8.08	8.47	8.83	9.00	8.65	8.24	8.13	9.14	9.57	8.97	8.71	0.49
% Volatile	39.47	38.98	39.45	39.53	39.82	39.15	39.01	39.16	39.17	37.90	39.22	38.25	39.17	0.49
% Fixed Carbon	49.40	48.39	49.24	48.90	48.29	48.50	49.30	49.20	49.25	49.46	47.90	50.01	48.89	0.53
BTU/lb	13124	12835	13081	13034	13034	12978	13084	13068	13019	12935	12839	12945	13003	97
% Sulfur	2.35	2.54	2.79	2.44	2.85	2.57	2.59	2.23	2.50	2.82	2.94	2.73	2.60	0.22
ULTIMATE (As Rec'd)														
% Moisture	2.69	3.37	3.23	3.10	3.06	3.35	3.04	3.40	3.45	3.50	3.31	2.77	3.23	0.24
% Carbon	72.89	71.25	72.71	72.38	72.32	71.80	72.44	72.05	72.38	71.14	71.40	72.04	72.07	0.59
% Hydrogen	5.08	5.02	5.06	5.10	4.97	5.01	4.96	5.04	5.02	4.90	4.91	4.89	5.01	0.07
% Nitrogen	1.27	1.24	1.27	1.24	1.09	1.12	1.24	1.32	1.33	1.31	1.15	1.42	1.23	0.08
% Chlorine	0.13	0.12	0.12	0.11	0.11	0.12	0.13	0.12	0.10	0.12	0.12	0.09	0.12	0.01
% Sulfur	2.35	2.54	2.79	2.44	2.85	2.57	2.59	2.23	2.50	2.82	2.94	2.73	2.60	0.22
% Ash	8.44	9.26	8.08	8.47	8.83	9.00	8.65	8.24	8.13	9.14	9.57	8.97	8.71	0.49
% Oxygen (Diff.)	7.15	7.20	6.74	7.16	6.77	7.03	6.95	7.60	7.09	7.07	6.60	7.09	7.03	0.27
ASH FUSION (Reducing)														
Initial Deformation												2050		
Soft (H=W)												2320		
Soft (H=1/2W)												2380		
Fluid												2520		
Hardgrove Grindability Index												47		
Free Swelling Index												4		

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TABLE 5-8

FUEL ANALYSIS - CENTURY COAL - TEST SITE D

TEST NO.	14	15	16	17	18	COMP	AVG	STD DEV
PROXIMATE (As Rec'd)								
% Moisture	3.09	2.69	2.62	2.59	2.39	2.94	2.68	0.26
% Ash	6.86	4.92	5.89	5.66	5.99	5.46	5.86	0.70
% Volatile	38.75	39.14	37.96	37.96	38.39	38.79	38.44	0.51
% Fixed Carbon	51.30	53.25	53.53	53.79	53.23	52.81	53.02	0.99
BTU/lb	13342	13829	13622	13691	13662	13709	13629	178
% Sulfur	2.04	1.15	1.11	0.86	0.98	1.00	1.23	0.47
ULTIMATE (As Rec'd)								
% Moisture	3.09	2.69	2.62	2.59	2.39	2.94	2.68	0.26
% Carbon	74.52	77.18	75.62	76.63	76.46	76.65	76.08	1.04
% Hydrogen	5.02	5.24	5.14	5.15	5.19	5.18	5.15	0.08
% Nitrogen	1.26	1.23	1.32	1.34	1.50	1.32	1.33	0.10
% Chlorine	0.10	0.13	0.13	0.15	0.13	0.04	0.13	0.02
% Sulfur	2.04	1.15	1.11	0.86	0.98	1.00	1.23	0.47
% Ash	6.86	4.92	5.89	5.66	5.99	5.46	5.86	0.70
% Oxygen (Diff)	7.11	7.46	8.17	7.62	7.36	7.41	7.54	0.40
ASH FUSION (Reducing)								
Initial Deformation						2680		
Soft (H=W)						2700		
Soft (H=1/2W)						2700		
Fluid						2700		
Hardgrove Grindability Index						40		
Free Swelling Index						3		

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TABLE 5-9

FUEL ANALYSIS - VICTORIA COAL
TEST SITE D

TEST NO.	22	23	AVG
PROXIMATE (As Rec'd)			
% Moisture	3.05	3.16	3.11
% Ash	6.47	6.96	6.72
% Volatile	37.43	37.06	37.25
% Fixed Carbon	53.05	52.82	52.94
Btu/lb	13453	13357	13405
% Sulfur	1.10	1.11	1.11
ULTIMATE (As Rec'd)			
% Moisture	3.05	3.16	3.11
% Carbon	75.08	74.84	74.96
% Hydrogen	4.98	5.02	5.00
% Nitrogen	1.27	1.32	1.30
% Chlorine	0.06	0.07	0.07
% Sulfur	1.10	1.11	1.11
% Ash	6.47	6.96	6.72
% Oxygen (Diff)	7.99	7.52	7.76
ASH FUSION (Reducing)			
Initial Deformation	2480	2700	
Soft (H=W)	2700	2700	
Soft (H=1/2W)	2700	2700	
Fluid	2700	2700	
Hardgrove Grindability Index	43	45	
Free Swelling Index	5-1/2	4	

TABLE 5-10

MINERAL ANALYSIS OF COAL ASH
TEST SITE D

Coal Test No.	Perfect 8 Comp	Century Comp	Victoria 22	 23	 Avg.
MINERAL ANALYSIS OF ASH					
Silica, SiO_2	45.24	47.07	49.83	50.60	50.22
Alumina, Al_2O_3	23.83	32.74	29.97	31.28	30.63
Titania, TiO_2	1.18	1.42	1.55	1.55	1.55
Ferric Oxide, Fe_2O_3	24.72	9.24	10.15	9.39	9.77
Lime, CaO	1.04	2.23	1.88	1.91	1.90
Magnesia, MgO	0.62	1.10	0.86	0.72	0.79
Potassium Oxide, K_2O	1.82	1.99	1.61	1.71	1.66
Sodium Oxide, Na_2O	0.42	0.63	0.54	0.42	0.48
Sulfur Trioxide, SO_3	0.62	1.85	1.38	0.96	1.17
Phos Pentoxide, P_2O_5	0.13	0.32	0.36	0.70	0.53
Undetermined	0.25	0.92	1.48	0.35	0.92
Silica Value	63.17	78.92	79.45	80.80	80.13
Base: Acid Ratio	0.41	0.19	0.18	0.17	0.18
T_{250} Temperature	2400°F	2730°F	2765°F	2785°F	2775°F
SULFUR FORMS (As Rec'd)					
% Pyritic Sulfur	1.46	0.19	0.27	0.29	0.28
% Sulfate Sulfur	0.12	0.02	0.07	0.06	0.07
% Organic Sulfur	1.15	0.79	0.76	0.76	0.76

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The more significant coal properties are presented in Table 5-11 on a heating value basis in order to allow for a more meaningful comparison. From this table it can be seen that moisture was relatively constant at 2.5, 2.0 and 2.3 lbs/10^6 Btu for the three coals. Coal moisture, therefore, was not considered a variable in these tests. Ash content of the coal shows some variation (6.7, 4.3, 5.0 lbs/10^6 Btu), but not enough to be considered really significant. Sulfur content does vary significantly -- between two percent for Perfect 8 coal and less than one percent for the other two coals.

TABLE 5-11

COAL PROPERTIES CORRECTED TO A CONSTANT 10^6 BTU BASIS

	Perfect 8 Coal	Century Coal	Victoria Coal
Moisture, lbs/10^6 Btu	2.5	2.0	2.3
Ash, lbs/10^6 Btu	6.7	4.3	5.0
Sulfur, lbs/10^6 Btu	2.0	0.90	0.83

The influence of coal properties on emissions and boiler efficiency is summarized below, with references to the relevant figures. Each of these relationships has been addressed elsewhere in the report but is reviewed here for convenience.

RELATIONSHIP BETWEEN COALS FIRED AND EMISSIONS

Parameter	Figure No.	Coal	Relationship to Coal
1. Excess O_2	5-6		None
2. Particulates (Boiler Outlet)	5-8		None
3. Particulates (Multiclone Outlet)	5-9	Perfect 8	Highest Average Particulates
		Century	Lowest Average Particulates
		Victoria	Insufficient Data
4. Nitric Oxide	5-10		None
5. Carbon Monoxide	5-16		None
6. Combustibles (Boiler Outlet Flyash)	5-19		None
7. Combustibles (Bottom Ash)	5-20	Perfect 8	Lowest Average Combustibles
		Century	Lowest Average Combustibles
		Victoria	Highest Average Combustibles
8. Boiler Efficiency	5-21	Perfect 8	Average Efficiency
		Century	Highest Efficiency
		Victoria	Lowest Efficiency
9. Particle Size Distribution of Flyash	5-25	Perfect 8	Highest % Passing 20 Micrometers
		Century	Lowest % Passing 20 Micrometers
		Victoria	Insufficient Data
10. SOx Emissions	Table 5-13		Proportional to Sulfur Content of Coal

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5.3.2 Coal Size Consistency

The individual coal samples and the composite coal samples were screened at the site using 1", 1/2", 1/4", #8 and #16 square mesh screens. The results of these screenings are presented in Table 5-12. The average coal size consistency and standard deviation for each of the three coals were determined and are plotted against the ABMA recommended limits for mass fed stokers in Figures 5-22, 5-23, and 5-24.

This parameter was not varied for test purposes and its natural fluctuations from test to test were small. All three coals were coarse, having low fines and falling at the lower limit of the ABMA curve. A generally accepted definition of "coal fines" is the percent by weight passing a 1/4" square mesh screen. By this definition, Perfect 8 coal had the lowest fines at 9.3% but also had the greatest spread in values at $\pm$4.5%. Century coal had 15.2$\pm$2.0% fines, and Victoria coal had 15.8$\pm$0.2% fines.

5.3.3 Sulfur Balance

Sulfur oxides -- SO_2 and SO_3 -- were measured in the flue gas during one test on Century coal and one test on Victoria coal. Coal and ash samples taken at the same time these tests were run were analyzed for sulfur content in order to determine sulfur balance. The results of this sulfur balance are presented in Table 5-13.

The sulfur balance was not good. It shows more sulfur being emitted from the boiler than is being input from the coal. It is not possible at this point to determine which measurement is in error, the sulfur input (fuel sulfur and coal flow) or the sulfur output (SOx in flue gas, sulfur in ash, and gas flow). However, it is safe to say that the most accurate determination of sulfur retention is to measure the sulfur in the ash directly rather than compare the sulfur input with the sulfur output. The measured sulfur retentions were as follows:

Century coal - 1.9% sulfur retained in the ash
Victoria coal - 2.1% sulfur retained in the ash

TABLE 5-12

AS FIRED COAL SIZE CONSISTENCY
TEST SITE D

	Test Number	PERCENT PASSING STATED SCREEN SIZE 1"	1/2"	1/4"	#8	#16
PERFECT 8 COAL	2	99.5	59.5	15.2	6.4	4.0
	3	98.4	65.8	20.1	7.6	4.3
	4	99.0	45.4	9.0	4.1	3.2
	5	99.8	36.3	5.5	2.8	2.3
	6	99.8	46.0	8.6	3.5	2.7
	7	99.2	38.9	4.7	2.4	2.0
	8	99.8	49.0	7.5	3.5	2.6
	9	98.3	38.6	7.0	3.9	3.0
	10	99.0	43.1	6.4	3.4	2.7
	12	99.8	54.2	9.0	3.5	2.4
	13	99.8	57.5	9.4	3.8	2.6
	Composite	99.3	47.0	8.5	4.3	3.2
	Average	99.3	48.6	9.3	4.1	2.9
	Std. Dev.	0.6	9.6	4.5	1.5	0.7
CENTURY COAL	14	98.5	50.2	13.3	6.3	4.5
	15	94.6	48.2	13.7	5.7	4.1
	16	96.1	48.2	14.3	5.2	2.9
	17	96.0	49.7	16.4	7.0	5.1
	18	95.0	52.3	18.1	7.6	5.4
	Composite	94.9	44.2	12.2	4.8	3.3
	Average	96.0	49.7	15.2	6.4	4.4
	Std. Dev.	1.5	1.7	2.0	1.0	1.0
VICTORIA COAL	22	88.2	39.5	15.9	7.7	4.1
	23	89.4	39.6	15.6	8.1	5.7
	Average	88.8	39.6	15.8	7.9	4.9
	Std. Dev.	0.8	0.1	0.2	0.3	1.1

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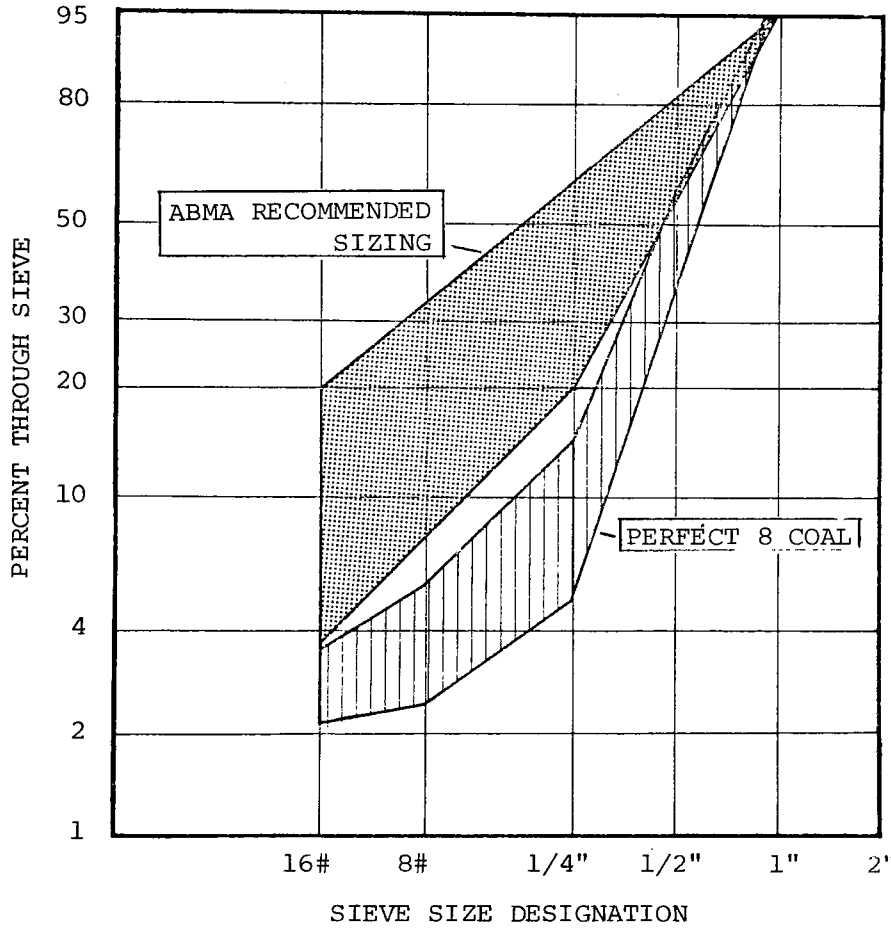

FIGURE 5-22. SIZE CONSISTENCY OF "AS FIRED" PERFECT 8 COAL VS ABMA RECOMMENDED SIZING FOR OVERFEED STOKERS

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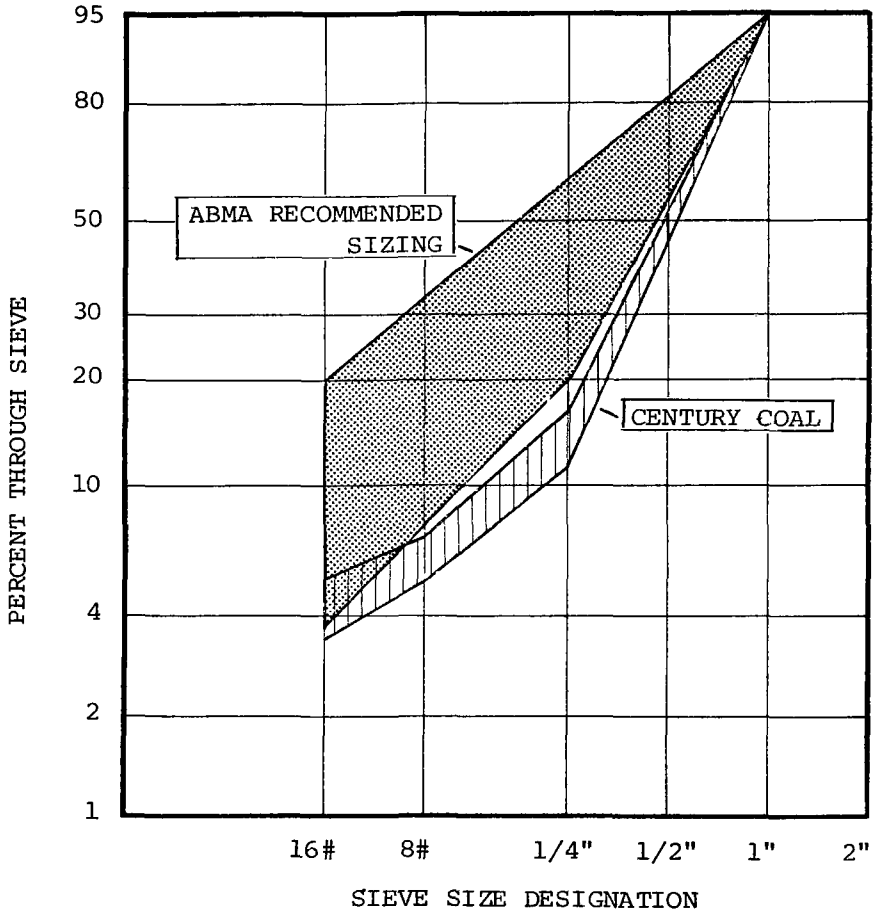

FIGURE 5-23. SIZE CONSISTENCY OF "AS FIRED" CENTURY COAL VS ABMA RECOMMENDED SIZING FOR OVERFEED STOKERS

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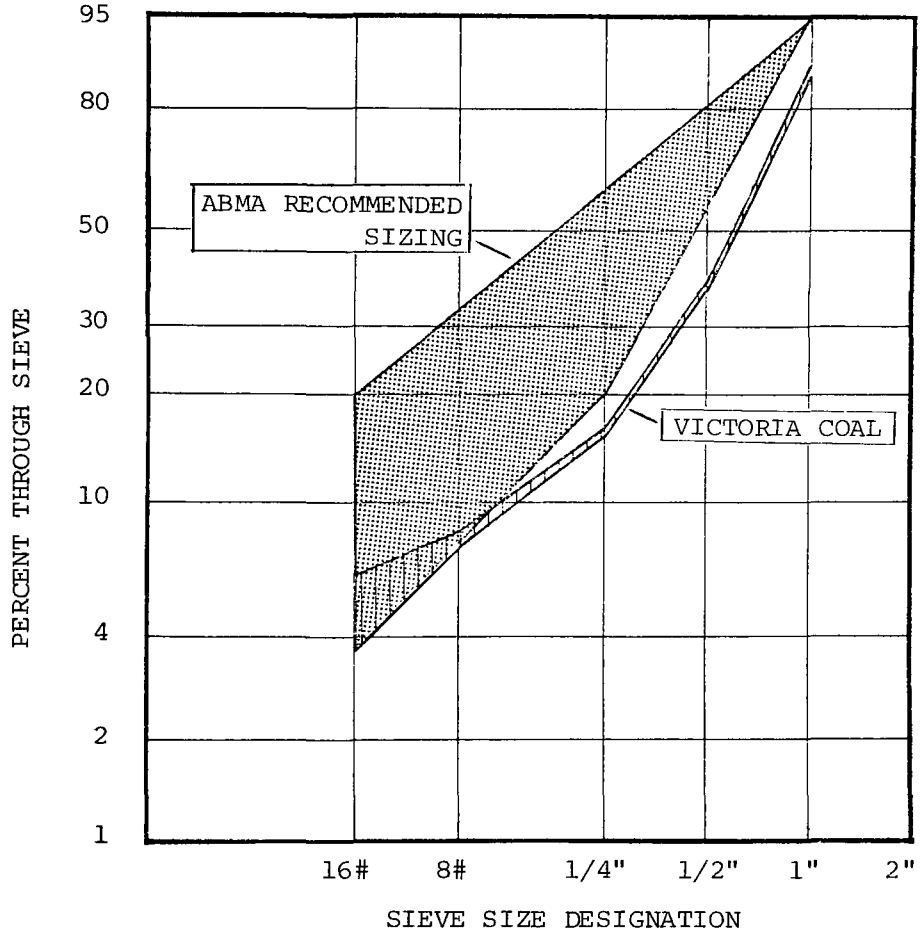

FIGURE 5-24. SIZE CONSISTENCY OF "AS FIRED" VICTORIA COAL VS ABMA RECOMMENDED SIZING FOR OVERFEED STOKERS

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TABLE 5-13

SULFUR BALANCE
TEST SITE D

	SULFUR IN FUEL		SULFUR IN BOTTOM ASH			SULFUR IN BLR HPR ASH			SULFUR IN FLYASH			SULFUR IN FLUE GAS		
Test No.	Fuel Sulfur %	As SO_2 lbs/10^6Btu	Ash Sulfur %	As SO_2 lbs/10^6Btu	Retention %	Ash Sulfur %	As SO_2 lbs/10^6Btu	Retention %	Ash Sulfur %	As SO_2 lbs/10^6Btu	Retention %	SOx ppm(dry)	As SO_2 lbs/10^6Btu	Fuel Sulfur Emitted, %*
18	0.98	1.435	0.16	0.018	1.25	0.40	0.005	0.34	0.62	0.005	0.35	1271	1.799	125
22	1.10	1.635	0.16	0.023	1.41	0.29	0.003	0.21	0.47	0.007	0.43	1293	1.815	111

* The imbalance between the sulfur in the fuel and the sulfur emitted can be attributed to measurement error.

5.4 PARTICLE SIZE DISTRIBUTION OF FLYASH

The purpose of the particle size distribution tests carried out under this program is to accumulate a data bank of particle size distribution data from all types of stoker boilers firing a variety of coals under a variety of firing conditions. This data will be valuable to manufacturers of dust collection equipment and to consulting engineers faced with the tasks of specifying such equipment.

Five particle size distribution tests were run at the boiler outlet employing the methodologies outlined in Table 5-14; three by Bahco classifier, one by Brink cascade impactor, and one by SASS cyclones. Each methodology has its own drawback, so the results of each test should be examined in light of the methodology used. A discussion of each method is included in Section 4.5. Test results are presented in Table 5-15 and Figures 5-25, 5-26 and 5-27.

At this test site it is especially important to point out that the size distribution data from the Bahco classifier tests require a correction for the lost portion of the sample. A significant fraction of the sampled flyash was lost because it was not collected by the cyclone. This lost fraction was collected on a filter following the cyclone and can be used to apply a correction to the data. For the three tests involved, the classified sample represents the following percent of the total sample:

Test 5 -- 62.2%
Test 17 -- 81.7%
Test 23 -- 70.8%

TABLE 5-14

DESCRIPTION OF PARTICLE SIZE DISTRIBUTION TESTS AT THE BOILER OUTLET - TEST SITE D

Test No.	Coal	% Design Capacity*	O_2 %	OFA "H_2O	Particle Size Distribution Methodology Used
5	Perfect 8	86	7.9	10.0	Bahco - Sieve
15	Century	88	7.8	15.5	Brink Impactor
17	Century	87	7.3	10.0	Bahco - Sieve
22	Victoria	59	10.2	12.0	SASS Cyclones
23	Victoria	61	10.4	12.5	Bahco - Sieve

*Design capacity is 90,000 lb stm/hr. Maximum obtainable load averaged 88% of design capacity due to draft loss from retrofit dust collector.

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TABLE 5-15

RESULTS OF PARTICLE SIZE DISTRIBUTION TESTS
AT THE BOILER OUTLET - TEST SITE D

Test Description	Size Distribution		Size Concentration	
	% Below 3μm	% Below 10μm	$lb/10^6 Btu$ Below 3μm	$lb/10^6 Btu$ Below 10 μm
Test 5 High Load - Bahco	3.5	18	0.029	0.15
Test 15 High Load - Brink	13.0	--	0.013	--
Test 17 High Load - Bahco	2.3	12	0.025	0.13
Test 22 Low Load - SASS	35.0	48	0.270	0.37
Test 23 Low Load - Bahco	1.3	5.4	0.010	0.04

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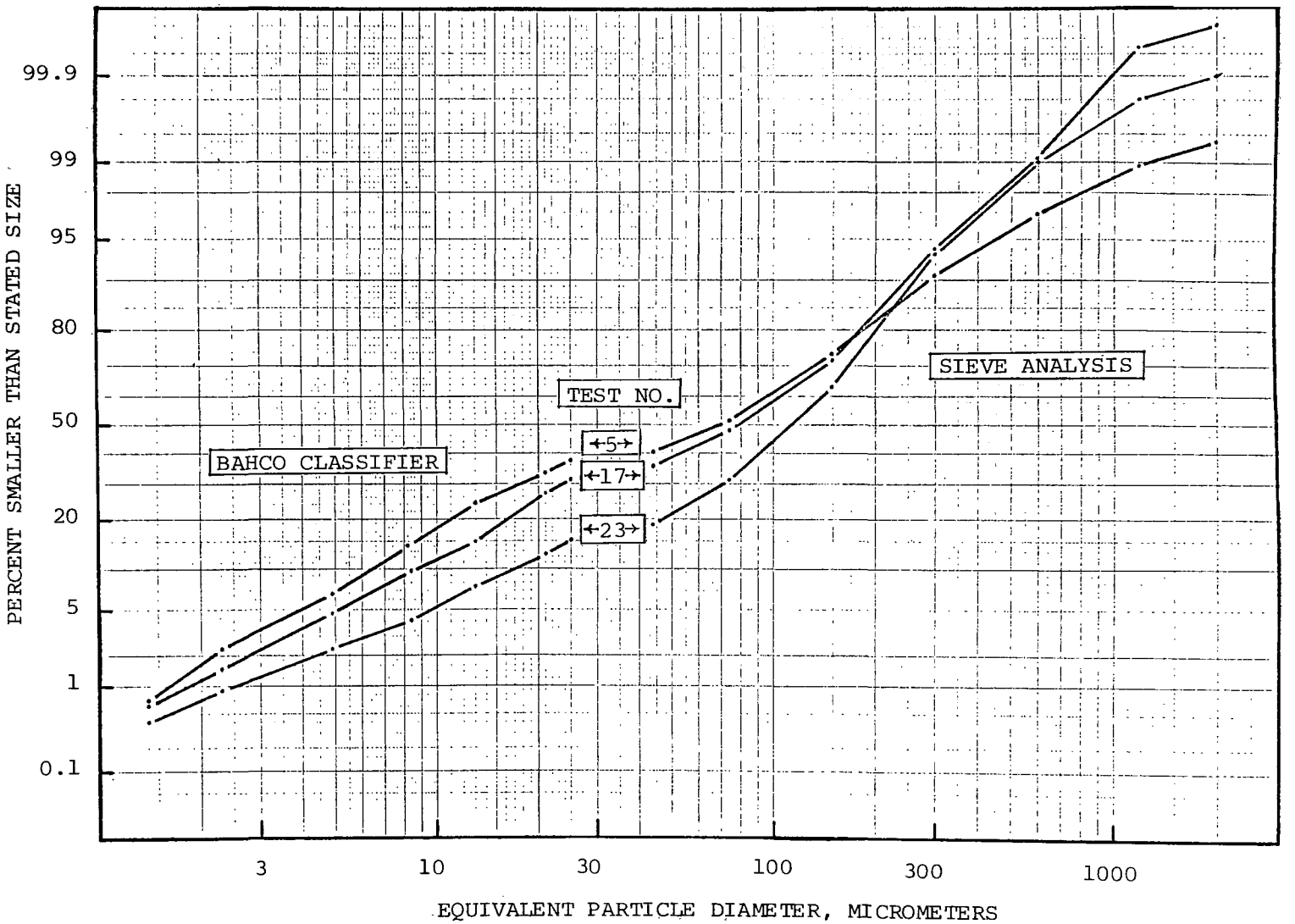

FIGURE 5-25. PARTICLE SIZE DISTRIBUTION OF THE BOILER OUTLET FLYASH FROM BAHCO CLASSIFIER AND SIEVE ANALYSIS

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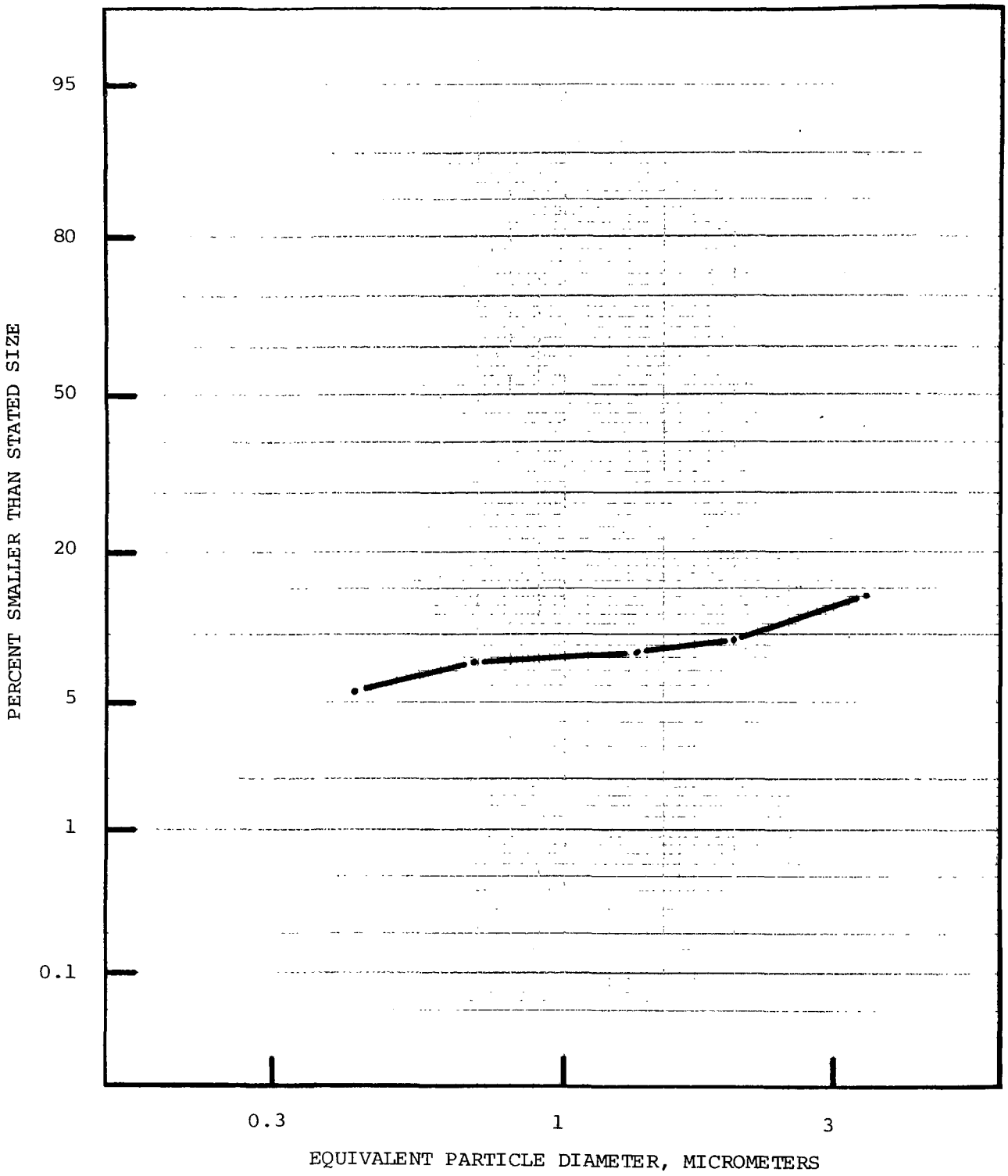

FIGURE 5-26. PARTICLE SIZE DISTRIBUTION AT THE BOILER OUTLET FROM BRINK CASCADE IMPACTOR - TEST SITE D

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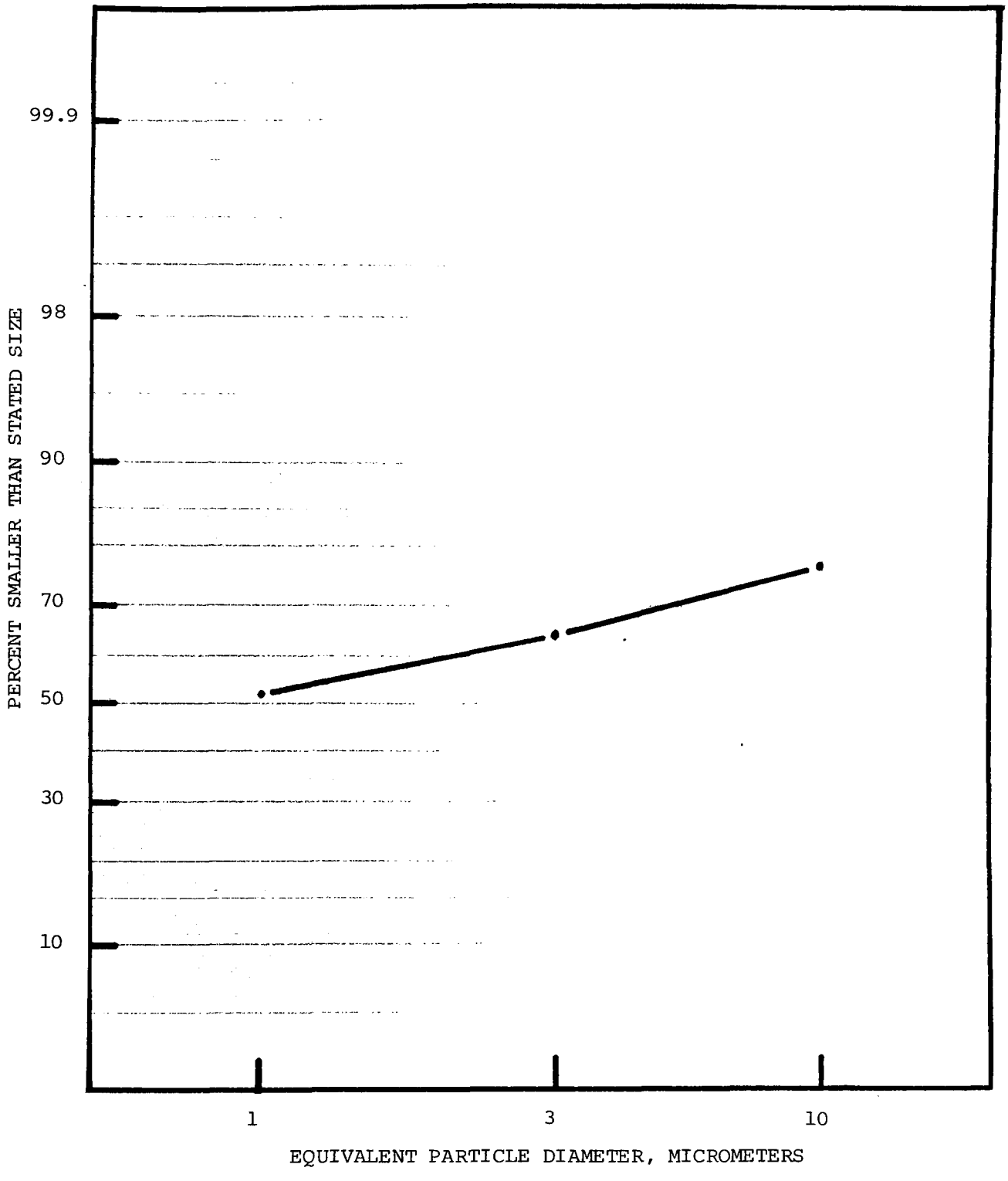

FIGURE 5-27. PARTICLE SIZE DISTRIBUTION AT THE BOILER OUTLET FROM SASS GRAVIMETRICS - TEST SITE D

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5.5 EFFICIENCY OF MULTICLONE DUST COLLECTOR

The multiclone dust collector efficiency was determined in sixteen tests under various boiler operating conditions. In each case the multiclone collection efficiency was well below its design efficiency of 90%. The test data is presented in Table 5-16 and plotted as a function of grate heat release in Figure 5-28.

The collection efficiency was greatest while burning Century coal, when it averaged 56.2% ±7.5%. While burning Perfect 8 coal, the collection efficiency averaged 39.9 ±11.9%. The collection efficiency for the single Victoria coal test was 21.9%.

The reason for the low dust collection efficiency may be related to the particle size distribution of the flyash. When corrected for the "lost sample" described in Section 5.4, the Bahco tests yield the following results:

Test 5	--	Perfect 8 coal	--	58% below 20μm
Test 17	--	Century coal	--	39% below 20μm
Test 23	--	Victoria coal	--	38% below 20μm

This data indicates that a large fraction of the particulates were small enough to pass through the collector without being captured.

5.6 MODIFIED SMOKE SPOT NUMBER

Smoke spot readings were taken with a Bacharach Smoke Spot Tester at the multiclone outlet during nine of the particulate tests (Table 5-17). One, two and three pump smoke spot readings were taken for each of these tests. The purpose of this exercise was to determine if a correlation existed between the smoke spot readings and either the particulate loading or opacity of the boiler's emissions. As seen in Figures 5-29 and 5-30, no correlation was found. Previous tests on spreader stokers had also shown no correlation.

TABLE 5-16

EFFICIENCY OF MULTICLONE DUST COLLECTOR
TEST SITE D

Test No.	Coal Type	% Design Capacity*	O_2 %	Particulate Loading lbs/10^6 Btu		Collector Efficiency, %
				Coll. Inlet	Coll. Outlet	
4	Perfect 8	64	9.3	0.664	0.557	16.1
5	Perfect 8	86	7.9	0.832	0.574	31.0
6	Perfect 8	65	8.7	0.694	0.372	46.4
7	Perfect 8	63	10.2	0.793	0.488	38.5
8	Perfect 8	66	9.7	0.788	0.328	58.4
9	Perfect 8	45	11.5	0.732	0.456	37.7
10	Perfect 8	63	9.9	0.707	0.354	49.9
12	Perfect 8	87	8.4	1.097	0.667	39.2
13B	Perfect 8	89	7.4	0.837	0.490	41.5
14	Century	87	7.5	1.336	0.754	43.6
15	Century	88	7.8	1.000	0.424	57.6
16	Century	64	8.7	0.798	0.319	60.0
17	Century	87	7.3	1.072	0.393	63.3
18	Century	79	8.1	0.969	0.421	56.6
23	Victoria	61	10.4	0.762	0.595	21.9

*Maximum obtainable load averaged 88% of design capacity due to draft loss from retrofit dust collector.

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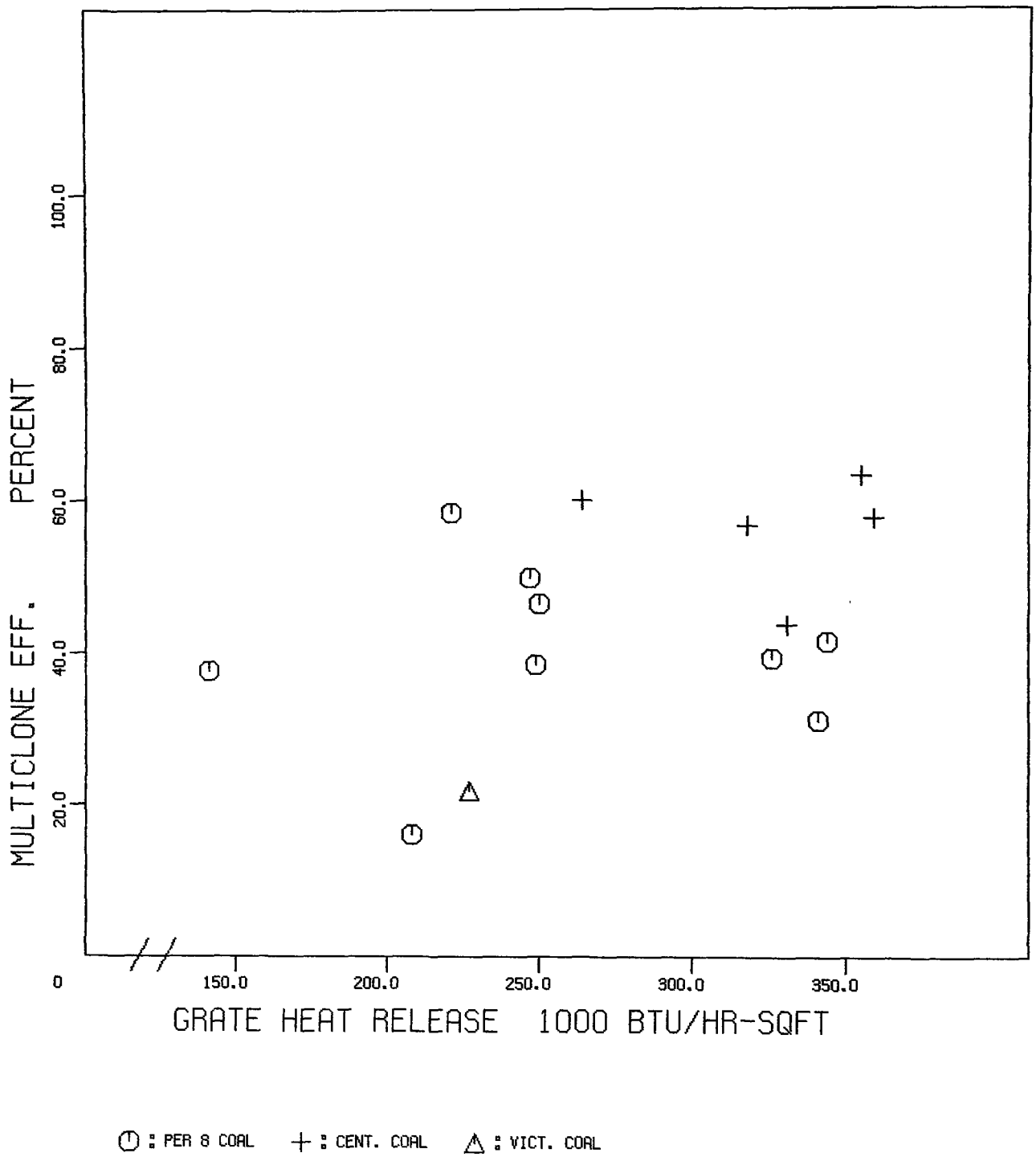

FIG. 5-28
MULTICLONE EFF. VS. GRATE HEAT RELEASE
TEST SITE D

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TABLE 5-17

MODIFIED SMOKE SPOT DATA
TEST SITE D

Test No.	AVERAGE SMOKE SPOT READING			Multiclone Out Particulate $lb/10^6$ Btu	Stack Opacity %
	1 Pump	2 Pumps	3 Pumps		
2	3.5	4.5	5.0	--	--
3	4.0	4.8	5.5	0.355	--
4	0.5	2.5	2.8	0.557	30
5	4.8	5.8	6.5	0.574	23
9	1.0	1.5	2.0	0.456	7
12	4.3	6.0	7.0	0.667	19
13	3.0	5.0	5.5	0.490	29
15	3.0	3.3	4.0	0.424	19
16	1.0	1.8	2.0	0.319	12

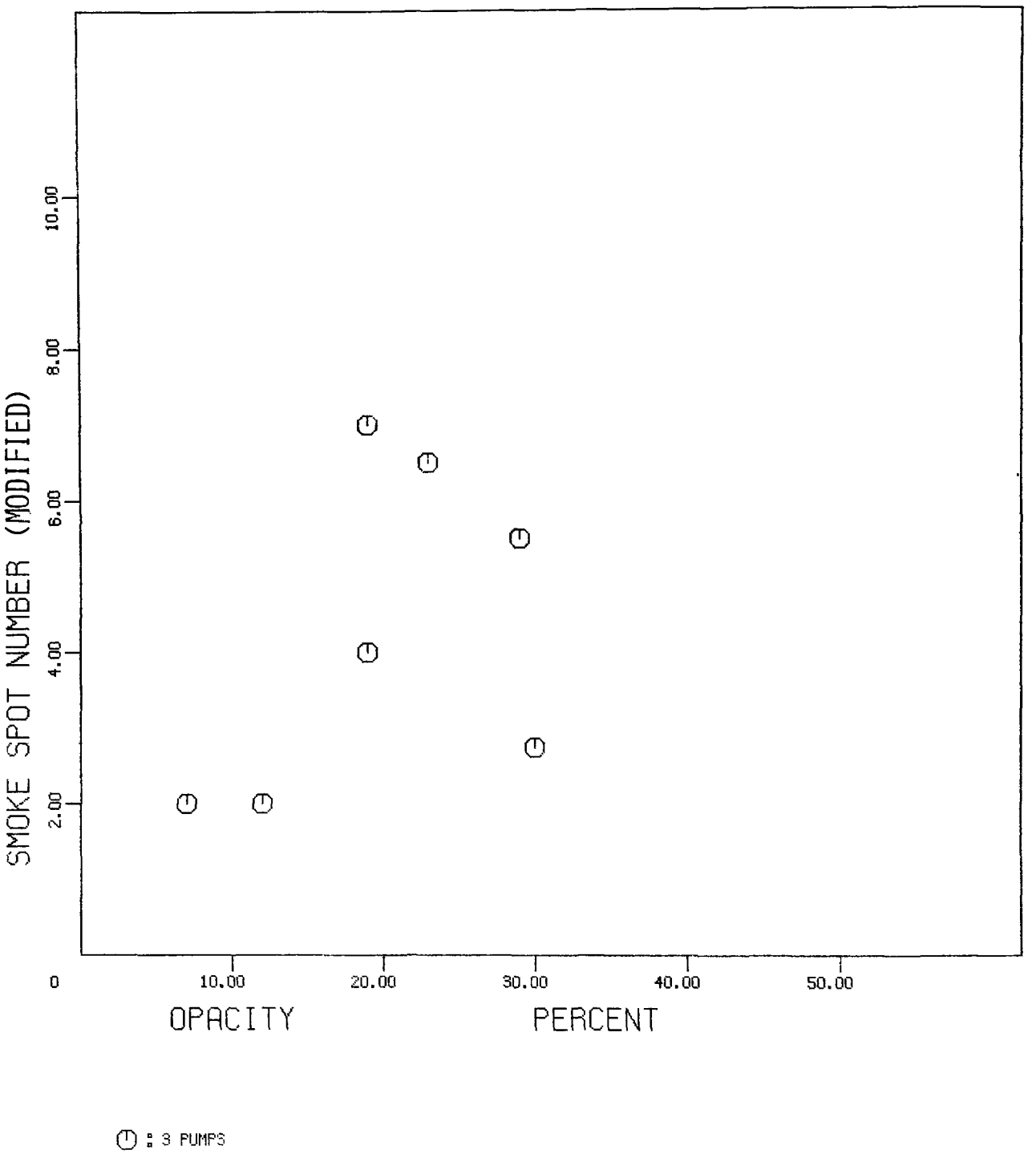

FIG. 5-29
SMOKE SPOT NUMBER VS. OPACITY
TEST SITE D

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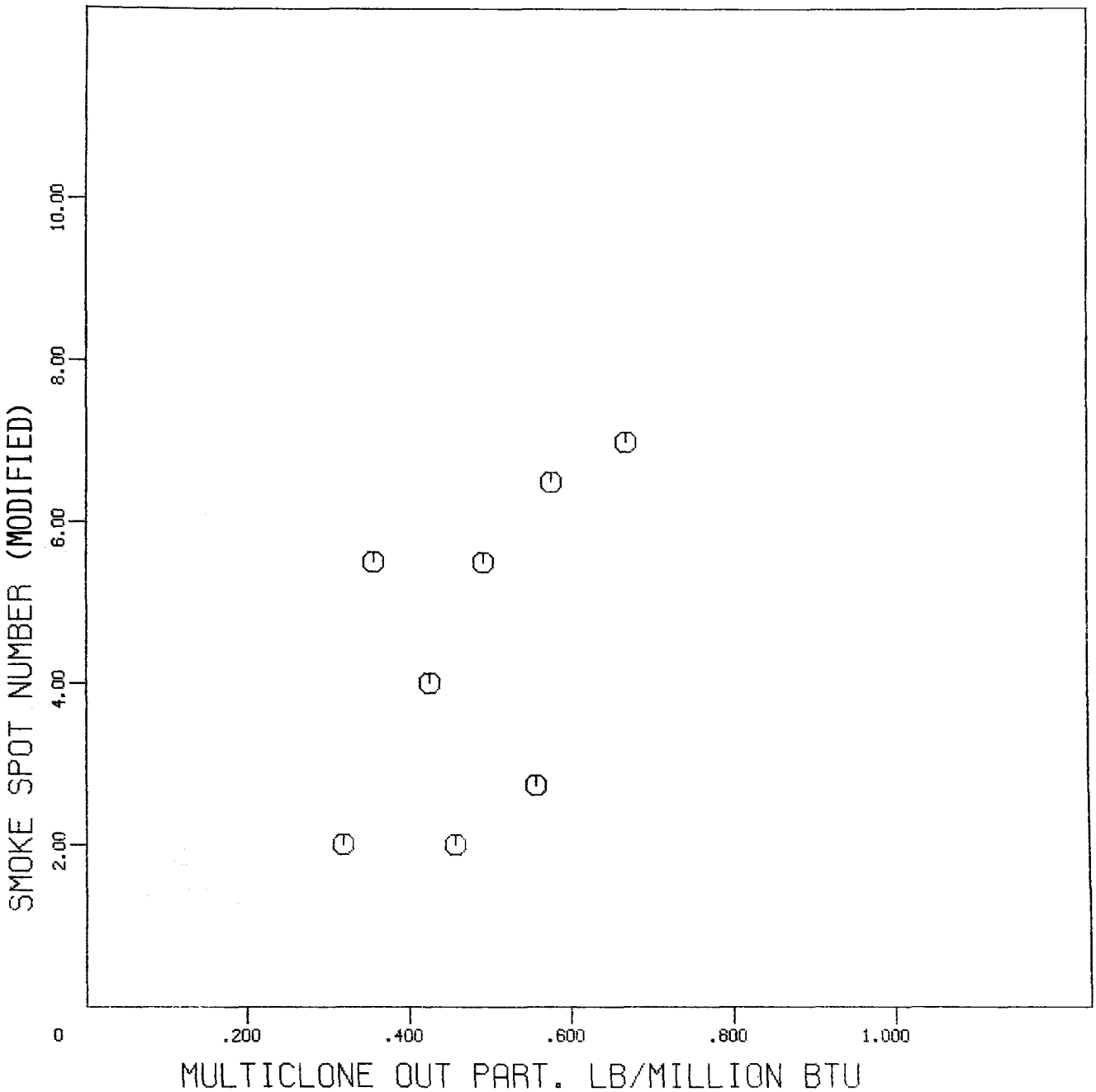

(1) = 3 PUMPS

FIG. 5-30
SMOKE SPOT NUMBER VS. MULTICLONE OUT PART.
TEST SITE D

15900-529

5.7 SOURCE ASSESSMENT SAMPLING SYSTEM

One SASS test was run at Test Site D. This test, No. 22, was originally intended to be run on both Perfect 8 coal and Century coal. However, both of these coals became unavailable when it came time to test and Victoria coal was tested instead. A single particulate test, No. 23, was run on this coal at the same firing conditions as the SASS test to supplement the data taken during that test.

All SASS test results will be reported under separate cover at the conclusion of this test program. The SASS sample catches will be analyzed by combined gas chromatography/mass spectroscopy for total polynuclear content. In addition, seven specific polynuclear aromatic hydrocarbons (PAH) will be sought. These are given in Table 5-18.

TABLE 5-18

POLYNUCLEAR AROMATIC HYDROCARBONS
ANALYZED IN THE SITE D SASS SAMPLE

Element Name	Molecular Weight	Molecular Formula
7,12 Dimethylbenz (a) anthracene	256	$C_{20}H_{16}$
Dibenz (a,h) anthracene	278	$C_{22}H_{14}$
Benzo (c) phenanthrene	228	$C_{18}H_{12}$
3-methyl cholanthrene	268	$C_{21}H_{16}$
Benzo (a) pyrene	252	$C_{20}H_{12}$
Dibenzo (a,h) pyrene	302	$C_{24}H_{14}$
Dibenzo (a,i) pyrene	302	$C_{24}H_{14}$
Dibenzo (c,g) carbazole	267	$C_{20}H_{13}N$

5.8 DATA TABLES

Tables 5-19 through 5-23 summarize the test data obtained at Test Site D. These tables, in conjunction with Table 2-1 in the Executive Summary, are included for reference purposes.

TABLE 5-19

PARTICULATE EMISSIONS
TEST SITE D

	Test No.	Coal*	% Des Cap**	O_2 %	EMISSIONS lb/10^6Btu	EMISSIONS gr/SCF	EMISSIONS lb/hr	Velocity ft/sec
BOILER OUTLET	4	P	64	9.3	0.664	0.264	35	6.57
	5	P	86	7.9	0.832	0.371	72	10.14
	6	P	65	8.7	0.694	0.291	44	7.29
	7	P	63	10.2	0.793	0.293	50	9.32
	8	P	66	9.7	0.788	0.305	44	8.92
	9	P	45	11.5	0.732	0.239	26	5.32
	10	P	63	9.9	0.707	0.267	44	8.16
	12	P	87	8.4	1.097	0.476	90	9.55
	13B	P	89	7.4	0.837	0.387	73	8.86
	14	C	87	7.5	1.336	0.615	114	9.39
	15	C	88	7.8	1.000	0.452	91	9.81
	16	C	64	8.7	0.798	0.339	53	8.12
	17	C	87	7.3	1.072	0.503	96	9.39
	18	C	79	8.1	0.969	0.427	78	10.94
	23	V	61	10.4	0.762	0.276	45	8.80
MECHANICAL COLLECTOR OUTLET	3	P	69	10.1	0.355	0.126	24	18.59
	4	P	64	9.3	0.557	0.208	29	13.36
	5	P	86	7.9	0.574	0.246	50	16.07
	6	P	65	8.7	0.372	0.142	24	13.74
	7	P	63	10.2	0.488	0.168	31	15.50
	8	P	66	9.7	0.328	0.118	18	17.09
	9	P	45	11.5	0.456	0.138	16	10.82
	10	P	63	9.9	0.354	0.127	22	14.03
	12	P	87	8.4	0.667	0.268	55	17.37
	13B	P	89	7.4	0.490	0.212	43	17.77
	14	C	87	7.5	0.754	0.329	64	14.97
	15	C	88	7.8	0.424	0.179	39	16.25
	16	C	64	8.7	0.319	0.125	21	14.62
	17	C	87	7.3	0.393	0.176	35	17.14
	18	C	79	8.1	0.421	0.176	34	18.09
	23	V	61	10.4	0.595	0.205	35	13.67

* P - Perfect 8 Coal
C - Century Coal
V - Victoria Coal

** Maximum obtainable load averaged 88% of design capacity due to draft loss from retrofit dust collector.

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TABLE 5-20

HEAT LOSSES AND EFFICIENCIES
TEST SITE D

TEST NO.	DRY GAS LOSS	MOISTURE IN FUEL	H_2O FROM COM-BUSTION OF H_2	COMBUSTIBLES IN MECH COLLECTED ASH	COMBUSTIBLES IN FLYASH	COMBUSTIBLES IN BOTTOM ASH	TOTAL COMBUSTIBLES IN REFUSE	RADIATION FROM BOILER	UNMEASURED	TOTAL LOSSES	EFFICIENCY
4	8.35	0.29	4.03	0.13	0.22	1.14	1.49	0.74	1.50	16.40	83.60
5	8.76	0.28	4.18	0.18	0.34	1.36	1.88	0.55	1.50	17.15	82.85
6	8.20	0.28	4.03	0.10	0.22	1.74	2.06	0.72	1.50	16.79	83.21
7	8.80	0.30	4.05	0.14	0.18	2.04	2.36	0.74	1.50	17.75	82.25
8	9.20	0.27	4.03	0.12	0.24	2.07	2.43	0.72	1.50	18.15	81.85
9	9.54	0.30	4.02	0.00	0.15	1.01	1.16	1.05	1.50	17.57	82.43
10	8.60	0.31	4.05	0.03	0.24*	0.68	0.95	0.74	1.50	16.15	83.85
12	8.10	0.32	4.02	0.05	0.21	2.00	2.26	0.54	1.50	16.74	83.26
13	7.25	0.30	4.01	0.09	0.35	2.63	3.07	0.53	1.50	16.66	83.34
14	7.85	0.27	4.00	0.11	0.81	0.95	1.87	0.55	1.50	16.03	83.97
15	8.11	0.23	4.03	0.09	0.34	0.61	1.04	0.54	1.50	15.45	84.55
16	7.78	0.22	3.95	0.11	0.30	0.85	1.26	0.73	1.50	15.44	84.56
17	7.63	0.22	3.97	0.02	0.47	0.81	1.30	0.54	1.50	15.16	84.84
18	7.76	0.20	3.98	0.27	0.41	1.28	1.96	0.60	1.50	16.00	84.00
23	8.58	0.28	3.97	0.05	0.29	3.51	3.85	0.77	1.50	18.95	81.05

* Average used where data was missing

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TABLE 5-21

PERCENT COMBUSTIBLES IN REFUSE
TEST SITE D

	Test No.	Boiler Hopper	Boiler Outlet	Mechanical Collector Hopper	Mechanical Collector Outlet	Bottom Ash
PERFECT 8 COAL	2	--	--	16.9	--	14.9
	3	--	35.2	11.9	--	33.1
	4	12.3	23.7	11.1	--	19.4
	5	17.5	28.8	--	28.4	15.1
	6	8.9	21.9	13.6	--	17.5
	7	11.8	16.0	10.7	--	19.6
	8	11.1	20.8	8.9	--	20.7
	9	0.0	14.4	17.5	--	11.8
	10	3.8	--	6.1	--	8.4
	11	--	--	--	--	--
	12	3.9	22.1	8.9	--	18.7
	13	6.6	28.2	8.9	--	22.6
	Average	8.4	23.5	11.5	28.4	18.3
CENTURY COAL	14	16.6	40.1	11.4	--	15.3
	15	18.7	23.6	16.3	--	14.5
	16	17.9	25.9	9.7	--	15.0
	17	3.3	30.8	--	27.8	15.9
	18	40.9	28.1	14.9	27.7	21.3
	Average	19.5	29.7	13.1	27.8	16.4
VICTORIA COAL	22	20.9	--	10.8	--	33.7
	23	4.8	26.5	--	--	35.9
	Average	12.9	26.5	10.8	--	34.8

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TABLE 5-22

AS FIRED COAL SIZE CONSISTENCY
TEST SITE D

	Test Number	PERCENT PASSING SCREEN SIZE 1"	1/2"	1/4"	#8	#16
PERFECT 8 COAL	2	99.5	59.5	15.2	6.4	4.0
	3	98.4	65.8	20.1	7.6	4.3
	4	99.0	45.4	9.0	4.1	3.2
	5	99.8	36.3	5.5	2.8	2.3
	6	99.8	46.0	8.6	3.5	2.7
	7	99.2	38.9	4.7	2.4	2.0
	8	99.8	49.0	7.5	3.5	2.6
	9	98.3	38.6	7.0	3.9	3.0
	10	99.0	43.1	6.4	3.4	2.7
	12	99.8	54.2	9.0	3.5	2.4
	13	99.8	57.5	9.4	3.8	2.6
	Composite*	99.3	47.0	8.5	4.3	3.2
	Average	99.3	48.6	9.3	4.1	2.9
CENTURY COAL	14	98.5	50.2	13.3	6.3	4.5
	15	94.6	48.2	13.7	5.7	4.1
	16	96.1	41.2	14.3	5.2	2.9
	17	96.0	49.7	16.4	7.0	5.1
	18	95.0	52.3	18.1	7.6	5.4
	Composite*	94.9	44.2	12.2	4.8	3.3
	Average	96.0	49.7	15.2	6.4	4.4
VICTORIA COAL	22	88.2	39.5	15.9	7.7	4.1
	23	89.4	39.6	15.6	8.1	5.7
	Average	88.8	39.6	15.8	7.9	4.9

* The composite sample includes a coal sample from each test on a given coal. It is not included in the coal's average size consistency.

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TABLE 5-23

STEAM FLOWS AND HEAT RELEASE RATES
TEST SITE D

Test No.	% Design Capacity*	Steam Flow 10^3lb/hr*	Heat Input 10^6Btu/hr	Front Foot Heat Release 10^6Btu/hr-ft	Grate Heat Release 10^3Btu/hr-ft^2	Furnace Heat Release 10^3Btu/hr-ft^3
2	72.9	65.6	69.2	4.58	280	20.2
3	69.3	62.4	67.5	4.35	266	19.2
4	63.8	57.4	52.6	3.40	208	14.9
5	85.5	77.0	86.4	5.58	341	24.5
6	65.2	58.6	63.2	4.08	250	18.0
7	63.3	57.0	63.1	4.07	249	17.9
8	65.6	59.0	56.0	3.62	221	15.9
9	44.5	40.1	35.0	2.30	141	10.1
10	63.2	56.9	62.5	4.03	247	17.8
11	52.1	46.9	49.8	3.25	199	14.3
12	87.4	78.6	82.5	5.32	326	23.4
13	89.3	80.3	87.2	5.62	344	24.8
14	86.8	78.0	85.1	5.41	331	23.8
15	88.1	79.3	90.8	5.86	359	25.8
16	64.1	57.7	66.8	4.31	264	19.0
17	87.5	78.7	89.8	5.80	355	25.5
18	79.0	71.1	80.6	5.20	318	22.9
22	59.1	53.2	60.8	3.92	240	17.3
23	61.0	54.9	59.3	3.83	234	16.9

* Maximum obtainable load averaged 79,000 lb stm/hr or 88% of design capacity. Load restriction was due to draft loss from retrofit dust collector.

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APPENDICES

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APPENDIX A

CONVERSION FACTORS

ENGLISH AND METRIC UNITS TO SI UNITS

To Convert From	To	Multiply By
in	cm	2.540
in^2	cm^2	6.452
ft	m	0.3048
ft^2	m^2	0.09290
ft^3	m^3	0.02832
lb	Kg	0.4536
lb/hr	Mg/s	0.1260
$lb/10^6BTU$	ng/J	430
g/Mcal	ng/J	239
BTU	J	1054
BTU/lb	J/kg	2324
BTU/hr	W	0.2929
J/sec	W	1.000
J/hr	W	3600
BTU/ft/hr	W/m	0.9609
BTU/ft/hr	J/hr/m	3459
$BTU/ft^2/hr$	W/m^2	3.152
$BTU/ft^2/hr$	$J/hr/m^2$	11349
$BTU/ft^3/hr$	W/m^3	10.34
$BTU/ft^3/hr$	$J/hr/m^3$	37234
psia	Pa	6895
$"H_2O$	Pa	249.1
Rankine	Celsius	C = 5/9R-273
Fahrenheit	Celsius	C = 5/9(F-32)
Celsius	Kelvin	K = C+273
Rankine	Kelvin	K = 5/9R

FOR TYPICAL COAL FUEL

ppm @ 3% O_2 (SO_2)	ng/J	($lb/10^6Btu$)	0.851 ($1.98x10^{-3}$)
ppm @ 3% O_2 (SO_3)	ng/J	($lb/10^6Btu$)	1.063 ($2.47x10^{-3}$)
ppm @ 3% O_2 (NO)*	ng/J	($lb/10^6Btu$)	0.399 ($9.28x10^{-4}$)
ppm @ 3% O_2 (NO_2)	ng/J	($lb/10^6Btu$)	0.611 ($1.42x10^{-3}$)
ppm @ 3% O_2 (CO)	ng/J	($lb/10^6Btu$)	0.372 ($8.65x10^{-4}$)
ppm @ 3% O_2 (CH_4)	ng/J	($lb/10^6Btu$)	0.213 ($4.95x10^{-4}$)

*Federal environmental regulations express NOx in terms of NO_2; thus NO units should be converted using the NO_2 conversion factor.

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APPENDIX B

CONVERSION FACTORS

SI UNITS TO ENGLISH AND METRIC UNITS

To Convert From	To	Multiply By
cm	in	0.3937
cm^2	in^2	0.1550
m	ft	3.281
m^2	ft^2	10.764
m^3	ft^3	35.315
Kg	lb	2.205
Mg/s	lb/hr	7.937
ng/J	$lb/10^6BTU$	0.00233
ng/J	g/Mcal	0.00418
J	BTU	0.000948
J/kg	BTU/lb	0.000430
J/hr/m	BTU/ft/hr	0.000289
$J/hr/m^2$	$BTU/ft^2/hr$	0.0000881
$J/hr/m^3$	$BTU/ft^3/hr$	0.0000269
W	BTU/hr	3.414
W	J/hr	0.000278
W/m	BTU/ft/hr	1.041
W/m^2	$BTU/ft^2/hr$	0.317
W/m^3	$BTU/ft^3/hr$	0.0967
Pa	psia	0.000145
Pa	$"H_2O$	0.004014
Kelvin	Fahrenheit	F = 1.8K-460
Celsius	Fahrenheit	F = 1.8C+32
Fahrenheit	Rankine	R = F+460
Kelvin	Rankine	R = 1.8K

FOR TYPICAL COAL FUEL

ng/J	ppm @ 3% O_2 (SO_2)	1.18
ng/J	ppm @ 3% O_2 (SO_3)	0.941
ng/J	ppm @ 3% O_2 (NO)	2.51
ng/J	ppm @ 3% O_2 (NO_2)	1.64
ng/J	ppm @ 3% O_2 (CO)	2.69
ng/J	ppm @ 3% O_2 (CH_4)	4.69

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APPENDIX C

SI PREFIXES

Multiplication Factor	Prefix	SI Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto*	h
10^{1}	deka*	da
10^{-1}	deci*	d
10^{-2}	centi*	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

*Not recommended but occasionally used

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EMISSION UNITS CONVERSION FACTORS
FOR TYPICAL COAL FUEL (HV = 13,320 BTU/LB)

To Obtain \ Multiply By		% Weight in Fuel		lbs/10^6Btu		grams/10^6Cal		PPM (Dry @ 3% O_2)		Grains/SCF. (Dry @ 12% CO_2)	
		S	N	SO_2	NO_2	SO_2	NO_2	SOx	NOx	SO_2	NO_2
% Weight In Fuel	S	1		0.666		0.370		13.2×10^{-4}		1.48	
	N				0.405		0.225		5.76×10^{-4}		.903
lbs/10^6Btu	SO_2	1.50		1		(.556)		19.8×10^{-4}		(2.23)	
	NO_2		2.47				(.556)		14.2×10^{-4}		(2.23)
grams/10^6Cal	SO_2	2.70		(1.8)		1		35.6×10^{-4}		(4.01)	
	NO_2		4.44		(1.8)				25.6×10^{-4}		(4.01)
PPM (Dry @ 3% O_2)	SOx	758		505		281		1		1127	
	NOx		1736		704		391				1566
Grains/SCF (Dry @ 12% CO_2)	SO_2	.676		(.448)		(.249)		8.87×10^{-4}		1	
	NO_2		1.11		(.448)		(.249)		6.39×10^{-4}		

NOTE: 1. Values in parenthesis can be used for all flue gas constituents such as oxides of carbon, oxides of nitrogen, oxides of sulfur, hydrocarbons, particulates, etc.
2. Standard reference temperature of 530°R was used.

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APPENDIX E

EPA METHOD 7 VS. THERMO ELECTRON INSTRUMENT

A special set of tests were run to determine the accuracy of our nitric oxide instrument. Eight NOx sample flasks were prepared and sent out by Truesdail Laboratories of Los Angeles, California. They were filled with flue gas by KVB and returned for analyses by the phenol disulfide (PDS) method, EPA method 7. At the same time the samples were taken, the nitric oxide concentration was measured with the Thermo Electron instrument.

The results are shown in the table below. The averages obtained by the instrument were from -2% to +2% off from the averages obtained by the PDS method. The PDS flasks were not completely filled and a high residual vacuum remained which made the oxygen analyses suspect. The difficult oxygen analyses may have caused two flasks to have poor results when the NO concentration was corrected to 3% O_2.

		Analyses by Truesdail		Analyses by KVB Instrument		
Test No.	Flask No.	NOx ppm (dry)	NOx, ppm dry at 3% O_2	NO ppm (dry)	NO, ppm dry at 3% O_2	Delta ppm
19	1344	177*	327*	153	228	
	1187	147	227	155	233	
	977	149	247	155	233	
	Average	148	237	154	231	-6
20	1349	136	254	147.5	254	
	972	140*	216*	147.5	254	
	1435	143	241	145	252	
	Average	140	248	147	253	+5
21	1457	159	306	155	289	
	1465	147	278	156	300	
	Average	153	292	155	295	+3

* Not included in average

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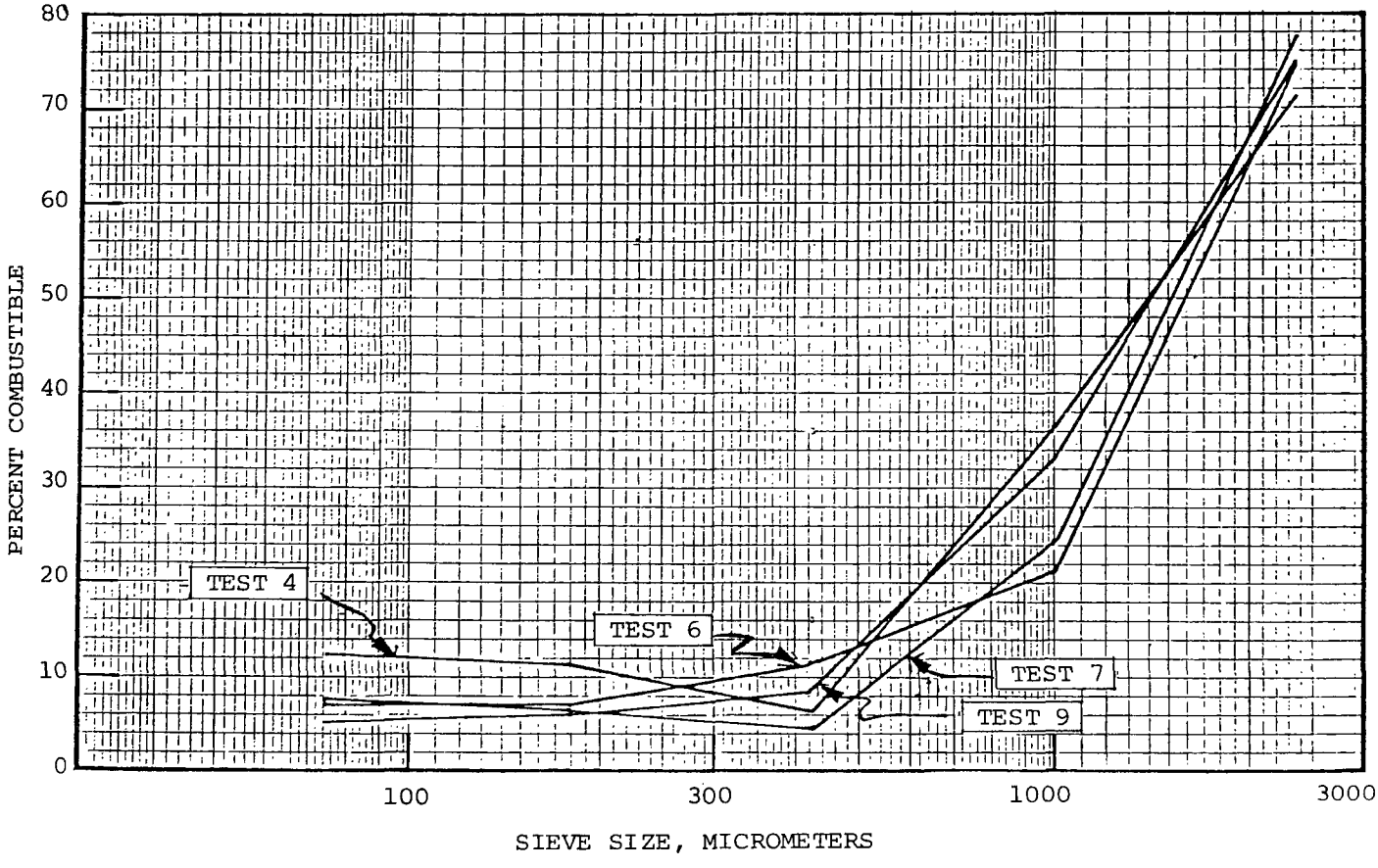
APPENDIX F

FLYASH COMBUSTIBLE CONTENT VS PARTICLE SIZE

Four boiler hopper ash samples from Site D were selected at random, screened into five size classifications, and baked for combustible determination. The results are presented below.

Size	% Mass by Size				% Combustibles by Size			
	Test 4	Test 6	Test 7	Test 9	Test 4	Test 6	Test 7	Test 9
0-75 µm	9.6	11.4	11.3	16.9	12.2	6.9	7.0	5.4
75-180 µm	21.5	22.6	21.3	30.8	11.5	6.7	6.6	6.3
180-425 µm	43.5	43.6	47.5	41.5	6.2	13.8	4.7	8.5
425-1000 µm	20.8	18.3	17.4	9.3	36.7	21.6	24.5	33.1
+1000 µm	4.5	4.1	2.5	1.5	71.2	74.4	77.3	74.5



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APPENDIX G

UNITS CONVERSION FROM PARTS PER MILLION (PPM) TO POUNDS PER MILLION BTU INPUT ($LB/10^6BTU$)

$$lb/10^6Btu = (ppm)(\text{fuel factor}, \frac{SCF}{10^6Btu})(O_2 \text{ correction, n.d.})(\text{density of emission}, \frac{lb}{SCF})(10^{-6})$$

$$\text{Fuel factor}, \frac{SCF^*}{10^6Btu} = 10^6[1.53C + 3.61H_2 + .14N_2 + .57S - .46O_2] \div (Btu/lb)$$

where C, H_2, N_2, S, O_2 & Btu/lb are from ultimate fuel analysis;

(a typical fuel factor for coal is 9820 $SCF/10^6Btu \pm 1000$)

O_2 correction, n.d. = $20.9 \div (20.9 - \%O_2)$

where $\%O_2$ is oxygen level on which ppm value is based;

for ppm @ 3% O_2, O_2 correction = $20.9 \div 17.9 = 1.168$

Density of emission =
- SO_2 - 0.1696 lb/SCF*
- NO - 0.0778 lb/SCF
- CO - 0.0724 lb/SCF
- CH_4 - 0.0415 lb/SCF

to convert $lbs/10^6Btu$ to ng/J multiply by 430

* Standard conditions are 70°F, 29.92 "Hg barometric pressure

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TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-79-237a	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Field Tests of Industrial Stoker Coal-fired Boilers for Emissions Control and Efficiency Improvement--Site D		5. REPORT DATE November 1979
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) J.E. Gabrielson, P.L. Langsjoen, and T.C. Kosvic		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS KVB, Inc. 6176 Olson Memorial Highway Minneapolis, Minnesota 55422		10. PROGRAM ELEMENT NO. EHE624
		11. CONTRACT/GRANT NO. IAG-D7-E681 (EPA) and EF-77-C-01-2609 (DOE)
12. SPONSORING AGENCY NAME AND ADDRESS **EPA, Office of Research and Development * Industrial Environmental Research Laboratory Research Triangle Park, NC 27711**		13. TYPE OF REPORT AND PERIOD COVERED Final; 7/78 - 9/78
		14. SPONSORING AGENCY CODE **EPA/600/13**

15. SUPPLEMENTARY NOTES IERL-RTP project officer is R.E. Hall. (*) Cosponsors are DoE (W.T. Harvey, Jr.) and the American Boiler Manufacturers Association. EPA-600/7-78-136a, -79-041a, and -79-130a are similar Site A, B, and C reports.

16. ABSTRACT The report gives results of field measurements made on a 90,000 lb/hr vibrating-grate-stoker boiler. The effect of various parameters on boiler emissions and efficiency was studied. Parameters included overfire air, excess air, boiler load, and fuel properties. Measurements included gaseous emissions, particulate emissions, particle size distribution of the flyash, and combustible content of the ash. Gaseous emissions measured were O_2, CO_2, CO, NO, SO_2, and SO_3 in the flue gas. Sample locations included the boiler outlet and the multiclone dust collecter outlet. In addition to test results and observations, the report describes the facility tested, coals fired, test equipment, and procedures. Increasing the overfire air flow above the minimum required to control opacity resulted in a slight increase in nitric oxide emissions, a slight increase in boiler efficiency, and mixed results with particulate loading. At maximum boiler load, the boiler outlet emissions averaged 1.02 lb/million Btu for particulate loading and 0.275 lb/million Btu for nitric oxide.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Air Pollution	Improvement	Air Pollution Control	13B	
Boilers	Efficiency	Stationary Sources	13A	
Combustion	Flue Gases	Combustion Modification	21B	
Coal	Fly Ash	Spreader Stokers	21D	
Field Tests	Particle Size	Particulate	14B	
Dust	Nitrogen Oxides	Overfire Air	11G	07B
Stokers	Sulfur Oxides	Flyash Reinjection		

18. DISTRIBUTION STATEMENT **Release to Public**	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 115
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)