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

Interagency Energy/Environment R&D Program Report

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by

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TABLE OF CONTENTS

Section		Page
	ACKNOWLEDGEMENTS	ii
	LIST OF FIGURES	v
	LIST OF TABLES	vii
1.0	INTRODUCTION	1
2.0	EXECUTIVE SUMMARY	3
3.0	DESCRIPTION OF FACILITY TESTED AND COALS FIRED	11
	3.1 Boiler C Description	11
	3.2 Overfire Air System	11
	3.3 Flyash Reinjection System	15
	3.4 Test Port Locations	16
	3.5 Coals Utilized	18
4.0	TEST EQUIPMENT AND PROCEDURES	21
	4.1 Gaseous Emissions Measurements	21
	4.1.1 Analytical Instruments and Related Equipment	21
	4.1.2 Recording Instruments	26
	4.1.3 Gas Sampling and Conditioning System	26
	4.2 Gaseous Emission Sampling Techniques	26
	4.3 Sulfur Oxides (SOx) Measurement and Procedures	28
	4.4 Particulates Measurement and Procedures	30
	4.5 Particle Size Distribution Measurement and Procedure	32
	4.6 Coal Sampling and Analysis Procedure	35
	4.7 Ash Collection and Analysis for Combustibles	36
	4.8 Boiler Efficiency Evaluation	37
	4.9 Modified Smoke Spot Number	38
	4.10 Trace Species Measurement	39
	4.11 Flyash Reinjection Evaluation	39
5.0	TEST RESULTS AND OBSERVATIONS	43
	5.1 Overfire Air	43
	5.1.1 Overfire Air Flow Rate Determination	43
	5.1.2 Particulate Loading vs Overfire Air	50
	5.1.3 Nitric Oxide vs Overfire Air	51
	5.1.4 Carbon Monoxide vs Overfire Air	56
	5.1.5 Boiler Efficiency vs Overfire Air	56
	5.2 Flyash Reinjection	61
	5.3 Excess Oxygen and Grate Heat Release	71
	5.3.1 Excess Oxygen Operating Levels	71
	5.3.2 Particulate Loading vs Excess Oxygen and Grate Heat Release	73
	5.3.3 Nitric Oxide vs Excess Oxygen and Grate Heat Release	77

KVB 15900-528

TABLE OF CONTENTS
Continued

Section		Page
	5.3.4 Carbon Monoxide vs Excess Oxygen and Grate Heat Release	77
	5.3.5 Combustibles in the Ash vs Excess Oxygen and Grate Heat Release	84
	5.3.6 Boiler Efficiency vs Excess Oxygen and Grate Heat Release	90
5.4	Coal Properties	92
	5.4.1 Coal Size Consistency	97
	5.4.2 Sulfur Balance	97
5.5	Particle Size Distribution of Flyash	102
5.6	Efficiency of Multiclone Dust Collector	108
5.7	Modified Smoke Spot Number	111
5.8	Source Assessment Sampling System	111
5.9	Data Tables	115
APPENDIX A -	Excess Air Investigation	122
APPENDIX B -	English and Metric Units to SI Units	126
APPENDIX C -	SI Units to English and Metric Units	127
APPENDIX D -	SI Prefixes	128
APPENDIX E -	Emission Units Conversion Factors for Typical Coal Fuel	129

A Supplement to this report containing all of the unreduced data obtained at Site C is available from NTIS or through EPA. The Supplement has the same EPA report number as this report but is followed by the letter "b" rather than "a". It also has the same title but is followed by the words, "Data Supplement." The Data Supplement contains no discussion, it is a compilation of hand written data sheets made available to researchers who wish to examine the data in greater depth than that covered in this report.

KVB 15900-528

LIST OF FIGURES

Figure		Page
3-1	Sectional Side Elevation and Plan View	12
3-2	Boiler C Sample Plane Geometry	17
4-1	Flow Schematic of Mobile Flue Gas Monitoring Laboratory	27
4-2	SOx Sample Probe Construction	29
4-3	Sulfur Oxides Sampling Train	29
4-4	Particulate Sampling Train	31
4-5	Brink Cascade Impactor Sampling Train Schematic	33
4-6	Field Service Type Smoke Tester	38
4-7	Source Assessment Sampling System (SASS) Flow Diagram	40
5-1	Overfire Air and Reinjection Air Flow Schematic	45
5-2	Pressure-Flow Relationship, OFA System	47
5-3	Pressure-Flow Relationship, OFA System	48
5-4	Contribution of Overfire Air and Reinjection Air to Total Combustion Air	49
5-5	Particulate Loading Broken Down into Combustible and Inorganic Fractions for Three Overfire Air Test Sets on Eastern Low Fusion Coal	53
5-6	Particulate Loading Broken Down into Combustible and Inorganic Fractions for Three Overfire Air Test Sets on Western Coal	55
5-7	Nitric Oxide Emissions vs Overfire Air	58
5-8	Carbon Monoxide Emissions vs Overfire Air	60
5-9	Flyash Flow Rates with Different Reinjection Configurations Eastern Low Fusion Coal	63
5-10	Flyash Flow Rates with Different Reinjection Configurations Western Coal	65
5-11	Particle Size Concentrations for Boiler Outlet Particulates under Full and Reduced Flyash Reinjection Conditions - Eastern Low Fusion Coal	67
5-12	Particle Size Concentrations for Boiler Outlet Particulates under Full and Reduced Flyash Reinjection Conditions - Western Coal	68
5-13	Particulate Concentration Reduction as a Function of Particle Diameter for the Change in Flyash Reinjection Configuration from Full to No Reinjection	69
5-14	Oxygen vs Grate Heat Release	72
5-15	Oxygen vs Grate Heat Release	74
5-16	Boiler Out Part. vs Grate Heat Release	75
5-17	Multiclone Out Part. vs Grate Heat Release	76
5-18	Nitric Oxide vs Grate Heat Release	78
5-19	Nitric Oxide vs Oxygen	79
5-20	Nitric Oxide vs Oxygen	80
5-21	Nitric Oxide vs Oxygen	81
5-22	Nitric Oxide vs Oxygen	82
5-23	Nitric Oxide Trends vs O_2 and Boiler Loading at Test Site C	83
5-24	Carbon Monoxide vs Grate Heat Release	85
5-25	Carbon Monoxide vs Oxygen - Eastern Low Fusion Coal	86

KVB 15900-528

LIST OF FIGURES
(Continued)

Figure		Page
5-26	Carbon Monoxide vs Oxygen - Western Coal	87
5-27	Boiler Out Comb. vs Grate Heat Release	88
5-28	Bottom Ash Comb. vs Grate Heat Release	89
5-29	Boiler Efficiency vs Grate Heat Release	91
5-30	Size Consistency of "As Fired" Eastern Low Fusion Coal vs ABMA Recommended Limits of Coal Sizing for Spreader Stokers	98
5-31	Size Consistency of "As Fired" Western Coal vs ABMA Recommended Limits of Coal Sizing for Spreader Stokers	99
5-32	Size Consistency of "As Fired" Eastern High Fusion Coal vs ABMA Recommended Limits of Coal Sizing for Spreader Stokers	100
5-33	Bahco Classifier and Sieve Analysis Particle Size Distribution	104
5-34	Particle Size Distribution from SASS Gravimetrics	105
5-35	Particle Size Distribution from Brink Cascade Impactor	107
5-36	Multiclone Efficiency vs Grate Heat Release	110
5-37	Smoke Spot Number vs Particulate Loading	113
5-38	Smoke Spot Number vs Combustible Loading	114

LIST OF TABLES

Table		Page
2-1	Emission Data Summary	8
3-1	Design Data	13
3-2	Predicted Performance	14
3-3	Average Coal Analysis	19
5-1	Overfire Air and Reinjection Air Flow Rates	46
5-2	Effect of Overfire Air on Emissions & Efficiency - Eastern Low Fusion Coal	52
5-3	Effect of Overfire Air on Emissions & Efficiency - Western Coal	54
5-4	Nitric Oxide Emissions vs Overfire Air	57
5-5	Carbon Monoxide Emissions vs Overfire Air	59
5-6	Effect of Flyash Reinjection on Emissions and Efficiency Burning Eastern Low Fusion Coal	62
5-7	Effect of Flyash Reinjection on Emissions and Efficiency Burning Western Coal	64
5-8	Fuel Analysis - Eastern Low Fusion Coal	93
5-9	Fuel Analysis - Western Coal	94
5-10	Fuel Analysis - Eastern High Fusion Coal	95
5-11	Mineral Analysis of Coal Ash	96
5-12	Sulfur Balance	101
5-13	Particle Size Distribution Tests and Methodology Used	103
5-14	Size Distribution and Concentration of Flyash at Boiler Outlet as a Function of Reinjection Configuration	106
5-15	Efficiency of Multiclone Dust Collector	109
5-16	Modified Smoke Spot Data	112
5-17	Polynuclear Aromatic Hydrocarbons Analyzed in Site C SASS Samples	115
5-18	Particulate Emissions	116
5-19	Heat Losses and Efficiencies	117
5-20	Percent Combustibles in Refuse	118
5-21	As Fired Coal Size Consistency	119
5-22	Steam Flows & Heat Release Rates	120

SECTION 1.0

INTRODUCTION

In recent years the vast majority of industrial boiler installations have been packaged or shop assembled gas and oil fired boiler units which could be purchased and installed at substantially lower costs than conventional coal burning boiler-stoker equipment. Because of the decline in the industrial coal market, little or no work has been done in recent years to improve specification data and information made available to consulting engineers and purchasers of coal burning boiler-stoker equipment. The current implementation of more rigid air pollution regulations has made it difficult for many coal burning installations to comply with required stack emission limits, and this has become a further negative influence on coal burning installations.

A field test program to address this problem has been awarded to the American Boiler Manufacturers Association (ABMA), (which, in turn, has subcontracted the field test portion to KVB, Inc., of Minneapolis, Minnesota). The program is sponsored by the 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.

The objective of the test program is to produce information which will increase manufacturers' ability to design and fabricate stoker boilers which are an economical and environmentally satisfactory alternative to importation and combustion of expensive oil. In order to do this, it is necessary to define stoker boiler designs which will provide efficient operation with 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 units.

Further objectives are to: provide assistance to stoker boiler operators in planning for 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 determine emissions and efficiency as functions of changes in coal analysis and sizing, degree of flyash reinjection, overfire air admission, ash handling, grate size, etc., for various boiler, furnace and stoker designs.

This report is the Final Technical report for the third of eleven boilers to be tested under the program described above. It contains a description of the facility tested, the coals fired, the test equipment and procedures, and the results and observations of testing. A data supplement to this report contains the "raw" data sheets from the 50 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, it acts as a research tool for further data reduction and analysis as new areas of interest are uncovered in subsequent testing.

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

Data in this report is presented in English units. It is EPA policy to use System International (S.I.) units in all reports. However, it was determined that English units were necessary in this case. 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 third site tested, this is the Final Technical Report for Test Site C under the program entitled, "A Testing Program to Update Equipment Specifications and Design Criteria for Stoker Fired Boilers."

KVB 15900-528

SECTION 2.0

EXECUTIVE SUMMARY

A coal fired spreader stoker rated at 182,500 lb/hr steam was extensively tested for emissions and efficiency between April 13 and July 5, 1978. This Section summarizes the test results in a bullet format with references to supportive figures, tables and commentary found in the main text of this report.

UNIT TESTED - Described in Section 3.0, pages 11-17

- Babcock & Wilcox Boiler

  Built 1975
  Single pass - two drum Stirling
  182,500 lb/hr rated capacity
  875 psig operating steam pressure
  900°F superheated steam temperature
  Economizer
  Air Heater

- Detroit Rotograte Stoker

  Spreader
  Traveling grate - front discharge
  Reinjection from multiclone D.C. and boiler hopper
  Two rows OFA on front wall and two rows on rear wall

COALS TESTED - Individual coal analysis given in Tables 5-8, 5-9, 5-10 and 5-11, pages 93-96. Commentary in Section 3.0, pages 18-19.

- Eastern Low Fusion Coal (referred to as E-Coal)

  12,260 BTU/lb
  11.2% Ash
  2.9% Sulfur
  5.3% Moisture
  1,985°F Initial Ash Deformation

- Western Coal (referred to as W-Coal)

  8,490 BTU/lb
  9.0% Ash
  0.7% Sulfur
  26% Moisture
  2,185°F Initial Ash Deformation

KVB 15900-528

- Eastern High Fusion Coal (referred to as H-Coal)

  11,850 BTU/lb
  9.2% Ash
  0.9% Sulfur
  9.1% Moisture
  2,145°F Initial Ash Deformation

OVERFIRE AIR TEST RESULTS - Described in Section 5.1, pages 43-60. Overfire air pressure was varied between 5" and 25" H_2O. These changes were made collectively, i.e., all four rows of air jets together, and selectively, i.e., bias pressures to the upper, lower, front and rear rows of air jets individually.

- Particulate Loading - High balanced overfire air produced the lowest particulate loadings, but the relationship between OFA and particulates is not statistically significant. (Sections 5.1.2, pages 50-51; Tables 5-2, 5-3, pages 52, 54; Figures 5-5, 5-6, pages 53, 55)

- Nitric Oxide - NO concentrations increased an average 9% when overfire air pressure was increased from 5" to 25" H_2O. The lower rear air jets were most responsible for this increase. (Section 5.1.3, pages 51, 56; Table 5-4, page 57)

- Carbon Monoxide - CO concentrations were reduced an average 30% when overfire air was increased from 5" to 25" H_2O. The lower rear air jets were most responsible for this reduction. (Section 5.1.4, page 56; Table 5-5, page 59)

- Overfire Air Flow Rate - OFA flow rates were measured for each row of jets at three static pressures. At maximum boiler capacity, OFA can account for as much as 33% of the total air introduced into the furnace. (Section 5.1.1, pages 43-50; Table 5-1, page 46; Figures 5-1, 5-2, 5-3, 5-4, pages 45, 47-49)

- Boiler Efficiency - Changes in boiler efficiency could not be related to OFA conditions. (Section 5.1.5, page 56; Tables 5-2, and 5-3, pages 52, 54)

FLYASH REINJECTION TEST RESULTS - Described in Section 5.2, pages 61-71. In a test series repeated on both E-Coal and W-Coal, flyash reinjection was stopped from the multiclone dust collector, and then from both the multiclone dust collector and the boiler hopper.

- Particulate Loading - Particulate loading was drastically reduced when reinjection was stopped. Seventy-five percent reductions in loading ($lb/10^6 BTU$) were measured at the boiler outlet and 45% reductions were measured at the multiclone outlet (see Table on page 61; also Tables 5-6, 5-7, pages 62, 64; Figures 5-9, 5-10, pages 63, 65)

KVB 15900-528

- Particle Size Distribution - Bahco Classifier and sieve tests show that particulate mass at the boiler outlet was reduced 80% in the size range 20-300 micrometers and 55% in the size range 0-20 micrometers. These reductions occurred when reinjection was stopped completely. (Figures 5-11, 5-12, 5-13, pages 67-69; commentary page 66)

- Combustion Efficiency - Stopping flyash reinjection did not reduce combustion efficiency if the assumption that 70% of the collected ash was reinjected is true. Because this figure is based on design specifications and not actual measurement, no definitive conclusion is made. (Commentary page 70)

- Multiclone Collection Efficiency - It decreased four percent when flyash reinjection was stopped. This decrease was due to a shift in particle size distribution toward finer particles. (Figure 5-36, page 110; commentary on page 108)

BOILER EMISSION PROFILES - Described in Section 5.3, pages 71-92. Boiler emissions were measured over the load range 55-100% of design capacity which corresponds to a grate heat release range of 250,000 to 500,000 BTU/hr-ft^2. Measured excess oxygen levels ranged from 7.2% to 12.5%

- Excess Oxygen Operating Levels - O_2 and load conditions (load expressed as grate heat release) under which all tests were run are shown in Figure 5-14, page 72. Particulate test conditions are profiled in Figure 5-15, page 74. The lower limit of 7% O_2 was thought to be high. This was the result of a coal segregation problem (report in appendix, page 122).

- Particulate Loading - Boiler outlet particulate loading profile in Figure 5-16, page 75. Multiclone outlet particulate loading profile in Figure 5-17, page 76. Particulate loading increased with grate heat release more than doubling between 300 and 500x10^3 BTU/hr-ft^2. At design capacity, boiler outlet loadings ranged from 28 to 36 lb/10^6 BTU. At the multiclone outlet the range was 0.74 to 1.07 lb/10^{6}BTU.

- Nitric Oxide - NO data is profiled in Figures 5-18 and 5-19, pages 78-79. NO trend lines are depicted in Figures 5-20, 5-21, 5-22, and 5-23, pages 80-83. NO increased by an average of 30 ppm for each one percent O_2 increase, at constant load. At design capacity, NO ranged from 250 to 400 ppm.

- Carbon Monoxide - CO data is profiled in Figures 5-24, 5-25 and 5-26, pages 85-87. CO increased with O_2 over the range tested. CO also increased with increasing grate heat release.

KVB 15900-528

BOILER EFFICIENCY - The boiler efficiency profile is shown in Figure 5-29, page 91. Boiler efficiency was invariant with load, being in the range of 77.5 to 83%.

DUST COLLECTOR EFFICIENCY - Multiclone dust collector efficiency was invariant with load. It averaged 96.7%. (Figure 5-36, page 110; commentary page 108, Section 5.6)

COAL PROPERTIES - Described in Section 5.4, pages 92-101. Three coal types were tested.

- Particulate loading was not affected, however, coal size consistency and coal ash did not vary greatly between coals. (Figures 5-16, 5-17, pages 75-76)
- Nitric oxide concentration was not affected (Figure 5-18, page 78)
- Carbon monoxide emissions were highest when burning Western coal where they ranged from 200-700 ppm. On the Eastern coals, CO levels remained below 200 ppm (Figures 5-25 and 5-26, pages 86-87)
- Combustibles in ash were affected as follows, (Figures 5-27, 5-28, pages 88, 89; Table 5-20, page 118):

	Boiler Out Comb.	Bottom Ash Comb.
E Coal	40%	8%
W Coal	11%	18%
H Coal	17%	1%

- Combustion efficiency was lowest for Western coal because of its high moisture content (Figure 5-29, page 91; Table, page 92)
- Coal size consistency was not a variable. Fines averaged 46% passing 1/4" for all three coals (Figures 5-30, 5-31, 5-32, pages 98-100; commentary page 97)
- Sulfur retention in the ash ranged from 6% to 18%. There is insufficient data to correlate sulfur retention with ash properties. (Table 5-12, page 101, commentary page 97)
- Particle size distribution did not vary signficantly with coal type (Section 5.5, pages 102-107; Figures 5-32, 5-33, 5-35, pages 104, 105, 107)

KVB 15900-528

SMOKE SPOT NUMBER - Described in Section 5.7, page 111. Measurements were taken at the multiclone outlet using 1, 2 and 3 pumps on a Bacharach smoke spot tester.

- Smoke spot numbers did not correlate with either particulate loading or combustible loading at the multiclone outlet. (Figures 5-37, 5-38, pages 113-114).

SOURCE ASSESSMENT SAMPLING SYSTEM - Described in Section 5.8 pages 111-115. Flue gas was sampled at the boiler outlet for polynuclear aromatic hydrocarbons and trace elements. Data will be presented in a separate report upon completion of this test program.

The emissions data is 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 of the un-reduced data obtained at Site C 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 C

Test No.	Date	Load %	Coal*	Test Description	O_2 % dry	CO_2 % dry	CO ppm dry	NO ppm dry	Part. Blr Out lb/10^6BTU	Part. Mech DC Out lb/10^6BTU	Excess Air %
1	4/13/78	99	E	As Found, Conditions	7.3	12.6	43	274			53
2	4/19/78			OFA Flow rate - Med OFA							
3				- High OFA							
4				- Low OFA							
5A	4/20/78	97	E	High OFA - High O_2	9.3	9.7	62	378			75
5B				- Med O_2	8.0	11.2	48	360			58
5C				- Low O_2	7.2	11.8	45	337			49
6A	4/20/78	92	E	Low OFA - Low O_2	8.8	10.2	48	303			68
6B				- Med O_2	10.1	9.2	132	338			87
6C				- High O_2	11.5	7.8	171	418			113
7A	4/21/78	93	E	Balanced OFA	9.2	10.1	57	316			74
7B				Reduced Front OFA	9.2	10.2	48	321			74
7C				Reduced Rear OFA	9.6	10.2	55	308			80
7D				Reduced Lower OFA	9.2	10.2	57	290			74
8	4/25/78	69	E	Low Load	10.2	8.8	65	353	13.1		88
9	5/01/78	89	E	Normal Flyash Reinjection	8.9	10.5	66	288	25.0	0.82	70
10	5/03/78	93	E	No Flyash Reinjection	9.1	10.1	55	356	6.0	0.48	72
11	5/03/78	93	E	Blr Hpr Reinjection Only	9.1	10.0	53	333	7.0	0.50	72
12	5/04/78	93	E	High Balanced OFA	8.9	10.1	53	273	19.0	0.69	69
13	5/04/78	91	E	Low Balanced OFA	8.9	10.3	103	230	21.1	0.64	69
14	5/09/78	93	E	Bias Upper OFA	9.2	10.0	49	326	20.9	0.94	74
15	5/10/78	91	E	Bias Lower OFA	9.1	10.1	53	328	22.6	0.78	72
16	5/11/78	93	E	Bias Front OFA	8.7	10.4	37	319	23.9	0.84	67
17A	5/12/78	76	E	High OFA - High O_2	10.4	8.9	37	282			92
17B				- Med O_2	9.4	10.1	23	244			77
17C				- Low O_2	8.3	11.0	21	227			62
18A	5/12/78	76	E	Low OFA - High O_2	9.8	10.0	37	300			84
18B				- Med O_2	8.6	11.0	32	233			66
18C				- Low O_2	7.4	12.0	26	212			52
19	5/12/78	92	E	Bias Rear OFA	8.7	10.4	44	326	25.1	0.88	67
20	5/13/78	55	E	Low Load	11.0	8.1	68	331	13.2	0.51	103
21A	5/16/78	77	W	High OFA - High O_2	10.3	9.2	296	355			90
21B				- Med O_2	9.2	10.0	168	352			73
21C				- Low O_2	8.1	11.6	154	350			60
22A	5/16/78	77	W	Low OFA - Med O_2	8.8	11.2	259	311			69
22B				- Low O_2	7.2	12.8	144	288			50
22C				- High O_2	10.0	9.4	361	361			85
23	5/17/78	100	W	High Balanced OFA	8.6	10.9	311	387	29.2	1.04	65
24	5/18/78	98	W	Low Balanced OFA	8.7	10.6	488	372	31.1	1.03	66
25	5/19/78	78	W	High Balanced OFA	8.6	11.2	173	358	20.4	0.55	66
26	5/23/78	99	W	Bias Upper OFA	9.9	9.8	395	394	34.0	1.04	84
27	5/24/78	100	W	Bias Lower OFA	8.9	10.5	287	387	31.6	1.03	69
28	5/25/78	99	W	Bias Front OFA	9.0	10.6	567	395	33.1	0.94	70
29	5/26/78	100	W	Bias Rear OFA	8.4	10.9	323	408	36.4	0.74	63
30A	5/29/78	59	W	High OFA - High O_2	11.5	8.2	232	400			114

KVB 15900-528

EMISSION DATA SUMMARY
TEST SITE C

(Continued)

Test No.	Date	Load %	Coal*	Test Description	O_2 % dry	CO_2 % dry	CO ppm dry	NO ppm dry	Part. Blr Out lb/10^6BTU	Part. Mech DC Out lb/10^6BTU	Excess Air %
30B				- Med O_2	11.0	8.6	198	379			103
30C				- Low O_2	10.0	9.6	151	361			86
31A	5/29/78	55	W	Low OFA - Low O_2	9.0	10.8	97	271			72
31B				- Med O_2	10.0	10.0	151	312			87
31C				- High O_2	11.0	8.9	199	325			104
32A	5/30/78	96	W	High OFA - Low O_2	7.2	12.2	163	301			50
32B				- Med O_2	8.3	11.2	249	341			62
32C				- High O_2	9.1	10.6	334	334			72
33A	5/30/78	96	W	Low OFA - Low OFA	8.1	10.6	266	322			58
33B				- Med O_2	9.0	10.0	421	346			70
33C				- High O_2	10.7	8.6	702	421			95
34A	5/30/78	95	W	Bias Front OFA	8.6	11.0	327	357			66
34B				Bias Rear OFA	8.5	11.0	296	375			64
34C				Bias Upper OFA	8.4	11.5	294	337			63
34D				Bias Lower OFA	8.5	11.5	281	375			65
35	5/31/78	55	W	Low Load	10.6	9.0	182	300	15.2	0.36	96
36	6/01/78	98	W	No Flyash Reinjection	8.1	11.4	247	357	8.6	0.52	59
37	6/01/78	98	W	OFA Flow Rate - Med OFA							
38				- High OFA							
39				- Low OFA							
40	6/02/78	102	W	Blr Hpr Reinjection Only	8.3	11.3	280	341	6.1	0.47	62
41	6/07/78	58	H	Low Load	11.3	8.3	57	383	16.2	0.54	110
42	6/09/78	99	H	High Load	9.4	10.6	132	289	28.0	1.07	78
43	6/13/78	78	H	Med Load	9.8	10.4	45	374	20.3	0.69	84
44	6/15/78	97	H	SASS, SOx†, and Brink	8.9	10.9	263	385			70
45	6/17/78	97	W	SASS, SOx and Brink	8.3	11.1	272	375			62
46	6/20/78	99	E	SASS, SOx and Brink	9.0	10.2	57	436			71
47	6/29/78	93	E		9.8	9.5	44	407			83
48A	6/29/78	93	E	High OFA	9.7	9.7	35	398			81
48B				Med OFA	9.3	10.1	33	397			75
48C				Low OFA	8.3	10.9	61	379			62
49A	7/05/78	58	E	High OFA - High O_2	12.5	7.2	139	373			138
49B				- Med O_2	10.5	8.6	52	336			94
49C				- Low O_2	9.0	9.8	30	308			70
50A	7/05/78	58	E	Low OFA - High O_2	10.9	8.8	72	358			102
50B				- Med O_2	8.9	10.3	67	283			70
50C				- Low O_2	7.2	11.6	120	216			49

NOTES: * E - Eastern Low Fusion Coal
W - Western Coal
H - Eastern High Fusion Coal

NO_2 and HC data was not obtained due to inserviceability of sampling and analyzing equipment

† SOx data was as follows: Test 44 SO_2 - 969 SO_3 7 ppm (dry)
45 SO_2 - 805 SO_3 5 ppm (dry)
46 SO_2 -1863 SO_3 8 ppm (dry)

All parts per million (ppm) concentrations are corrected to 3% O_2

KVB 15900-528

SECTION 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 C. The coals utilized in this test series are also discussed.

3.1 BOILER C DESCRIPTION

The boiler tested is a single pass two drum Stirling boiler built by Babcock and Wilcox Company in 1975. It has continuous rating of 182,500 lb/hr steam at 875 psig and 900°F. An unusual characteristic of this boiler is its large "nose", the intrusion on the back waterwall used to shield the superheat pendants from radiant heat. A side elevation of the boiler is illustrated in Figure 3-1.

The boiler is fired by a Detroit Rotograte Stoker having seven spreaders and a traveling grate with front ash discharge. Design data on the boiler and stoker are listed in Table 3-1. Predicted performance data is given in Table 3-2.

The boiler's collection equipment includes a UOP multiclone dust collector and an electrostatic precipitator. The multiclone is described in further detail in Section 3.3, Flyash Reinjection System.

3.2 OVERFIRE AIR SYSTEM

The overfire air system on Boiler C consists of two rows of air jets on the back wall and two rows on the front wall. The overfire air is supplied by an independent fan and is not preheated.

The overfire air design data is as follows:

Front Upper Row:	27-3/4" jets by B&W Spaced at 12" 6'3-1/8" above grate 25° below horizontal

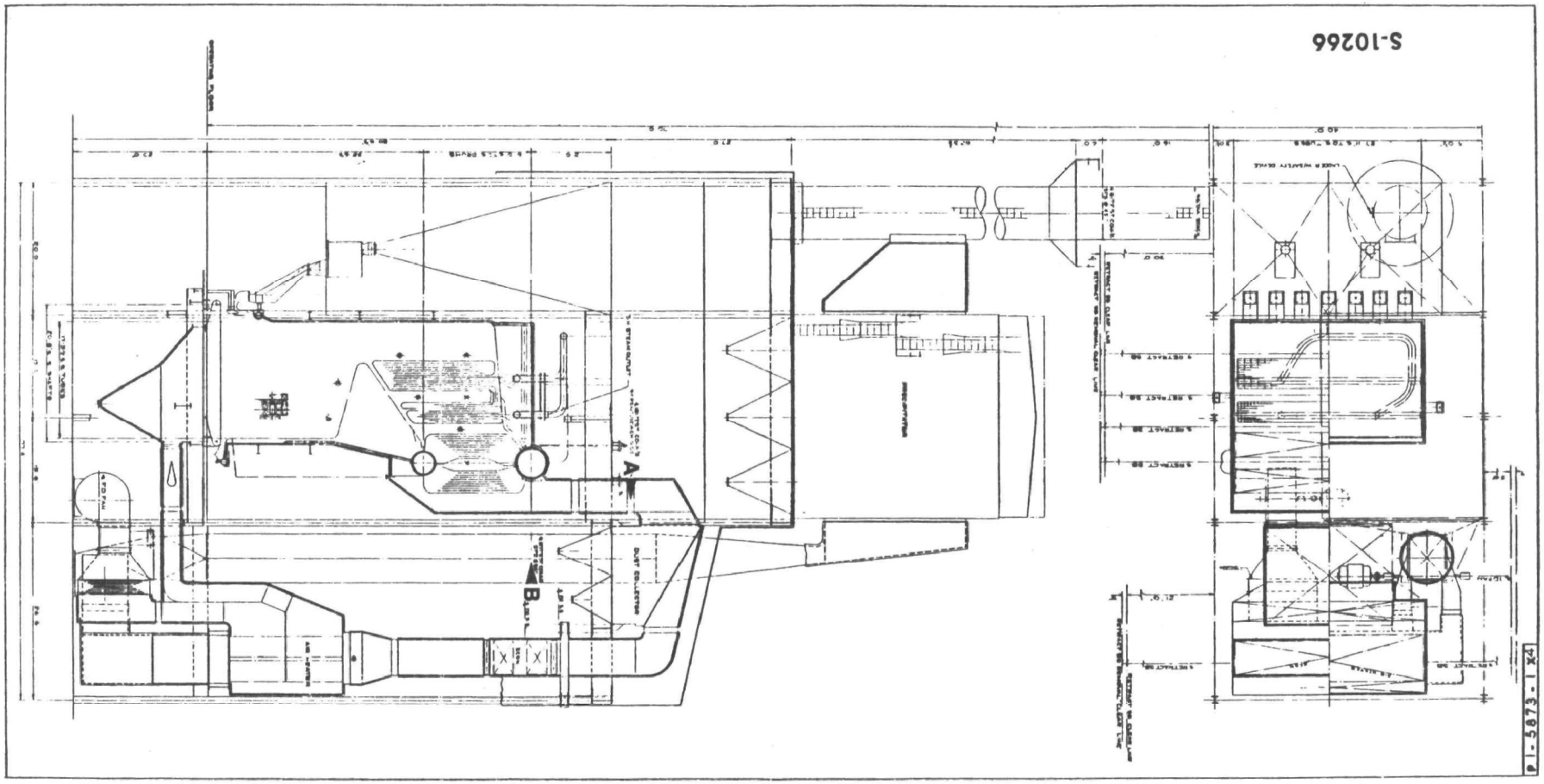


FIGURE 3-1. SECTIONAL SIDE ELEVATION AND PLAN VIEW - TEST SITE C

A - BOILER OUTLET SAMPLING PLANE
B - MULTICLONE DUST COLLECTOR OUTLET SAMPLING PLANE

TABLE 3-1

DESIGN DATA
TEST SITE C

BOILER:	Type	Two Drum Stirling-SPB
	Boiler Heating Surface	21,925 ft^2
	Water Wall Heating Surface	2,906 ft^2
	Design Pressure	1,025 psig
	Tube Diameter	2.5 inches
SUPERHEATER:	Heating Surface	10,520 ft^2
	No. of Steam Passes	2
STEAM TEMP CONTROL:	Type	Spray Attemperator
	Location	Intermediate
ECONOMIZER:	Type	Continuous Bare Tube
	Heating Surface	8,620 ft^2
	Design Pressure	1,050 psig
	Tube Length	28 ft
	Tube Diameter	2 inches
AIR HEATER:	Type	Tubular
	Heating Surface	22,217 ft^2
FURNACE:	Volume	12,100 ft^3
	Flat Projected Heating Surface to Face of Convection Surface	3,432 ft^2
STOKER:	Type	Spreader with Traveling Grate
	Width	27'-1.5"
	Length	19'- 0"
	Effective Grate Area	515.4 ft^2
HEAT RATES:	Steam Actual	182,500 lb/hr
	Input to Furnace	249×10^6 BTU/hr
	Total Heat Available	224.9×10^6 BTU/hr
	Furnace Width Heat Release	9.2×10^6 BTU/Ft Furnace Width-hr
	Grate Heat Release	483×10^3 BTU/ft^2 Grate-hr
	Furnace Liberation	20.6×10^3 BTU/ft^3-hr
	Heat Available to Conv. Surface	65.2×10^3 BTU/ft^2-hr

TABLE 3-2

PREDICTED PERFORMANCE - TEST SITE C

Steam Leaving Superheater	182,500 lb/hr
Fuel	Coal*
Excess Air Leaving Boiler	32 %
Coal Flow	29,600 lb/hr
Flue Gas Leaving Boiler	265,000 lb/hr
Air Leaving Air Heater	206,000 lb/hr+
Steam Pressure at SH Outlet	875 psig
Economizer to Drum Pressure Drop	4 psig
Drum to SH Outlet Pressure Drop	30 psig
Temp. Steam Leaving Superheater	900 °F
Temp. Flue Gas Leaving Boiler	622 °F
Temp. Flue Gas Leaving Economizer	445 °F
Temp. Flue Gas Leaving Air Heater	320 °F
Temp. Water Entering Economizer	370 °F
Temp. Water Leaving Economizer	437 °F
Temp. Air Entering Air Heater	130 °F ++
Temp. Air Leaving Air Heater	302 °F
Furnace & Convection Draft Loss	0.9 "H_2O
Dust Collector & Precipitator Draft Loss	1.6 "H_2O
Air Heater & Economizer Draft Loss	2.2 "H_2O
Flues to Stack Draft Loss	0.8 "H_2O
Net Furnace to Stack Draft Loss	5.5 "H_2O
Stoker Draft Loss	1.2 "H_2O
Air Duct Draft Loss	0.4 "H_2O
Air Heater Air Draft Loss	0.4 "H_2O
Steam Coil Air Heater Draft Loss	0.4 "H_2O++
Net FD Fan to Furnace Draft Loss	2.4 "H_2O
Dry Gas Heat Loss	4.5 %
H_2O and H_2 in Fuel Heat Loss	7.4 %
Moisture in Air Heat Loss	0.1 %
Unburned Combustible Heat Loss	4.7 %+++
Radiation Heat Loss	0.4 %
Unaccounted for and Manufacturers Margin	1.5 %
Total Heat Loss	18.6 %
Efficiency of Unit	81.4 %

+Based on 88% air leaving A.H.
++Based on Steam coil A.H. in operation
+++Based on 0% reinjection from dust collector

*Predicted performance is based on combustion air entering at 80°F, 0.013 lb moisture/lb dry air, 29.25 in. Hg. barometric pressure and coal fuel containing 26.5% moisture, 29.0% volatile matter, 34.4% fixed carbon, 10.1% ash, 8,419 BTU/lb

Front Lower Row:	29-3/4" jets by Detroit Stoker Company Spaced at 10-5/8" Estimated 1'6" above grate Angle unknown
Rear Upper Row:	28-1" jets by B&W Spaced at alternately 13-1/2" and 9" 6'1" above grate 9° below horizontal
Rear Lower Row:	13-1-1/4" jets by Detroit Stoker Spaced at alternately 18" and 2'3" (end jets at 4'6") 1'6" above grate horizontal

3.3 FLYASH REINJECTION SYSTEM

Boiler C reinjects flyash continuously from the boiler hopper and from a portion of the multiclone dust collector.

The dust collector is a UOP Design 106 Dynamic Centrifugal Collector designed to preclean flue gas prior to an economizer. It was designed for a medium efficiency of 87%. It has the capability of segregating the collected flyash to a certain extent so that the larger particles - those having the highest combustible content - are collected in the rear hoppers and reinjected to the furnace. The finer particles are collected in the front hoppers and discarded. The reinjected portion of the flyash represents approximately 70% of the flyash collected. The "dynamic" feature permits a slight variation of this percentage through a simple lever adjustment.

The predicted performance of the dust collector is given below. It is based on a flyash analyzing 35% less than ten micrometers as determined by the Bahco Analyzer Method, and corrected to a specific gravity of 2.5.

	Load 1	Load 2	Load 3
Lbs gas/hr	433,400	396,000	290,840
Operating Temperature, °F	600	650	620
ACFM	211,700	185,920	132,734
Collector Resistance, "H_2O	2.85	2.38	1.28
Collector Efficiency	87	85	85

Further design data on the flyash reinjection system is as follows:

Boiler Hopper:	Seven discharge nozzles Spaced at 3'0" to 4'4-1/2" (variable) 1'6" above grate 4° below horizontal
Dust Collector Hopper:	Sixteen discharge nozzles Spaced at 18" to 4'8" (variable) in pairs 9" apart 1'6" above grate 4° below horizontal

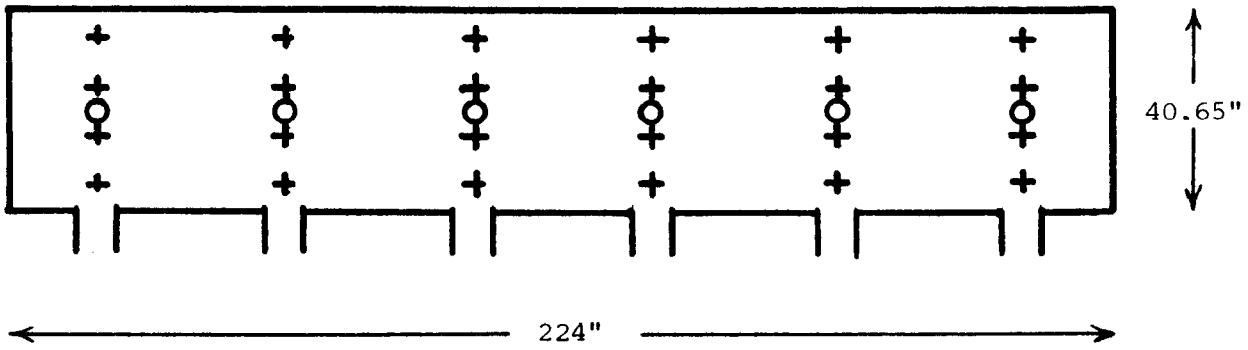
3.4 TEST PORT LOCATIONS

Emission measurements were made at two locations. These were the boiler outlet (before the multiclone dust collector) and the multiclone outlet (after the economizer and air heater but before the ESP). The locations of these sample points are shown in Figure 3-1. Their geometry are shown in Figure 3-2.

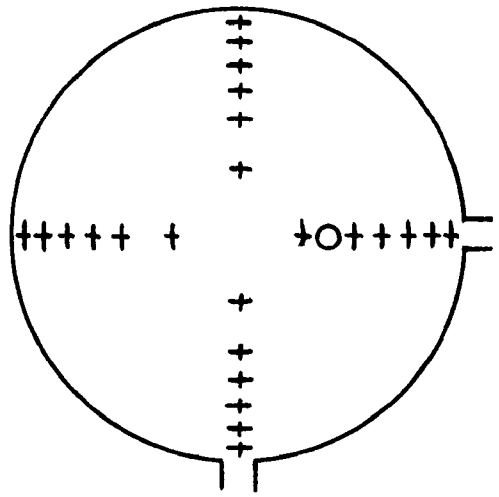
Whenever particulate loading was measured, it was measured simultaneously at both locations using 24 point sample traverses. Gaseous measurements of O_2, CO_2, CO, and NO were obtained by pulling samples individually and compositely from six probes distributed along the width of the boiler outlet duct. SOx measurements and SASS samples for organic and trace element determinations were obtained from a single point within the boiler outlet duct.

A heated sample line was attached to one of the middle gaseous probes at the boiler outlet. It's purpose was to eliminate losses due to condensation when measuring NO_2 and unburned hydrocarbons. However, problems with the sample line and electro mechanical problems with both the hydrocarbon analyzer and the NOx converter prevented these measurements from being made.

BOILER OUTLET SAMPLING PLANE



MULTICLONE OUTLET SAMPLING PLANE
Diameter = 89.4"



Boiler Outlet Cross Sectional Area = 63.23 ft^2
Multiclone Outlet Cross Sectional Area = 43.59 ft^2

KEY: + Particulate Sample Point
o Gaseous Sample Point

Figure 3-2. BOILER C SAMPLE PLANE GEOMETRY

3.5 COALS UTILIZED

Three coal types were fired at Test Site C. These were an Eastern low fusion coal, a Western coal, and an Eastern high fusion coal. They are referred to as E, W and H coals, respectively, in the accompanying tables and figures. Coal samples were taken for each test involving particulate or SASS sampling. The average analyses obtained from these samples are presented in Table 3-3. They show significant differences in moisture, sulfur and BTU contents. The analyses for each coal sample are presented in Section 5.0, Test Results and Observations, Tables 5-8 through 5-11.

TABLE 3-3

AVERAGE COAL ANALYSIS
TEST SITE C

	Eastern Low Fusion (E Coal)	Western Coal (W Coal)	Eastern High Fusion (H Coal)
% Moisture	5.3	25.6	9.1
% Ash	11.2	9.0	9.2
% Volatile	35.0	29.0	30.9
% Fixed Carbon	48.5	36.4	50.7
BTU/lb	12260	8490	11850
% Sulfur	2.9	0.7	0.9
Initial Ash Deformation, °F	1985	2185	2145
Hardgrove Grindability Index	62	49	44
Free Swelling Index	7	0	1
Fines, % passing 1/4"	46	48	44

SECTION 4.0

TEST EQUIPMENT AND PROCEDURES

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

4.1 GASEOUS EMISSIONS MEASUREMENTS (NO, NO_2, CO, CO_2, O_2, HC)

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

4.1.1 Analytical Instruments and Related Equipment

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

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

- Nitric Oxide/total oxides of nitrogen (NO/NOx)

  Thermo Electron Model 10 Chemiluminescent Analyzer

  Range: 0-2.5, 10, 25, 100, 250, 1000, 2500, 10,000 ppm NO

  Accuracy: $\pm 1\%$ of full scale

- Carbon Monoxide

Beckman Model 315B NDIR Analyzer

Range: 0-500 and 0-2000 ppm CO

Accuracy: ±1% of full scale

- Carbon Dioxide

Beckman Model 864 NDIR Analyzer

Range: 0-5% and 0-20% CO_2

Accuracy: ±1% of full scale

- Oxygen

Teledyne Model 326A Fuel Cell Analyzer

Range: 0-5, 10 and 25% O_2 full scale

Accuracy: ±1% of full scale

- Hydrocarbons

Beckman Model 402 Flame Ionization Analyzer

Range: 5 ppm full scale to 10% full scale

Accuracy: ±1% of full scale

The oxides of nitrogen monitoring instrument used is a Thermo Electron chemiluminescent nitric oxide analyzer. The operational basis of the instrument is the chemiluminescent reaction of NO and O_2 to form NO_2. Light emission results when electronically excited NO_2 molecules revert to their ground state. This 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 through an air 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 which insures that no water collects in the pump.

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

Specifications: Accuracy 1% of full scale
Span Stability ±1% of full scale in 24 hours
Zero Stability ±1 ppm in 24 hours
Power Requirements 115±10V, 60 Hz, 1000 watts
Response 90% of full scale in 1 sec. (NOx mode),
0.7 sec NO mode
Output 4-20 ma
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 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 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 ± 15 V rms
Response: 90% of full scale in 0.5 or 2.5 sec.
Precision: ±1% of full scale
Output: 4-20 ma

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 ± 15 V rms
Response: 90% of full scale in 0.5 or 2.5 sec.
Precision: ±1% of full scale
Output: 4-20 ma

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%-hrs.

Power Requirement: 115 VAC, 50-60 Hz, 100 watts

Output: 4-20 ma

Hydrocarbons are measured using a Beckman Model 402 hydrocarbon analyzer which utilizes the flame ionization method of detection. The sample is drawn through a heated line to prevent the loss of higher molecular weight hydrocarbons to the analyzer. 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 an electronic measuring 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

4.1.2 Recording Instruments

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

Chart Size: 9-3/4 inch

Accuracy: $\pm 0.25\%$

Linearity: $<0.1\%$

Line Voltage: 120V $\pm$ 10% at 60 Hz

Span Step Response: 1 second

4.1.3 Gas Sampling and Conditioning System

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

4.2 GASEOUS EMISSION SAMPLING TECHNIQUES (NOx, CO, CO_2, O_2, HC)

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

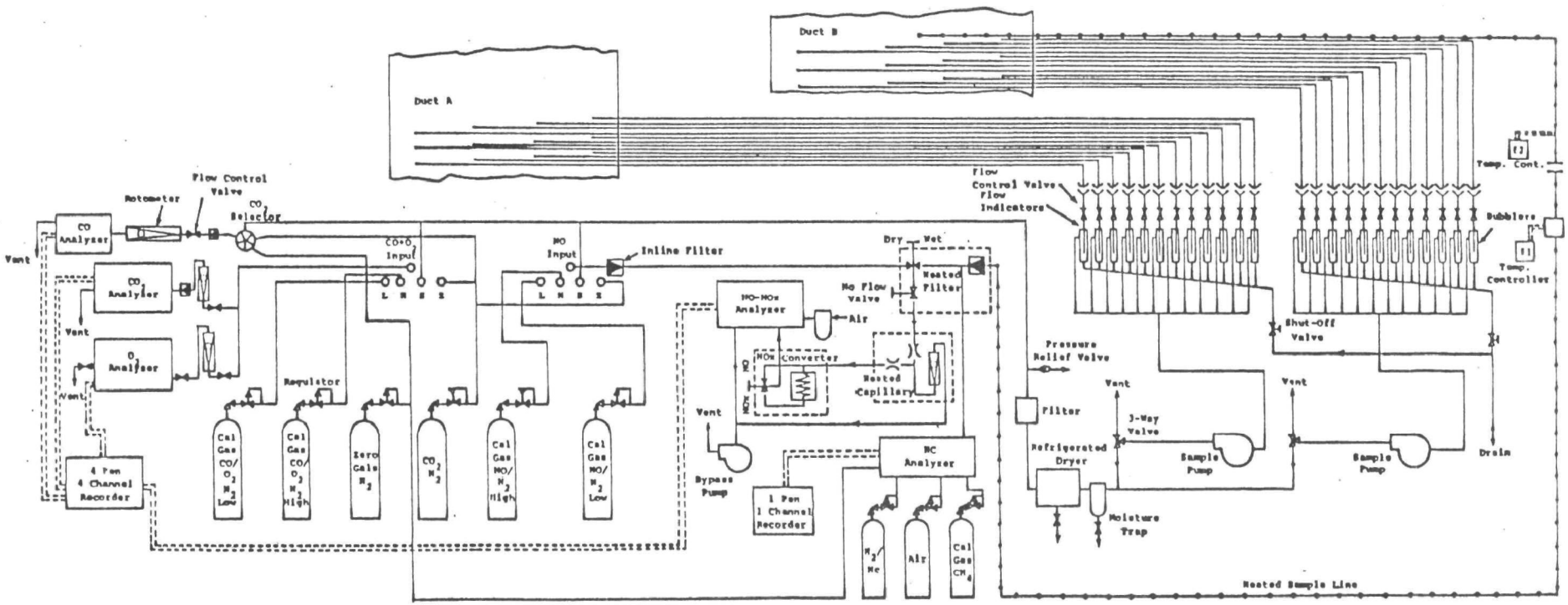


Figure 4-1. Flow schematic of mobile flue gas monitoring laboratory.

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

4.3 SULFUR OXIDES (SOx) MEASUREMENT AND PROCEDURES

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

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

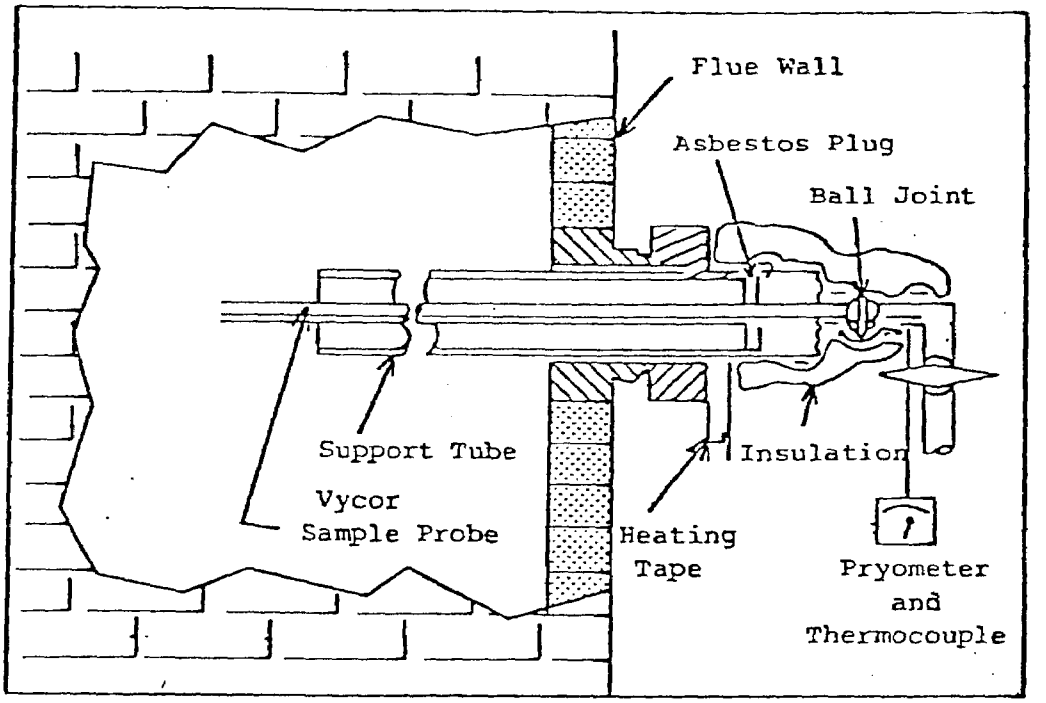


Figure 4-2. SOx Sample Probe Construction

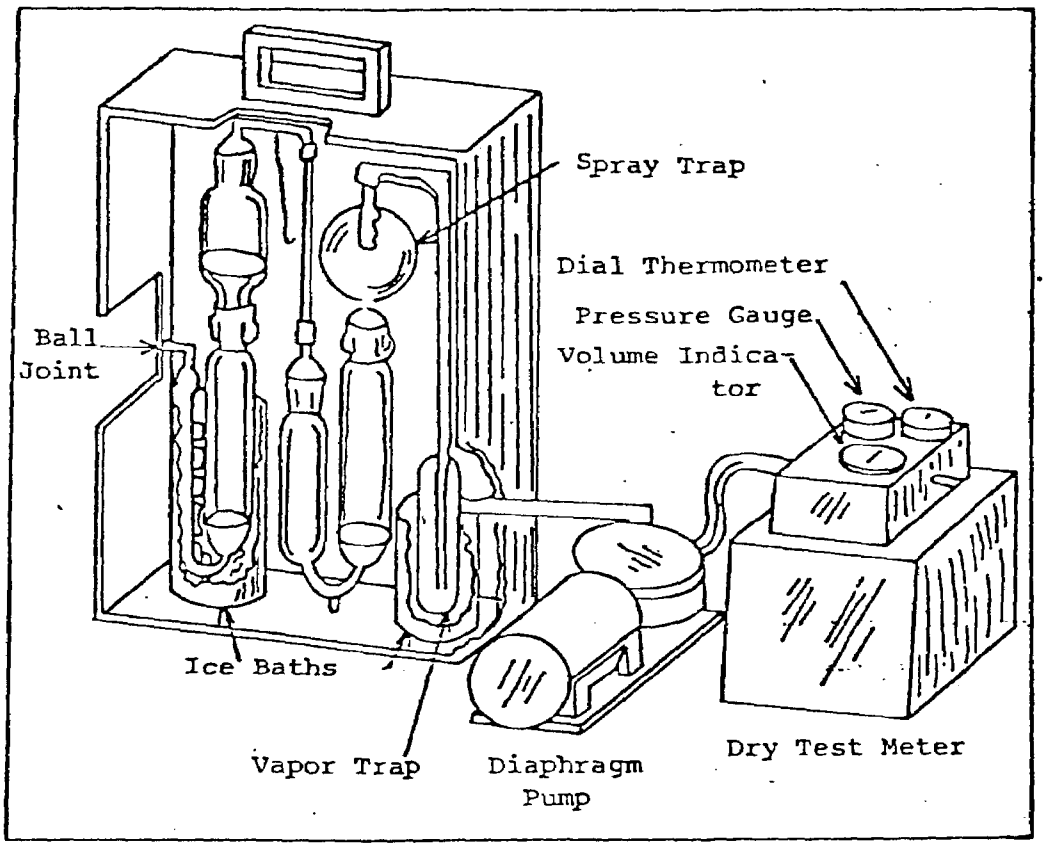


Figure 4-3. Sulfur Oxides Sampling Train

The gas sample is drawn from the flue by a single probe made of quartz glass inserted into the duct approximately one-third to one-half way. The inlet end of the probe holds a quartz wool filter to remove particulate matter. It is important that the entire probe temperature be kept above the dew point of sulfuric acid during sampling (minimum temperature of 260°C). This is accomplished by wrapping the probe with a heating tape.

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

4.4 PARTICULATES MEASUREMENT AND PROCEDURES

Particulate samples are taken at the same sample ports as the gaseous emission samples using a Joy Manufacturing Company portable effluent sampler (Figure 4-4). This system, which meets the EPA design specifications for Test Method 5, Determination of Particulate Emissions from Stationary Sources (Federal Register, Volume 36, No. 27, page 24888, December 23, 1971), is used to perform both the initial velocity traverse and the particulate sample collection. Dry particulates are collected in a heated case using first a cyclone to separate particles larger than 5 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 thermister indicator. A pitot tube system is provided for setting sample flows to obtain isokinetic sampling conditions.

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

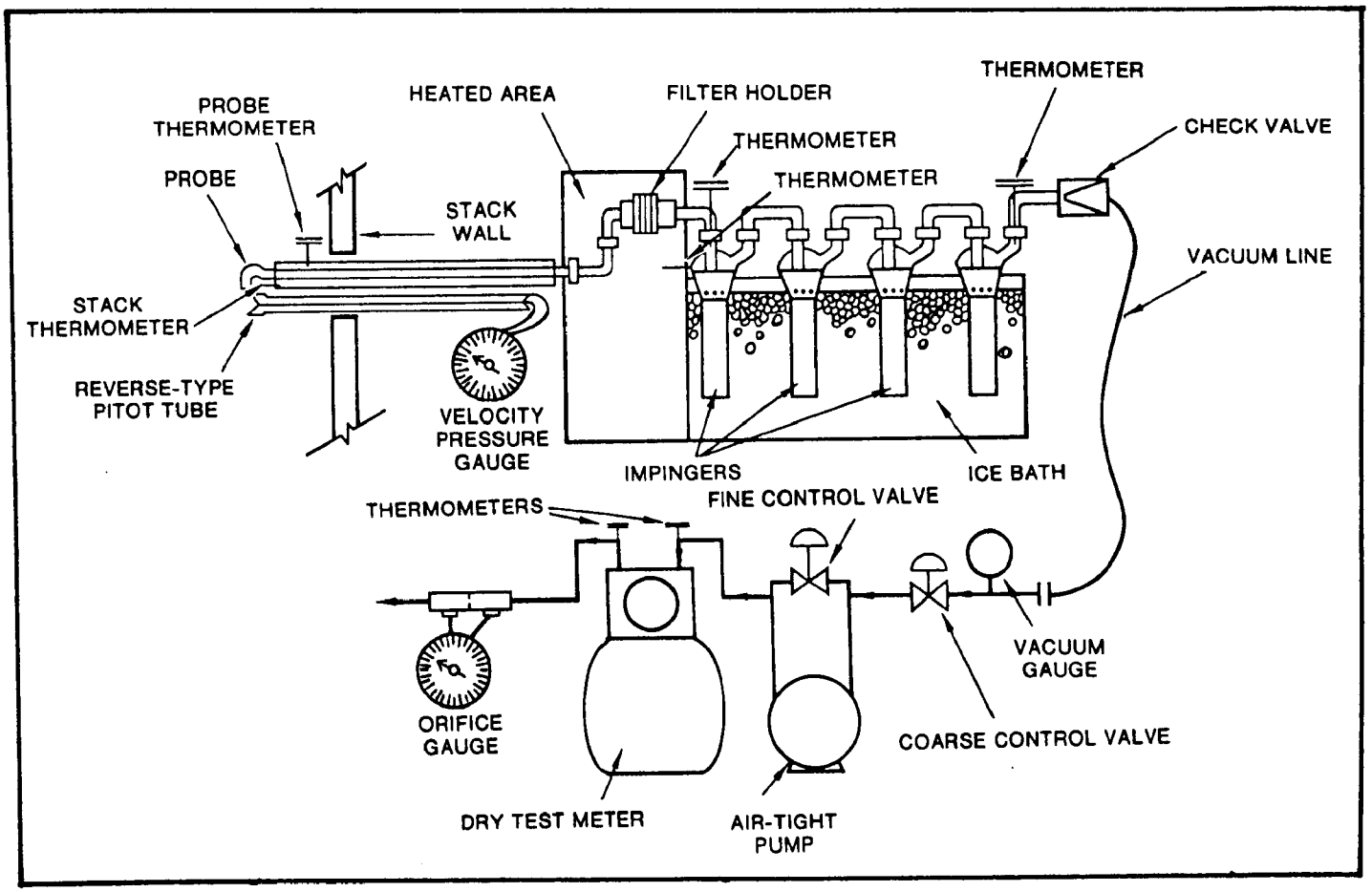


Figure 4-4. Particulate Sampling Train

4.5 PARTICLE SIZE DISTRIBUTION MEASUREMENT AND PROCEDURE

Particle size distribution is measured using several methodologies. These include the Brink Cascade Impactor, SASS cyclones, and the Bahco Classifier. Each is discussed below.

The Brink Model "B" Cascade Impactor is a five stage, low sample rate, cascade impactor suitable for measurements in high mass loading situations. A schematic of the Brink sampling train is shown in Figure 4-5. Samples are pulled isokinetically from a single sample point. The flow rate through the impactor is held constant during sampling to preserve the impaction cut points.

Gelman type A-E binderless glass fiber filter paper is used as the collection substrate. The main purpose of the glass mats is to reduce re-entrainment due to particle bounce. The 5/8 inch diameter mats are cut from larger stock with a cork bore and inserted in the collection plates. The collection plates with mats installed are desiccated 24 hours before tare weighing. After sampling, all particles adhering to the impactor walls are brushed down onto the collection plate immediately below. The plates are again desiccated 24 hours before weighing.

The cyclone catch is brushed onto a tare weighed paper, desiccated and weighed. The final filter, cut from the same fiber glass stock as the collection plate substrates, is treated the same as the collection plates.

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.

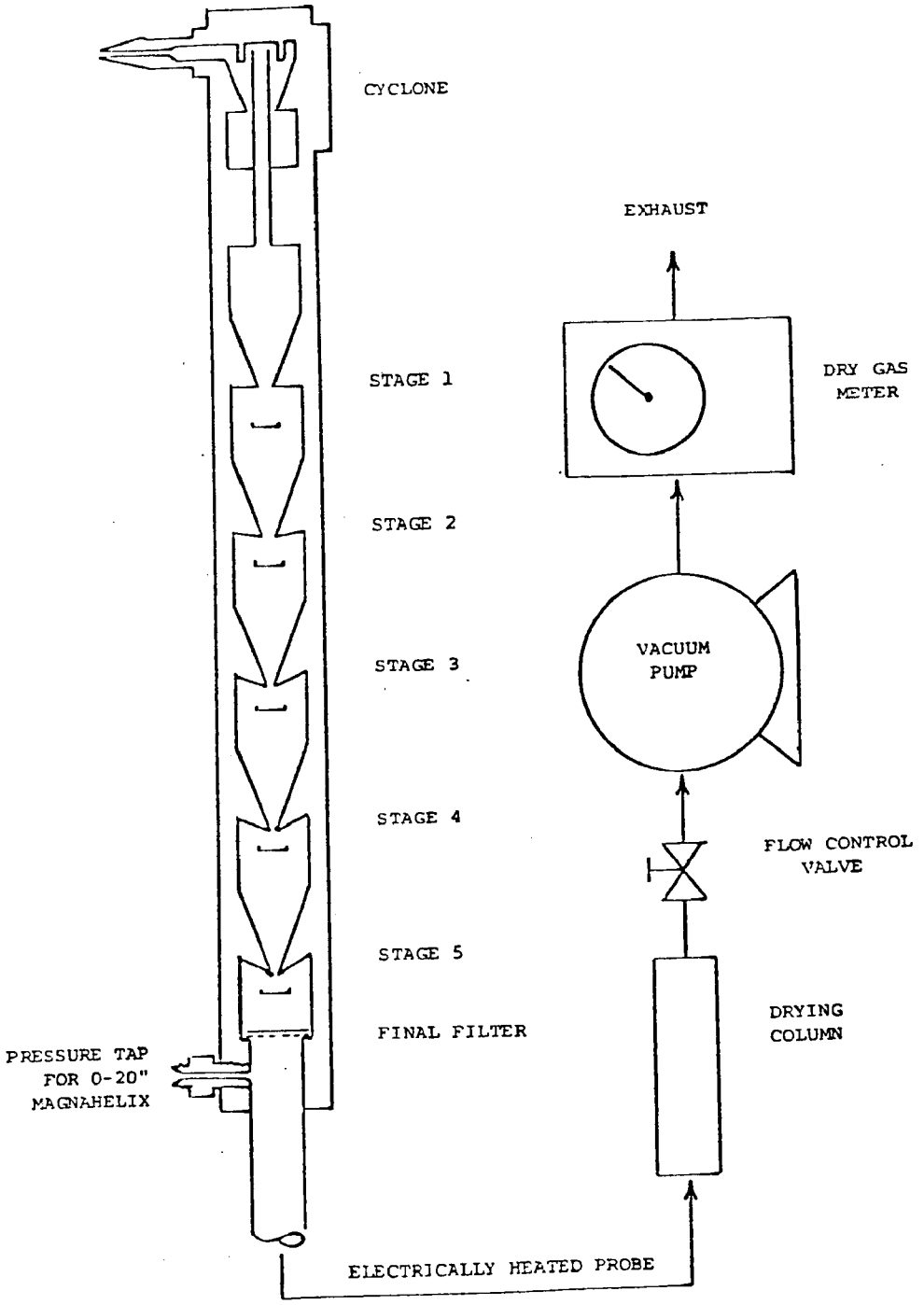


Figure 4-5. Brink cascade impactor sampling train schematic.

KVB 15900-528

The impactor is placed in the duct for 20-30 minutes prior to sampling to allow it to be heated to stack temperature. During this warmup period, the sample nozzle is turned away from the direction of gas flow so that no particulates will be collected. Once hot, the stages are re-tightened with pipe wrenches to prevent leakage. The impactor's nozzle is then turned into the gas stream for collecting the particulate sample.

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 re-entrainment, a rule of thumb is that no stage should be loaded above 10 mg.

The volume of dry gas sampled is measured with a dry gas meter. This allows calculation of actual isokinetics. The dry gas volume is also used to convert test results to concentration units. Stack moisture used for calculating isokinetics is measured with the EPA Method 5 sample train during concurrent particulate sampling.

In addition to the Brink Cascade Impactor, particle sizing is accomplished by several other methods. The SASS train utilizes three sized cyclones and a final filter under controlled temperature and flow rates to achieve gravimetric separation at ten, three and one micrometers.

Selected flyash samples are sent to an independent laboratory for sizing using the Bahco centrifugal classifier (PTC 28).

Each of the three particle sizing methods described above has its advantages and disadvantages. None is ideal for the intended application.

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 a laboratory technique and is thus 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 C came from the cyclone in the EPA Method 5 particulate train. These samples are spatially representative because they were taken

from a 24-point sample matrix. However, much of the sample below about seven micrometers was lost to the filter. The Bahco test data are presented in combination with sieve analysis of the same sample. No attempt was made to correct for the lost portion of the sample.

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 also has some disadvantages. Because it is a single point sampler, spatial stratification of particulate matter within the duct will yield erroneous results. Unfortunately, the particles at the outlets of stoker boilers may be considerably stratified. Another disadvantage is its small classification range (0.3 to 3.0 micrometers) and its small sample nozzle (1.5 to 2.0 mm maximum diameter). Both are inadequate for the job at hand. The particles being collected at the boiler outlet are often as large as the sample nozzle.

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

4.6 COAL SAMPLING AND ANALYSIS PROCEDURE

Coal samples are taken during each test from the units two coal scales. The samples are 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 belts discharge end to catch all of the coal over a short increment of time (approximately five seconds).

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

The sample to be used for sieve analysis is weighed, dried in an oven at 220°F for about four hours, and re-weighed. Drying of the coal is necessary for good separation of fines. If the coal is wet, fines cling to the larger pieces of coal and to each other. Once dry, the coal is sized using a six tray Gilson Model PS-3 Porta Screen. Screen sizes used are 1", 1/2", 1/4", #8 and #16 mesh. Screen area per tray is 14"x14". The coal in each tray is weighed on a triple beam balance to the nearest 0.1 gram.

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

4.7 ASH COLLECTION AND ANALYSIS FOR COMBUSTIBLES

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.

Bottom ash samples are collected in several increments and from several locations along the discharge end of the grate. These samples are mixed, quartered, and sent to Commercial Testing and Engineering Company for combustible determination. Bottom ash samples cannot be obtained directly from the ash pit because it is a wet hopper design.

Multiclone ash samples are taken from ports near the base of the multiclone hopper. This sample, approximately two quarts in size, is sent to Commercial Testing and Engineering Company for combustible determination.

4.8 BOILER EFFICIENCY EVALUATION

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

Unlike the ASME test form where 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.

Certain assumptions are necessary to carry out the combustible loss calculations. The collection rate of bottom ash is based on the assumption that 50% of the ash in the coal ends up as bottom ash. The discarded portion of the flyash collected by the dust collector is assumed to be 30%. The remaining 70% is reinjected according to collector design specifications. This 30-70 collector split was not confirmed by test.

4.9 MODIFIED SMOKE SPOT NUMBER

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

Smoke spot measurements are obtained by pulling a fixed volume of flue gas through a standard filter paper. The color (or shade) of the spot that is produced is matched visually with a standard smoke spot scale. The result is a "Smoke Number" which is used to characterize the density of smoke in the flue gas.

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

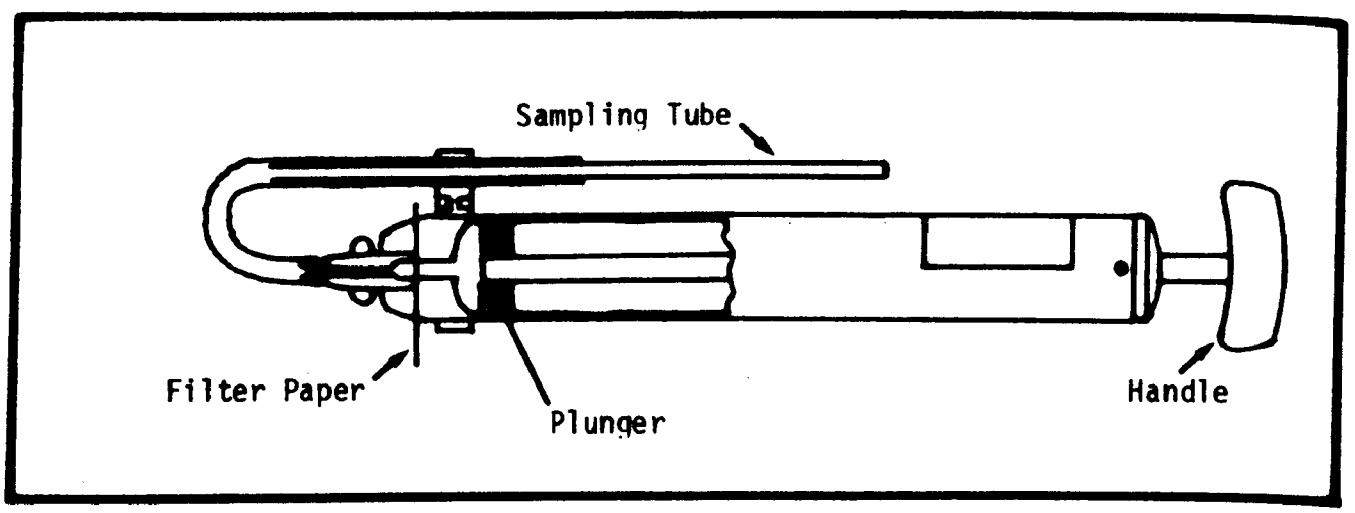


Figure 4-6. Field Service Type Smoke Tester

4.10 TRACE SPECIES MEASUREMENT

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

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

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

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

4.11 FLYASH REINJECTION EVALUATION

The procedure for altering the flyash reinjection rate from the boiler hopper was as follows. First, the butterfly valves controlling the reinjection air flow were closed. Because the valves do not seal shut completely, a small amount of air still passes through the reinjection lines.

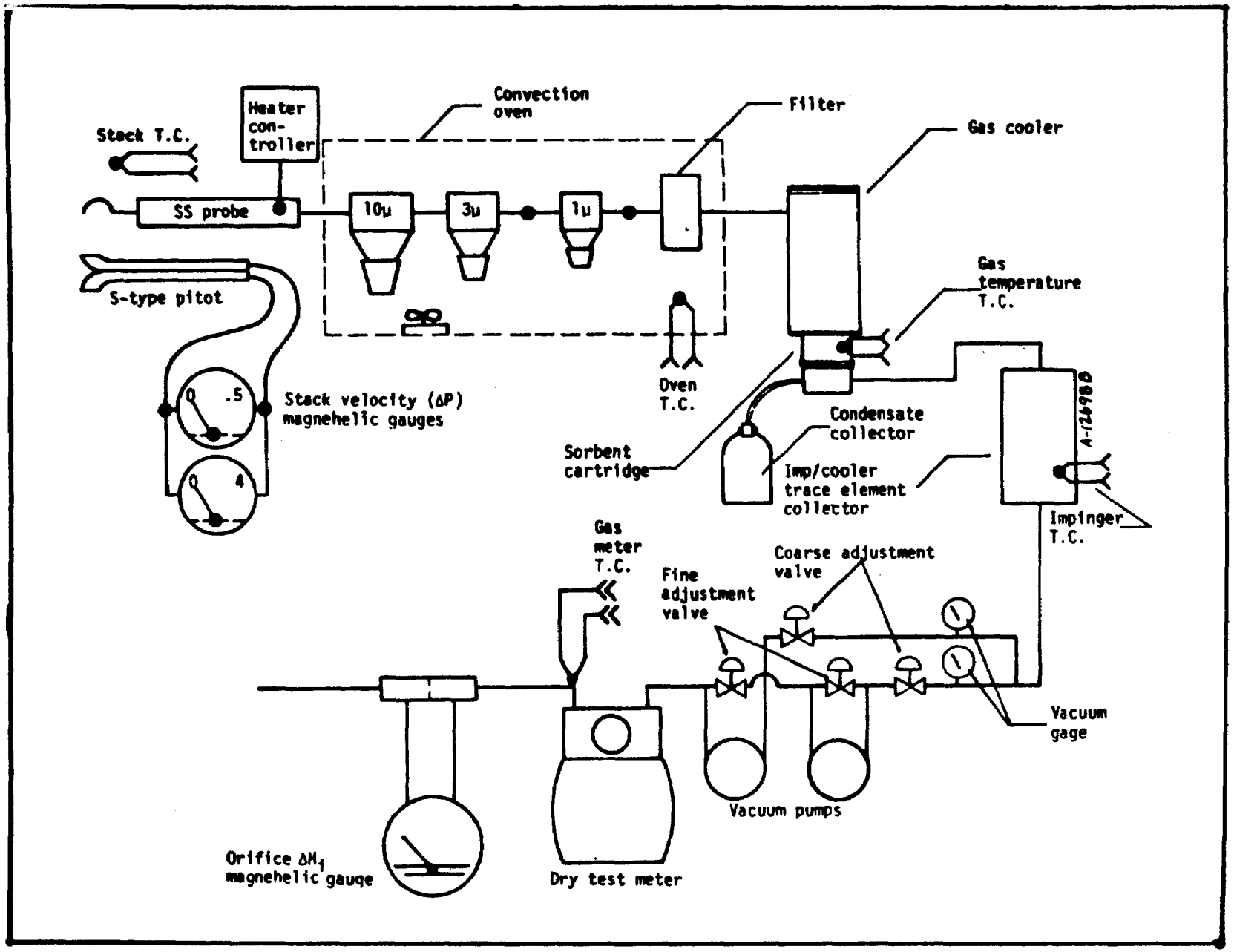


FIGURE 4-7. Source Assessment Sampling System (SASS) Flow Diagram

Secondly, the plates beneath the venturi sections of the reinjection lines were removed. Several layers of heavy aluminum foil were wrapped around the venturi sections so that no flyash could enter the reinjection line. Instead, the flyash would fall straight on through to the floor of the boiler room.

Thirdly, tare weighed barrels were placed under each reinjection venturi section for collection of the flyash. The boiler hopper downspouts had rotary air seals which prevented the ambient air from entering the boiler hopper through the open lines.

The time each barrel was placed under the open downspout and the time each was removed was recorded. From this data, the flyash collection rate was measured from each line individually and from the boiler hopper as a whole. It is understood that the collection rates are not the same as the reinjection rates would be under the same firing conditions. This is because reinjecting flyash increases the particulate loading through the boiler which, in turn, would undoubtedly increase the flyash reinjection rate.

It is believed that following these procedures prevented any of the boiler hopper flyash from being reinjected to the boiler. In other words, a true 0% boiler hopper reinjection rate was established for test purposes.

The procedure for altering the flyash reinjection rate from the multiclone dust collector differed from that of the boiler hopper. Multiclone hopper ash was diverted to a storage bin by means of a set of gate valves on each downspout. This bin had no observation ports on it or other means of determining collection rate. Therefore, the collection rate of the multiclone hopper was determined by measuring the dust loading entering and leaving the multiclone. This was accomplished by running two EPA Method 5 Particulate sampling trains simultaneously across the dust collector.

It is believed that these procedures produced a true 0% multiclone ash reinjection configuration.

SECTION 5.0

TEST RESULTS AND OBSERVATIONS

This Section presents the results of the tests performed on Boiler C. Observations are made regarding the influence on gaseous and particulate emissions and efficiency as the control parameters were varied. Fifty tests were conducted in a defined test matrix to develop this data. Data tables 5-18 through 5-22 are included at the end of this section for reference.

5.1 OVERFIRE AIR

The most extensively studied variable on Boiler C was overfire air. It was increased, decreased, biased front, rear, upper and lower in a program designed to determine which row(s) of jets most effectively reduce emissions and increase combustion efficiency.

The overfire air tests were duplicated on two coals. They were first run on Eastern low fusion coal, and then repeated on Western coal. The air flow rates through each row of overfire air and flyash reinjection jets were measured as functions of static pressure in the air ducts.

Test data indicates that the lower rear row of air jets was most effective in reducing carbon monoxide, but was also responsible for an increase in nitric oxide emissions. Particulate loadings were lowest when overfire air flow was highest. These results are discussed in detail in the following subsections. The first subsection discusses the overfire air system and how the air flow rates were measured.

5.1.1 Overfire Air Flow Rate Determination

Overfire air flow rates and flyash reinjection air flow rates were carefully measured at three overfire air (OFA) settings corresponding to 5, 15

and 25" H_2O pressure at the fan. This test data was used to generate a set of curves relating static pressure of the various OFA ducts to their corresponding air flow rates in lb/hr. Having established the pressure-flow relationships, the overfire air injection rates to the furnace were determined for each test based on the duct static pressures.

The overfire air flow determinations were made during tests 2, 3, and 4 on April 19, 1978, and again during test 37, 38 and 39 on June 1, 1978. Test results for both dates were similar. Only the April 19 test results will be presented here.

Velocity measurements were made at the locations shown schematically in Figure 5-1. Each overfire air header was fed from both ends so that velocity measurements were required at both ends. Each of the ten measurement locations was traversed with a standard pitot tube. A twelve or sixteen point traverse was used depending on duct diameter, and was made from two angles 90° apart.

The measured velocities were converted to pounds per hour air flow. The results are shown in Table 5-1 for the case where the air pressures to the individual air headers (i.e., front upper, front lower, etc.) are approximately balanced. The front lower overfire air header feeds cooling air to the coal feeder tuyeres and air swept cut-off plates in addition to a row of underfeeder air jets. Therefore, its air flow rate is higher than the others. With this one exception, the balance is quite good.

Overfire air flow rates are related to overfire air pressures by Bernoulli's equation for fluid flow through an orifice. One form of this equation is:

$$\frac{\Delta P}{\rho} = \frac{\Delta v^2}{2g}$$

The velocity (v) is proportional to the square root of the pressure drop (ΔP). Therefore, the air flow rate in lb/hr should be nearly proportional to the square root of the static pressure in the overfire air jet headers. This relationship held true as shown in Figures 5-2 and 5-3. With these pressure flow relationship plots, the overfire air and reinjection air flow rates can be determined for any set of conditions. All that is required are the static pressures in the ducts of interests.

KVB 15900-528

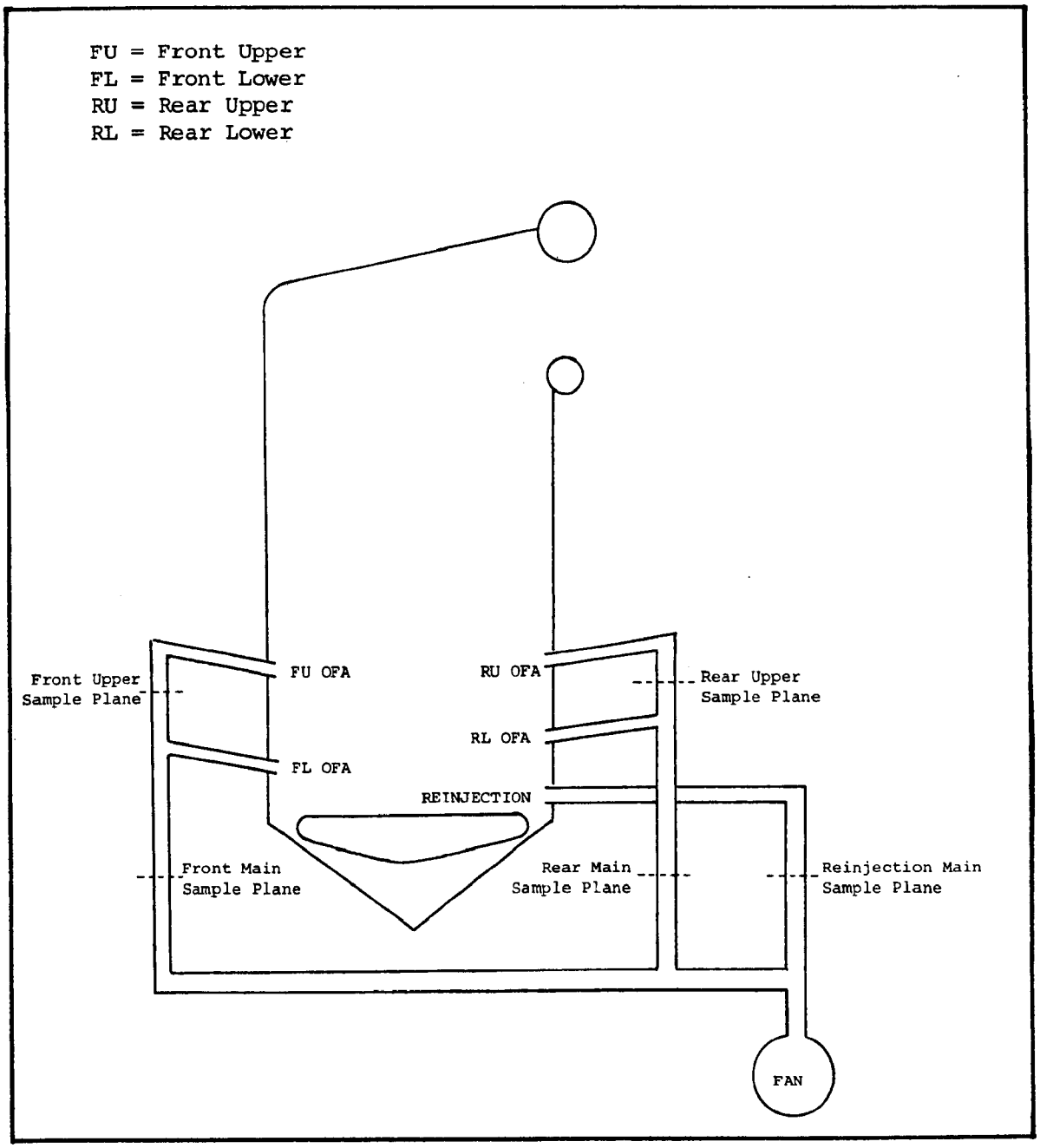


FIGURE 5-1. OVERFIRE AIR AND REINJECTION AIR FLOW SCHEMATIC

TABLE 5-1

OVERFIRE AIR AND REINJECTION AIR FLOW RATES
TEST SITE C

5" H_2O OVERFIRE AIR PRESSURE

Main Duct	Air Flow lb/hr	Split	Branch Duct	Air Flow lb/hr	Split w/o Reinjection Air
Front OFA	17309	48%	Front Upper	3386	13%
			*Front Lower	13923	54%
Rear OFA	8375	24%	Rear Upper	3844	15%
			*Rear Lower	4531	18%
Reinjection Air	10158	28%			

15" H_2O OVERFIRE AIR PRESSURE

Main Duct	Air Flow lb/hr	Split	Branch Duct	Air Flow lb/hr	Split w/o Reinjection Air
Front OFA	32921	51%	Front Upper	6300	13%
			*Front Lower	26621	55%
Rear OFA	15850	25%	Rear Upper	7053	14%
			*Rear Lower	8797	18%
Reinjection Air	15611	24%			

25" H_2O OVERFIRE AIR PRESSURE

Main Duct	Air Flow lb/hr	Split	Branch Duct	Air Flow lb/hr	Split w/o Reinjection Air
Front OFA	41966	53%	Front Upper	8287	13%
			*Front Lower	33679	54%
Rear OFA	20001	25%	Rear Upper	9919	16%
			*Rear Lower	10082	16%
Reinjection Air	17349	22%			

*Determined by Difference, Not Measured

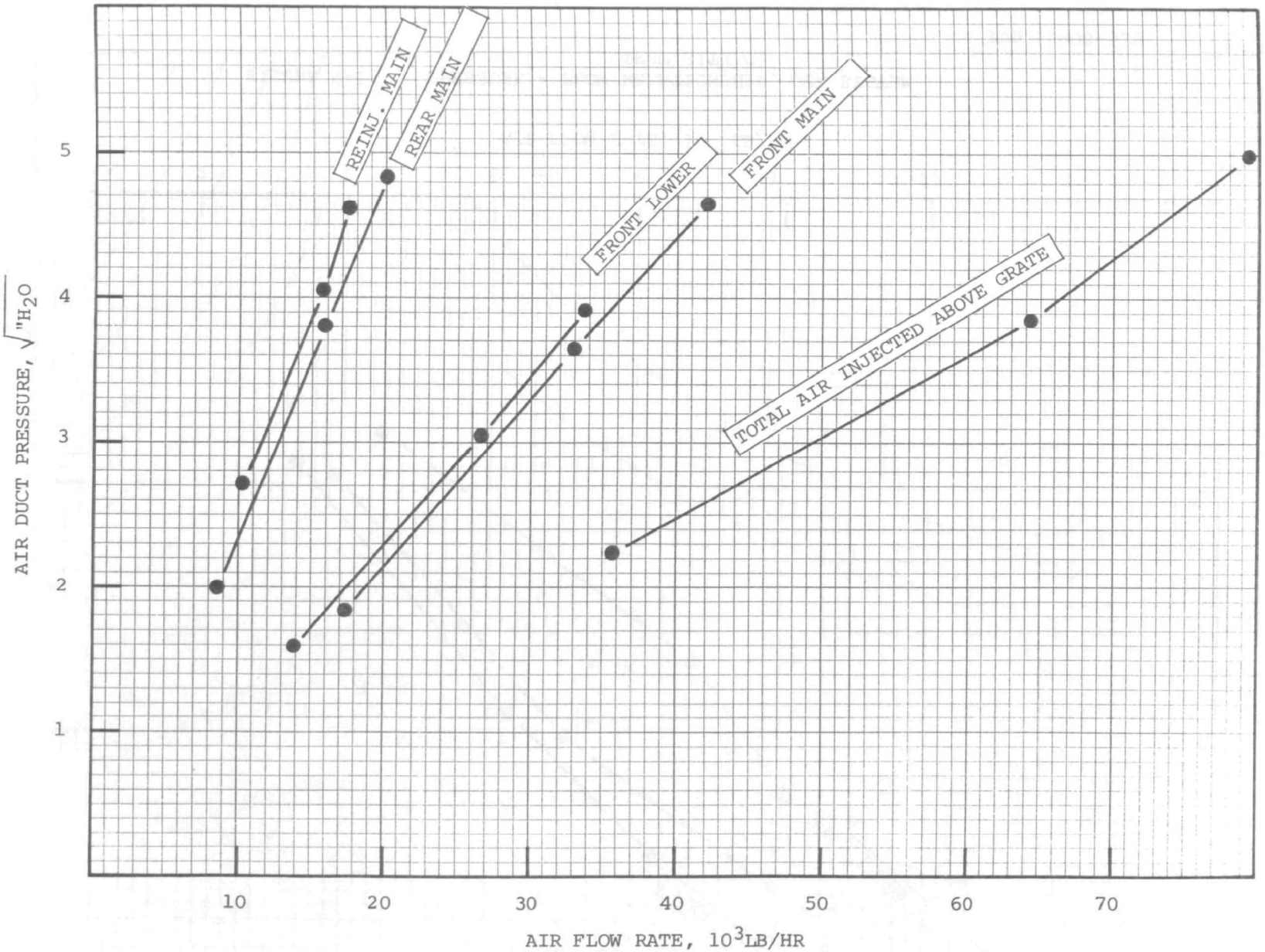


FIGURE 5-2 PRESSURE - FLOW RELATIONSHIP, OFA SYSTEM
TEST SITE C

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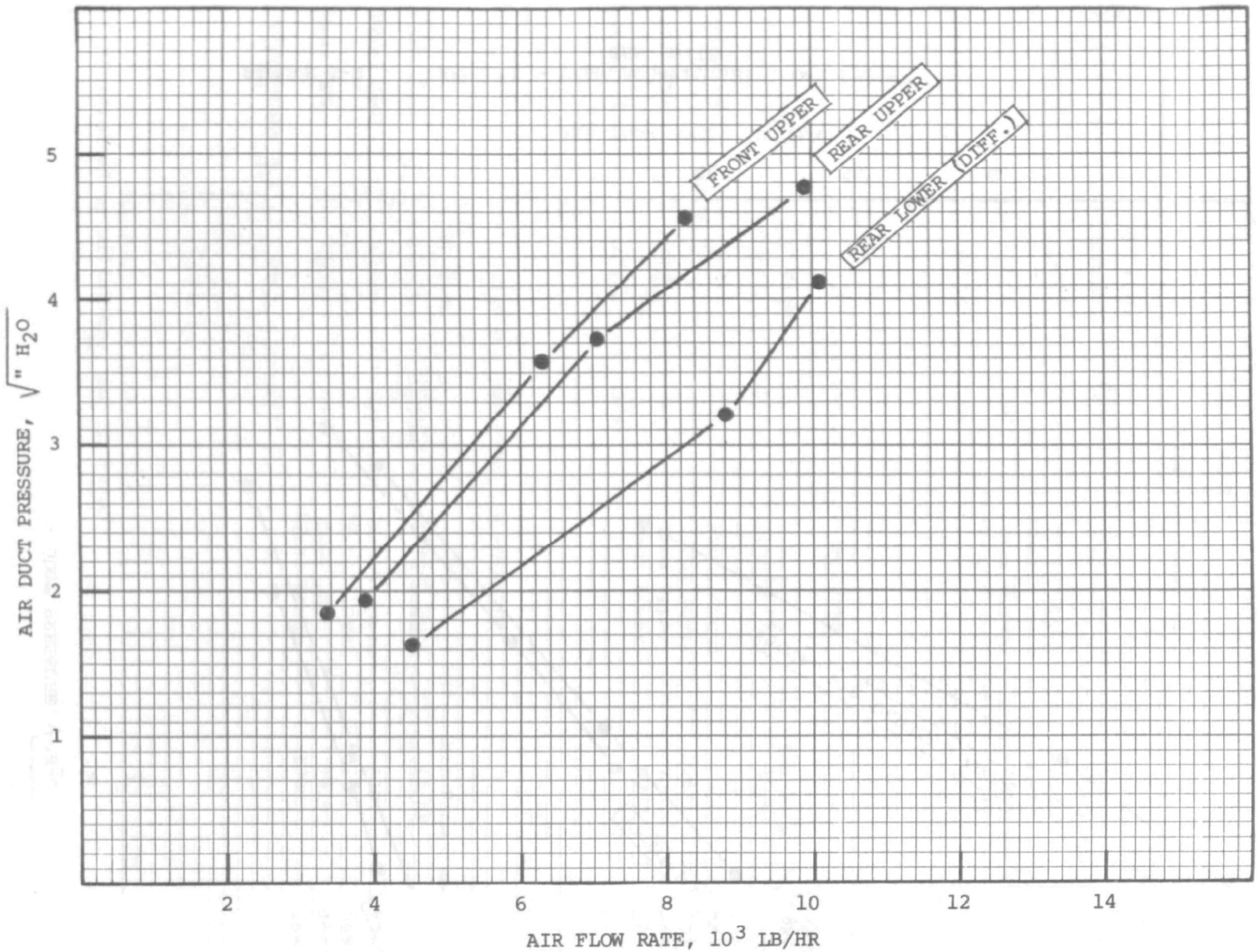

FIGURE 5-3 PRESSURE - FLOW RELATIONSHIP, OFA SYSTEM
TEST SITE C

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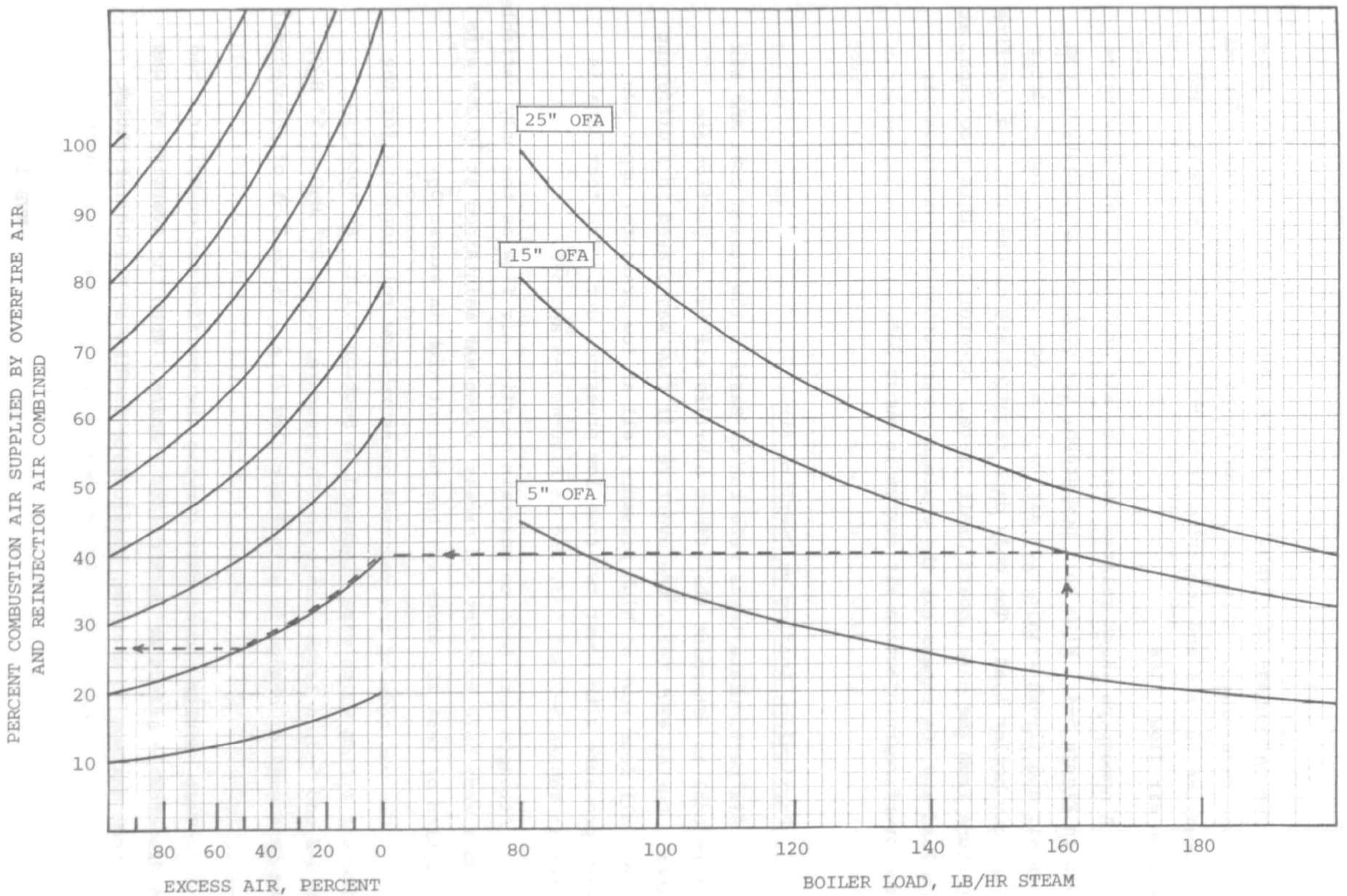


FIGURE 5-4 CONTRIBUTION OF OVERFIRE AIR AND REINJECTION AIR TO TOTAL COMBUSTION AIR TEST SITE C

KVB 15900-528

The percentage of combustion air introduced into the furnace above the grate was determined. This was accomplished by calculating the lb/hr gas flow through the furnace and comparing it to the measured overfire air and reinjection air flow rates.

A nomograph which relates overfire air pressure to air flow rates is given in Figure 5-4. With this nomograph, the combined contribution from overfire air and flyash reinjection air to total combustion air can be determined for any boiler load. The only data required are excess air, and overfire air pressure from the panel board draft gauge. According to this nomograph, at maximum load and 30% excess air the maximum contribution to combustion air from the overfire/reinjection air system is about 33%.

5.1.2 Particulate Loading vs Overfire Air

Six particulate tests were run on Eastern low fusion coal and six on Western coal to determine the effect overfire air has on particulate emissions. During each test, the overfire air flow was biased in a different way, i.e., all four rows at high pressure, all at low pressure, upper two rows high pressure with lower two rows low pressure, etc. The test data is presented in Tables 5-2 and 5-3, and in Figures 5-5 and 5-6.

Attempts were made to maintain overfire air flow as the only variable. Thus, loads were held constant and excess oxygen was maintained at $\pm 0.25\%$ with the exception of test 26, which was one percent high in excess O_2.

Use was made of the measured pressure-flow relationships for the overfire air system which were discussed in Section 5.1.1. As noted in Tables 5-2 and 5-3, a large change in OFA pressure (i.e., 20" H_2O to 5" H_2O) results in a smaller change in actual air flow (i.e., 5% to 2.5% of theoretical air).

Test results showed that varying the overfire air on Boiler C had little discernable effect on particulate loading. When the overfire air was lowered from maximum to minimum, particulate loading at the boiler outlet

increased 11% on Eastern coal (Tests 12 and 13) and increased 8% on Western coal (Tests 23 and 24). Accuracy of the measurements is probably in the range of ±5%. For this reason, small changes on the order of ten percent or less require a large number of tests to establish that observed trends are real.

In like manner, biasing upper, lower, front and rear overfire air flows had little discernable effect on particulate loading. Biasing upper overfire air versus lower overfire air resulted in an eight percent decrease in particulate loading on Eastern coal and an eight percent increase in particulate loading on Western coal. Such inconsistency can be viewed as normal scatter in the data. Biasing front OFA versus rear OFA decreased particulate loading at the boiler outlet by five percent and ten percent for the Eastern and Western coals, respectively. Again, the changes are not statistically significant.

The multiclone outlet particulate loadings for these tests do not follow the trends of the boiler outlet loadings. This reaffirms the conclusion that the changes in particulate loading were masked by normal scatter in the data. It is noted, however, that the lowest particulate loading occurred under "high balanced" overfire air conditions during both test series.

5.1.3 Nitric Oxide vs Overfire Air

Definite trends were established in nitric oxide emissions as the overfire air conditions were changed. These trends, however, were slight and were partially masked by the small variations in excess oxygen.

The excess oxygen variable was eliminated by first establishing the average NO-O_2 trend as a 30 ppm increase in NO for each one percent increase in excess O_2. (Refer to Section 5.3.3 and Figure 5-23 for the basis of this NO-O_2 relationship.) Each measured NO value was corrected to 9% O_2 using this relationship. In those cases where an NO-O_2 curve was already established (i.e., tests 5 A-C, 6 A-C, etc.), the nine percent O_2 intercept value was used.

The corrected test results are presented in Table 5-4 and Figure 5-7. An increase in overfire air pressure from a low of 5" H_2O to a high of 25" H_2O resulted in an average increase in nitric oxide concentration of nine percent ±12%. Putting most of the overfire air through the lower rows

TABLE 5-2

EFFECT OF OVERFIRE AIR ON EMISSIONS & EFFICIENCY
EASTERN LOW FUSION COAL - TEST SITE C

Test No.	12	13	14	15	16	19
Description	High Balanced OFA	Low Balanced OFA	Bias Upper OFA	Bias Lower OFA	Bias Front OFA	Bias Rear OFA
OVERFIRE AIR CONDITIONS						
Front Upper, "H_2O/% Theoretical Air	17.2/4.4	5.8/2.6	20.2/4.8	5.7/2.6	15.0/4.1	2.1/1.6
Front Lower, "H_2O/% Theoretical Air	17.1/20.9	5.9/12.8	6.2/13.0	15.4/20.4	15.0/18.6	2.1/7.6
Rear Upper, "H_2O/% Theoretical Air	18.0/5.0	6.1/2.9	20.2/5.4	4.9/2.6	5.0/2.6	22.2/5.2
Rear Lower, "H_2O/% Theoretical Air	15.7/5.8	5.6/3.9	5.8/3.9	14.4/5.8	5.1/3.7	17.5/7.1
Reinjection, "H_2O/% Theoretical Air	17.0/9.4	9.0/6.9	17.8/6.3	16.3/9.5	16.3/9.3	17.6/9.6
Total Above Grate Air, % Theoretical Air	45.5	29.1	33.4	40.9	38.3	31.1
Total Undergrate Air, % Theoretical Air	123.8	140.3	140.2	131.3	128.5	135.7
Total Combustion Air, % Theoretical Air	169.3	169.4	173.6	172.2	166.8	166.8
FIRING CONDITIONS						
Coal Supplier*	E	E	E	E	E	E
Load, % of Capacity	93	91	93	91	93	92
Grate Heat Release, 10^3BTU/ft^2/hr	433	400	431	425	417	418
Coal Sizing, % Passing 1/4"	42	46	47	47	49	43
Excess Air, %	69	69	74	72	67	67
BOILER OUTLET EMISSIONS						
Particulate Loading, lb/10^6BTU	19.0	21.1	20.9	22.6	23.9	25.1
Combustible Loading, lb/10^6BTU	9.1	6.5	5.1	10.4	13.3	10.5
Inorganic Ash Loading, lb/10^6BTU	9.9	14.6	15.8	12.2	10.5	14.7
Combustibles in Flyash, %	47.8	30.8	24.4	46.0	55.9	41.6
O_2, % (dry)	8.9	8.9	9.2	9.1	8.7	8.7
CO, ppm (dry) @ 3% O_2	53	103	49	53	37	44
NO, ppm (dry) @ 3% O_2	273	230	326	328	319	326
MULITCLONE OUTLET EMISSIONS						
Particulate Loading, lb/10^6BTU	0.69	0.64	0.94	0.78	0.84	0.88
Combustible Loading, lb/10^6BTU	0.11	0.16	0.19	0.16	0.14	0.15
Inorganic Ash Loading, lb/10^6BTU	0.58	0.48	0.75	0.63	0.70	0.73
Combustibles in Flyash, %	16.5	25.3	19.8	19.8	16.9	17.4
Multiclone Collection Efficiency,	96.4	97.0	95.5	96.5	96.5	96.5
HEAT LOSSES, %						
Dry Gas Loss	8.02	8.28	7.89	7.98	7.71	8.08
Moisture in Fuel	0.57	0.59	0.32	0.43	0.41	0.46
H_2O from Combustion of H_2	4.50	4.72	4.33	4.38	4.42	4.41
Combustibles in Collected Flyash	2.40	5.14	2.01	1.80	2.32	2.55
Combustibles in Emitted Flyash	0.17	0.25	0.27	0.23	0.22	0.23
Combustibles in Bottom Ash	1.29	1.62	0.13	0.09	0.37	1.38
Radiation Loss	0.42	0.44	0.42	0.44	0.42	0.42
Unmeasured Losses	1.50	1.50	1.50	1.50	1.50	1.50
Total Losses	18.87	22.54	16.87	16.85	17.37	19.03
Boiler Efficiency	81.13	77.46	83.13	83.15	82.63	80.97

* E - Eastern Low Fusion Coal

KVB 15900-528

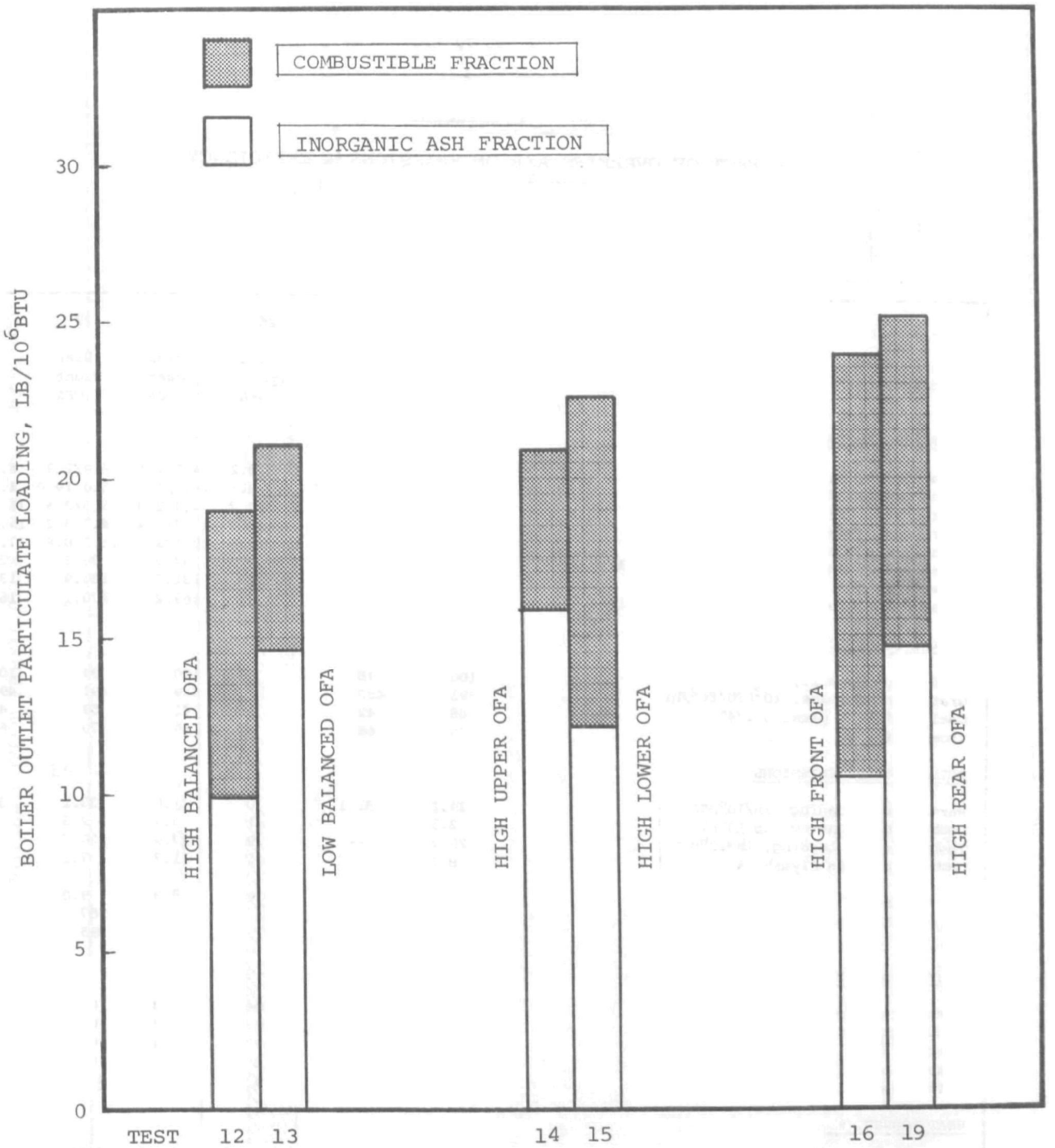


FIGURE 5-5 PARTICULATE LOADING BROKEN DOWN INTO COMBUSTIBLE AND INORGANIC FRACTIONS FOR THREE OVERFIRE AIR TEST SETS ON EASTERN LOW FUSION COAL - TEST SITE C

KVB 15900-528

TABLE 5-3

EFFECT OF OVERFIRE AIR ON EMISSIONS & EFFICIENCY
WESTERN COAL - TEST SITE C

Test No.	23	24	26	27	28	29
Description	High Balanced OFA	Low Balanced OFA	Bias Upper OFA	Bias Lower OFA	Bias Front OFA	Bias Rear OFA
OVERFIRE AIR CONDITIONS						
Front Upper, "H_2O/% Theoretical Air	17.7/4.3	4.3/2.1	17.5/4.2	4.5/2.1	16.0/2.9	4.7/2.2
Front Lower, "H_2O/% Theoretical Air	18.0/20.0	4.8/10.7	3.6/9.1	16.7/19.2	16.0/19.0	4.2/9.7
Rear Upper, "H_2O/% Theoretical Air	19.6/5.0	5.1/2.5	18.0/4.7	4.4/2.3	5.3/2.5	18.3/4.7
Rear Lower, "H_2O/% Theoretical Air	16.2/5.5	5.6/3.7	3.9/3.0	15.7/5.4	4.3/3.2	15.2/4.7
Reinjection, "H_2O/% Theoretical Air	17.2/8.8	18.6/9.2	16.1/8.6	18.1/8.5	18.0/8.6	17.9/8.6
Total Above Grate Air, % Theoretical Air	43.6	28.2	29.6	37.5	36.2	29.9
Undergrate Air, % Theoretical Air	121.8	137.8	154.2	131.7	133.9	132.8
Total Combustion Air, % Theoretical Air	165.4	166.0	183.8	169.2	170.1	162.6
FIRING CONDITIONS						
Load, % of Capacity	100	98	99	100	99	100
Grate Heat Release, 10^3BTU/ft^2/hr	491	480	481	459	491	494
Coal Sizing, % passing 1/4"	48	42	52	42	59	49
Excess Air, %	65	66	84	69	70	63
BOILER OUTLET EMISSIONS						
Particulate Loading, lb/10^6BTU	29.2	31.1	34.0	31.6	33.1	36.4
Combustible Loading, lb/10^6BTU	2.5	--	4.1	3.7	2.3	--
Inorganic Ash Loading, lb/10^6BTU	26.7	--	29.9	27.9	30.7	--
Combustibles in Flyash, %	8.7	--	12.1	11.7	7.1	--
O_2, % (dry)	8.6	8.7	9.9	8.9	9.0	8.4
CO, ppm (dry) @ 3% O_2	311	488	395	287	567	323
NO, ppm (dry) @ 3% O_2	387	372	394	387	395	408
MULTICLONE OUTLET EMISSIONS						
Particulate Loading, lb/10^6BTU	1.04	1.03	1.04	1.03	0.94	0.74
Combustible Loading, lb/10^6BTU	0.08	0.06	0.07	0.08	0.06	0.03
Inorganic Ash Loading, lb/10^6BTU	0.96	0.96	0.97	0.95	0.88	0.71
Combustibles in Flyash, %	7.5	6.2	6.3	7.3	6.3	3.6
Multiclone Collection Efficiency, %	96.4	96.7	96.9	96.7	97.2	98.0
HEAT LOSSES, %						
Dry Gas Loss	8.01	7.90	8.74	8.07	7.83	7.54
Moisture in Fuel	3.47	3.52	3.64	3.06	3.64	3.52
H_2O from Combustion of H_2	6.29	6.16	6.28	6.02	6.49	6.25
Combustibles in Collected Flyash	0.97	0.50	0.62	0.56	0.62	0.50
Combustibles in Emitted Flyash	0.11	0.10	0.09	0.12	0.09	0.04
Combustibles in Bottom Ash	1.55	1.44	0.45	2.45	2.04	0.49
Radiation Loss	0.40	0.40	0.40	0.40	0.40	0.40
Unmeasured Losses	1.50	1.50	1.50	1.50	1.50	1.50
Total Losses	22.30	21.52	21.72	22.18	22.61	20.24
Boiler Efficiency	77.70	78.48	78.28	77.82	77.39	79.76

KVB 15900-528

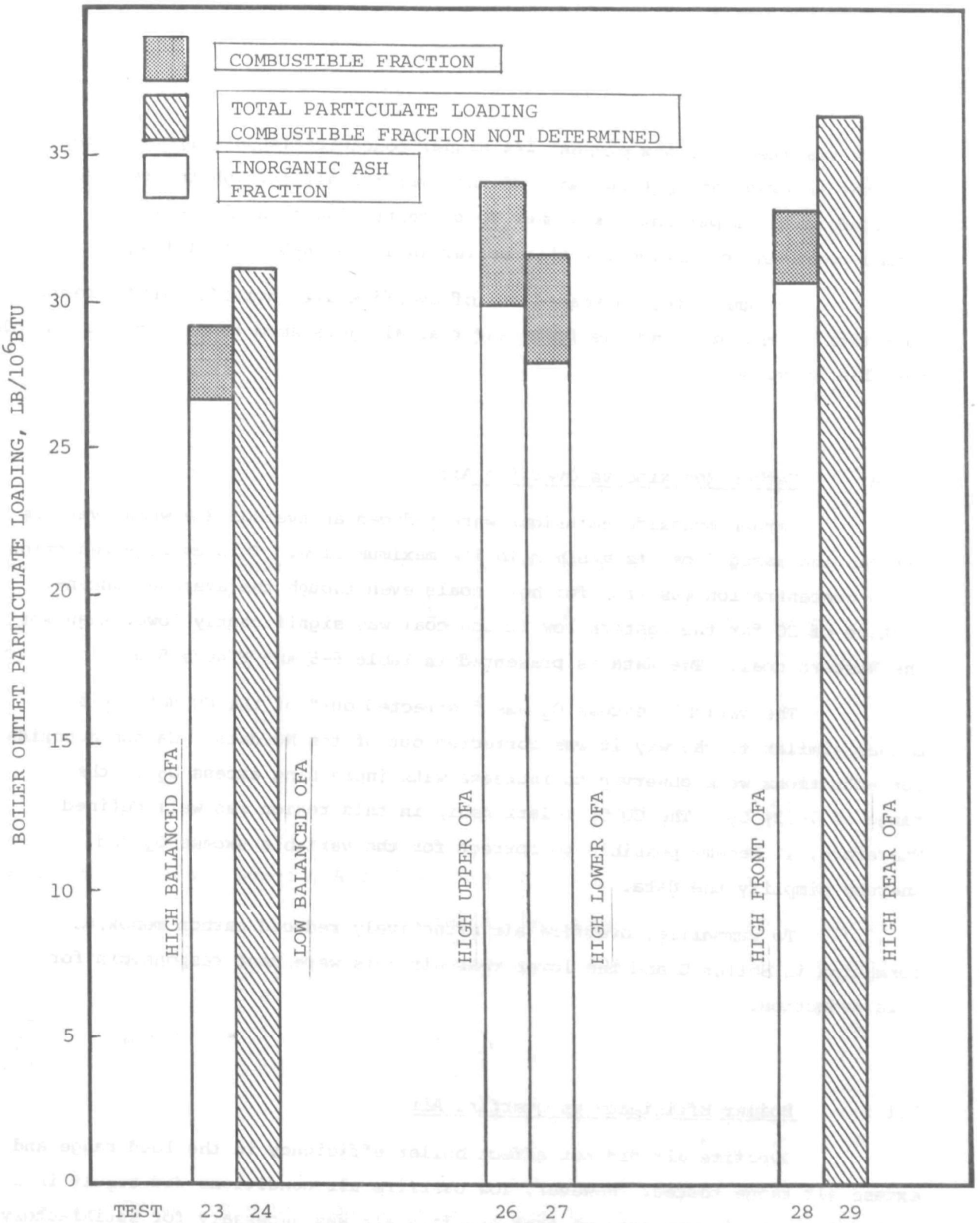


FIGURE 5-6 PARTICULATE LOADING BROKEN DOWN INTO COMBUSTIBLE AND INORGANIC FRACTIONS FOR THREE OVERFIRE AIR TEST SETS ON WESTERN COAL -- TEST SITE C

KVB 15900-528

of jets resulted in a six percent ±4% higher concentration of nitric oxide than the reverse, and putting most of the overfire air through the rear jets resulted in a six percent ±3% higher NO concentration than the reverse. Normal operating condition for this boiler is 15-20" H_2O at full load.

To summarize, increased use of overfire air increases nitric oxide formation in Boiler C and the lower and rear air jets seem to be most responsible for this increase.

5.1.4 Carbon Monoxide vs Overfire Air

Carbon monoxide emissions were reduced an average 30% when overfire air was increased from its minimum to its maximum flow. This average reduction in CO concentration was true for both coals even though the average concentration of CO for the Eastern low fusion coal was significantly lower than for the Western coal. The data is presented in Table 5-5 and Figure 5-8.

The variable excess O_2 was "corrected out" of the CO data in a manner similar to the way it was corrected out of the NO data. Carbon monoxide concentrations were observed to increase with increasing excess O_2 in the range of 7-12% O_2. The CO-O_2 relationship in this region was well defined. Therefore, it became possible to correct for the variable excess O_2 and thereby simplify the data.

To summarize, overfire air effectively reduced carbon monoxide formation in Boiler C and the lower rear air jets were most responsible for this reduction.

5.1.5 Boiler Efficiency vs Overfire Air

Overfire air did not affect boiler efficiency in the load range and excess air range tested. However, low overfire air conditions did result in a smoky plume and it was evident that overfire air was necessary for satisfactory stoker operation.

Heat loss and boiler efficiency numbers are included in Tables 5-2 and 5-3.

KVB 15900-528

TABLE 5-4

NITRIC OXIDE EMISSIONS VS OVERFIRE AIR
TEST SITE C

High Balanced OFA vs Low Balanced OFA

Test No.	Coal	Load, %	Nitric Oxide, ppm (dry) @ 3% O_2* Low OFA	High OFA	Percent Change
5-6	E	94	308	374	+21
12-13	E	92	233	276	+18
17-18	E	76	257	237	-8
21-22	W	77	320	352	+10
23-24	W	99	381	399	+5
30-31	W	57	271	331	+22
49-50	E	58	287	308	+7
48A-48C	E	93	400	377	-6
				Mean	+9
				Standard Deviation	12%

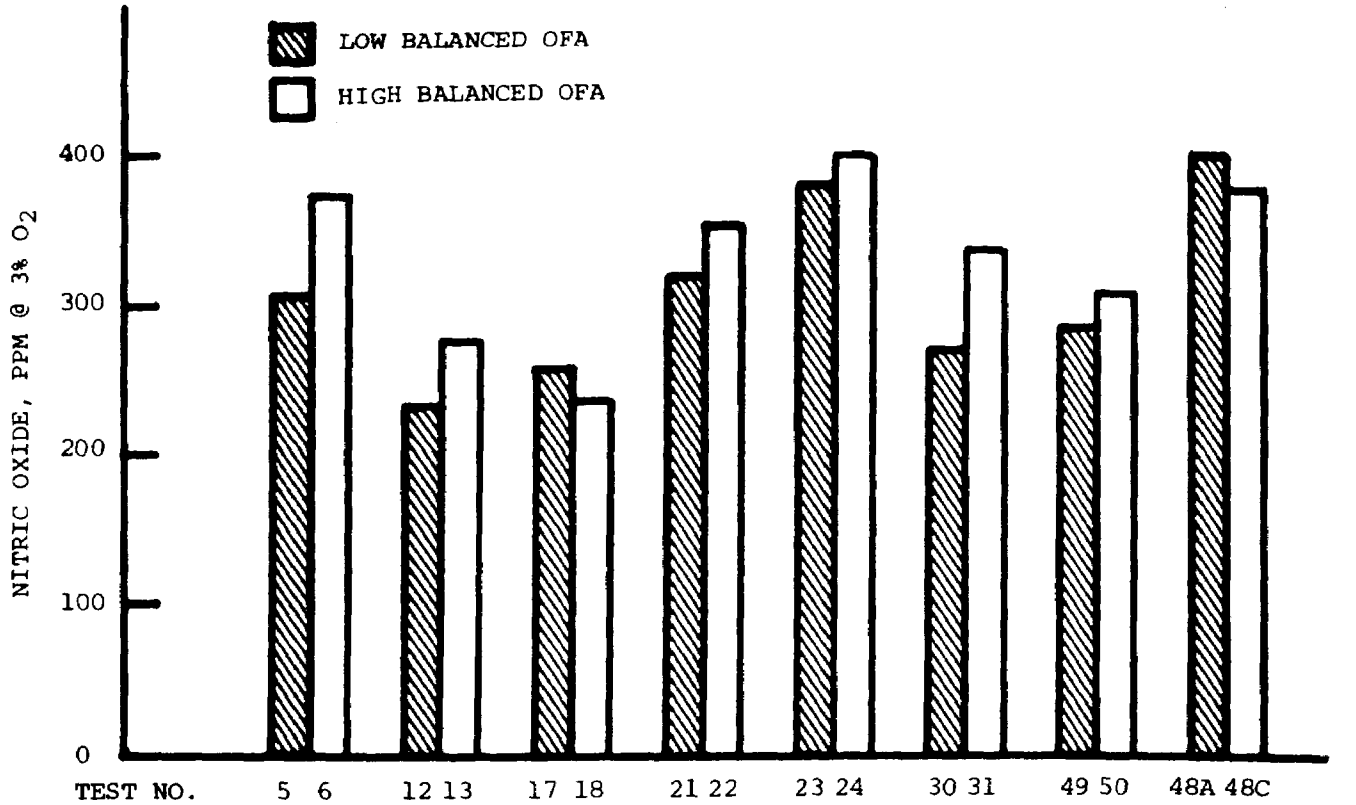
High Upper Front and Rear OFA vs High Lower Front and Rear OFA

Test No.	Coal	Load, %	Nitric Oxide, ppm (dry) @ 3% O_2* High Upper OFA	High Lower OFA	Percent Change
14-15	E	92	320	325	+2
26-27	W	100	367	390	+6
34C-34D	W	95	355	390	+10
				Mean	+6
				Standard Deviation	4%

High Front Upper and Lower OFA vs High Rear Upper and Lower OFA

Test No.	Coal	Load, %	Nitric Oxide, ppm (dry) @ 3% O_2* High Front OFA	High Rear OFA	Percent Change
7B-7C	E	93	290	315	+9
16-19	E	92	328	335	+2
28-29	W	99	395	426	+8
34A-34B	W	95	369	390	+6
				Mean	+6
				Standard Deviation	3%

* Nitric Oxide concentrations were corrected for the effect of oxygen to a constant 9% O_2 by applying the factor 30 ppm increase in NO for each one percent increase in O_2



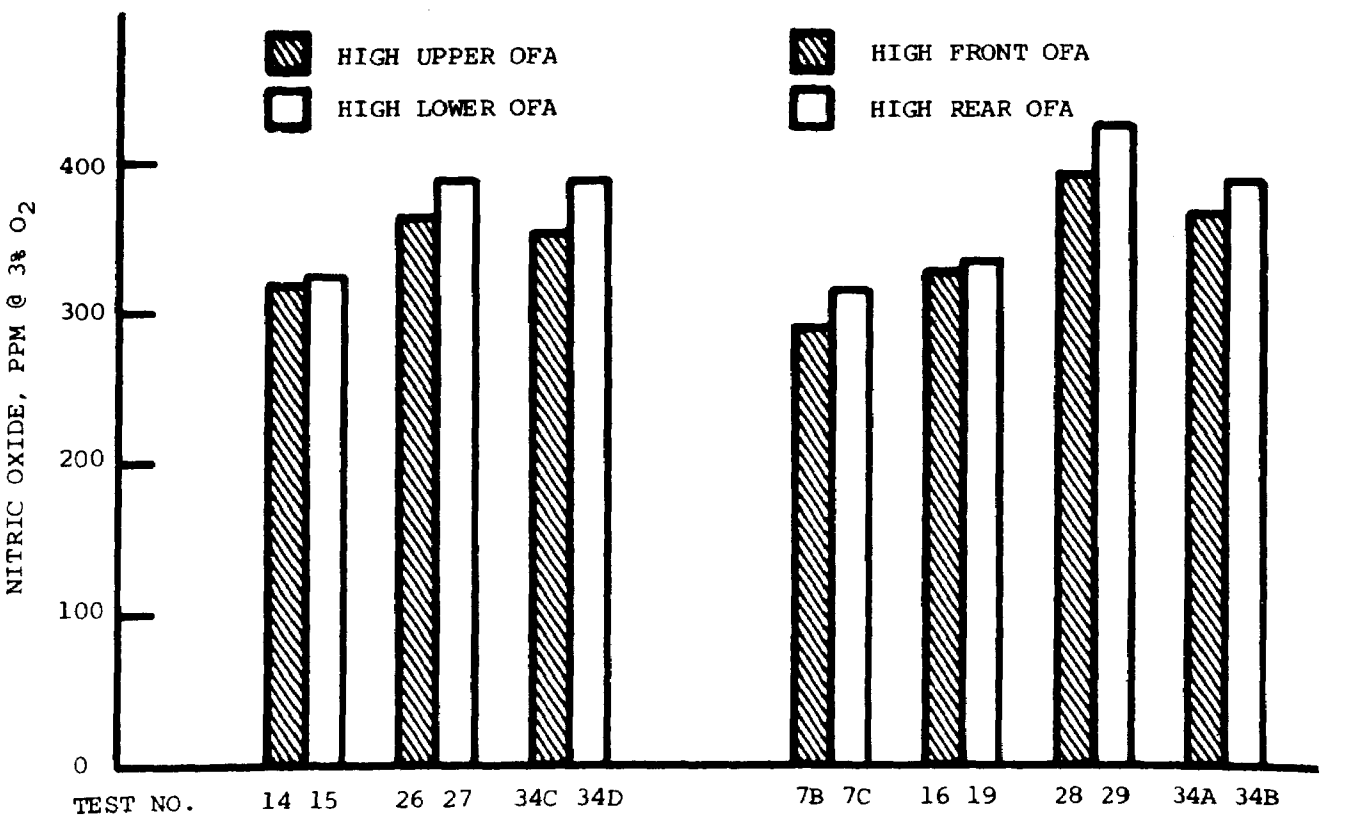


FIGURE 5-7 NITRIC OXIDE EMISSIONS VS OVERFIRE AIR
TEST SITE C

TABLE 5-5

CARBON MONOXIDE EMISSIONS VS OVERFIRE AIR
TEST SITE C

High Balanced OFA vs Low Balanced OFA

Test No.	Coal	Load, %	Carbon Monoxide, ppm (dry) @ 3% O_2* Low OFA	High OFA	Percent Change
5-6	E	97	55	55	0
12-13	E	92	103	53	-49
17-18	E	76	33	23	-30
21-22	W	77	273	163	-40
23-24	W	99	488	311	-36
30-31	W	59	100	100	0
32-33	W	96	420	320	-24
48A-48C	E	93	69	32	-54
49-50	E	58	66	30	-55
				Mean	-32%
				Standard Deviation	21%

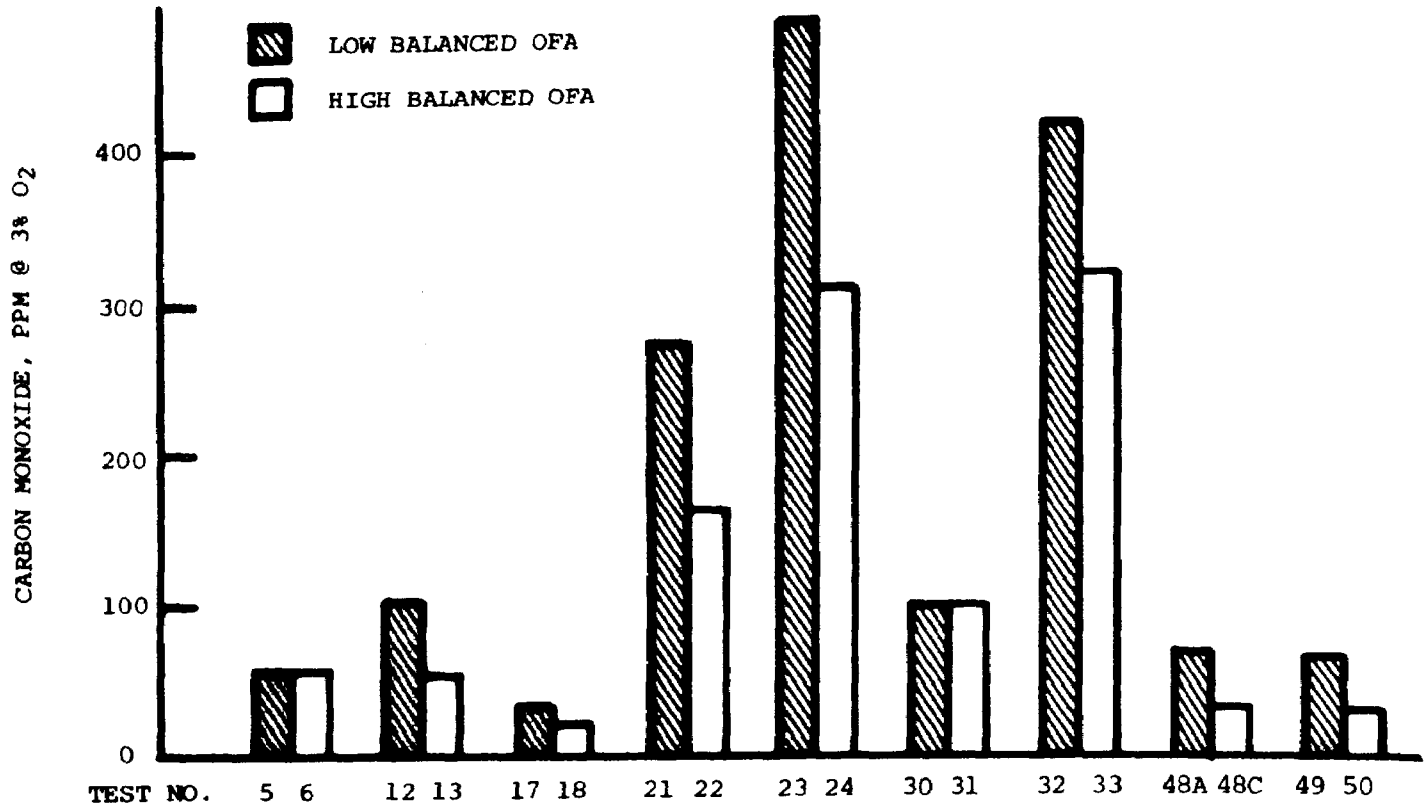
High Upper Front and Rear OFA vs High Lower Front and Rear OFA

Test No.	Coal	Load, %	Carbon Monoxide, ppm (dry) @ 3% O_2* High Upper OFA	High Lower OFA	Percent Change
14-15	E	92	48	53	+10
26-27	W	100	314	294	-6
34C-34D	W	95	347	323	-7
				Mean	-1%
				Standard Deviation	10%

High Front Upper and Lower OFA vs High Rear Upper and Lower OFA

Test No.	Coal	Load, %	Carbon Monoxide, ppm (dry) @ 3% O_2* High Front OFA	High Rear OFA	Percent Change
7B-7C	E	93	52	47	-10
16-19	E	92	38	45	+18
28-29	W	99	569	380	-33
34A-34B	W	95	358	332	-7
				Mean	-8%
				Standard Deviation	21%

* Carbon Monoxide concentrations were corrected for the effect of oxygen to a constant 9% O_2 by applying the CO-O_2 relationship found in Figures 5-23 and 5-24.



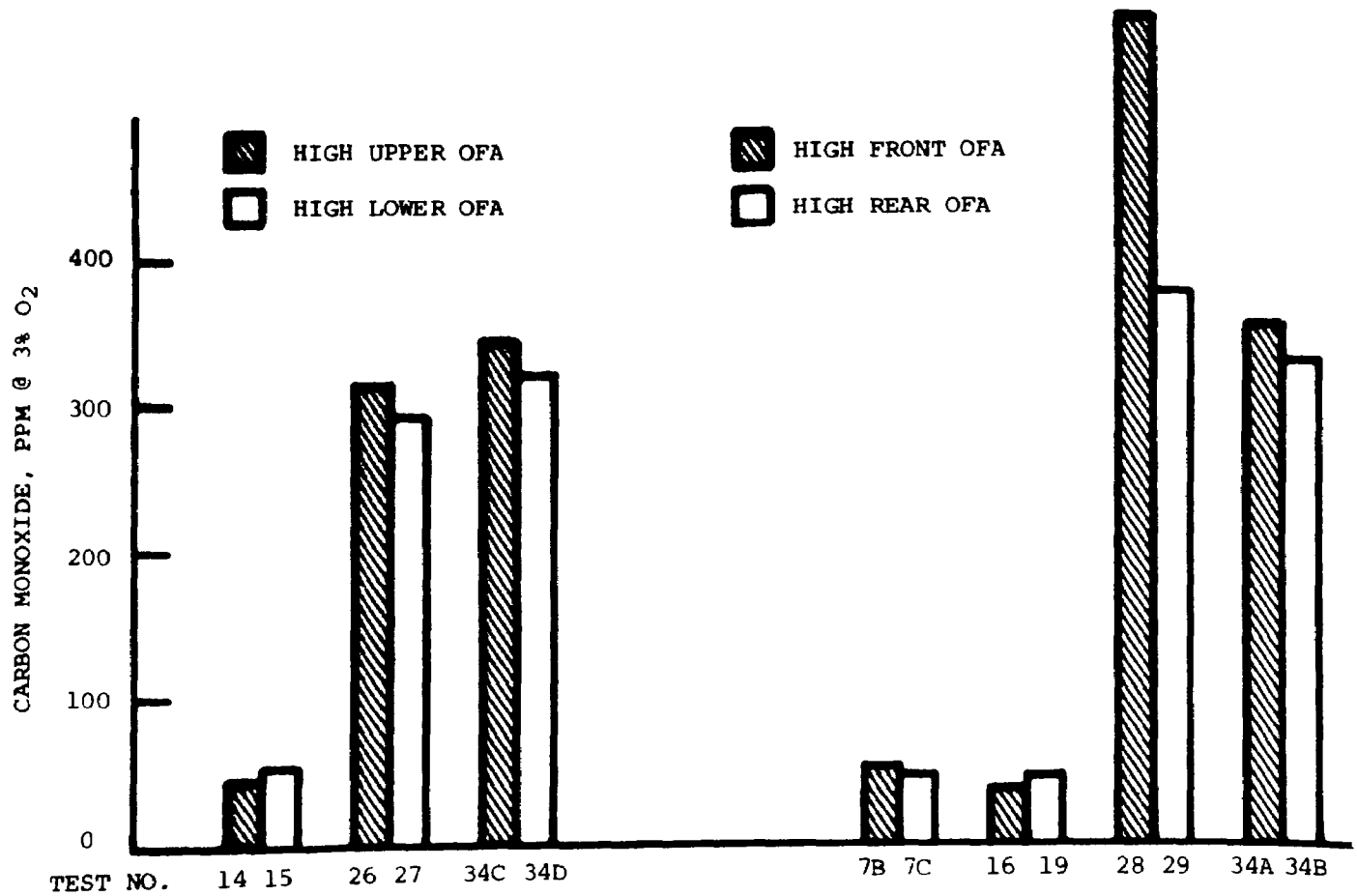


FIGURE 5-8 CARBON MONOXIDE EMISSIONS VS OVERFIRE AIR
TEST SITE C

5.2 FLYASH REINJECTION

Tests for emissions and efficiency were run under three configurations of the boiler's flyash reinjection system. These configurations were:

1. Full Reinjection - This is the normal configuration which includes full reinjection from the boiler hopper and partial reinjection from the segregating multiclone dust collector. (It is assumed that 70% of the multiclone hopper ash is reinjected, based on multiclone design specifications, unless otherwise stated.)

2. Boiler Hopper Reinjection - All ash collected by the multiclone dust collector is diverted to the plant's wet slurry system.

3. No Reinjection - In addition to diverting the multiclone ash away from the furnace, all the boiler hopper ash is collected in barrels and its collection rate is measured.

This series of reinjection tests was run on both the Eastern Low Fusion coal and the Western coal. A detailed description of test procedures is given in Section 4.11. The test results are summarized in Tables 5-6 and 5-7. Discussion of these results follows.

Particulate loadings at both the boiler outlet and the multiclone outlet were dramatically reduced when flyash reinjection was stopped. At the boiler outlet the reductions were on the order of 75%, at the multiclone outlet, 45%. The following table further illustrates the magnitude of the reductions.

PARTICULATE LOADING VS REINJECTION CONFIGURATION

	Full Reinj.	Blr Hpr Reinj.	No Reinj.
E. Coal, Blr Out, lb/10^6BTU	25.0	7.0	6.0
W. Coal, Blr Out, lb/10^6BTU	31.1	6.2	8.6
E. Coal, D.C. Out, lb/10^6BTU	0.82	0.50	0.48
W. Coal, D.C. Out, lb/10^6BTU	1.03	0.47	0.52

In Figures 5-9 and 5-10, the flyash flow rates in lb/hr are schematically illustrated for the different reinjection configurations. The rates shown at the boiler outlet, multiclone collector outlet and boiler hopper were directly measured. The collection rate of the multiclone is determined

TABLE 5-6

EFFECT OF FLYASH REINJECTION ON EMISSIONS AND EFFICIENCY
BURNING EASTERN LOW FUSION COAL
TEST SITE C

	Test No. 9	Test No. 11	Test No. 10
Flyash Reinjection Rate	Full	Boiler Hopper Only	None
FIRING CONDITIONS			
Coal Supplier	E	E	E
Load, % of Capacity	89	93	93
Grate Heat Release, 10^3BTU/ft^2/hr	397	440	451
Coal Sizing, % passing 1/4"	52	50	43
Excess Air, %	70	72	72
BOILER OUTLET EMISSIONS			
Particulate Loading, lb/10^6BTU	25.00	7.00	6.02
Combustible Loading, lb/10^6BTU	--	4.00	--
Inorganic Ash Loading, lb/10^6BTU	--	3.00	--
Combustibles in Flyash, %	--	57.2	--
O_2, % (dry)	8.9	9.1	9.1
CO, ppm (dry) @ 3% O_2	66	53	55
NO, ppm (dry) @ 3% O_2	288	333	356
MULTICLONE OUTLET EMISSIONS			
Particulate Loading, lb/10^6BTU	0.815	0.496	0.481
Combustible Loading, lb/10^6BTU	0.142	0.143	0.114
Inorganic Ash Loading, lb/10^6BTU	0.673	0.353	0.367
Combustibles in Flyash, %	17.4	28.9	23.6
Multiclone Collection Efficiency, %	96.7	92.9	92.0
HEAT LOSSES, %			
Dry Gas Loss	7.56	8.12	7.92
Moisture in Fuel	0.56	0.63	0.62
H_2O from Combustion of H_2	4.59	4.56	4.53
Combustibles in Collected Flyash*	3.43	3.86	2.32
Combustibles in Emitted Flyash	0.21	0.19	0.15
Combustibles in Bottom Ash	0.05	0.10	0.15
Radiation Loss	0.44	0.42	0.42
Unmeasured Losses	1.50	1.50	1.50
Total Losses	18.34	19.38	17.61
Boiler Efficiency	81.66	80.62	82.39

* Based on 70% reinjection from the dust collector

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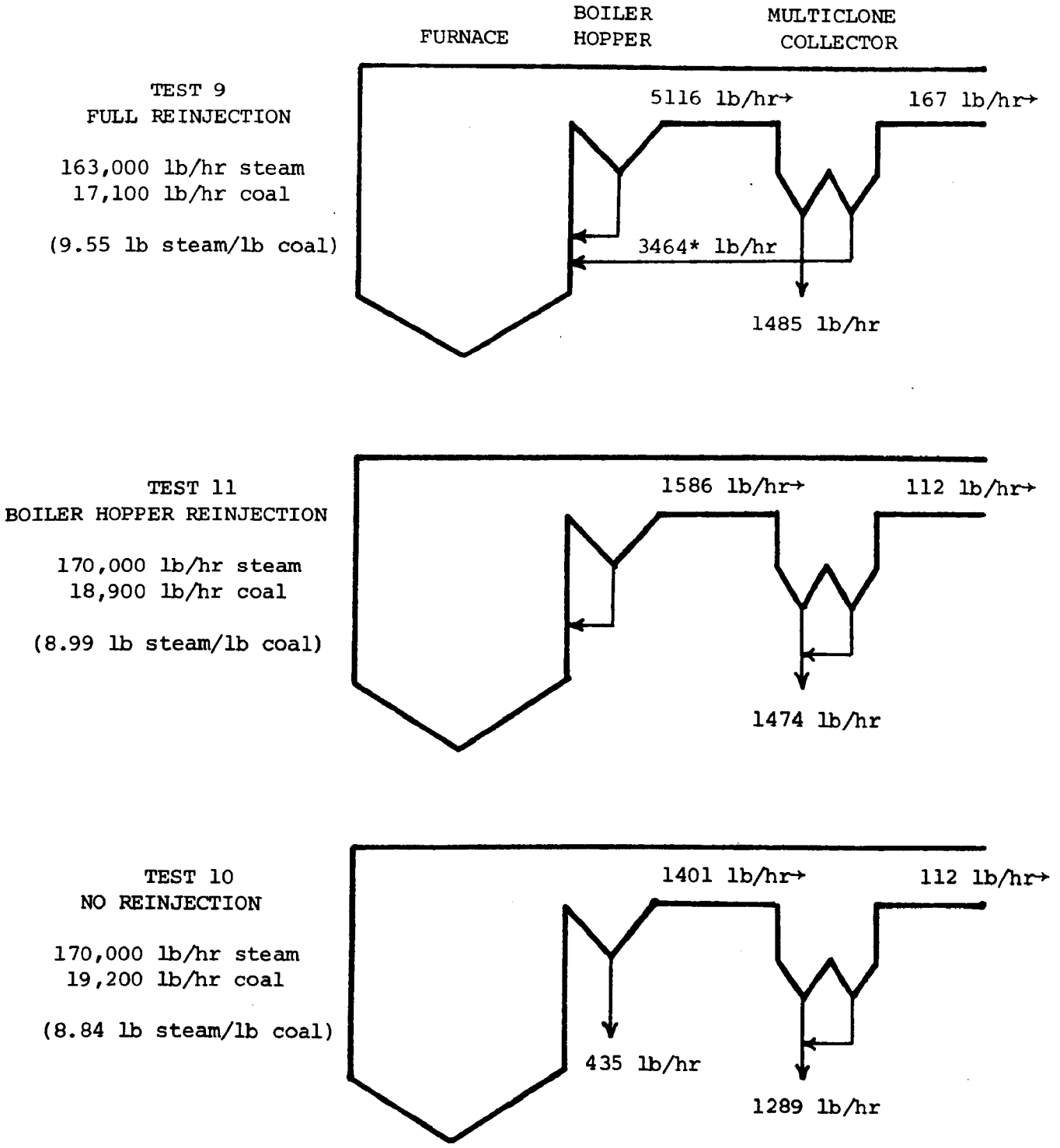


* Assuming 70% Reinjection

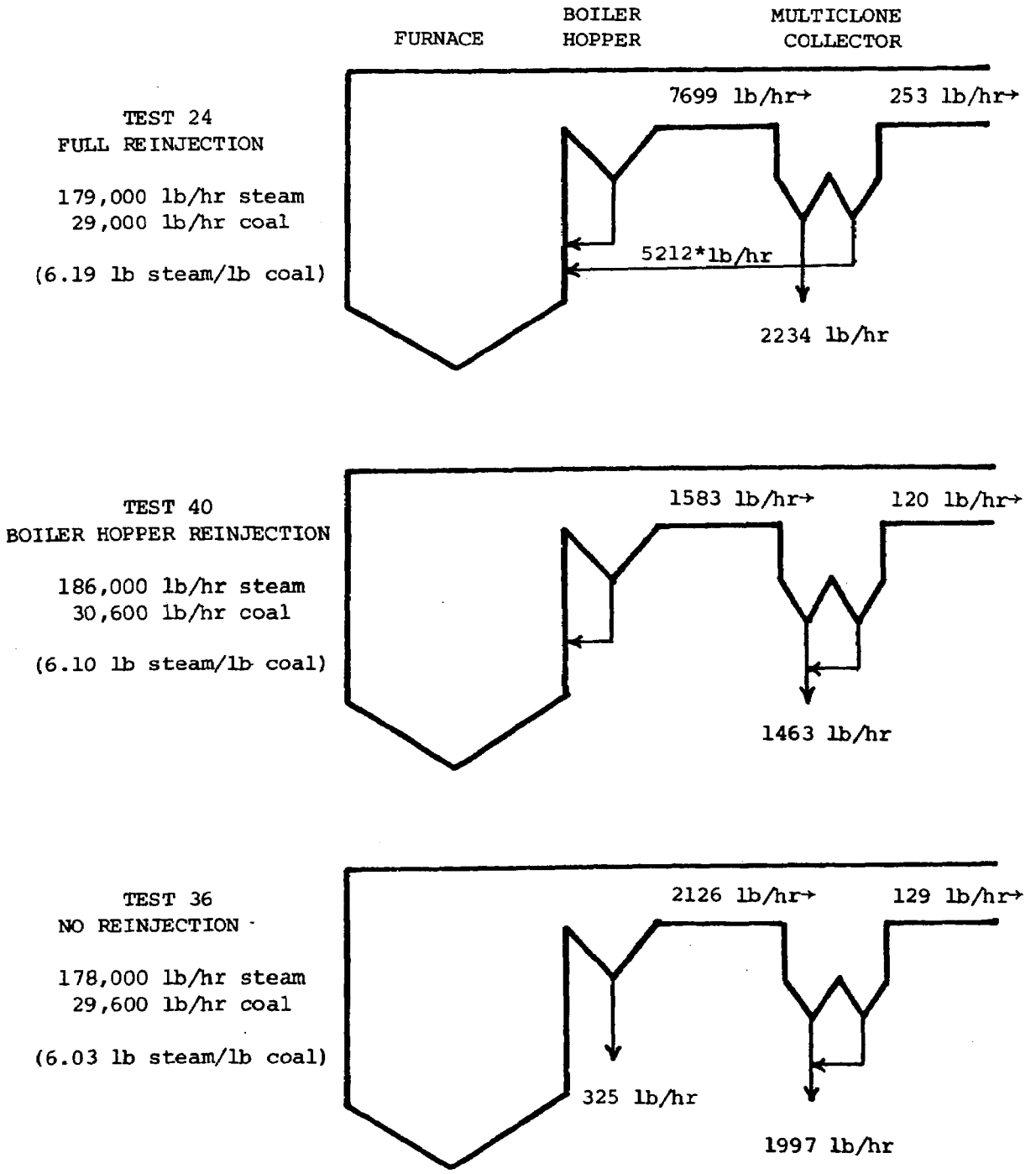
FIGURE 5-9 FLYASH FLOW RATES WITH DIFFERENT REINJECTION CONFIGURATIONS EASTERN LOW FUSION COAL - TEST SITE C

TABLE 5-7

EFFECT OF FLYASH REINJECTION ON EMISSIONS AND EFFICIENCY
BURNING WESTERN COAL
TEST SITE C

	Test No. 24	Test No. 40	Test No. 36
Flyash Reinjection Rate	Full	Boiler Hopper Only	None
FIRING CONDITIONS			
Coal Supplier	W	W	W
Load, % of Capacity	98	102	98
Grate Heat Release, 10^3BTU/ft^2/hr	480	499	482
Coal Sizing, % passing 1/4"	42	46	49
Excess Air, %	66	62	59
BOILER OUTLET EMISSIONS			
Particulate Loading, lb/10^6BTU	31.14	6.15	8.57
Combustible Loading, lb/10^6BTU	--	--	--
Inorganic Ash Loading, lb/10^6BTU	--	--	--
Combustibles in Flyash, %	--	--	--
O_2, % (dry)	8.7	8.3	8.1
CO, ppm (dry) @ 3% O_2	488	280	247
NO, ppm (dry) @ 3% O_2	372	341	357
MULTICLONE OUTLET EMISSIONS			
Particulate Loading, lb/10^6BTU	1.025	0.466	0.519
Combustible Loading, lb/10^6BTU	0.064	0.058	0.071
Inorganic Ash Loading, lb/10^6BTU	0.961	0.408	0.448
Combustibles in Flyash, %	6.2	12.4	13.7
Multiclone Collection Efficiency, %	96.7	92.4	93.9
HEAT LOSSES, %			
Dry Gas Loss	7.90	7.54	7.39
Moisture in Fuel	3.52	3.57	3.57
H_2O from Combustion of H_2	6.16	6.29	6.27
Combustibles in Collected Flyash*	0.50	1.45	1.26
Combustibles in Emitted Flyash	0.10	0.09	0.11
Combustibles in Bottom Ash	1.44	0.02	0.20
Radiation Loss	0.40	0.40	0.40
Unmeasured Losses	1.50	1.50	1.50
Total Losses	21.52	20.86	20.70
Boiler Efficiency	78.48	79.14	79.30

* Based on 70% reinjection from the dust collector



* Assuming 70% Reinjection

FIGURE 5-10 FLYASH FLOW RATES WITH DIFFERENT REINJECTION CONFIGURATIONS WESTERN COAL - TEST SITE C

by difference of the inlet and outlet rates. It was assumed (based on design data) that 70% of the multiclone ash was deposited in the back hopper and 30% in the front. The back hopper ash is normally reinjected. The measured rates may be considered accurate to two significant digits at best.

The Bahco Classifier was used to determine particle size distributions at the boiler outlet for selected tests. In Figures 5-11 and 5-12, the Bahco data was combined with the particulate loading data to form particle size concentration plots. This was done for the conditions of full reinjection and no reinjection on both coals. These figures graphically illustrate that the bulk of particulate mass is in the size range of 50-500 micrometers with peak concentrations near 100 micrometers.

Figure 5-13 shows that when flyash reinjection is stopped, the greatest reductions in particulate loading are in the size range of 20-300 micrometers where they average about 80%. Below 20 micrometers the mass reduction is closer to 55%. This partially accounts for the observed 45% particulate loading reductions after the multiclone dust collector when a 75% reduction was seen entering the collector. What exits the collector is primarily below 20 micrometers.

No relationship between nitric oxide emissions and flyash reinjection was demonstrated. As seen in the table below, there was a large change in NO measured during the E coal test series. However, this was not repeated in the W coal test series. More data is required to draw a definite conclusion. There is no reason to believe, at this time, that NO emissions should be affected.

NITRIC OXIDE VS REINJECTION CONFIGURATION

	Full Reinj.	Blr Hpr Reinj.	No Reinj.
E. Coal, ppm*	291	330	353
W. Coal, ppm	381	362	384

*Because the tests were at slightly different O_2's, the NO concentrations are corrected to 9% O_2 using the relationship: $+1\%O_2 = +30$ ppm NO.

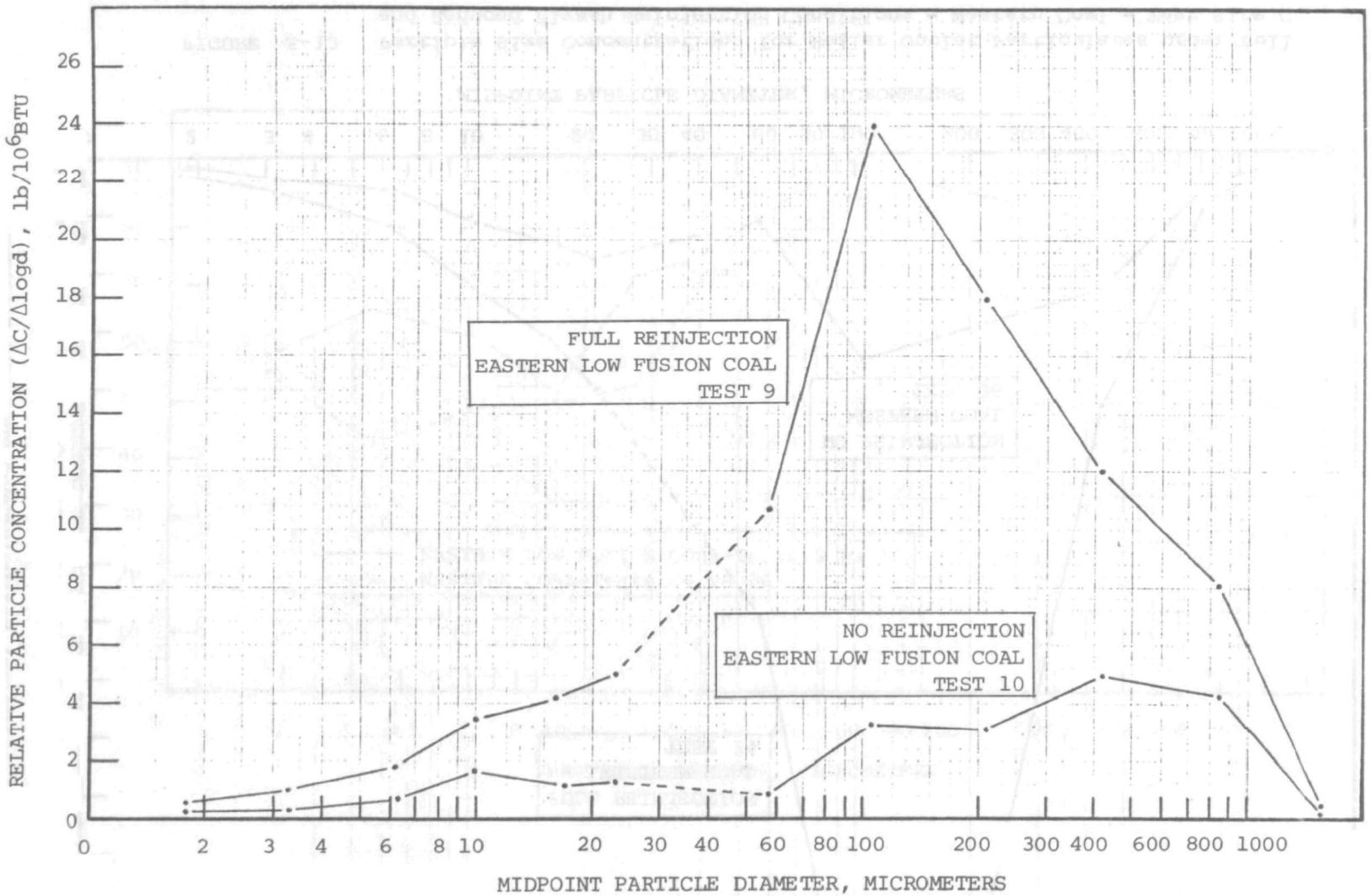


FIGURE 5-11 Particle Size Concentrations for Boiler Outlet Particulates under Full and Reduced Flyash Reinjection Conditions - Eastern Low Fusion Coal - Test Site C

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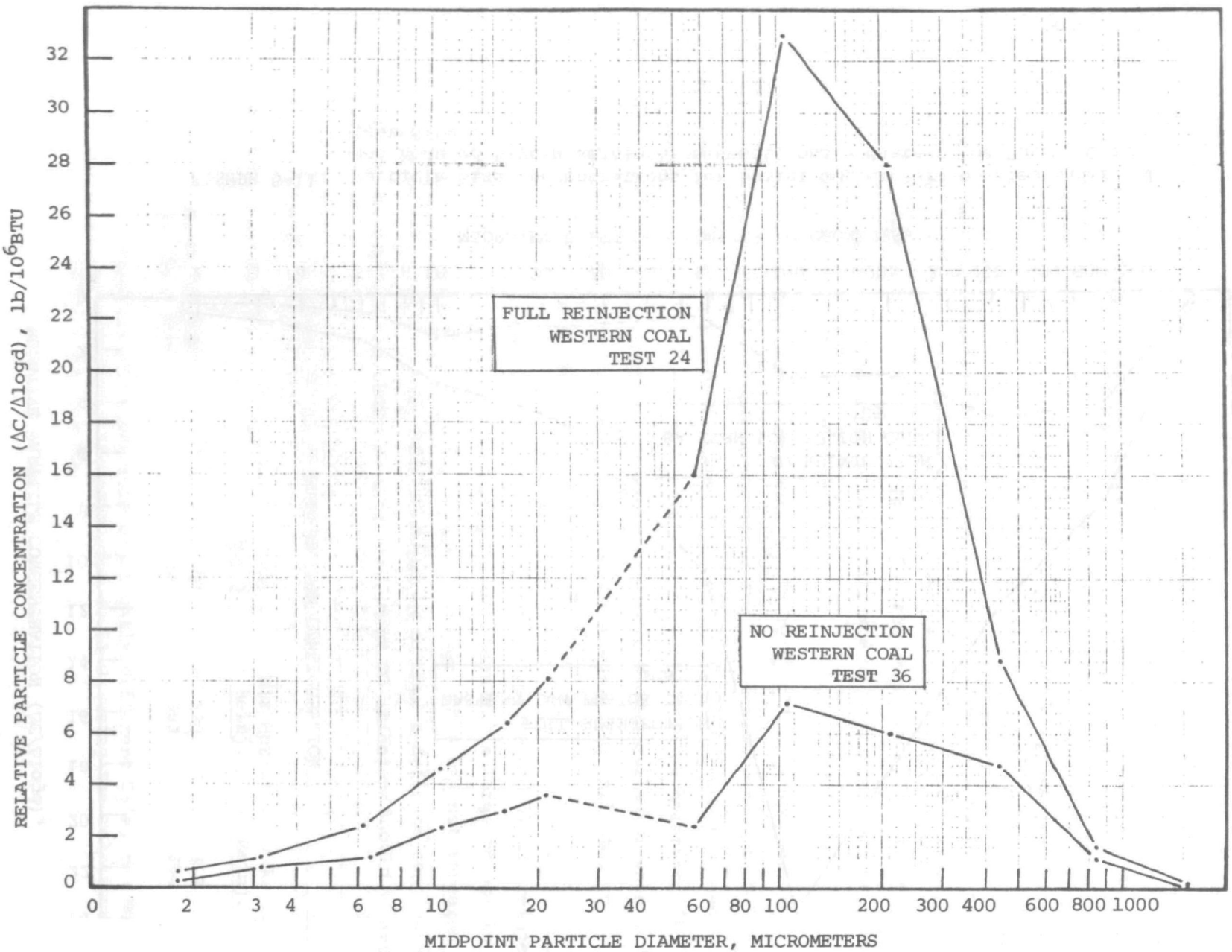


FIGURE 5-12 Particle Size Concentrations for Boiler Outlet Particulates under Full and Reduced Flyash Reinjection Conditions - Western Coal - Test Site C

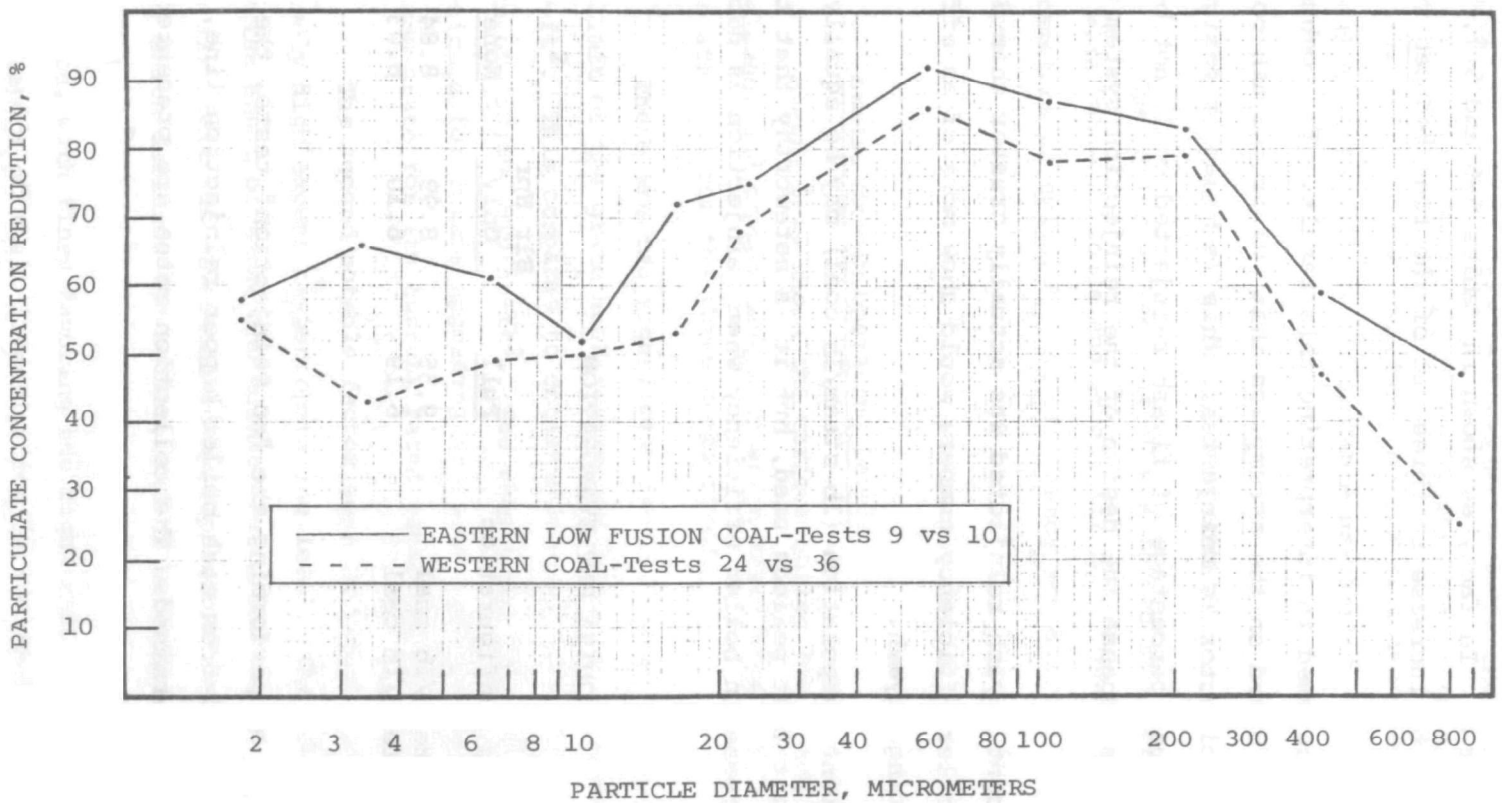


FIGURE 5-13 Particulate Concentration Reduction as a Function of Particle Diameter for the Change in Flyash Reinjection Configuration from Full to No Reinjection - Test Site C

KVB 15900-528

Flyash reinjection was not found to be responsible for a large efficiency gain on Boiler C. In fact, as shown in Tables 5-6 and 5-7, boiler efficiency seemed to increase in three out of the four reduced reinjection tests.

Caution must be used in interpreting this result. The combustibles heat loss calculation is based on the assumption that 70% of the ash collected by the multiclone dust collector is reinjected. This is based on design specifications. The actual percentage of flyash reinjected could not be measured during the tests because the design of the reinjection system would not allow it.

If the percent flyash reinjected was actually greater than 70% of that collected, the boiler efficiency numbers would show more of an efficiency advantage for reinjecting flyash.

The equivalent evaporation (lb steam/lb coal) may be equally unreliable for the short test periods used, but it is noteworthy that they show a consistent decrease in boiler efficiency when reinjection is decreased and stopped.

EQUIVALENT EVAPORATION

Reinjection Configuration	Full	Blr Hpr Only	None
E. Coal, lb steam/lb coal	9.55	8.99	8.84
W. Coal, lb steam/lb coal	6.19	6.10	6.03

In the course of performing the "no reinjection" tests, the flyash collection rate was measured from each boiler hopper reinjection line, and the flyash bulk density was determined. The collection rates are presented in the table below. The bulk density was determined to be 16.6 lb/ft^3 on the Eastern Low Fusion coal ash.

FLYASH COLLECTION RATES BY BOILER HOPPER LINE
E ↔ W

Line	1	2	3	4	5	6	7
E. Coal, lb/hr	60	54	59	41	46	69	106
W. Coal, lb/hr	37	43	48	14	34	71	79

In summary, by eliminating flyash reinjection the boiler outlet particulate loading dropped an average 74% while the multiclone outlet particulate loading dropped an average 45%. Other emissions were not significantly affected. At the same time, boiler efficiency results are inconclusive because they depend upon a questionable assumption.

5.3 EXCESS OXYGEN AND GRATE HEAT RELEASE

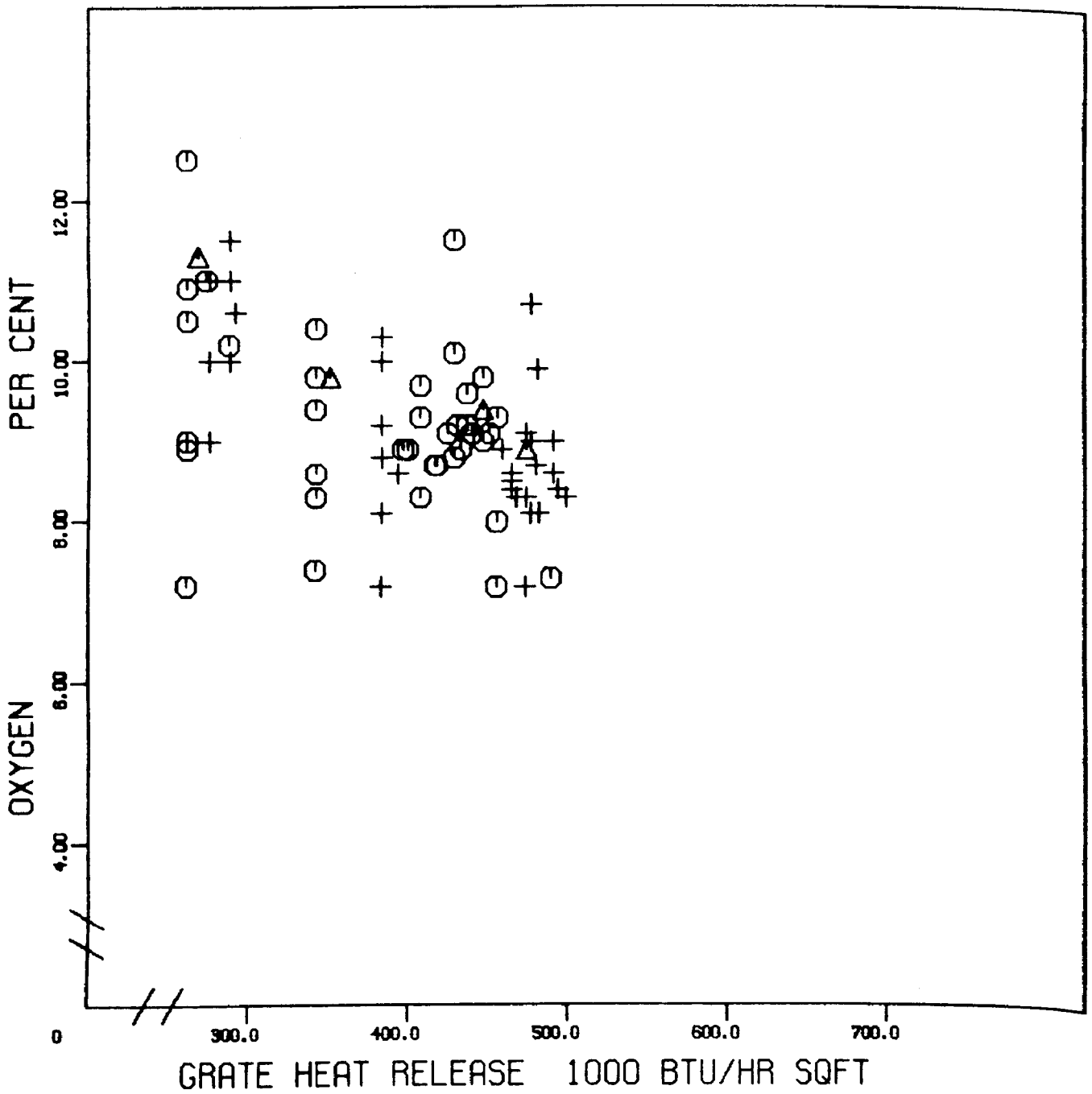
The boiler at Test Site C was tested for emissions and efficiency over a wide range of loads and excess air conditions. The impact of these two parameters on emissions and efficiency are discussed in the following paragraphs.

5.3.1 Excess Oxygen Operating Levels

Figure 5-14 shows the various boiler loads (expressed as Grate Heat Release) and oxygen levels at which tests were run on Boiler C. Different symbols are used for the three coals fired.

There are two significant factors evident in this figure. The upper limit of the grate heat release on Boiler C is approximately 500,000 BTU/hr-ft^2. This compares to obtainable grate heat releases for spreader stokers of 750,000 BTU/hr-ft^2. The reason for this difference is that Boiler C was designed for future upgrading in steam capacity and, therefore, has an oversized grate for its current rated capacity.

The second notable factor seen in Figure 5-14 is the boiler's relatively high excess oxygen operating level. The lower limit of 7% O_2 was set by the onset of smoke and clinkering on the grate. This seemingly high excess air limit was investigated by representatives from Babcock and Wilcox Company which designed the boiler, and by Detroit Stoker which supplied the stoker. Their conclusion was that the problem was caused by "chronic coal segregation, with fines favoring the right side and burning in suspension." The full report of their investigation is included in the appendix.



⊙ : E COAL + : W COAL △ : W COAL

FIG. 5-14
OXYGEN VS. GRATE HEAT RELEASE
TEST SITE C

15900-528

Another factor which may account for the high excess air limit is the oversized grate and furnace area. One hundred percent capacity on this boiler is equivalent to 67% capacity on a boiler designed for a 750,000 BTU/hr-ft^2 grate heat release. Stoker furnaces require more excess air as the load (or grate heat release) is reduced to maintain efficient combustion.

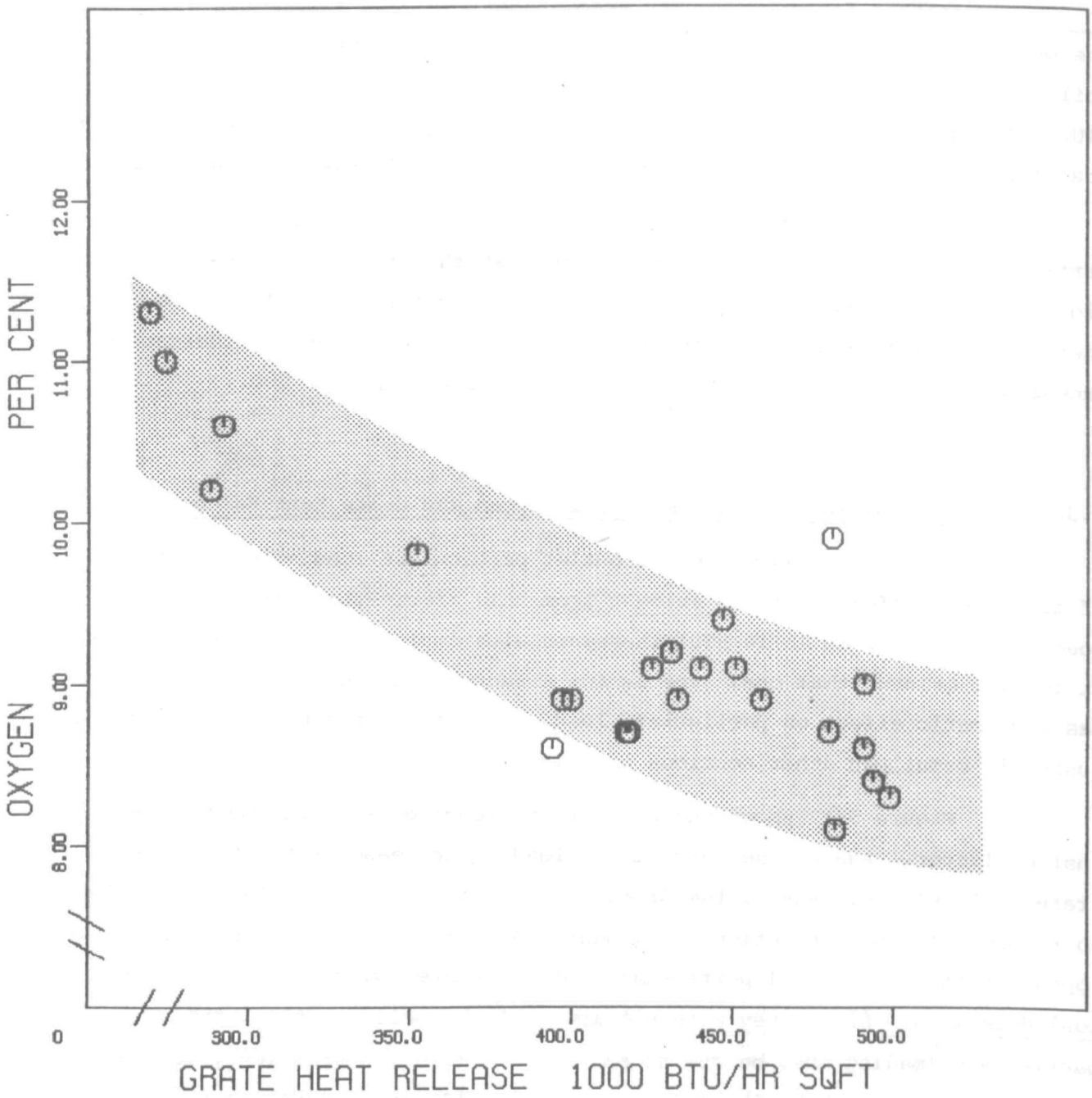
Figure 5-15 shows the boiler load and oxygen levels at which the particulate loading tests were run. (Note that the previous figure, Figure 5-14, included not only particulate loading tests but also tests where only gaseous emissions were measured.) Here, the trend of increasing excess air with decreasing grate heat release is evident.

5.3.2 Particulate Loading vs Excess Oxygen and Grate Heat Release

Figure 5-16 shows boiler outlet particulate loading as a function of grate heat release. It is evident from this figure that particulate loading (expressed in lb/10^{6}BTU) increases with increasing grate heat release. It is also evident that coal type is not a factor whereas flyash reinjection has a dramatic effect on particulate loading. Both of these subjects are discussed in detail in other sections of this report.

Figure 5-17 shows the particulate loading after the multiclone dust collector. Again, the particulate loading increases with increasing grate heat release. Again, the dramatic decrease in particulate loading due to reduced flyash reinjection is evident. At this location on the boiler, it appears that Western coal particulate emissions are lower than the Eastern coal emissions. Since they were not lower at the boiler outlet, the reduced particulate loading must be due to increased collection efficiency of the Western coal's flyash by the multiclone dust collector. (Multiclone collection efficiency is discussed in a later section.) In the same way, it appears that the collection efficiency of the Eastern High Fusion coal ash (H-Coal) may have been slightly lower than for the other two coals.

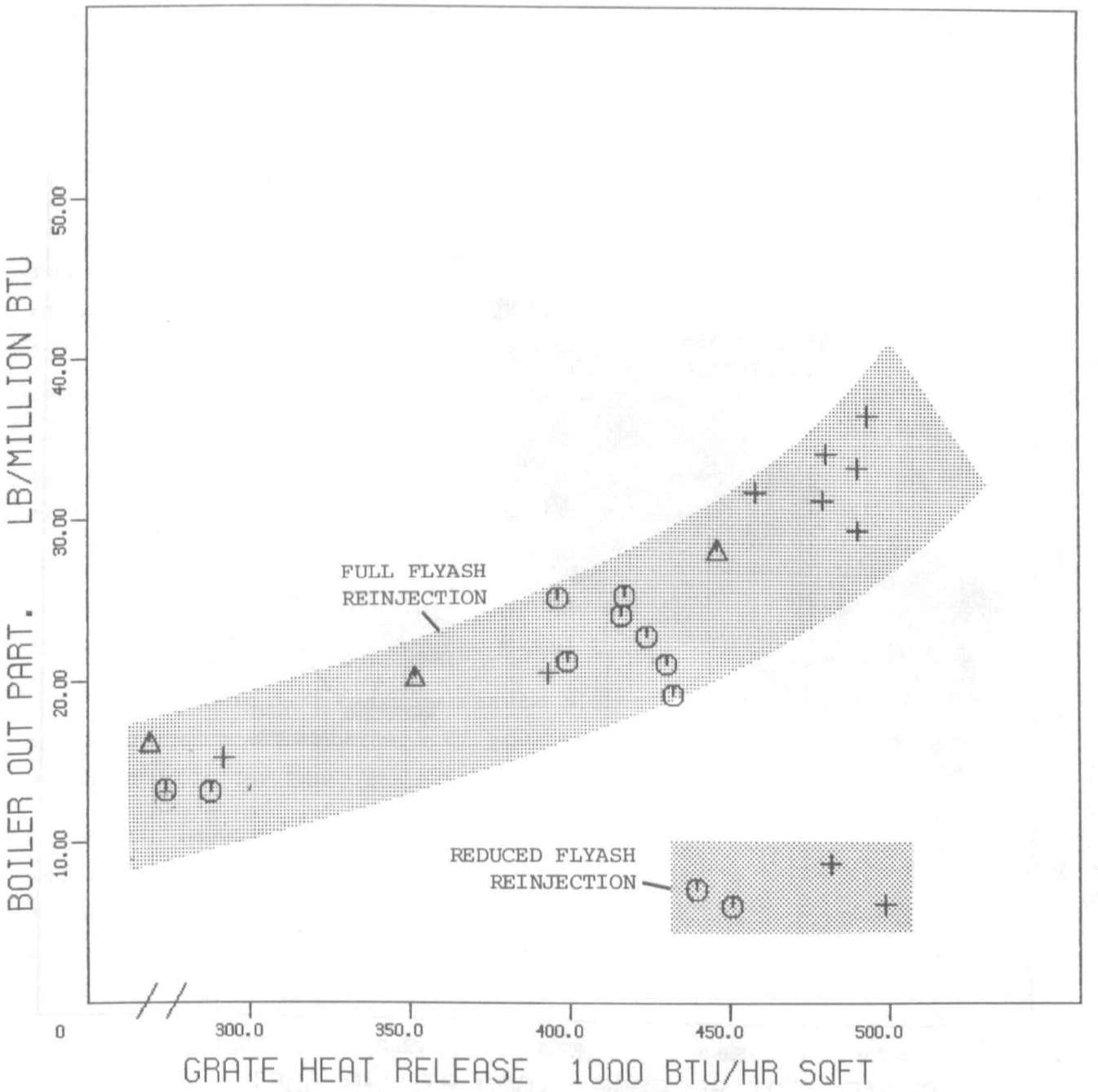
These observations concerning the collection efficiency of the different coal's ash are only suggested by the data. They are by no means substantiated by the limited data, and should not be considered as conclusive evidence.



Ⓣ : PART TEST

FIG. 5-15
OXYGEN VS. GRATE HEAT RELEASE
TEST SITE C

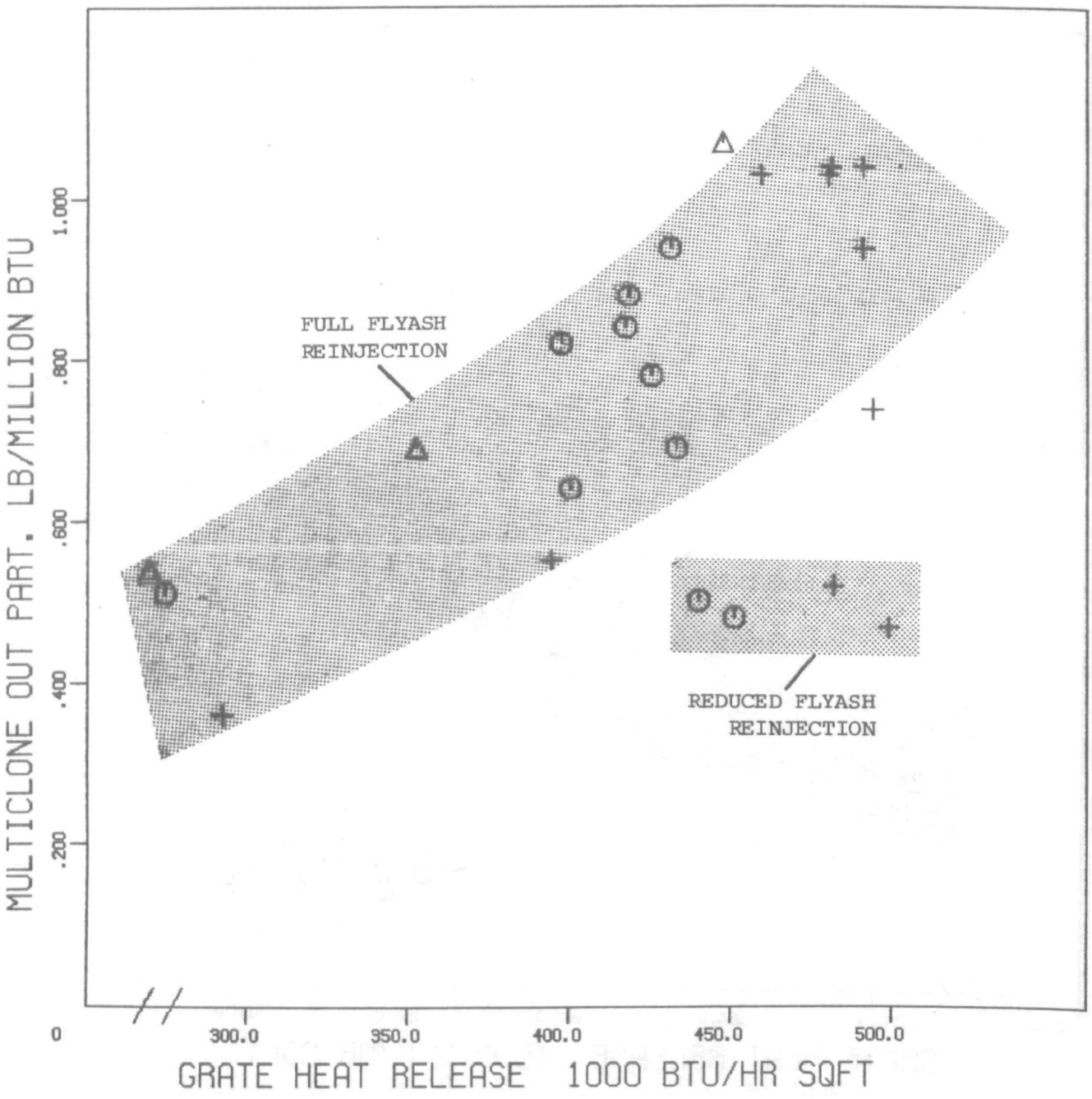
15900-528



⊕ : E COAL + : W COAL △ : H COAL

FIG. 5-16
BOILER OUT PART. VS. GRATE HEAT RELEASE
TEST SITE C

15900-528



⊙ : E COAL + : W COAL △ : H COAL

FIG. 5-17
MULTICLONE OUT PART. VS. GRATE HEAT RELEASE
TEST SITE C

15900-528

No tests were run to document the effect of excess air on particulate loadings at Test Site C.

5.3.3 Nitric Oxide vs Excess Oxygen and Grate Heat Release

Figure 5-18 presents all the measured nitric oxide emissions as a function of grate heat release and coal type. This figure shows that the range of nitric oxide concentration levels for Boiler C is generally 200-450 ppm. The increase in nitric oxide concentration with increasing grate heat release is barely evident because of the off-setting effect of decreasing excess oxygen level with increasing grate heat release. The wide range in nitric oxide concentration levels is a function of, 1) the wide range of excess oxygen levels tested, and 2) unaccounted for scatter in the data.

This figure (Figure 5-18) also suggests that coal type was not a factor in nitric oxide concentration. The average fuel nitrogen levels in the three coals tested at Site C were: E-Coal 1.32%, W-Coal 1.02%, and H-Coal 1.41%.

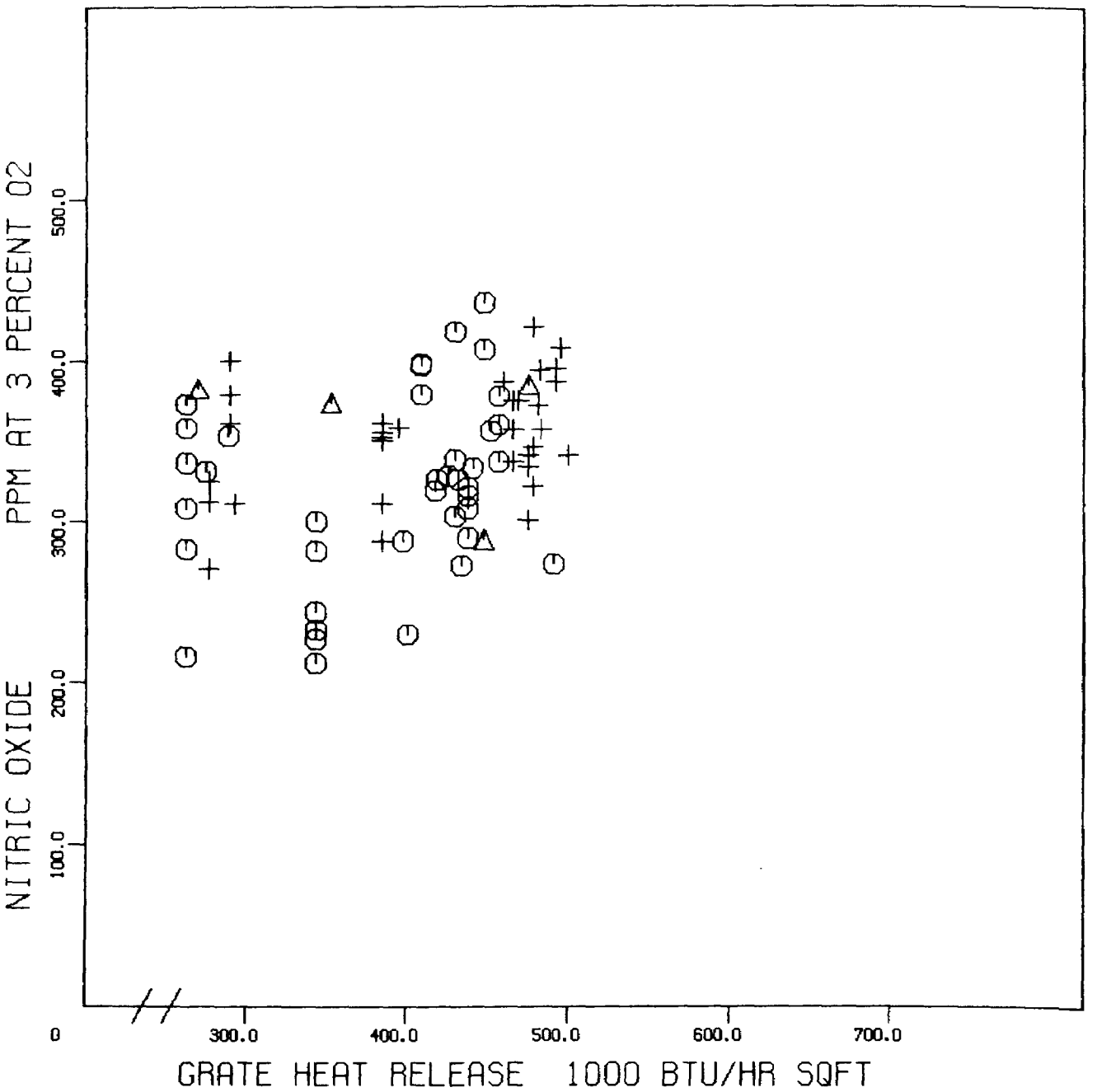
Figure 5-19 presents all the nitric oxide data as a function of excess oxygen and three levels of grate heat release. It is plotted on an expanded scale for later comparison with similar data from other boiler types.

Reducing the scale to fit the data, and plotting each grate heat release range separately gives the plots shown in Figures 5-20, 5-21 and 5-22. Those test points which were obtained in rapid succession ($\sim$20 minutes between NO readings as percent O_2 is changed) to isolate unwanted variables are connected by lines. They best illustrate the trend of NO vs O_2.

Figure 5-23 illustrates the trends in nitric oxide emissions from Boiler C as grate heat release and excess oxygen are changed. The absolute magnitude of the nitric oxide emissions at a given grate heat release and excess oxygen level may deviate significantly from these trend lines due to other NO related variables.

5.3.4 Carbon Monoxide vs Excess Oxygen and Grate Heat Release

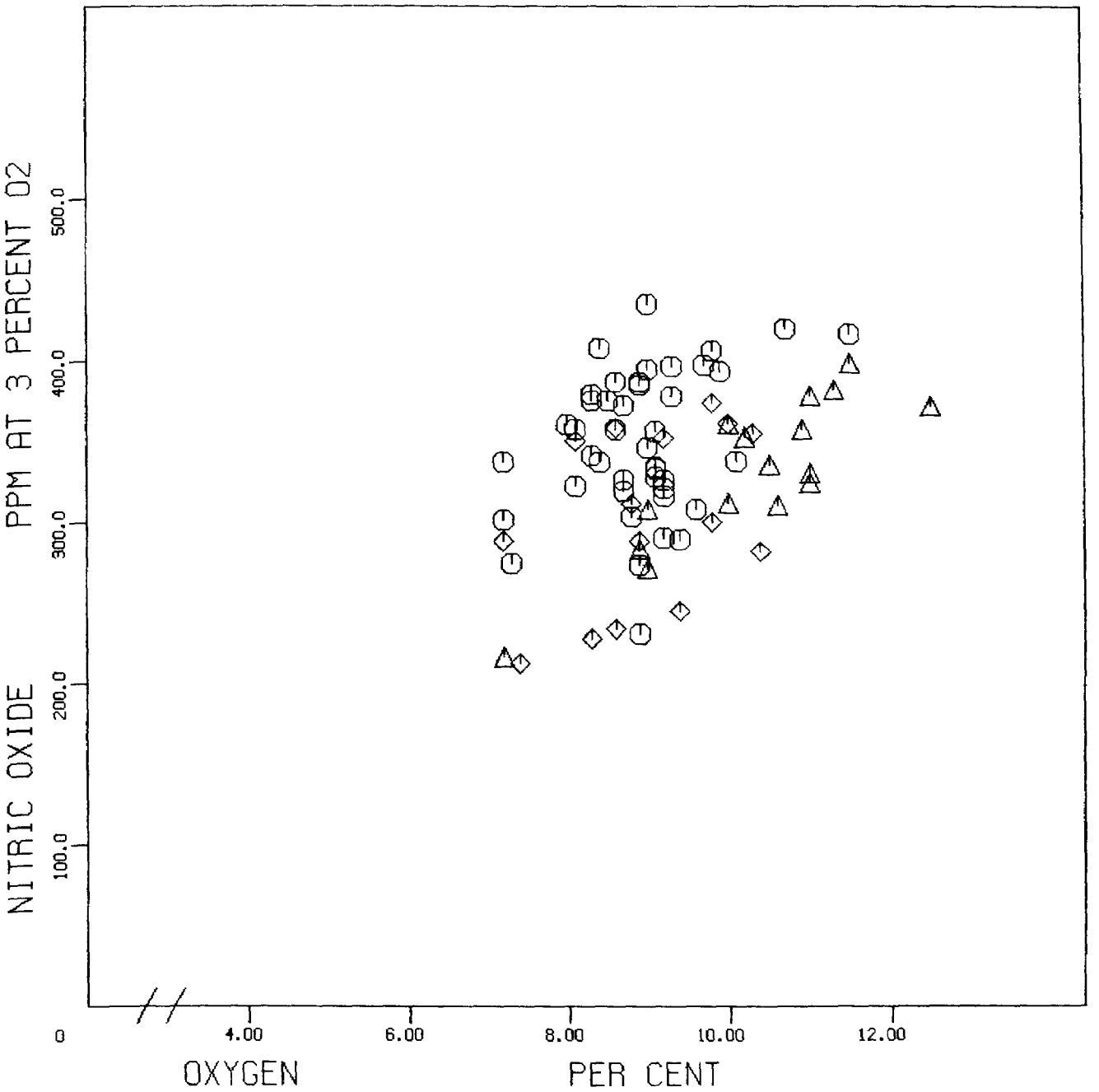
Figure 5-24 shows all of the carbon monoxide data obtained plotted against grate heat release. Again, the expanded scale is used for later comparison with similar data from other boilers.



⊕ : E COAL + : W COAL △ : H COAL

FIG. 5-18
NITRIC OXIDE VS. GRATE HEAT RELEASE
TEST SITE C

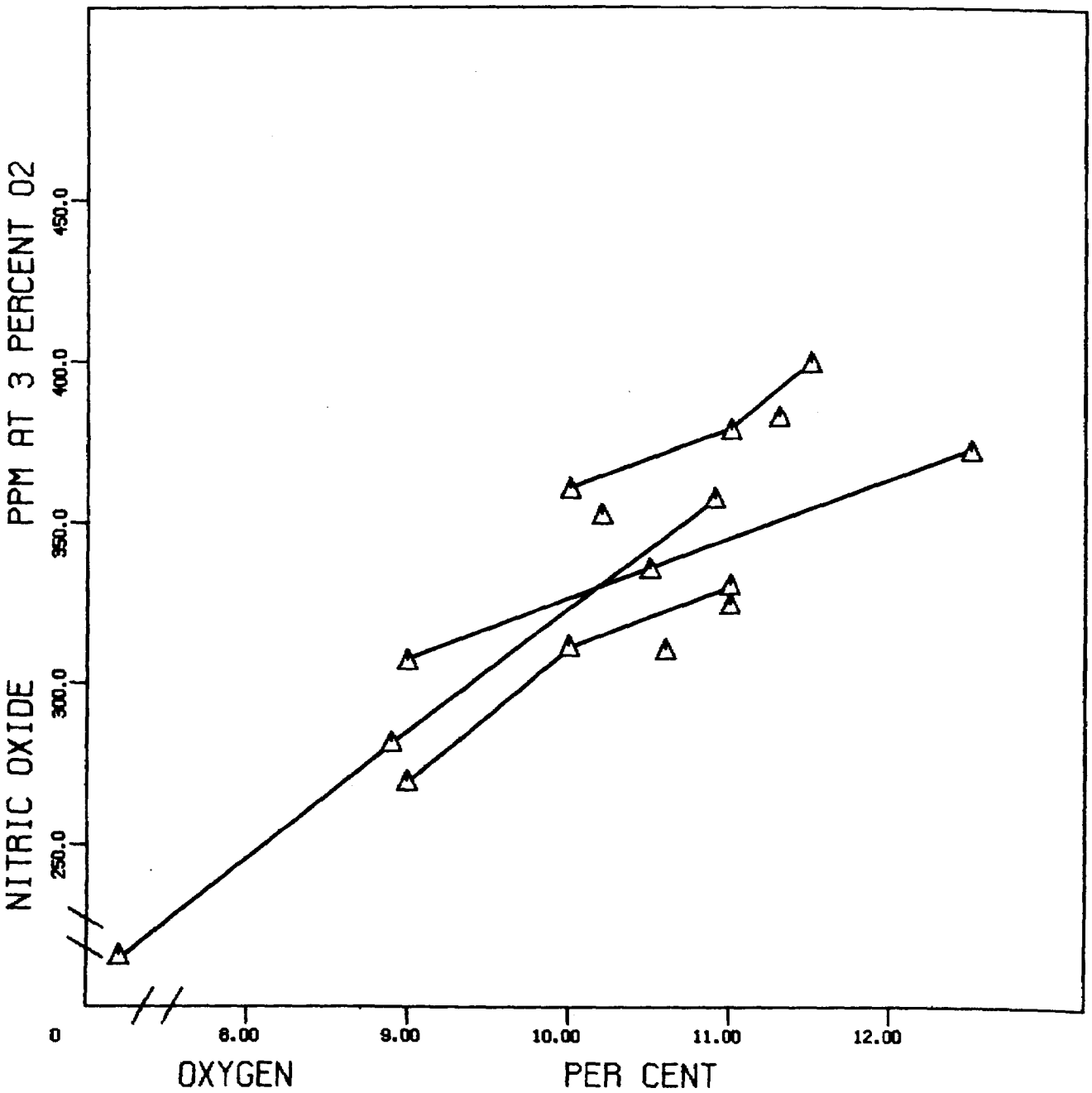
15900-528



△ : 200-299GHR ◇ : 300-399GHR ⏲ : 400-499GHR

FIG. 5-19
NITRIC OXIDE VS. OXYGEN
TEST SITE C

15900-528



△ : 200-299GHR

FIG. 5-20
NITRIC OXIDE VS. OXYGEN
TEST SITE C

15900-528

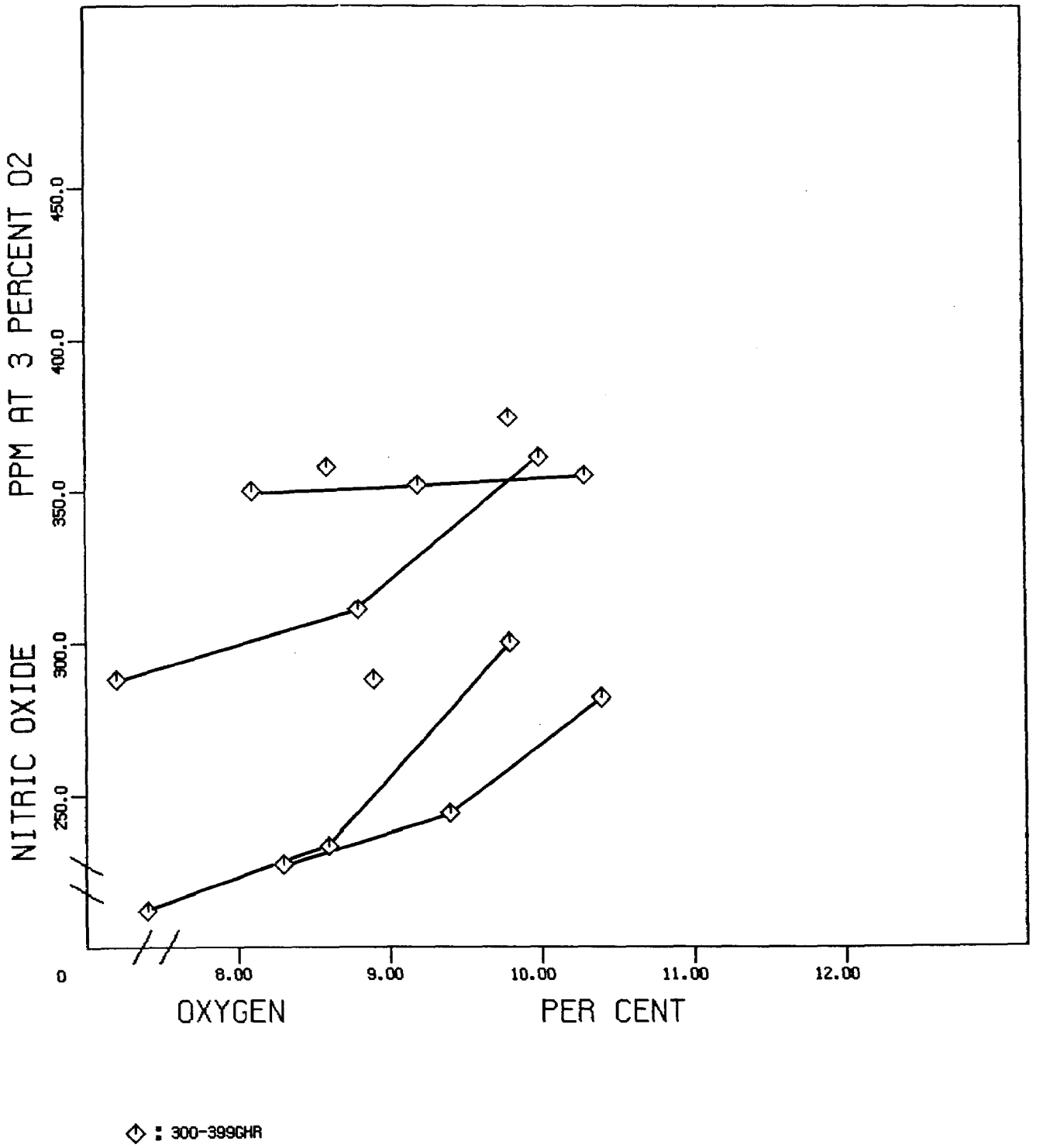
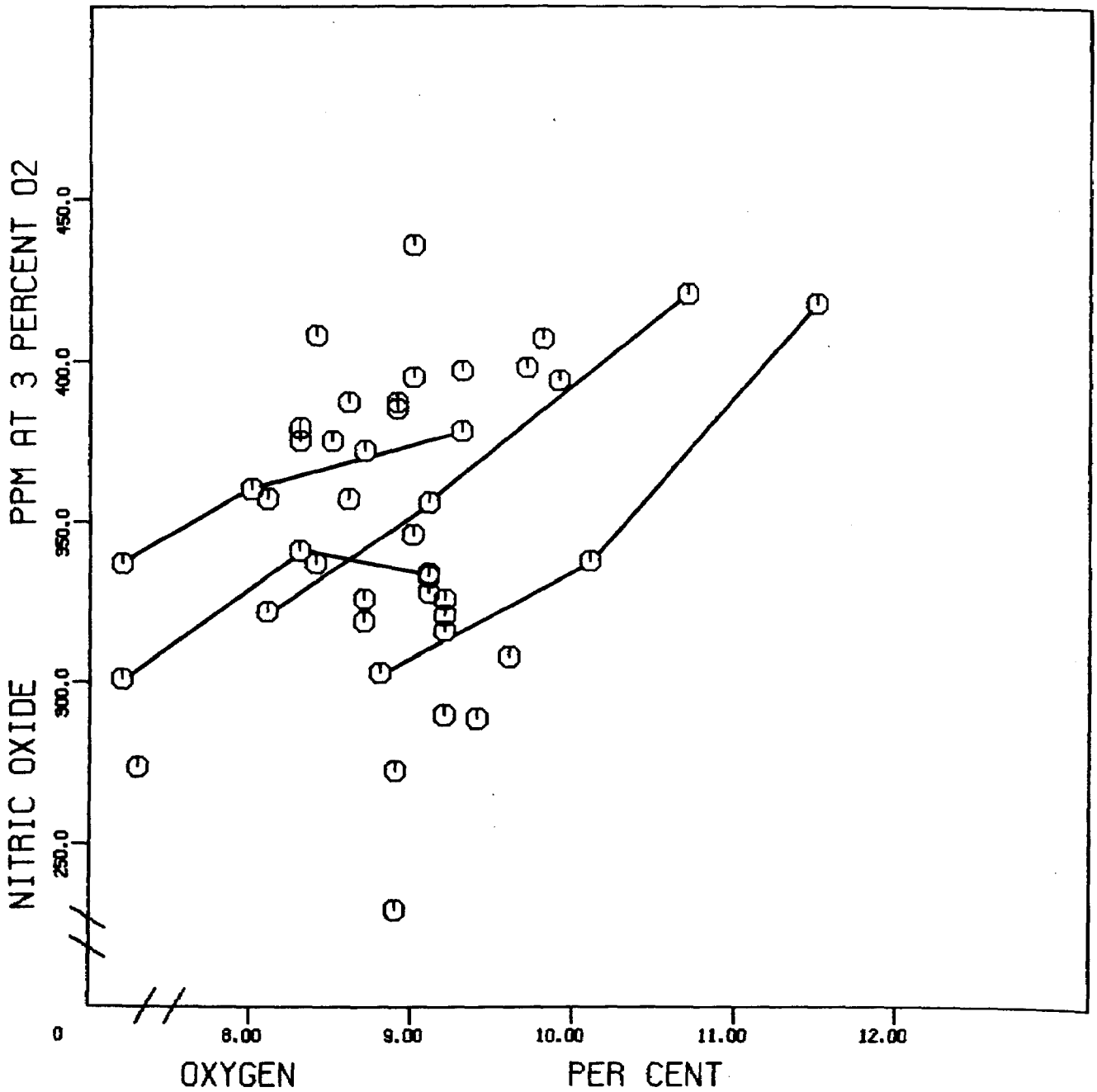


FIG. 5-21
NITRIC OXIDE VS. OXYGEN
TEST SITE C

15900-528



: 400-499GHR

FIG. 5-22
NITRIC OXIDE VS. OXYGEN
TEST SITE C

15900-528

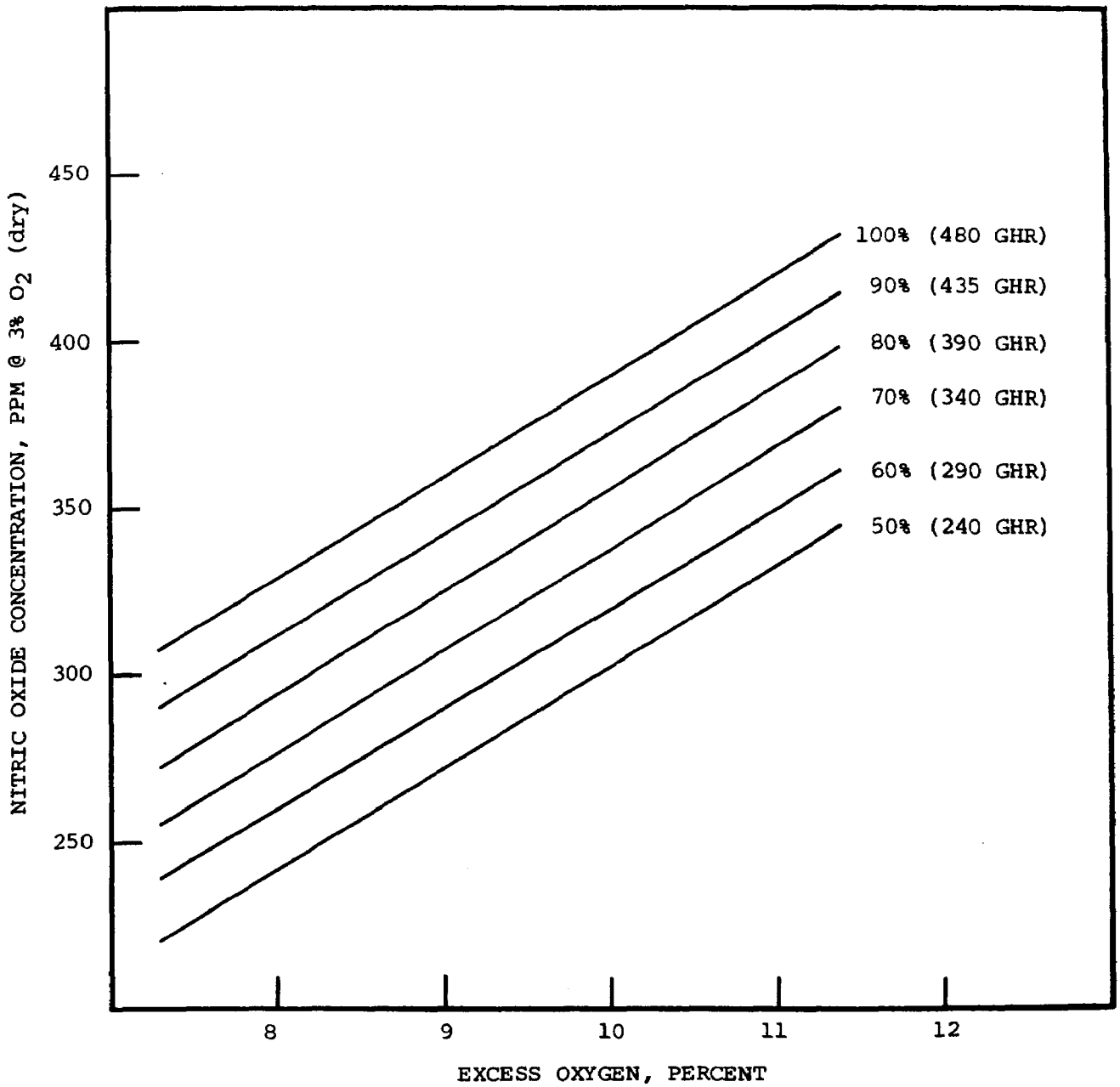


Figure 5-23 Nitric Oxide trends vs O_2 and boiler loading at Test Site C. NO was observed to increase an average 30 ppm for each one percent O_2 increase at all boiler loads. The increase in NO with boiler load was not well established and the trend shown above is little more than an educated guess. (GHR = Grate Heat Release, 10^3BTU/ft^2-hr)

Figure 5-24 shows that firing Western coal produced significantly greater concentrations of carbon monoxide than firing either of the Eastern coals. At full capacity, Eastern coal CO remained below 200 ppm while Western coal ranged from 200 to 600 ppm (with only two exceptions). It is also apparent that carbon monoxide increases with grate heat release on this boiler.

Carbon monoxide is plotted against oxygen for both coals in Figures 5-25 and 5-26. This time the scale has been shortened to fit the data, and only the data points obtained in rapid succession (∿20 minutes between CO readings as percent O_2 is varied) are shown. These are connected by lines and labeled as to firing conditions.

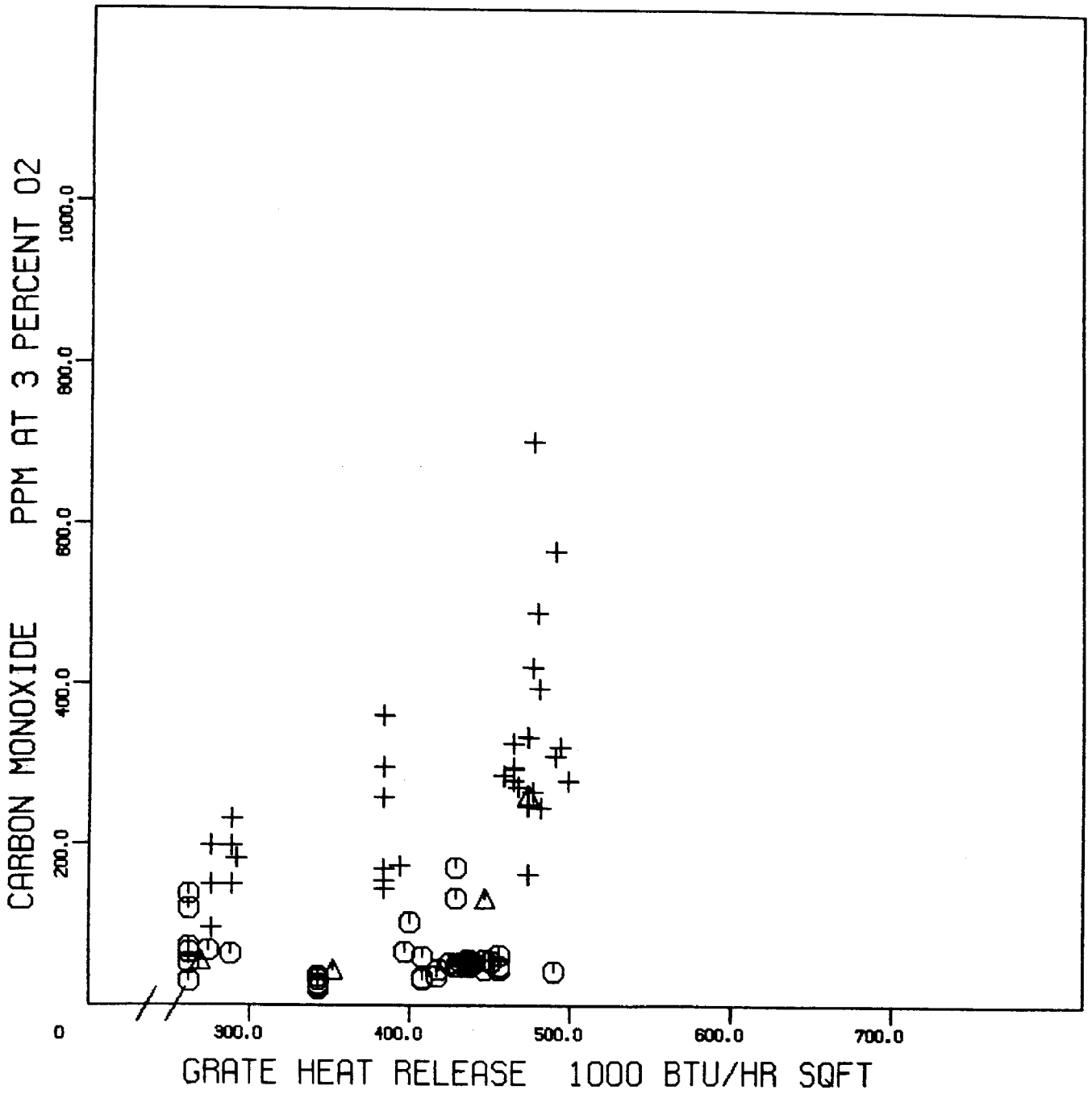
It is clear from these plots that overfire air had an effect on CO emissions. At any given grate heat release, the condition of maximum overfire air showed lower CO levels than the condition of minimum overfire air. This is as it should be. It shows that the overfire air is doing its job of improving combustion through induced turbulance in the flame zone.

5.3.5 Combustibles in the Ash vs Excess Oxygen and Grate Heat Release

Combustible levels in the flyash and bottom ash were very definitely a function of coal type at Test Site C. The combustible levels are plotted against grate heat release and coal type in Figures 5-27 and 5-28.

Western coal averaged ten percent combustibles in the boiler outlet flyash while Eastern Low Fusion coal averaged 40% combustibles. This is a very significant difference. There was no overlap in the two sets of data.

Bottom ash combustible levels averaged 18% while burning Western coal and 8% while burning Eastern Low Fusion coal. They averaged only 1.3% while burning Eastern High Fusion coal. The following table (top of page 90) lists some of the possible contributing factors for these differences.



⊙ : E COAL + : W COAL △ : H COAL

FIG. 5-24
CARBON MONOXIDE VS. GRATE HEAT RELEASE
TEST SITE C

15900-528

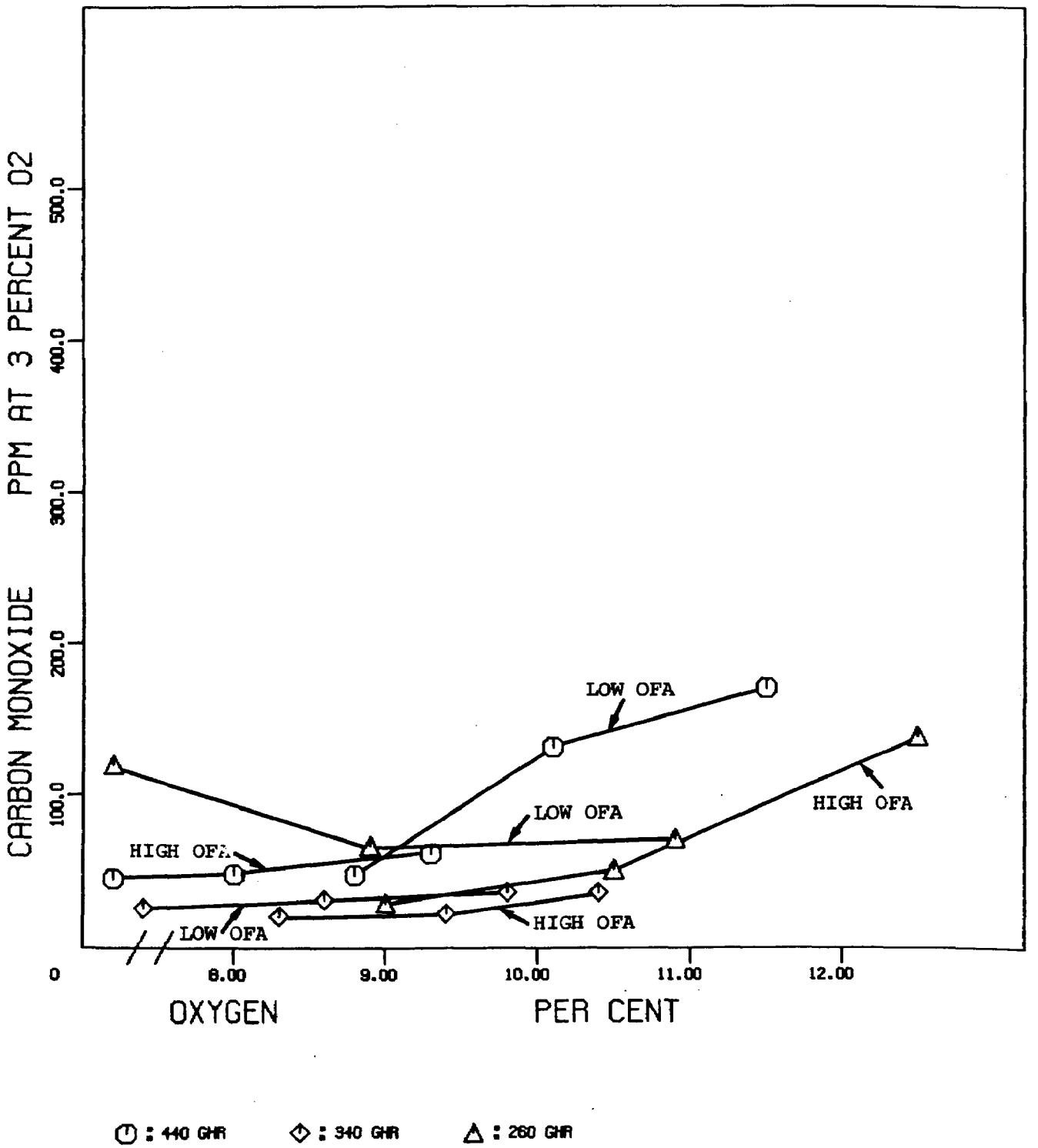
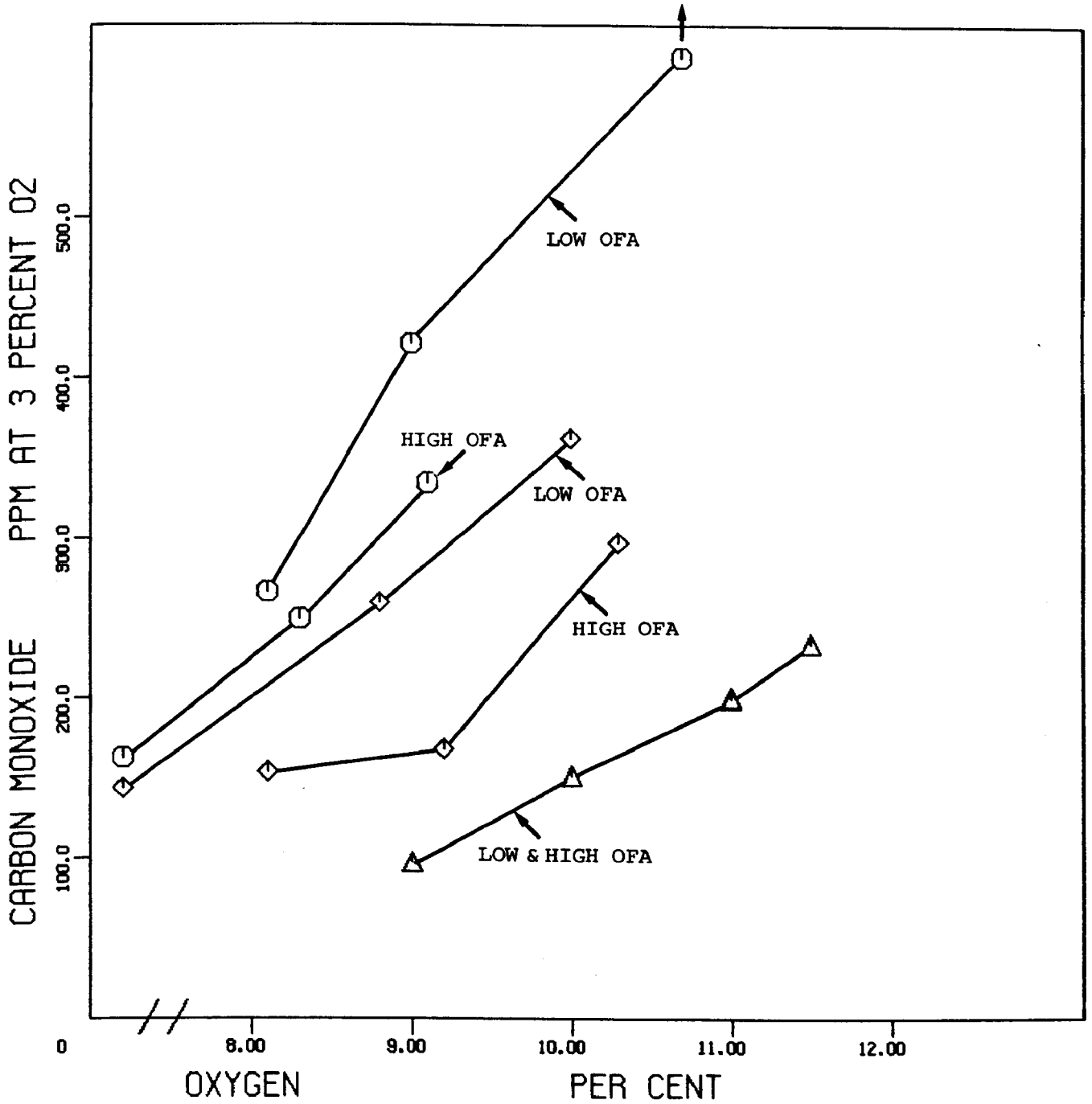


FIG. 5-25 EASTERN LOW FUSION COAL
CARBON MONOXIDE VS. OXYGEN
TEST SITE C

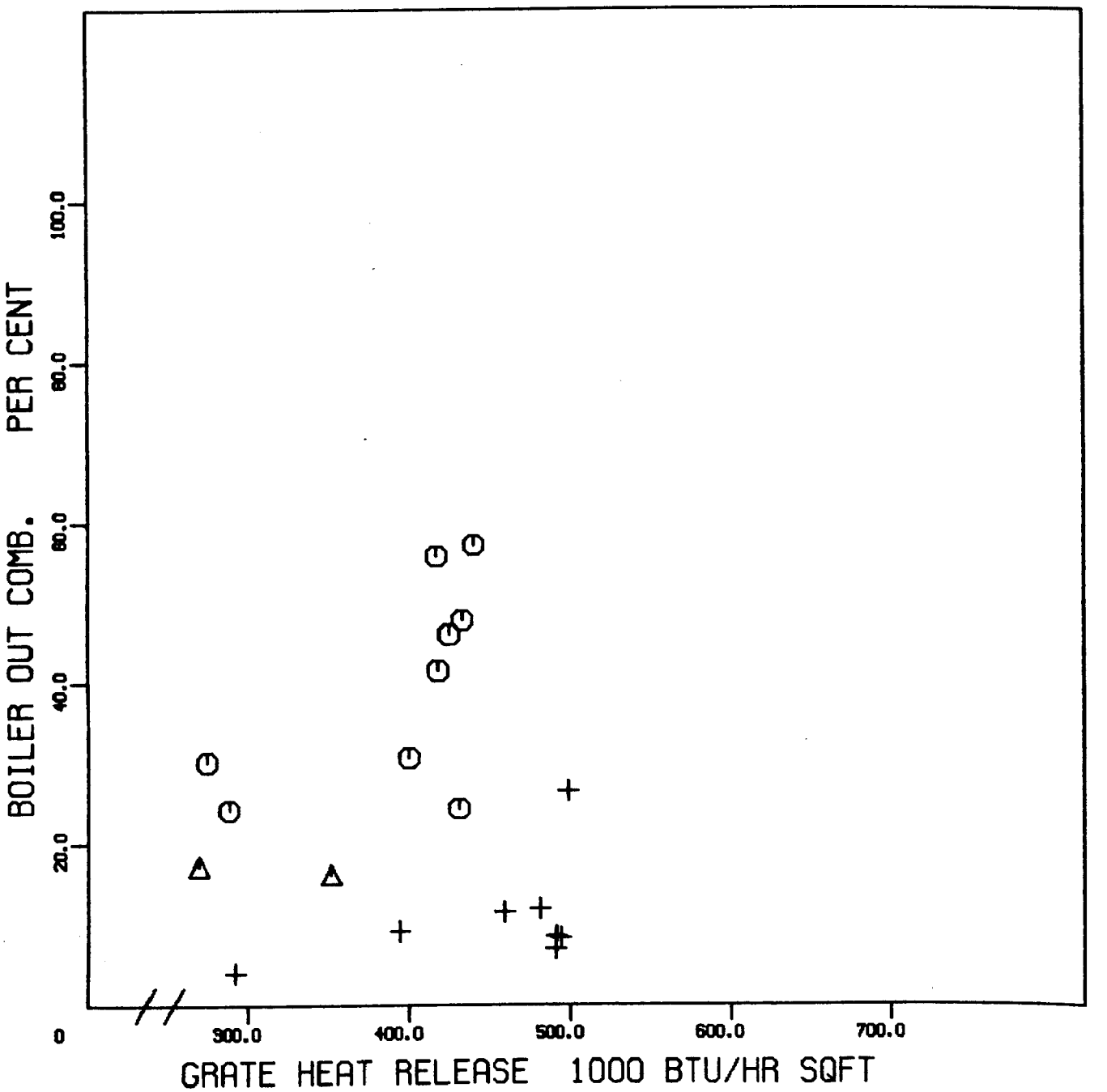
15900-528



◇ : 380 GHR △ : 280 GHR ⓘ : 480 GHR

FIG. 5-26 WESTERN COAL
CARBON MONOXIDE VS. OXYGEN
TEST SITE C

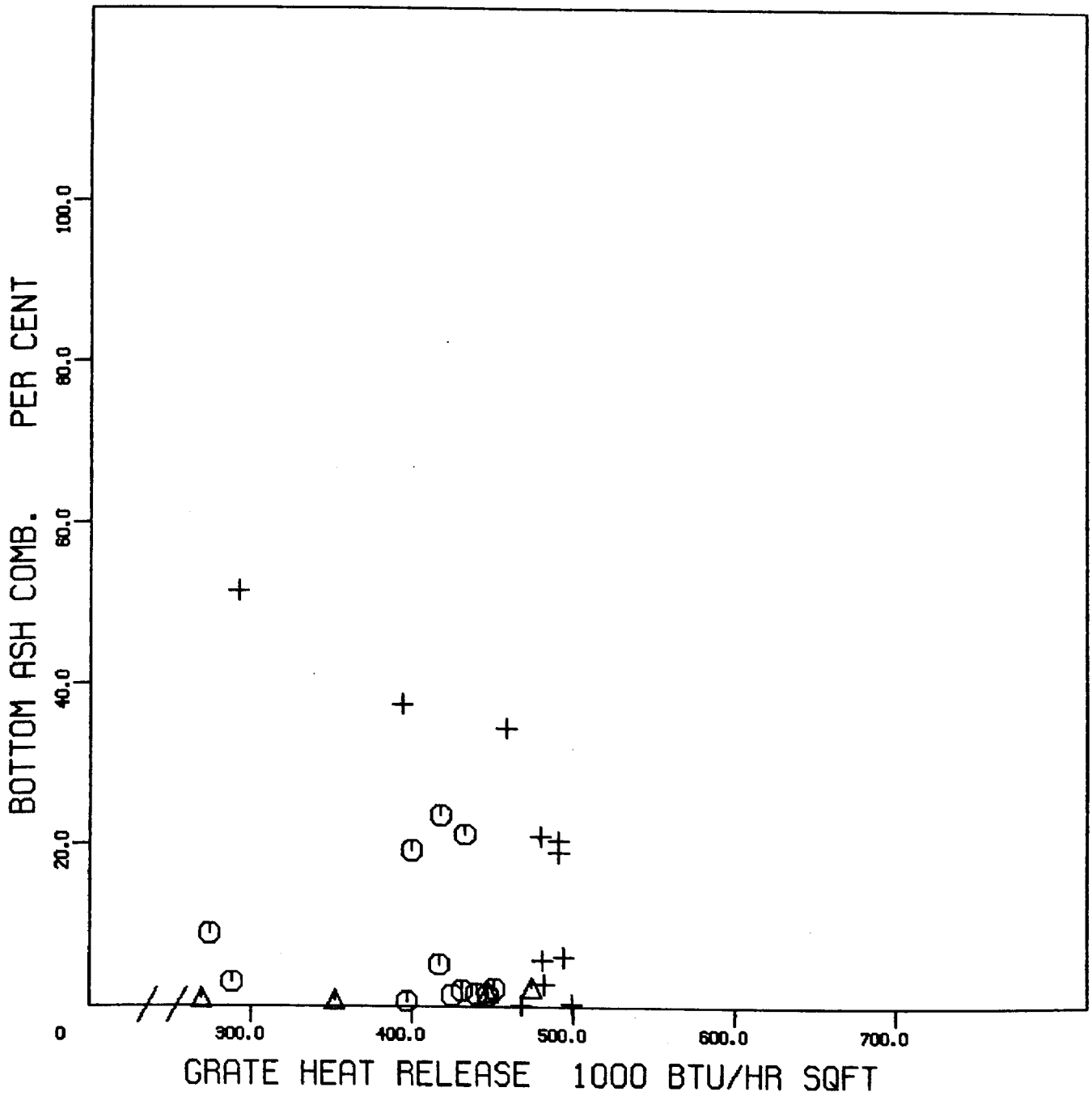
15900-526



⊙ : E COAL + : W COAL △ : H COAL

FIG. 5-27
BOILER OUT COMB. VS. GRATE HEAT RELEASE
TEST SITE C

15900-528



⊙ : E COAL + : W COAL △ : H COAL

FIG. 5-28
BOTTOM ASH COMB. VS. GRATE HEAT RELEASE
TEST SITE C

15900-528

	% Comb In Bottom Ash	Initial Deformation Temp, °F	Free Swelling Index	Coal Fines %	Fuel Moisture %	Fuel Volatiles %
W Coal	18	2183	0	48	26	29
E Coal	8	1985	7	46	5	35
H Coal	1.3	2145	1	44	9	31

The differences are probably accounted for by a combination of factors. For instance, the high level of combustibles in the Western coal's bottom ash may have resulted from poor ignition characteristics due to its high moisture and low volatiles. The low level of bottom ash combustibles in the Eastern high fusion coal (H Coal) may have been a function of its high ash fusion temperature and low moisture. These arguments are only speculative. The only conclusion is that the differences were a function of coal type.

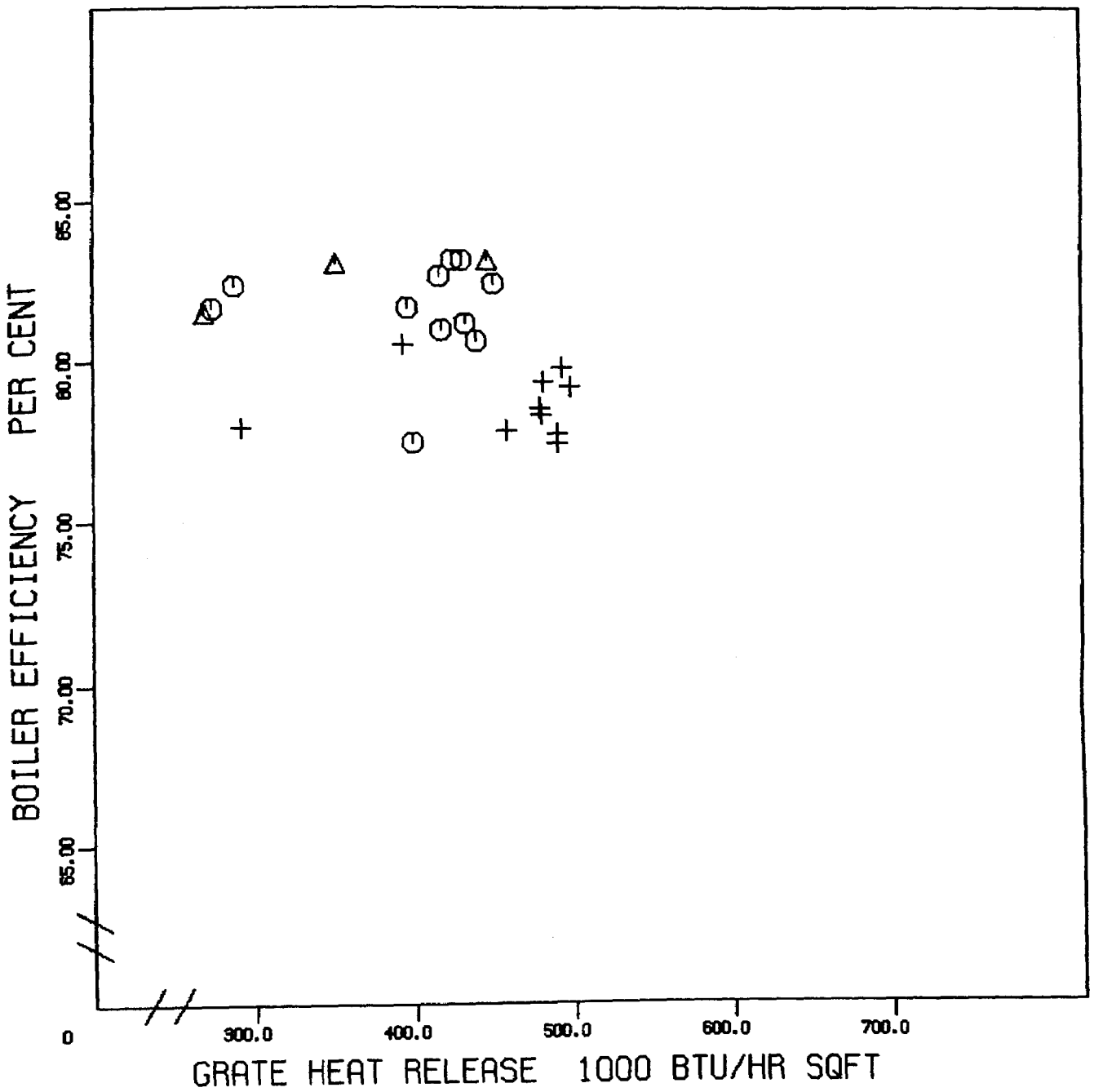
5.3.6 Boiler Efficiency vs Excess Oxygen and Grate Heat Release

Boiler efficiency is plotted as a function of grate heat release and coal type in Figure 5-29. The range is generally 77.5% to 85%. The data strongly suggests that Western coal is not burned as efficiently as Eastern coal in Boiler C.

Heat loss calculations show that one of the primary reasons boiler efficiency is low when burning Western coal is its high moisture content. The table below illustrates the heat loss differences between the coal types tested.

	AVERAGE HEAT LOSSES, PERCENT						BOILER EFFICIENCY PERCENT
	Dry Gas	Moisture In Fuel	H_2O From H_2 in Fuel	Total Combustibles	Radiation & Unmeasured	Total Losses	
E Coal	8.22	0.51	4.50	3.25	1.98	18.44	81.56
W Coal	7.95	3.51	6.25	1.71	1.96	21.37	78.63
H Coal	8.57	0.89	4.56	1.33	2.08	17.43	82.57

KVB 15900-528



⊙ : E COAL + : W COAL △ : H COAL

FIG. 5-29
BOILER EFFICIENCY VS. GRATE HEAT RELEASE
TEST SITE C

15900-528

5.4 COAL PROPERTIES

The chemical properties of the three coals fired at Site C, i.e., Eastern low fusion, Western and Eastern high fusion, are given in Tables 5-8, 5-9, 5-10 and 5-11. The chemical properties are also summarized in Section 3.5. These tables show that the test coals had some very significant differences. Three of the coal properties are computed on a constant heating value basis in the table below to present a more meaningful comparison.

COAL PROPERTIES CORRECTED TO A CONSTANT 10^6BTU BASIS

	Eastern Low Fusion	Western	Eastern High Fusion
Moisture, lb/10^6BTU	4.3	30.2	7.7
Ash, lb/10^6BTU	9.1	10.6	7.8
Sulfur, lb/10^6BTU	2.36	0.82	0.74

Most of the coal related emissions and efficiency differences have already been pointed out. Boiler outlet particulate loading (Figure 5-16) did not vary significantly as a function of coal type. However, coal ash and coal size consistency in the coals fired were similar. Multiclone outlet particulate loading (Figure 5-17) was lowest for the Western coal because of increased collection efficiency of the multiclone dust collector.

Nitric oxide emissions (Figure 5-18) were not affected by coal type. Carbon monoxide emissions (Figure 5-24) were significantly higher when firing Western coal than when firing either of the Eastern coals. The Western coal also exhibited the lowest combustible fraction in the boiler outlet flyash (Figure 5-27) and the lowest boiler efficiency (Figure 5-29).

TABLE 5-8

FUEL ANALYSIS - EASTERN LOW FUSION COAL
TEST SITE C

TEST NO.	8	9	10	11	12	13	14	15	16	19	20	46	COMP	AVG	STD DEV
PROXIMATE (As Rec)															
% Moisture	6.87	5.86	6.47	6.53	5.99	5.88	3.48	4.63	4.38	4.89	4.18	4.54	2.36	5.31	1.09
% Ash	12.52	12.01	10.73	10.81	10.43	13.75	10.95	10.19	12.23	10.27	10.54	9.66	11.32	11.17	1.19
% Volatile	34.86	36.50	35.55	34.50	34.81	33.77	35.86	35.53	33.69	33.92	35.79	35.49	36.15	35.02	0.91
% Fixed Carbon	45.75	45.63	47.25	48.16	48.77	46.60	49.71	49.65	49.70	50.92	49.49	50.31	50.17	48.50	1.80
BTU/lb	11810	11974	12111	11992	12184	11607	12678	12539	12340	12500	12576	12831	12678	12262	376
% Sulfur	2.51	3.05	2.89	2.65	2.70	5.00	2.74	3.00	2.44	2.25	2.85	2.57	2.95	2.89	0.70
ULTIMATE (As Rec)															
% Moisture												4.54	2.36		
% Carbon												71.46	70.64		
% Hydrogen												4.79	4.79		
% Nitrogen												1.04	1.32		
% Chlorine												0.07	0.06		
% Sulfur												2.57	2.95		
% Ash												9.66	11.32		
% Oxygen (Diff)												5.87	6.56		
ASH FUSION (Reducing)															
Initial Deformation												2060	1985		
Soft (H=W)												2180	2130		
Soft (H=1/2W)												2310	2265		
Fluid												2430	2390		
HARDGROVE GRINDABILITY INDEX													62		
FREE SWELLING INDEX													7		

KVB 15900-528

TABLE 5-9

FUEL ANALYSIS - WESTERN COAL
TEST SITE C

TEST NO.	23	24	25	26	27	28	29	35	36	40	44	45	COMP	AVG	STD DEV
PROXIMATE (As Rec)															
% Moisture	25.35	26.02	26.25	26.35	23.50	25.46	25.77	26.10	26.02	26.05	24.12	26.57	24.44	25.63	0.93
% Ash	9.02	8.20	8.18	9.15	8.88	12.14	9.19	9.22	8.50	8.56	8.63	8.59	9.05	9.02	1.05
% Volatile	29.36	28.28	28.11	27.97	30.09	27.82	29.08	30.81	28.69	28.95	29.59	28.59	30.35	28.95	0.90
% Fixed Carbon	36.27	37.50	37.46	36.53	37.53	34.58	35.96	33.87	36.79	36.44	37.66	36.25	36.16	36.40	1.18
BTU/lb	8480	8527	8558	8407	8877	8060	8419	8502	8388	8417	8823	8457	8614	8493	209
% Sulfur	0.86	0.67	0.53	0.99	0.99	0.54	0.59	0.81	0.64	0.72	0.56	0.54	0.69	0.70	0.17
ULTIMATE (As Rec)															
% Moisture											24.12	26.57	24.44	25.35	
% Carbon											51.96	49.90	50.91	50.93	
% Hydrogen											3.37	3.17	3.29	3.27	
% Nitrogen											1.00	1.04	0.77	1.02	
% chlorine											0.02	0.01	0.01	0.02	
% Sulfur											0.56	0.54	0.69	0.55	
% Ash											8.63	8.59	9.05	8.61	
% Oxygen (Diff)											10.34	10.18	10.84	10.26	
ASH FUSION (Reducing)															
Initial Deformation											2175	2190	2175	2183	
Soft (H=W)											2240	2250	2260	2245	
Soft (H=1/2W)											2290	2325	2335	2308	
Fluid											2330	2395	2400	2363	
HARDGROVE GRINDABILITY INDEX													49		
FREE SWELLING INDEX													0		
% EQUILIBRIUM MOISTURE													24.19		

TABLE 5-10

FUEL ANALYSIS - EASTERN HIGH FUSION
TEST SITE C

TEST NO.	41	42	43	COMP	AVG	STD DEV
PROXIMATE (As Rec)						
% Moisture	9.72	9.38	8.17	13.27	9.09	0.81
% Ash	8.29	10.95	8.49	7.93	9.24	1.48
% Volatile	31.73	29.79	31.31	31.55	30.94	1.02
% Fixed Carbon	50.26	49.88	52.03	47.25	50.72	1.15
BTU/lb	11944	11513	12106	11219	11854	307
% Sulfur	0.74	0.93	0.96	0.75	0.88	0.12
ULTIMATE (As Rec)						
% Moisture				13.27		
% Carbon				64.30		
% Hydrogen				4.02		
% Nitrogen				1.41		
% Chlorine				0.07		
% Sulfur				0.75		
% Ash				7.93		
% Oxygen (Diff)				8.25		
ASH FUSION (Reducing)						
Initial Deformation				2145		
Soft (H=W)				2235		
Soft (H=1/2W)				2330		
Fluid				2420		
HARDGROVE GRINDABILITY INDEX				44		
FREE SWELLING INDEX				1		

KVB 15900-528

TABLE 5-11

MINERAL ANALYSIS OF COAL ASH - TEST SITE C

COAL TEST NO.	EASTERN LOW FUSION 46	COMP	AVG	WESTERN 44	45	COMP	AVG	EASTERN HIGH FUSION COMP
MINERAL ANALYSIS OF ASH								
Silica, SiO_2	43.76	43.62	43.69	43.62	43.61	40.60	42.61	49.23
Alumina, Al_2O_3	21.64	21.07	21.36	16.42	18.57	18.56	17.85	23.21
Titania, TiO_2	1.03	1.10	1.07	0.88	0.99	0.88	0.92	1.14
Ferric Oxide, Fe_2O_3	24.83	22.99	23.91	4.49	5.13	7.40	5.67	10.05
Lime, CaO	2.45	2.30	2.38	16.00	12.80	13.10	13.97	5.50
Magnesia, MgO	0.90	3.20	2.05	3.60	4.04	3.84	3.83	2.12
Potassium Oxide, K_2O	1.65	1.85	1.75	0.55	0.60	0.70	0.62	1.75
Sodium Oxide, Na_2O	0.60	0.52	0.56	0.45	0.60	0.72	0.59	0.50
Sulfur Trioxide, SO_3	2.81	3.01	2.91	12.69	12.25	13.89	12.94	6.24
Phos. Pentoxide, P_2O_5	0.21	0.24	0.23	0.21	0.18	0.18	0.19	0.18
Undetermined	0.12	0.10	0.11	1.09	1.23	0.13	0.82	0.08
Silica Value	60.83	60.49	60.66	64.42	66.50	62.52	64.48	73.59
Base: Acid Ratio	0.46	0.47	0.47	0.41	0.37	0.43	0.40	0.27
T_{250} Temperature	2340	2335	2338	2400	2450	2375	2408	2590
% Pyritic Sulfur	1.27		1.27	0.15	0.04		0.10	
% Sulfate Sulfur	0.23		0.23	0.02	0.01		0.015	
% Organic Sulfur	1.07		1.07	0.39	0.49		0.44	

KVB 15900-528

5.4.1 Coal Size Consistency

As-fired coal size consistency was measured for each test involving particulate loading or particle sizing. This parameter was not varied for test purposes, and its natural fluctuations from test to test were small. Figures 5-30, 5-31 and 5-32 plot the mean and standard deviation limits of the measured coal sizing against the ABMA recommended limits of coal sizing for spreader stokers. All three coal sizings fall generally at the upper limit (high fines side) of the ABMA limits. A generally accepted definition of "coal fines" is the percent by weight passing a 1/4" square mesh screen. By this definition, all three coals had similar fines (E coal 46%, W coal 48%, H coal 44%). Coal size consistency was not a variable in these tests.

5.4.2 Sulfur Balance

Sulfur oxides were measured during three tests, one for each of the three coals. When the fuel analysis for these three tests were received, however, it became apparent that test number 44 which was thought to be Eastern high fusion coal was actually more similar to the Western coal. A sulfur balance was made for each of these three tests and appears in Table 5-12.

Sulfur retention in the ash was measured directly. The percentage of sulfur retention was found to be on the order of:

Eastern low fusion coal	-	13% sulfur retention
Western coal	-	18% sulfur retention
Eastern high fusion coal	-	6% sulfur retention

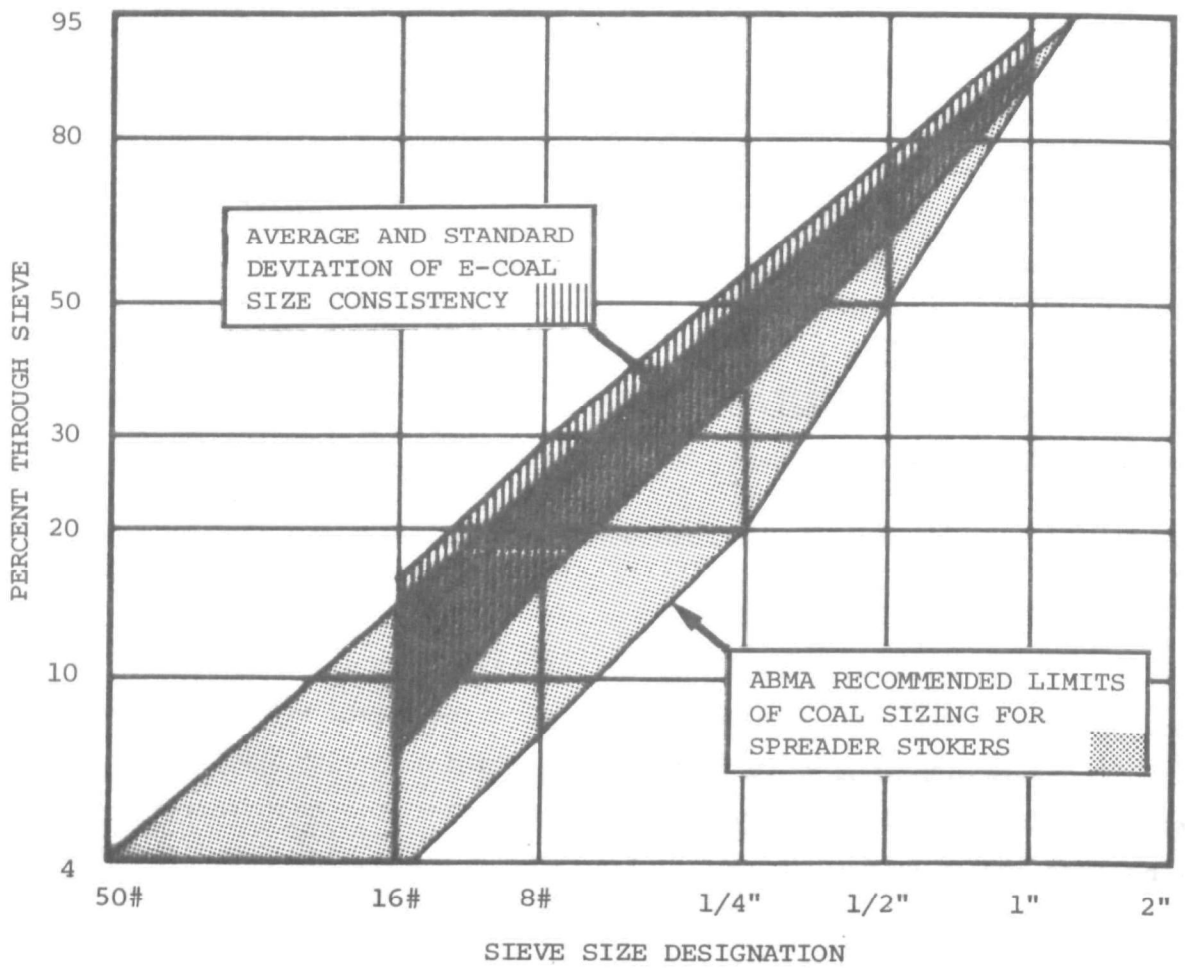


Figure 5-30 Size Consistency of "As Fired" Eastern Low Fusion Coal (E-Coal) vs ABMA Recommended Limits of Coal Sizing for Spreader Stokers - Test Site C.

KVB 15900-528

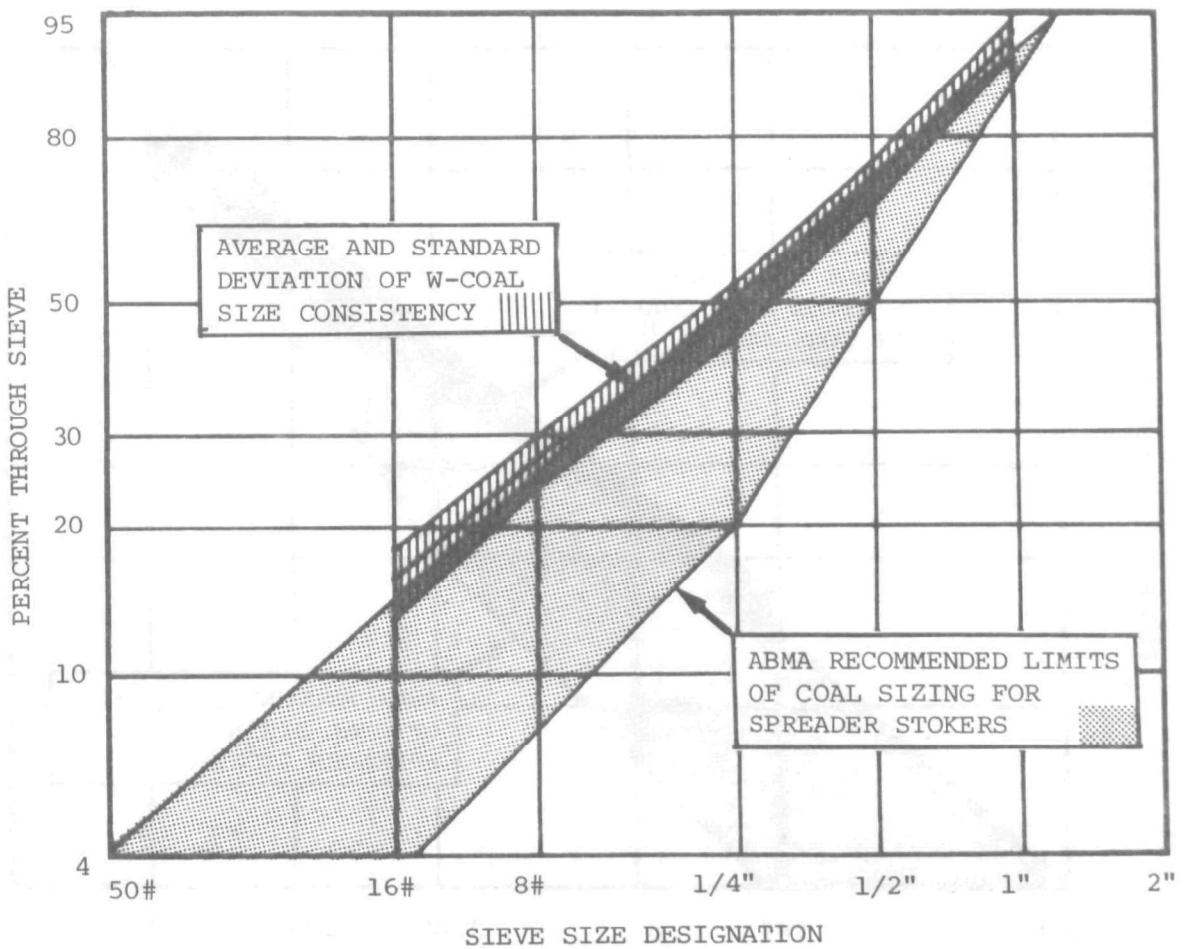


Figure 5-31 Size Consistency of "As Fired" Western Coal (W-Coal) vs ABMA Recommended Limits of Coal Sizing for Spreader Stokers - Test Site C.

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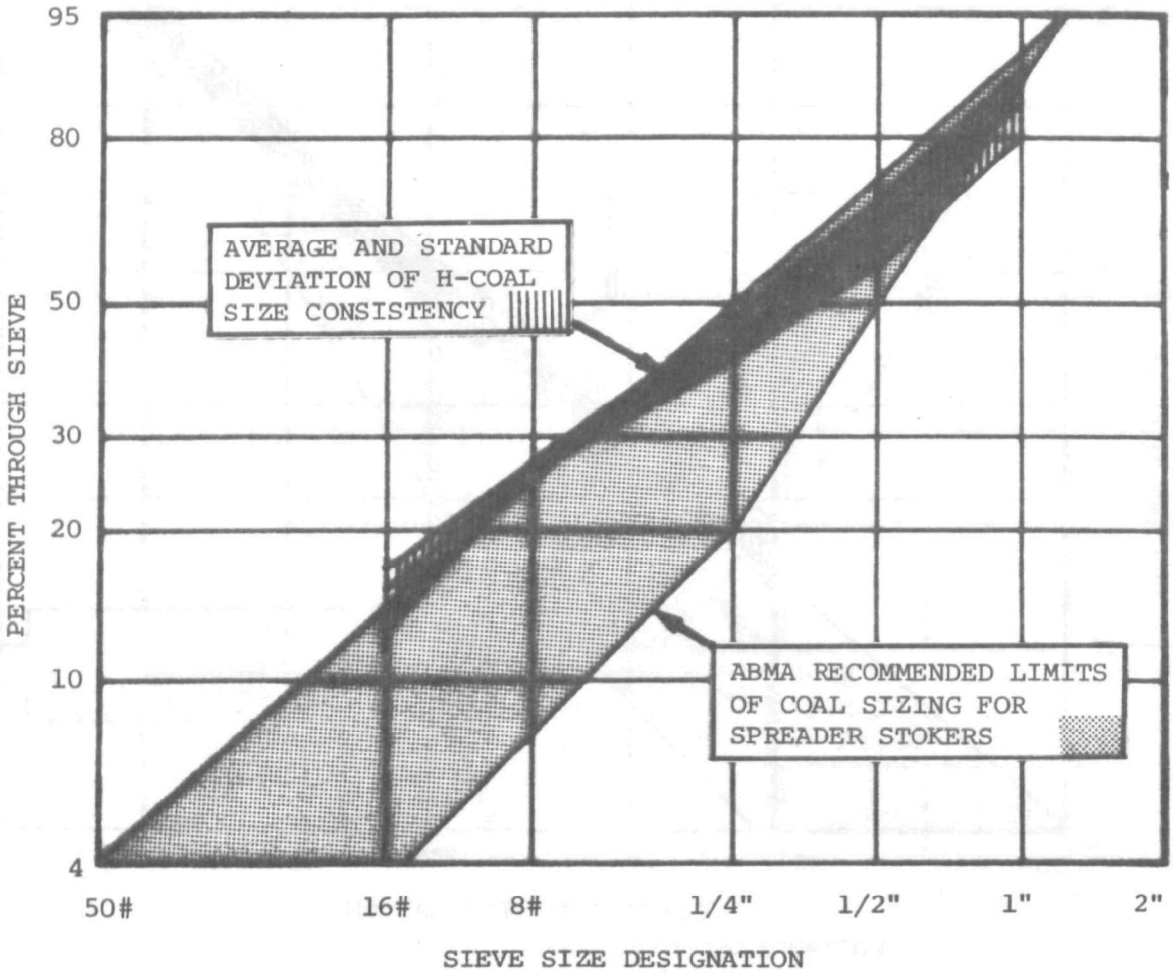

Figure 5-32 Size Consistency of "As Fired" Eastern High Fusion Coal (H-Coal) vs ABMA Recommended Limits of Coal Sizing for Spreader Stokers - Test Site C.

KVB 15900-528

TABLE 5-12

SULFUR BALANCE
TEST SITE C

	SULFUR IN FUEL		SULFUR IN BOTTOM ASH			SULFUR IN FLYASH			SULFUR IN FLUE GAS		
Test No.	Fuel Sulfur %	As SO_2 lb/10^6BTU	Ash Sulfur %	As SO_2 lb/10^6BTU	Retention %	Ash Sulfur %	As SO_2 lb/10^6BTU	Retention %	SOx ppm(dry)	SOx as SO_2 lb/10^6BTU	Fuel Sulfur Emitted, %
44	0.56	1.269	0.35	0.038	3.0	0.19	0.125	9.9	976	1.948	154
45	0.54	1.277	0.45	0.048	3.8	0.28	0.185	14.5	810	1.616	127
46	2.57	4.006	0.66	0.061	1.5	0.30	0.184	4.6	1871	3.733	93

KVB 15900-528

5.5 PARTICLE SIZE DISTRIBUTION OF FLYASH

A total of ten particle size distribution tests were run at Test Site C. These tests were run under varying conditions of coal type and flyash reinjection configurations. All but two of these tests were run at the boiler outlet. Table 5-13 lists the particle size distribution tests and methodology used.

The particle size distribution data are plotted in Figures 5-33, 5-34, and 5-35. Each graph represents all the particle sizing data for one particle sizing method. Description and commentary on the various methods is given in Section 4.5.

Coal type was examined as a variable in the particle sizing tests. All three coals had very similar particle size distribution profiles. The small differences observed were not significant. The following table presents the test results at three and ten micrometers.

SIZE DISTRIBUTION AND CONCENTRATION OF FLYASH
AT BOILER OUTLET AS A FUNCTION OF COAL TYPE

	BAHCO CLASSIFIER		SASS CYCLONES	
% Below	3μm	10μm	3μm	10μm
Eastern Low Fusion Coal	1.4	5.0	2.0	10.2
Eastern High Fusion Coal	1.6	4.8	1.3	6.8
Western Coal	1.2	4.7	1.0	6.1
$lb/10^6$BTU Below	3μm	10μm	3μm	10μm
Eastern Low Fusion Coal	0.36	1.25	--	--
Eastern High Fusion Coal	0.45	1.34	--	--
Western Coal	0.36	1.46	--	--

Flyash reinjection configuration was also examined as a variable. When flyash reinjection was stopped, the particle size distribution shifted toward the smaller particles. The particle size concentration, however, dropped about 50% below three and ten micrometers. Table 5-14 illustrates this data.

TABLE 5-13

PARTICLE SIZE DISTRIBUTION TESTS
AND METHODOLOGY USED
TEST SITE C

Test No.	Coal*	Load %	Flyash Reinjection	Particle Size Distribution Methodology Used	
				Boiler Outlet	Multiclone Outlet
9	E	89	Yes	Bahco-Sieve	--
10	E	93	No	Bahco-Sieve	--
24	W	98	Yes	Bahco-Sieve	--
36	W	98	No	Bahco-Seive	Brink Impactor
42	H	99	Yes	Bahco-Sieve	--
44	H†	97	Yes	SASS Cyclone	--
45	W	97	Yes	SASS Cyclone	Brink Impactor
46	E	99	Yes	SASS Cyclone	--

* E - Eastern Low Fusion Coal
W - Western Coal
H - Eastern High Fusion Coal

† Test 44 had a coal analysis more nearly like Western coal than the Eastern High Fusion coal it was presumed to be.

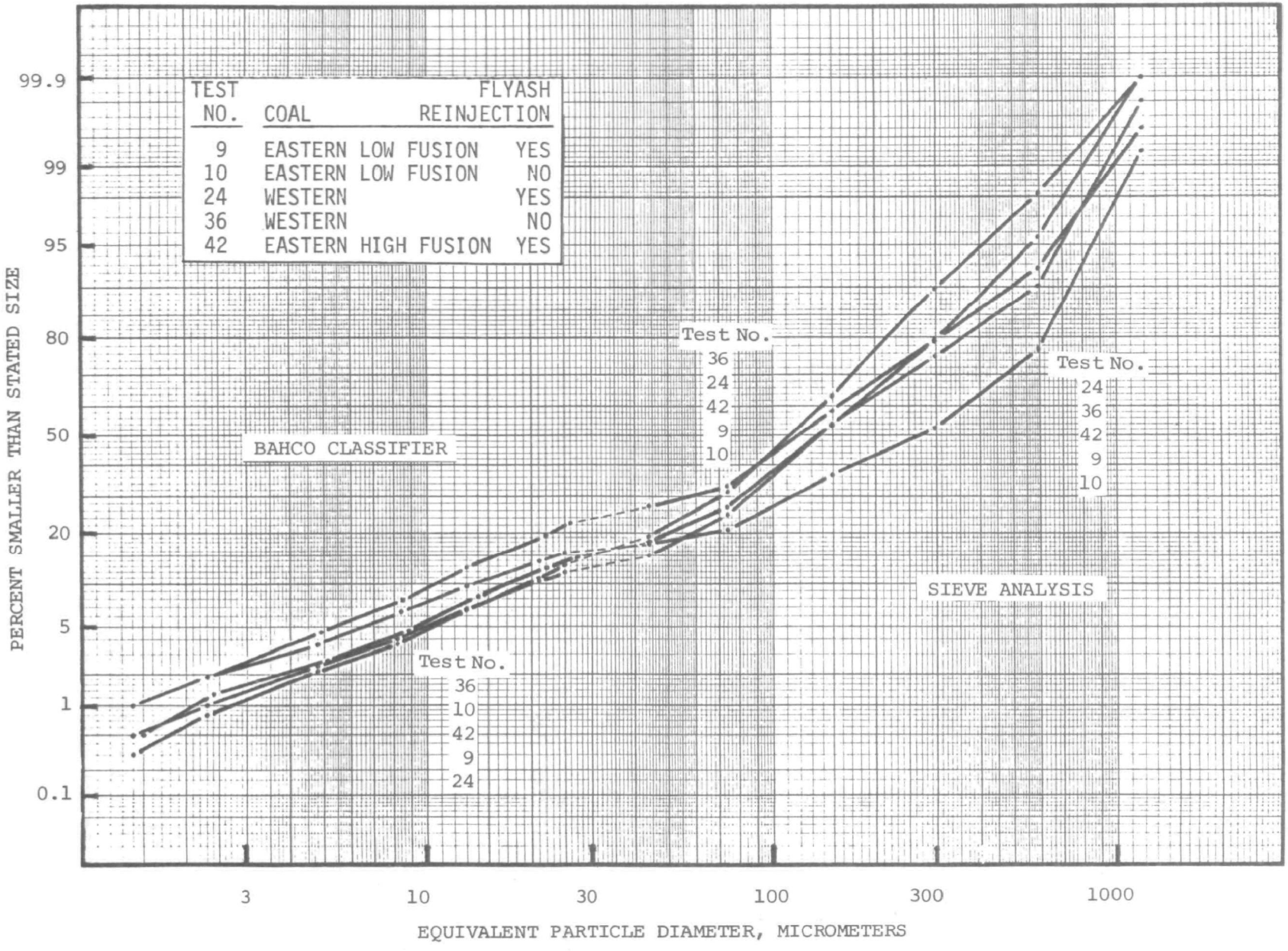

FIGURE 5-33 Bahco Classifier and Sieve Analysis Particle Size Distribution
Test Site C

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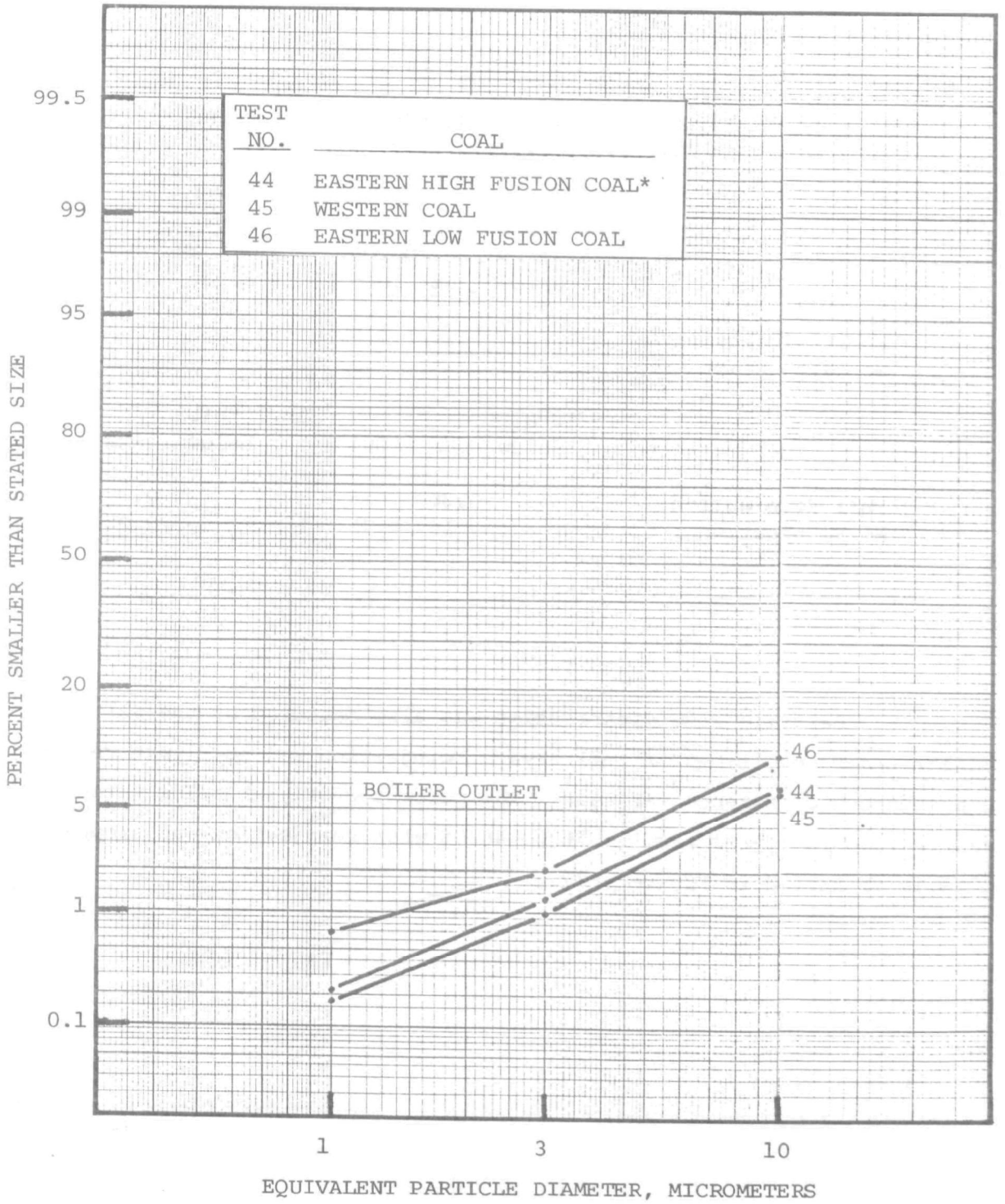

FIGURE 5-34 Particle Size Distribution from SASS Gravimetrics - Test Site C

TABLE 5-14

SIZE DISTRIBUTION AND CONCENTRATION OF FLYASH
AT BOILER OUTLET AS A FUNCTION OF REINJECTION CONFIGURATION
TEST SITE C

	EASTERN LOW FUSION			WESTERN		
	% Below	3μm	10μm	% Below	3μm	10μm
Full Reinjection		1.4	5.0		1.2	4.7
No Reinjection		2.4	7.5		2.6	9.4
	$lb/10^6BTU$ Below	3μm	10μm	$lb/10^6BTU$ Below	3μm	10μm
Full Reinjection		0.36	1.25		0.36	1.46
No Reinjection		0.14	0.45		0.22	0.81

Particle size distribution was also measured at the multiclone outlet under conditions of full flyash reinjection and no flyash reinjection. A pronounced difference was seen. The percent of flyash below three micrometers increased from 14.7% to 46.0% when reinjection was stopped. This data is presented in Figure 5-35.

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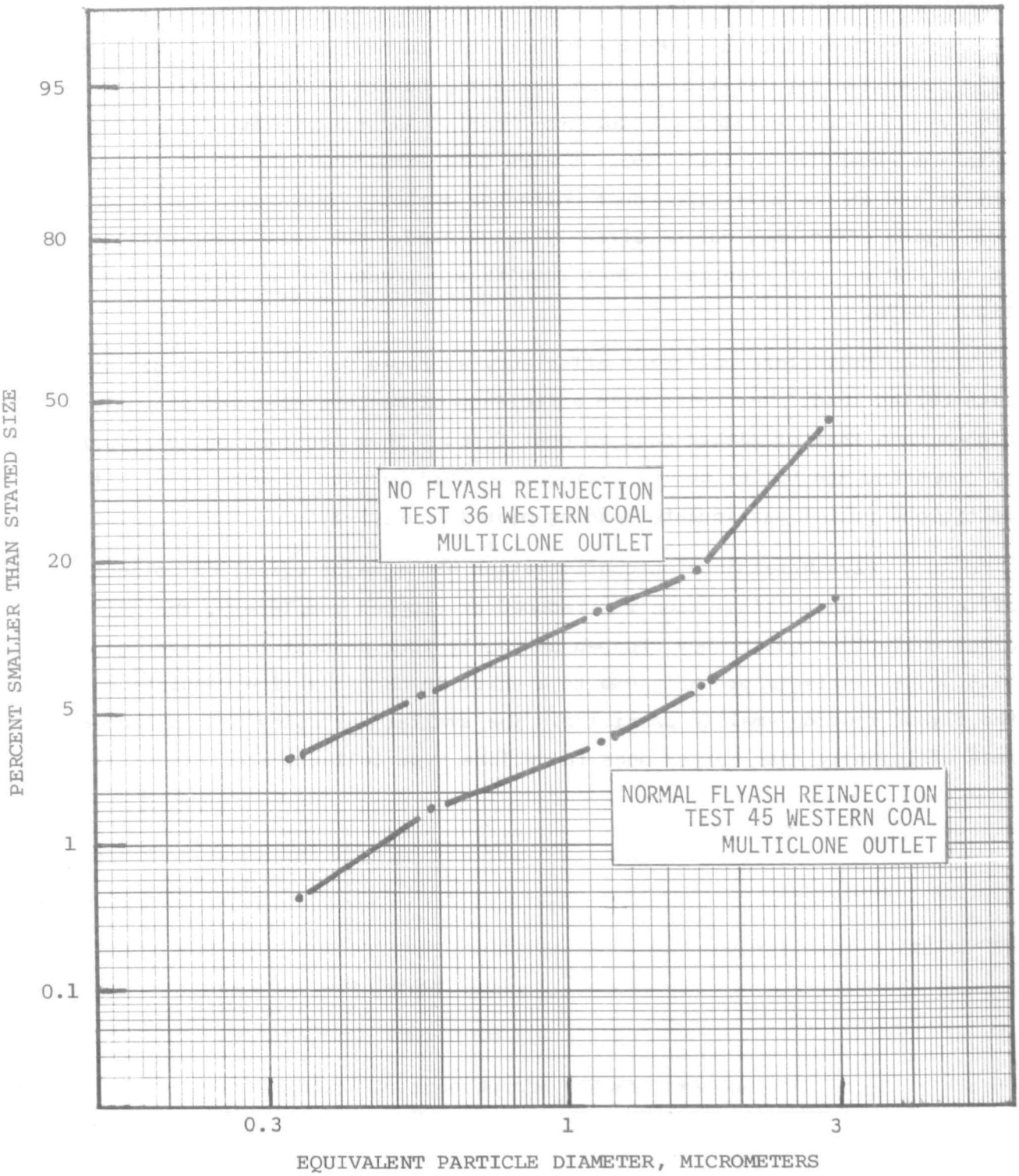

FIGURE 5-35 Particle Size Distribution from Brink Cascade Impactor - Test Site C

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5.6 EFFICIENCY OF MULTICLONE DUST COLLECTOR

The emission control equipment of the boiler at Site C consisted of a selective type multiclone dust collector having a design efficiency of 87%, and an electrostatic precipitator (ESP). All particulate measurements with the exception of test number 8 were made simultaneously at the boiler outlet and at the multiclone dust collector outlet. Therefore, multiclone collection efficiency can be directly calculated. The collection efficiency of the ESP was not measured. Test results are presented in Table 5-15 and Figure 5-36.

Multiclone collector efficiency averaged 96.7 $\pm$0.6% and did not vary with boiler load. The collection efficiency of Western coal was slightly higher than that of either Eastern coal fired. This observation is supported by comparing the boiler outlet particulate loading plot (Figure 5-16) with the multiclone outlet particulate loading plot (Figure 5-17).

Flyash reinjection configuration had a major effect on collection efficiency. When reinjection was reduced or stopped completely, the multiclone collection efficiency dropped by nearly four percent to an average 92.8 $\pm$0.8%. This is probably due to a shift in particle size consistency of the flyash towards smaller particles. The smaller particles are collected less efficiently than larger ones in cyclone type collectors.

TABLE 5-15

EFFICIENCY OF MULTICLONE DUST COLLECTOR
TEST SITE C

Test No.	Coal* Type	Load %	O_2 %	Flyash Reinj.	PART LOADING LB/10^6BTU Coll Inlet	Coll Outlet	COLLECTOR EFFICIENCY, %
9	E	89	8.9	Yes	25.0	0.82	96.7
10	E	93	9.1	No	6.0	0.48	92.0
11	E	93	9.1	No	7.0	0.50	92.9
12	E	93	8.9	Yes	19.0	0.69	96.4
13	E	91	8.9	Yes	21.1	0.64	97.0
14	E	93	9.2	Yes	20.9	0.94	95.5
15	E	91	9.1	Yes	22.6	0.78	96.5
16	E	93	8.7	Yes	23.9	0.84	96.5
19	E	92	8.7	Yes	25.1	0.88	96.5
20	E	55	11.0	Yes	13.2	0.51	96.2
23	W	100	8.6	Yes	29.2	1.04	96.4
24	W	98	8.7	Yes	31.1	1.03	96.7
25	W	78	8.6	Yes	20.4	0.55	97.3
26	W	99	9.9	Yes	34.0	1.04	96.9
27	W	100	8.9	Yes	31.6	1.03	96.7
28	W	99	9.0	Yes	33.1	0.94	97.2
29	W	100	8.4	Yes	36.4	0.74	98.0
35	W	55	10.6	Yes	15.2	0.36	97.7
36	W	98	8.1	No	8.6	0.52	93.9
40	W	102	8.3	No	6.1	0.47	92.4
41	H	58	11.3	Yes	16.2	0.54	96.7
42	H	99	9.4	Yes	28.0	1.07	96.2
43	H	78	9.8	Yes	20.3	0.69	96.6
						Average†	96.7 ±0.6

* E - Eastern Low Fusion Coal
W - Western Coal
H - Eastern High Fusion Coal

† - Average does not inlcude the reduced reinjection tests 10, 11, 36 and 40

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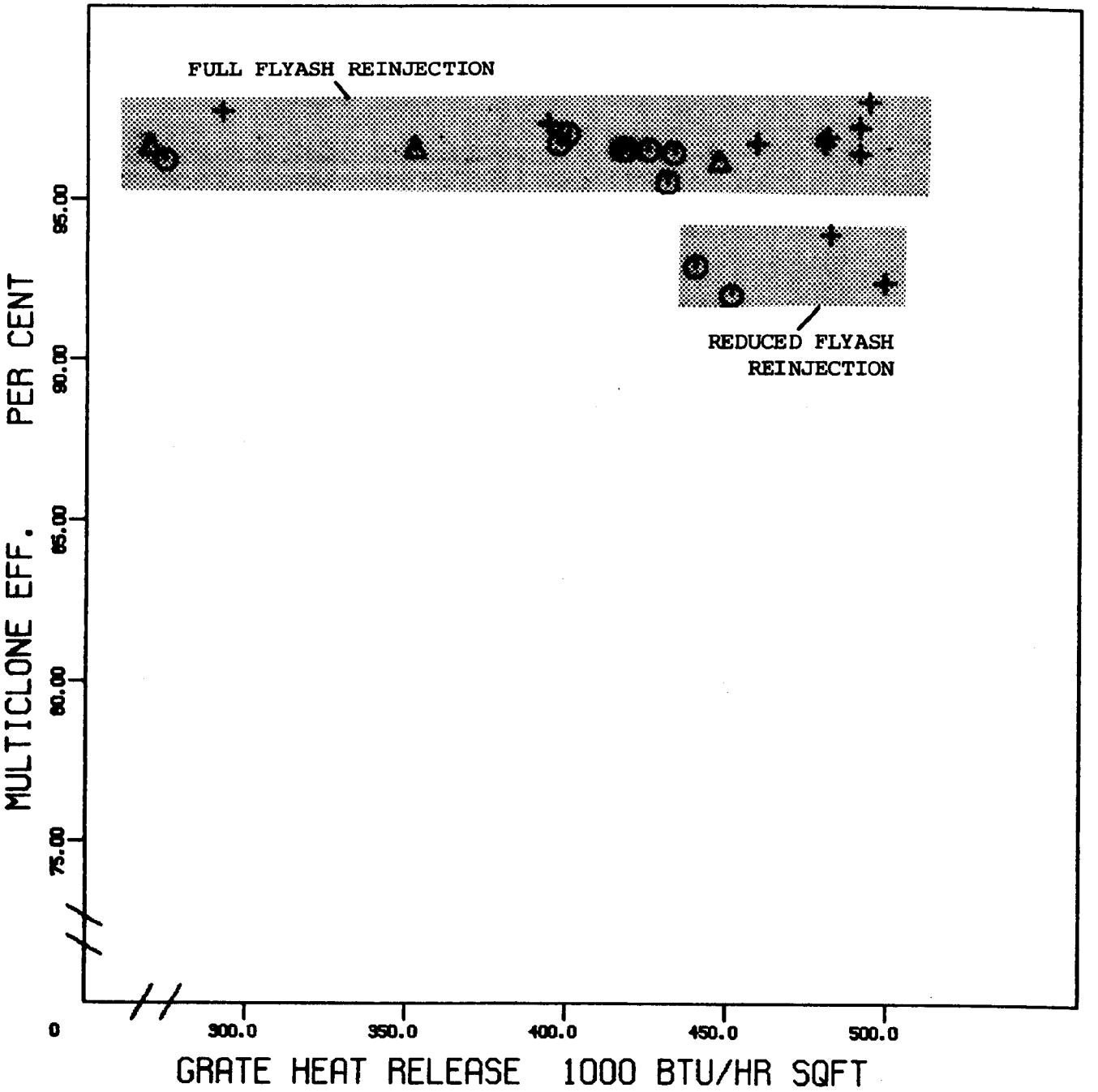

⊙ : E COAL + : W COAL △ : H COAL

FIG. 5-36
MULTICLONE EFF. VS. GRATE HEAT RELEASE
TEST SITE C

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5.7 MODIFIED SMOKE SPOT NUMBER

Smoke Spot readings were taken with a Bacharach Smoke Spot Tester at the multiclone outlet. The pump was stroked once, twice or three times each sample instead of the specified ten times required on an oil-fired unit by ASTM D2156-65. Test results are presented in Table 5-16 and are plotted against particulate loading and combustible loading in Figures 5-37 and 5-38.

The purpose of this exercise was to develop a quick and easy method of estimating either particulate loading or combustible loading from stoker-fired boilers. It is observed in Figures 5-37 and 5-38 that no correlation could be made.

Based on this data, the modified smoke spot technique is not a useful method for estimating particulate or combustible loadings at the multiclone outlet of spreader stokers.

5.8 SOURCE ASSESSMENT SAMPLING SYSTEM

Three SASS tests were run at Test Site C. The plan was to run one test on each of the three test coals. However, fuel analyses showed that what had been thought to be Eastern High Fusion coal (Test 44) was actually Western coal.

The table below shows the conditions under which the tests were run. Boiler load, excess oxygen and overfire air were similar for each test.

SASS TESTS RUN AT SITE C

Test No.	Sample Location	Coal Type	Load %	O_2 %	OFA "H_2O	Contractor For Analysis
44	Boiler Outlet	H*	97	8.9	24	Battelle
45	Boiler Outlet	W	97	8.3	24	Battelle
46	Boiler Outlet	E	99	9.0	23	Battelle

E - Eastern Low Fusion Coal
W - Western Coal
H - Eastern High Fusion Coal

* Test 44 is believed to be Western coal based on fuel analysis

TABLE 5-16

MODIFIED SMOKE SPOT DATA
TEST SITE C

Test No.	Avg Reading 1 Pump	Avg Reading 2 Pumps	Avg Reading 3 Pumps	Particulate Loading $lb/10^6 BTU$	Combustible Loading $lb/10^6 BTU$
23	2	3	4	1.038	0.078
24	2	3	4	1.025	0.064
25	2.5	3	4	0.545	0.046
26	2	3	4	1.038	0.065
27	3	5	6	1.028	0.075
28	2	3	3.5	0.938	0.059
29	2	3	4	0.738	0.027
35	0.75	1.5	1.75	0.356	--
36	2	3	4	0.519	0.071
40	1.5	2.75	3.25	0.466	0.058
41	2.25	3.25	4	0.538	0.144
42	2	3	4.25	1.072	0.195
43	2	4	5	0.685	0.164

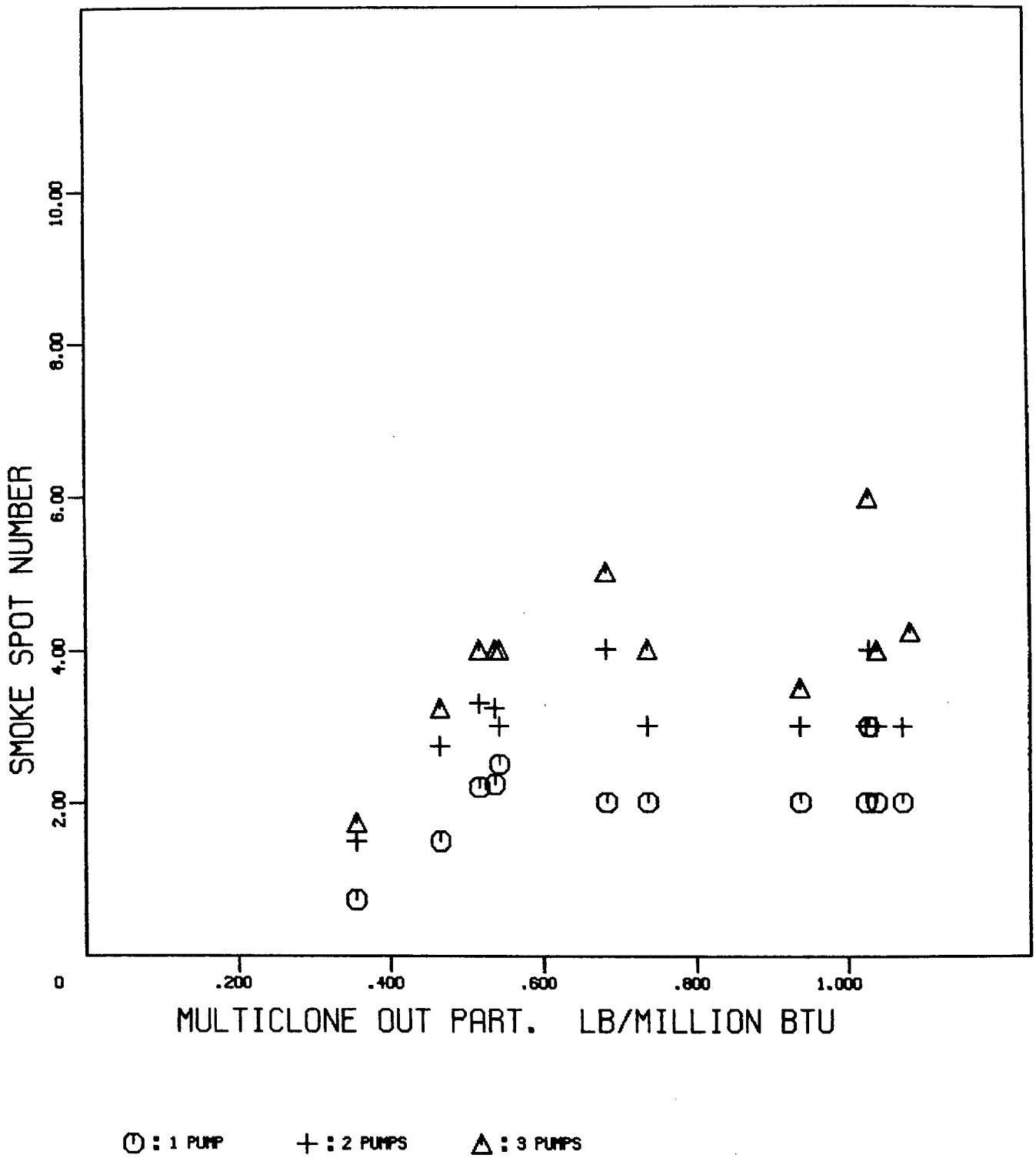

FIG. 5-37
SMOKE SPOT NUMBER VS. MULTICLONE OUT PART.
TEST SITE C

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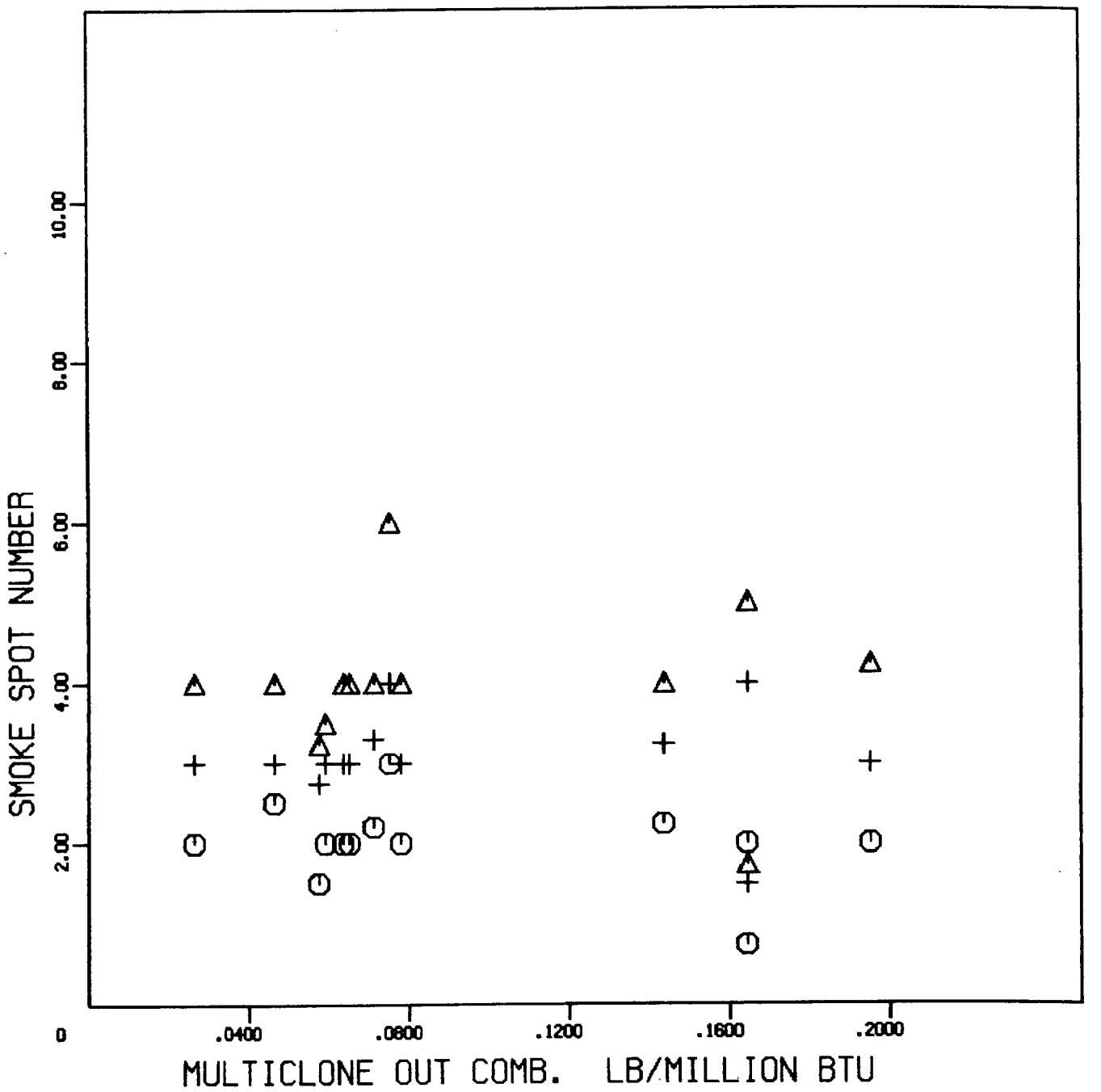

⊙ : 1 PUMP + : 2 PUMPS △ : 3 PUMPS

FIG. 5-38
SMOKE SPOT NUMBER VS. MULTICLONE OUT COMB.
TEST SITE C

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All SASS test results will be reported under separate cover at the conclusion of this test program. The SASS sample catches will be analyzed by combined gas chromatography/mass spectroscopy for total polynuclear content. In addition, seven specific polynuclear aromatic hydrocarbons (PAH) will be sought. These are given in Table 5-17.

TABLE 5-17

POLYNUCLEAR AROMATIC HYDROCARBONS
ANALYZED IN SITE C SASS SAMPLES

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

5.9 DATA TABLES

Tables 5-18 through 5-22 summarize the test data obtained at Test Site C. These tables, in conjunction with Table 2-1 in the Executive Summary, are included for reference purposes.

TABLE 5-18

PARTICULATE EMISSIONS
TEST SITE C

	Test No.	Coal*	Load %	O_2 %	EMISSIONS lb/10^6BTU	gr/SCF	lb/hr	Velocity ft/sec
BOILER OUTLET	8	E	69	10.2	13.09	4.79	1940	36.87
	9	E	89	8.9	25.00	10.25	5116	37.49
	10	E	93	9.1	6.02	2.43	1401	38.31
	11	E	93	9.1	7.00	2.82	1586	39.19
	12	E	93	8.9	19.02	7.80	4239	39.57
	13	E	91	8.9	21.11	8.66	4348	36.17
	14	E	93	9.2	20.88	8.35	4640	39.81
	15	E	91	9.1	22.63	9.12	4956	36.18
	16	E	93	8.7	23.86	9.94	5130	40.20
	19	E	92	8.7	25.14	10.48	5410	39.71
	20	E	55	11.0	13.23	4.48	1867	29.78
	23	W	100	8.6	29.22	12.28	7392	47.58
	24	W	98	8.7	31.14	12.98	7699	46.92
	25	W	78	8.6	20.39	8.57	4140	34.88
	26	W	99	9.9	33.99	12.78	8423	47.23
	27	W	100	8.9	31.59	12.95	7477	45.81
	28	W	99	9.0	33.09	13.46	8364	47.29
	29	W	100	8.4	36.42	15.55	9280	47.93
	35	W	55	10.6	15.16	5.34	2283	28.58
	36	W	98	8.1	8.57	3.75	2126	45.84
	40	W	102	8.3	6.15	2.65	1583	47.82
	41	H	58	11.3	16.19	5.32	2243	32.69
	42	H	99	9.4	28.00	11.00	6447	47.01
	43	H	78	9.8	20.29	7.70	3684	35.91
MECHANICAL COLLECTOR OUTLET	9	E	89	8.9	0.815	0.334	167	37.40
	10	E	93	9.1	0.481	0.194	112	37.90
	11	E	93	9.1	0.496	0.200	112	39.30
	12	E	93	8.9	0.690	0.302	154	38.74
	13	E	91	8.9	0.637	0.285	131	36.15
	14	E	93	9.2	0.936	0.381	208	40.57
	15	E	91	9.1	0.784	0.327	172	39.26
	16	E	93	8.7	0.842	0.359	181	38.95
	19	E	92	8.7	0.878	0.369	189	38.06
	20	E	55	11.0	0.509	0.178	72	30.85
	23	W	100	8.6	1.038	0.440	263	45.11
	24	W	98	8.7	1.025	0.434	253	46.40
	25	W	78	8.6	0.545	0.231	111	35.86
	26	W	99	9.9	1.038	0.404	257	44.39
	27	W	100	8.9	1.028	0.428	243	45.65
	28	W	99	9.0	0.938	0.378	237	48.12
	29	W	100	8.4	0.738	0.310	188	45.97
	35	W	55	10.6	0.356	0.123	54	32.76
	36	W	98	8.1	0.519	0.229	129	45.77
	40	W	102	8.3	0.466	0.199	120	45.80
	41	H	58	11.3	0.538	0.175	75	31.56
	42	H	99	9.4	1.072	0.418	247	45.30
	43	H	78	9.8	0.685	0.262	124	34.53

* E - Eastern Low Fusion Coal
W - Western Coal
H - Eastern High Fusion Coal

KVB 15900-528

TABLE 5-19

HEAT LOSSES AND EFFICIENCIES
TEST SITE C

	TEST NO.	DRY GAS LOSS	MOISTURE IN FUEL	H_2O FROM COMBUSTION OF H_2	COMBUSTIBLES IN MECH COLLECTED ASH	COMBUSTIBLES IN FLYASH	COMBUSTIBLES IN BOTTOM ASH	TOTAL COMBUSTIBLES IN REFUSE	RADIATION FROM BOILER	UNMEASURED	TOTAL LOSSES	EFFICIENCY
EASTERN LOW FUSION	8	9.02	0.67	4.64	0.91	0.24	0.23	1.38	0.63	1.5	17.66	82.34
	9	7.56	0.56	4.59	3.43	0.21	0.05	3.69	0.44	1.5	18.34	81.66
	10	7.92	0.62	4.53	2.32	0.15	0.15	2.62	0.42	1.5	17.61	82.39
	11	8.12	0.63	4.56	3.86	0.19	0.10	4.15	0.42	1.5	19.38	80.62
	12	8.02	0.57	4.50	2.40	0.17	1.29	3.86	0.42	1.5	18.87	81.13
	13	8.28	0.59	4.72	5.14	0.25	1.62	7.01	0.44	1.5	22.54	77.46
	14	7.89	0.32	4.33	2.01	0.27	0.13	2.41	0.42	1.5	16.87	83.13
	15	7.98	0.43	4.38	1.80	0.23	0.09	2.12	0.44	1.5	16.85	83.15
	16	7.71	0.41	4.42	2.32	0.22	0.37	2.91	0.42	1.5	17.37	82.63
	19	8.08	0.46	4.41	2.55	0.23	1.38	4.16	0.42	1.5	19.03	80.97
	20	9.84	0.38	4.38	1.20	0.24	0.05	1.49	0.78	1.5	18.37	81.63
WESTERN COAL	23	8.01	3.47	6.29	0.97	0.11	1.55	2.63	0.40	1.5	22.30	77.70
	24	7.90	3.52	6.16	0.50	0.10	1.44	2.04	0.40	1.5	21.52	78.48
	25	7.24	3.51	6.10	0.25	0.07	0.26	0.58	0.58	1.5	19.51	80.49
	26	8.74	3.64	6.28	0.62	0.09	0.45	1.16	0.40	1.5	21.72	78.28
	27	8.07	3.06	6.02	0.56	0.12	2.45	3.13	0.40	1.5	22.18	77.82
	28	7.83	3.64	6.49	0.62	0.09	2.04	2.75	0.40	1.5	22.61	77.39
	29	7.54	3.52	6.25	0.50	0.04	0.49	1.03	0.40	1.5	20.24	79.76
	35	9.25	3.55	6.31	0.21	0.04	0.40	0.65	0.78	1.5	22.04	77.96
	36	7.39	3.57	6.27	1.26	0.11	0.20	1.57	0.40	1.5	20.70	79.30
	40	7.54	3.57	6.29	1.45	0.09	0.02	1.56	0.40	1.5	20.86	79.14
EASTERN HIGH FUSION	41	9.80	0.95	4.54	0.75	0.21	0.01	0.97	0.75	1.5	18.51	81.49
	42	7.62	0.94	4.63	1.32	0.30	0.13	1.75	0.40	1.5	16.84	83.16
	43	8.28	0.79	4.50	1.04	0.24	0.00	1.28	0.58	1.5	16.93	83.07

KVB 15900-528

TABLE 5-20

PERCENT COMBUSTIBLES IN REFUSE
TEST SITE C

	Test No.	Boiler Hopper	Boiler Outlet	Mechanical Collector Hopper	Mechanical Collector Outlet	Bottom Ash
EASTERN LOW FUSION COAL	8	--	24.2	16.9	--	3.0
	9	--	--	32.6	17.4	0.7
	10	48.3	--	21.6	23.6	2.3
	11	--	57.2	40.9	28.9	1.6
	12	--	47.8	30.2	16.5	21.2
	13	--	30.8	57.7	25.3	19.2
	14	--	24.4	23.2	19.8	2.1
	15	--	46.0	19.0	19.8	1.5
	16	--	55.9	23.2	16.9	5.3
	19	--	41.6	24.1	17.4	23.6
	20	--	30.2	21.7	31.5	9.1
	46	--	--	14.1	--	1.5
	AVERAGE	48.3	39.8	27.1	21.7	7.6
WESTERN COAL	23	--	8.7	7.9	7.5	20.4
	24	--	--	3.8	6.2	21.1
	25	--	9.2	2.9	8.5	37.5
	26	--	12.1	4.3	6.3	5.8
	27	--	11.7	4.2	7.3	34.4
	28	--	7.1	4.4	6.3	19.0
	29	--	8.4	3.2	3.6	6.3
	35	--	4.0	3.3	--	51.4
	36	48.9	--	9.3	13.7	2.8
	40	--	26.6	17.6	12.4	0.3
	45	--	--	4.2	--	0.2
	AVERAGE	48.9	11.0	5.9	8.0	18.1
EASTERN HIGH FUSION COAL	41	--	17.2	11.1	26.7	1.1
	42	--	--	11.3	18.2	1.9
	43	--	16.2	12.2	24.0	0.8
	44*	--	--	6.9	--	2.5
	AVERAGE	--	16.7	11.5	23.0	1.3

* Fuel analysis indicate that Test 44 was Western Coal and not Eastern High Fusion coal as thought. It is not included in the Eastern High Fusion Coal average.

TABLE 5-21

AS FIRED COAL SIZE CONSISTENCY
TEST SITE C

	Test Number	PERCENT PASSING STATED SCREEN SIZE 1"	1/2"	1/4"	#8	#16
EASTERN LOW FUSION COAL	8	86	62	37	10	5
	9	90	74	52	27	13
	10	88	66	43	18	8
	11	88	71	50	22	9
	12	89	66	42	16	6
	13	91	71	46	19	7
	14	91	70	47	25	12
	15	91	67	47	25	13
	16	90	70	49	27	14
	19	88	63	43	23	13
	20	92	72	50	28	14
	46	88	66	45	25	16
	* 47 f#1	96	78	53	29	18
	47 f#2	92	76	55	33	19
	47 f#3	94	76	51	27	14
	47 f#4	90	45	18	7	4
	47 f#5	93	74	50	22	12
	47 f#6	91	77	61	34	18
	47 f#7	91	65	40	21	11
	47 AVG	92	70	47	25	14
	†Composite	92	71	47	21	10
	AVERAGE	90	68	46	22	11
WESTERN COAL	23	91	67	48	30	15
	24	93	67	42	24	15
	25	94	68	44	26	18
	26	94	75	52	28	16
	27	93	66	42	21	11
	28	96	81	59	34	20
	29	92	71	49	29	18
	35	90	68	45	24	14
	36	95	72	49	26	14
	40	93	71	46	25	16
	45	93	71	49	27	15
	Composite	93	70	47	26	16
	AVERAGE	93	71	48	27	16
EASTERN HIGH FUSION	41	85	65	47	26	12
	42	78	54	40	26	18
	43	84	62	43	26	16
	44	91	70	46	26	16
	Composite	86	66	47	26	14
	AVERAGE	85	63	44	26	16

* During Test 47, coal samples were taken individually from each coal feeder. Only the average of the seven feeders is averaged with the other tests.

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

TABLE 5-22

STEAM FLOWS & HEAT RELEASE RATES
TEST SITE C

Test No.	Capacity %	Steam Flow 10^3lb/hr	Heat Input 10^6BTU/hr	Front Foot Heat Release 10^4BTU/ft/hr	Grate Heat Release 10^3BTU/ft^2/hr	Furnace Heat Release 10^2BTU/ft^3/hr
1*	98.6	179.9	252.7	931.5	490.2	208.8
5*	96.9	176.8	235.1	866.7	456.2	194.3
6*	91.8	167.5	221.3	815.9	429.4	182.9
7*	92.5	168.8	225.3	830.6	437.1	186.2
8	69.0	125.9	148.2	546.4	287.5	122.5
9	89.5	163.3	204.7	754.7	397.2	169.2
10	93.0	169.7	232.5	857.1	451.1	192.1
11	93.0	169.7	226.5	835.0	439.5	187.2
12	93.0	169.8	222.9	821.8	432.5	184.2
13	90.8	165.6	206.0	759.4	399.7	170.2
14	93.0	169.7	222.2	819.2	431.1	183.6
15	91.3	166.5	219.0	807.4	424.9	181.0
16	92.7	169.2	215.0	792.6	417.2	177.7
17	76.0	138.7	176.6	651.1	342.6	146.0
18	76.0	138.7	176.6	651.1	342.6	146.0
19	92.1	168.0	215.2	793.3	417.5	177.9
20	55.3	100.9	141.1	520.2	273.8	116.6
21*	76.7	140.0	197.9	729.6	384.0	163.6
22*	76.7	140.0	197.9	729.6	384.0	163.6
23	99.6	181.7	252.9	932.4	490.7	209.0
24	98.4	179.5	247.2	911.3	479.6	204.3
25	78.2	142.7	203.0	748.4	393.9	167.7
26	99.2	181.0	247.8	913.5	480.8	204.8
27	100.3	183.0	236.7	872.6	459.3	195.6
28	99.1	180.9	252.8	932.0	490.5	208.9
29	99.8	182.0	254.8	939.4	494.4	210.6
30*	58.5	106.8	148.9	548.9	288.9	123.1
31*	55.2	100.7	142.0	523.5	275.5	117.4
32*	95.7	174.6	244.3	900.6	474.0	201.9
33*	96.3	175.8	245.7	905.8	476.7	203.1
34*	95.0	173.3	239.7	883.7	465.1	198.1
35	54.9	100.1	150.5	554.8	292.0	124.4
36	97.7	178.4	248.2	915.0	481.6	205.1
40	102.2	186.4	257.4	949.9	499.4	212.7
41	57.6	105.2	138.5	510.6	268.7	114.5
42	98.9	180.4	230.3	849.0	446.8	190.3
43	77.9	142.3	181.6	669.5	352.3	150.1
44	97.1	177.2	244.4	901.0	474.2	202.0
45	97.4	177.7	241.2	889.2	468.0	199.3
46	99.0	180.7	230.2	848.7	446.6	190.2
48*	92.5	168.8	210.2	775.0	407.9	173.7
49*	58.0	105.9	135.2	498.3	262.2	111.7
50*	58.0	105.9	135.2	498.3	262.2	111.7

* An average BTU/lb was used, for tests 1-7, 17-18, 48-50 - 12,262
for tests 21, 22, 30-34 - 8,493

KVB 15900-528

APPENDICES

	Page
APPENDIX A - EXCESS AIR INVESTIGATION	122
APPENDIX B - ENGLISH AND METRIC UNITS TO SI UNITS . . .	126
APPENDIX C - SI UNITS TO ENGLISH AND METRIC UNITS . . .	127
APPENDIX D - SI PREFIXES	128
APPENDIX E - EMISSIONS UNITS CONVERSION FACTORS . . .	129

THE BABCOCK & WILCOX COMPANY
POWER GENERATION GROUP

To P. E. RALSTON - MANAGER FIELD ENGINEERING 21K

From S. E. KNIGHT - DESIGN SERVICE COORDINATOR 21K

BDS 663-6

Cust.

File No. or Ref. S-10266

Subj. EXCESS AIR

Date JULY 7, 1978

This letter to cover one customer and one subject only.

Visited this job June 26, 27 and 28, 1978 with A. J. Kraus of Detroit Stoker to either reduce excess air to design, or, to find the reason why excess air was being carried high.

KVB, Incorporated, is running a series of tests on this boiler as part of EPA testing of stoker units.

This 28 foot wide SPB was designed to generate 182.5 M pph of 875 psig 900°F steam with 370°F feedwater firing Montana high fusion temperature sub-bituminous coal of 8416 BTU/lb. Performance was also checked for 275 M pph, (300 M 2 hour peak), firing eastern bituminous of 12,000 BTU/lb. Note that the eastern bituminous is the normal coal and was being burned during our visit. Load is restricted to 182.5 M pph in order to stay below 249 MKB input. Even though a variance was available for testing, (the owner) would not operate above this EPA limit.

Customer's Lear Siegler single point oxygen analyzer, located at the dust collector outlet, was out of service. The instrument operates on a wet flue gas basis, which means it reads about 0.4 percent oxygen lower than the dry basis Orsat for this fuel.

On Monday June 26, 1978 at a load of 155 M pph and indicated air flow of 175, Orsats at the KVB test truck, reading the boiler outlet taps, showed 7.6 percent oxygen at the boiler left side, 9.5 percent oxygen just left of center, 10.4 percent oxygen on the right side, and, 8.4 percent oxygen composite. KVB readings were 8.35 percent left, 9.8 percent off center, 11.2 percent right, and, 9 percent composite.

On Tuesday June 27, 1978 at 165 M pph and indicated air flow of 185 M, oxygen by Orsat at the boiler outlet test tap elevation was 8 percent left, 9 percent off center, and, 10.4 percent right.

The penthouse seal air fan was shut off.

Orsat read 7.4 percent left, 9.2 percent off center, 10.6 percent right.

Boiler hopper re-injection air was reduced to 9 inches w.g. from 12 inches w.g.; coal feed was increased to the right side, and, the air flow was decreased to a spread of 10 M, that is, 165 M steam flow, 175 air flow.

Oxygen by Orsat was 6.3 percent left, 7.8 percent off center, 8.8 percent right. With mild clinkering starting on the left of the stoker, the air flow spread was returned to 20 M overnight.

Wednesday June 28, 1978 at a similar firing rate and 10 M air flow spread, the left No. 1 and No. 3 dust re-injection lines from the dust collector were shut off.

Oxygen by Orsat was 5.8 percent left, 8 percent off center, 9 percent right.

Coal feed was increased on three right side feeders.

Oxygen was 6.6 percent left, 8.6 percent off center, 9 percent right. Mild clinkering was again starting on the left side.

Conclusions:

1. The right side of the unit has a constant 3 percent higher oxygen than the left side. The furnace shows a much heavier fuel and ash bed on the left side, tapering off to nothing on the right side. There is heavy left side dust reinjection from the dust collector.

   Combined, this is strong evidence of chronic coal segregation, with fines favoring the right side and burning in suspension.

2. Orsat readings were about 0.5 percent oxygen less than KVB's Teledyne oxygen analyzer readings.

3. Customer's wet basis oxygen analyzer can be expected to read about 0.4 percent oxygen lower than the dry basis Orsat or Teledyne on this fuel.

Recommendations:

1. Any further effort to balance the excess air across the unit should start by achieving a balanced, non-segregated coal feed to the coal hopper. Note that a conveyor belt feeds coal to the center of this wide hopper. A number of stationary or moveable devices are available to reduce hopper segration.

2. Leave the penthouse seal air fan shut off, unless future inspections show that dust is collecting in the penthouse.

3. Correct the temperature recorder problem that put the flue gas and air temperature thermocouples out of service.

S. E. Knight

S. E. Knight

SEK:cw

BDS 120-1

THE BABCOCK & WILCOX COMPANY

DATE			6-26-78	6-27-78	6-28-78		
TIME			2:30 PM	1:45 PM	1:45 PM		
LOAD	MPPH		155	165	160		
IND. AIR FLOW	"		175	175	170		
DRUM PRESS.	PSIG		—	895	895		
HEADER PRESS.	"		—	870	870		
STEAM TEMP.	°F			830(?)	825(?)		
FEEDWATER TO ECON.	°F			368	360		
FEEDWATER TO DRUM	°F			429	422		
FD OUT.	W.G.		2.3	—	2.1		
A.H. INLET	"		1.7	—	1.55		
A.H. OUT.	"		1.5	1.5	1.45		
STOKER	"		1.05	1.0	0.95		
FNC.	"		(-) 0.2	(-) 0.15	(-) 0.15		
BOILER OUT.	"		(-) 0.6	(-) 0.6	(-) 0.6		
DUST. COL. OUT.	"		(-) 2.05	(-) 2.0	(-) 1.95		
ECON. OUT.	"		(-) 3.9	(-) 3.9	(-) 3.75		
A.H. OUT.	"		(-) 4.8	(-) 4.8	(-) 4.7		
I.D. FAN OUT.	"		+ 7.2	—			
PRECIP. OUT.	"		0	—			
O'FIRE AIR			19	20	20		
GRATE TEMPS. 1				816(?)			
2				781(?)			
3				688			
4				603			
5				648			
6				650			
AIR & FLUE GAS							
TEMPS. NOT READING							
A.H. TUBE 1				305			
2				308			
3				310			
4				312			

CUSTOMER

SUBJECT PANEL BOARD DATA

JOB NO. 5-10266

BY 6/26,27,28/78

DATE AJK & SEK

KYB 15900-528

APPENDIX B
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
9/Mcal	ng/J	239
BTU	J	1054
BTU/lb	J/kg	0.002324
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
COAL FUEL ONLY		
ppm @ 3% O_2 (SO_2)	ng/J	0.851
ppm @ 3% O_2 (SO_3)	ng/J	1.063
ppm @ 3% O_2 (NO)	ng/J	0.399
ppm @ 3% O_2 (NO_2)	ng/J	0.611
ppm @ 3% O_2 (CO)	ng/J	0.372
ppm @ 3% O_2 (CH_4)	ng/J	0.213

KVB 15900-528

APPENDIX C

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	$lb/10^6 BTU$	0.00233
ng/J	g/Mcal	0.00418
J	BTU	0.000948
J/kg	BTU/lb	4.303
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

COAL FUEL ONLY

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

KVB 15900-528

APPENDIX D

SI PREFIXES

Multiplication Factor	Prefix	SI Symbol
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 E

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

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

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

KVB 15900-528

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

1. REPORT NO. EPA-600/7-79-130a	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Field Tests of Industrial Stoker Coal-fired Boilers for Emissions Control and Efficiency Improvement--Site C		5. REPORT DATE May 1979
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) J.E. Gabrielson, P.L. Langsjoen, and T.C. Kosvic		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS KVB, Inc. 6176 Olson Memorial Highway Minneapolis, Minnesota 55422		10. PROGRAM ELEMENT NO. EHE624
		11. CONTRACT/GRANT NO. EPA-IAG-D7-E681 and DoE-EF-77-C-01-2609
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development* Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; 4/78 - 7/78
		14. SPONSORING AGENCY CODE EPA/600/13

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

16. ABSTRACT The report gives results of field measurements made on a 182,500 lb/hr spreader stoker boiler. The effect of various parameters on boiler emissions and efficiency was studied. Parameters included overfire air, flyash reinjection, excess air, boiler load, and fuel properties. Measurements included gaseous and particulate emissions, particle size distribution of the flyash, and combustible content of the ash. Gaseous emissions measured were O2, CO2, CO, NO, SO2, and SO3 in the flue gas. Sample locations included the boiler, multiclone, and electrostatic precipitator outlets. In addition to test results and observations, the report describes the facility tested, coals fired, test equipment, and procedures. Stopping flyash reinjection reduced particulate loading at the boiler outlet by 75%, and reduced particulate loading at the multiclone outlet by 45%. Increasing the overfire air from 5 to 25 in. H2O resulted in a 9% increase in NO emissions. At design capacity, the boiler emitted between 27.5 and 35.5 lb/million Btu particulate matter and between 340 and 410 ppm NO at the boiler outlet.

17. KEY WORDS AND DOCUMENT ANALYSIS

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

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