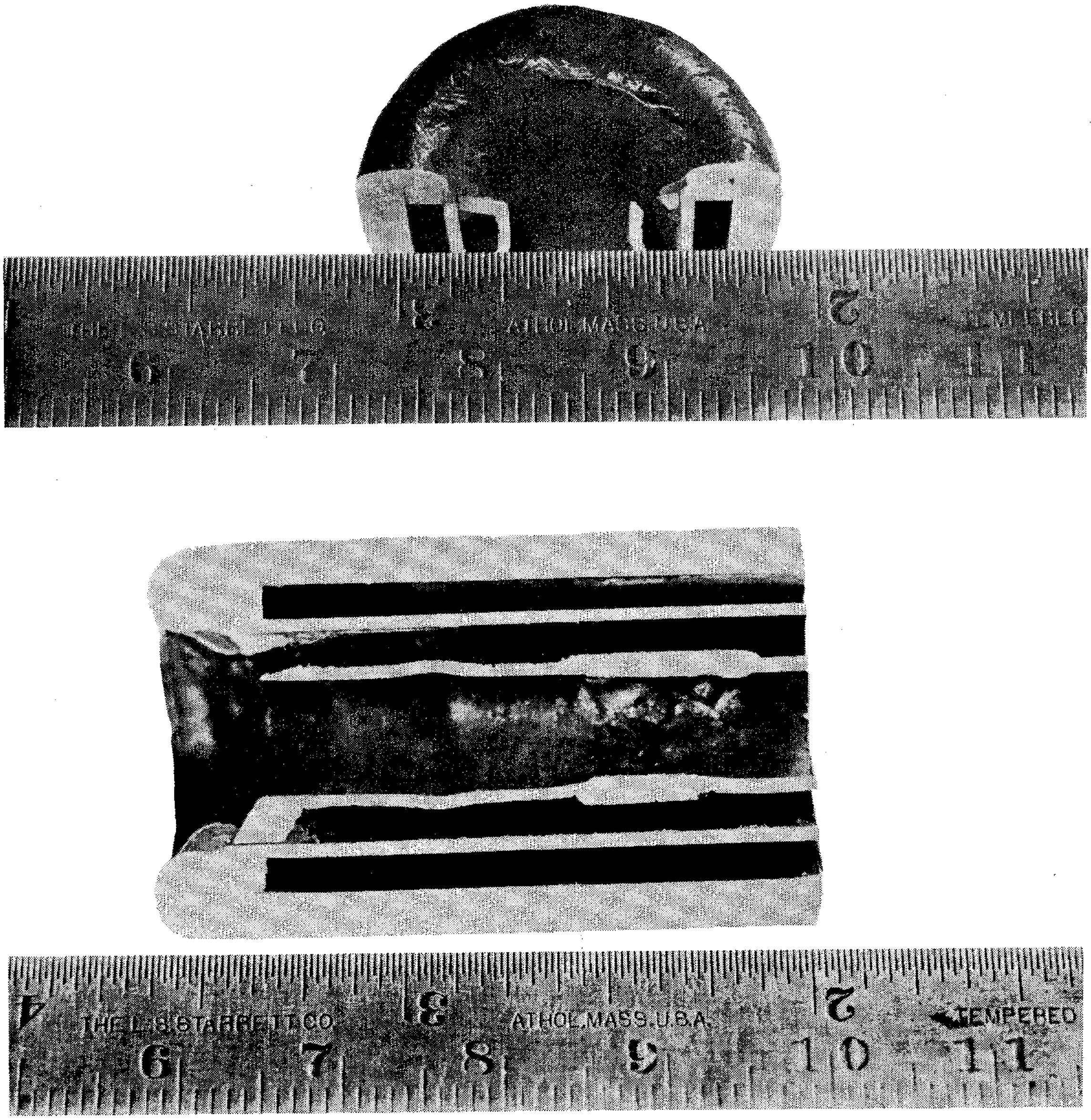

FIGURE 26. - Cutaway View of Pilot Burner.

COAL GASIFIED

All gasification runs were made with Sewickley-bed, run-of-mine bituminous coal from the Bunker mine, Morgantown, W. Va. The coal was crushed in a hammer mill and comminuted in a Raymond pulverizer to yield 70 percent through 200-mesh. Table 3 shows the average analysis of the coal used.

PILOT-PLANT OPERATING PROCEDURES

Experiments were conducted at four operating pressures--75, 100, 150, and 300 p.s.i.g., three coal rates--400, 700, and 1,000 pounds per hour, and oxygen-to-coal ratios ranging from 8 to 11 std. c.f. per pound. Combinations of these test conditions (particularly conditions of high coal rate and low operating pressure) imposed excessive demands on the gasifier and scrubber, because gas and water flow rates were much higher than design specifications. Each major change in test conditions necessitated changing the orifice plates of the orifice meters for the raw materials and product gas and, sometimes, for the cooling water. Consequently, the runs were not made in uninterrupted succession but were accompanied by frequent shutdowns for checking coal feed rates, changing orifices, making construction and operational changes, and building up a supply of oxygen or pulverized coal.

TABLE 3. - Average analysis and standard deviation of analyses of coal used in high-pressure gasification runs 23 to 68

		Standard deviation
Ultimate analysis:	Percent	
Moisture	1.6	0.27
Hydrogen	4.8	.20
Total carbon	70.9	1.50
Nitrogen	1.4	.82
Oxygen	6.2	.66
Sulfur	1.3	.61
Ash	13.8	1.41
Calorific value:	B.t.u.	
As-received	12,750	222
Moisture and ash free	15,070	74
Fusibility of ash:	°F.	
Initial deformation	2,090	90
Softening temperature	2,240	86
Fluidity temperature	2,460	83
Screen analysis:	Percent	
Minus-20, plus-50-mesh	0.4	.33
Minus-50, plus-100-mesh	4.4	1.83
Minus-100, plus-140-mesh	8.9	3.25
Minus-140, plus-200-mesh	15.0	3.17
Minus-200-mesh	71.3	6.21

The following procedure was standard for a 300 p.s.i.g. operating run:

1. Make oxygen available to the pilot-burner valve.

2. Start the natural gas compressor.

3. Establish water flow in the gasifier cooling coils and the gasifier and scrubber sprays.

4. Purge the coal-feed line with inert gas, and remove the plug at the "Y" on the coal-feed inlet of the reactant-injection burner.

5. Start the steam ejector to purge air from the gasifier. Reduce the purge, then make sure the product-gas letdown valve or its bypass is open so that products of combustion from the pilot burner can escape from the gasifier.

6. Light the pilot burner with the spark ignitor in the coal pipe of the reactant-injection burner, then remove the ignitor and replace the plug in the coal feed line.

7. Cut off steam to the ejector.

8. Place oxygen and natural gas to the pilot burner on automatic control.

9. When temperature in the gasifier has leveled off, pressurize the gasifier to 200 p.s.i.g. with inert gas.

10. Admit 1,000° F. steam in the quantity desired for the run.

11. Check the gas leaving the gasifier with an Orsat gas analyzer. If oxygen does not exceed 0.5 percent the gasifier is ready for coal and oxygen, provided the Fireye still indicates the pilot burner is alight.

12. Set the gasifier pressure controller at 300 p.s.i.g. and admit coal at the required rate, then 4 seconds later admit oxygen. If there is a tendency for the pressure in the gasifier to exceed 300 p.s.i.g., open the gas letdown valve bypass.

13. Shut off the oxygen to the pilot burner and replace the flow of natural gas with 100 std. c.f. per hour of inert gas. Maintain the inert-gas flow to insure that the pilot-burner nose is kept clear of slag so that the coal gasification flame can keep the Fireye energized.

For a test run at 300 p.s.i.g., the pressure in the gasifier was held at 200 p.s.i.g. until the coal and oxygen were admitted. If the gasifier was brought to normal operating pressure before the reactants were admitted, the gasification of the coal would cause a sudden increase in pressure that would activate the safety system and cut off the supply of oxygen and coal.

SAMPLING GASES AND RESIDUES PRODUCED DURING GASIFICATION

Gases

The gas-sampling schedule for each gasification run was as follows:

1. A spot Orsat analysis was made of make gas each half hour.

2. Three gas samples were collected simultaneously for each data period of each run for complete analysis--one sample from the gasifier proper, one from the scrubber, and one from the flare stack.

3. A spot gas sample was taken each half hour for complete analysis, if desired.

4. Three composite gas samples were collected each data period of each run.

Table 4 shows typical gas analyses for various combinations of oxygen-to-coal ratio and pressure.

TABLE 4. - Typical gas analyses for various combinations of oxygen-to-coal ratio and pressure

Gasifier pressure, p.s.i.g.	Oxygen-to-coal ratio, std. c.f./lb.	Gas composition, volume-percent					
		CO_2	H_2	CO	CH_4	Illuminants	N_2
75...........	8.62	12.8	34.4	48.6	0.5	0.5	3.2
100...........	8.41	11.4	34.7	48.0	.5	.5	4.9
150...........	8.74	10.4	34.3	50.9	.4	.5	3.5
300...........	8.74	9.3	34.1	50.3	.4	.5	5.4
75...........	9.83	13.7	32.5	50.0	.3	.5	2.8
100...........	9.66	12.0	33.0	50.7	.4	.5	3.4
150...........	9.80	10.9	32.6	52.2	.3	.5	3.4
300...........	9.86	10.4	32.5	51.3	.3	.5	5.0
75...........	10.81	15.2	31.0	49.5	.4	.5	3.4
100...........	10.56	13.1	31.8	50.4	.3	.5	4.0
150...........	10.64	11.6	31.2	53.1	.3	.5	3.4
300...........	11.18	12.7	30.5	51.2	.3	.5	4.9

Residues

The solid residual material produced during a high-pressure gasification run consists of fly ash, char, coke, clinker, and particles of refractory material. During some test runs, residue samples from the gasifier and scrubber were taken every half hour of each data period. (See fig. 1, p. 5, for location of residue sampling points.) These residues were measured and analyzed to provide information for material balances for the process and to determine their physical and chemical characteristics. Information about the characteristics of residues is important to the design and operation of synthesis-gas purification systems.17/ Moreover, the material balance is valuable for determining carbon gasified and for checking flowmeter measurements of the product gases.

17/ Strimbeck, G. R., Cordiner, J. B., Jr., Taylor, H. G., Plants, K. D., and Schmidt, L. D., Progress Report on Operation of Pressure-Gasification Pilot Plant Utilizing Pulverized Coal and Oxygen: Bureau of Mines Rept. of Investigations 4971, 1953, pp. 24 and 25.

EXPERIMENTAL PLAN

The experimental runs covered in this report provided considerable information on the operability of the pilot-plant equipment and the relative merits of both the refractory-lined gasifier (runs P-23 to P-35) and the gasifier with the water-cooled lining--discussed on the preceding pages of this report. However, only the gasifier with the water-cooled liner was used for the experiment designed to determine the effects of varying operating conditions. After several gasification runs were made to test the redesigned gasifier and associated equipment and to provide additional training for operators (runs P-36 to P-42), a factorial experiment, runs P-43 to P-68, was set up. A factorial experiment is a series of tests relating to a process, in which independent variables within the process are set at two or more levels or values; trials of the process are then carried out with all possible combinations of the values of the independent variables.

The primary purpose of the experiment was to determine the effect of coal rate, oxygen-to-coal ratio, and pressure on the economy of the process and on related variables; hence, three levels of coal rate, three levels of oxygen-to-coal ratios, and four levels of pressure, with replication, were used. Runs were repeated if the experimental conditions did not approximate those desired.

It was found that the coal feed could not be set at the specific rates desired for the factorial experiment, which meant that the oxygen-to-coal ratio also could not be set at the desired levels. As a result, it was impractical to obtain, at certain specific levels of coal rate and oxygen-to-coal ratio, the 72 periods originally planned for the experiment. (Although the coal-feed rate could not be set consistently at a desired level, the rate could be maintained throughout a run period within 3 percent of the actual value. Actual coal rates were determined after each test by weighing the total amount of coal charged to the feeder during the run and subtracting the amount remaining in the feeder after the run.) As the independent variables could not be set at specific levels, data analyses appropriate to a factorial experiment could not be used, and standard regression calculations were applied.

ACCURACY OF RESULTS

Measuring Reactants and Product Gases

The average error of the oxygen flow probably was about 1 percent and the average error of steam and coal flows about 2 percent.

Because the product gas contained dust and moisture, its measurement was subject to larger errors. Two meters--an orifice type and a positive-displacement type, both installed downstream from the pressure letdown valve--were used to measure the product gas. The standard deviation of the difference in flow, as measured by these two meters, was 5 percent.

A composite sample of product gas, collected continuously throughout each run, was analyzed with a precision Orsat apparatus. The experimental error of the sampling and analytical procedure is difficult to estimate.

Errors in oxygen requirement, coal requirement, and carbon gasified (percent) were caused primarily by errors in product-gas and coal-rate measurements and product-gas analyses. Errors in the heat loss were due primarily to errors in measuring cooling-water temperatures and rates. The exit-gas temperature was calculated from the heat balance, which, to balance, generally required the addition or subtraction of rather large, unaccounted-for quantities of heat.

Gas Analysis

Simultaneous gas samples were taken from the exit of the reaction zone, the scrubber outlet, and the flare stack (see fig. 1, p. 5) to determine if the composition of the gas was changed by the scrubber. Analyzed by a precision Orsat, the samples at these points differed only slightly in composition, the differences being due at least partly to sampling and purging difficulties in taking samples from vessels containing gases at elevated pressure. The largest gaseous constituent of the scrubber water was CO_2, but analyses of the water leaving the scrubber indicated that the amount of CO_2 absorbed in the water would change the gas analysis by no more than 0.3 percent.

The differences in Orsat analyses indicated that the water-gas shift reaction took place before the gas passed the sampling point in the gasifier.

Approximately 10 percent of the sulfur in the coal was removed by the gasifier and scrubber sprays.

Calculations and Graphs

Accuracy of the results, including calculations and graphs, is discussed in Appendix II.

RESULTS--DISCUSSION AND ANALYSIS

Appendix I, table 5, gives the operating conditions of the experimental tests and the principal results used in the correlations developed.

The data were analyzed in the following three groups, subdivided according to pressure: Group I, pressure levels of 75 and 100 p.s.i.g.; group II, 100 and 150 p.s.i.g.; and group III, 150 and 300 p.s.i.g. The result would be essentially the same if all data were used and a cubic relation was established for the pressure, but the deviations in the data were considered too large to warrant the use of an equation of such high degree. The effect of dividing the data into the three groups is to replace a continuous curve with three straight segments, the 100 to 150 p.s.i.g. group being included to see that the middle segment joins the two end segments. In other words, for 100 p.s.i.g., essentially the same result should be obtained from the 75 to 100 group as from the 100 to 150 group.

Except for the 150 to 300 p.s.i.g. group, in which a pressure-coal rate interaction term was added to the equations for the correlations involving oxygen requirement, coal requirement, and carbon gasified, an empirical equation containing the following terms was fitted to each section of the data.

1. Linear pressure.
2. Linear coal rate.
3. Linear oxygen-to-coal ratio.
4. Quadratic coal rate.
5. Quadratic oxygen-to-coal ratio.
6. Interaction of coal rate multiplied by oxygen-to-coal ratio.
7. Constant term.

The pressure-coal rate interaction term was used for the heat-loss correlation of the two lower pressure groups. The standard procedure of multiple regression analysis was used.[18/] Matrices were formed from the sums of squares and cross products of the independent variables, the matrices were inverted, and the seven coefficients were determined. The equations thus found were used to plot the results of the gasification runs.

Appendix II gives additional details about the method of calculation and includes the tables of values used in the regression calculations and the equations used to code the data to obtain conformable matrices.

The differences between the experimental values and those found from the equations are given in Appendix I, tables 6, 7, and 8. The differences between the two sets of calculated values at 100 and 150 p.s.i.g. may also be found from these tables.

As empirical equations were used to represent the data, the equations apply to the conditions used to obtain the data, that is, to an entrainment gasifier with the same heat loss and for the range of independent variables used in the tests.

Figures 27 and 28 are presented to illustrate the scatter of the data. These graphs permit a comparison of the measured values and the values computed from the equations.

Effect of Varying Operating Conditions

Carbon Gasified, Percent

Figure 29 shows that the percentage of carbon gasified is mainly a function of oxygen-to-coal ratio; the effects of other factors are small by comparison. In the oxygen-to-coal ratio range covered, the curves rise sharply but begin to level off, which must occur before a carbon gasified percentage of 100 is reached. At 75 p.s.i.g., the conversion of carbon to gas was highest when the coal rate was lowest, and conversion was lowest when the coal

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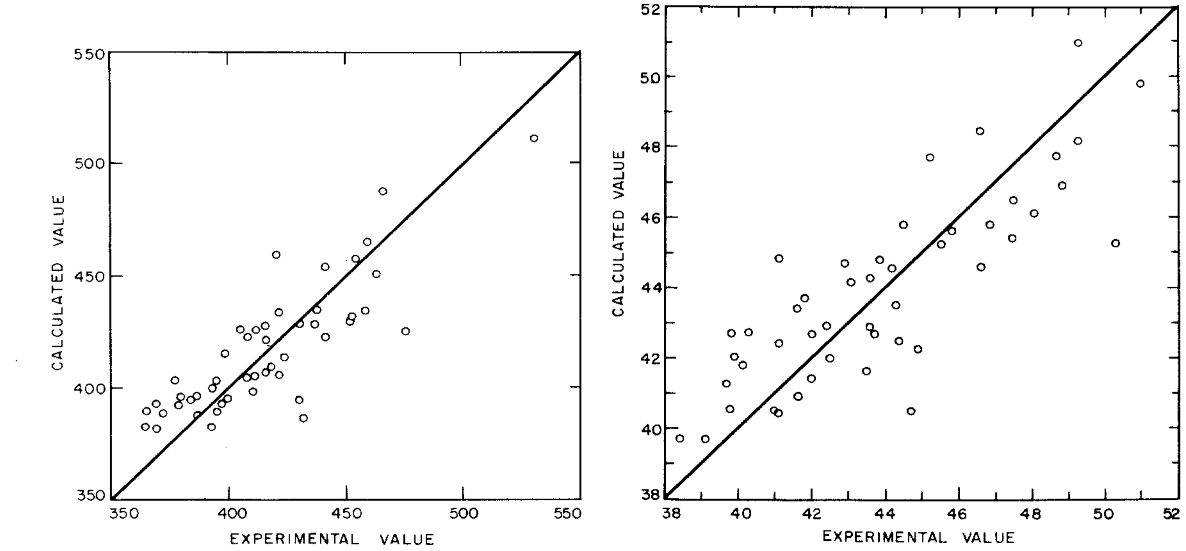
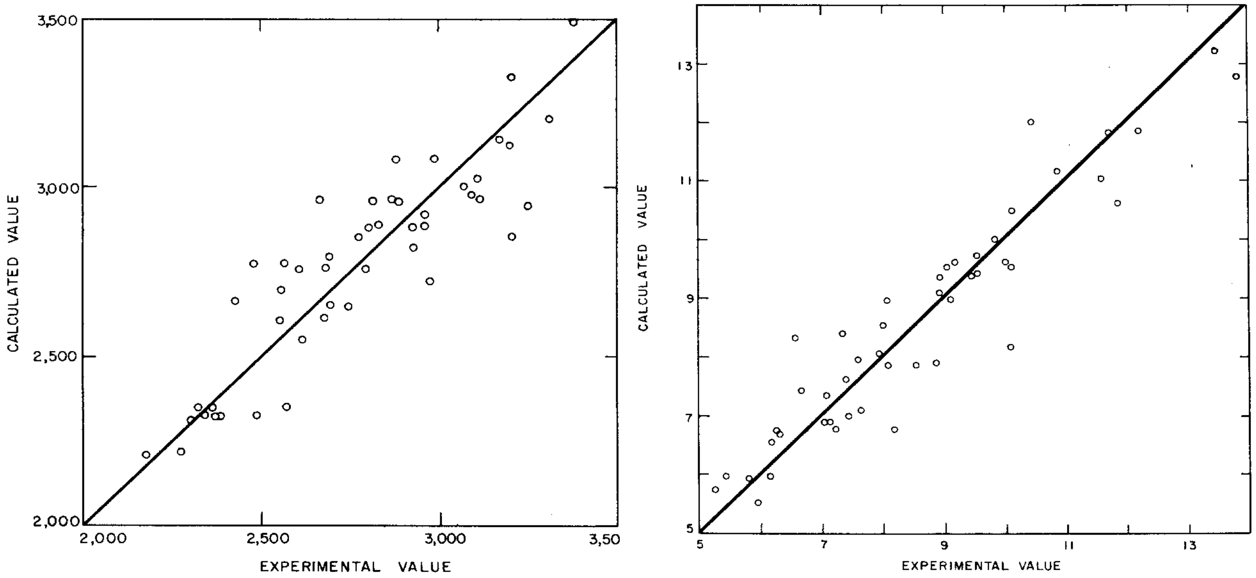
[18/] Davies, Owen L., The Design and Analysis of Industrial Experiments: Hafner Publishing Co., New York, N.Y., 1954, pp. 552-561.



OXYGEN REQUIREMENT,
STD. CU. FT. / M. STD. CU. FT. (CO+H$_2$)

COAL REQUIREMENT,
LBS./M. STD. CU. FT. (CO+H$_2$)



EXIT GAS TEMPERATURE, DEGREES F.

HEAT LOSS, HUNDRED B.T.U./LB. COAL

FIGURE 27. - Scatter of Data About Correlations; Gasifier Pressure, 75 and 100 p.s.i.g.

rate was highest. At 300 p.s.i.g., the opposite condition prevailed. A possible explanation is that at the lowest pressure the residence time (interval during which the reactants are in the reaction zone of the gasifier) is the limiting factor, and decreasing the coal rate increases the carbon gasified. On the other hand, at the highest pressure, heat loss is the limiting factor, and increasing the coal rate increases the carbon gasified (percent). The carbon gasified at the two intermediate pressures is in a transition region between these two extremes. For the 400-pound-per-hour coal rate, the effect of pressure on the carbon gasified was essentially zero; for coal rates of 700

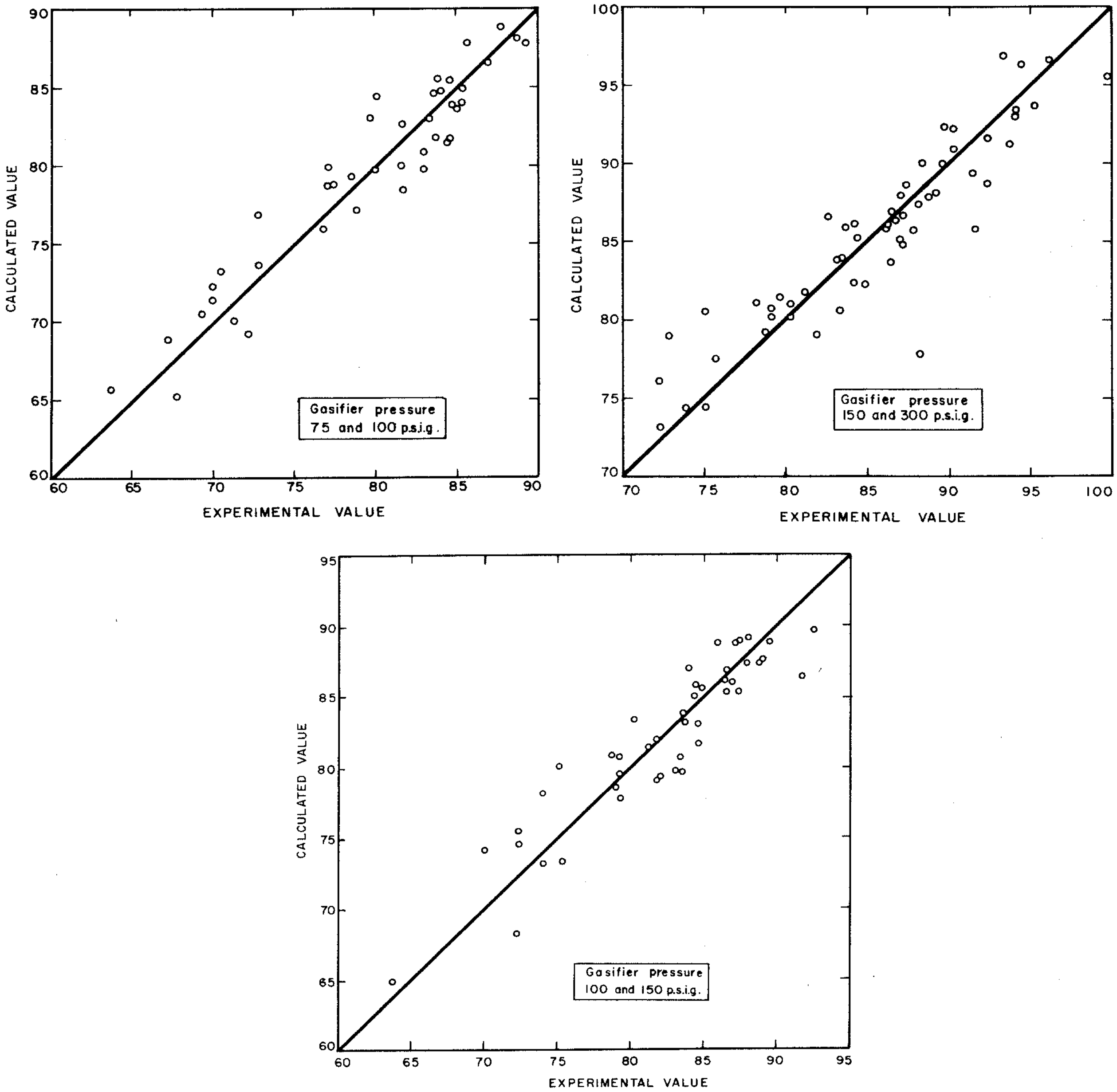


FIGURE 28. - Scatter of Data About Correlations; Carbon Gasified, Percent.

and 1,000 pounds per hour, the values at 100 and 150 p.s.i.g. were about the same, but the carbon gasified was lower at 75 p.s.i.g. and higher at 300 p.s.i.g.

Oxygen Requirement

As shown in figure 30, the effects of pressure and coal rate on oxygen requirement (std. c.f. per thousand std. c.f. CO + H_2 produced) were larger than on carbon gasified (percent); that is, although still largely a function

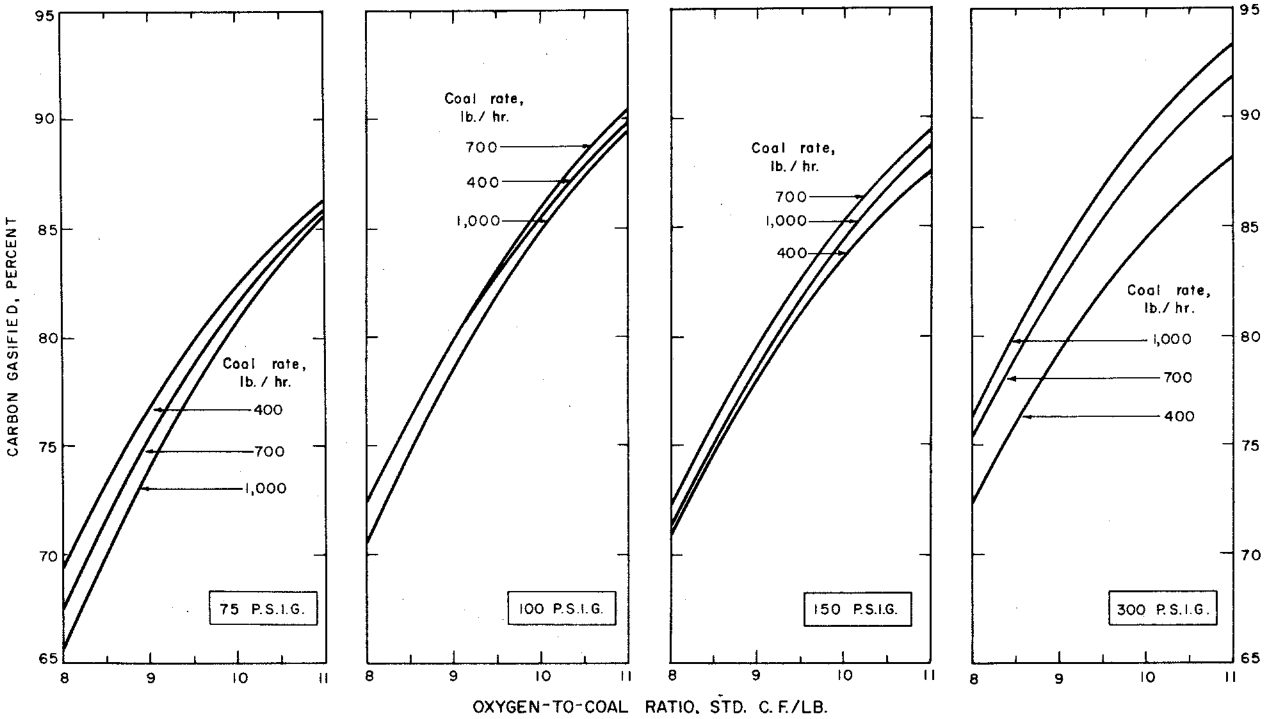


FIGURE 29. - Effect of Oxygen-to-Coal Ratio on Carbon Gasified, Percent; Gasifier Pressure, 75, 100, 150, and 300 p.s.i.g.

of oxygen-to-coal ratio, the oxygen requirement changed proportionately more with pressure and coal rate than did the percentage of carbon gasified. For the two lower pressures, 75 and 100 p.s.i.g., and the two lower coal rates, 400 and 700 pound per hour, the oxygen requirement reached a minimum at 8 to 8.5 std. c.f. of oxygen per pound of coal. For the three lower pressures, 75, 100, and 150 p.s.i.g., the oxygen requirements at coal rates of 400 and 700 pounds per hour were almost the same and were indistinguishable over most of the range of oxygen-to-coal ratios. For the three lower pressures, the oxygen requirement at a coal rate of 1,000 pounds per hour was higher than at the other two coal rates, whereas the reverse was true at 300 p.s.i.g. As discussed under Carbon Gasified, Percent, this change probably was caused by the opposing effects of residence time and heat loss. The oxygen requirement at a coal rate of 400 pounds per hour was about the same at the two higher pressures and increased slowly with a decrease in pressure. However, for the 1,000-pound-per-hour coal rate, the oxygen requirement increased markedly with decreased pressure throughout the entire range of pressures. The change in oxygen requirement with pressure for the 700-pound-per-hour coal rate was less than for the 1,000-pound-per-hour rate but more than for the 400-pound-per-hour rate.

Coal Requirement

The coal requirement (pounds per thousand std. c.f. of $CO + H_2$ produced), which is primarily a function of oxygen-to-coal ratio--the pressure and

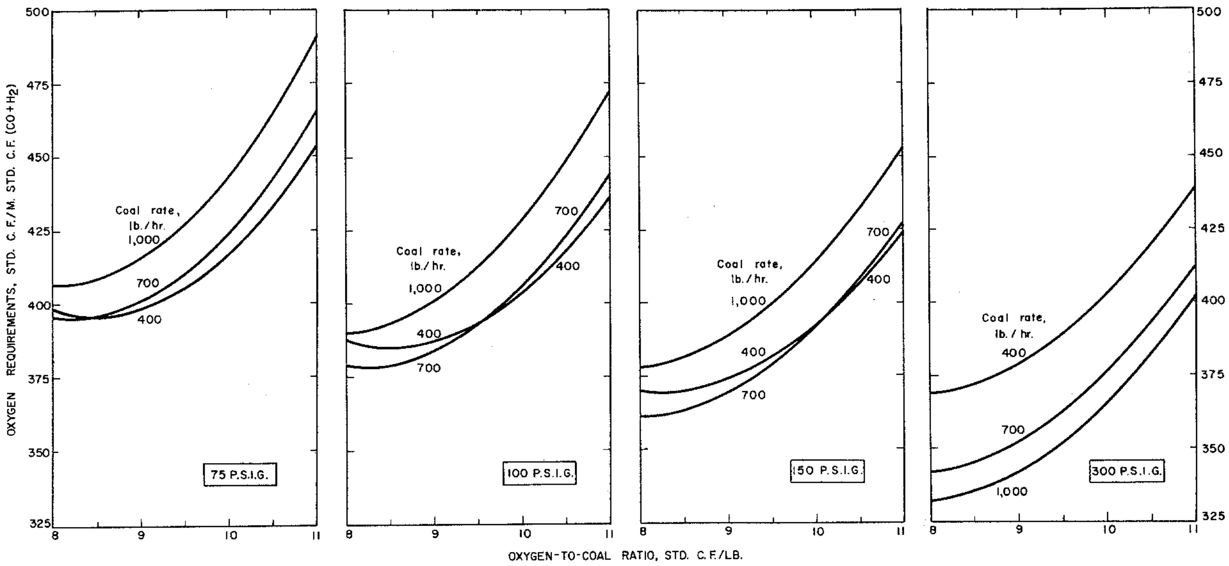


FIGURE 30. - Effect of Oxygen-to-Coal Ratio on Oxygen Requirement; Gasifier Pressure, 75, 100, 150, and 300 p.s.i.g.

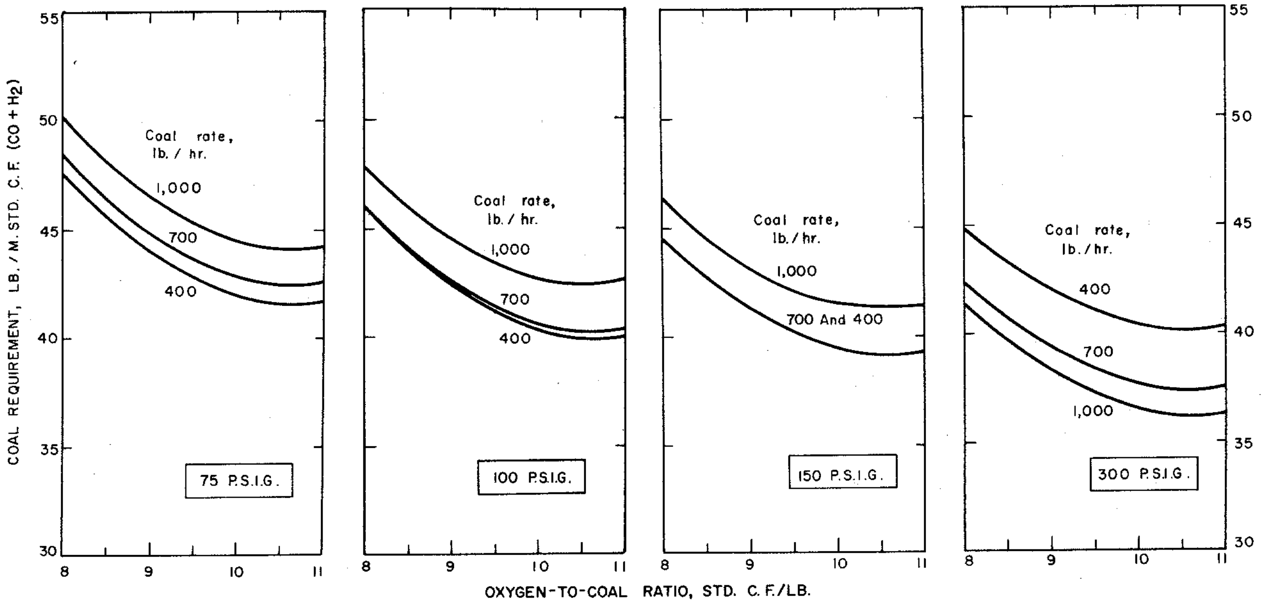


FIGURE 31. - Effect of Oxygen-to-Coal Ratio on Coal Requirement; Gasifier Pressure, 75, 100, 150, and 300 p.s.i.g.