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

by

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R. D. Bessette	Island Creek Coal Company
T. Davis	Combustion Engineering
N. H. Johnson	Detroit Stoker
K. Luuri	Riley Stoker
D. McCoy	E. Keeler Company
J. Mullan	National Coal Association
E. A. Nelson	Zurn Industries
E. Poitras	The McBurney Corporation
P. E. Ralston	Babcock and Wilcox
D. C. Reschley	Detroit Stoker
R. A. Santos	Zurn Industries

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Finally, our gratitude goes to the host boiler facilities which invited us to test their boilers. At their request, all participating 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 sixth 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. A report containing operating guidelines for boiler operators will also be written, along with a separate report covering trace species data. These reports will be available to interested parties through the EPA Technical Information Section and NTIS.

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 sixth site tested, this is the final technical report for Test Site F under the program entitled, "A Testing Program to Update Equipment Specifications and Design Criteria for Stoker Fired Boilers."

2.0 EXECUTIVE SUMMARY

A coal fired spreader stoker rated at 80,000 lbs steam/hr was extensively tested for emissions and efficiency between December 18, 1978, and February 14, 1979. This section summarizes the results of these tests 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 9-13.

- Keeler Boiler

  Built 1977
  Type MKB
  80,000 lbs/hr rated capacity
  150 psig operating steam pressure
  Saturated steam
  Economizer

- Detroit Rotograte Stoker

  Spreader type
  Traveling grate with front ash discharge
  Flyash reinjection from economizer and boiler hopper
  Two rows OFA on front and two rows on back water walls

COALS TESTED: Individual coal analysis results given in Tables 5-17, 5-18 and 5-19, pages 78-80. Commentary in Section 3.0, page 13.

- Pennsylvania A Coal

  13,242 Btu/lb
  10.55% Ash
  1.47% Sulfur
  4.06% Moisture
  2560°F Initial ash deformation temperature

- Pennsylvania B Coal

  13,596 Btu/lb
  8.96% Ash
  1.00% Sulfur
  3.69% Moisture
  2700+°F Initial ash deformation temperature

OVERFIRE AIR TEST RESULTS: Overfire air pressure was varied over its operating range when the boiler was operated at design capacity (Section 5.1, pages 35-39, Table 5-1, page 36.)

The baseline OFA configuration put most of the OFA through the front jet. The maximum OFA configuration shifted some of the OFA from the front to the rear jets. This change had little effect on emissions. An overall reduction in OFA pressure resulted in degradation of emissions.

- Particulate Loading

  Particulate loading increased 50% at the economizer outlet and 38% at the multiclone outlet when overfire air pressure was reduced. The percentage of combustible material in the flyash remained constant as overfire air conditions were varied. (Section 5.1.1, page 37; Table 5-2, page 37.)

- Nitric Oxide

  Nitric oxide concentration was observed to increase by 12% when overfire air pressure was reduced. (Section 5.1.2, page 37; Table 5-3, page 38.)

- Carbon Monoxide and Unburned Hydrocarbons

  Carbon monoxide was highest under low overfire air conditions but remained below 700 ppm in all tests. Unburned hydrocarbons gave mixed results in two overfire air test series. (Section 5.1.3, page 38; Table 5-4, page 38.)

- Boiler Efficiency

  Boiler efficiency decreased four percent under low overfire air conditions. Three percent of this loss resulted from increased combustible losses in the flyash. The remaining one percent loss is thought to be unrelated to the change in overfire air conditions. (Section 5.1.4, page 39; Table 5-5, page 39.)

FLYASH REINJECTION: Boiler F pneumatically reinjects flyash from the economizer hopper. During one test this reinjection was stopped. (Section 5.2, page 40.)

- Economizer Collection Rate

  The economizer was found to collect ten percent of the particulate mass entering it under high load, no reinjection conditions. (Section 5.2.1, page 40, Table 5-6, page 40.)

- Particulate Loading

  Reduced reinjection resulted in a 5 to 27% drop in particulate loading at the economizer outlet depending on which baseline test it is compared to. (Section 5.2.2, page 41, Table 5-7, page 41.)

- Boiler Efficiency

  The flyash collected by the economizer hopper represents a potential efficiency gain of 0.6% if fully recovered through reinjection to the furnace. (Section 5.2.3, page 42.)

BOILER EMISSION PROFILES: Boiler emissions and efficiency were measured over the load range 52-102% of design capacity which corresponds to a grate heat release range of 338,000 to 693,000 Btu/hr-ft^2. Measured oxygen levels ranged from 4.6 to 12.7%. (Section 5.3, page 42.)

- Excess Oxygen Operating Levels

  At full capacity, the boiler was able to meet the manufacturers design performance of 30% excess air (5% oxygen). More excess air was required at lower loads. (Section 5.3.1, page 42; Figure 5-1, page 43.)

- Particulate Loading

  At full load and normal operating conditions, the particulate loading averaged 6.00 ± 0.75 lbs/10^6Btu at the economizer outlet and 1.05 ± 0.20 lbs/10^6 Btu at the multiclone outlet. At 75% of capacity, the economizer outlet particulate loadings were 20% lower than at full load. On the average, 24% of the coals' ash was carried over as flyash. (Section 5.3.2, page 44; Table 5-8, page 44, Figures 5-2 and 5-3, pages 45 and 47.)

- Stack Opacity

  Stack opacity remained low at all loads tested. (Section 5.3.3, page 46; Figure 5-4, page 48.)

- Nitrogen Oxides

  Nitric oxide (NO) increased by 0.051 lbs/10^6 Btu for each one percent increase in oxygen at constant load. NO also increased with increasing load at constant O_2. However, because excess oxygen decreased with increasing load under normal firing conditions, nitric oxide averages about 0.45 lbs/10^6 Btu (330 ppm) at all loads.

Nitrogen Dioxide (NO_2) averaged 0.005 lbs/10^6 Btu (4 ppm) at all loads and showed a tendency to increase with increasing O_2 at the lower loads. (Section 5.3.4, page 46; Table 5-9, page 49; Figures 5-5 through 5-12, pages 50-57.)

- Sulfur Oxides

  Four percent of the fuel sulfur was retained in the ash while the remaining 96% was converted to SO_2 and SO_3. (Section 5.3.5, page 58; Figures 5-13 and 5-14, pages 59 - 60, Table 5-10, page 61.)

- Hydrocarbons

  Unburned hydrocarbons averaged 7.6 ppm at full load, 14.8 ppm at 75% load and 0.0 ppm at 50% load. (Section 5.3.6, page 61; Table 5-11, page 61; Figures 5-15 and 5-16, pages 62-63.)

- Carbon Monoxide

  Carbon monoxide remained below 400 ppm except under high load low O_2 conditions and low load high O_2 conditions. (Section 5.3.7, page 64; Figures 5-17 and 5-18, pages 65-66.)

- Combustibles in the Ash

  Combustibles averaged 67% in the economizer outlet flyash, 47% in the multiclone outlet flyash, and 12% in the bottom ash. In general, they did not vary with load or O_2. (Section 5.3.8, page 64; Figures 5-19 thru 5-24, pages 67-72.)

BOILER EFFICIENCY: Boiler efficiency averaged 78.1% at full load, 80.3% at 75% load, and 81.5% at 50% load. The manufacturers predicted efficiency was 83.1% and reflects a much lower combustible heat loss. (Section 5.3.9, page 64, Tables 5-12, 5-13 and 5-14, pages 74-75; Figure 5-25, page 73.)

COAL PROPERTIES: Penn B coal was lower in ash (8.96 vs 10.55%) and lower in sulfur (1.00% vs 1.47%) than the Penn A coal. However, with the exception of sulfur oxide emissions, the change in coals had no impact on boiler emissions or efficiency. (Section 5.4, page 77; Tables 5-16 thru 5-26, pages 77-88.)

PARTICLE SIZE DISTRIBUTION OF FLYASH: Eleven particle size distribution measurements were made at the economizer outlet. Results vary with measurement technique. (Section 5.5, page 88; Tables 5-27 and 5-28, pages 89 & 90; Figures 5-28, 5-29 and 5-30, pages 91-93.)

EFFICIENCY OF MULTICLONE DUST COLLECTOR: Multiclone collection efficiency averaged 82% at full load compared to the manufacturers design efficiency of 85%. At 75% load the efficiency dropped to 78%. (Section 5.6, page 94; Figure 5-31, page 96; Table 5-20, page 82.)

SOURCE ASSESSMENT SAMPLING SYSTEM: Flue gas was sampled for polynuclear aromatic hydrocarbons and trace elements during one full load test on each of the two coals. Data will be presented in a separate report at completion of test program. (Section 5.7, page 94; Table 5-30, 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 F 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 F

Test No.	Date	Load %	Coal	Test Description	Excess Air %	O_2 % dry	CO_2 % dry	CO ppm dry	NO ppm dry	NO lb/10^6 Btu	NO_2 lb/10^6 Btu	SO_2 lb/10^6 Btu	HC ppm wet	Part Econ Out lb/10^6Btu	Part D.C. Out lb/10^6Btu	Opacity %	Special Tests
1	12/18/78	75	A	Med Load - Baseline	69	8.9	10.0	146	343	0.467	0.001	1.828	0	--	--	8.0	
2	12/18/78	75	A	- High O_2	78	9.5	9.6	173	395	0.538	0.007	1.600	14	--	--	8.0	
3	12/18/79	75	A	- High O_2	97	10.7	8.2	233	426	0.580	0.010	1.429	18	--	--	8.0	
4	12/18/79	75	A	- Low O_2	56	7.8	11.6	137	322	0.439	0.004	1.815	28	--	--	8.0	
5	12/19/78	54	A	Low Load - Baseline	77	9.4	10.0	175	297	0.405	0.004	1.758	0	5.076	--	8.0	
6	12/20/78	53	A	Low Load - Baseline	69	8.8	10.6	112	294	0.401	0.004	2.057	0	--	--	2.2	
7	12/20/78	53	A	- Med High O_2	112	11.3	9.0	252	369	0.503	0.015	2.229	0	--	--	2.3	
8	12/20/78	53	A	- Low O_2	50	7.2	12.5	77	237	0.323	0.008	2.151	0	--	--	2.2	
9	12/20/78	53	A	- High O_2	144	12.7	7.3	420	442	0.602	0.011	2.188	0	--	--	2.2	
10	1/04/79	98	A	High Load - Baseline	61	8.2	11.1	252	348	0.474	0.000	2.022	0	--	--	2.5	
11	1/05/79	99	A	High Load - Baseline	59	8.1	10.8	231	413	0.563	0.010	2.254	0	--	--	2.5	
12	1/05/79	99	A	- High O_2	65	8.5	11.0	222	397	0.541	0.004	2.147	0	--	--	2.5	
13	1/05/79	99	A	- Low O_2	32	5.4	12.8	612	269	0.366	0.003	2.146	12	--	--	2.5	
14	1/05/79	99	A	- Med O_2	42	6.4	12.8	251	309	0.421	0.000	2.254	12	--	--	2.5	
15	1/08/79	99	A	High Load - High O_2	56	7.8	11.1	250	384	0.523	0.001	1.871	1	5.926	1.329	2.9	
16A	1/09/79	100	A	High Load - Baseline OFA	54	7.6	12.0	228	OOS	OOS	OOS	1.807	13	--	--	2.5	
16B	1/09/79	100	A	- Max OFA	50	7.2	12.8	163	OOS	OOS	OOS	1.919	13	--	--	2.5	
16C	1/09/79	100	A	- Low OFA	63	8.3	11.8	378	OOS	OOS	OOS	1.919	0	--	--	4.8	
17	1/10/79	99	A	High Load - Low O_2	45	6.7	12.5	382	OOS	OOS	OOS	1.846	9	5.510	1.130	3.9	
18	1/15/79	99	A	High Load - High OFA	34	5.5	13.4	429	263	0.358	0.007	2.150	5	6.136	0.771	OOS	
19	1/16/79	99	A	High Load - Low OFA	37	5.9	12.6	607	309	0.421	0.007	2.297	16	8.785	1.256	4.2	
20	1/17/79	75	A	Med Load - Baseline	63	8.4	10.7	100	342	0.466	0.004	2.107	15	4.008	--	3.2	
21	1/24/79	76	A	Med Load - Baseline	58	8.0	11.0	107	314	0.428	0.003	2.425	27	5.567	1.262	OOS	
22	1/31/79	99	A	High Load - Optimum O_2 OFA	38	6.0	13.2	352	281	0.384	0.001	2.188	16	--	--	OOS	SASS, SO_3
23	2/01/79	100	A	High Load - Optimum O_2 OFA	41	6.3	13.2	221	298	0.406	0.003	2.049	12	5.240	0.998	OOS	Brink (no reinj)
24	2/06/79	102	A	High Load - Optimum O_2 OFA	30	5.0	14.5	549	289	0.392	0.000	2.182	OOS	7.183	1.031	OOS	Brink
23A	2/08/79	99	A	High Load - Optimum O_2 OFA	37	5.9	12.5	186	282	0.384	0.004	2.686	OOS	--	--	OOS	Brink (no reinj)
25	2/12/79	99	B	High Load - High O_2	61	8.3	10.3	172	395	0.538	0.035	1.369	OOS	--	--	OOS	
26	2/12/79	99	B	- Baseline	47	7.0	11.6	253	323	0.440	0.004	1.328	OOS	--	--	OOS	
27	2/12/79	99	B	- Med Low O_2	41	6.4	11.8	198	297	0.405	0.003	1.369	OOS	--	--	OOS	
28	2/12/79	99	B	- Low O_2	26	4.6	12.8	437	264	0.360	0.011	1.330	OOS	--	--	OOS	
29	2/12/79	101	B	High Load - Optimum O_2 OFA	29	5.0	13.3	361	266	0.362	0.001	1.342	OOS	5.944	1.392	OOS	Brink
30	2/13/79	97	B	High Load - Optimum O_2 OFA	45	6.8	11.7	284	299	0.391	0.000	1.342	5	--	--	OOS	SASS, SO_3
31	2/14/79	75	B	Med Load - Baseline	84	9.9	9.2	139	328	0.447	0.007	1.179	14	--	--	OOS	
32	2/14/79	75	B	- High O_2	115	11.5	8.4	207	452	0.616	0.005	1.475	8	--	--	OOS	
33	2/14/79	75	B	- Med Low O_2	61	8.2	11.4	78	290	0.395	0.000	1.232	14	--	--	OOS	
34	2/14/79	75	B	- Low O_2	40	6.2	12.4	96	228	0.311	0.001	1.236	10	--	--	OOS	
35	2/14/79	76	B	Med Load - Baseline	67	8.7	10.7	107	380	0.517	--	--	--	4.726	1.026	OOS	

A - Penn A Coal
B - Penn B Coal

OOS - Analyzer out of service
ppm - parts per million by volume corrected to 3% O_2
Load - % of units design capacity

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 F. The coals used in this test series are also discussed.

3.1 BOILER F DESCRIPTION

Boiler F was built by E. Keeler Company in 1977 and equipped with a spreader stoker from Detroit Stoker Company. The boiler is rated at 80,000 lbs/hour continuous operation at 150 psig saturated steam. It has a multiple pass boiler section, tubular economizer and mechanical dust collector. A boiler schematic is presented in Figure 3-1.

The Detroit Rotograte stoker has three coal feeders and continuous front end ash discharge. The effective area of the grate is 141.4 ft^2. Design data on the boiler and stoker are presented in Table 3-1. Predicted performance data and the results of a 1977 acceptance test are presented in Table 3-2.

3.2 OVERFIRE AIR SYSTEM

The boiler is equipped with both front and rear overfire air. There are upper and lower jets on both water walls.

3.3 FLYASH REINJECTION

Flyash is pneumatically reinjected from both the boiler dust hopper and the economizer dust hopper, but not from the mechanical dust collector. During two tests at this site, flyash reinjection from the economizer dust hopper was interrupted in an attempt to determine boiler efficiency gains due to reinjection from economizer hopper.

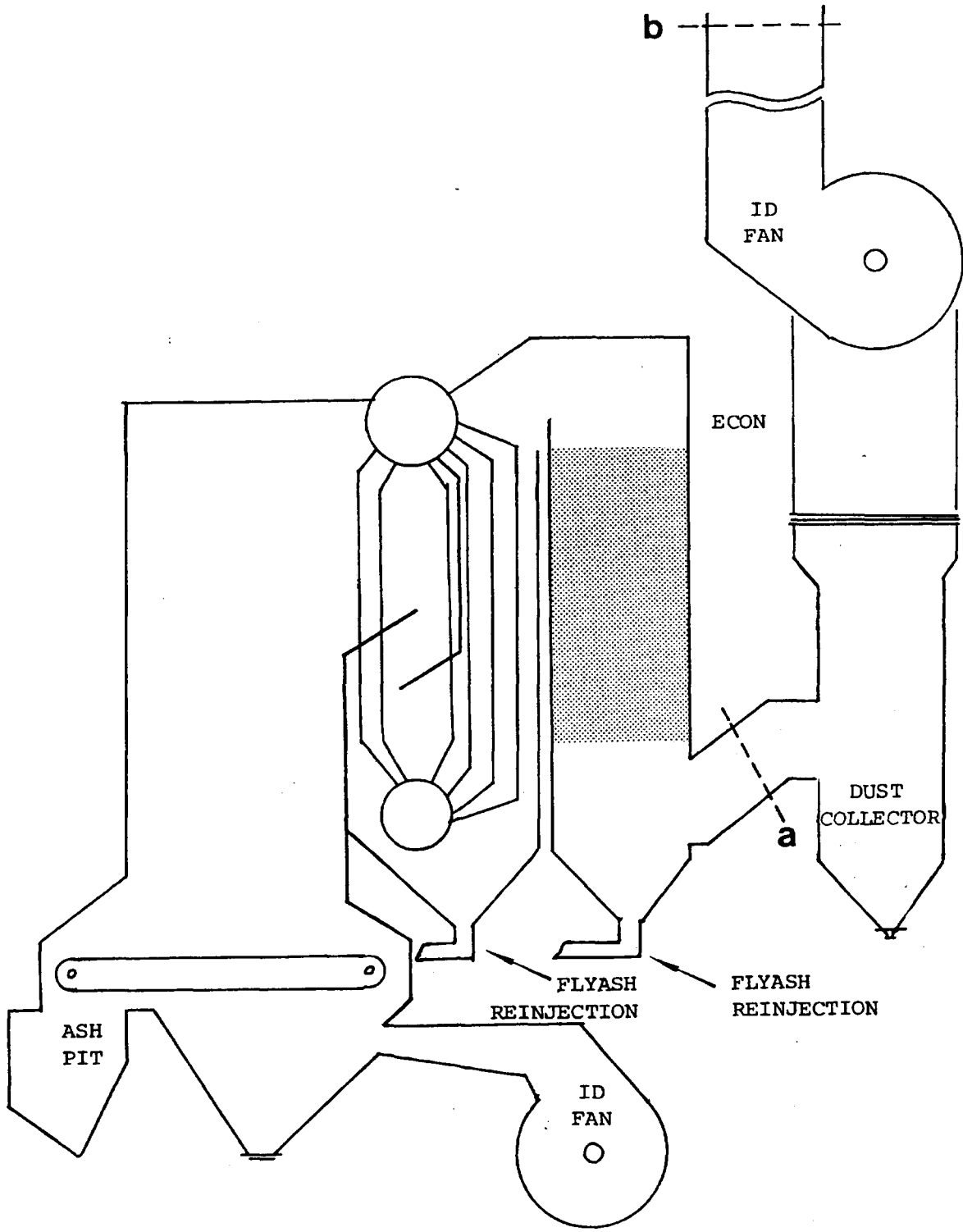


FIGURE 3-1. Schematic of Boiler F

a - Economizer Outlet Sampling Plant
b - Dust Collector Sampling Plane

TABLE 3-1

DESIGN DATA
TEST SITE F

BOILER:	Manufacturer	E. Keeler Company
	Type	MKB Type
	Boiler Heating Surface	8,980 ft^2
	Design Pressure	200 psig
	Tube Diameter	2-1/2 "
ECONOMIZER:	Type	Tubular
	Heating Surface	3,017 ft^2
	Design Pressure	250 psig
	Tube Diameter	--
FURNACE:	Volume	4,150 ft^3
STOKER:	Manufacturer	Detroit Stoker
	Type	Rotograte
	Width	10'10.5"
	Length	14' 8"
	Effective Grate Area	141.4 ft^2
HEAT RATES:	Steam Flow	80,000 lbs/hr
	Input to Furnace	97.5×10^6 Btu/hr
	Furnace Width Heat Release	8.96×10^6 Btu/ft-hr
	Grate Heat Release	688×10^3 Btu/ft^2-hr
	Furnace Liberation	23.5×10^3 Btu/ft^3-hr

TABLE 3-2

PREDICTED AND ACTUAL PERFORMANCE DATA

	Guarantee Maximum Continuous	1977 Acceptance Test
Steam Flow, lbs/hr	80,000	81,803
Heat Output, 10^6Btu/hr	80.73	82.37
Fuel Burned, lbs/hr	7,205	--
Steam Pressure, psig	150	143.8
Steam Temperature, °F	Saturated	Saturated
F.W. to Economizer, °F	228	220
F.W. to Boiler, °F	289	318
Ambient Air Temperature, °F	80	--
Gas Temp. Leaving Furn., °F	1,900	--
Gas Temp. Leaving Boiler, °F	560	542
Gas Temp. Leaving Econ., °F	350	377
Excess Air at Boiler Exit, %	30	--
Excess Air at Econ. Exit, %	30	37
Air Entering Unit, lbs/hr	97,270	--
Wet Gas at Furnace Exit, lbs/hr	95,480	--
Wet Gas at Econ. Exit, lbs/hr	99,200	110,887
Furnace Draft Loss, "H_2O	0.15	--
Boiler Draft Loss, "H_2O	1.00	--
Economizer Draft Loss, "H_2O	3.30	--
Dust Collector Draft Loss, "H_2O	2.50	--
Flues, Dampers Draft Loss, "H_2O	0.65	--
Stack Draft Loss, "H_2O	--	--
Total Loss, "H_2O	7.60	--
Liberation, Furnace Vol., Btu/hr-ft^3	23,450	24,199
Meter Pressure Drop Through Economizer, psi	7.5	--
Dry Gas Losses, %	6.33	7.60
H_2 in Fuel Losses, %	3.63	4.10
Moisture in Fuel and Air Losses, %	0.16	0.34
Unburned Combustibles, %	4.70	4.10
Radiation, %	0.58	0.58
Unaccounted, %	1.50	1.50
Total Losses, %	16.90	18.35
Efficiency, %	83.10	81.65

3.4 TEST PORT LOCATIONS

Emission measurements were made at two locations -- at the economizer outlet and at the dust collector outlet. The locations of these sample sites are shown in Figure 3-1. Their geometry is shown in Figure 3-2.

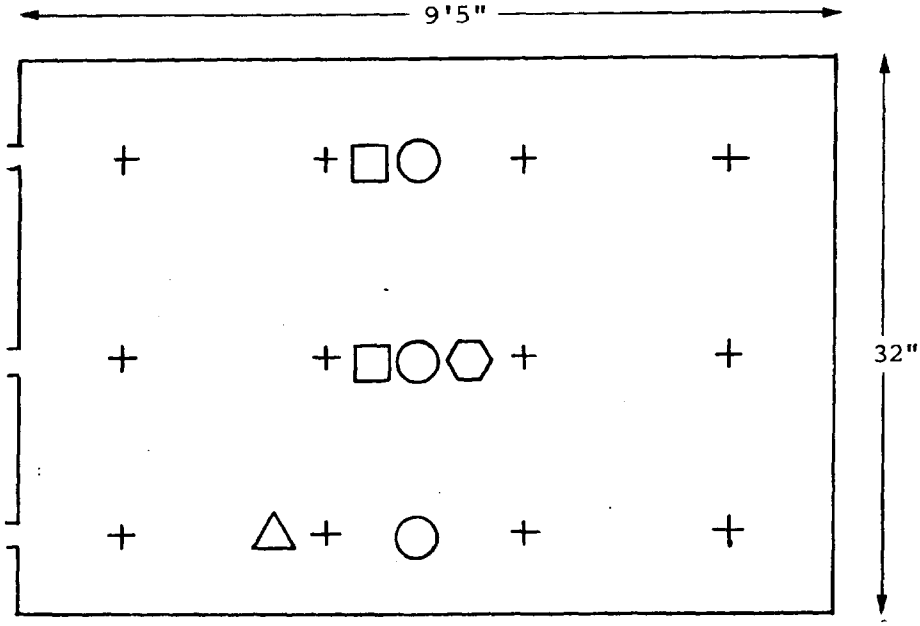
Whenever particulate loading was measured, it was measured simultaneously at both locations using 12-point traverses. Gaseous measurements of O_2, CO_2, CO, NO, NO_2, SO_2 and HC were obtained by pulling samples individually and compositely from selected points. SO_3 measurements, Brink samples for flyash sizing and SASS samples for organic and trace element determinations were each obtained from single points within the duct.

3.5 PARTICULATE COLLECTION EQUIPMENT

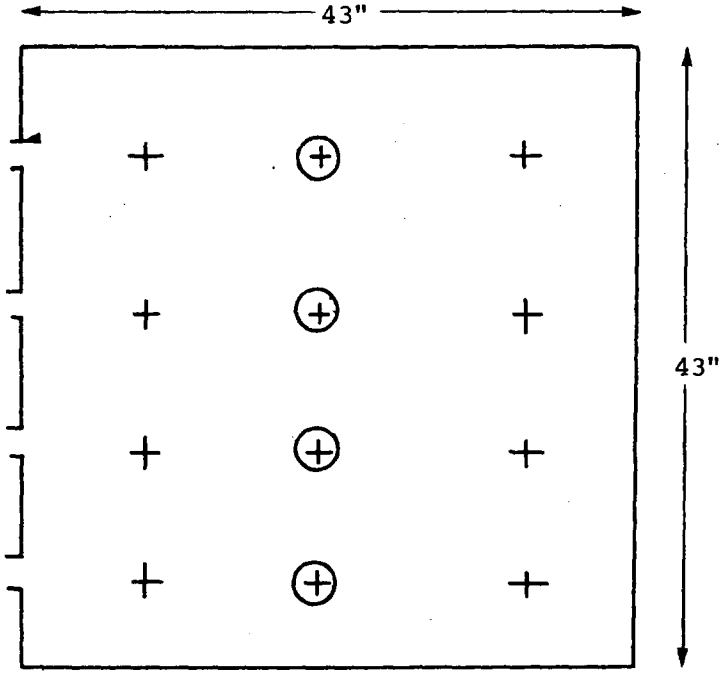
The boiler is equipped with a Zurn mechanical dust collector. The collector has 63 tubes of 9-inch diameter and has a design efficiency of 85%.

3.6 COALS UTILIZED

Two coals were fired at Test Site F. These are referred to as Pennsylvania A coal and Pennsylvania B coal in this report. Coal samples were taken for each test involving particulate or SASS sampling. The average coal analyses obtained from these samples are presented in Table 3-3. The primary coal at this site was Pennsylvania A. The secondary coal was specially prepared -- washed and mechanically treated -- high grade metallurgical coal. While Pennsylvania B coal was lower in both ash and sulfur content than Pennsylvania A coal, the differences are not great and, as a matter of fact, these slight differences in the coal had little impact on the combustion and emission characteristics of the boiler. The analyses of each individual coal sample are presented in Section 5.0, Test Results and Observations, Tables 5-17 through 5-19.



Economizer Outlet Sampling Plane
Cross Sectional Area = 25.11 ft^2



Dust Collector Outlet Sampling Plane
Cross Sectional Area = 12.84 ft^2

+ Particulate Mass Sampling Point
○ Gaseous Sampling Point
□ SASS Sampling Point
△ SO_3 Sampling Point
⬡ Brink Sampling Point

FIGURE 3-2. Boiler F Sample Plane Geometry

TABLE 3-3

AVERAGE COAL ANALYSIS
TEST SITE F

	Penn A Coal	Penn B Coal
PROXIMATE (As Rec'd)		
% Moisture	4.06	3.69
% Ash	10.55	8.96
% Volatile	22.74	25.75
% Fixed Carbon	62.65	61.61
Btu/lb	13242	13596
% Sulfur	1.47	1.00
ULTIMATE (As Rec'd)		
% Moisture	3.28	3.69
% Carbon	75.14	76.36
% Hydrogen	4.61	4.69
% Nitrogen	1.23	1.12
% Chlorine	0.15	0.17
% Sulfur	1.42	1.00
% Ash	10.52	8.96
% Oxygen (Diff)	3.68	4.03

4.0 TEST EQUIPMENT AND PROCEDURES

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

4.1 GASEOUS EMISSIONS MEASUREMENTS (NOx, CO, CO_2, O_2, HC, SO_2)

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 by the EPA 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), gaseous hydrocarbons (HC), and sulfur dioxide (SO_2).

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:	$\pm$1% of full scale

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

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

Constituent:	Sulfur Dioxide
Analyzer:	Dupont Model 400 Photometric Analyzer
Range:	0-200 ppm and 0-2000 ppm
Accuracy:	$\pm$1% of reading plus $\pm$1/4% of full scale range

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 $\pm$1% of full scale in 24 hours
Zero stability $\pm$1 ppm in 24 hours
Power requirements 115$\pm$10V, 60 Hz, 1000 watts

Response 90% of full scale in 1 sec. (NOx mode), 0.7 sec. NO mode
Output 4-20 ma
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
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

Sulfur Dioxide. Sulfur dioxide is measured by a Dupont Model 400 photometric analyzer. This analyzer measures the difference in absorption of two distinct wavelengths (ultraviolet) by the sample. The radiation from a selected light source passes through the sample and then into the photometer unit where the radiation is split by a semi-transparent mirror into two beams. One beam is directed to a phototube through a filter which removes all wavelengths except the "measuring" wavelength, which is strongly absorbed by the constituent in the sample. A second beam falls on a reference phototube, after passing through an optical filter which transmits only the "reference" wavelength. The latter is absorbed only weakly, or not at all, by the constituent in the sample cell. The phototubes translate these intensities to proportional electric currents in the amplifier. In the amplifier, full correction is made for the logarithmic relationships between the ratio of the intensities and concentration or thickness (in accordance with Beer's Law). The output is, therefore, linearly proportional, at all times, to the concentration and thickness of the sample. The instrument has a lower detection limit of 2 ppm and full scale ranges of 0-200 and 0-2000 ppm.

Specifications:
Noise less than 1/4%
Drift less than 1% full scale in 24 hours
Accuracy (±1% of analyzer reading)+(±1/4% of full scale range)
Sample cell 304 stainless steel, quartz windows
Flow rate 6 CFH
Light source is mercury vapor, tungsten, or "Osram" discharge type lamps
Power rating 500 watts maximum, 115 V, 60 Hz
Reproducibility 1/4% of scale
Electronic response 90% in 1 sec
Sample temperature 378 K (220°F)
Output 4-20 ma d.c.

4.1.2 Gas Sampling and Conditioning System

A flow schematic of the flue gas sampling and analysis system is shown in Figure 4-1. The sampling system uses 3 positive displacement diaphragm pumps to continuously draw flue gas from the stack into the laboratory. The sample pumps pull from 6 unheated sample lines. Selector valves allow composites of up to 6 points to be sampled at one time. The probes are connected to the sample pumps with 0.95 cm (3/8") or 0.64 cm (1/4") nylon line. The positive displacement diaphragm sample pumps provide unheated sample gas to the refrigerated condenser (to reduce the dew point to 35°F), a rotameter with flow control valve, and to the O_2, NO, CO, and CO_2 instrumentation. Flow to the individual analyzers is measured and controlled with rotameters and flow control valves. Excess sample is vented to the atmosphere.

To obtain a representative sample for the analysis of NO_2, SO_2 and hydrocarbons, the sample must be kept above its dew point, since heavy hydrocarbons may be condensible and SO_2 and NO_2 are quite soluble in water. For this reason, a separate, electrically-heated, sample line is used to bring the sample into the laboratory for analysis. The sample line is 0.64 cm (1/4-inch) Teflon line, electrically traced and thermally insulated to maintain a sample temperature of up to 400°F. Metal bellows pumps provide sample to the hydrocarbon, SO_2 and NOx analyzers.

4.1.3 Continuous Measurements

The laboratory trailer is equipped with analytical instruments to continuously measure concentrations of NO, NO_2, CO, CO_2, O_2, SO_2, and hydrocarbons. All of the continuous monitoring instruments and sample handling system are mounted in the self-contained mobile laboratory. The entire system requires only connection to on-site water, power, and sampling lines to become fully operational. The instruments themselves are shock mounted on a metal console panel. The sample flow control measurement, and selection, together with instrument calibration are all performed from the console face.

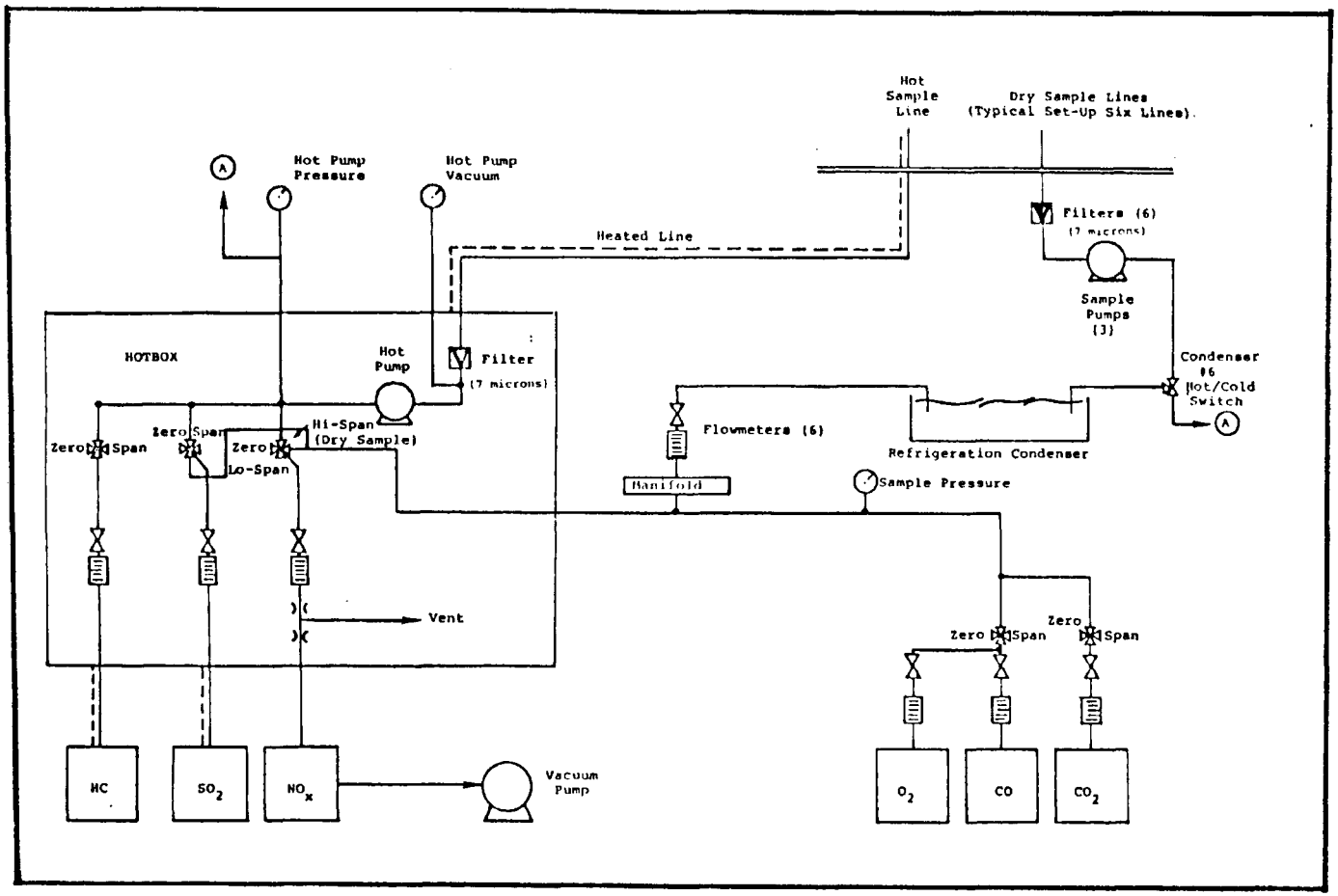


FIGURE 4-1. Flue Gas Sampling and Analyzing System

4.2 SULFUR OXIDES (SOx)

Goksoyr-Ross Method -- Wet Chemical Method

The Goksoyr-Ross Controlled Condensate (G/R) method is used for the wet chemical SO_2/SO_3 determination. It is a desirable method because of its simplicity and clean separation of particulate matter, SO_2 and H_2SO_4 (SO_3). This procedure is based on the separation of $H_2SO_4(SO_3)$ from SO_2 by cooling the gas stream below the dew point of H_2SO_4 but above the H_2O dew point. Figure 4-2 illustrates schematically the G/R test system.

Particulate matter is first removed from exhaust gas stream by means of a quartz glass filter placed in the heated glass filter holder. Tissue-quartz filters are recommended because of their proven inertness to H_2SO_4. The filter system is heated by a heating tape so that the gas out temperature of 260°C (500°F) is maintained. This temperature is imperative to ensure that none of the H_2SO_4 will condense in the filter holder or on the filter.

The condensation coil where the H_2SO_4 is collected is cooled by water which is maintained at 60°C (140°F) by a heater/recirculator. This temperature is adequate to reduce the exhaust gas to below the dew point of H_2SO_4.

Three impingers are shown in Figure 4-2. The first impinger is filled with 3% H_2O_2 to absorb SO_2. The second impinger is to remove carry over moisture and the third contains a thermometer to measure the exhaust gas temperature to the dry gas meter and pump. The sampling rate is 2.3 lpm (0.08 CFM).

For both SO_2 and H_2SO_4 determination, the analytical procedure is identical. The H_2SO_4 sample is washed from the back part of the filter holder and the coil using distilled water. The sample from the first impinger which is assumed to be absorbed and reacted SO_2 in the form of H_2SO_4 is recovered with distilled water washing. The amount of H_2SO_4 in the condensate from the coil and from the H_2O_2 impinger is measured by H+ titration. Bromphenol Blue is used with NaOH as the titrant.

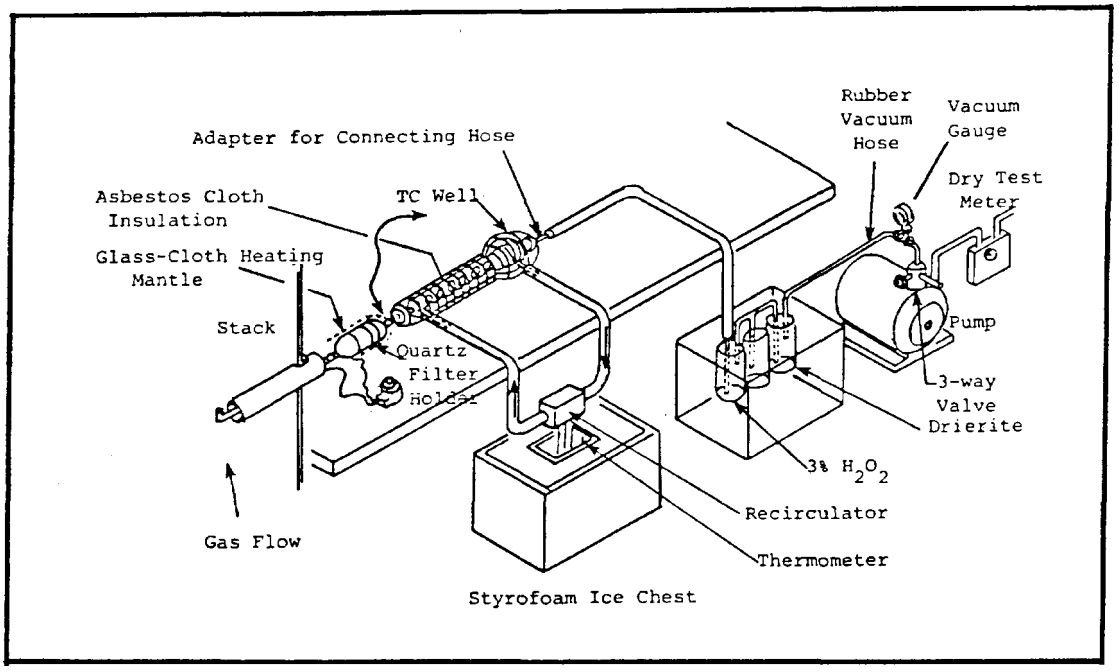


FIGURE 4-2. Schematic of Goksoyr-Ross Controlled Condensation System (CCS).

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 4-3). 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 $\pm$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.

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

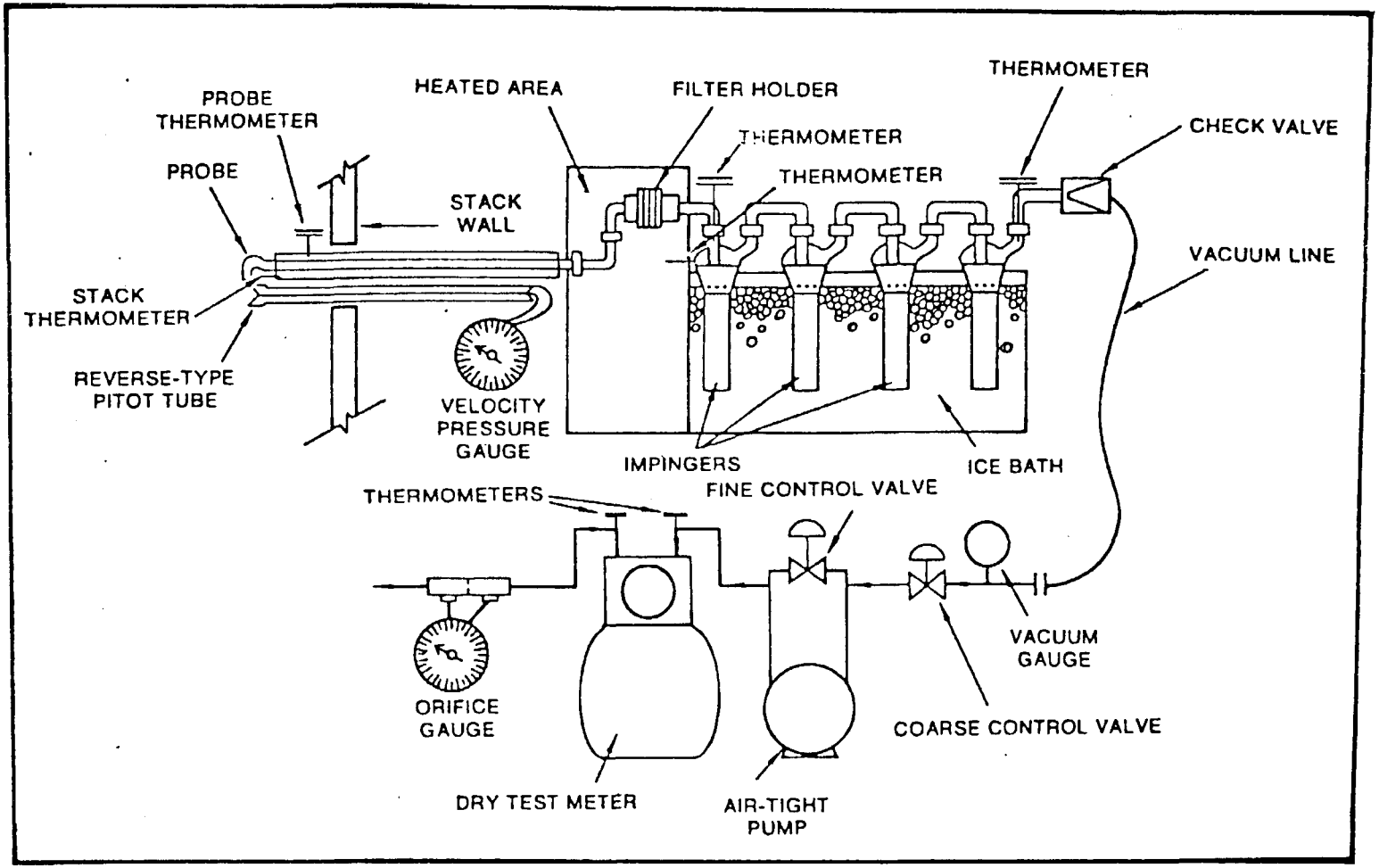


FIGURE 4-3. EPA Method 5 Particulate Sampling Train

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 4-4.

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 F came from the cyclone in the EPA Method 5 particulate train. These samples are spatially representative because they are taken from a 12-point sample matrix. However, 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

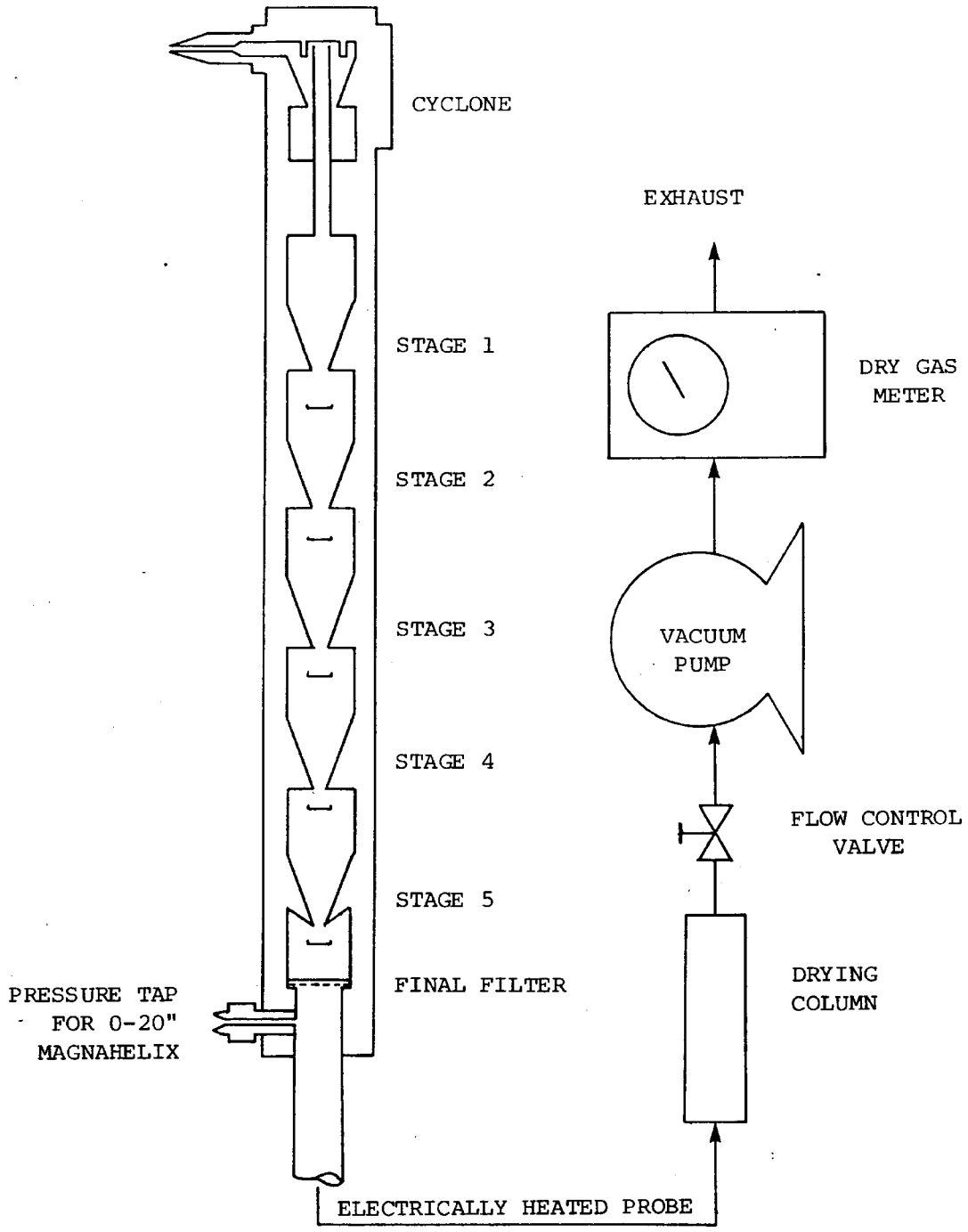


FIGURE 4-4. Brink Cascade Impactor Sampling Train Schematic

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 4.8.

4.5 COAL SAMPLING AND ANALYSIS PROCEDURE

Coal samples at Test Site F were taken during each test from the unit's coal scale. 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 the feeder. This is repeated five more times 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 point samples are obtained.

The sample to be used for sieve analysis is air dried overnight. 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 F the bottom ash samples were collected in several increments from the grate during 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, com-

bustible 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 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 4-5). 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.

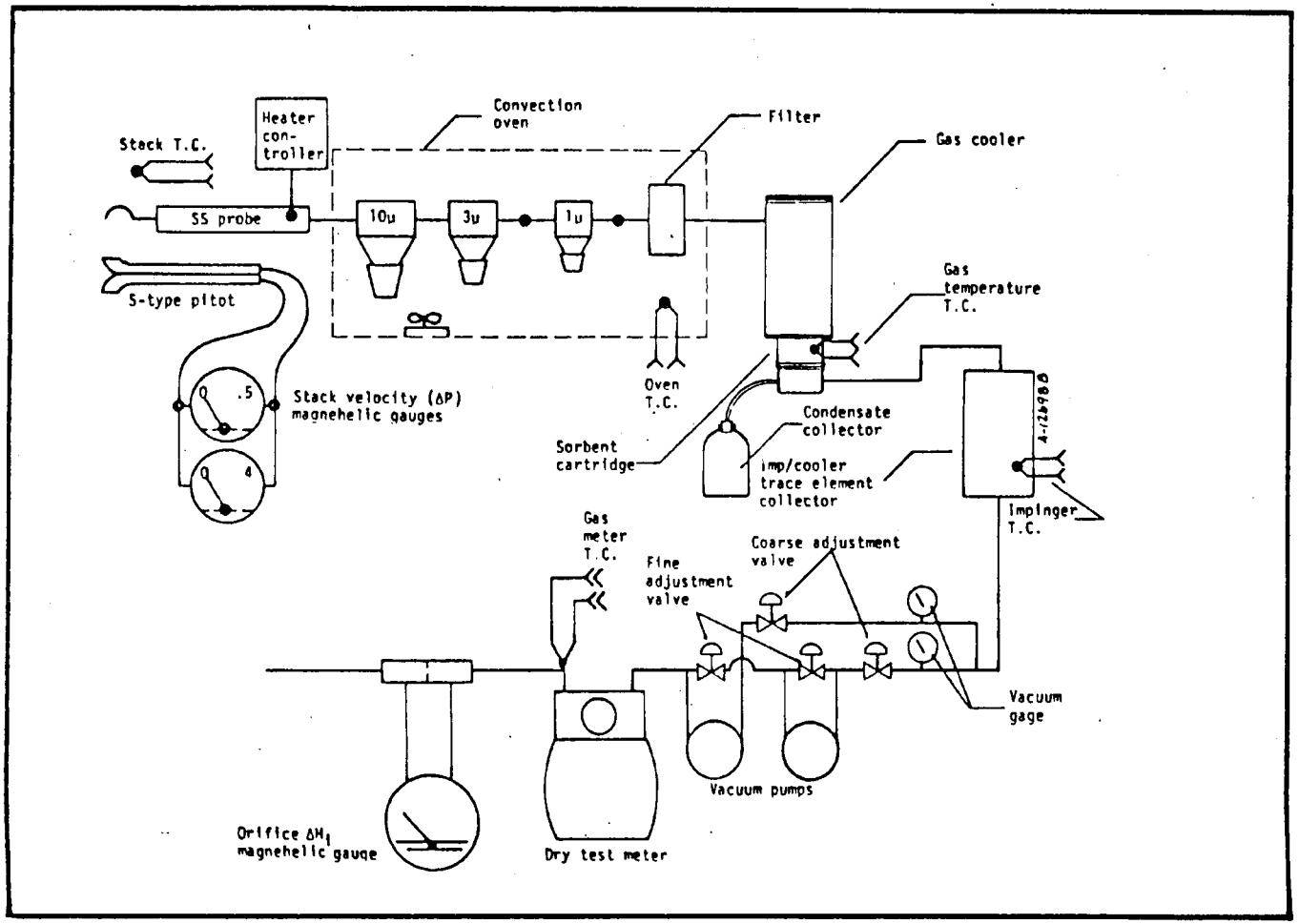


FIGURE 4-5. Source Assessment Sampling (SASS) Flow Diagram

5.0 TEST RESULTS AND OBSERVATIONS

This Section presents the results of tests performed on Boiler F. Observations are made regarding the influence on efficiency and on gaseous and particulate emissions as the control parameters were varied. Thirty-five defined tests were conducted over a two-month test period to develop this data. Reference should be made to Table 2-1 in the Executive Summary and to Tables 5-31 through 5-34 at the end of this section when reading through the following discussion.

5.1 OVERFIRE AIR

Boiler F had a standard overfire air configuration consisting of two rows of air jets on the rear water wall and two rows on the front water wall, the lower front row of air jets being an integral part of the coal spreaders. Air flow to each row of overfire air jets could be controlled to a certain extent by a system of butterfly valves. Static pressure in each overfire air header was used as a measure of relative air flow.

A series of tests were run in which overfire air pressure (and thus overfire air flow) was the independent variable. Emissions and efficiency were measured as the overfire air pressures were varied to determine which overfire air settings were optimum in terms of emissions and boiler efficiency. The test results are presented in Table 5-1 and discussed in the following paragraphs. These tests indicated that baseline and maximum overfire air conditions gave somewhat better results than low overfire air condition.

There was no clear indication whether the baseline condition, which put most of the overfire air through the front wall, was any better or worse than the maximum overfire air condition which increased the overfire air flow through the rear wall. However, for the purposes of this test program, the maximum overfire air condition was selected as the optimum condition and used in several subsequent tests.

TABLE 5-1

EFFECT OF OVERFIRE AIR ON EMISSIONS AND EFFICIENCY
TEST SITE F

Test No. Description	16A Base-line	16B Max OFA	16C Low OFA	17 Base-line	18 Max OFA	19 Low OFA
OVERFIRE AIR CONDITIONS						
Front Upper, "H_2O	13.2	11.1	5.2	13.6	10.8	4.9
Front Lower, "H_2O	9.9	10.0	6.6	10.3	10.2	6.9
Rear Upper, "H_2O	1.3	4.4	2.7	1.0	4.8	2.4
Rear Lower, "H_2O	5.3	8.3	2.8	5.3	8.2	2.8
FIRING CONDITIONS						
Load, % of Capacity	100	100	100	99	99	99
Grate Heat Release, 10^3Btu/hr-ft^2	668	668	668	659	648	665
Coal	Penn A	Penn A	Penn A	Penn A	Penn A	Penn A
Coal Fines, % Passing 1/4"	--	--	--	24	16	31
Excess Air, %	54	50	63	45	34	37
ECONOMIZER OUTLET EMISSIONS						
Particulate Loading, lbs/10^6Btu	--	--	--	5.51	6.14	8.79
Combustible Loading, lbs/10^6Btu	--	--	--	3.86	4.38	6.32
Inorganic Ash Loading, lbs/10^6Btu	--	--	--	1.65	1.75	2.47
Combustibles in Flyash, %	--	--	--	70.1	71.4	71.9
O_2, % (dry)	7.6	7.2	8.3	6.7	5.5	5.9
CO, ppm (dry) @ 3% O_2	228	163	378	382	429	607
NO, lbs/10^6Btu	OOS	OOS	OOS	OOS	0.358	0.421
HC, ppm (dry) @ 3% O_2	13	13	0	9	5	16
Opacity, %	2.5	2.5	4.8	3.9	--	4.2
MULTICLONE OUTLET EMISSIONS						
Particulate Loading, lbs/10^6Btu	--	--	--	1.13	0.77	1.26
Combustible Loading, lbs/10^6Btu	--	--	--	0.51	0.32	0.58
Inorganic Ash Loading, lbs/10^6Btu	--	--	--	0.62	0.45	0.68
Combustibles in Flyash, %	--	--	--	45.0	41.3	46.1
Multiclone Collection Efficiency, %	--	--	--	79.5	87.4	85.7
HEAT LOSSES, %						
Dry Gas	--	--	--	7.78	7.07	8.48
Moisture in Fuel	--	--	--	0.47	0.52	0.74
H_2O from Combustion of H_2	--	--	--	3.75	3.89	3.96
Combustibles in Flyash	--	--	--	5.50	6.24	9.00
Combustibles in Bottom Ash	--	--	--	1.70	1.04	1.46
Radiation	--	--	--	0.52	0.52	0.52
Unmeasured	--	--	--	1.50	1.50	1.50
Total Losses	--	--	--	21.22	20.78	25.66
Boiler Efficiency	--	--	--	78.78	79.22	74.34

OOS - Analyzer Out-of-Service

5.1.1 Particulate Loading vs Overfire Air

Particulate loading was lowest when the overfire air pressure was high, as it was in the baseline and maximum overfire air tests. The particulate vs overfire air test data are shown in Table 5-2.

TABLE 5-2

PARTICULATE LOADING VS OVERFIRE AIR

Test No.	Overfire Air	Economizer Outlet Particulate lbs/10^6 Btu	Multiclone Outlet Particulate lbs/10^6 Btu
17	Baseline	5.51	1.13
18	High	6.14	0.77
19	Low	8.79	1.26

The lowest economizer outlet particulate loading occurred under baseline conditions (Test 17) when the overfire air pressures were very high in the front and lower in the rear. After the multiclone dust collector, the lowest particulate loading occurred under the maximum overfire air conditions (Test 18) in which the air flow to the rear jets was increased. Low overfire air pressures produced significantly higher particulate loadings at both the economizer outlet and the multiclone outlet.

The combustible content of the economizer outlet flyash from Tests 17, 18 and 19 was basically constant at 70.1%, 71.4% and 71.9%, respectively. Therefore, it cannot be said that high overfire air decreased the percent combustibles in the flyash. However, high overfire air did produce the lowest particulate loadings and it is concluded that high overfire air in either the baseline or maximum configuration is the desirable mode of operation on this unit.

5.1.2 Nitric Oxide vs Overfire Air

The nitric oxide (NO) data from Tests 18 and 19 indicate that high overfire air pressure reduces this emission. However, it must be kept in mind that the evidence is limited to only two data points and is, therefore, rather

weak. When a correction is made for the effect of oxygen on nitric oxide levels (NO increases 0.051 lbs/10^6 Btu for each 1% O_2 increase, Figure 5-10), the reduction in nitric oxide due solely to increased overfire air pressure is only 11%. This reduction is not very significant. The test data are presented in Table 5-3.

TABLE 5-3

NITRIC OXIDE VS OVERFIRE AIR

Test No.	Overfire Air	% O_2	Measured Nitric Oxide lbs/10^6 Btu	Nitric Oxide Corrected to 5.5% O_2 lbs/10^6 Btu
18	High	5.5	0.358	0.358
19	Low	5.9	0.421	0.401

5.1.3 Carbon Monoxide and Unburned Hydrocarbons vs Overfire Air

Carbon monoxide (CO) was lowest at high overfire air settings. Unburned hydrocarbons (HC) gave mixed results. It is concluded from this data that the two high overfire air pressure tests had the highest combustion efficiency. The only discrepancy was the zero HC measurement during low overfire air, Test 16C. The test data are given in Table 5-4.

TABLE 5-4

CARBON MONOXIDE AND HYDROCARBONS VS OVERFIRE AIR

Test No.	Overfire Air	Carbon Monoxide ppm @ 3% O_2 (dry)	Unburned Hydrocarbons ppm @ 3% O_2 (wet)
16A	Baseline	228	13
16B	High	163	13
16C	Low	378	0
17	Baseline	382	9
18	High	429	5
19	Low	607	16

5.1.4 Boiler Efficiency vs Overfire Air

Boiler efficiency was more than four percent higher during the baseline and maximum overfire air tests than it was during the low overfire air test. Three percent of this increase comes directly from reduced combustible losses in the flyash and may be attributed to the increase in overfire air induced turbulence. The remaining one percent difference in efficiency appears in the dry gas loss and loss due to moisture in fuel categories. These two losses are unrelated to the overfire air conditions. The heat losses for the overfire air tests are shown in Table 5-1 and summarized in Table 5-5.

TABLE 5-5

BOILER EFFICIENCY VS OVERFIRE AIR

Test No.	Overfire Air	Heat Loss Due to Comb in Flyash, %	Boiler Efficiency, %
17	Baseline	5.50	78.78
18	High	6.24	79.22
19	Low	9.00	74.34

5.2 FLYASH REINJECTION

Boiler F does not reinject flyash from the mechanical dust collector. However, it does reinject flyash pneumatically and continuously from the economizer hopper and from the boiler hopper. During one test, Test 23, the flyash collecting in the economizer hopper was diverted to barrels rather than reinjected. This resulted in a 5%-27% drop (depending on which test you compare it to) in particulate mass loading at the economizer outlet when compared to the full reinjection test data. The data also indicate that during Test 23, ten percent of the flyash entering the economizer was collected in the economizer flyash hopper. This test will be described in more detail below.

It is important to remember that at this site particulates were sampled after the economizer and not at the boiler outlet, as at the other sites. This sampling location was chosen because physical limitations prevented particulate sampling upstream of the economizer. Test 23, during which the rate

of flyash collection in the economizer hopper was measured, provides some indications, however, of the "collection efficiency" of the economizer and, hence, a factor that can be used to correct for the location of the particulate sampling plane when comparing particulate data from this site with particulate data from other sites.

5.2.1 Reduced Flyash Reinjection, Test No. 23

During Test 23, flyash reinjection from the economizer hopper was stopped completely for 7-1/2 hours. This was accomplished by closing the reinjection air dampers and by closing gate valves on the economizer hopper discharge lines. The economizer ash collection rate was also measured by diverting the ash to tare weighed barrels. This rate measurement was made during the last two hours of the test and is presented in Table 5-6.

TABLE 5-6

ECONOMIZER ASH COLLECTION RATE
TEST NO. 23 - TEST SITE F

Location	Tare Wt.	Final Wt.	Δ Wt.
Right Hopper	36.5 lb.	46.0 lb.	9.5 lb.
Center Hopper	50.0 lb.	129.0 lb.	79.0 lb.
Left Hopper	41.0 lb.	69.0 lb.	28.0 lb.
		Total Sample Collected	116.5 lb.

Stop Time 18:05
Start Time 15:55
Sampling Time 2:10 = 2.167 hours

$$\text{Sample Collection Rate} = \frac{116.5}{2.167} = 54 \text{ lb/hr}$$

Particulate mass loading at economizer outlet = 507 lb/hr (measured)

Particulate mass loading at boiler outlet = 507+59 lb/hr = 561 lb/hr (calculated)

Percent flyash collected by economizer = 10%

Based on the data from Test 23 it may be assumed that the particulate loadings at the boiler outlet are about ten percent higher than the loadings at the economizer outlet for all tests.

5.2.2 Particulate Loadings vs Flyash Reinjection

The reduced flyash reinjection test gave the lowest economizer outlet particulate loading of all seven particulate tests at full load. This result would be expected since past experience has shown that a significant fraction of the reinjected flyash is reentrained in the flue gas stream.

The magnitude of the reduction was not well established due to the difficulty of controlling other parameters and because only a single reduced reinjection test was run. As shown in Table 5-7, the magnitude of the reduction in particulate loading was in the range of 5% to 27%.

TABLE 5-7

PARTICULATE LOADING VS FLYASH REINJECTION

Test No.	Flyash Reinj	Test Conditions			Economizer Outlet Particulate Loading lbs/10^6 Btu	% by Which Test 23 Particulate Loading is Lower
		% Load	% O_2	OFA		
23	No	100	6.3	High	5.24	--
17	Yes	99	6.7	Norm	5.51	5%
15	Yes	99	7.8	Norm	5.93	12%
18	Yes	99	5.5	High	6.14	15%
24	Yes	102	5.0	High	7.18	27%

100% load = unit's design capacity of 80,000 lb stm/hr.

5.2.3 Boiler Efficiency vs Flyash Reinjection

Test 23 showed that the economizer was collecting flyash at the rate of 54 pounds per hour while the boiler was at its design capacity of 80,000 pounds per hour of steam. The boiler hopper flyash contained 70.53% combustible matter by weight. Translated into heating units, the economizer hopper flyash represents 0.6% of the heat input to the boiler. Therefore, maximum potential efficiency gain resulting from economizer ash reinjection is 0.6% (based on Test 23 data). The actual efficiency gain would be somewhat less since some of the reinjected flyash is reentrained in the flue gas stream and not collected or combusted the second time around.

5.3 EXCESS OXYGEN AND GRATE HEAT RELEASE

The boiler at Test Site F was tested for emissions and boiler efficiency at three boiler loadings representing 100%, 75% and 50% of design steaming capacity. At each load the boiler was tested over a wide range of excess air conditions. This section profiles the various emissions and the boiler efficiencies as a function of these two variables.

Boiler steam loading is expressed in terms of grate heat release. At full load, the measured grate heat release on this unit was about 670,000 Btu/hr-ft^2. Excess air is expressed in terms of percent oxygen in the flue gas.

5.3.1 Excess Oxygen Operating Levels

Figure 5-1 depicts the various conditions of grate heat release and excess oxygen under which tests were run on the boiler at Site F. Different symbols are used to distinguish between the two coals fired.

Full design capacity was easily met on this unit without any significant deterioration in combustion efficiency. At full capacity the unit was operated at oxygen levels as low as 5% (30% excess air) without problems for periods of up to 7.5 hours. Five percent O_2 is considered very good for a stoker boiler and meets the manufacturer's design performance of 30% excess

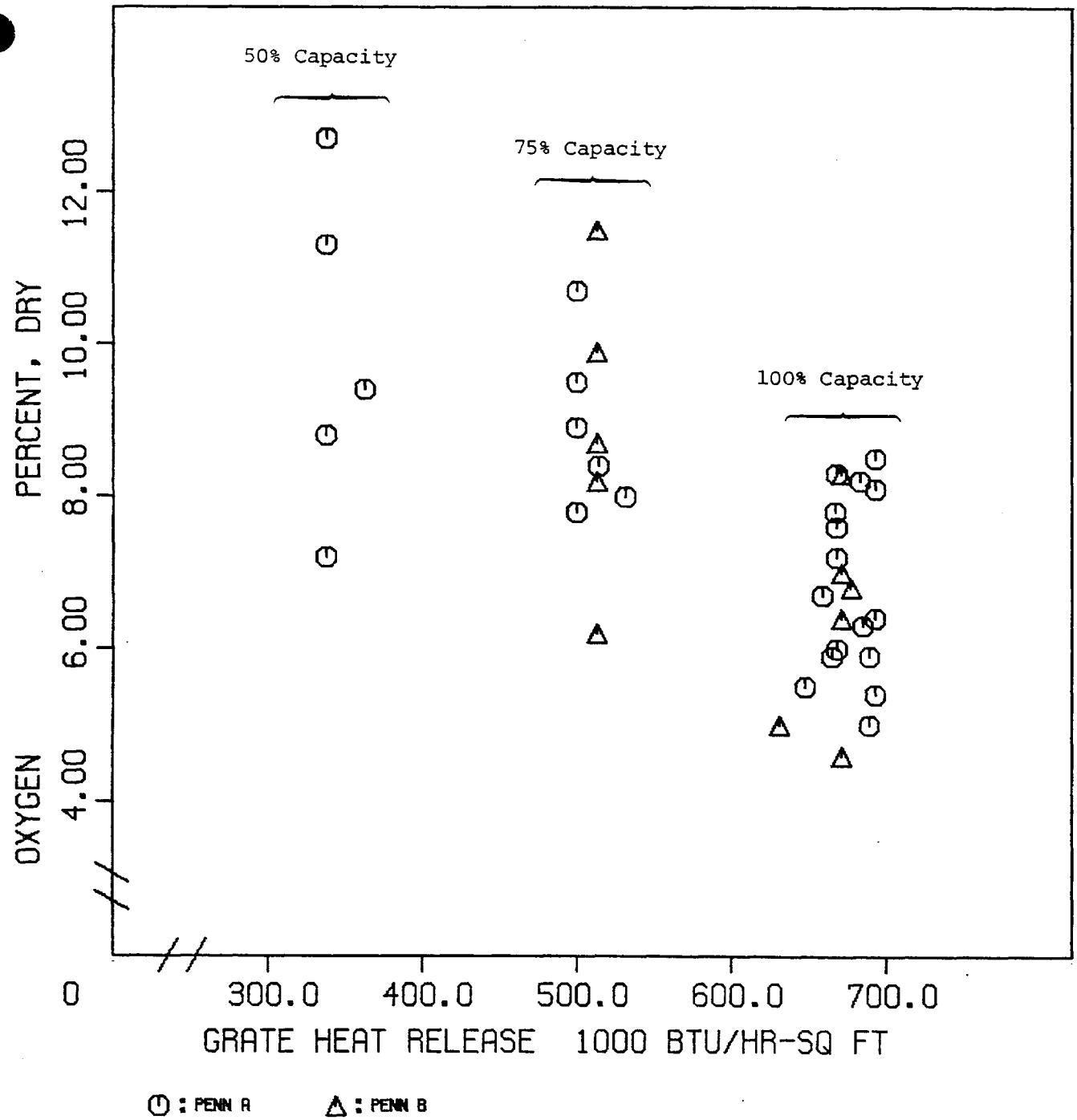


FIG. 5-1

OXYGEN VS. GRATE HEAT RELEASE

TEST SITE F

This Plot Shows the Range in Oxygen Level Under Which Tests were Conducted

air. Long term tests greater than 7.5 hours were not attempted because such testing is outside the scope of this program.

5.3.2 Particulate Loading vs Grate Heat Release

Figure 5-2 profiles the particulate loading at the economizer outlet as a function of grate heat release. Different symbols are used for the two coals fired, and the solid symbol represents the reduced reinjection Test 23. Boiler outlet particulate loadings were not measured because boiler geometry prevented it. However, it was determined, as is described in Section 5.2, that particulate loadings were about ten percent higher at the boiler outlet than at the economizer outlet.

The shaded area of Figure 5-2 encompasses the particulate data obtained under what could be called normal operating conditions. It shows a general increase in particulates with load above 500,000 Btu/hr-ft^2 grate heat release. At full load (670,000 Btu/hr-ft^2) the particulate mass loading under normal operating conditions ranged between 5.5 lbs/10^6 Btu and 7.2 lbs/10^6 Btu. At 75% load (500,000 Btu/hr-ft^2) the particulate mass loading ranged between 4.0 and 5.6 lbs/10^6 Btu.

The average ash carryover was 24% in those tests run under normal firing conditions. Ash carryover did not vary significantly between the two coals. Table 5-8 shows the basis for this determination.

TABLE 5-8

ASH CARRYOVER VS COAL TYPE
TEST SITE F

Coal	Average Ash Content of Coal lbs/10^6 Btu	Average Ash Content of Flyash lbs/10^6 Btu	Average Ash Carryover, %
Penn A	7.97	1.97	24.7
Penn B	6.59	1.46	22.2

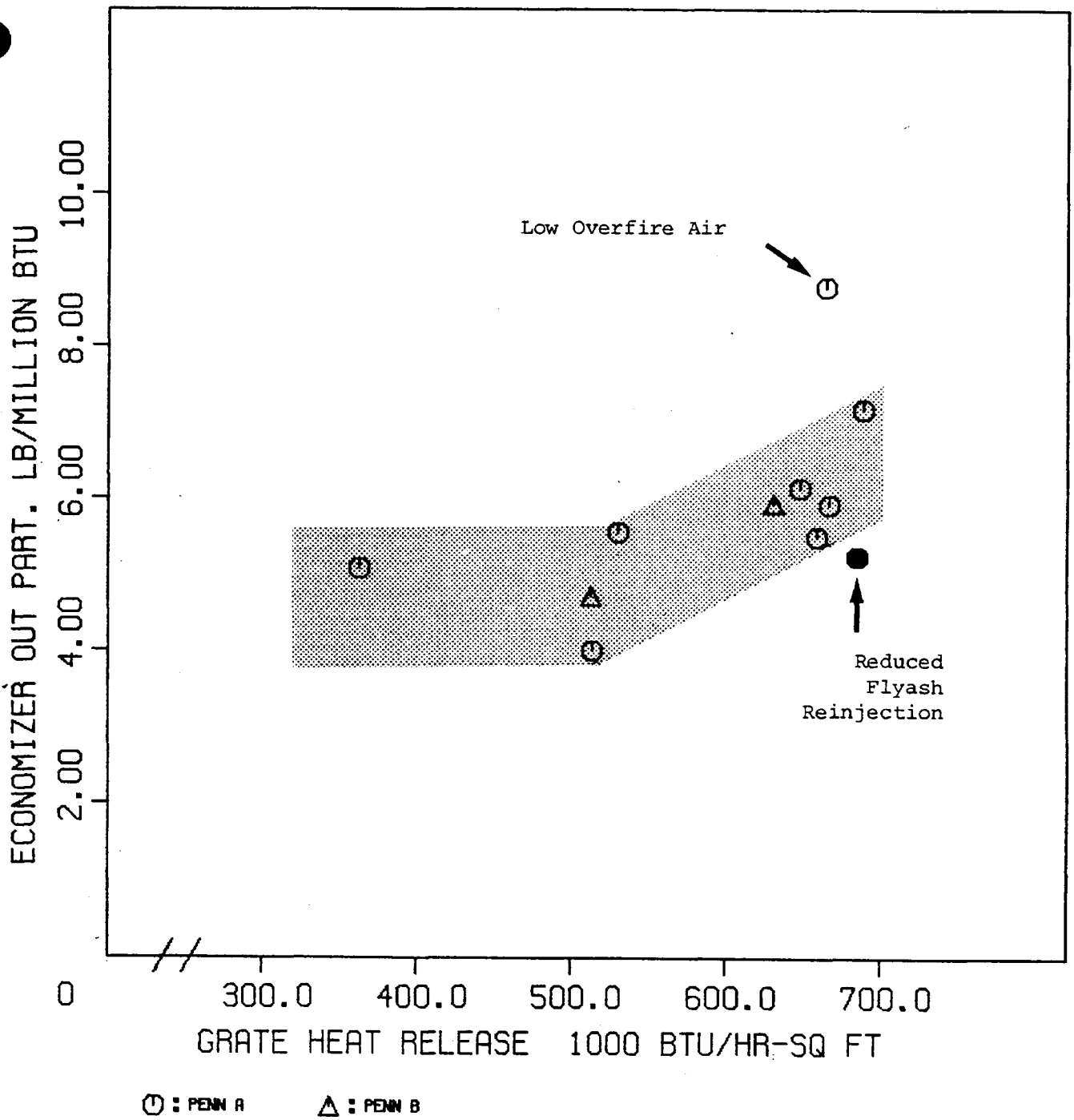


FIG. 5-2

ECONOMIZER OUT PART. VS. GRATE HEAT RELEASE
TEST SITE F

Shaded Area Encompasses Data Obtained Under Normal Operating Conditions

Particulate loadings were measured at the dust collector outlet simultaneously with measurements made at the economizer outlet for nine of the eleven particulate tests. These data are plotted against grate heat release in Figure 5-3. Different symbols are used for each coal and flyash reinjection configuration.

Particulate loadings at the dust collector outlet averaged 1.13 lbs/10^6 Btu and ranged in value from a low of 0.77 lbs/10^6 Btu to a high of 1.39 lbs/10^6 Btu. Mechanical dust collector efficiency averaged 81% and will be discussed further in Section 5.6.

5.3.3 Stack Opacity vs Grate Heat Release

Stack opacity was measured during several tests by a transmissometer. The transmissometer's calibration was not checked and, therefore, absolute values may not be reliable. However, relative values, as test variables were varied, are of interest. Figure 5-4 plots opacity versus grate heat release and shows that opacity did not rise very much at full load. This is one of several indications that combustion efficiency did not deteriorate at full load.

5.3.4 Nitric Oxide vs Oxygen and Grate Heat Release

Nitric oxide (NO) and nitrogen dioxide (NO_2) concentrations were measured during each test in units of parts per million (ppm) by volume. A chemiluminescent NOx analyzer was used to make these measurements. The ppm units have been converted to units of lbs/10^6 Btu in this report so they can be more easily compared with existing and proposed emission standards. Table 2-1 in the Executive Summary lists the nitric oxide data in units of ppm for the convenience of those who prefer these units.

Nitric oxide concentrations are known to increase with load at constant excess air, and to increase with excess air at constant load. These two factors often cancel themselves out in normal boiler operation because excess air usually decreases as load increases. Such was the case with Boiler F.

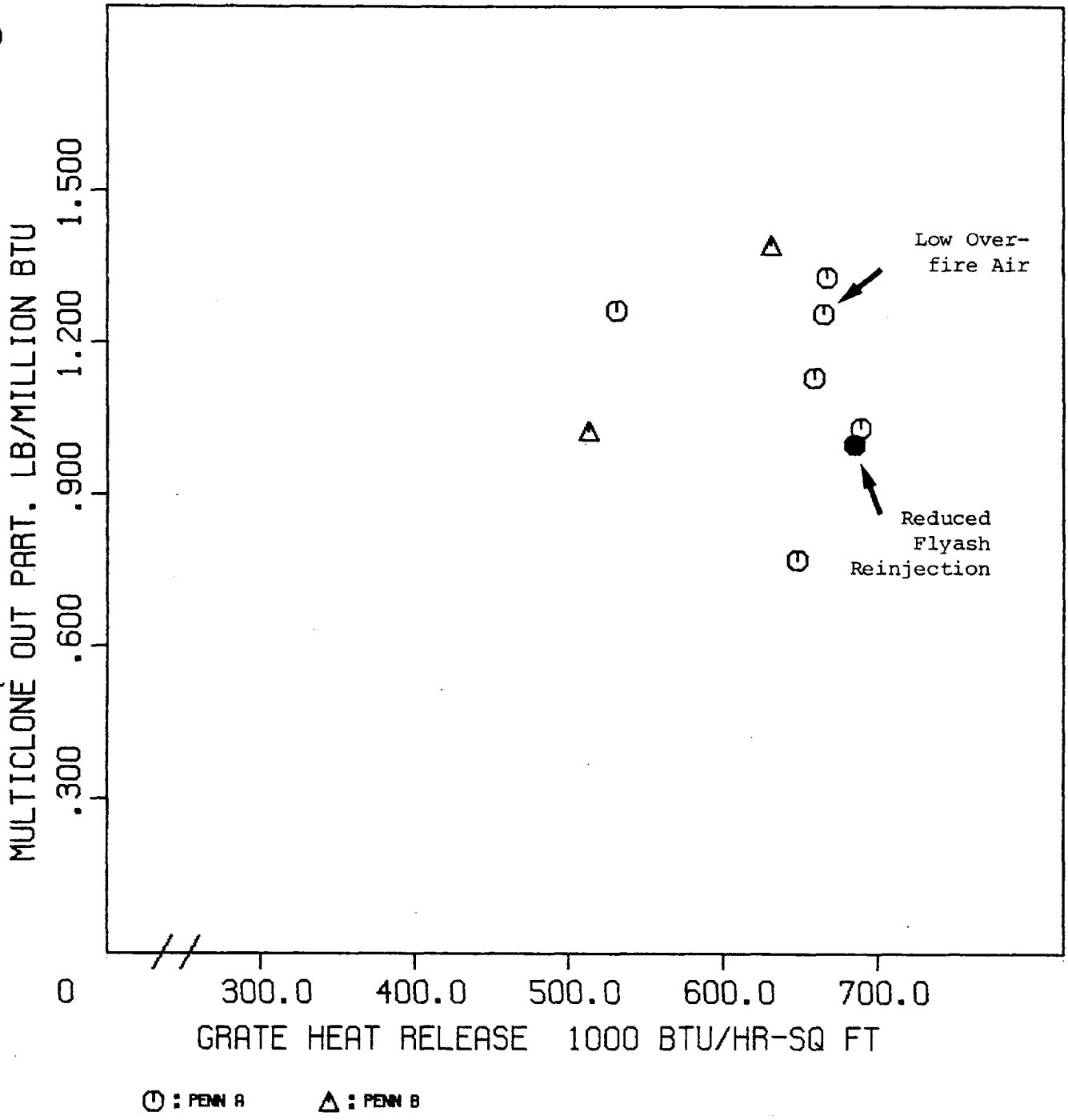


FIG. 5-3

MULTICLONE OUT PART. VS. GRATE HEAT RELEASE
TEST SITE F

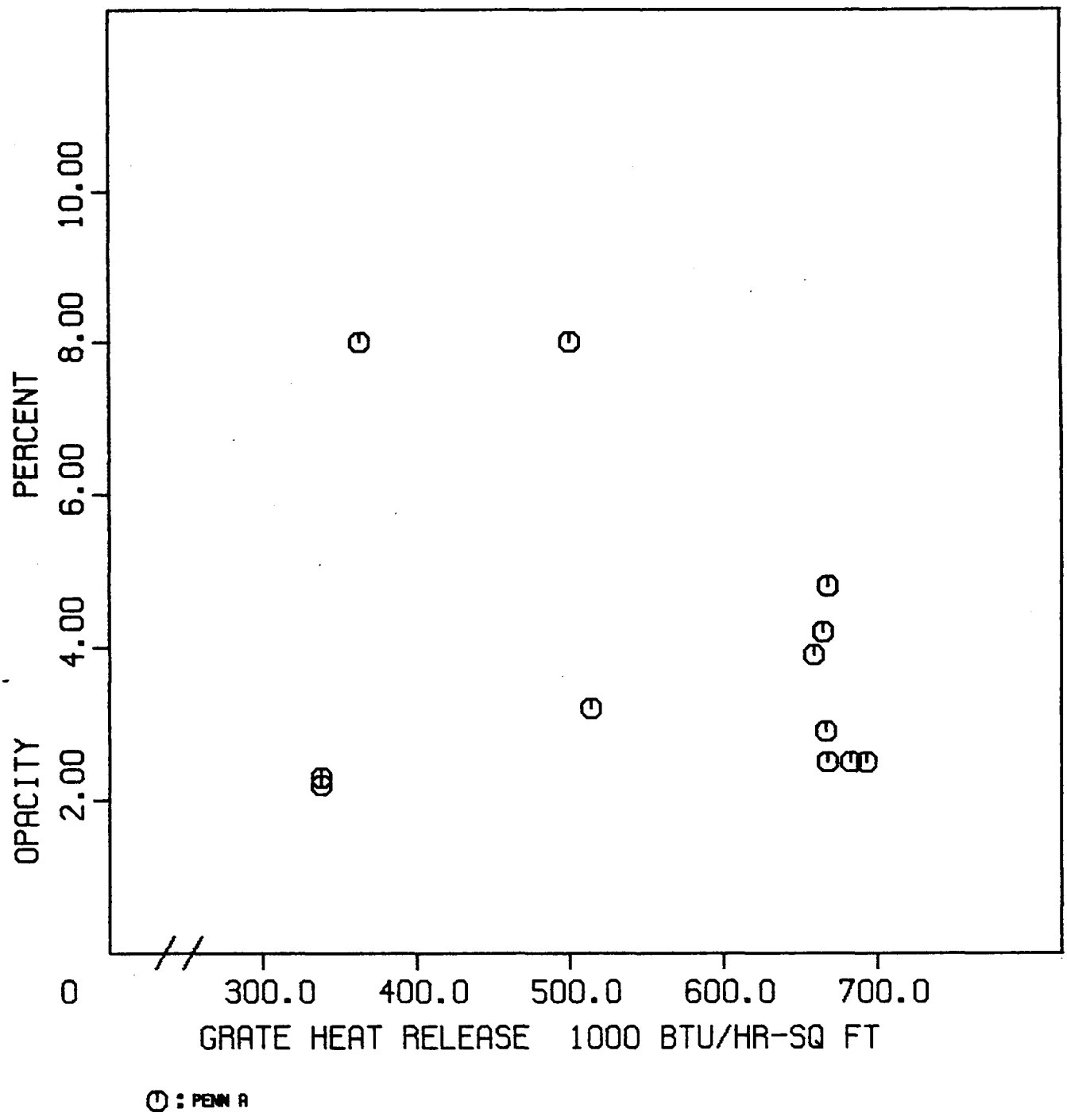


FIG. 5-4
OPACITY VS. GRATE HEAT RELEASE
TEST SITE F

Figure 5-5 presents the nitric oxide data as a function of grate heat release under the various excess air conditions encountered during testing. The nitric oxide emissions are stable over all loads. Table 5-9 illustrates this independence of load under normal operating excess air.

TABLE 5-9

NITRIC OXIDE VS LOAD AT NORMAL EXCESS AIR

	Nitric Oxide $lb/10^6$ Btu	Nitric Oxide ppm @ 3% O_2
100% Load	0.429 ± 0.068	316 ± 50
75% Load	0.473 ± 0.086	347 ± 63
50% Load	0.447 ± 0.108	328 ± 79

Figure 5-6 presents the nitric oxide data as a function of oxygen in the flue gas at three grate heat release ranges. In this figure, the effects of boiler load and excess air are separated and both become evident.

The nitric oxide data in each grate heat release range (load range) are plotted versus oxygen on an expanded scale in Figures 5-7, 5-8 and 5-9. In each of these plots a trend line was determined by linear regression analysis. The three trend lines are combined in Figure 5-10 to form a nitric oxide trend line plot which could be used for predicting nitric oxide concentrations on the unit. The slope of these trend lines indicates that nitric oxide increases by 0.051 $lbs/10^6$ Btu for each one percent increase in oxygen.

Nitrogen dioxide (NO_2) was also measured at this test site. At the economizer outlet, NO_2 averaged 0.005 $lbs/10^6$ Btu (4 ppm). Concentrations this small are very difficult to measure accurately with the chemiluminescent NOx analyzer and could be in error by as much as 100%. The nitrogen dioxide (NO_2) data are presented in Figure 5-11 as a function of grate heat release, and in Figure 5-12 as a function of oxygen for three grate heat release ranges. There is evidence in Figure 5-12 that NO_2 increases with increasing O_2 at the lower loads.

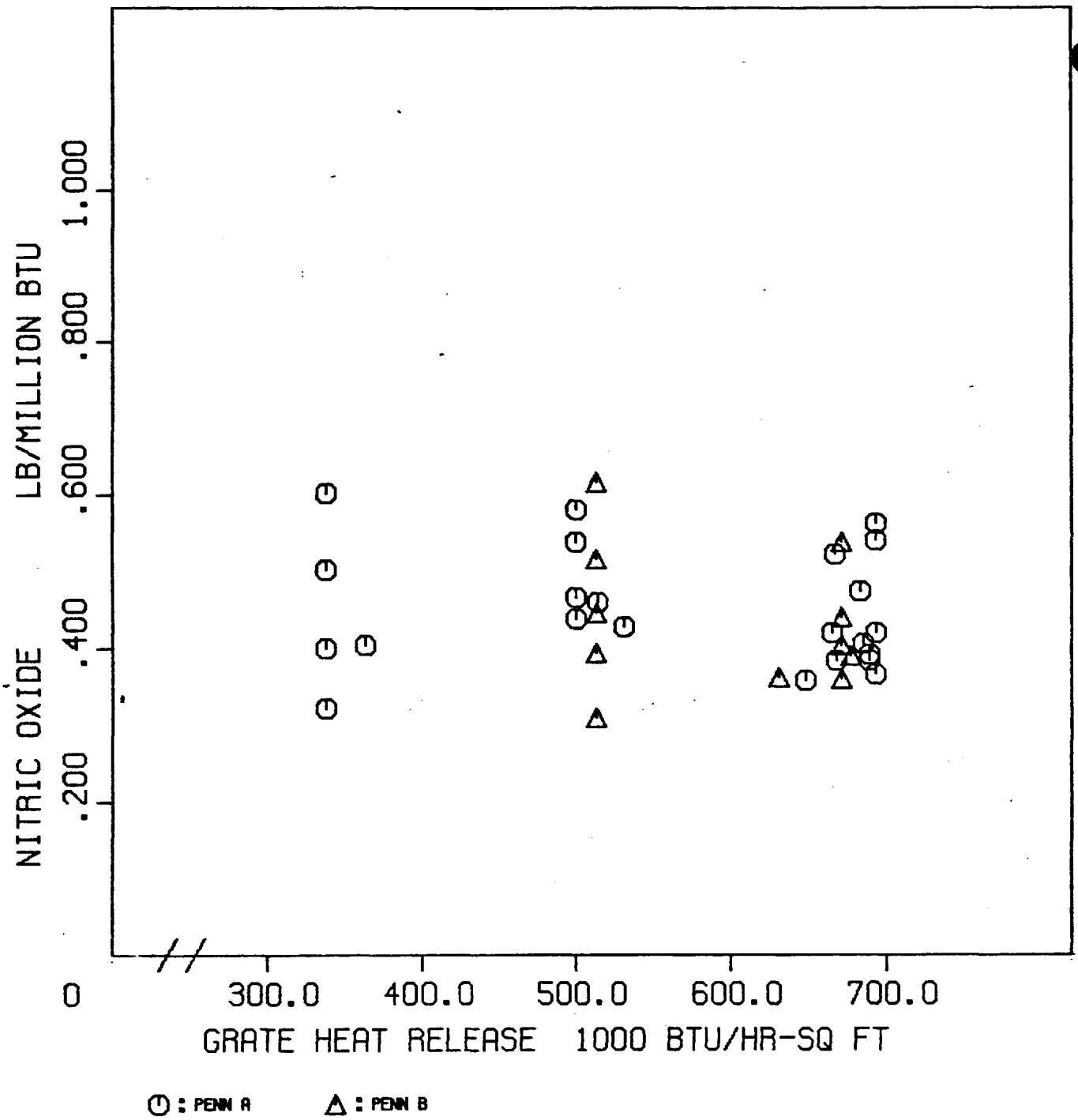


FIG. 5-5
NITRIC OXIDE VS. GRATE HEAT RELEASE
TEST SITE F

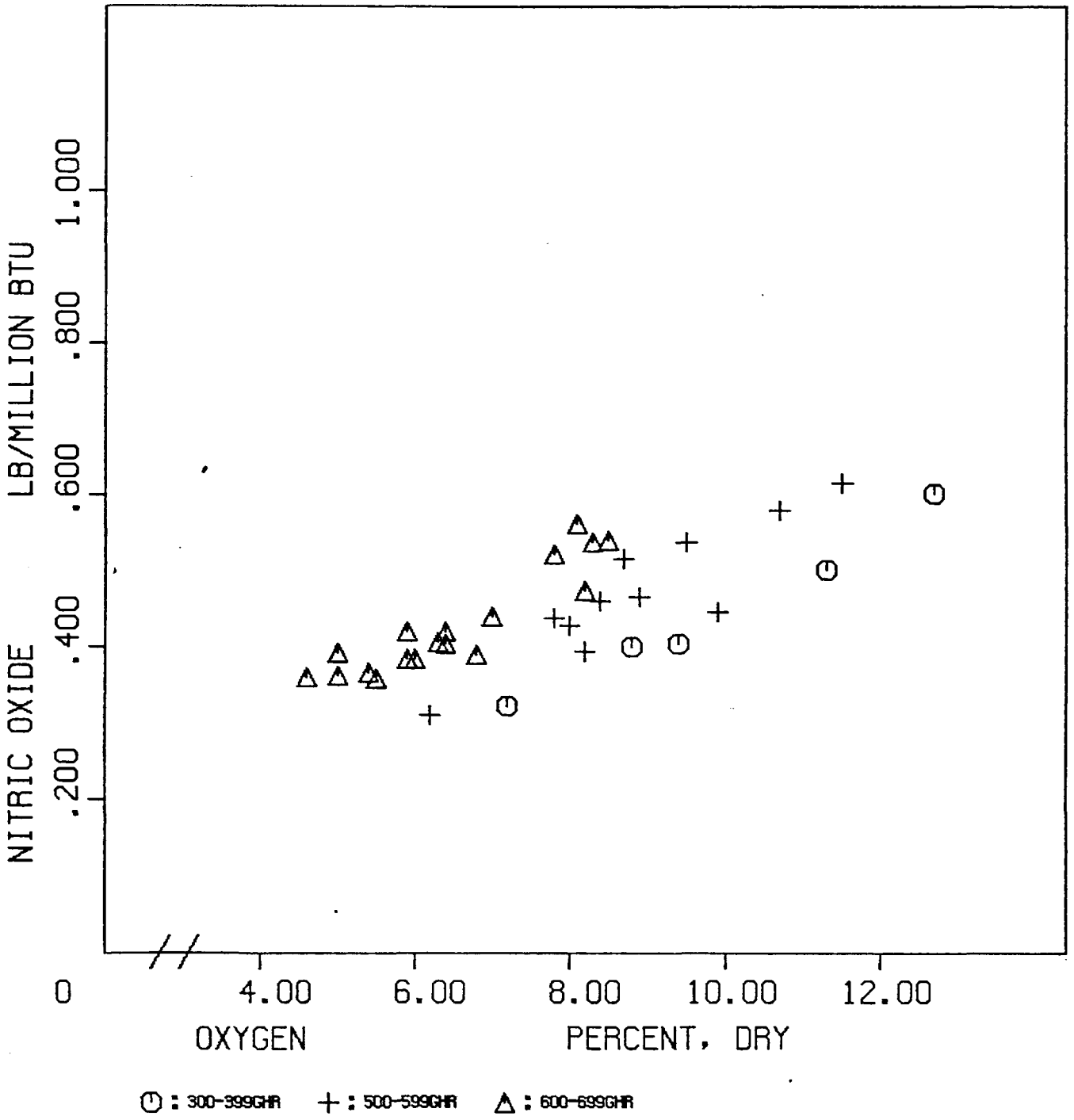


FIG. 5-6
NITRIC OXIDE VS. OXYGEN
TEST SITE F

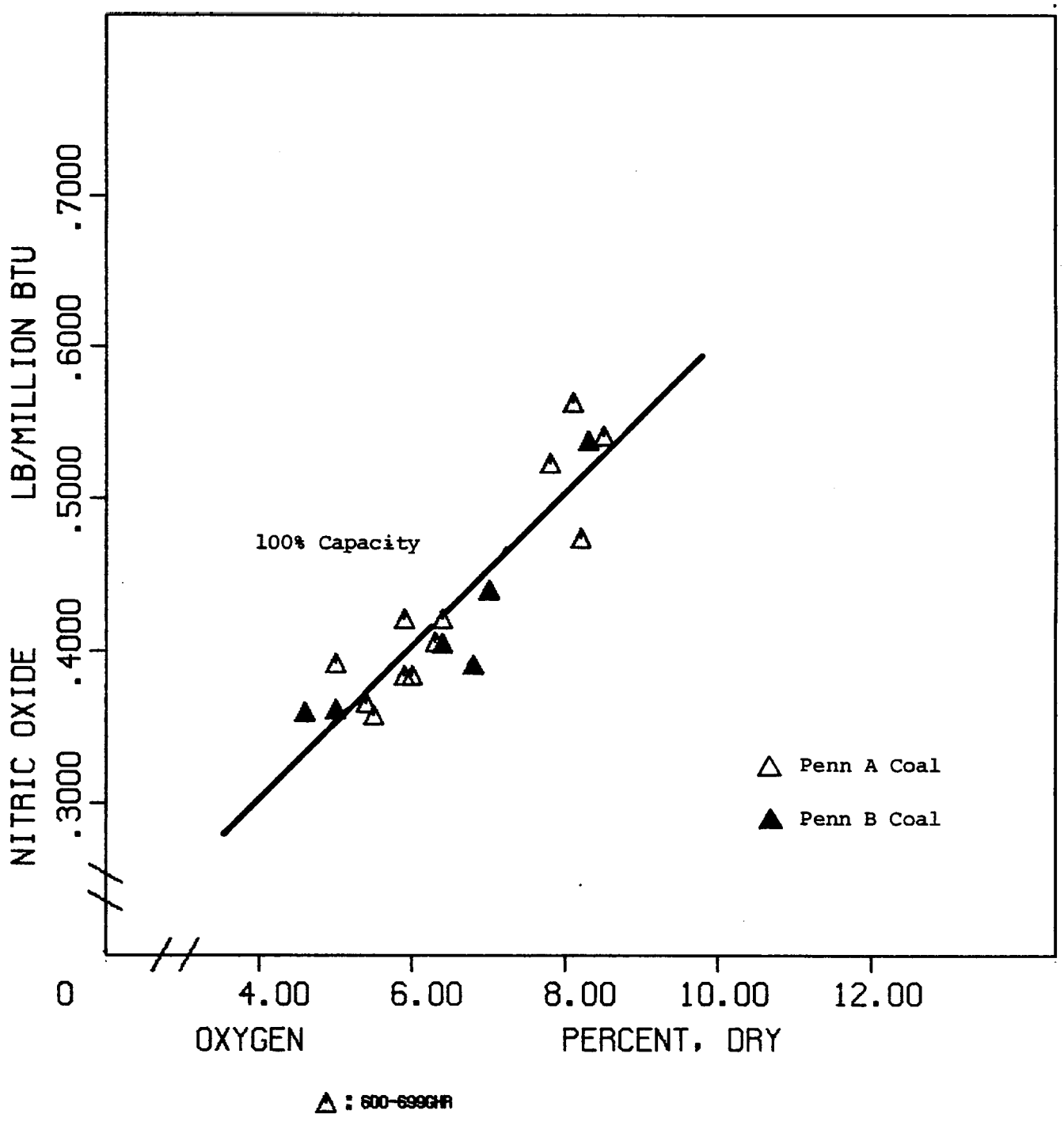


FIG. 5-7
NITRIC OXIDE VS. OXYGEN
TEST SITE F

Linear Regression Applied by Method of Least Squares
Coefficient of Determination = 0.83
Slope = 0.051 lbs $NO/10^6$ Btu per 1% O_2

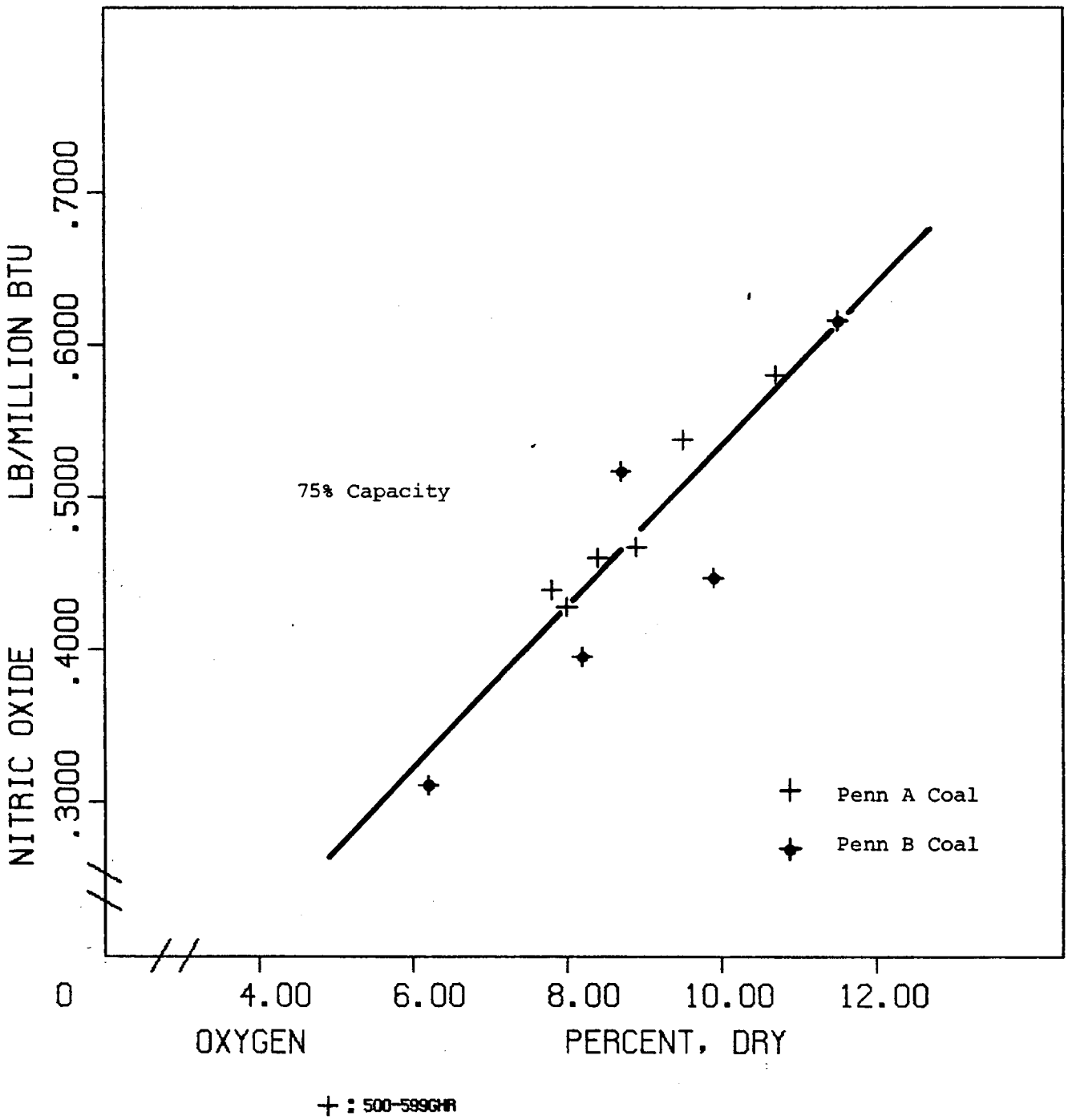


FIG. 5-8
NITRIC OXIDE VS. OXYGEN
TEST SITE F

Linear Regression Applied by Method of Least Squares
Coefficient of Determination = 0.82
Slope = 0.053 lbs NO/10^6 Btu per 1% O_2

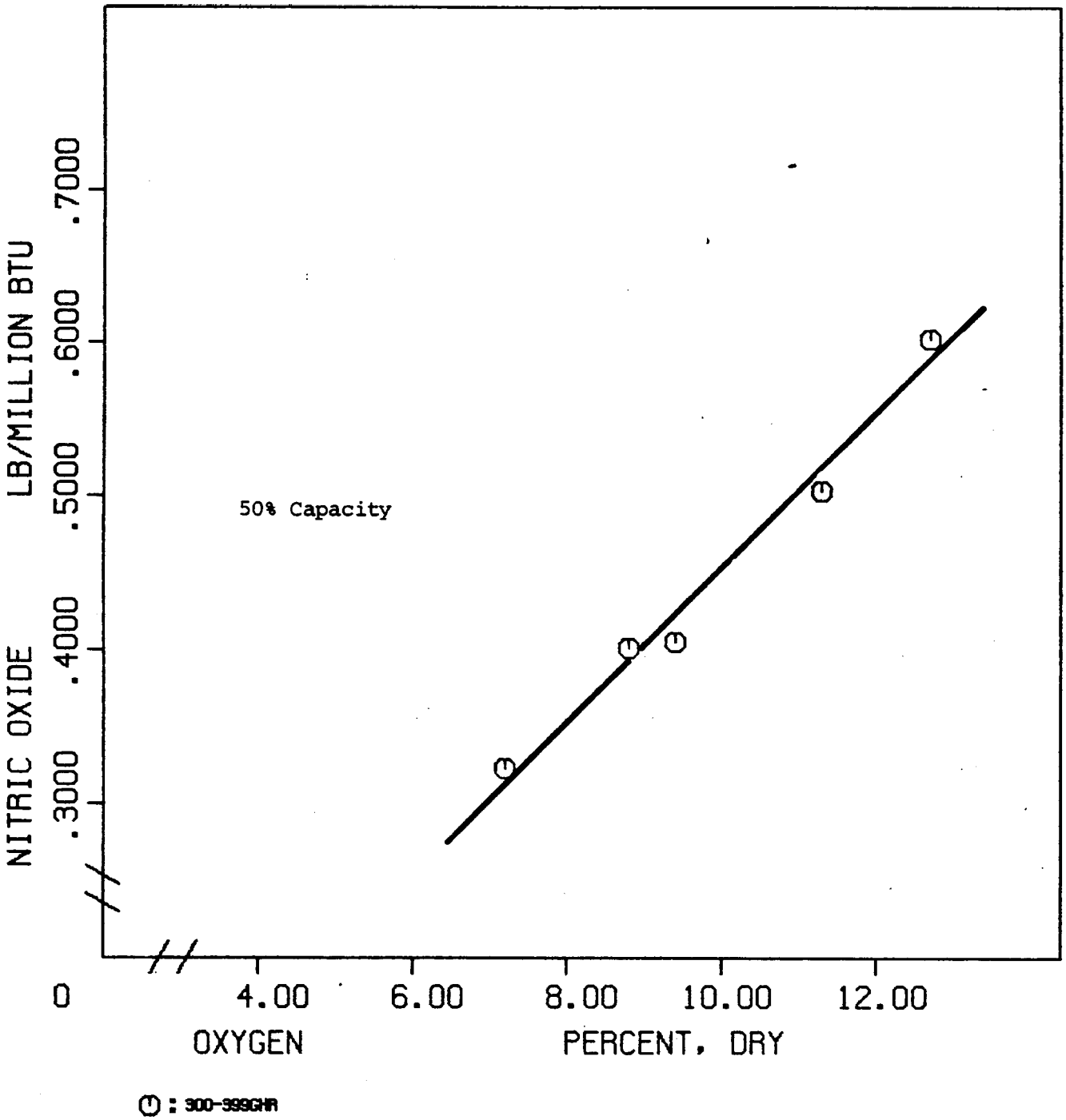


FIG. 5-9
NITRIC OXIDE VS. OXYGEN
TEST SITE F

Linear Regression Applied by Method of Least Squares
Coefficient of Determination = 0.98
Slope = 0.050 lbs NO/10^6 Btu per 1% O_2

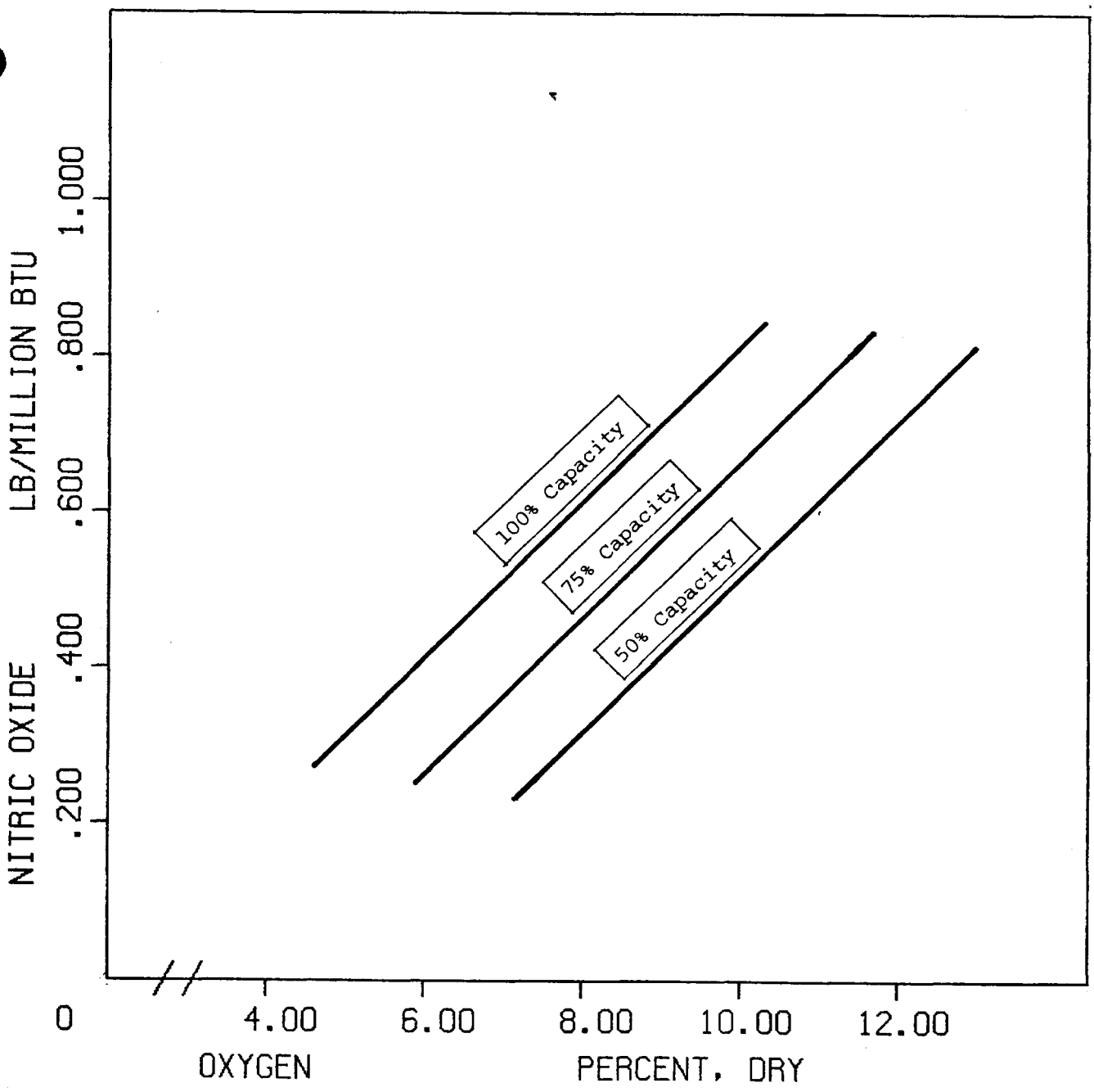


FIG. 5-10
NITRIC OXIDE VS. OXYGEN
TEST SITE F

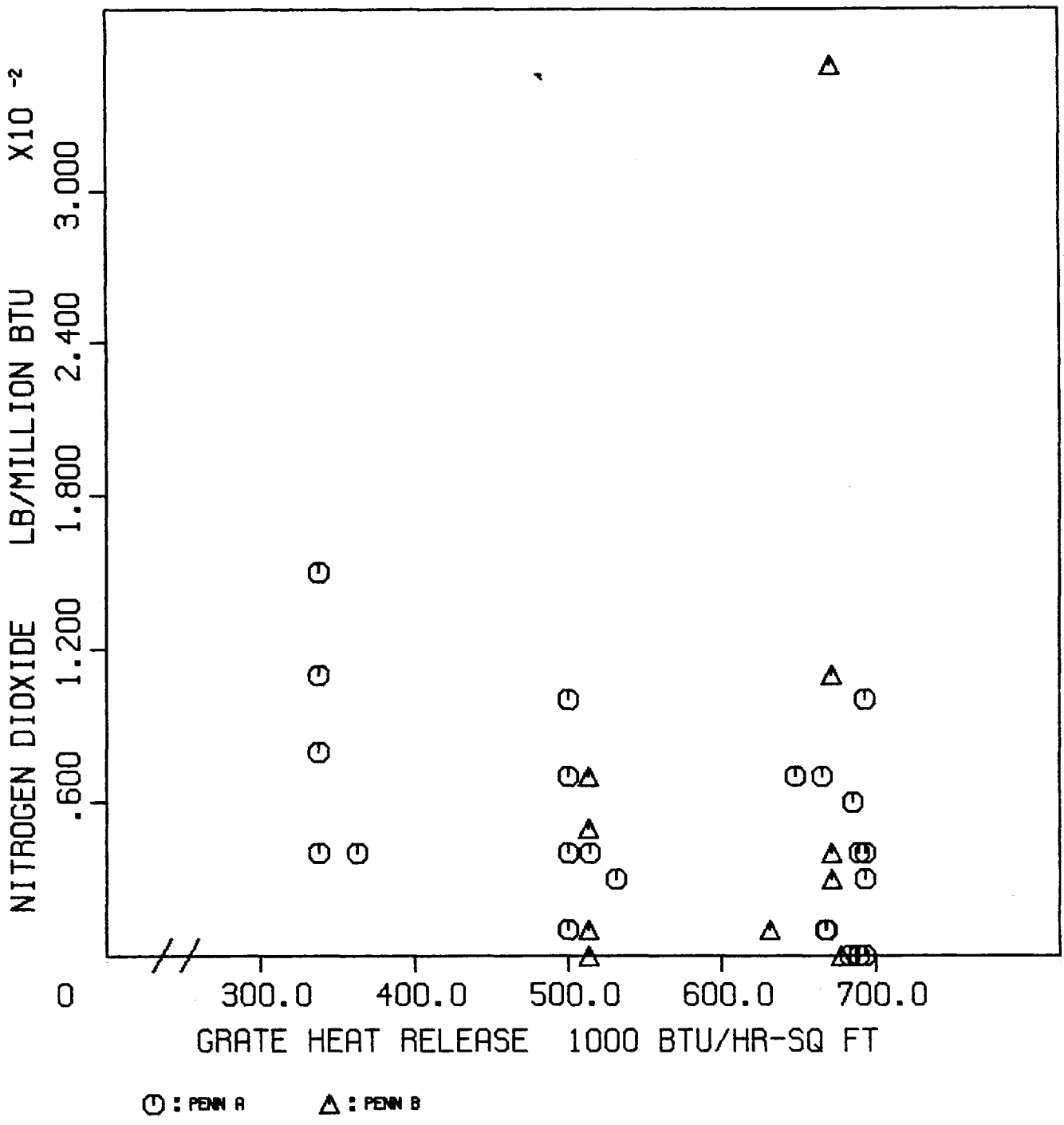


FIG. 5-11
NITROGEN DIOXIDE VS. GRATE HEAT RELEASE
TEST SITE F

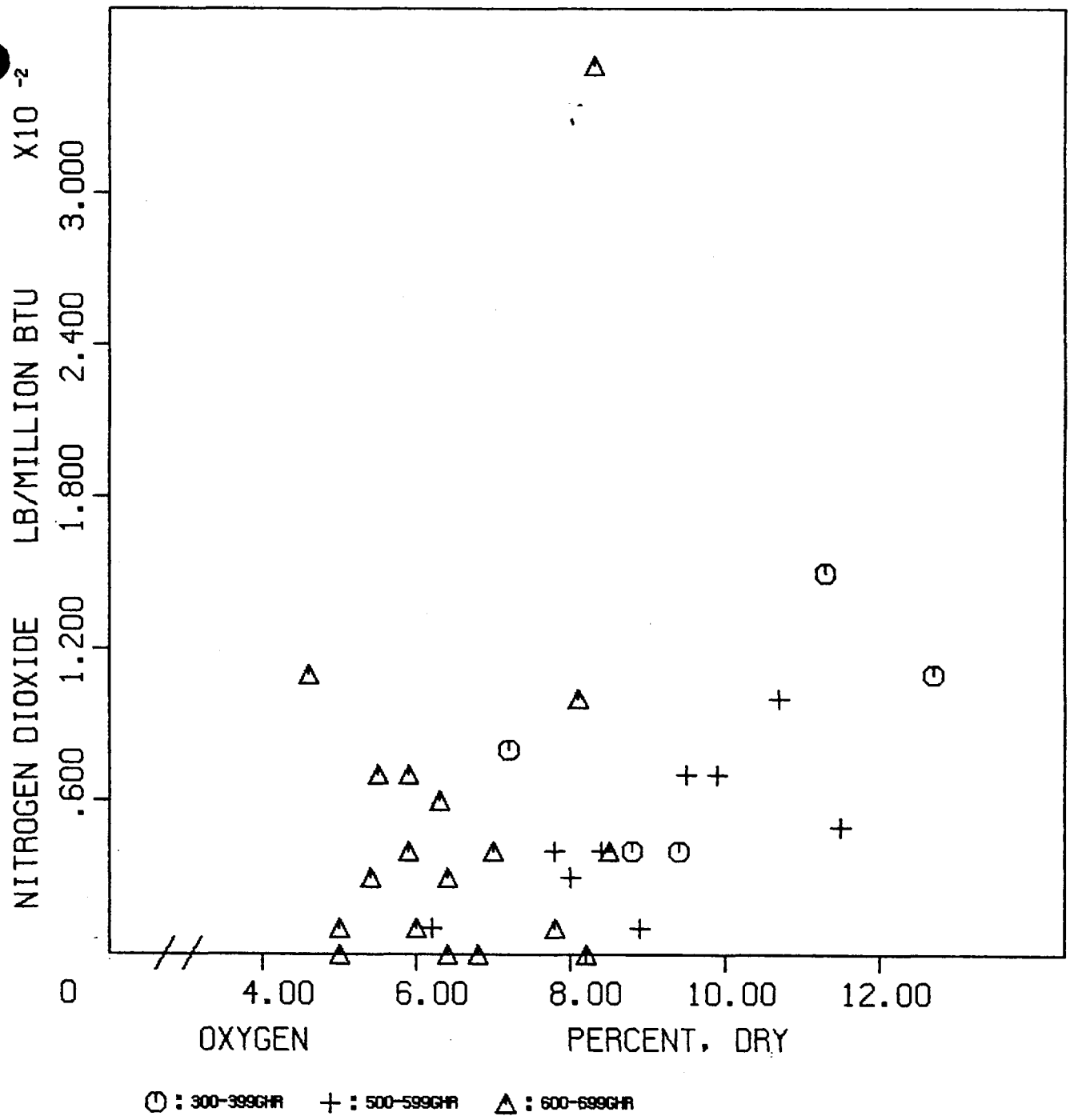


FIG. 5-12
NITROGEN DIOXIDE VS. OXYGEN
TEST SITE F

5.3.5 Sulfur Oxides vs Fuel Sulfur

Sulfur dioxide (SO_2) was measured during each test using an NDIR type continuous monitor. Sulfur trioxide (SO_3) was measured once while firing each of the two coals using a wet chemical method called the Goksoyr-Ross method. The test data and their significance are discussed in this section.

Sulfur dioxide (SO_2) concentrations are directly related to the sulfur content of the fuel. SO_2 was not observed to vary with load or O_2. The small fraction of fuel sulfur which is not converted to SO_2 is either retained in the ash or converted to SO_3 and other sulfur compounds. As a check on this relationship and on the validity of the data, the measured sulfur dioxide concentration was plotted against fuel sulfur in Figure 5-13. The diagonal line represents 100% conversion of fuel sulfur to SO_2.

Ash samples taken during two tests indicate that 4% of the fuel sulfur was retained in the ash. Assuming 96% conversion of fuel sulfur to SO_2 for all tests, the average error in the measurement technique was 7%. This is not out of line with expected performance of the instruments and techniques. Some of the sulfur oxides data could not be associated with a coal sample and were, therefore, not included in this determination.

Figure 5-14 presents all of the SO_2 measurements made at Site F as a function of grate heat release. A wide variation in SO_2 concentration is seen on the primary coal, Penn A. It can be shown that these variations are due primarily to variations in fuel sulfur and only secondary to measurement error.

The sulfur trioxide (SO_3) test data are presented in Table 5-10. Because the data are limited to two data points, no discussion or conclusions will be attempted.

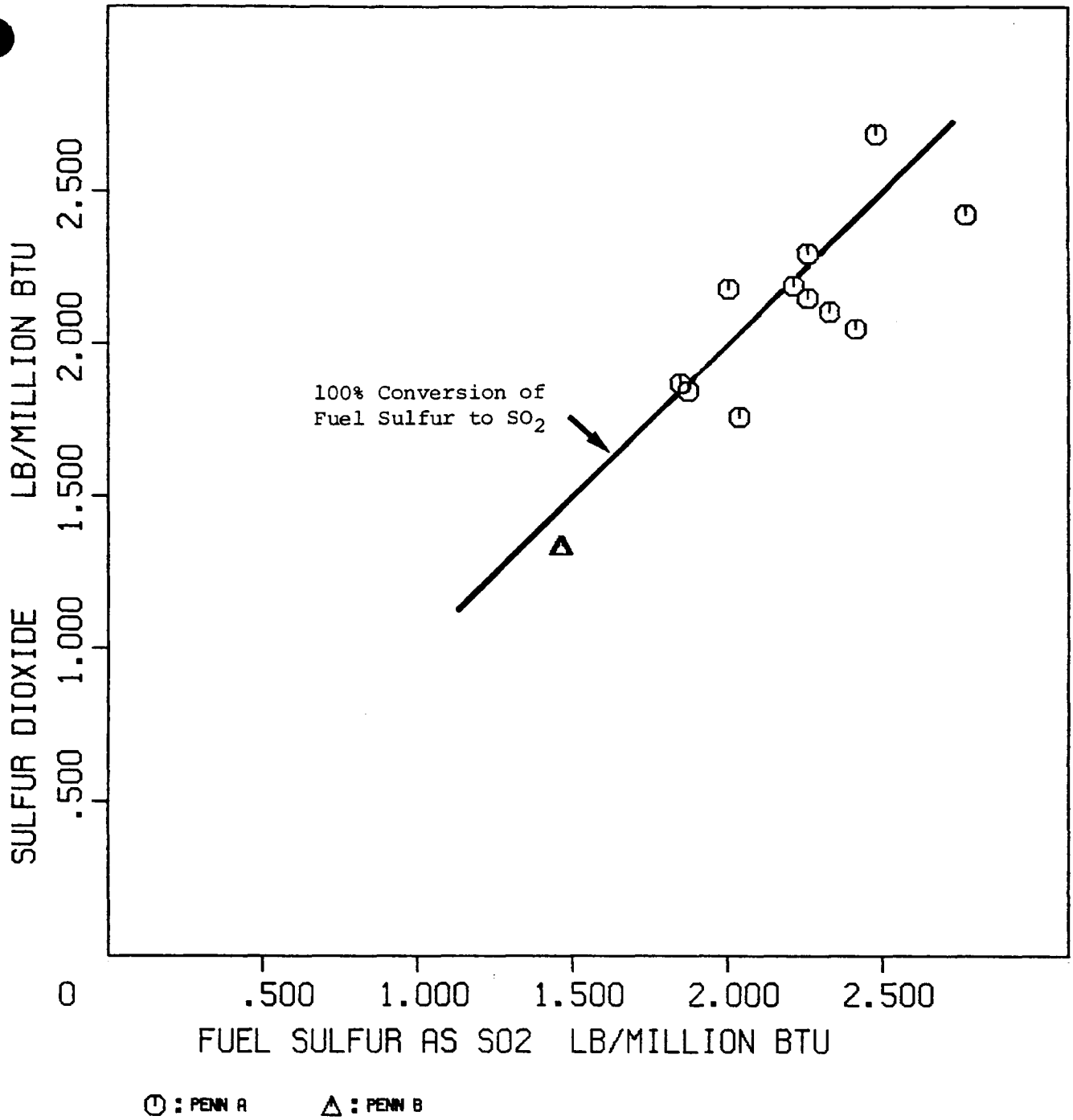


FIG. 5-13
SULFUR DIOXIDE VS. FUEL SULFUR AS SO2
TEST SITE F

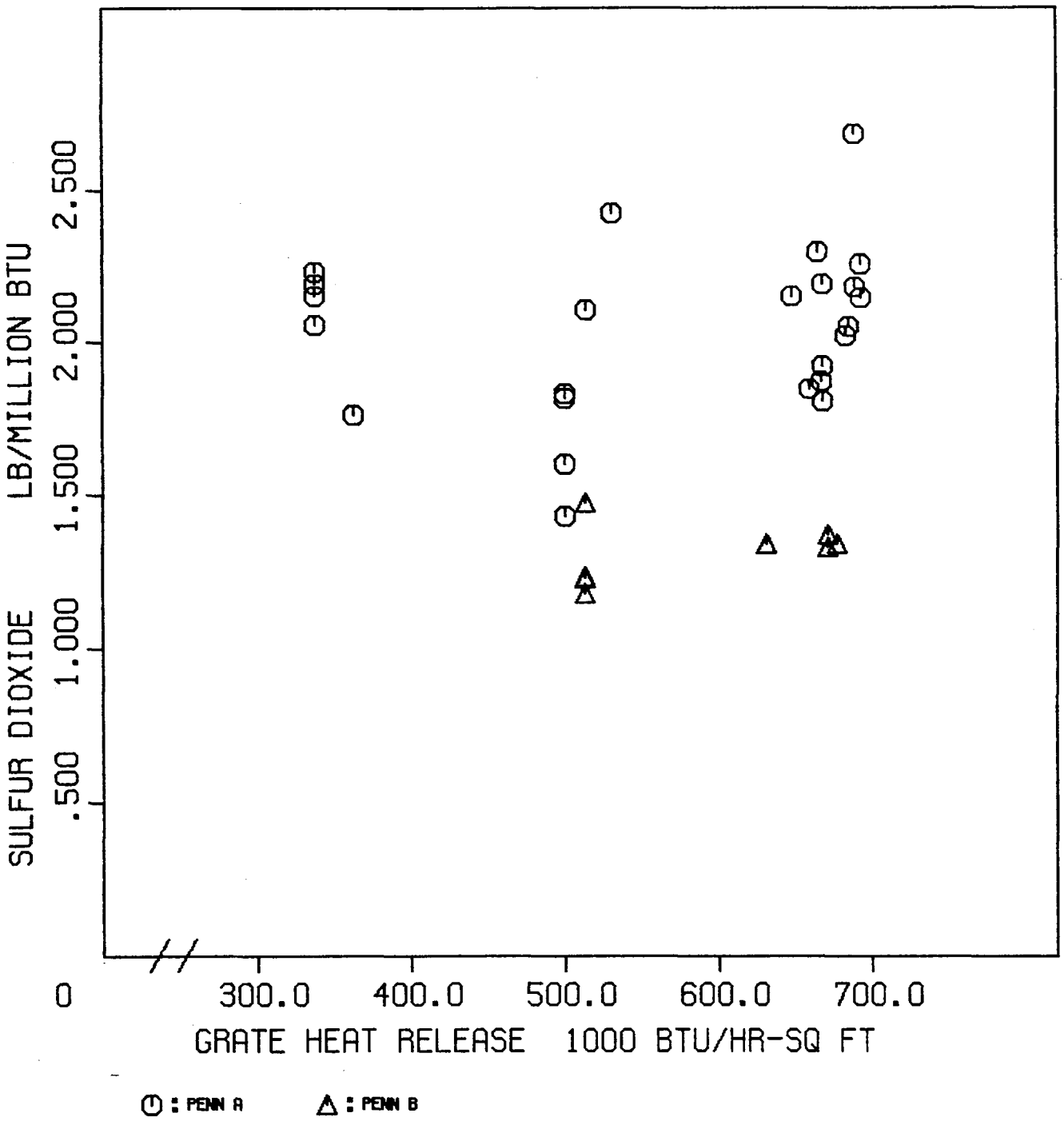


FIG. 5-14
SULFUR DIOXIDE VS. GRATE HEAT RELEASE
TEST SITE F

TABLE 5-10

SULFUR TRIOXIDE TEST DATA

Test No.	Coal	Test Conditions			SOx ppm @ 3% O_2	
		% Load	% O_2	OFA	SO_2	SO_3
22	Penn A	99	6.0	High	1126	0
30	Penn B	97	6.8	High	695	22

5.3.6 Hydrocarbons vs Oxygen and Grate Heat Release

Unburned hydrocarbons (HC) were measured with a heated sample line and a continuous monitoring instrument utilizing the flame ionization method of detection. Test data are plotted as a function of grate heat release in Figure 5-15, and as a function of oxygen in Figure 5-16.

There is some indication that the concentration of hydrocarbons in the flue gas may be load dependent. No hydrocarbons were measured at 50% load, while 75% load and 100% load tests showed measurable concentrations. The data averaged by load are given in Table 5-11.

TABLE 5-11

HYDROCARBON VS BOILER LOAD

	No. of Measurements	Average HC, ppm
100% Load	15	7.6 ± 6.3
75% Load	10	14.8 ± 8.3
50% Load	5	0.0

It is also noteworthy that measured hydrocarbon concentrations at full load were zero above 8% O_2 but measurable below 8% O_2. This trend, shown in Figure 5-16, did not hold true at 75% load.

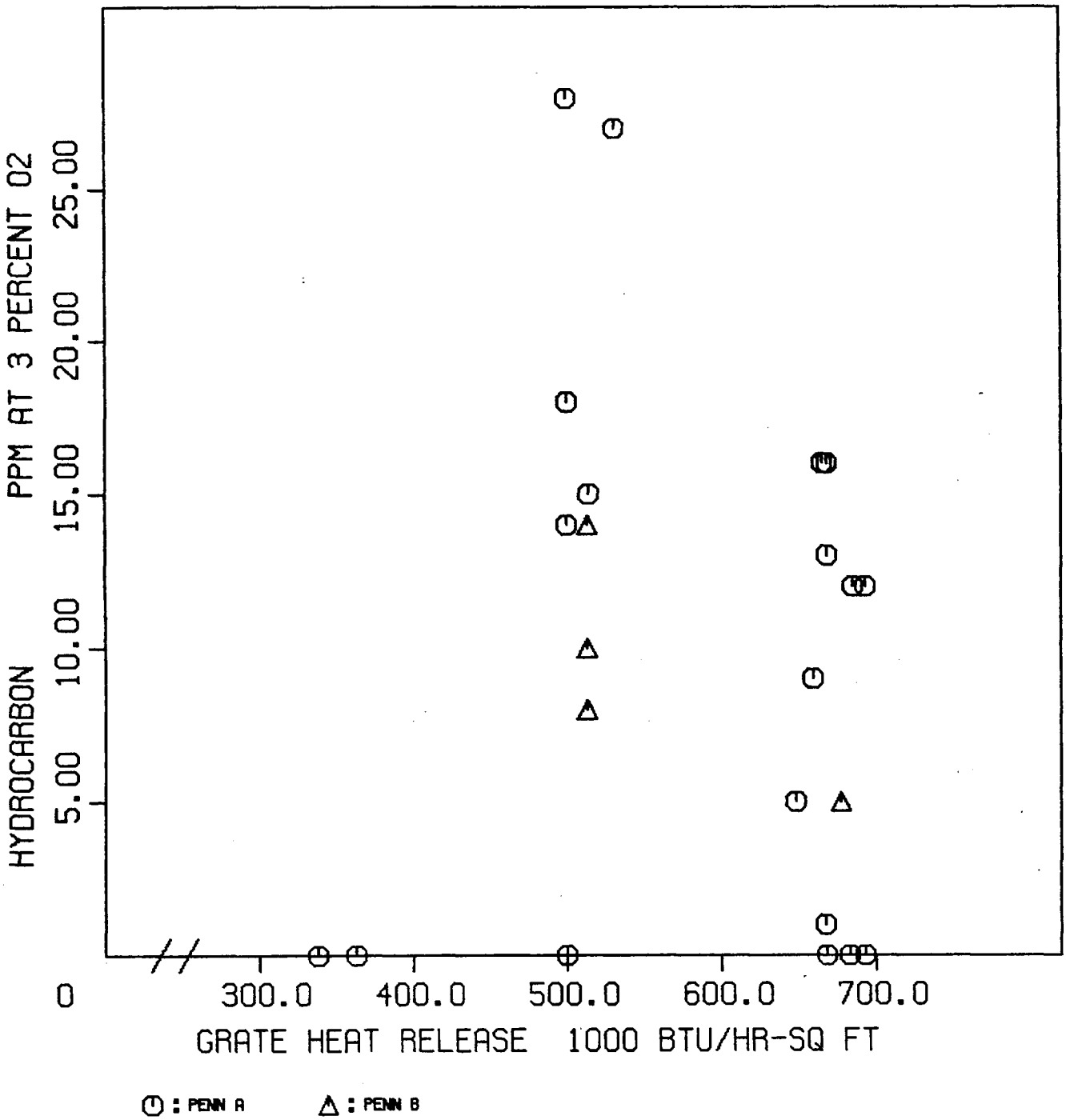


FIG. 5-15
HYDROCARBON VS. GRATE HEAT RELEASE
TEST SITE F

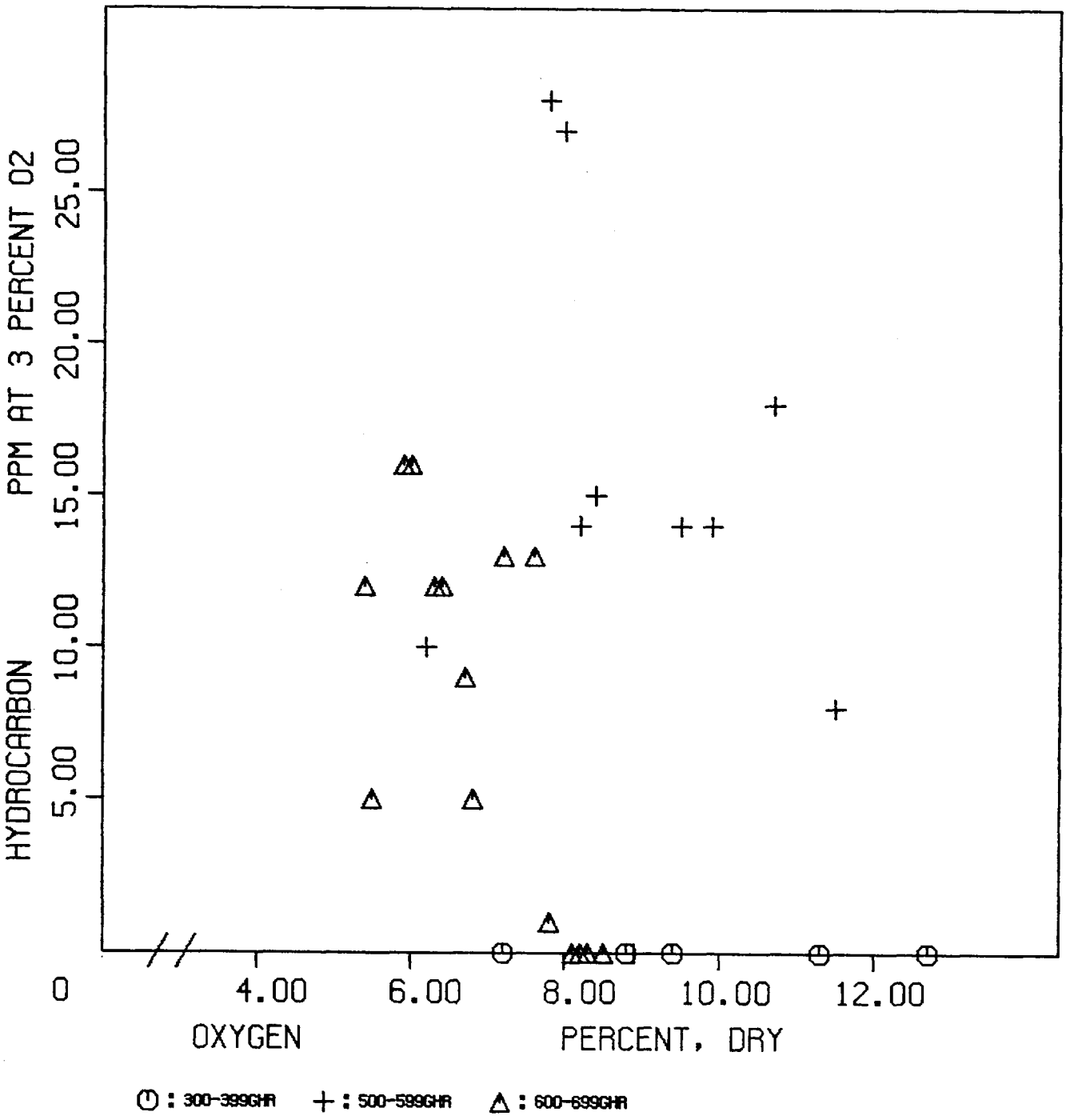


FIG. 5-16
HYDROCARBON VS. OXYGEN
TEST SITE F

5.3.7 Carbon Monoxide vs Oxygen and Grate Heat Release

Carbon monoxide (CO) was measured with an NDIR continuous monitor in units of parts per million (ppm) by volume. The data are plotted as a function of grate heat release in Figure 5-17, and as a function of oxygen in Figure 5-18.

Carbon monoxide concentrations were highest under high load low O_2 conditions and under low load high O_2 conditions. In between these extremes the carbon monoxide concentration remained below 400 ppm (0.04%) which is considered acceptable for a coal-fired stoker boiler.

5.3.8 Combustibles in the Ash vs Oxygen and Grate Heat Release

Flyash samples collected at the economizer outlet and at the multiclone dust collector outlet were baked in a high temperature oven for determination of combustible content. Bottom ash samples were also processed in this manner. The test data for each of the sample locations are plotted against grate heat release in Figures 5-19, 5-20, and 5-21. The data are plotted against oxygen in the flue gas in Figures 5-22, 5-23 and 5-24.

In general, the combustible fractions in the various ashes did not vary as functions of either grate heat release or oxygen. Although the data are limited, they are seen to remain relatively constant. The one exception is the economizer outlet sample taken at low load (363 GHR) and high O_2 (9.4%). This sample contained only 50% combustibles compared to the average 69% combustible content for the other economizer outlet flyash samples.

Average combustible content for the three sample locations were $66.6 \pm 7.6\%$ at the economizer outlet, $46.5 \pm 3.2\%$ at the dust collector outlet, and $12.4 \pm 5.2\%$ in the bottom ash.

5.3.9 Boiler Efficiency vs Grate Heat Release

Boiler efficiency was determined using the ASME heat loss method for all tests which included a particulate mass loading determination. The test data, plotted in Figure 5-25, shows a general decrease in efficiency as grate heat release increases. The reason for this decrease in efficiency is best illustrated in Table 5-12.

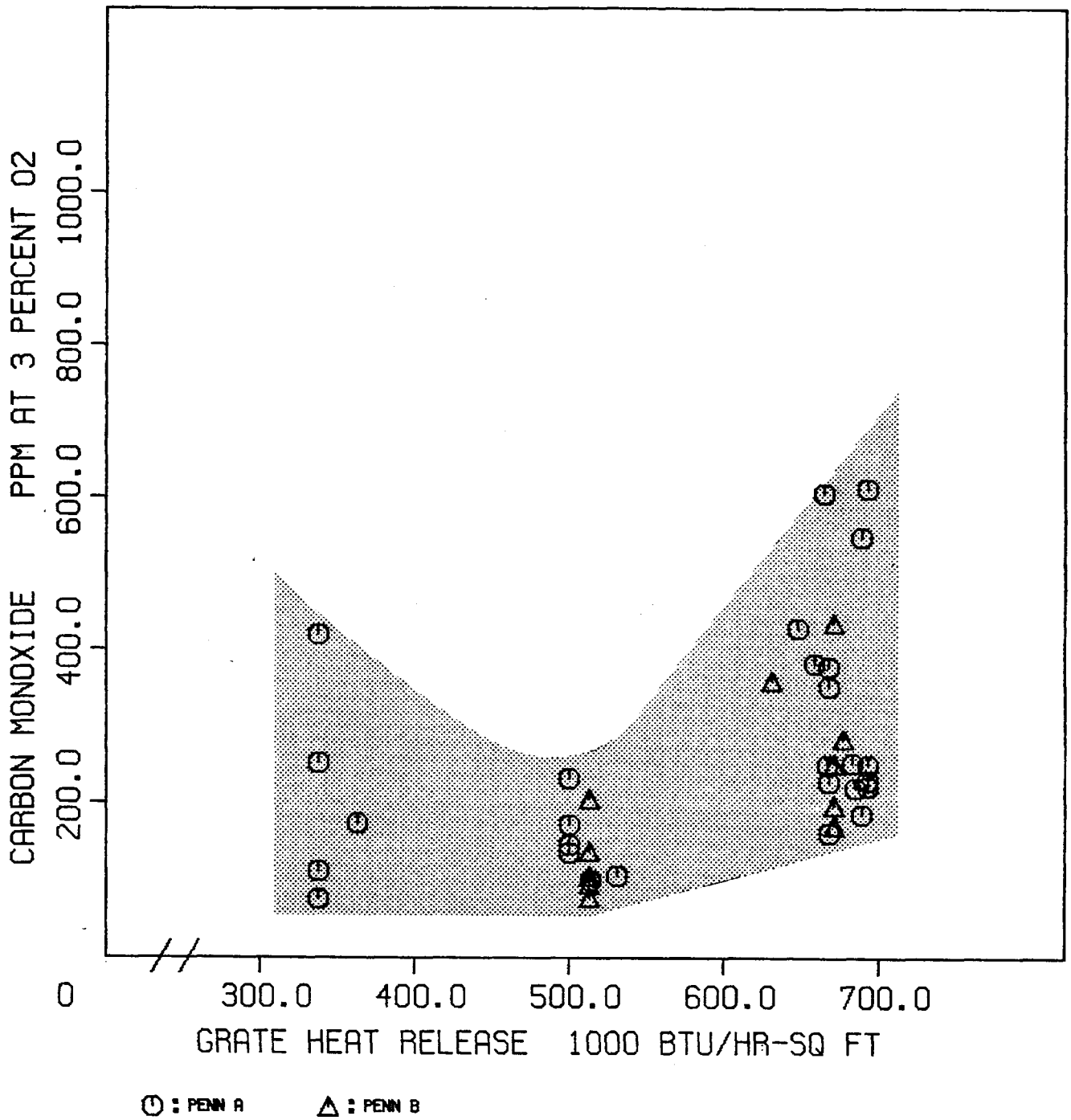


FIG. 5-17

CARBON MONOXIDE VS. GRATE HEAT RELEASE
TEST SITE F

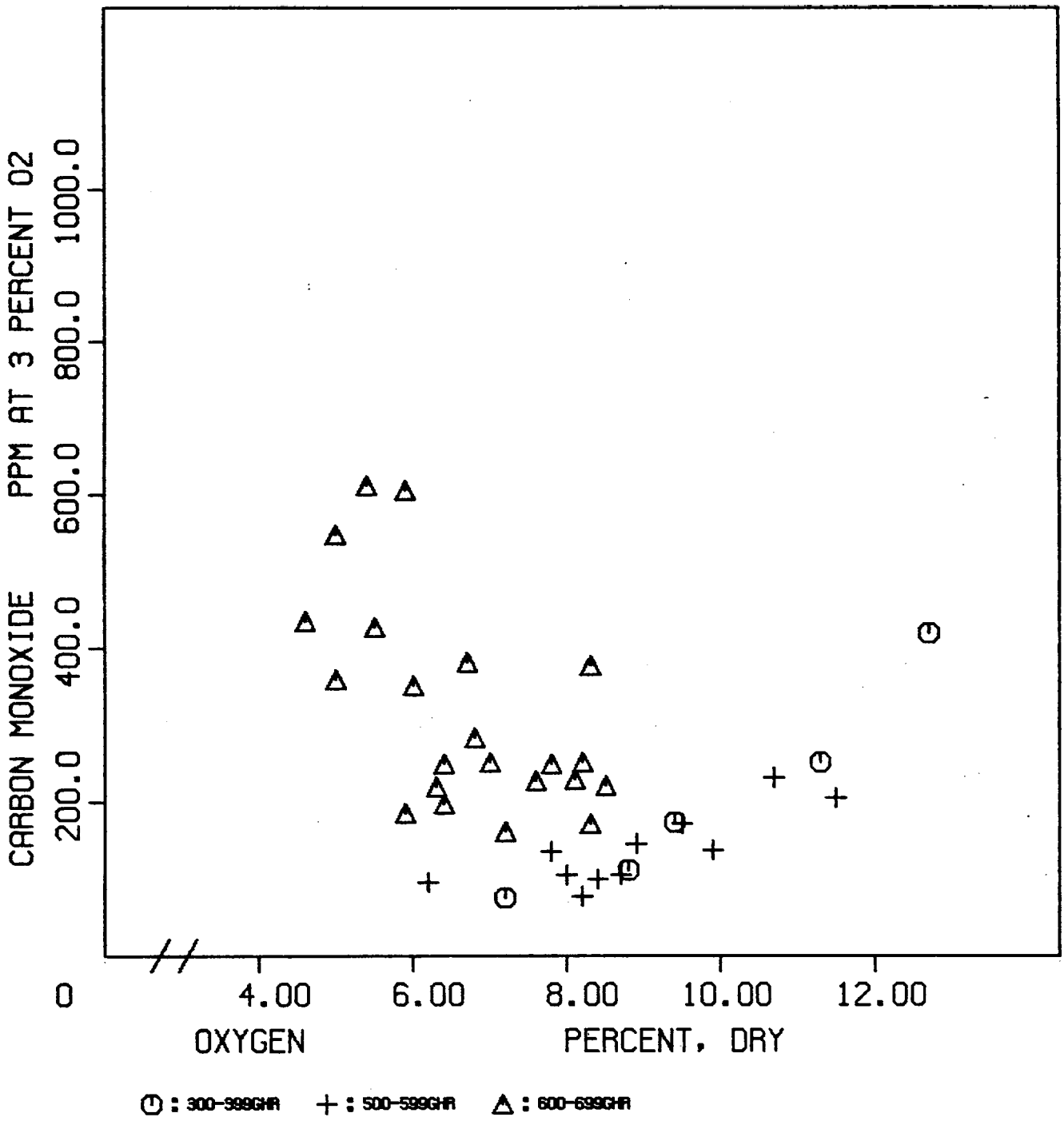


FIG. 5-18
CARBON MONOXIDE VS. OXYGEN
TEST SITE F

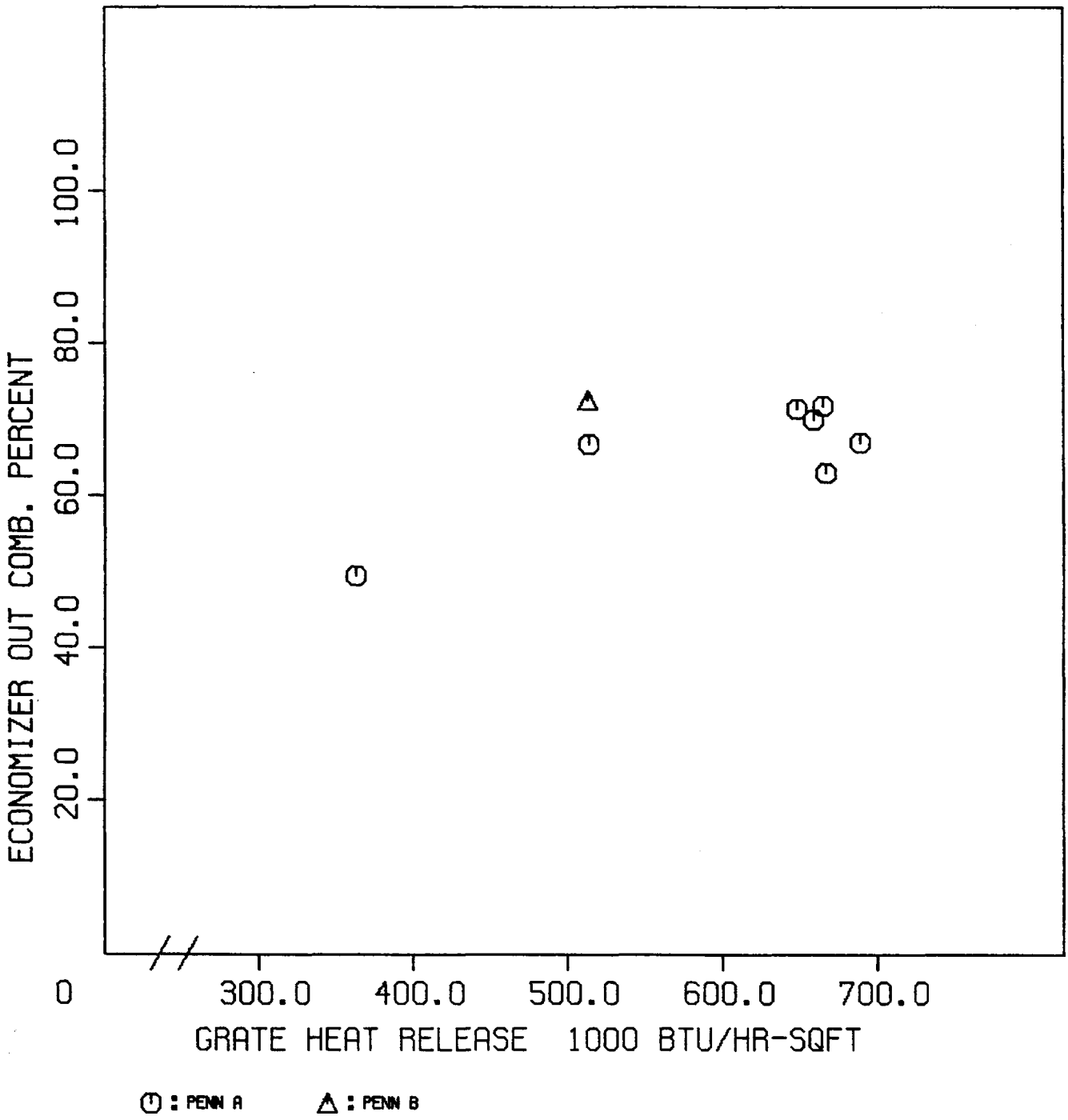


FIG. 5-19

ECONOMIZER OUT COMB. VS. GRATE HEAT RELEASE
TEST SITE F

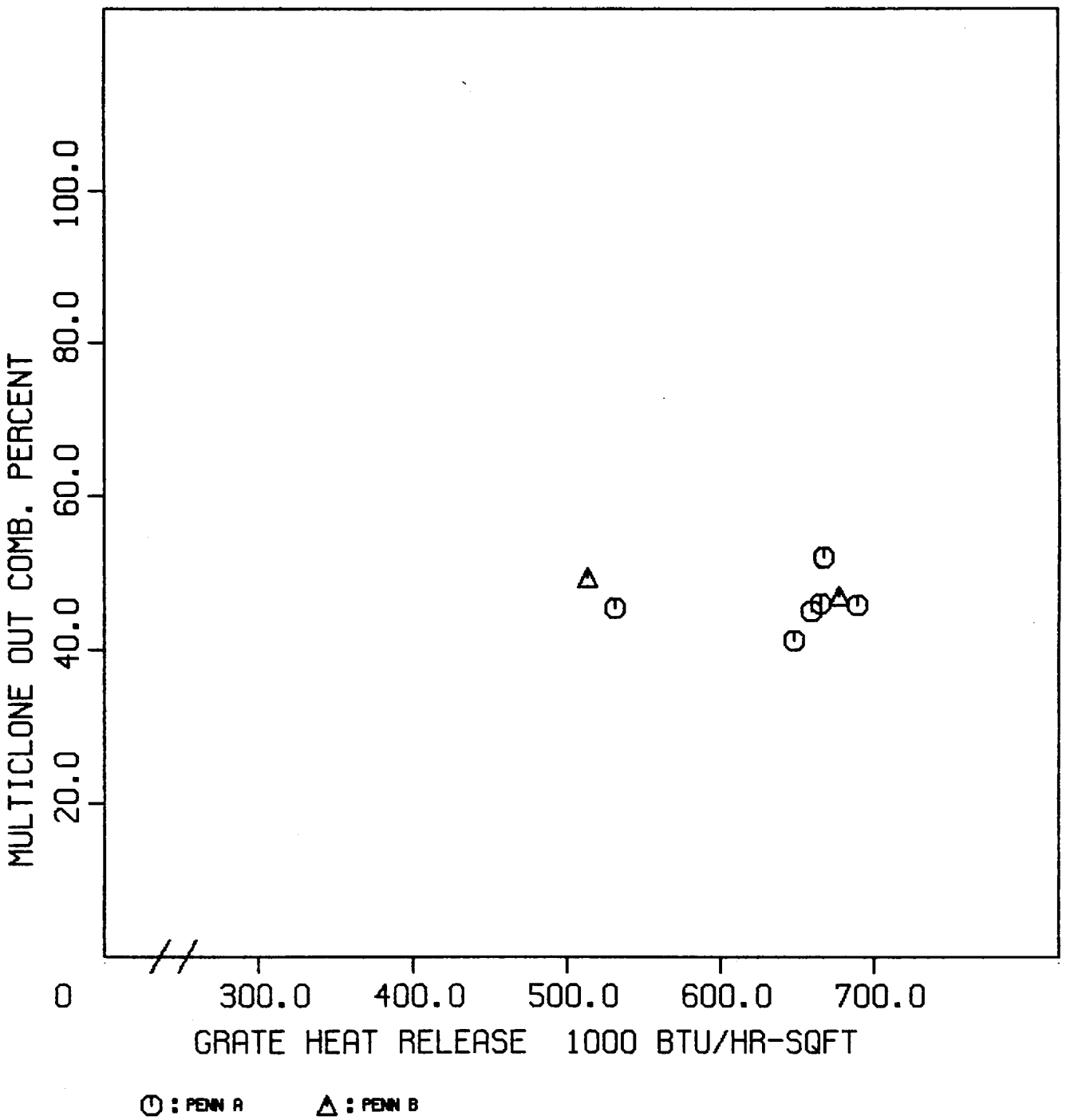


FIG. 5-20

MULTICLONE OUT COMB. VS. GRATE HEAT RELEASE
TEST SITE F

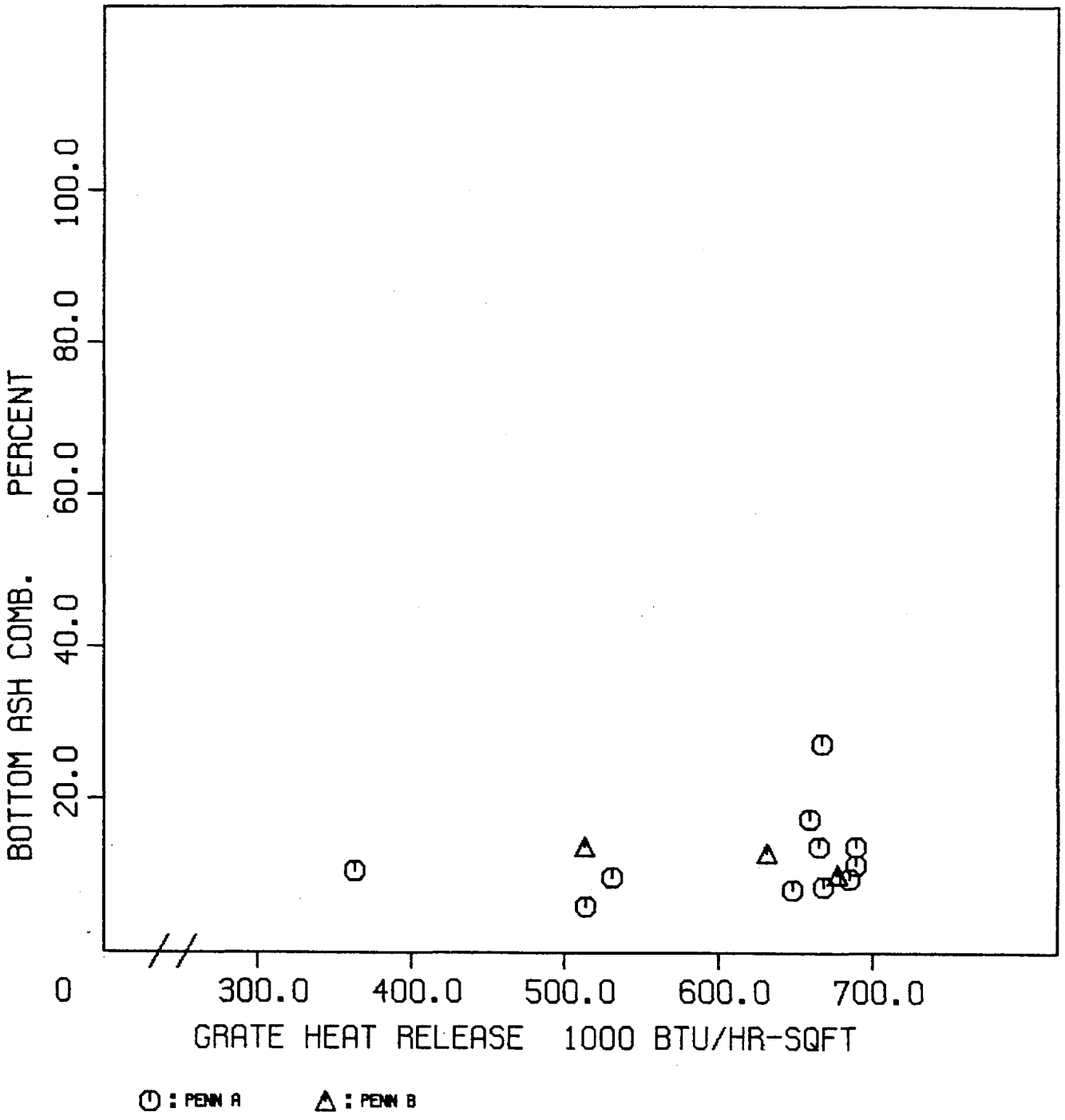


FIG. 5-21

BOTTOM ASH COMB. VS. GRATE HEAT RELEASE
TEST SITE F

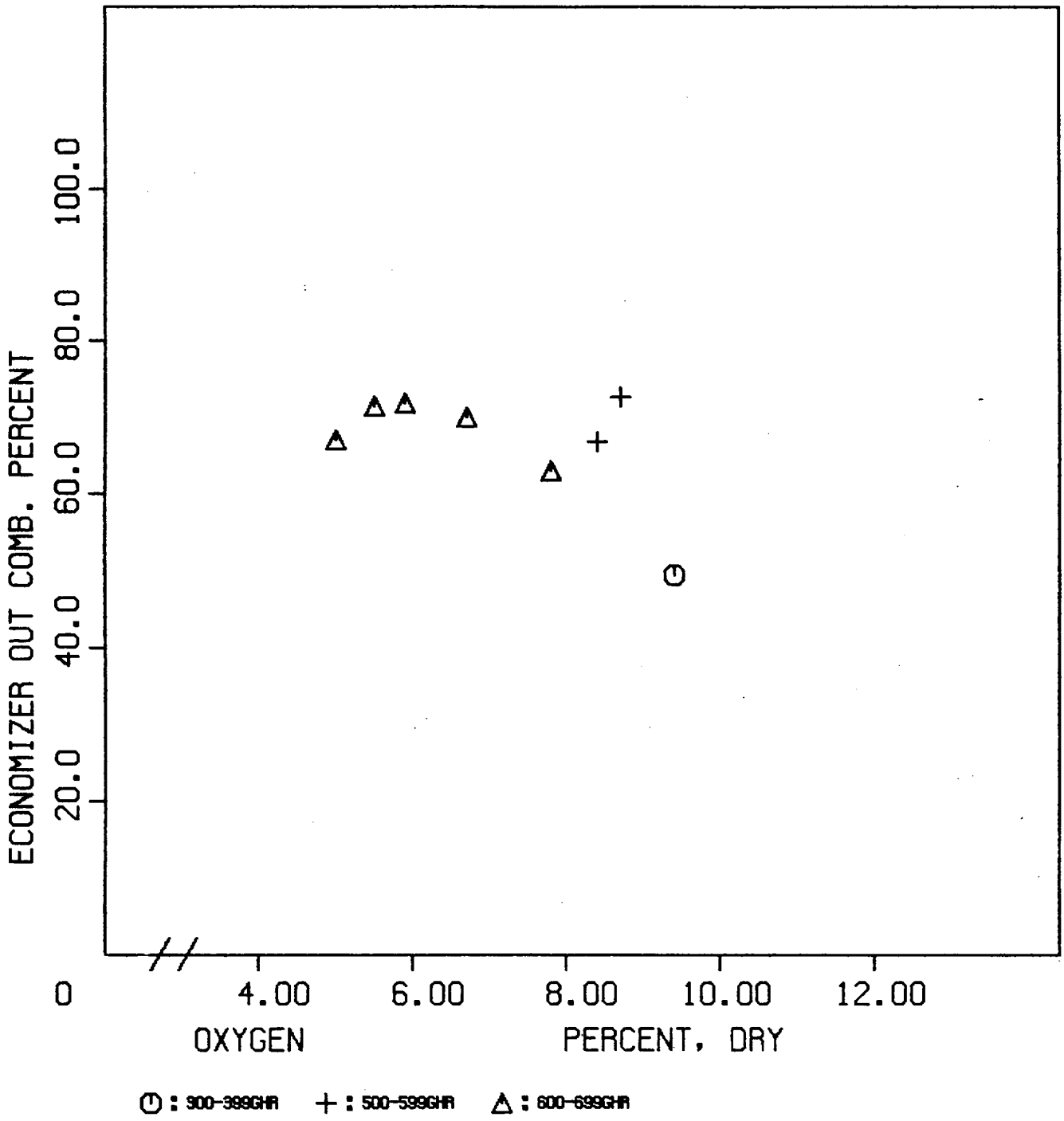


FIG. 5-22
ECONOMIZER OUT COMB. VS. OXYGEN
TEST SITE F

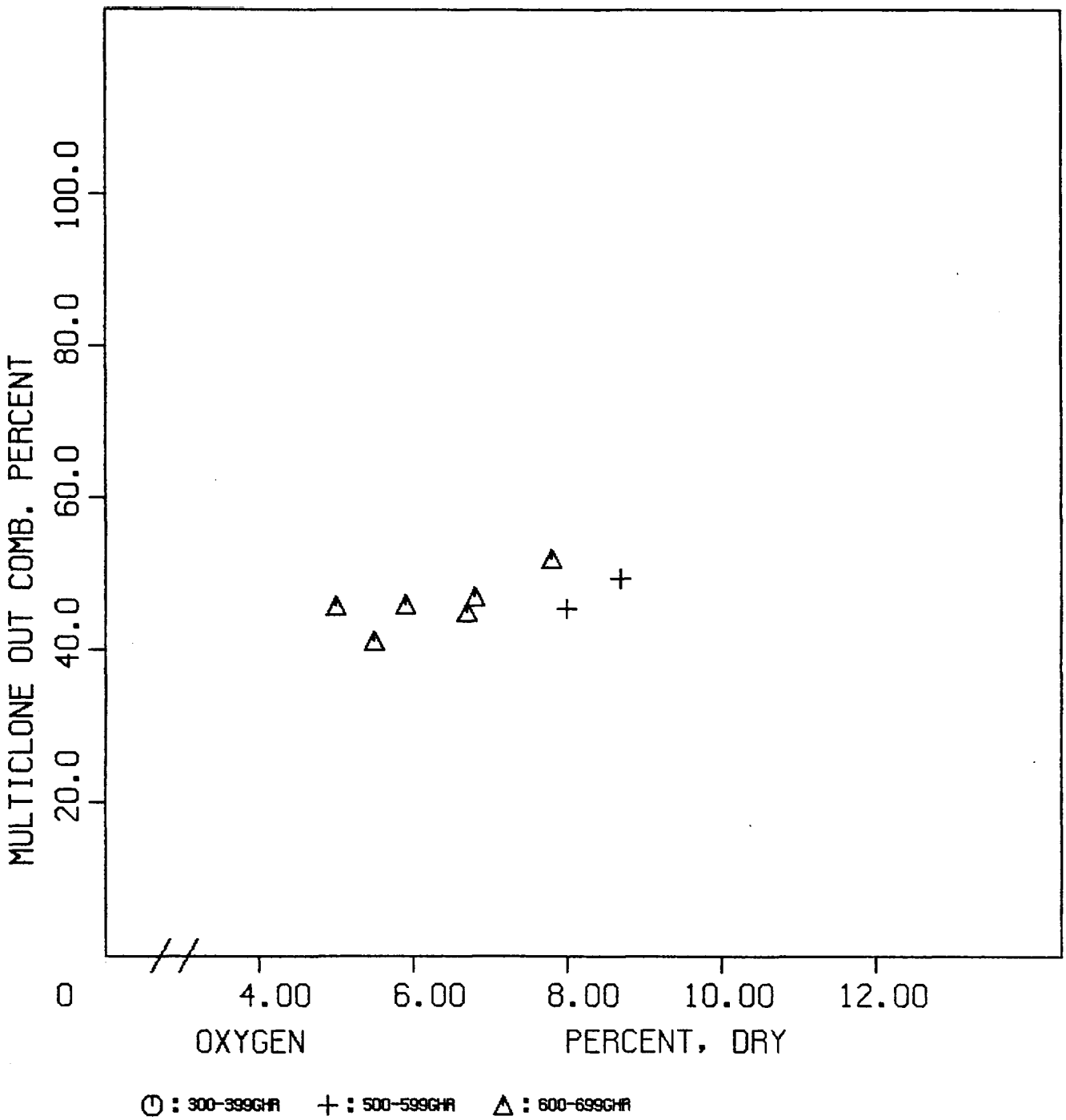


FIG. 5-23
MULTICLONE OUT COMB. VS. OXYGEN
TEST SITE F

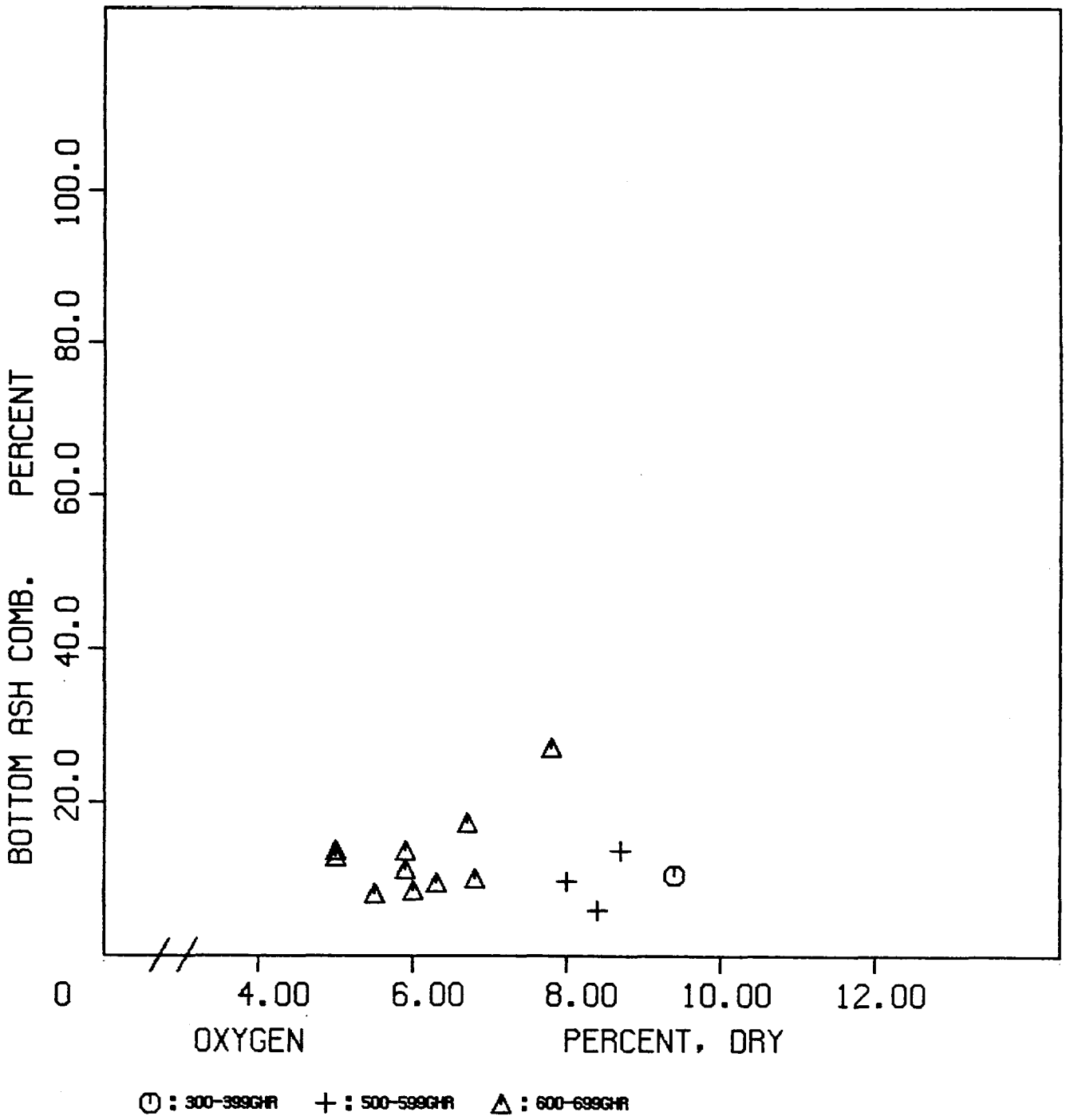


FIG. 5-24

BOTTOM ASH COMB. VS. OXYGEN
TEST SITE F

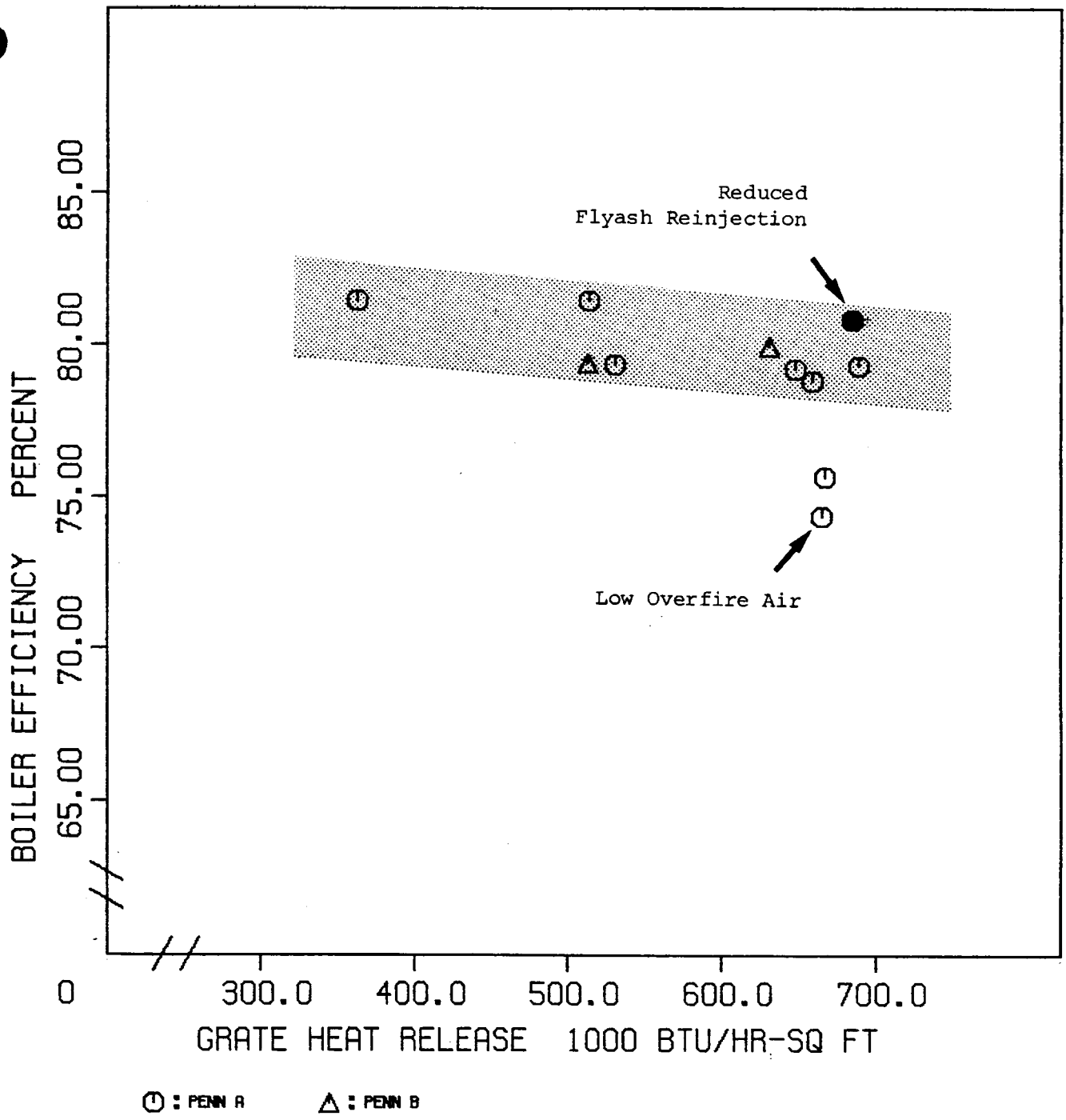


FIG. 5-25

BOILER EFFICIENCY VS. GRATE HEAT RELEASE
TEST SITE F

TABLE 5-12

BOILER EFFICIENCY VS LOAD

	Average Heat Losses				Boiler
	Dry Gas	Combustibles	Radiation	Other	Efficiency
100% Load	7.8	7.9	0.5	5.7	78.1
75% Load	8.5	5.2	0.7	5.3	80.3
50% Load	7.5	4.5	0.9	5.6	81.5

This Table shows that combustibles played a major roll in determining boiler efficiency. The increase in combustible heat loss with load accounts for the decrease in boiler efficiency.

Boiler efficiency heat loss parameters and calculations are compared to the manufacturers predicted performance data in Tables 5-13 and 5-14. Data from a 1977 boiler acceptance test are also included. In comparing these tests, the only real discrepancy was found in the combustible heat loss category.

Combustible heat losses measured in this program were 3 to 4% higher than those measured and predicted earlier. It is suspected that the heat loss was calculated differently in this test program than it was in the acceptance test or by the boiler manufacturer. To help clarify the issue, the data and assumptions used to calculate combustible loss for Tests 24 and 29 are given in Table 5-15. The heat losses in Table 5-13 are not adjusted to the design coal.

TABLE 5-13

PREDICTED VS MEASURED HEAT LOSSES

	Dry Gas	Moisture in Fuel	H_2O From H_2 in Fuel	Total Combustibles	Radiation	Unmeasured	BOILER EFFICIENCY
Mfg. Predicted Performance	6.33	0.16*	3.63	4.70	0.58	1.50	83.10
1977 Acceptance Test	7.60	0.34	4.10	4.23	0.58	1.50	81.65
Test 24 - Penn A Coal	6.37	0.31	3.71	8.33†	0.50	1.50	79.28
Test 29 - Penn B Coal	6.86	0.31	3.68	7.18†	0.51	1.50	79.96

* The manufacturer listed a heat loss due to moisture in the air of 0.16%, but did not list a separate heat loss due to moisture in the fuel.

† High combustible heat loss of tests 24 and 29 may be due in part to method of calculation.

TABLE 5-14

PREDICTED VS MEASURED PERFORMANCE DATA

	Manufacturers Predicted Performance	Customers Acceptance Test, 1977	Test 24 Penn A Coal	Test 29 Penn B Coal
Steam Flow, lbs/hr	80,000	81,803	81,957	80,400
Fuel Flow, lbs/hr	7,205	8,050	7,495	6,552
Steam Pressure, psig	150	143.8	143.0	139.7
Steam Temperature, °F	Saturated	Saturated	Saturated	Saturated
FW to Economizer, °F	228	220	220	220
Gas Temperature Leaving Economizer, °F	350	377	370	373
Excess Air, %	30	36.8	29.9	29.4
Boiler Efficiency, %	83.10	81.65	79.28	79.96

TABLE 5-15

CALCULATION OF COMBUSTIBLE HEAT LOSS

	Test 24	Test 29
% Combustible in Flyash (Measured)	67.0	72.6
Lbs flyash/10^6 Btu Coal (Measured)	7.183	5.944
Btu/lb Combustible (Determined in Previous Tests)	14,250	14,250
* HEAT LOSS DUE TO COMBUSTIBLES IN FLYASH	6.86%	6.15%
% Combustible in Bottom Ash (Measured)	13.8	13.1
** Lbs Bottom Ash/10^6 Btu Coal (Calculated by Mass Balance)	7.464	5.551
Btu/lb Combustible	14,250	14,250
* HEAT LOSS DUE TO COMBUSTIBLES IN BOTTOM ASH	1.47%	1.04%
TOTAL COMBUSTIBLE HEAT LOSS	8.33%	7.19%

* Heat Loss Calculated as Follows:

$$\text{Combustible Heat Loss} = \frac{\text{lbs ash}}{10^6 \text{ Btu}} \times \frac{\% \text{ Comb in ash}}{100} \times \frac{\text{Btu}}{\text{lbs comb}} \times 10^{-4}$$

** Ash in Coal Minus Ash in Flyash = Ash in Bottom Ash, with Appropriate Corrections for Combustibles:

$$\text{Lbs Bottom Ash}/10^6 \text{ Btu Coal} = \frac{\left(\frac{\% \text{ ash in coal}}{\text{Btu/lb coal}}\right)(10^4) - \left(\frac{\text{lbs flyash}}{10^6 \text{ Btu}}\right)\left(1 - \frac{\% \text{ Comb in flyash}}{100}\right)}{\left(1 - \frac{\% \text{ Comb in bottom ash}}{100}\right)}$$

5.4 COAL PROPERTIES

Two coals were tested in Boiler F. The primary coal is called Pennsylvania A coal in this report, or Penn A for short. The secondary coal was specially ordered for this test program. It was a washed and mechanically treated high grade metallurgical coal. This special coal, called Penn B in this report, was lower in ash and sulfur than the primary coal.

This section describes coal properties and their impact on emissions and boiler efficiency. Except for sulfur oxide emissions, the two coals performed similarly.

5.4.1 Chemical Composition of the Coals

Representative coal samples were obtained from the unit's single coal scale during each particulate test and SASS test. Each of these coal samples was given a proximate analysis. In addition, two selected samples of each coal were given an ultimate analysis, and tested for ash fusion temperature, Hardgrove grindability index, free swelling index, and mineral composition of the ash.

The two coals differ primarily in their moisture, ash and sulfur content. These three coal properties are presented in Table 5-16 on a heating value basis in order to allow for a more meaningful comparison. This Table shows that the Pennsylvania B coal was a better coal than Pennsylvania A in that it was lower in moisture, ash and sulfur.

TABLE 5-16

COAL PROPERTIES CORRECTED TO A CONSTANT 10^6 BTU BASIS

	Penn A Coal	Penn B Coal
Moisture, lbs/10^6 Btu	3.1	2.7
Ash, lbs/10^6 Btu	8.0	6.6
Sulfur, lbs/10^6 Btu	1.11	0.74

The individual coal analyses are tabulated in Tables 5-17, 5-18, and 5-19.

TABLE 5-17

FUEL ANALYSIS - PENNSYLVANIA A COAL
TEST SITE F

TEST NO.	05	15	17	18	19	20	21	22	23	23A	24	AVG	STD DEV
PROXIMATE (As Rec)													
% Moisture	4.80	5.69	5.26	5.58	7.76	2.26	1.99	3.13	2.28	2.51	3.42	4.06	1.87
% Ash	10.80	10.96	9.69	12.50	11.08	8.43	11.15	9.44	9.45	11.01	11.59	10.55	1.17
% Volatile	14.03	22.86	23.86	22.66	22.45	25.22	23.99	23.58	24.20	23.92	23.32	22.74	2.99
%Fixed Carbon	70.37	60.49	61.19	59.26	58.71	64.09	62.87	63.85	64.07	62.56	61.67	62.65	3.15
Btu/lb	13145	12975	13223	12649	12501	13813	13347	13627	13750	13467	13164	13242	85
% Sulfur	1.34	1.20	1.24	1.43	1.35	1.61	1.85	1.51	1.66	1.67	1.32	1.47	0.21
ULTIMATE (As Rec)													
% Moisture								3.13	--	--	3.42	3.28	0.21
% Carbon								76.57	--	--	73.70	75.14	2.03
% Hydrogen								4.69	--	--	4.53	4.61	0.11
% Nitrogen								1.26	--	--	1.20	1.23	0.04
% Chlorine								0.15	--	--	0.14	0.15	0.01
% Sulfur								1.51	--	--	1.32	1.42	0.13
% Ash								9.44	--	--	11.59	10.52	1.52
% Oxygen (Diff)								3.25	--	--	4.10	3.68	0.60
ASH FUSION (Reducing)													
Initial Deformation								2420	--	--	2700+		
Soft (H-W)								2600	--	--	2700+		
Soft (H-1/2W)								2650	--	--	2700+		
Fluid								2700+	--	--	2700+		
HARDGROVE GRINDABILITY INDEX								96	--	--	89	92.5	4.95
FREE SWELLING INDEX								9	--	--	9	9	--

TABLE 5-18

FUEL ANALYSIS - PENNSYLVANIA B COAL
TEST SITE F

Test No.	29	30	AVG	STD DEV
PROXIMATE (As Rec)				
% Moisture	3.54	3.84	3.69	0.21
% Ash	8.79	9.12	8.96	0.23
% Volatile	26.10	25.39	25.75	0.50
% Fixed Carbon	61.57	61.55	61.61	0.06
Btu/lb	13623	13568	13596	39
% Sulfur	1.00	0.99	1.00	0.01
ULTIMATE (As Rec)				
% Moisture	3.54	3.84	3.69	0.21
% Carbon	76.62	76.09	76.36	0.37
% Hydrogen	4.70	4.68	4.69	0.01
% Nitrogen	1.15	1.09	1.12	0.04
% Chlorine	0.17	0.17	0.17	--
% Sulfur	1.00	0.99	1.00	0.01
% Ash	8.79	9.12	8.96	0.23
% Oxygen (Diff)	4.03	4.02	4.03	0.01
ASH FUSION (Red)	2700+	2700+	2700+	--
Initial Deformation	2700+	2700+	2700+	--
Soft (H=W)	2700+	2700+	2700+	--
Soft (H=1/2W)	2700+	2700+	2700+	--
Fluid	2700+	2700+	2700+	--
HARDGROVE GRINDABILITY	81	84	82.5	2.12
FREE SWELLING INDEX	9	9	9	--

TABLE 5-19

MINERAL ANALYSIS OF COAL ASH
TEST SITE F

COAL	PENNSYLVANIA A			PENNSYLVANIA B		
TEST NO.	22	24	Average	29	30	Average
Silica, SiO_2	41.47	48.65	45.06	47.74	47.95	47.85
Alumina, Al_2O_3	32.72	32.14	32.43	34.17	32.66	33.42
Titania, TiO_2	1.23	1.47	1.35	1.38	1.46	1.42
Ferric Oxide, feO_3	16.23	10.23	13.23	9.21	10.68	9.95
Lime, CaO	2.52	1.93	2.23	1.32	1.45	1.39
Magnesia, MgO	0.64	0.70	0.67	0.57	0.74	0.66
Potassium Oxide, K_2O	1.59	2.21	1.90	1.74	2.15	1.95
Sodium Oxide, Na_2O	0.35	0.23	0.29	0.37	0.44	0.41
Sulfur Trioxide, SO_3	2.00	1.71	1.86	1.43	1.38	1.41
Phos. Pentoxide, P_2O_5	0.82	0.41	0.62	0.30	0.45	0.38
Undetermined	0.28	0.17	0.23	1.55	0.36	0.96
Silica Value	68.14	79.09	73.62	81.14	78.84	79.99
Base: Acid Ratio	0.28	0.19	0.24	0.16	0.19	0.18
T_{250} Temperature	2575°F	2735°F	2655°F	2805°F	2730°F	2768°F
% Pyritic Sulfur	0.83	0.52	0.68	0.33	0.44	0.39
% Sulfate Sulfur	0.00	0.08	0.04	0.00	0.00	0.00
% Organic Sulfur	0.68	0.72	0.70	0.67	0.55	0.61

5.4.2 Coal Size Consistency

The individual 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 5-20. The standard deviation of the coal size consistency for each coal is plotted against the ABMA recommended limits for spreader stokers in Figures 5-26 and 5-27.

The average size consistencies of the two coals were nearly identical. It is also evident that the coal size consistency did not vary greatly from test to test. Therefore, it appears that coal size consistency was not a variable in these tests. Coal fines, defined as the percent by weight passing a 1/4" screen, averaged 27% for Penn A coal and 28% for Penn B coal.

5.4.3 Effect of Coal Properties on Emissions and Efficiency

The influence that changing coals -- from Penn A to Penn B -- had on boiler emissions and efficiency is discussed below. Frequent references are made to figures in Section 5.3, Excess Oxygen and Grate Heat Release, which illustrate the differences between the two coals.

Excess Oxygen Operating Conditions. The data indicate that Penn A coal and Penn B coal did not require significantly different excess air conditions to achieve efficient combustion. Figure 5-1 shows that tests were run over the same range of oxygen levels for both coals.

Particulate Mass Loading. Both of the coals tested produced essentially the same particulate mass loadings even though they differed in ash and sulfur content. This conclusion is based on examination of the data in Figure 5-2 and Table 5-21.

Perhaps the best illustration is given in Figure 5-2 where the two Penn B coal tests are in the midrange of the data from the Penn A coal tests. The Penn A and B particulate loadings are similar.

Table 5-21 examines the data closer. In this table the two Penn B tests are compared only with Penn A tests run under similar conditions of load, oxygen and overfire air. The small differences in particulate loading are not consistent between loads or sample locations. Therefore, it is concluded that no significant change in particulate mass loading was measured when the coal was changed.

TABLE 5-20

AS FIRED COAL SIZE CONSISTENCY
TEST SITE F

Test No.	PERCENT PASSING STATED SCREEN SIZE 1"	1/2"	1/4"	#8	#16
15	94.8	54.9	24.6	17.3	14.7
17	93.0	60.8	23.5	13.7	10.9
18	93.4	48.5	16.2	10.7	9.0
19	97.6	66.4	30.5	18.7	14.2
20	97.5	68.8	31.7	18.6	13.9
21	97.1	66.1	24.9	15.4	12.1
22	94.2	58.9	22.8	13.7	10.9
23	95.1	56.3	21.8	13.1	10.5
23A	96.8	68.1	32.2	18.6	13.9
24	98.5	72.8	36.7	21.4	15.7
Penn A Average	95.8	62.2	26.5	16.1	12.6
29	97.0	56.9	28.4	16.8	11.9
30	96.0	64.6	28.4	16.8	12.3
35	97.1	56.8	27.9	17.6	13.0
Penn B Average	96.7	59.4	28.2	17.1	12.4

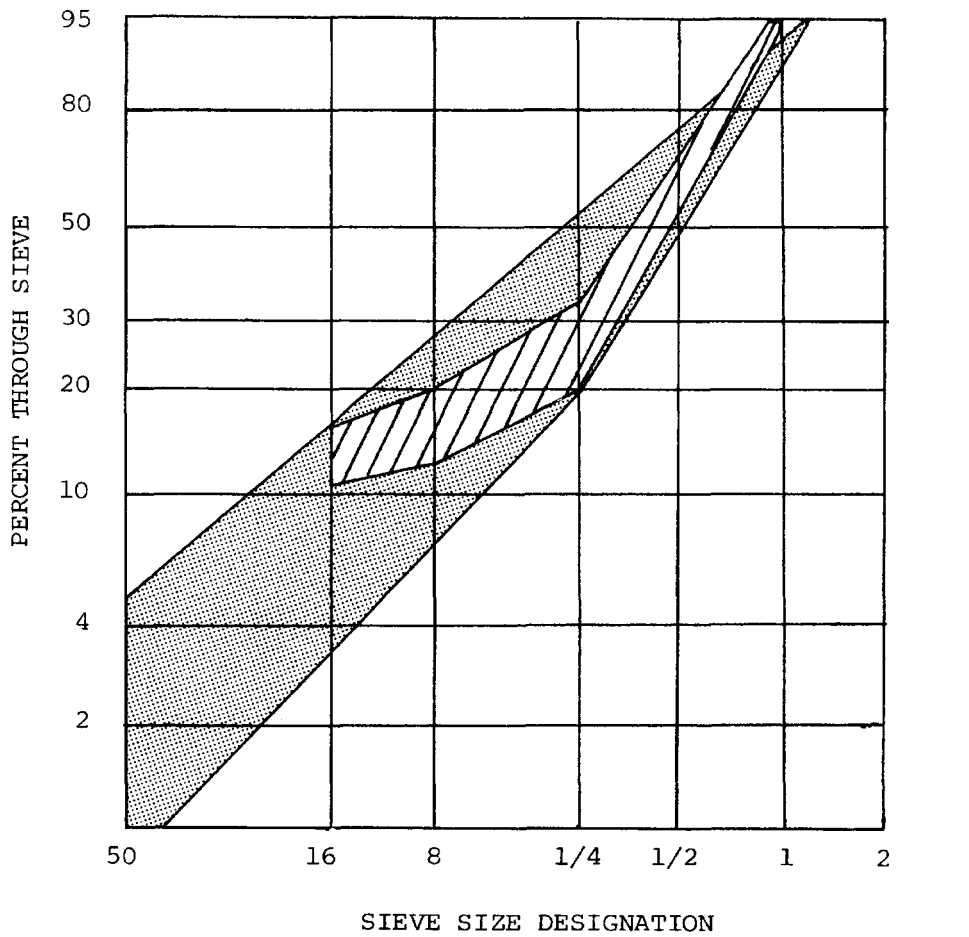


FIGURE 5-26. Size Consistency of "As Fired" Penn A Coal vs ABMA Recommended Limits of Coal Sizing for Spreader Stokers - Test Site F

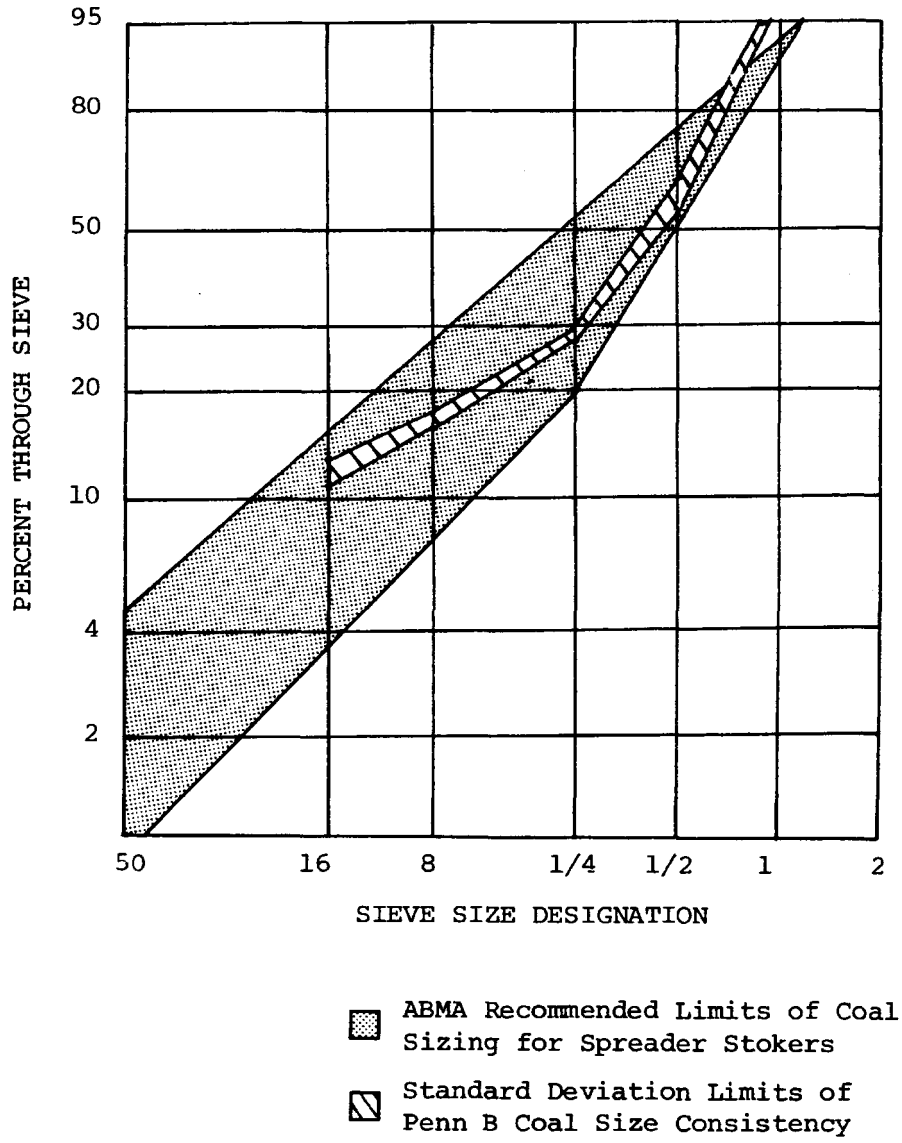


FIGURE 5-27. Size Consistency of "As Fired" Penn B Coal vs ABMA Recommended Limits of Coal Sizing for Spreader Stokers - Test Site F

TABLE 5-21

EFFECT OF COAL CHANGE ON PARTICULATE LOADING

	TEST DESCRIPTION				PARTICULATE Lbs/10^6 Btu	
	Test No.	% Load	% O_2	OFA	Econ Out	D.C. Out
Penn A Coal	18	99	5.5	High	6.1	0.8
Penn A Coal	24	103	5.0	High	7.2	1.0
Penn B Coal	29	101	5.0	High	5.9	1.4
Penn A Coal	20	75	8.4	Norm	4.0	NA
Penn A Coal	21	76	8.0	Norm	5.6	1.3
Penn B Coal	35	76	8.7	Norm	4.7	1.0

Ash Carryover. The percent of the coal ash carried over as flyash was similar for both coals fired. Ash carryover averaged 24.7% on the Penn A tests and 22.2% on the Penn B tests. The basis for this determination was given previously in Table 5-8.

Nitric Oxide. Nitric oxide concentrations may have been slightly less when firing Penn B coal because its fuel nitrogen content was 11% lower than that of Penn A. The observed difference is so slight, however, that it is nearly lost in the normal data scatter. Penn B coal contained 2.71 lbs/ 10^6 Btu nitrogen, expressed as NO_2, compared to Penn A at 3.05 lbs $NO_2/10^6$ Btu. The similarity of nitric oxide concentrations is shown in Figures 5-7 and 5-8.

Sulfur Dioxide. Sulfur dioxide concentrations were directly proportional to the sulfur content of the fuel within measurement accuracies. This relationship is illustrated in Figure 5-13. A sulfur balance was attempted for the two tests for which complete sulfur information was available. This sulfur balance, shown in Table 5-22, is very good within measurement accuracies.

For both coals, four percent of the fuel sulfur was retained in the ash while the remainder was converted to SO_2 and SO_3.

TABLE 5-22

SULFUR BALANCE - BOILER F

	Sulfur in Fuel lbs/10^6Btu as SO_2	Sulfur in Flue Gas lbs/10^6Btu as SO_2	Sulfur in Bottom Ash lbs/10^6Btu as SO_2	Sulfur in Flyash lbs/10^6Btu as SO_2
Penn A (Test 22)	2.22	2.19	0.01	0.08
Penn B (Test 30)	1.46	1.38	0.01	0.05

Hydrocarbons. Unburned hydrocarbon (HC) concentrations were in the same general range for both coals. Table 5-23 shows the average measured HC concentrations for both coals at two loads. Although Penn A coal averages slightly higher than Penn B coal, the difference is not significant due to the large variations in measured concentrations. Figure 5-15 shows the range of HC concentration measured.

TABLE 5-23

AVERAGE HYDROCARBON CONCENTRATIONS VS COAL

	Penn A Coal	Penn B Coal
75% Load	17	12
100% Load	8	5

Carbon Monoxide. Like the unburned hydrocarbons, the carbon monoxide (CO) concentration did not change appreciably with change in coal. Although the average CO concentrations shown in Table 5-24 indicate that Penn A coal

averaged higher CO than Penn B coal, the range of values (Figure 5-17) indicates that this is not significant. Both coals produced CO within the same general range of values.

TABLE 5-24

AVERAGE CARBON MONOXIDE CONCENTRATIONS VS COAL

	Penn A Coal	Penn B Coal
75% Load	149 ± 49	125 ± 51
100% Load	332 ± 148	284 ± 100

Combustibles in the Ash. Percent combustibles in the bottom ash and in the flyash were similar for both coals. This is illustrated in Figure 5-19, 5-20, and 5-21. The average combustible data are presented in Table 5-25.

TABLE 5-25

AVERAGE PERCENT COMBUSTIBLE IN ASH

	Penn A Coal	Penn B Coal
Economizer Outlet	66	73
Multiclone Outlet	46	48
Bottom Ash	12	12

Boiler Efficiency. Boiler efficiency was not altered by the fuel change. Moisture related losses were similar because hydrogen and moisture in the coals were similar. Combustible losses were also similar. Table 5-26 presents the heat losses and boiler efficiency for nearly identical full load tests in both coals. Penn B coal gave a higher boiler efficiency because of a lower combustible heat loss. However, there is no evidence indicating that Penn B coal would consistently have a combustible heat loss that was lower than Penn A coal.

TABLE 5-26

BOILER EFFICIENCY VS COAL

	BOILER HEAT LOSSES, %				
	Dry Gas	Moisture Related	Combus-tible	Other	BOILER EFFICIENCY, %
Penn A Coal (Test 24)	7.1	4.0	8.3	2.0	78.6
Penn B Coal (Test 29)	7.5	4.0	7.2	2.0	79.3

5.5 PARTICLE SIZE DISTRIBUTION OF FLYASH

Eleven particle size distribution determinations were made at the economizer outlet (multiclone dust collector inlet) on Boiler F. These determinations were made using a Bahco classifier, a Brink cascade impactor, and a SASS cyclone train. Firing conditions for the particle size distribution tests are shown in Table 5-27.

The test results are presented in Table 5-28, and in figures 5-28, 5-29, and 5-30. It is especially important to note the differences in sample methodologies because each has its drawbacks. A discussion of each method is included in Section 4.4.

The Bahco classifier sample was collected with a cyclone. As a result, a fraction of the sample (4 to 9%) was not captured and the results are biased such that they indicate fewer particles below about 15 micrometers than there actually were. It is hoped that appropriate corrections can be made to the Bahco data at some future date using the measured cyclone collection efficiency (shown in Table 5-28, last column) and the theoretical cyclone collection efficiencies by particle size.

The Brink and SASS particle size distribution data should be accurate and require no corrections. However, these are single point measurements, whereas the Bahco data was obtained with a 24-point traverse of the duct. Single point samples are suspect for reasons of size stratification within the duct.

TABLE 5-27

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

Test No.	Coal	Load %	O_2 %	OFA	Particle Size Distribution Methodology Used
5	Penn A	54	9.4	Norm	Bahco - Sieve
21	Penn A	76	8.0	Norm	Bahco - Sieve
23	Penn A	100	6.3	High	Bahco - Sieve
24	Penn A	102	5.0	High	Bahco - Sieve
29	Penn B	101	5.0	High	Bahco - Sieve
23	Penn A	100	6.3	High	Brink Impactor
23A	Penn A	99	5.9	High	Brink Impactor
24	Penn A	102	5.0	High	Brink Impactor
29	Penn B	101	5.0	High	Brink Impactor
22	Penn A	99	6.0	High	SASS Cyclones
30	Penn B	97	6.8	High	SASS Cyclones

TABLE 5-28

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

Test No.	Test Description	Size Distribution % Below 3 µm	Size Distribution % Below 10 µm	Size Concentration lbs/10^6Btu Below 3 µm	Size Concentration lbs/10^6Btu Below 10 µm	Sample Collection Efficiency %
5	Low Load - Bahco	1.8	8.9	0.091	0.452	96.2
21	Med Load - Bahco	1.0	2.4	0.055	0.134	91.0
23	High Load - Bahco	1.5	2.9	0.079	0.152	94.0
24	High Load - Bahco	1.2	2.9	0.086	0.208	93.8
29	High Load - Bahco	1.4	3.5	0.083	0.208	93.9
23	High Load - Brink	2.2	--	0.115	--	100
23A	High Load - Brink	12.5	--	0.655	--	100
24	High Load - Brink	5.0	--	0.359	--	100
29	High Load - Brink	6.5	--	0.386	--	100
22	High Load - SASS	3.4	9.8	0.186	0.540	100
30	High Load - SASS	4.6	12.9	0.250	0.707	100

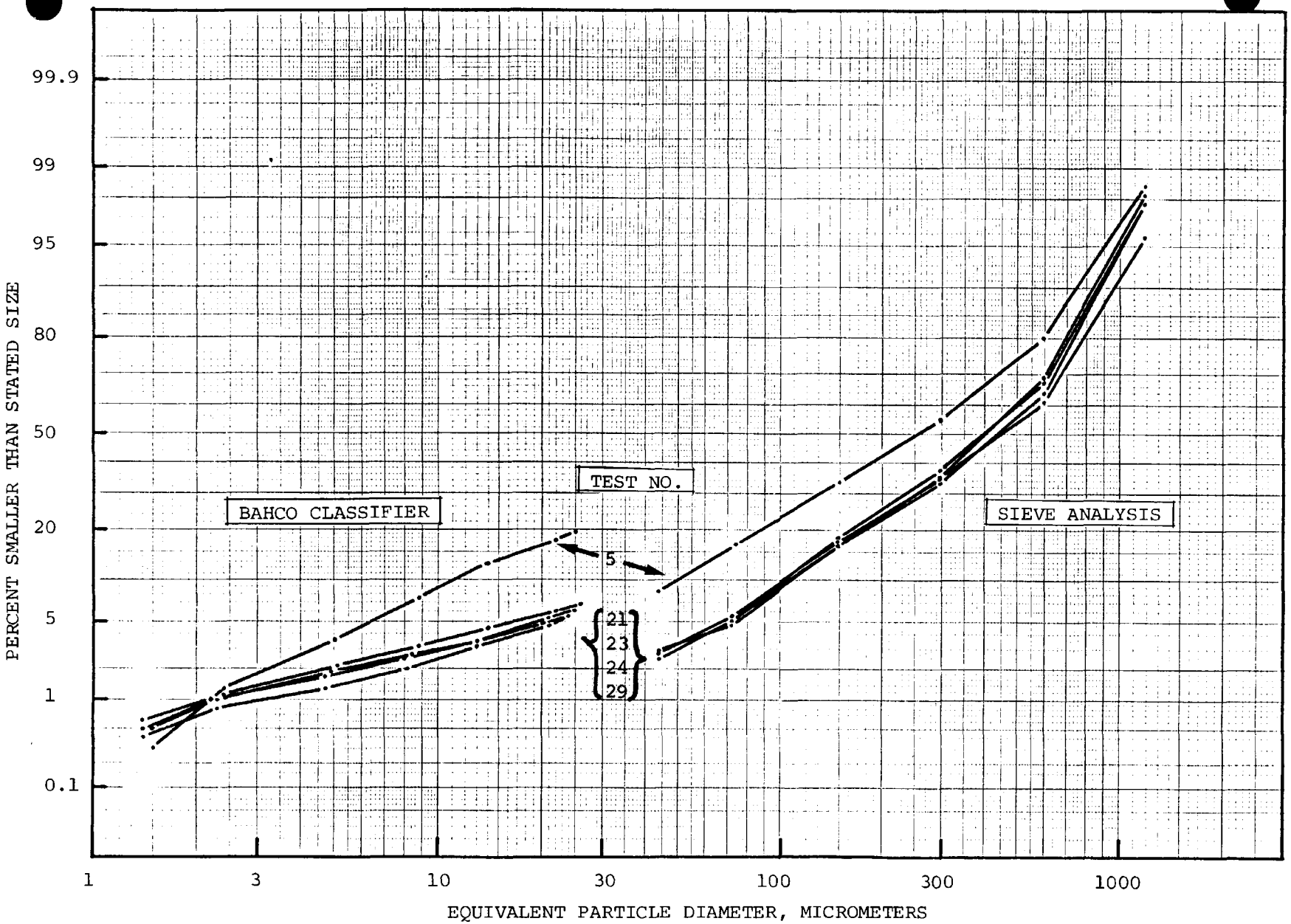


FIGURE 5-28 Particle Size Distribution at the Economizer Outlet from Bahco Classifier and Sieve Analysis - Test Site F.

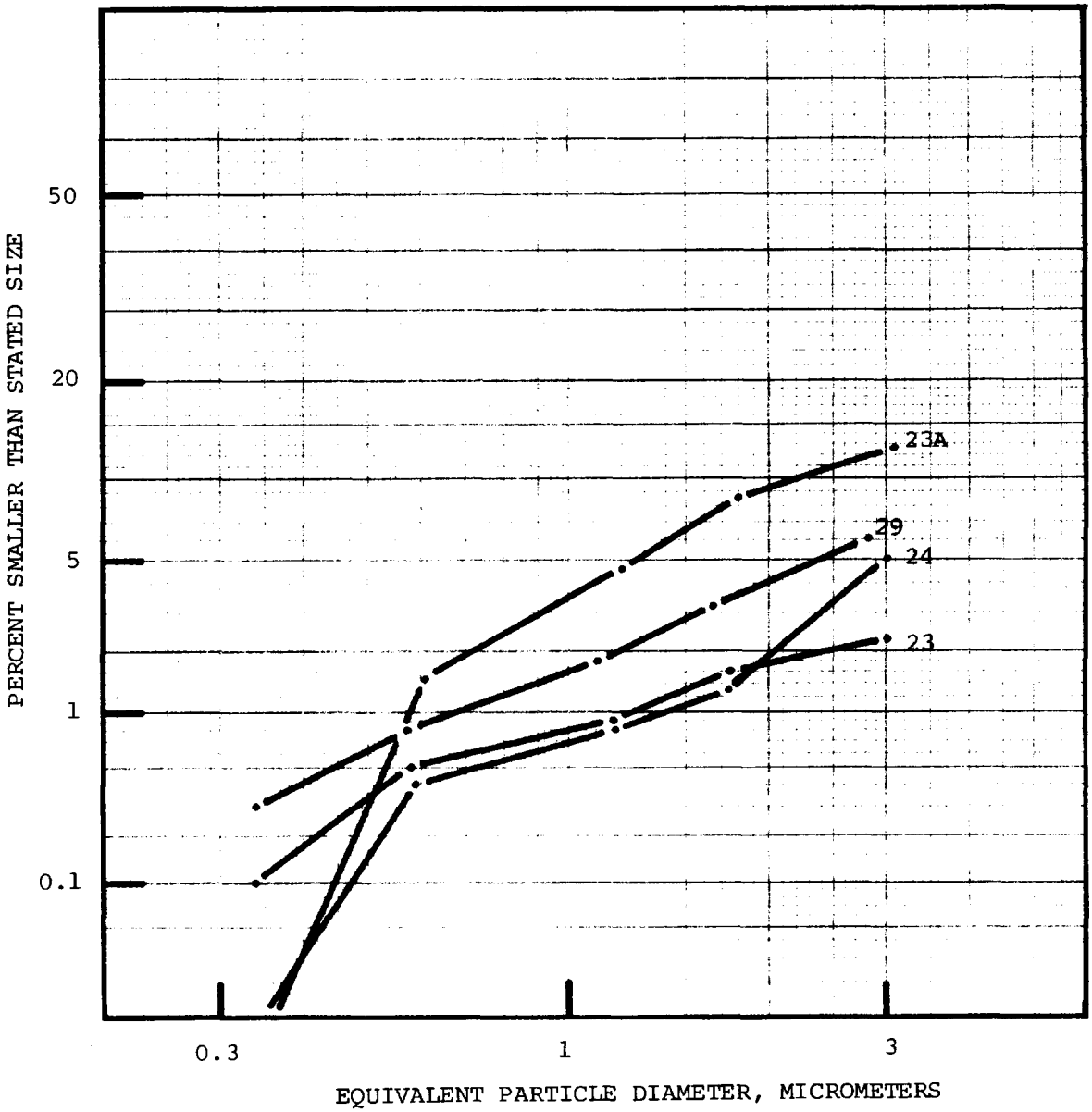


FIGURE 5-29. Particle Size Distribution at the Economizer Outlet from Brink Cascade Impactor - Test Site F

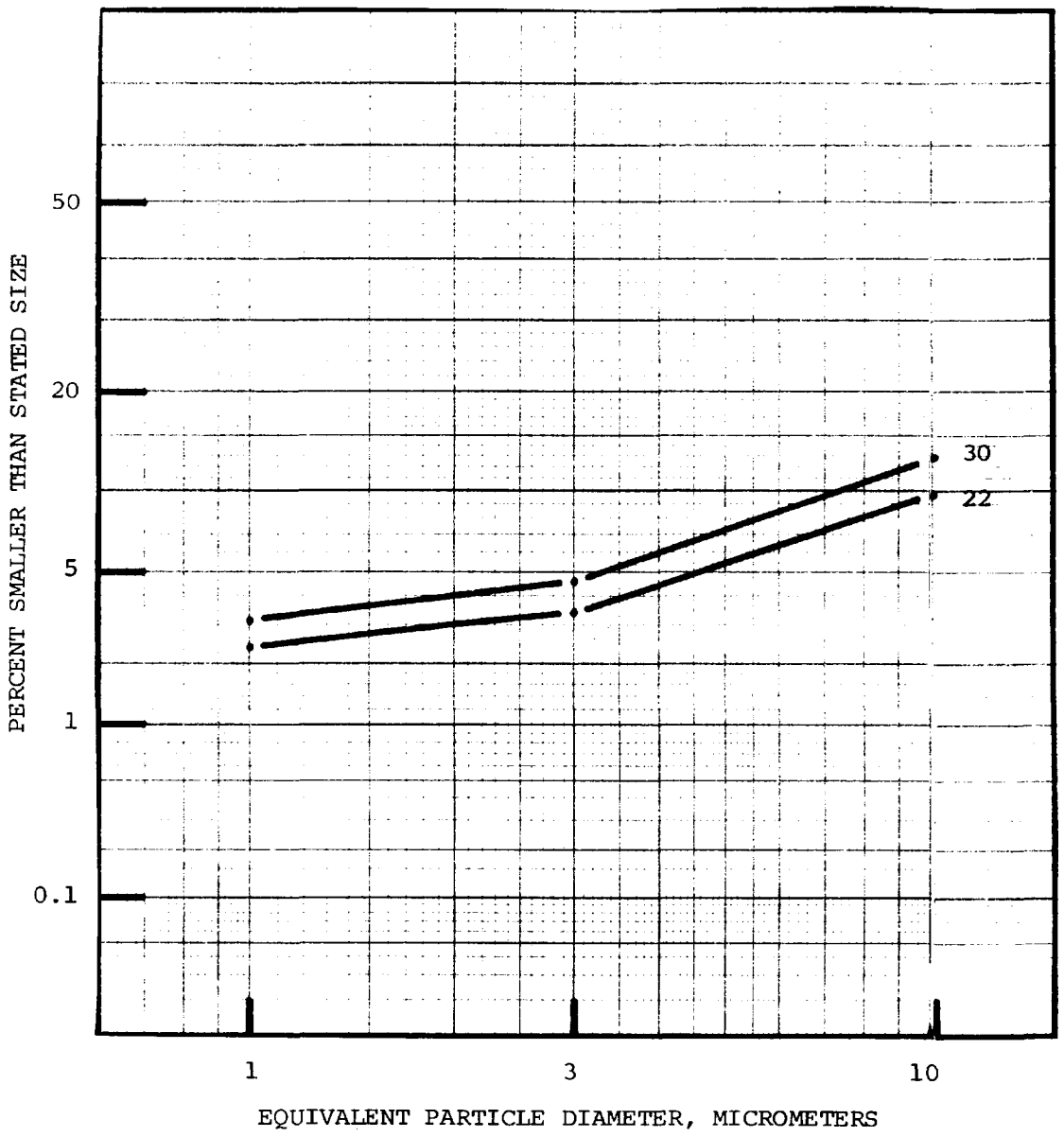


FIGURE 5-30. Particle Size Distribution at the Economizer Outlet from SASS Gravimetrics - Test Site F

5.6 EFFICIENCY OF MULTICLONE DUST COLLECTOR

The collection efficiency of the multiclone dust collector was determined in nine tests under various boiler operating conditions. The data were obtained by measuring the particulate loadings simultaneously at the inlet and outlet of the dust collector. Test data are presented in Table 5-29 and plotted as a function of grate heat release in Figure 5-31.

The design efficiency of the dust collector, as supplied by the manufacturer, was supposed to be 85% at maximum continuous load. The measured collection efficiencies agreed well with the design efficiency. At full load the measured efficiency ranged from 77 to 87% and averaged 82%. At 75% load the dust collector efficiency averaged 78%.

TABLE 5-29

EFFICIENCY OF DUST COLLECTOR
TEST SITE F

Test No.	Coal Type	Load %	O_2 %	Particulate Loading lb/10^6Btu Collector Inlet	Particulate Loading lb/10^6Btu Collector Outlet	Collector Efficiency %
15	Penn A	99	7.8	5.926	1.329	77.6
17	Penn A	99	6.7	5.510	1.130	79.5
18	Penn A	99	5.5	6.136	0.771	87.4
19	Penn A	99	5.9	8.785	1.256	85.7
21	Penn A	76	8.0	5.567	1.262	77.3
23	Penn A	100	6.3	5.240	0.998	81.0
24	Penn A	103	5.0	7.183	1.031	85.6
29	Penn B	101	5.0	5.944	1.392	76.6
35	Penn B	76	8.7	4.726	1.026	78.3
					AVERAGE	81.0

5.7 SOURCE ASSESSMENT SAMPLING SYSTEM (SASS)

Two SASS tests were run at Test Site F, one on each of the two coals at full load. 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 listed in Table 5-30.

TABLE 5-30

POLYNUCLEAR AROMATIC HYDROCARBONS
ANALYZED IN THE SITE F 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	$C_{20}H_{13}N$

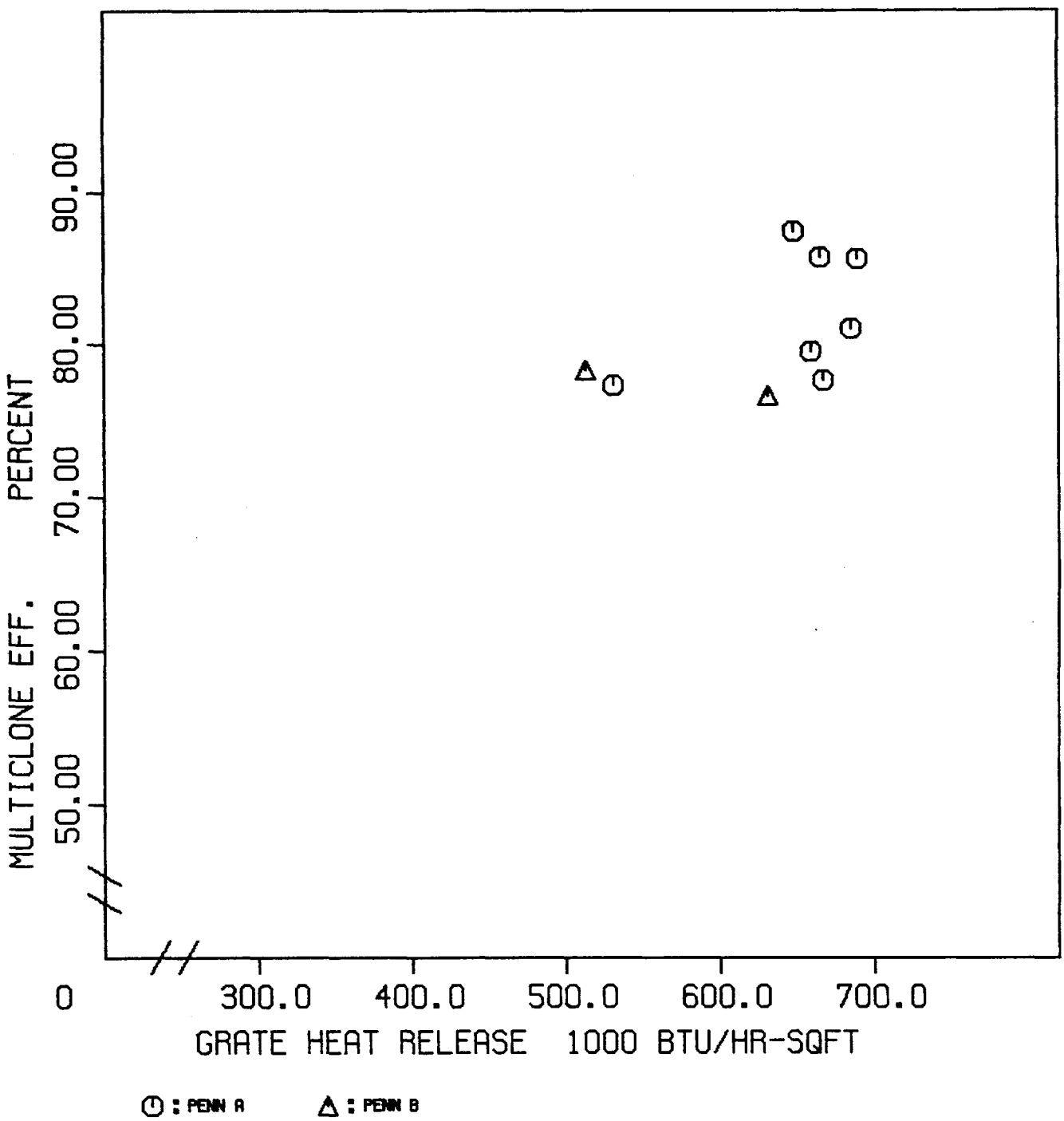


FIG. 5-31
MULTICLONE EFF. VS. GRATE HEAT RELEASE
TEST SITE F

5.8 DATA TABLES

Tables 5-31 through 5-34 summarize the test data obtained at Test Site F. These tables, in conjunction with Table 2-1 in the Executive Summary, are included for reference purposes.

TABLE 5-31

PARTICULATE EMISSIONS
TEST SITE F

	Test No	Coal	Load %	O_2 %	EMISSIONS lb/10^6Btu	EMISSIONS gr/SCF	EMISSIONS lb/hr	Velocity ft/sec
BOILER OUTLET	05	Penn A	54	9.4	5.076	2.009	261	20.18
	15	Penn A	99	7.8	5.926	2.638	558	39.52
	17	Penn A	99	6.7	5.510	2.708	513	34.77
	18	Penn A	99	5.5	6.136	3.125	562	30.87
	19	Penn A	99	5.9	8.785	4.309	826	29.71
	20	Penn A	75	8.4	4.008	1.809	291	27.82
	21	Penn A	76	8.0	5.567	2.503	418	28.96
	23	Penn A	100	6.3	5.240	2.748	507	31.70
	24	Penn A	103	5.0	7.183	3.932	709	29.10
	29	Penn B	101	5.0	5.944	3.243	531	29.74
	35	Penn B	76	8.7	4.726	1.935	336	28.14
MECHANICAL COLLECTOR OUTLET	15	Penn A	99	7.8	1.329	0.547	125	59.23
	17	Penn A	99	6.7	1.130	0.516	105	56.51
	18	Penn A	99	5.5	0.771	0.362	71	49.75
	19	Penn A	99	5.9	1.256	0.563	118	49.56
	21	Penn A	76	8.0	1.262	0.528	95	45.64
	23	Penn A	100	6.3	0.998	0.470	97	53.48
	24	Penn A	103	5.0	1.031	0.511	102	49.97
	29	Penn B	101	5.0	1.392	0.699	124	46.21
	35	Penn B	76	8.7	1.026	0.376	73	47.63

Load % is based on the steam flow integrator readings compared to the unit's nameplate, or design, capacity of 80,000 lb stm/hr.

TABLE 5-32

HEAT LOSSES AND EFFICIENCIES
TEST SITE F

	TEST NO.	DRY GAS LOSS	MOISTURE IN FUEL	H_2O FROM COMBUSTION OF H_2	COMBUSTIBLES IN FLYASH	COMBUSTIBLES IN BOTTOM ASH	TOTAL COMBUSTIBLES IN REFUSE	RADIATION FROM BOILER	UNMEASURED	TOTAL LOSSES	EFFICIENCY
PENNSYLVANIA A COAL	05	7.49	0.42	3.64	3.58	0.96	4.54	0.94	1.50	18.53	81.47
	15	9.33	0.52	3.82	5.32	3.34	8.66	0.52	1.50	24.35	75.65
	17	7.78	0.47	3.75	5.50	1.70	7.20	0.52	1.50	21.22	78.78
	18	7.07	0.52	3.89	6.24	1.04	7.28	0.52	1.50	20.78	79.22
	19	8.48	0.74	3.96	9.00	1.46	10.46	0.52	1.50	25.66	74.34
	20	8.65	0.19	3.56	3.82	0.44	4.26	0.68	1.50	18.84	81.46
	21	8.44	0.18	3.67	5.20	1.01	6.21	0.67	1.50	20.67	79.33
	23	7.16	0.20	3.59	5.45	0.77	6.22	0.51	1.50	19.18	80.82
	24	6.37	0.31	3.71	6.86	1.47	8.33	0.50	1.50	20.72	79.28
PENN B COAL	29	6.86	0.31	3.68	6.15	1.03	7.18	0.51	1.50	20.04	79.96
	35	8.36	0.34	3.70	4.80	1.22	6.02	0.67	1.50	20.59	79.41

TABLE 5-33

PERCENT COMBUSTIBLES IN REFUSE
TEST SITE F

	Test No.	Economizer Outlet	Economizer Hopper	Multiclone Outlet	Multiclone Hopper	Bottom Ash
PENNSYLVANIA A COAL	05	49.5				10.62
	15	63.1		52.1		27.23
	17	70.1		45.0		17.34
	18	71.4		41.3		8.21
	19	71.9		46.1		13.79
	20	66.9				6.05
	21			45.5		9.90
	22				65.90	8.62
	23		70.53		56.63	9.60
	23A				63.27	11.42
	24	67.0		45.8	63.45	13.81
	Average	65.5	70.53	46.0	62.31	12.42
PENN B COAL	29					13.07
	30			47.0	64.51	10.19
	35	72.6		49.5		13.82
	Average	72.6		48.3	64.51	12.36

TABLE 5-34

STEAM FLOWS AND HEAT RELEASE RATES
TEST SITE F

Test No.	Capacity %	Steam Flow 10^3lb/hr	Heat Input* 10^6Btu/hr	Heat Output+ 10^6Btu/hr	Front Foot Heat Release 10^4Btu/hr-ft	Grate Heat Release 10^3Btu/hr-ft^2	Furnace Heat Release 10^2Btu/hr-ft^3
01	75.0	60.029	70.7	71.8	650.2	500.1	170.4
02	75.0	60.029	70.7	71.8	650.2	500.1	170.4
03	75.0	60.029	70.7	71.8	650.2	500.1	170.4
04	75.0	60.029	70.7	71.8	650.2	500.1	170.4
05	53.8	43.000	51.4	51.4	472.1	363.2	123.7
06	52.9	42.300	47.8	50.5	439.7	338.2	115.2
07	52.9	42.300	47.8	50.5	439.7	338.2	115.2
08	52.9	42.300	47.8	50.5	439.7	338.2	115.2
09	52.9	42.300	47.8	50.5	439.7	338.2	115.2
10	97.6	78.134	96.6	93.4	888.7	683.4	232.9
11	99.1	79.290	98.0	94.8	901.4	693.3	236.2
12	99.1	79.290	98.0	94.8	901.4	693.3	236.2
13	99.1	79.290	98.0	94.8	901.4	693.3	236.2
14	99.1	79.290	98.0	94.8	901.4	693.3	236.2
15	98.8	78.973	94.2	94.4	866.6	666.5	227.1
16	95.9	76.750	94.4	91.7	868.1	667.7	227.5
17	99.1	79.333	93.2	94.8	856.6	658.8	224.5
18	99.1	79.323	91.6	94.9	842.0	647.6	220.6
19	99.1	79.282	94.1	94.8	865.1	665.3	226.7
20	74.7	59.754	72.6	71.4	667.6	513.5	174.9
21	76.4	61.116	75.1	73.1	690.4	531.0	180.9
22	99.3	79.473	94.4	95.0	868.0	667.6	227.5
23	100.0	79.989	96.8	95.6	890.2	684.7	233.3
23A	99.3	79.472	97.5	95.0	896.3	689.3	234.9
24	102.4	81.957	98.7	98.0	907.3	689.4	234.8
25	99.4	79.488	94.8	95.0	872.1	670.7	228.5
26	99.4	79.488	94.8	95.0	872.1	670.7	228.5
27	99.4	79.488	94.8	95.0	872.1	670.7	228.5
28	99.4	79.488	94.8	95.0	872.1	670.7	228.5
29	100.5	80.400	89.3	96.1	820.8	631.3	215.1
30	101.9	81.499	95.7	97.4	880.1	676.9	230.6
31	75.0	59.970	72.5	71.7	666.8	512.8	174.7
32	75.0	59.970	72.5	71.7	666.8	512.8	174.7
33	75.0	59.970	72.5	71.7	666.8	512.8	174.7
34	75.0	59.970	72.5	71.7	666.8	512.8	174.7
35	75.8	60.616	72.6	72.4	667.9	512.8	174.7

* Heat input is based on lb/hr coal x Btu/lb coal,

\+ Heat output is based on lb/hr steam, steam temperature and pressure. Sometimes inaccuracies in the steam flow integrator and/or coal scales create heat output values which are greater than the heat input values.

APPENDICES

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.

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

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

APPENDIX D

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	
% Weight In Fuel 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)	
lbs/10^6Btu 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)	
grams/10^6Cal NO_2		4.44		(1.8)				25.6×10^{-4}		(4.01)
PPM (Dry @ 3% O_2) SOx	758		505		281		1		1127	
PPM (Dry @ 3% O_2) NOx		1736		704		391				1566
Grains/SCF (Dry @ 12% CO_2) SO_2	.676		(.448)		(.249)		8.87×10^{-4}		1	
Grains/SCF (Dry @ 12% CO_2) 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.

APPENDIX E

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

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

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

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

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

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

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

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

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/7-80-065a		

4. TITLE AND SUBTITLE	5. REPORT DATE
Field Tests of Industrial Stoker Coal-fired Boilers for Emissions Control and Efficiency Improvement--Site F	March 1980
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
P. L. Langsjoen, R. J. Tidona, and J. E. Gabrielson	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
KVB, Inc. 6176 Olson Memorial Highway Minneapolis, Minnesota 55422	EHE624
	11. CONTRACT/GRANT NO.
	IAG-D7-E681 (EPA) and EF-77-C-01-2609 (DOE)
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
EPA, Office of Research and Development * Industrial Environmental Research Laboratory Research Triangle Park, NC 27711	Final; 12/78-2/79
	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 Assoc. EPA-600/7-78-136a, -79-041a, -79-130a, -79-147a, and -80-064a are Site A, B, C, D, and E reports.

16. ABSTRACT The report gives results of field measurements made on an 80,000 lb/hr coal-fired spreader-stoker boiler. The effects of various parameters on boiler emissions and efficiency were studied. Parameters included overfire air, flyash injection, excess air, boiler load, and coal properties. Measurements included O2, CO2, CO, NO, NO2, SO2, SO3, HC, controlled and uncontrolled particulate loading, particle size distribution of the uncontrolled flyash, and combustible content of the ash. In addition to test results and observations, the report describes the facility tested, coals fired, test equipment, and procedures. Particulate loading on this unit averaged 6.00 lb/million Btu uncontrolled and 1.05 lb/million Btu controlled at full load. Nitric oxide emissions averaged 0.45 lb/million Btu (330 ppm) at all loads.

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	
Stokers	Sulfur Oxides	Flyash Reinjection	

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
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