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Analysis of Test Data From IGT High Pressure Fluidized-Bed Gasifier PDU Volume I

Topical Report

S.A. Newman

September 1988

Work Performed Under Contract No.: DE-AC21-86MC23077

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Foster Wheeler USA Corporation
Clinton, New Jersey

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Perryville Corporate Park
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ANALYSIS OF TEST DATA FROM IGT

HIGH PRESSURE FLUIDIZED-BED GASIFIER PDU

VOLUME - 1

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1.0 SUMMARY

An assessment of IGT's experimental data on fluidized-bed coal gasification at pressures in the range of 100-450 psig was conducted by Foster Wheeler, in conjunction with the City University of New York (CUNY) as a subcontractor. The objective of this study was to evaluate the quality, reliability, and usefulness of IGT's data which was obtained in an eight inch diameter gasifier PDU.

Foster Wheeler's effort focused on the results of IGT's Phase-2 test program in which fifteen steady state tests were conducted on Illinois No. 6 bituminous coal, Montana Rosebud subbituminous coal and North Dakota lignite. The scope of this analysis included an independent check on the reported study state conditions and overall balances, as well as correlating the data relative to gas phase equilibrium and the effects of operating parameters. The results of Foster Wheeler's assessment are summarized in Volume-1 of this report.

The data evaluation effort conducted by CUNY was directed at comparing IGT's experimental data with the fluidized-bed gasifier model developed by CUNY. In addition, the usefulness of IGT's data relative to the design and performance of a commercial scale gasifier was assessed. Volume-2 of this report summarizes the results of CUNY's evaluation.

Foster Wheeler's assessment concluded that, with only one exception, IGT's Phase-2 tests met the criteria for steady state operation of the PDU. The single test on Illinois bituminous coal was judged not to represent a steady state condition due to its relative short duration. The overall heat and mass balances for the steady state tests were found to be satisfactory. However, only two of the fourteen tests on subbituminous coal and lignite showed good closures on the carbon and hydrogen elemental balances, that is within $\pm 5\%$. The general lack of acceptable closures was believed to stem from the following:

- Use of infrequent bomb sampling and subsequent analysis to determine the product gas composition. IGT employed this technique since the on-line gas chromatograph was not operable.

- Difficulty in obtaining an accurate measurement of the wet product gas flow rate and the corresponding moisture content.

Correlation of the gasifier PDU performance with operating variables, such as pressure, temperature, and steam/carbon ratio, was complicated by IGT's inability to operate at conditions established for the planned test matrix. Consequently, the test results generally reflected the combined effects of two or more variables. Nevertheless, the following trends were indicated by the data from both the Phase-1 and Phase-2 test programs:

- For a given gasifier size, the coal feed rate increases with operating pressure. This effect is a direct result of the higher mass throughput of gas allowed at higher pressures for a fixed superficial velocity.

- While the methane yield exceeds the predicted equilibrium values by several orders of magnitude, the experimental gas compositions approach that for water gas shift equilibrium. The non-equilibrium methane content is typical of fluidized bed gasification in which coal undergoes devolatilization with subsequent cracking of the heavy hydrocarbon species.

- The fraction of the converted carbon used to form methane appears to increase directly with system pressure.

- Particulate loading in the product gas varies directly with the mass velocity, or the product of the linear velocity and gas density.

While the above trends are not surprising, the fact that the experimental data are not contradictory is significant. Such agreement tends to support a degree of consistency and meaning to IGT's results.

2.0 INTRODUCTION

During the period of November 1984 through August 1987, the Institute of Gas Technology (IGT) conducted a coal gasification test program in a pressurized fluidized bed process development unit (PDU). The primary objective of the IGT program, which was sponsored by the Gas Research Institute under GRI Contract No. 5084-221-1040, was to obtain a data base on fluidized bed, ash agglomerating gasification for three important U.S. coals at pressures up to 500 psig.

Under the technical support services provided for the DOE/GRI Joint Coal Gasification Research Program, Foster Wheeler conducted an analysis of experimental data obtained by IGT in their high pressure fluidized-bed gasifier PDU. The data analysis was performed in conjunction with the City University of New York (CUNY) as a subcontractor to Foster Wheeler.

The objective of this work was to assess the quality, reliability, and usefulness of the IGT data which was generated over a pressure range of 100-450 psig. The overall study was conducted as parallel efforts in which Foster Wheeler focused on the quality of the experimental data and CUNY evaluated the suitability of the data for projecting the design and performance of a commercial scale gasifier. Volume-1 of this report summarizes the results of Foster Wheeler's analysis while CUNY's assessment is detailed in Volume-2.

3.0 SCOPE OF STUDY

The purpose of this study was to analyze the experimental data obtained by the Institute of Gas Technology (IGT), in a high pressure fluidized-bed gasifier PDU at 100-450 psig, relative to the quality, reliability and usefulness of the test data. The scope of the data analysis effort included the following tasks:

1. Data Quality - This effort included checking the attainment of steady state operating conditions, checking the steady state average data values, and independently determining the closures on heat, mass, and elemental balances.

2. Data Correlation - Assess the experimental data relative to the approach to gas phase equilibrium, the effect of pressure on coal throughput, methane production and fines entrainment, and the effects of operating parameters on carbon conversion.

3. Data Evaluation - Compare IGT's experimental results with model predictions and evaluate the data relative to the design and performance of commercial scale fluidized-bed gasifiers.

Analysis of the IGT data was conducted by Foster Wheeler in conjunction with the City University of New York (CUNY) as a subcontractor. Foster Wheeler's effort encompassed the data quality and data correlation tasks. This portion of the analysis focused on the steady state data from IGT's Phase-2 tests, as summarized in Table 3.1, which were performed on Illinois No. 6 bituminous coal, Montana subbituminous coal, and North Dakota lignite at 200-450 psig. Correlation of these data included the earlier Phase-1 tests which IGT obtained on similar coals at 100-300 psig, as shown in Table 3.2. Assessment of data quality from the Phase-1 program was the subject of a previous Foster Wheeler study (1).

The present analysis was based on the test data made available from IGT (2), including the hourly data logs and analyses of the feed coals, product gases, and solid effluent streams.

The data evaluation effort, under Task-3, was conducted by CUNY. This effort included the following scope of work, as applied to the IGT data from both the Phase-1 and Phase-2 test program:

- Check the steady state data for consistency using the invariant technique developed at CUNY.

- Compare the individual IGT runs with predictions based on the kinetic model developed at CUNY.

- Develop simplified performance criteria, such as the molar ratio of oxygen to converted carbon for fuel gas and methane formation, which provides a basis for ranking with other gasifiers.

- Analyze the usefulness of the IGT data for predicting the performance of a commercial gasifier.

The results of CUNY's evaluation of IGT's data are presented in Volume-2 of this report.

TABLE 3.1

IGT PHASE-2 TEST PROGRAM*

CASE	RUN NO.	COAL TYPE	OPERATING PRESSURE, PSIG	STEADY STATE DURATION, HRS
1	5-1-1	Montana Rosebud Subbituminous	201	8
2	5-1-2A	Montana Rosebud Subbituminous	300	6
3	5-1-2B	Montana Rosebud Subbituminous	302	7
4	5-2-1	Montana Rosebud Subbituminous	450	10
5	5-2-2	Montana Rosebud Subbituminous	450	5
6	5-2-3	Montana Rosebud Subbituminous	449	5
7	5-3-1	Montana Rosebud Subbituminous	449	6
8	5-3-2	Montana Rosebud Subbituminous	448	5
9	5-3-3	Montana Rosebud Subbituminous	448	8
10	6-1-1	North Dakota Lignite	200	8
11	6-2-1	North Dakota Lignite	300	7
12	6-2-2	North Dakota Lignite	448	8
13	6-2-3	North Dakota Lignite	447	5
14	6-2-4	North Dakota Lignite	447	4
15	7-2-7	Illinois No. 6 Bituminous	151	3

*Conducted during August - December 1986.

TABLE 3.2

IGT PHASE-1 TEST PROGRAM*

CASE	RUN NO.	COAL TYPE	OPERATING PRESSURE, PSIG	STEADY STATE DURATION, HRS
1	1-2	Pittsburgh No. 8 Bituminous	97	4
2	2-6A	Montana Rosebud Subbituminous	96	4
3	2-6B	Montana Rosebud Subbituminous	195	8
4	3-2	Montana Rosebud Subbituminous	198	6
5	3-1	Montana Rosebud Subbituminous	282	8
6	4-2A	North Dakota Lignite	95	5
7	4-2B	North Dakota Lignite	193	4
8	4-1	North Dakota Lignite	292	4

*Conducted during February - September 1985.

4.0 VERIFICATION OF STEADY STATE

For each of the fifteen set points reported by IGT for their Phase-2 program, Foster Wheeler independently checked the attainment of steady state operating conditions. Based on the hourly data logs, the average hourly values for the coal, steam, oxygen, and nitrogen purge feed rates were determined via an arithmetic averaging technique. Table 4.1 shows the average feed rates and temperatures calculated by Foster Wheeler compared to those reported by IGT for each set point condition. The underlined values shown in this table represent average feed rates where differences appeared. Minor differences in the steam feed rates were apparent in only three test runs, i.e.

	Steam, Mol/Hr		
Case No.	FW	IGT	% Difference
10	26.35	25.46	3.4
11	39.44	39.31	0.3
15	23.16	22.52	2.8

In verifying the attainment of steady state conditions, Foster Wheeler applied the criteria established by IGT to the data reported for each run. These criteria require that at least four hours of operation be obtained for each steady state period and, in addition, that the deviation from the mean reported parameter not exceed the following:

Steam Flow	± 5%
Coal Feed	± 5%
Gasifier Pressure	± 5%
Bed Temperature	±50°F

Foster Wheeler checked IGT's hourly data for each of the fifteen runs to determine if the steady state values were within the specified tolerances. As shown in Table 4.2, all of the Phase-2 set points met the steady state criteria except for Cases 4 and 5. In these two cases, the maximum deviation for the coal feed rates exceeded the allowable tolerance by a small margin, i.e. about 8% versus 5%.

TABLE 4.1

COMPARISON OF AVERAGE FEED CONDITIONS

CASE NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
GRI RUN NO.	5-1	5-1	5-1	5-2	5-2	5-2	5-3	5-3	5-3	6-1	6-2	6-2	6-2	6-2	7-2
SET POINT	1	2A	2B	1	2	3	1	3	2	1	1	2	3	4	7
COAL TYPE	MONTANA ROSEBUD SUBBITUMINOUS									NORTH DAKOTA LIGNITE					ILLINOIS NO. 6
FW BASIS															
COAL FEED, LB/HR	352.9	537.1	479.8	499.7	866.1	661.6	531.0	379.4	834.2	260.7	345.1	487.7	590.2	865.2	200.1
IGT BASIS															
COAL FEED, LB/HR	352.9	537.1	479.7	499.7	866.2	661.5	531.0	379.4	834.2	260.6	345.1	487.9	590.2	865.2	200.1
FW BASIS-MOL/HR															
GRID GAS (H2O)	23.08	30.48	31.36	46.86	43.41	44.32	46.65	44.89	41.02	18.63	30.86	40.38	35.47	34.89	14.71
VENTURI GAS (H2O)	3.91	5.85	5.49	5.16	5.31	5.73	6.00	5.31	8.32	3.23	2.15	2.90	3.34	3.33	5.00
JET GAS															
H2O	4.54	5.28	5.69	7.80	7.72	6.72	7.11	9.58	8.97	4.49	6.43	6.54	6.79	8.64	3.45
O2	5.15	6.78	5.76	8.25	11.88	9.78	8.93	6.80	13.33	3.70	4.97	6.59	7.37	10.48	4.04
NITROGEN	6.95	10.06	10.67	17.23	14.68	14.56	12.91	16.30	16.17	8.67	11.17	16.73	16.75	16.87	7.30
IGT BASIS-MOL/HR															
GRID GAS (H2O)	23.09	30.48	31.36	46.86	43.41	44.32	46.65	44.89	41.02	18.00	30.61	40.38	35.47	34.89	14.30
VENTURI GAS (H2O)	3.92	5.85	5.49	5.15	5.31	5.73	6.00	5.31	8.32	3.12	2.33	2.90	3.34	3.33	4.86
JET GAS															
H2O	4.54	5.28	5.69	7.80	7.73	6.72	7.11	9.58	8.97	4.34	6.37	6.54	6.79	8.64	3.36
O2	5.15	6.78	5.76	8.25	11.88	9.78	8.93	6.80	13.33	3.70	4.97	6.59	7.37	10.48	4.04
NITROGEN	6.96	10.06	10.67	17.23	14.68	14.56	12.91	16.30	16.17	8.66	11.17	16.73	16.75	16.87	7.30
FW BASIS-TEMP, °F															
GRID GAS	749	680	679	566	597	597	560	584	591	667	627	584	601	613	658
VENTURI GAS	831	773	779	694	725	722	673	708	672	739	735	721	730	738	722
JET GAS	353	380	384	409	399	402	405	415	387	354	391	411	409	397	342
IGT BASIS-TEMP, °F															
GRID GAS	749	680	679	566	597	597	560	584	591	667	627	584	601	613	658
VENTURI GAS	831	773	779	694	725	722	673	708	672	739	735	721	730	738	722
JET GAS	353	380	384	409	399	402	405	415	387	354	391	411	409	397	342

TABLE 4.2

VERIFICATION OF STEADY STATE CONDITIONS

CASE NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
GRI RUN NO.	5-1	5-1	5-1	5-2	5-2	5-2	5-3	5-3	5-3	6-1	6-2	6-2	6-2	6-2	7-2
SET POINT	1	2A	2B	1	2	3	1	3	2	1	1	2	3	4	7
COAL TYPE	MONTANA ROSEBUD SUBBITUMINOUS									NORTH DAKOTA LIGNITE					ILLINOIS NO. 6
STEAM, MOL/HR	31.54	41.60	42.54	59.82	56.45	56.77	59.75	59.78	58.31	26.35	39.45	49.82	45.60	46.86	23.16
MAX. DEVIATION, %	1.7	2.9	4.1	0.5	0.5	1.5	0.4	0.9	0.6	1.3	1.0	3.7	1.5	1.1	0.2
COAL, LB/HR	352.9	537.1	479.8	499.7	866.1	661.6	531.0	379.4	834.2	260.7	345.1	487.9	590.2	865.2	200.1
MAX. DEVIATION, %	3.6	2.7	3.7	8.5	7.0	2.3	0.3	1.2	0.6	0.7	4.1	0.5	0.4	2.0	1.7
PRESSURE, PSIG	201.6	299.6	301.7	450.1	449.7	448.7	448.5	448.0	447.5	200.1	300.1	447.9	446.8	446.9	151.1
MAX. DEVIATION, %	0.5	1.1	2.0	0.1	0.2	1.0	0.4	0.2	0.1	0.5	0.3	0.2	0.1	0.1	0.1
BED TEMP., °F	1566.0	1565.0	1549.0	1501.0	1548.0	1553.0	1538.0	1456.0	1654.0	1418.0	1405.0	1396.0	1407.0	1485.0	1738.0
MAX. DEVIATION, °F	21	21	26	11	11	16	27	7	17	7	5	13	15	3	24

NOTE: "Max. Deviation" represents the maximum absolute hourly percent deviation from the mean for steam rate, coal rate, and pressure. For bed temperature it represents the maximum absolute temperature deviation from the mean.

5.0 DATA ANALYSIS

In the course of independently checking the overall heat, mass, and elemental balances for the Phase-2 PDU tests, Foster Wheeler derived steady state values for the solids analyses, product gas rates, and product gas compositions. These were developed from the available hourly data logs via arithmetic averaging.

The average coal feed analyses, which were developed from IGT's individual coal samples taken during each steady state period, are given in Table 5.1. In five of the fifteen cases, the average coal analysis calculated by Foster Wheeler differed slightly from IGT's reported values. These differences, shown below, are attributed to Foster Wheeler's decision not to include analyses of coal samples taken at the beginning of the set points in the averaging procedure.

	Coal Analysis Difference (IGT-FW)%			
Case	Ash	C	H	O
4	0.24	-0.35	-0.08	0.23
5	0.31	-0.63	-0.04	0.17
9	-0.12	0.63	0.02	-0.52
12	0.12	0.01	0.0	-0.01
13	-0.52	0.40	0.04	0.0

Similarly, the flow rates and analyses for the gasifier bottom ash and the cyclone captured fines were averaged from the available IGT hourly data. These are tabulated for each steady state in Table 5.2. IGT did not measure the overhead fines carryover from the cyclone which were lost to the product gas. Periodically, IGT estimated the cyclone operating efficiency based on the weight and size distribution of the collected solids. The calculated cyclone efficiencies ranged from 93% to 99%. Due to the lack of measured fines loss in the product gas, Foster Wheeler arbitrarily assumed, for mass balance purposes, this loss to equal 10% of the collected cyclone fines in each case.

Furthermore, in developing the mass balances, the quantities of dry product gas and water in the product gas stream had to be calculated since these values were not directly measured. Both IGT and Foster Wheeler determined the dry product gas flow rates by forcing a nitrogen balance around the PDU system. Accordingly, the dry product gas rate was equal to the measured nitrogen feed rate divided by the nitrogen composition in the dry product gas.

TABLE 5.1

COAL FEED ANALYSES(1)

CASE NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
GRI RUN NO.	5-1	5-1	5-1	5-2	5-2	5-2	5-3	5-3	5-3	6-1	6-2	6-2	6-2	6-2	7-2
SET POINT	1	2A	2B	1	2	3	1	3	2	1	1	2	3	4	7
COAL TYPE	MONTANA ROSEBUD SUBBITUMINOUS									NORTH DAKOTA LIGNITE					ILLINOIS NO. 6
ULTIMATE ANALYSIS, wt%	FW BASIS														
ASH	10.15	9.69	9.70	9.66	9.18	9.17	10.86	9.80	10.72	12.08	12.89	12.73	13.37	13.46	10.45
CARBON	65.18	65.86	66.17	65.94	66.47	66.27	64.03	65.54	63.65	60.02	62.35	62.56	62.00	62.11	68.84
HYDROGEN	4.32	4.35	4.51	4.41	4.48	4.34	4.43	4.30	4.22	4.03	3.70	3.67	3.65	3.56	4.80
SULFUR	1.13	1.04	1.11	0.98	0.75	0.73	0.92	0.75	0.80	0.91	0.87	0.93	0.91	0.97	3.94
NITROGEN	1.00	1.19	1.06	1.10	1.07	1.17	1.10	1.17	1.22	0.93	0.98	1.00	1.00	1.05	1.21
OXYGEN	18.22	17.87	17.45	17.91	18.05	18.32	18.66	18.44	19.39	22.03	19.21	19.11	19.07	18.85	10.76
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
NUMBER OF ANALYSES	2	1	1	2	1	2	2	2	2	3	3	3	1	1	1
ULTIMATE ANALYSIS, wt%	IGT BASIS														
ASH	10.15	9.69	9.70	9.90	9.49	9.17	10.85	9.80	10.60	12.08	12.89	12.85	12.85	13.42	10.45
CARBON	65.18	65.86	66.17	65.59	65.84	66.28	64.05	65.57	64.28	60.02	62.35	62.57	62.40	62.11	68.84
HYDROGEN	4.32	4.35	4.51	4.33	4.44	4.35	4.43	4.29	4.24	4.03	3.70	3.67	3.69	3.59	4.80
SULFUR	1.13	1.04	1.11	0.95	0.93	0.73	0.92	0.74	0.82	0.91	0.87	0.93	0.97	0.93	3.94
NITROGEN	1.00	1.19	1.06	1.09	1.08	1.16	1.09	1.17	1.19	0.93	0.98	1.00	1.02	1.03	1.21
OXYGEN	18.22	17.87	17.45	18.14	18.22	18.31	18.66	18.43	18.87	22.03	19.21	19.10	19.07	18.92	10.76
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
NUMBER OF ANALYSES	1	1	1	3	2	2	2	2	3	3	3	3	2	2	1

NOTES: (1) Dry basis.

TABLE 5.2

ASH AND CYCLONE FINES ANALYSES(1)

CASE NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
GRI RUN NO.	5-1	5-1	5-1	5-2	5-2	5-2	5-3	5-3	5-3	6-1	6-2	6-2	6-2	6-2	7-2
SET POINT	1	2A	2B	1	2	3	1	3	2	1	1	2	3	4	7
COAL TYPE	MONTANA ROSEBUD SUBBITUMINOUS									NORTH DAKOTA LIGNITE					ILLINOIS NO. 6
ASH FLOW RATE, lb/hr	22.7	46.8	51.5	60.0	99.1	60.4	43.3	41.9	63.1	21.3	36.5	53.7	71.5	108.0	20.4
NUMBER OF ANALYSES	8	6	5	10	5	5	6	5	8	8	7	8	5	4	3
CYCLONE FINES FLOW RATE, lb/hr	45.7	78.2	88.5	48.9	69.8	55.8	59.2	46.7	59.4	39.9	49.3	65.2	76.6	73.1	26.3
NUMBER OF ANALYSES	8	6	5	10	5	5	6	5	8	8	7	8	5	4	3
ULTIMATE ANALYSIS, wt%	ASH														
ASH	31.38	31.48	25.21	32.46	34.20	40.62	45.37	26.89	79.41	41.47	40.12	37.74	42.33	50.38	73.45
CARBON	63.71	63.28	68.54	63.07	61.60	55.28	51.27	67.15	19.58	52.84	55.84	57.59	53.28	45.45	25.02
HYDROGEN	0.83	1.06	1.28	1.01	0.97	0.73	0.75	0.95	0.29	0.87	0.51	0.71	0.49	0.42	0.21
SULFUR	1.44	1.65	1.46	0.96	0.70	0.82	1.04	0.80	0.44	1.09	0.71	0.70	0.88	0.75	1.08
NITROGEN	1.05	0.64	0.68	0.23	0.07	0.06	0.40	0.79	0.22	0.38	0.75	0.76	0.65	0.50	0.20
OXYGEN	1.59	1.89	2.83	2.27	2.46	2.49	1.17	3.42	0.06	3.35	2.07	2.50	2.37	2.47	0.04
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
NUMBER OF ANALYSES	1	1	1	4	2	3	3	3	4	4	4	4	3	3	2
ULTIMATE ANALYSIS, WT%	CYCLONE FINES														
ASH	42.91	34.19	28.36	48.04	49.71	51.89	47.78	38.32	44.80	43.44	50.03	50.59	44.35	45.87	32.19
CARBON	53.17	60.85	67.55	47.91	45.33	44.86	49.24	57.75	51.82	49.93	45.87	46.19	51.97	51.95	57.80
HYDROGEN	0.70	0.74	0.96	0.58	0.51	0.52	0.82	0.80	0.67	0.98	0.49	0.45	0.62	0.39	1.15
SULFUR	0.31	0.37	0.32	0.31	0.25	0.17	0.31	0.52	0.20	0.32	0.15	0.13	0.14	0.12	1.14
NITROGEN	0.59	0.49	0.56	0.32	0.40	0.32	0.33	0.62	0.40	0.38	0.72	0.68	0.67	0.76	0.40
OXYGEN	2.32	3.36	2.25	2.84	3.80	2.24	1.52	1.99	2.11	4.95	2.74	1.96	2.25	0.91	7.32
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
NUMBER OF ANALYSES	1	1	1	3	1	2	2	2	2	2	3	3	1	2	1

NOTE: (1) Dry basis.

During the Phase-2 test program, IGT was unable to shakedown the on-line gas chromatograph system which was installed to continuously analyze the product gas composition. Consequently, the gas compositions were periodically determined via bomb samples which were subsequently submitted for laboratory analysis. For each steady state period, Foster Wheeler derived an average product gas composition from the reported bomb sample analyses. Each gas analysis was first normalized to 100% on a dry basis and the number of analyses taken over the steady state duration were then arithmetically averaged. Table 5.3 compares the average dry gas compositions derived by both Foster Wheeler and IGT, together with the corresponding calculated flows of dry product gas. In general, there was good agreement between the Foster Wheeler and IGT values. Only in three cases, did the calculated dry gas rates differ by more than 5%. These differences were directly attributable to the variation in the averaged nitrogen compositions.

In developing their overall balances, IGT elected to ignore the measured flow rates of wet product gas which were determined by an orifice meter. Consequently, IGT determined the water content in the gasifier product gas via forcing the hydrogen balance around the PDU system. Foster Wheeler, however, chose to utilize the available measured data and, accordingly, calculated the product gas water content by subtracting the measured quench water rate from the wet product gas rate. The resulting wet product gas rates and compositions are summarized in Table 5.4. The main differences between the IGT and Foster Wheeler calculated gas rates are in the estimated water contents. In general, the values calculated from measured data are, on the average, 10% higher than the water contents established from the hydrogen elemental balance.

The hydrogen sulfide content in the product gas, as indicated in Table 5.4, was determined via a sulfur balance. Therefore, the moles of sulfur in the gas is equal to the sulfur content of the coal feed minus the sulfur remaining in the ash and cyclone fines. This method was also employed by IGT.

Foster Wheeler used an in-house computer program to develop overall material, elemental, and heat balances for each of the fifteen Phase-2 cases. As shown in Figure 5.1, the input consisted of five inlet and four outlet streams. The inlet streams included coal feed, grid gas, venturi gas, jet gas and nitrogen purge gas. The outlet streams consisted of the product gas, the fines in the product gas, gasifier ash, and the collected cyclone fines. The steady state values employed for these streams were those derived by Foster Wheeler from IGT's hourly data logs.

The overall balances were calculated in terms of percent closure, which is defined as [(In-Out)/In] x 100. The calculated closures for the overall material, elemental, and enthalpy balances are shown in Table 5.5.

TABLE 5.3

DRY PRODUCT GAS COMPOSITIONS

CASE NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
GRI RUN NO.	5-1	5-1	5-1	5-2	5-2	5-2	5-3	5-3	5-3	6-1	6-2	6-2	6-2	6-2	7-2
SET POINT	1	2A	2B	1	2	3	1	3	2	1	1	2	3	4	7
COAL TYPE	MONTANA ROSEBUD SUBBITUMINOUS									NORTH DAKOTA LIGNITE					ILLINOIS NO. 6
PRESSURE, psig	201	300	302	450	450	449	449	448	448	200	300	448	447	447	151
FREEBOARD TEMP, °F	1580	1533	1461	1549	1633	1610	1590	1491	1706	1431	1419	1413	1426	1531	1775
REACTION GAS, MOL/HR	FW BASIS														
H2	8.44	11.65	8.69	12.89	25.00	15.69	13.19	8.30	24.32	6.61	9.05	10.21	13.21	19.81	4.78
N2	7.03	10.22	10.83	17.41	14.94	14.76	13.05	16.26	16.44	8.74	11.23	16.83	16.85	17.04	7.30
CO	3.11	4.26	2.12	3.72	14.23	6.41	4.25	1.92	13.81	1.61	1.88	2.12	3.46	7.92	2.34
CO2	6.56	6.95	7.92	12.79	19.11	14.12	14.58	9.24	18.80	5.80	8.54	11.44	12.87	17.53	4.72
CH4	1.32	2.30	1.85	2.78	5.27	3.31	2.77	1.84	4.82	0.96	1.49	2.06	2.84	4.04	1.15
H2S	0.10	0.12	0.12	0.12	0.16	0.12	0.12	0.06	0.17	0.05	0.07	0.10	0.11	0.18	0.22
	26.56	35.50	31.53	49.61	78.71	54.41	47.96	37.62	78.36	23.77	32.26	42.76	49.34	66.52	20.51
NUMBER OF GAS ANALYSES AVERAGED	2	1	2	5	2	5	3	2	5	4	6	8	5	2	2
REACTION GAS, MOL/HR	IGT BASIS														
H2	9.15	11.62	10.74	12.23	24.99	15.66	13.21	8.32	24.69	6.53	8.97	10.17	13.19	20.65	5.38
N2	7.06	10.24	10.80	17.40	14.97	14.81	13.08	16.42	16.47	8.73	11.25	16.84	16.89	17.09	7.37
CO	3.23	4.26	2.88	3.44	13.80	6.41	4.29	1.91	13.97	1.61	1.88	2.14	3.49	8.57	2.68
CO2	7.98	6.96	9.38	12.49	19.33	14.18	14.57	9.38	19.00	5.79	8.56	11.57	13.20	18.72	5.15
CH4	1.39	2.39	2.17	2.71	5.09	3.33	2.77	1.95	4.95	1.08	1.69	2.32	3.20	4.39	1.37
H2S	0.10	0.13	0.12	0.11	0.20	0.12	0.12	0.06	0.17	0.05	0.07	0.10	0.12	0.17	0.22
	28.91	35.60	36.09	48.38	78.38	54.51	48.04	38.04	79.25	23.79	32.42	43.14	50.09	69.59	22.17
NUMBER OF GAS ANALYSES AVERAGED	NOT REPORTED														

TABLE 5.4

WET PRODUCT GAS COMPOSITIONS

CASE NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
GRI RUN NO.	5-1	5-1	5-1	5-2	5-2	5-2	5-3	5-3	5-3	6-1	6-2	6-2	6-2	6-2	7-2
SET POINT	1	2A	2B	1	2	3	1	3	2	1	1	2	3	4	7
COAL TYPE	MONTANA ROSEBUD SUBBITUMINOUS									NORTH DAKOTA LIGNITE					ILLINOIS NO. 6
PRESSURE, psig	201	300	302	450	450	449	449	448	448	200	300	448	447	447	151
FREEBOARD TEMP,°F	1580	1533	1461	1549	1633	1610	1590	1491	1706	1431	1419	1413	1426	1531	1775
REACTION GAS, MOL/HR FW BASIS	FW BASIS														
H2	8.44	11.65	8.69	12.89	25.00	15.69	13.19	8.30	24.32	6.61	9.05	10.21	13.21	19.81	4.78
N2	7.03	10.22	10.83	17.41	14.94	14.76	13.05	16.26	16.44	8.74	11.23	16.83	16.85	17.04	7.30
CO	3.11	4.26	2.12	3.72	14.23	6.41	4.25	1.92	13.81	1.61	1.88	2.12	3.46	7.92	2.34
CO2	6.56	6.95	7.92	12.79	19.11	14.12	14.58	9.24	18.80	5.80	8.54	11.44	12.87	17.53	4.72
CH4	1.32	2.30	1.85	2.78	5.27	3.31	2.77	1.84	4.82	0.96	1.49	2.06	2.84	4.04	1.15
H2O	31.29	43.45	42.96	54.86	40.30	52.77	57.69	61.84	49.27	26.58	39.84	52.30	47.97	46.04	19.58
H2S	0.10	0.12	0.12	0.12	0.16	0.12	0.12	0.06	0.17	0.05	0.07	0.10	0.11	0.18	0.22
	57.85	78.95	74.49	104.47	119.01	107.18	105.65	99.46	127.63	50.35	72.10	95.06	97.31	112.56	40.09
REACTION GAS, MOL/HR IGT BASIS															
H2	9.15	11.62	10.74	12.23	24.99	15.66	13.21	8.32	24.69	6.53	8.97	10.17	13.19	20.65	5.38
N2	7.06	10.24	10.80	17.40	14.97	14.81	13.08	16.42	16.47	8.73	11.25	16.84	16.89	17.09	7.37
CO	3.23	4.26	2.88	3.44	13.80	6.41	4.29	1.91	13.97	1.61	1.88	2.14	3.49	8.57	2.68
CO2	7.98	6.96	9.38	12.49	19.33	14.18	14.57	9.38	19.00	5.79	8.56	11.57	13.20	18.72	5.15
CH4	1.39	2.39	2.17	2.71	5.09	3.33	2.77	1.95	4.95	1.08	1.69	2.32	3.20	4.39	1.37
H2O	27.48	37.47	39.10	53.88	42.18	50.27	54.01	56.74	44.38	22.72	34.91	46.63	40.46	38.58	19.07
H2S	0.10	0.13	0.12	0.11	0.20	0.12	0.12	0.06	0.17	0.05	0.07	0.10	0.12	0.17	0.22
	56.39	73.07	75.19	102.26	120.56	104.78	102.05	94.78	123.63	46.51	67.33	89.77	90.55	108.17	41.24

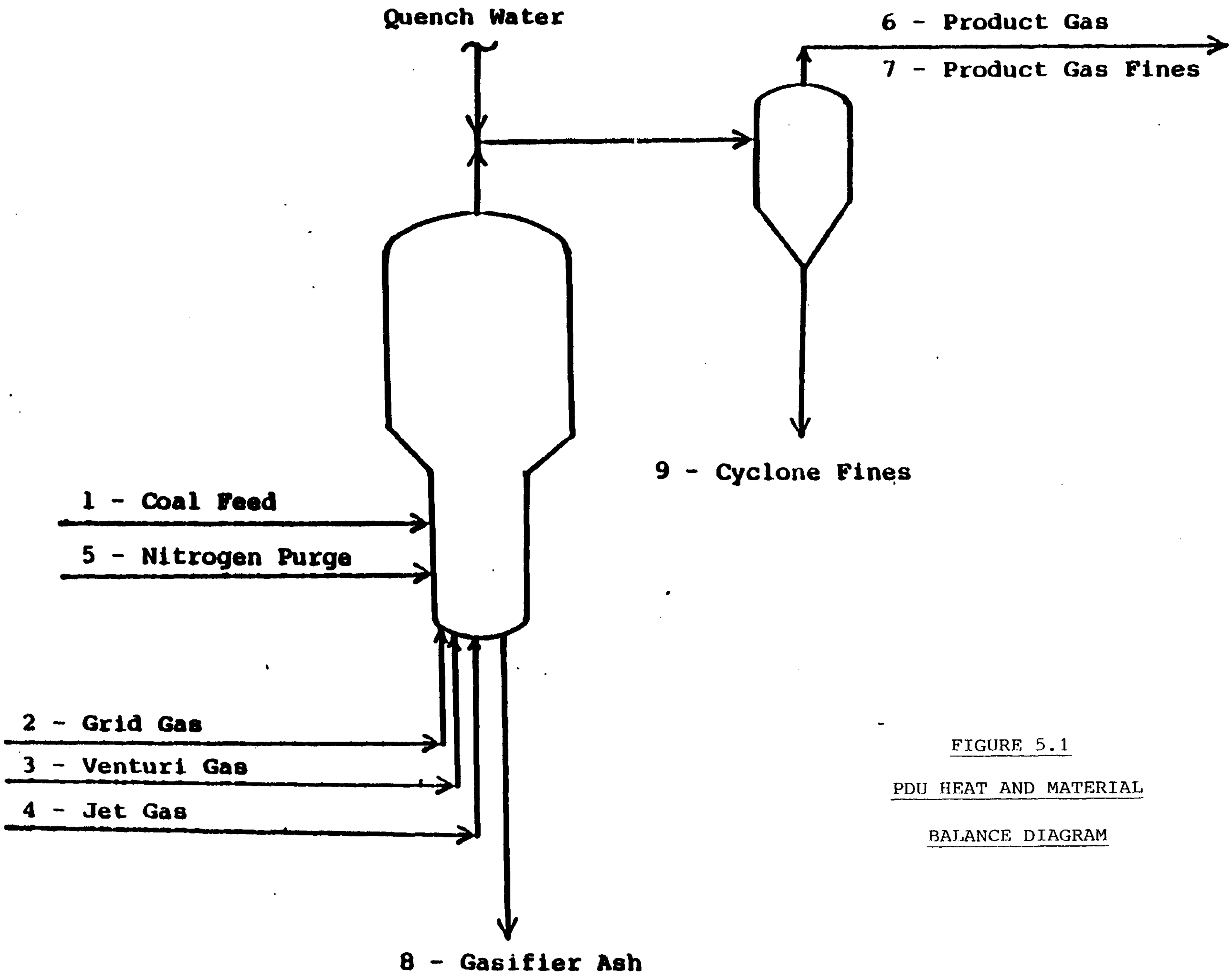


FIGURE 5.1

PDU HEAT AND MATERIAL

BALANCE DIAGRAM

TABLE 5.5

OVERALL MATERIAL AND ENERGY BALANCES

CASE NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
GRI RUN NO.	5-1	5-1	5-1	5-2	5-2	5-2	5-3	5-3	5-3	6-1	6-2	6-2	6-2	6-2	7-2
SET POINT	1	2A	2B	1	2	3	1	2	3	1	1	2	3	4	7
COAL TYPE	MONTANA ROSEBUD SUBBITUMINOUS									NORTH DAKOTA LIGNITE					ILLINOIS NO. 6
COAL FEED, LB/HR	352.9	537.1	479.8	499.7	866.1	661.6	531.0	379.4	834.2	260.7	345.1	487.7	590.2	865.2	200.1
***BALANCE CLOSURES, % - FOSTER WHEELER BASIS**															
CARBON	20.6	25.5	13.8	1.2	-7.3	13.1	-2.9	2.3	-4.1	5.5	-4.4	0.2	-4.3	-2.6	8.4
HYDROGEN	-7.6	-10.8	-2.3	-2.2	2.1	-3.5	-5.1	-7.0	-12.0	-8.0	-9.1	-8.5	-11.9	-8.8	4.0
OXYGEN	-2.1	1.6	0.7	-0.5	0.5	-1.3	-5.8	-3.3	-1.4	-3.0	-5.4	-6.9	-7.5	-4.6	4.6
NITROGEN	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SULFUR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ASH	16.5	8.4	1.9	-3.8	0.3	-1.4	3.1	28.6	27.3	8.5	-11.8	3.4	-4.3	2.7	-21.6
OVERALL MASS	2.3	5.2	2.5	-0.4	-1.0	1.2	-4.2	-1.9	-2.2	-1.3	-4.5	-4.6	-5.5	-3.3	-3.7
OVERALL ENTHALPY	-4.9	-0.5	-1.3	-3.8	5.1	-1.7	-5.9	-2.7	-4.2	-3.5	-5.5	-6.6	-8.2	-3.2	5.8
***BALANCE CLOSURES, % - IGT BASIS**															
CARBON	6.0	25.8	6.0	4.7	-7.4	13.3	-1.3	1.7	6.2	4.7	-3.8	-0.5	-5.4	-7.7	1.0
HYDROGEN	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OXYGEN	0.1	1.5	1.2	0.2	-1.4	1.5	1.5	2.7	3.0	4.3	2.8	0.6	2.3	0.6	0.7
NITROGEN	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SULFUR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ASH	21.8	13.9	9.3	4.9	7.1	2.8	9.7	8.5	0.2	1.9	4.7	-4.5	-8.6	7.0	9.4
OVERALL MASS	2.6	11.4	1.9	1.7	-2.0	3.1	-0.9	2.0	0.7	3.1	1.1	0.2	0.3	0.7	0.7
OVERALL ENTHALPY	11.3	11.8	2.6	1.9	7.0	8.9	1.5	2.1	6.9	0.9	6.5	-0.9	-6.4	-7.4	1.2

*PERCENT CLOSURE = [(IN-OUT)/IN] x 100

Based on Foster Wheeler's analyses, the overall mass and enthalpy balances for the Phase-2 steady states were generally good. With only a few exceptions, these closures were within the generally accepted range of 100 ±5%. The closures on heat balance, however, are deceiving since the enthalpy reference base results in a large absolute value for the denominator in the closure calculation. Except for Case 5, the enthalpy balances result in a positive heat loss from the PDU system, as would be expected. To gain a perspective on the magnitude of the calculated heat losses, these losses are represented as percentages of the heat of combustion of the corresponding coal feeds in Table 5.6. On this basis, half of the Phase-2 runs show heat losses which exceed 5% of the coal heating value. For these cases, the heat losses ranged from 8% to 16% of the coal heating value, which is judged to be excessively high.

Unlike the IGT balances in which the hydrogen balance was forced to establish the product gas water content, the Foster Wheeler results show acceptable closures on the hydrogen balance, ±5%, for only six of the fifteen cases. Furthermore, when these are considered in conjunction with to the carbon balances obtained, there appears to be only two cases in which the overall heat, mass, and elemental balance closures are in the acceptable range, i.e. Cases 4 and 7.

Table 5.6

CALCULATED PDU HEAT LOSSES

CASE	HEAT LOSS 1000 BTU/HR	HEAT LOSS % COAL HHV
1	331	9.0
2	154	2.7
3	118	2.5
4	95	1.9
5	-165	-1.7
6	319	4.8
7	613	11.9
8	340	9.2
9	967	7.7
10	258	11.3
11	7	0.2
12	637	15.5
13	626	12.9
14	231	3.3
15	-7	-0.3

6.0 DATA CORRELATION

As part of the Phase-2 test program, it was IGT's intention to investigate the effects of temperature, coal feed rate, and the steam/oxygen ratio on carbon conversion for both the Montana subbituminous coal and North Dakota lignite. Unfortunately, as shown in Table 6.1, the actual PDU operating conditions deviated considerably from the planned test matrices. Consequently, the effects of these operating variables were obscured by simultaneous changes in two or more parameters.

In conjunction with the earlier Phase-1 test data obtained at 100-300 psig, Foster Wheeler attempted to correlate the Phase-2 data relative to the following:

- Effects of operating parameters such as temperature, pressure, steam/carbon ratio on carbon conversion.
- Approach of the measured gas composition to the calculated equilibrium values.
- Effect of pressure on coal throughput, methane make, and fines entrainment.

6.1 Carbon Conversion

The carbon conversion levels obtained in the Phase-2 tests are shown in Table 6.2, together with the corresponding bed temperature and oxygen/steam feed ratio. These conversion levels are based on the product gas rate and gas analyses. Except for four cases, the Foster Wheeler calculated conversions agree with those reported by IGT. As expected, the exceptions correspond to those cases in which the calculated carbon balances are significantly different from IGT's balances, shown in Table 5.5.

The effects of temperature and oxygen/steam ratio on carbon conversion are indicated in Figures 6.1-6.4 for Montana subbituminous coal and North Dakota lignite. These plots incorporate the Phase-1 data which were obtained at 100-300 psig. No trend could be established for the Illinois bituminous coal since only one data point was available.

The relationship between bed temperature and oxygen/steam ratio is more diffuse than was indicated by the Phase-1 data alone. The latter clearly showed a direct variation of bed temperature with increasing oxygen to steam feed ratio. While such a relationship is still evident for the subbituminous coal, the Phase-2 data for lignite tend to obscure this effect.

As would be expected, the plots of carbon conversion with bed temperature indicate a direct correlation. This is particularly apparent when the data having questionable carbon balances are

TABLE 6.1
COMPARISON OF PLANNED AND ACTUAL TEST CONDITIONS

	NUMBER		PRESSURE, PSIG		BED TEMP, °F		COAL FEED LB/H		STEAM MOL/H		OXYGEN, MOL/H		STEAM/C RATIO MOL/MOL		OXYGEN/C RATIO MOL/MOL		SUPERFICIAL VELOCITY FT/S	
COAL TYPE	PLAN	RUN	PLAN	RUN	PLAN	RUN	PLAN	RUN	PLAN	RUN	PLAN	RUN	PLAN	RUN	PLAN	RUN	PLAN	RUN
MONTANA	2	5-2(1)	500	450	1550	1501	762	500	51.3	59.8	11.5	8.3	1.43	2.40	0.32	0.33	2.1	2.5
ROSEBUD	3A	5-2(2)	500	450	1550	1548	538	866	51.3	56.4	9.0	11.9	2.02	1.30	0.35	0.27	2.0	2.5
SUB-	3B	5-2(3)	500	449	1550	1553	1078	662	51.3	56.8	15.1	9.8	1.01	1.71	0.30	0.29	2.2	2.5
BITUMINOUS	3C	5-3(1)	500	449	1450	1538	762	531	51.3	59.8	10.9	8.9	1.43	2.36	0.30	0.35	2.0	2.5
	3D	5-3(2)	500	448	1650	1456	762	379	51.3	59.8	12.1	6.8	1.43	3.28	0.34	0.37	2.2	2.5
	3E	5-3(3)	300	448	1550	1652	466	834	31.5	58.3	7.3	13.3	1.43	1.50	0.33	0.34	2.1	2.4
	3F	5-1(1)	200	201	1550	1566	318	353	21.5	31.5	5.1	5.2	1.43	1.74	0.34	0.28	2.1	2.9
NORTH	5	6-2(2)	500	448	1400	1396	895	488	63.3	49.8	11.3	6.6	1.64	2.42	0.29	0.32	2.3	1.9
DAKOTA	6A	6-2(3)	500	447	1400	1407	633	590	63.3	45.6	8.8	7.4	2.32	1.83	0.32	0.30	2.2	1.8
LIGNITE	6B	6-2(4)	500	447	1400	1485	1266	865	63.3	46.9	14.9	10.5	1.16	1.30	0.27	0.29	2.4	2.1
	6C	-----	500	---	1300	----	895	---	63.3	----	10.6	----	1.64	----	0.28	----	2.2	---
	6D	-----	500	---	1500	----	895	---	63.3	----	12.0	----	1.64	----	0.31	----	2.4	---
	6E	6-1(1)	300	300	1400	1405	547	345	38.7	39.4	7.1	5.0	1.64	2.63	0.30	0.33	2.3	2.2
	6F	6-2(1)	200	200	1400	1418	373	261	26.4	26.4	5.0	3.7	1.64	2.29	0.31	0.32	2.3	2.2

TABLE 6.2

CARBON CONVERSION LEVELS

CASE NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
GRI RUN NO.	5-1	5-1	5-1	5-2	5-2	5-2	5-3	5-3	5-3	6-1	6-2	6-2	6-2	6-2	7-2
SET POINT	1	2A	2B	1	2	3	1	3	2	1	1	2	3	4	7
COAL TYPE	MONTANTA ROSEBUD STUBBITUMINOUS									NORTH DAKOTA LIGNITE					ILLINOIS NO. 6
PRESSURE, psig	201	300	302	450	450	449	449	448	448	200	300	448	447	447	151
BED TEMPERATURE, °F	1566	1565	1549	1501	1548	1553	1538	1456	1652	1418	1405	1396	1407	1485	1738
OXYGEN FEED RATIO (lbs O_2 fed/lb C fed)	0.758	0.662	0.653	0 884	0.729	0.785	0.939	0.993	0.914	0 856	0.882	0.836	0.789	0.774	0.985
STEAM FEED RATIO (lb steam fed/lb C fed)	2.612	2.287	2.716	3.607	1.951	2.564	3.537	4.915	2.250	3.433	3.942	3.560	2.749	1.948	3.177
OXYGEN/STEAM RATIO (lb O_2 fed/lb steam fed)	0.290	0.290	0.241	0.245	0.374	0.306	0.265	0.202	0.406	0.249	0.224	0.235	0.287	0.397	0.310
CARBON CONVERSION, %(1)															
FW BASIS	60.7	49.5	50.6	77.5	89.0	71.8	85.2	71.3	96.3	72.7	79.3	74.4	77.1	81.7	75.1
IGT BASIS	69.6	49.9	61.4	75.1	88.8	72.0	85.4	72.6	97.0	73.7	80.8	76.3	80.0	87.7	84.2

NOTES: (1) Based on product gas analysis.

FIGURE 6.1

TEMPERATURE DEPENDENCE - SUBBITUMINOUS COAL

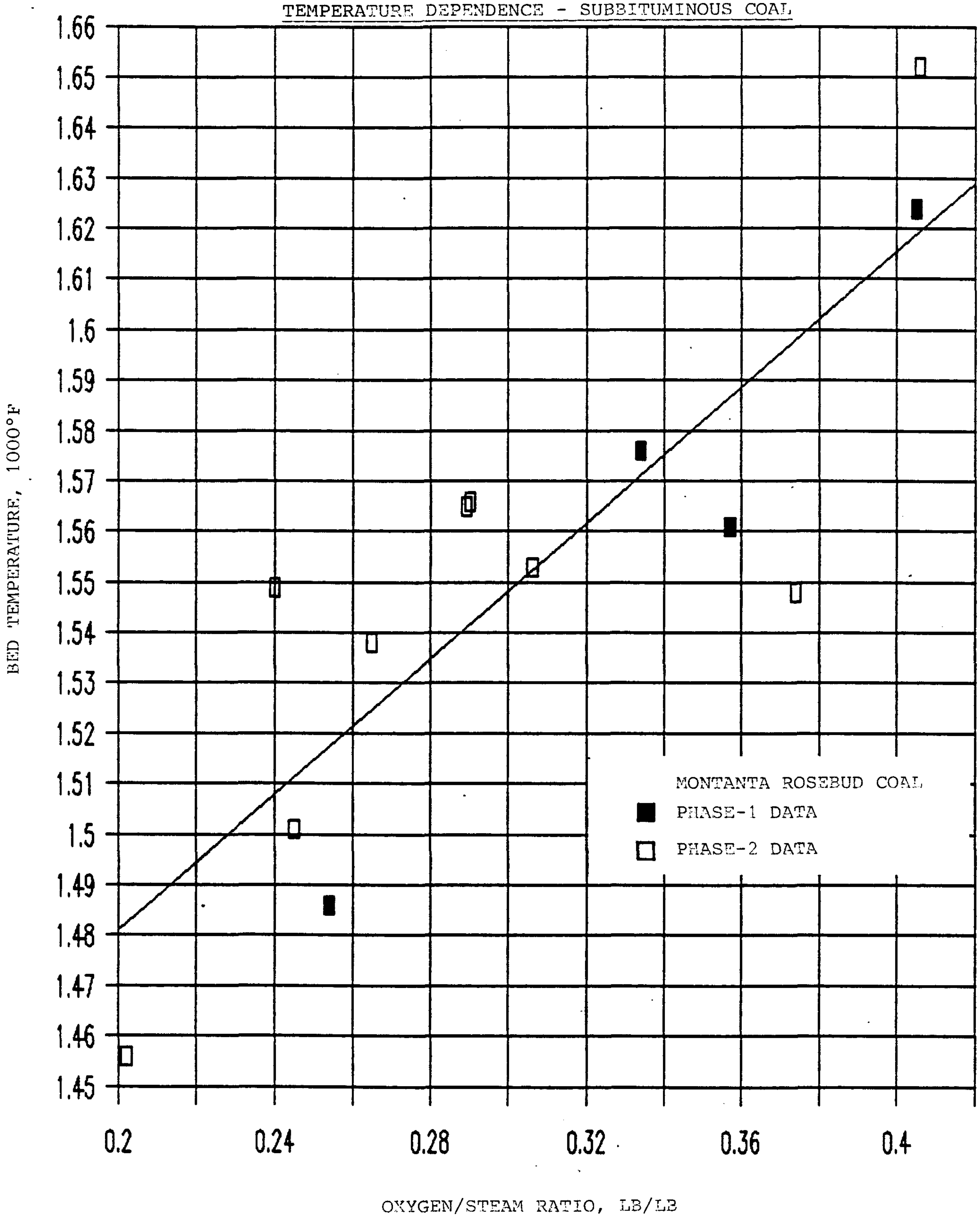


FIGURE 6.2

CARBON CONVERSION - SUBBITUMINOUS COAL

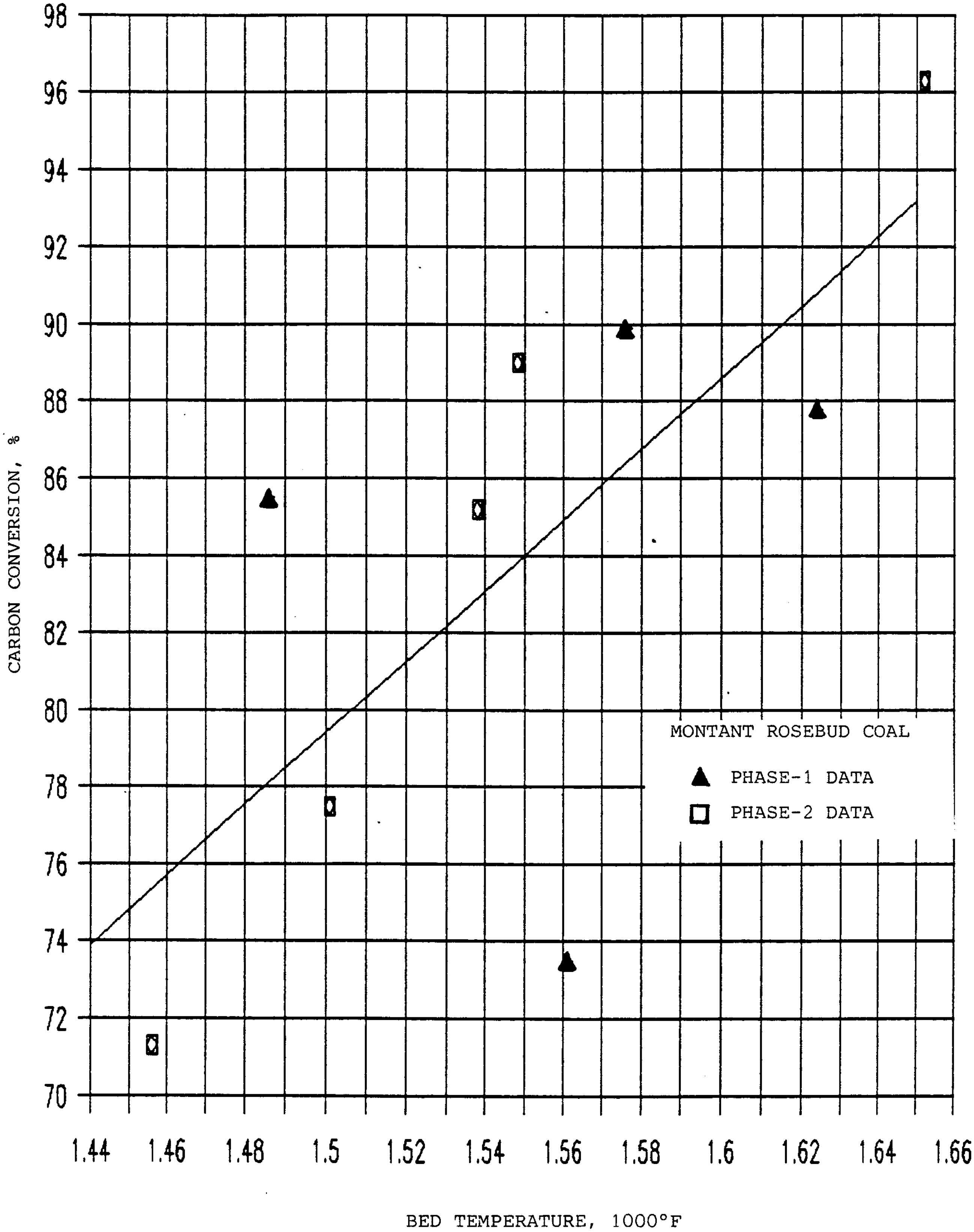


FIGURE 6.3

TEMPERATURE DEPENDENCE - LIGNITE

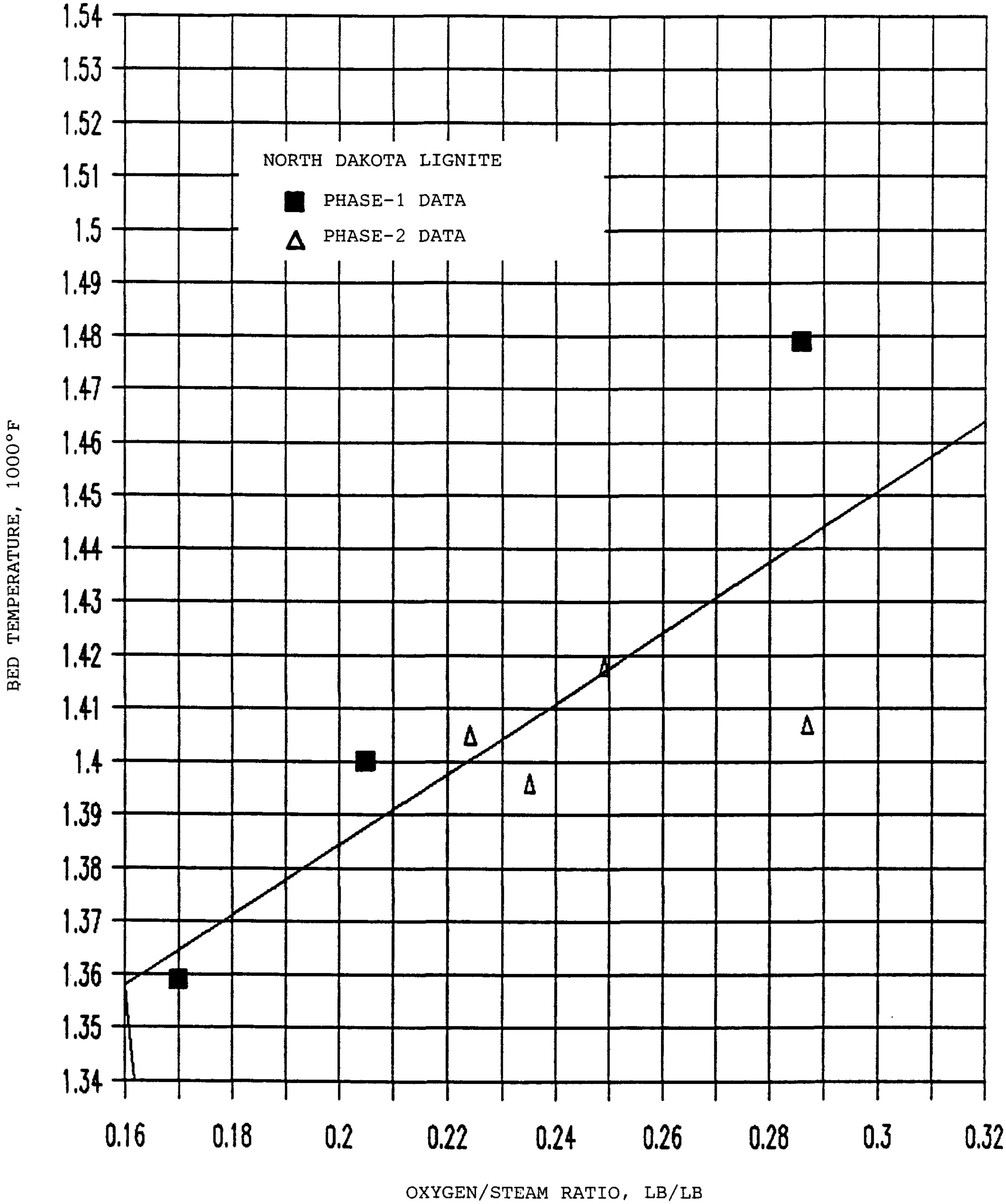
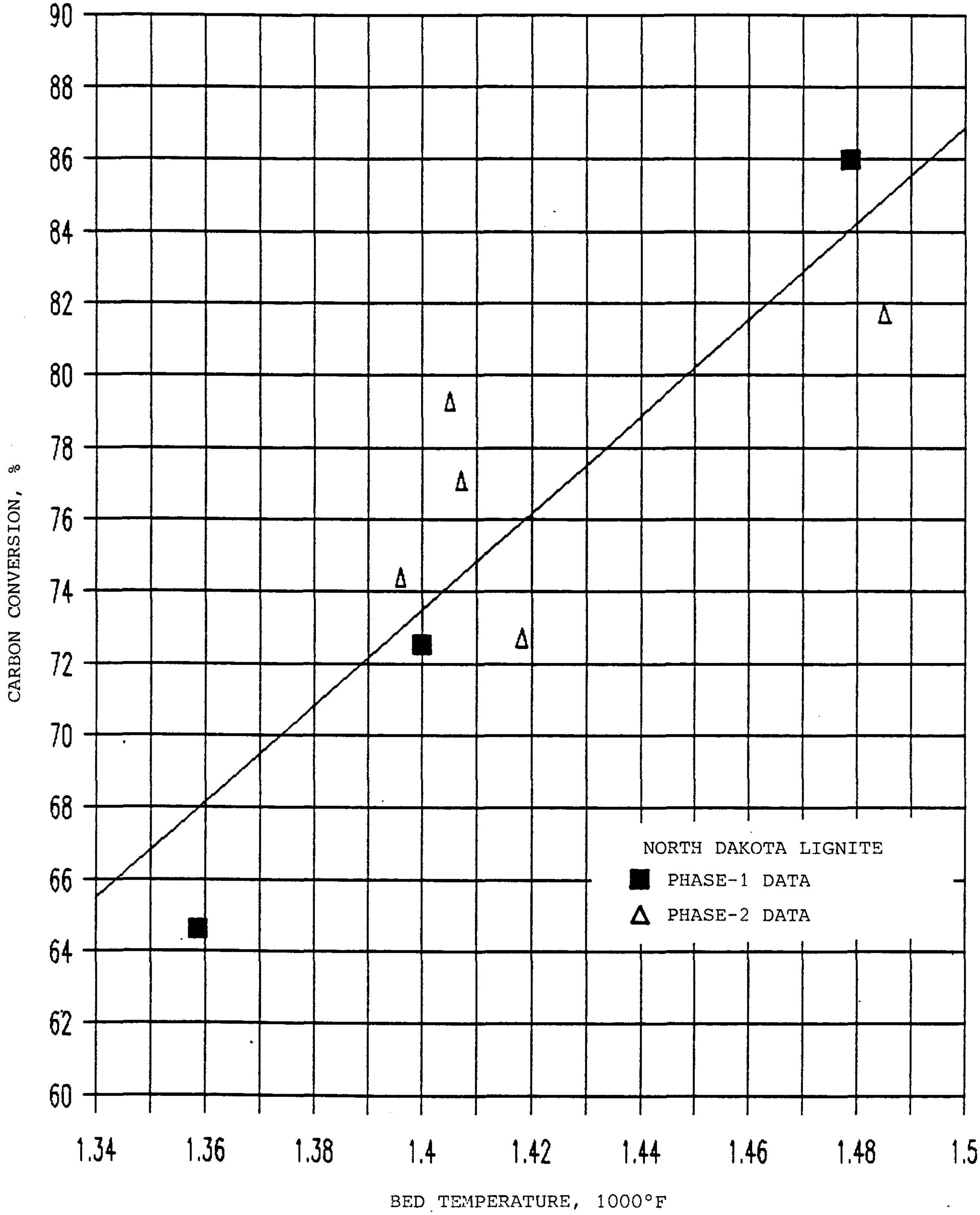


FIGURE 6.4

CARBON CONVERSION - LIGNITE



neglected, as shown in Figures 6.2 and 6.4. There is no readily apparent effect of pressure on carbon conversion. This is understandable since pressure has a relatively small positive influence on the gasification kinetics (4), roughly proportional to 1 + P/(1 + P). Consequently, over a pressure range of 200 to 450 psig, the effect on rate would be less than 5%, all else being constant.

The concepts of cold gas efficiency and the critical ratio of oxygen to carbon for coal gasification are directly related to carbon conversion. The experimental cold gas efficiency is defined as the product gas rate times the gas higher heating value divided by the coal feed rate times its higher heating value. Calculated cold gas efficiencies for the Phase-2 test results are give in Table 6.3.

A maximum theoretical cold gas efficiency (1) can also be calculated for each case, based on the ultimate analysis of the coal, the percent of stoichiometric combustion oxygen fed, and the fraction of the coal carbon converted. Appendix-A contains a sample calculation of this parameter. Values of the calculated theoretical cold gas efficiencies for the Phase-2 data are also included in Table 6.3. The extent of agreement between the actual and theoretical efficiency values gives an indication of the consistency of the product gas compositions. For nine of the Phase-2 cases, the agreement between the cold gas efficiencies is within 5%.

The criteria developed by CUNY (4) may be used to determine whether the fluidized-bed gasifier PDU was operated in a true gasification mode or in a partial oxidation mode. This is based on a critical oxygen to carbon ratio (Rc) above which the combustion of carbon, or carbon monoxide, to carbon dioxide occurs. In this case, if the carbon reacts with all of the oxygen first, there would be no carbon left for gasification with steam. If the actual oxygen to carbon ratio (R) is greater than Rc, that is Rc-R is negative, the system will operate in a partial combustion mode. If R is less than Rc (Rc-R is positive) then there will be increasing amounts of carbon or carbon monoxide available for the steam reaction to occur, and thus the system will operate progressively in the gasification mode.

For a fuel of composition CH_xO_y, the value for Rc is defined as:

$$Rc = (1-y)/2$$

The values for R are simply the moles of oxygen fed per atom of carbon converted from the coal feed. As shown in Table 6.3, the negative values of Rc-R for the Phase-2 data indicate that the majority of these PDU tests were conducted in the partial oxidation mode. Consequently, the usefulness of the data in scaling the PDU performance to a commercial gasifier is questionable.

TABLE 6.3

CONVERSION EFFICIENCY AND OXYGEN USAGE

CASE NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
GRI RUN NO.	5-1	5-1	5-1	5-2	5-2	5-2	5-3	5-3	5-3	6-1	6-2	6-2	6-2	6-2	7-2
SET POINT	1	2A	2B	1	2	3	1	3	2	1	1	2	3	4	7
COAL TYPE	----------MONTANTA ROSEBUD SUBBITUMINOUS----------									----------NORTH DAKOTA LIGNITE----------					ILLINOIS NO. 6
PRESSURE, psig	201	300	302	450	450	449	449	448	448	200	300	448	447	447	151
PRODUCT GAS FLOW RATE, lb-mol/hr	57.85	78.95	74.49	104.47	119.01	107.18	105.65	99.46	127.63	50.35	72.10	95.06	97.31	112.56	40.09
PRODUCT GAS HHV, Btu/scf	88.8	94.7	73.2	79.1	152.3	98.7	80.7	52.4	135.7	72.8	70.7	64.6	85.7	117.1	90.0
COAL FEED RATE, lb/hr	352.9	537.1	479.8	499.7	866.1	661.6	531.0	379.4	834.2	260.7	345.1	487.7	590.2	865.2	200.1
COAL HHV,(1) Btu/lb	10,462	10,364	9,970	10,145	10,144	10,152	9,699	9,700	9,573	8,751	8,533	8,477	8,281	8,148	11,895
ACTUAL COLD GAS EFFICIENCY, %	52.8	50.9	43.2	61.8	78.3	59.7	62.7	53.7	82.2	60.9	65.6	56.5	64.7	70.8	57.4
MAXIMUM THEORETICAL COLD GAS EFFICIENCY, %	49.8	40.9	43.8	64.9	86.5	62.2	71.7	51.9	83.6	57.6	65.2	61.0	66.0	73.0	59.6
% DIFFERENCE	6.0	24.5	-1.4	-4.7	-9.5	-4.0	-12.5	-3.4	-1.7	5.7	0.6	-7.3	-2.8	-2.9	-3.6
Rc, MOLES O_2/ATOM C	0.395	0.398	0.401	0.398	0.398	0.396	0.391	0.394	0.386	0.362	0.384	0.385	0.385	0.386	0.441
R, MOLES O_2/ ATOM CONVERTED C	0.469	0.502	0.484	0.428	0.308	0.410	0.413	0.523	0.356	0.442	0.417	0.422	0.384	0.355	0.492
Rc-R	-0.074	-0.104	-0.083	-0.030	0.090	-0.014	-0.022	-0.129	0.030	-0.080	-0.033	-0.037	-0.001	0.031	-0.051

NOTES: (1) As feed basis.

6.2 Product Gas Equilibrium

The experimental gas compositions were compared to the equilibrium gas phase as predicted via free energy minimization. Table 6.4 summarizes this comparison.

As expected, the measured methane contents are considerably higher than the equilibrium values. For lignite, which is the most reactive of the coals tested, the actual methane compositions exceed the equilibrium predictions by an order of magnitude. For bituminous coals, the actual and equilibrium methane compositions differ by several orders of magnitude.

With the exception of those cases for which the carbon balances were poor, the product gas compositions were close to equilibrium relative to the water gas shift reaction. The gas compositions based on IGT's calculation method were somewhat closer to the equilibrium value than were the Foster Wheeler gas compositions. This suggests that forcing the hydrogen balance to zero to establish the water content of the gas phase may be more accurate than developing the water content from the measured product gas. This tends to confirm IGT's speculation that the product gas orifice meter was inaccurate and a new type of device is required in order to obtain reliable product gas flow measurements.

6.3 Pressure Effects

In conjunction with IGT's Phase-1 data, the Phase-2 test results were analyzed with respect to the effects of operating pressure on the coal throughput, the methane yield, and entrainment of fines. The pertinent Phase-2 data are summarized in Table 6.5.

In reporting their data, IGT addressed the coal throughput in terms of an MAF coal gasification rate, which is the ratio of the MAF coal feed rate to the char/ash inventory of the fluidized bed. This rate, however, is a misnomer since it is actually a space velocity term which represents the apparent residence time of the coal feed in the fluid bed. All other conditions being equal, the achieved coal conversion would be expected to decrease with increasing space velocity. Figure 6.5 shows a plot of the IGT "gasification rate" with system pressure. While the Phase-1 data for Montana subbituminous coal and North Dakota lignite indicated a proportionality of this rate term with pressure, the Phase-2 data clearly shows that the coal space velocity is an independent variable. Accordingly, at a given pressure, the space velocity is not unique unless the temperature and conversion are fixed.

The fact that, for a fixed gasifier size, the coal feed rate increases with the operating pressure is due to operation in a bubbling fluid bed which is largely determined by the gas linear velocity. At a constant linear velocity, the allowable mass flow of steam and oxygen increase directly with pressure, and consequently, so does the coal feed rate.

TABLE 6.4

GAS PHASE EQUILIBRIA

CASE NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
GRI RUN NO.	5-1	5-1	5-1	5-2	5-2	5-2	5-3	5-3	5-3	6-1	6-2	6-2	6-2	6-2	7-2
SET POINT	1	2A	2B	1	2	3	1	3	2	1	1	2	3	4	7
COAL TYPE	MONTANA ROSEBUD SUBBITUMINOUS									NORTH DAKOTA LIGNITE					ILLINOIS NO. 6
PRESSURE, psig	201	300	302	450	450	449	449	448	448	200	300	448	447	447	151
FREEBOARD TEMP,°F	1580	1533	1461	1549	1633	1610	1590	1491	1706	1431	1419	1413	1426	1531	1775
MEASURED PRODUCT GAS, MOLE %															
H2	15.9	14.8	11.7	12.3	21.0	14.6	12.5	8.3	19.1	13.1	12.6	10.7	13.6	17.6	11.9
N2	13.2	12.9	14.5	16.6	12.6	13.8	12.4	16.3	12.9	17.4	15.6	17.7	17.3	15.1	18.2
CO	5.9	5.4	2.8	3.6	12.0	6.0	4.0	1.9	10.8	3.2	2.7	2.2	3.7	7.0	5.8
CO2	12.4	8.8	10.6	12.2	16.1	13.2	13.8	9.3	14.7	11.5	11.8	12.0	13.2	15.6	11.8
CH4	2.5	2.9	2.5	2.7	4.4	3.1	2.6	1.9	3.8	1.9	2.1	2.2	2.9	3.6	2.9
H20	49.91	55.05	57.75	52.49	33.77	49.19	54.59	62.24	38.57	52.79	55.11	55.098	49.184	40.938	48.859
H2S	0.19	0.15	0.15	0.11	0.13	0.11	0.11	0.06	0.13	0.11	0.090	0.102	0.116	0.162	0.541
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.000	100.000	100.000	100.000	100.000
PREDICTED PRODUCT GAS, MOLE %															
H2	21.6	25.1	21.6	19.3	27.8	22.4	19.2	14.5	21.1	21.0	17.9	16.2	19.4	23.7	19.7
N2	11.6	13.2	12.6	15.9	11.7	13.0	11.8	15.8	13.0	16.2	14.8	17.1	16.6	14.4	17.2
CO	6.1	6.4	7.4	5.3	15.7	7.9	6.0	2.5	11.4	4.2	3.5	3.2	4.8	9.5	8.0
CO2	12.1	10.9	16.0	12.1	13.7	12.9	13.4	10.2	15.1	11.1	12.1	12.3	13.3	14.4	11.4
CH4	0.04	0.3	0.6	0.2	1.0	0.3	0.1	0.06	0.1	0.2	0.22	0.36	0.87	0.97	0.004
H20	48.39	43.95	41.67	47.09	29.98	43.4	49.4	56.88	39.18	47.2	51.394	50.741	44.918	36.876	43.184
H2S	0.17	0.15	0.13	0.11	0.12	0.10	0.10	0.06	0.12	0.10	0.086	0.099	0.112	0.154	0.512
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.000	100.000	100.000	100.000	100.000
APPROACH TO WATER-GAS-SHIFT EQUILIBRIUM(1)	146	477	181	71	-35	133	33	252	16	124	76	48	68	-18	77

NOTES: (1) Equilibrium temperature minus freeboard temperature.

TABLE 6.5

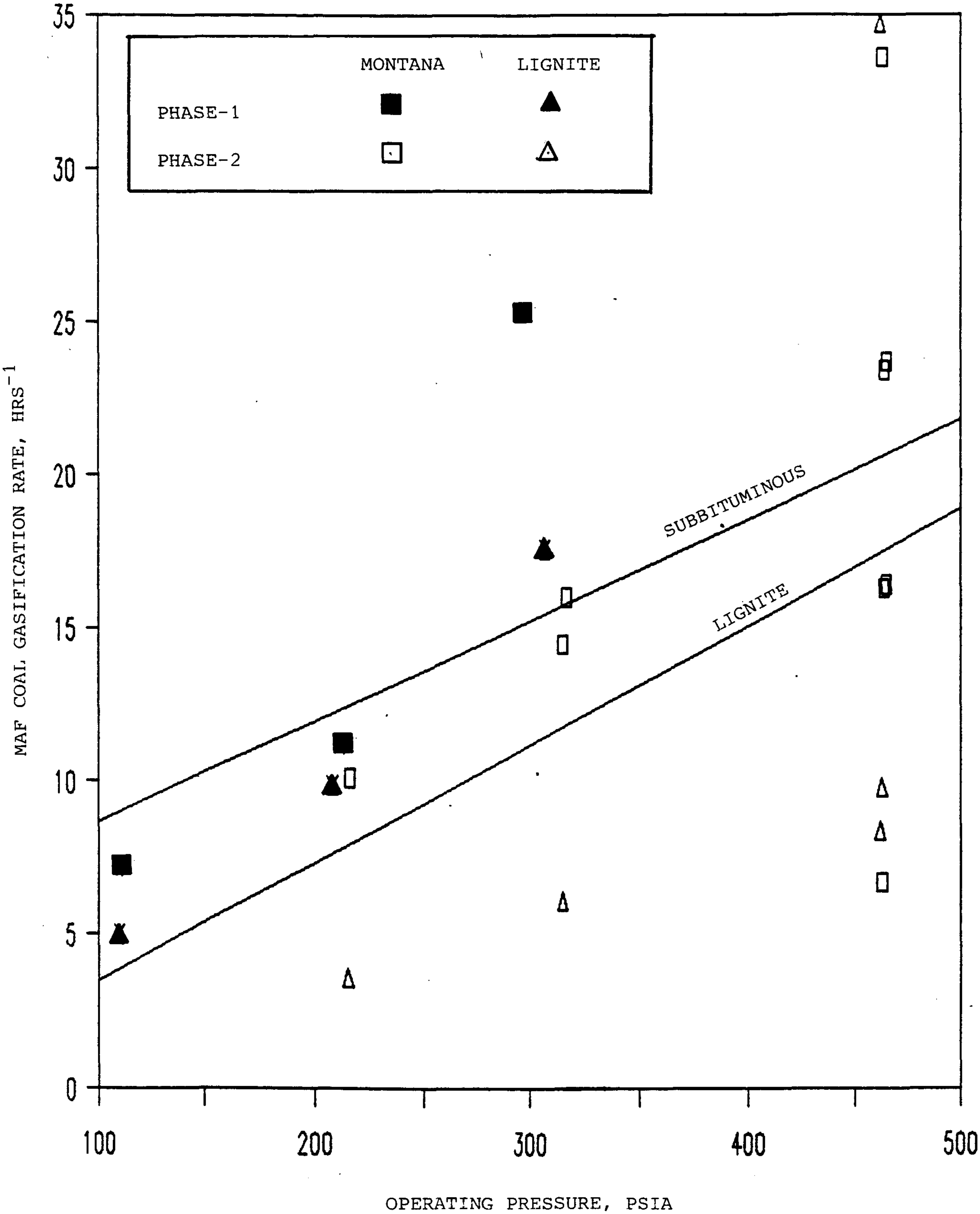
PRESSURE EFFECTS

CASE NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
GRI RUN NO.	5-1	5-1	5-1	5-2	5-2	5-2	5-3	5-3	5-3	6-1	6-2	6-2	6-2	6-2	7-2
SET POINT	1	2A	2B	1	2	3	1	3	2	1	1	2	3	4	7
COAL TYPE	---MONTANA ROSEBUD STUBBITUMINOUS---									---NORTH DAKOTA LIGNITE---					ILLINOIS NO. 6
PRESSURE, psig	201	300	302	450	450	449	449	448	448	200	300	448	447	447	151
COAL FEED RATE, lb/hr	352.9	537.1	479.8	499.7	866.1	661.6	531.0	379.4	834.2	260.7	345.1	487.7	590.2	865.2	200.1
MAF COAL FEED RATE, lb/hr	299.9	449.4	385.1	409.4	712.4	546.7	423.6	301.5	654.8	202.5	251.9	351.7	417.5	603.7	170.8
BED INVENTORY, lb	29.8	31.0	24.0	25.0	30.1	23.4	26.0	45.2	19.5	56.1	41.1	35.8	49.7	17.4	38.3
SOLID SPACE VELOCITY, hr^{-1}(1)	10.1	14.5	16.0	16.4	23.7	23.4	16.3	6.7	33.6	3.6	6.1	9.8	8.4	34.7	4.5
FRACTION OF CARBON CONVERTED, f_c	0.607	0.495	0.506	0.775	0.890	0.718	0.852	0.713	0.963	0.727	0.793	0.744	0.771	0.817	0.751
CH_4 MAKE, lb/hr	21.2	36.9	29.7	44.6	84.5	53.1	44.4	29.5	77.3	15.4	23.9	33.0	45.6	64.8	18.4
lb CH_4/lb MAF COAL	0.071	0.082	0.077	0.109	0.119	0.097	0.105	0.098	0.118	0.076	0.095	0.094	0.109	0.107	0.108
% FEED C TO CH_4	7.3	8.4	7.9	11.2	12.1	10.0	10.1	10.1	12.4	8.3	9.9	9.8	11.4	11.2	10.5
COLLECTED FINES RATE, lb/hr	45.7	78.2	88.5	48.9	69.8	55.8	59.2	46.7	59.4	39.9	49.3	65.2	76.6	73.1	26.3
COLLECTED FINES, lb/lb COAL FEED	0.129	0.146	0.184	0.098	0.081	0.084	0.111	0.123	0.071	0.153	0.143	0.134	0.130	0.084	0.131

NOTES: (1) Ratio of MAF coal feed rate to bed inventory.

FIGURE 6.5

EFFECT OF PRESSURE ON GASIFICATION RATE



This is illustrated in Figure 6.6 which shows that the steam feed rate was essentially proportional to operating pressure for all of the Phase-1 and Phase-2 data. Therefore, the coal feed rate increases with pressure approximately in accordance with the steam/coal ratio employed.

The methane yield, in terms of the percent of feed carbon converted to methane, generally increases with operating pressure, as illustrated in Figure 6.7 and 6.8. For North Dakota lignite, the Phase-1 and Phase-2 data follow the same general trend. However, for the Montana subbituminous coal, the Phase-1 methane yields appear to be higher than those for Phase-2. This difference could not be ascribed to the coal feedstock since the MAF volatile contents were consistently in the 41-42% range. In an attempt to rationalize the methane data from the subbituminous coal tests, possible correlations with other variables were examined, since the data plotted in Figure 6.7 and 6.8 were obtained under a variety of operating conditions other than pressure. The relative lack of scatter for the lignite data suggested that the lignite tests were perhaps conducted over a more limited range of other variables than were the subbituminous tests.

The Phase-1 and Phase-2 methane data were analyzed relative to potential variables which would be expected to influence the methane yield, such as carbon conversion, temperature, and steam level. The most likely variable to effect the methane yield was the carbon conversion level, which is partially a function of temperature. Consequently, the conversion level was factored in by correlating the methane selectivity with pressure, as indicated in Figure 6.9 and 6.10. Although, the data as plotted in this fashion are still fairly scattered, the trend with pressure is obvious and the Phase-1 and Phase-2 data tend to merge.

The absolute effects of pressure on fines carryover from the PDU gasifier could not be established from the data since IGT did not measure the particulate loading in the cyclone overhead. However, assuming that the cyclone operated at constant efficiency, the data should indicate the relative effects. The experimental entrainment data, based on the solids collected in the cyclone, for both Phase-1 and Phase-2 are summarized in Table 6.6.

The entrainment of solids from a fluidized bed is expected to vary directly with the linear velocity, V_g, and with gas density $_G$, in which the latter dependence is a function of operating pressure. In general, IGT's entrainment data follow this relationship, as illustrated in Figures 6.11 and 6.12 where fines loading is plotted against mass velocity for the Phase-1 and Phase-2 data.

TABLE 6.6

FINES ENTRAINMENT DATA

PHASE	CASE NO.	PRESSURE PSIA	OVERHEAD FINES LB / LB Coal	OVERHEAD FINES LB / $1000ft^3$	GAS* VELOCITY fps	GAS DENSITY LB/ft^3	GAS MASS VELOCITY LB/ft^2-hr
			MONTANA SUBBITUMINOUS				
1	2	111	0.100	3.8	0.87	0.103	323
	3	210	0.100	5.9	0.69	0.200	497
	4	213	0.088	6.1	0.81	0.204	595
2	1	216	0.129	7.9	0.92	0.202	669
	2	315	0.146	14.3	0.86	0.286	885
	3	317	0.184	17.5	0.80	0.295	850
1	5	297	0.090	7.0	0.67	0.303	731
2	4	465	0.098	10.3	0.74	0.468	1247
	5	465	0.081	12.6	0.87	0.456	1428
	6	464	0.084	11.2	0.79	0.454	1291
	7	464	0.111	12.1	0.77	0.458	1270
	8	463	0.123	10.6	0.70	0.476	1200
	9	463	0.071	9.5	0.98	0.431	1521
			NORTH DAKOTA LIGNITE				
2	10	215	0.153	8.5	0.74	0.223	594
	11	315	0.143	10.7	0.72	0.328	850
1	8	307	0.095	9.1	0.72	0.311	806
2	12	463	0.134	15.9	0.64	0.489	1127
	13	462	0.130	18.2	0.66	0.491	1167
	14	462	0.084	14.4	0.80	0.465	1339

*Velocity in 18 inch diameter freeboard section.

FIGURE 6.6

EFFECT OF PRESSURE ON GASIFIER THROUGHPUT

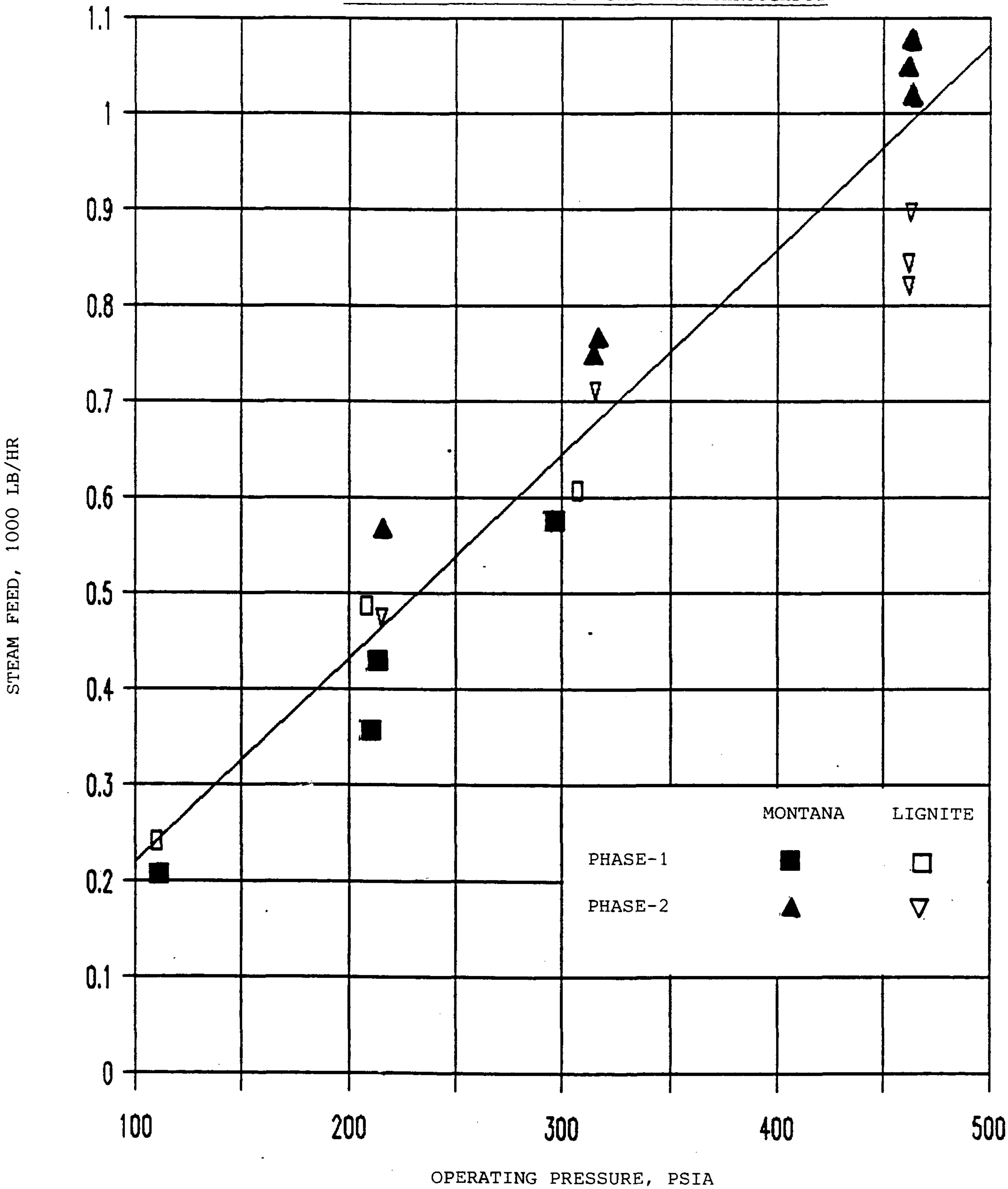


FIGURE 6.7

METHANE FORMATION - SUBBITUMINOUS COAL

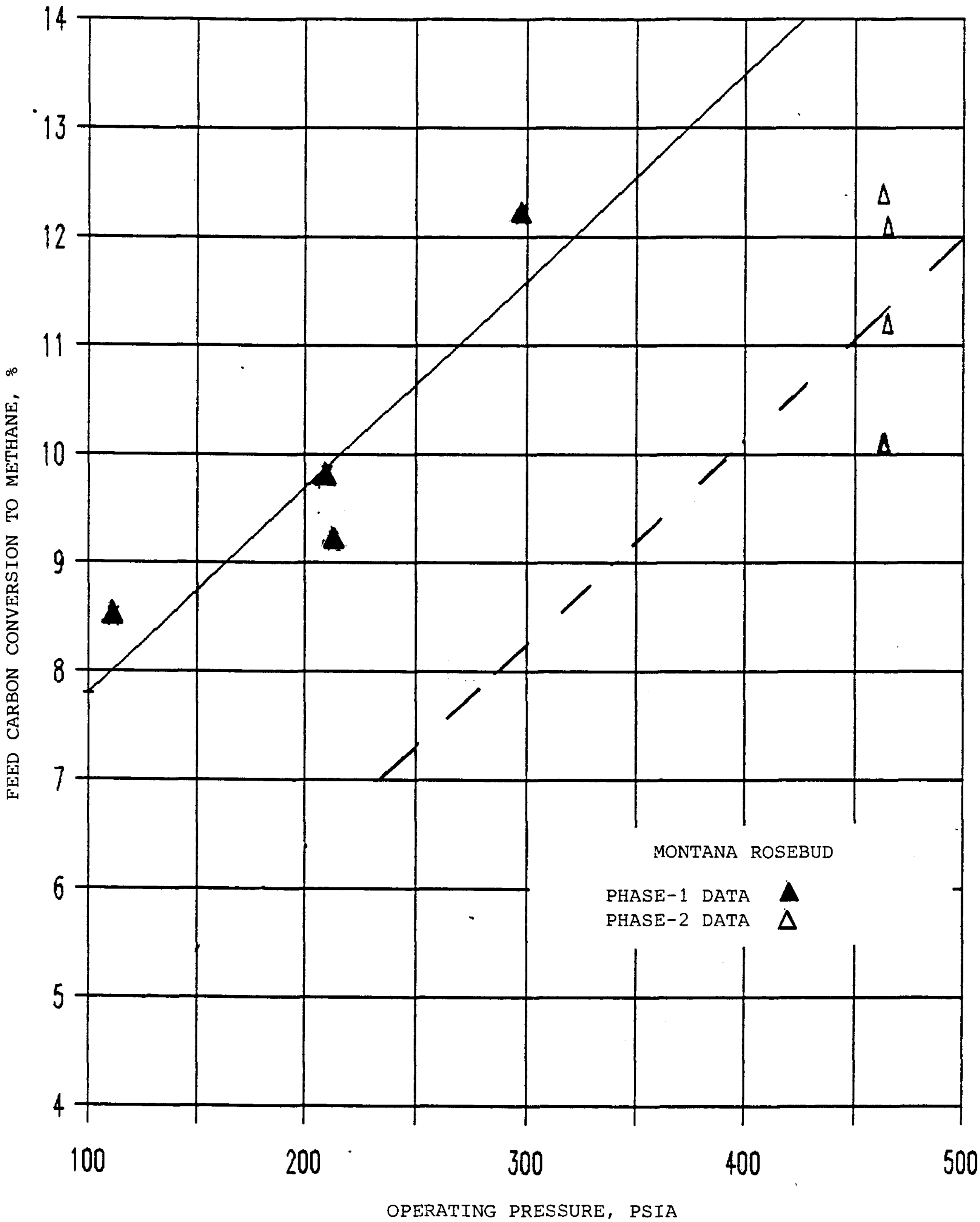


FIGURE 6.8

METHANE FORMATION - LIGNITE

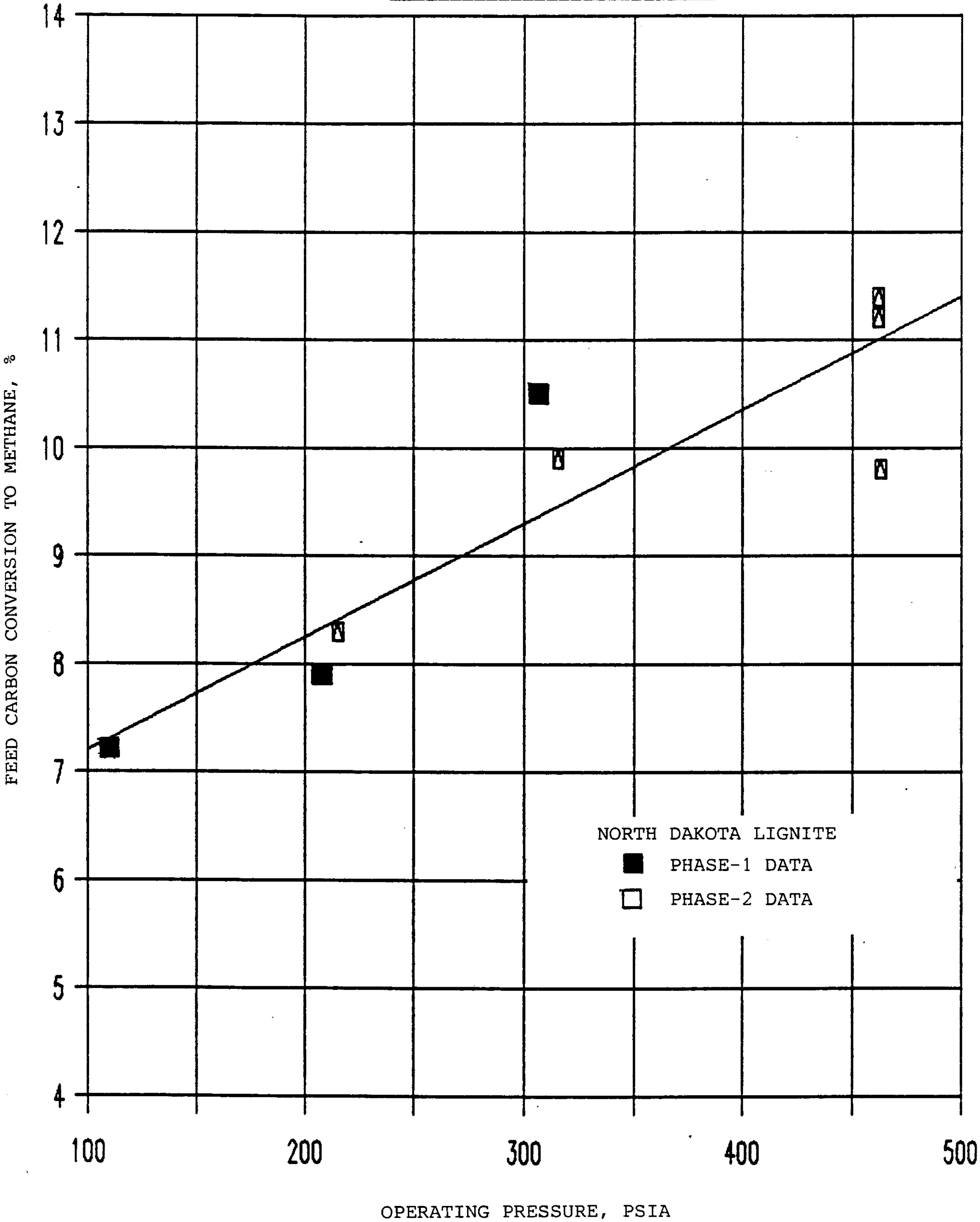


FIGURE 6.9

METHANE SELECTIVITY - SUBBITUMINOUS COAL

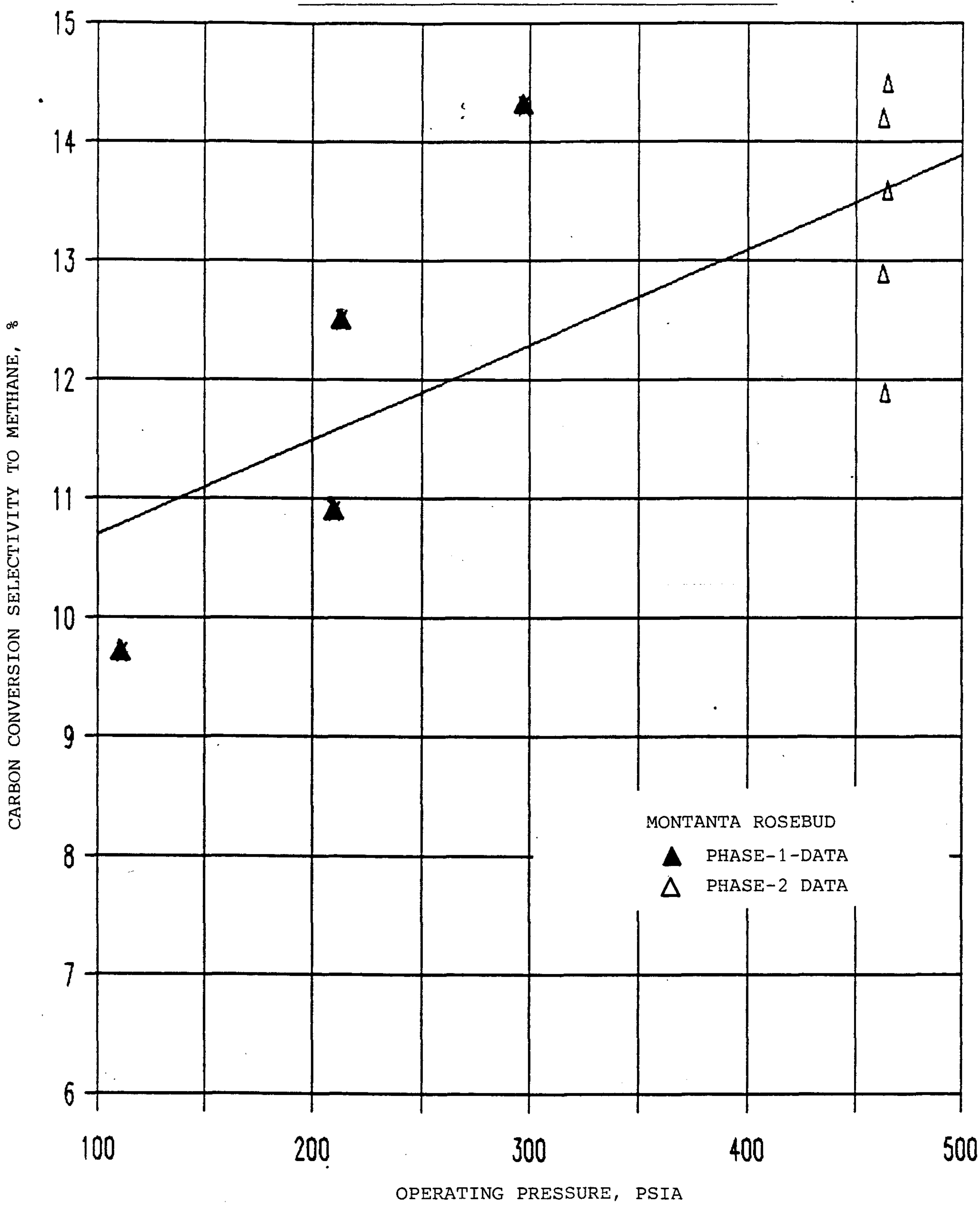


FIGURE 6.10

METHANE SELECTIVITY - LIGNITE

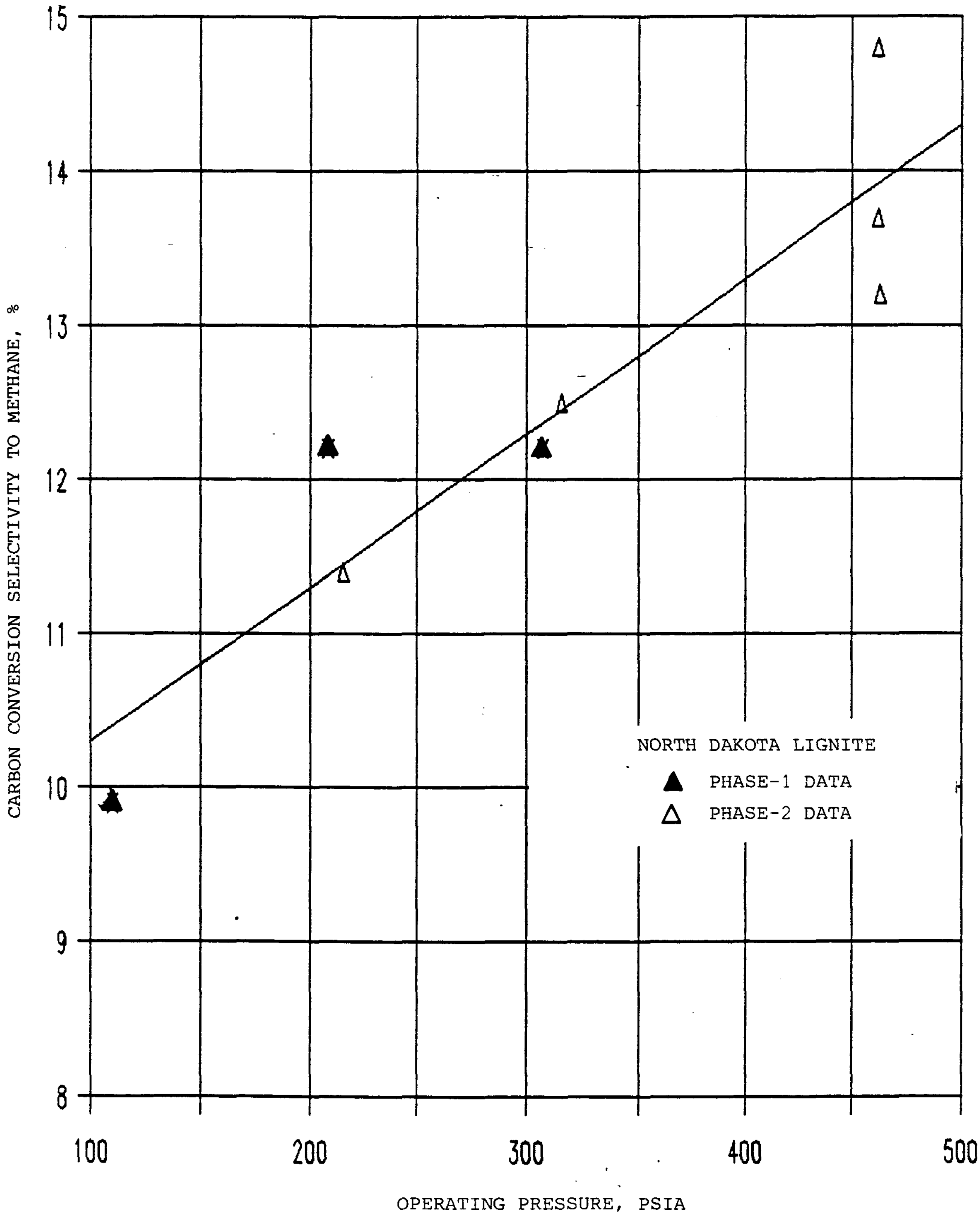


FIGURE 6.11

FINES ENTRAINMENT - SUBBITUMINOUS COAL

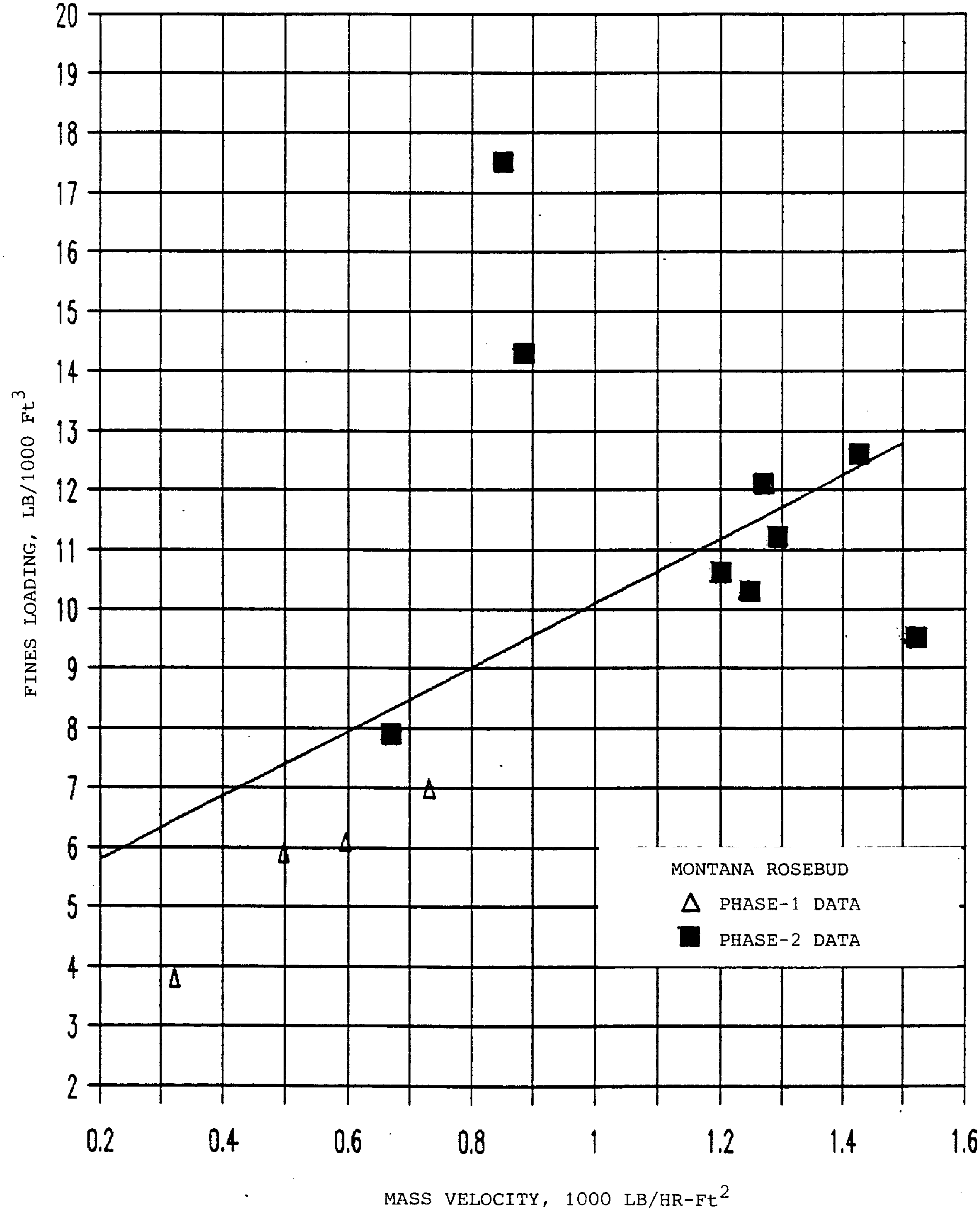
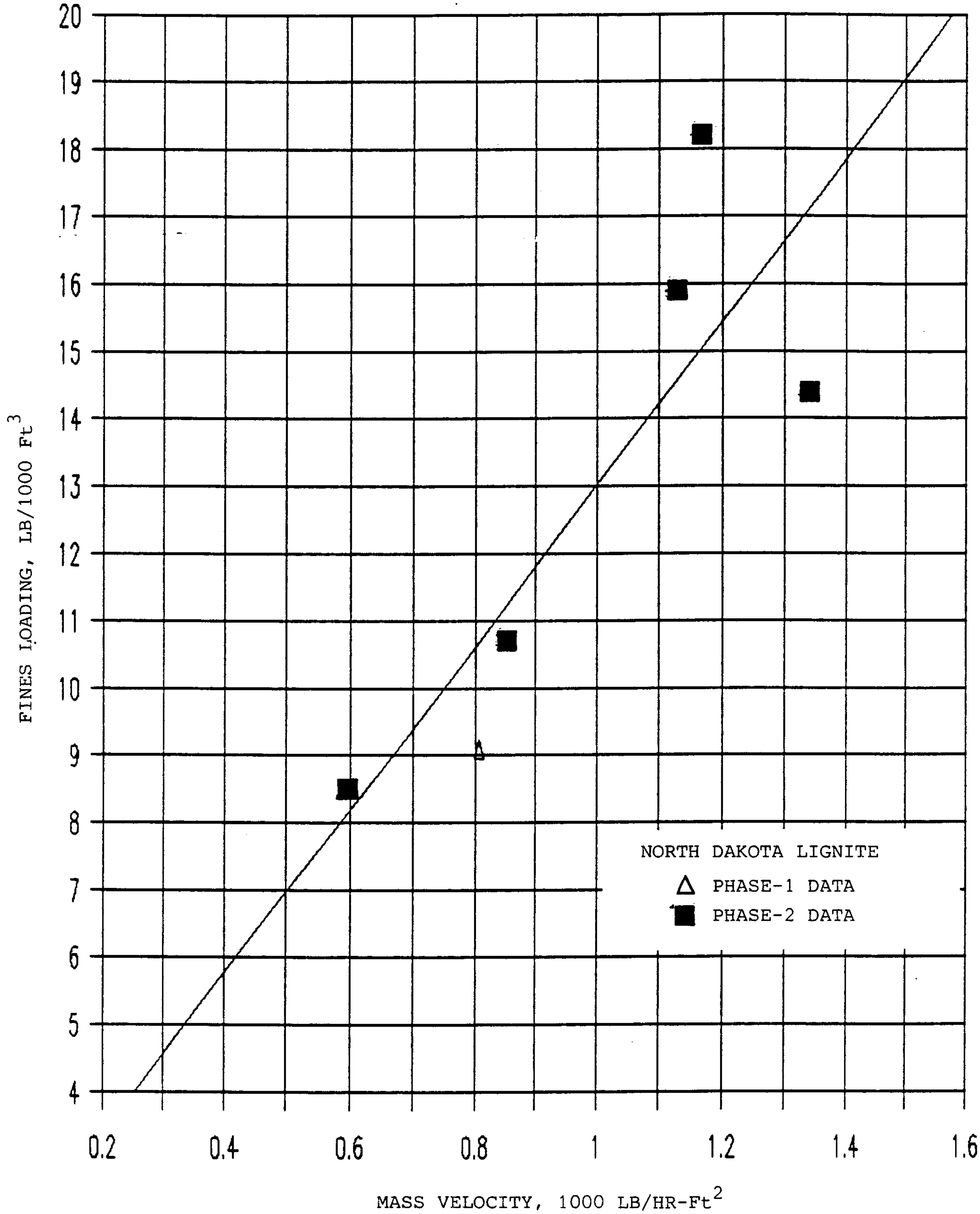


FIGURE 6.12

FINES ENTRAINMENT - LIGNITE



7.0 ASSESSMENT OF DATA QUALITY

Based on Foster Wheeler's analysis and correlation of the Phase-2 test results, the quality of IGT's data was assessed as follows:

- Except for the single test on Illinois bituminous coal, the Phase-2 tests met the established criteria for steady state operation of the PDU. The short run time obtained for the Illinois No. 6 test makes it doubtful that the results are representative of a true steady state test.

- In general, the tests conducted on Montana subbituminous coal and North Dakota lignite met the steady state criteria as established for PDU operating conditions. With only minor differences, Foster Wheeler agreed with the steady state feed rates reported by IGT.

- The overall mass and heat balance closures were generally within the range of ±5%, which is acceptable for the type of PDU test work conducted. However, the carbon and hydrogen elemental balances, as determined by Foster Wheeler, showed closures which were greater than ±5% in most of the tests. Consequently, the Phase-2 test results are questionable in view of these inconsistencies in elemental balances.

- The major problem areas, which likely contributed to the poor elemental balances, were IGT's techniques for measuring the product gas flow rate and gas composition. Due to lack of confidence in the product gas flow rate, IGT elected to ignore this data in establishing the moisture content and overall hydrogen balance. In any future work, a flow meter which is not affected by moisture content and particulate matter should be employed, such as a laser Doppler instrument.

  Because of difficulties with their on-line gas chromatograph, IGT used bomb samples to obtain product gas analyses. These measurements were taken at infrequent intervals during the steady state periods and the subsequent gas analyses, which were made after unspecified time delays, resulted in questionable results. Continuous gas chromatographic analyses is the only reliable technique for obtaining a representative measurement of the product gas composition, which is a primary requirement for meaningful PDU tests.

One of the objectives of IGT's test program was to investigate the effects of certain operating variables, such as temperature, steam/coal ratio, coal feed rate, and operating pressure. However, the actual test conditions did not correspond to the planned test matrix. Presumably, this was due to operating problems experienced by IGT. Consequently, the effects of individual operating variables on PDU performance were generally obscured. Nevertheless, the results of the Phase-2 data, in conjunction with the earlier Phase-1 data, indicated the following trends:

- In general, carbon conversion increased with the bed temperature. However, the carbon conversion levels were relatively low, less than 80%, for most of the Phase-2 runs. Furthermore, except for three runs, the PDU was operated in a partial combustion mode, as indicated by negative values of R_c-R.

- The product gas compositions showed reasonable agreement with the water gas shift equilibrium. As expected, the experimental methane composition exceeded the gas phase equilibrium value by at least an order of magnitude. In addition, the selectivity of carbon conversion to methane generally increased with system pressure.

- The relative entrainment of solids from the fluid bed gasifier, in terms of the particulate loading in product gas, showed an increasing trend with gas mass velocity. Data on the absolute solids carryover were not available since IGT did not measure the particulate content in the cyclone overhead gas.

The above data trends were not surprising. In this sense, the IGT experimental data were generally consistent with the expected results.

8.0 LITERATURE REFERENCES

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APPENDIX- A

Sample Calculation of the Maximum Theoretical Cold Gas Efficiency

To calculate the maximum theoretical cold gas efficiency based on the coal composition, percent of stoichiometric combustion oxygen fed, and the fraction of carbon converted, it is assumed that the hydrogen in the coal will form hydrogen gas, the available oxygen will convert carbon to carbon monoxide, and the remaining carbon will react with steam to form carbon monoxide and hydrogen gas. For example, the relevant information and reactions are as follows:

- The coal composition is $CH_{0.687}$ (0.056 H_2O)
- The oxygen fed = 0.365 moles O_2/atom of C fed
- The fraction of carbon converted = 0.799
- $(0.799)\ C + (0.687)\ H + (0.365)\ O_2 + (0.069)\ H_2O \longrightarrow$ Products

Base on the above reaction, the following product slate is obtained:

(1) 0.3435 H_2 (from coal)
(2) 0.730 CO (from coal + O_2)
(3) 0.069 CO (from coal + H_2O)
(4) 0.069 H_2 (from coal + H_2O)

Accordingly, the total production of CO and H_2 are:

CO total = 0.799 moles
H_2 total = 0.4125 moles

The maximum theoretical cold gas efficiency is then calculated by dividing the heating value of the gas formed from the above reaction by the molecular weight of the coal, per atom of carbon (on a MAF basis), times the coal higher heating value on a MAF basis. The information needed and the calculation are as follows:

- Coal molecular weight (MAF) = 14.352 lb/atom of carbon
- Coal HHV (MAF) = 15,025 Btu/lb
- CO HHV = 121,764 Btu/lb-mol
- H_2 HHV = 123,178 Btu/lb mol

Consequently, the maximum theoretical cold gas efficiency is:

$$= \left[\frac{0.799\ (121,764) + 0.4125\ (123,178)}{14.352\ (15,025)}\right] \times 100 \quad = 68.68\%$$