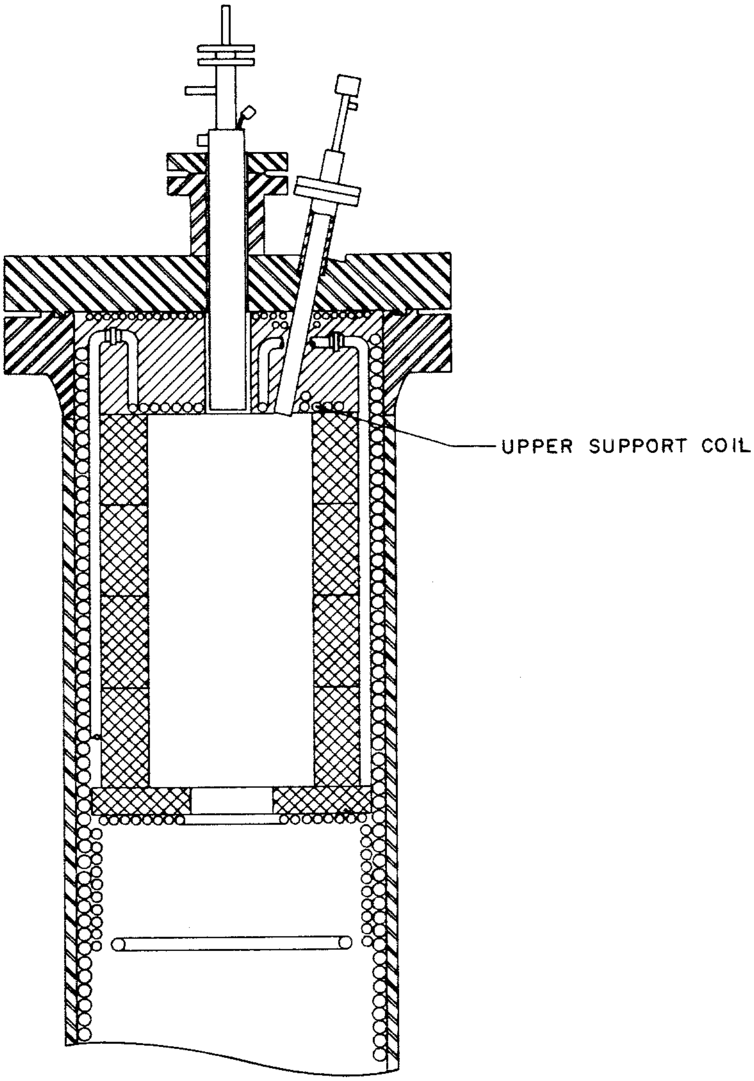

FIGURE 5. - Refractory-Lined Gasifier Modified by Addition of Upper Support Coil.

Data from operations with each of the two gasifiers were first correlated separately, without taking into account the effect of heat loss. Results from the water-cooled gasifier were published.[8] Results from the refractory-lined gasifier are given in table A-2. The combined data were then correlated by the same procedure with heat loss added as an independent variable. These correlations are presented in the graphs of this report.

ACCURACY OF RESULTS

Flow Measurement of Reactants and Product Gas

Based on calculations with the run data rather than on the planned values, the error in measuring oxygen to the gasifier averaged about 1 percent; the error in coal and steam rates averaged about 2 percent.

Flow measurement of the product gas was subject to somewhat larger errors because of the entrained dust and moisture. An orifice and a positive-displacement meter were used to measure the product gas. Standard deviation of the difference in flow given by these two meters was 3.8 percent.

Errors in carbon gasified and oxygen and coal requirement were caused chiefly by errors in measuring coal-feed rate and product-gas flow. Errors in heat loss were due mainly to errors in measuring temperature and flow rate of water used to cool the gasifier.

[8]Holden, J. H., Strimbeck, G. R., McGee, J. P., Wilmott, L. F., and Hirst, L. L., Operation of Pressure-Gasification Pilot Plant Utilizing Pulverized Coal and Oxygen. A Progress Report: Bureau of Mines Rept. of Investigations 5573, 1960, 56 pp.

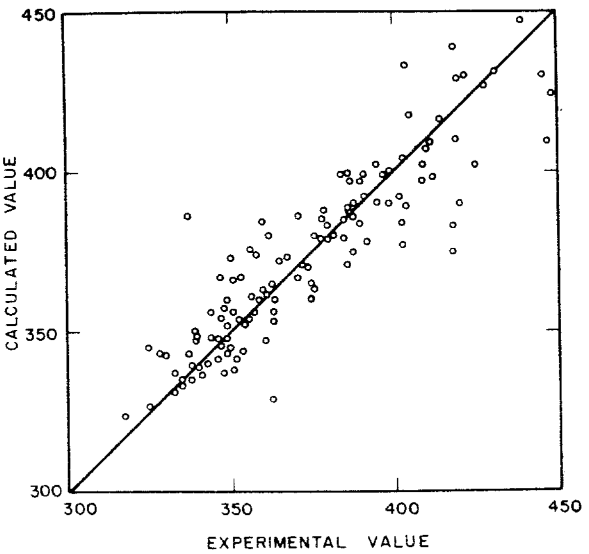

FIGURE 6. - Scatter of Data About the Correlation; Oxygen Requirement.

Calculations and Graphs

Table A-5 gives the differences between the experimental values and values determined from the equations which were fitted to the data. Figure 6, which permits a comparison of the measured values and the values computed from the equations, illustrates a typical scatter of data. Table A-4 presents an analysis of variance for the three correlations. Standard deviations for the separate sets of data that did not include the heat loss variable and for combined data that included heat loss were essentially the same. This indicates that the inclusion of the heat loss as a variable accounts for the difference between the two sets of tests.

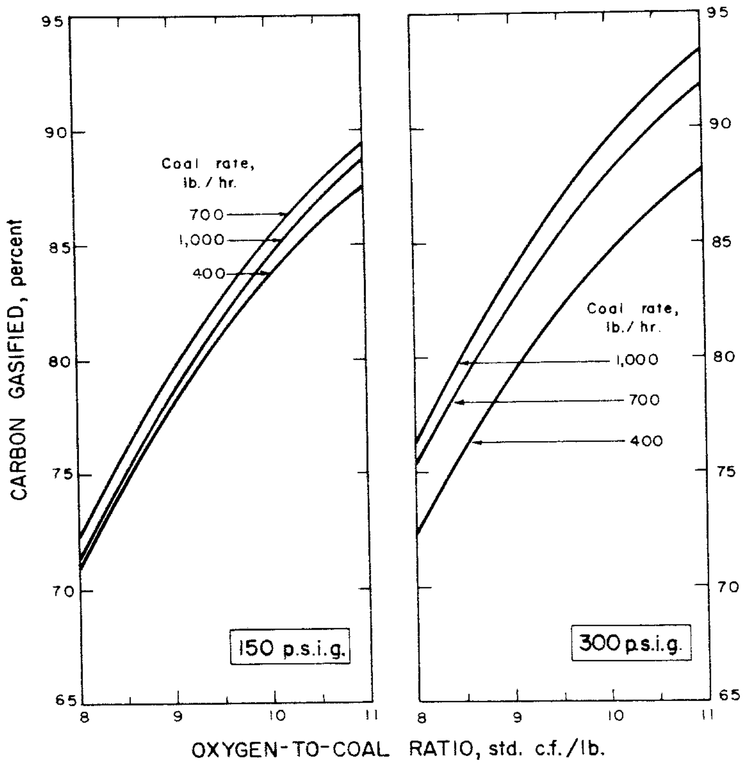

FIGURE 7. - Effect of Oxygen-to-Coal Ratio on Carbon Gasified, in Percent. Gasifier pressure is 150 and 300 p.s.i.g.

RESULTS--DISCUSSION AND ANALYSIS

Effect of Change in Operating Conditions on Essential Variables in the Process

As indicated previously, certain dependent variables govern the economy of the pressure-gasification process. These variables include the percent of carbon in the coal that is converted to gas and the quantities of coal and oxygen required to produce a given volume of gas. It is important for design and development of the process to know how these factors are influenced by controllable (independent) operating variables, such as oxygen and coal-feed rates and ratios. Another variable in the process, the quantity of heat lost through the walls of the gasifier, can significantly affect the relationship between these

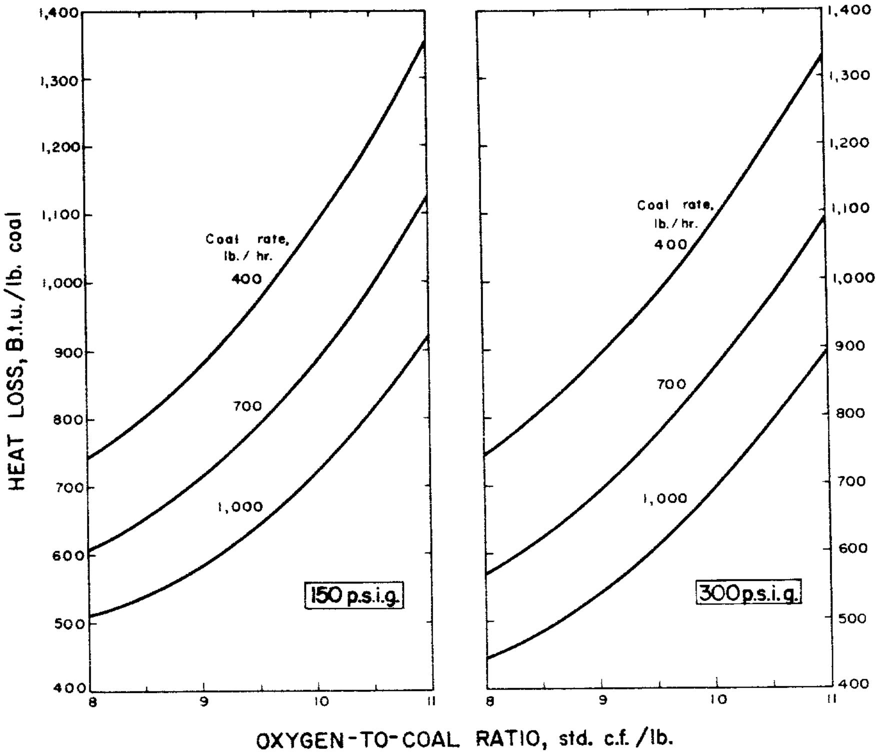

FIGURE 8. - Effect of Oxygen-to-Coal Ratio on Heat Loss. Gasifier pressure is 150 and 300 p.s.i.g.

factors. These factors and the influence of heat loss are discussed.

Percentage of Carbon Gasified

Figure 7 is a graph of the percentage of carbon gasified in the water-cooled gasifier as a function of the oxygen-to-coal ratio. Figure 8 shows the variation in heat loss that accompanied these tests, and figure 7 shows that at 300 p.s.i.g. the use of higher coal rates resulted in greater conversion of carbon. Inasmuch as residence time (the length of time the reactants are in the reaction space) is inversely proportional to the coal-feed

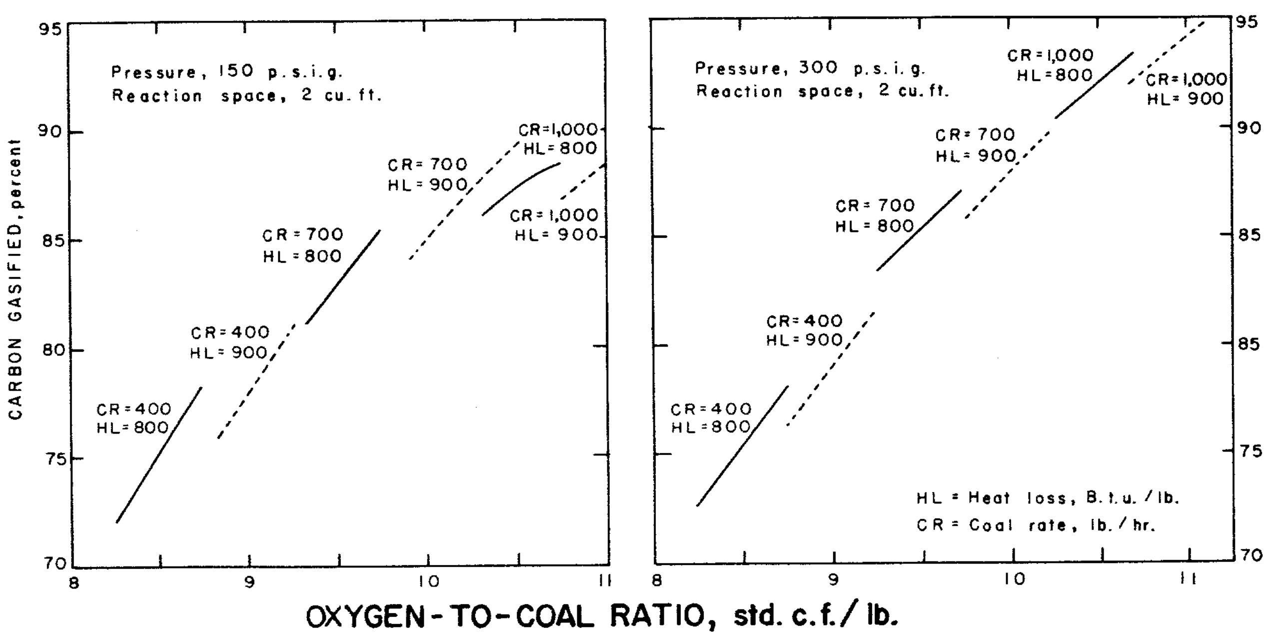

FIGURE 9. - Effect of Oxygen-to-Coal Ratio on Percentage of Carbon Gasified at Constant Heat Loss.

rate, this result is the reverse of what would normally be expected. Figure 9 shows the same results when the effect of the variation in heat loss is taken into account. (The family of lines in figure 9 are at constant heat loss.) At 300 p.s.i.g., raising the coal-feed rate, figure 9, had little effect on the functional relationship between carbon gasified and oxygen-to-coal ratio; the three lines representing a heat loss of 800 B.t.u./lb. of coal (solid lines) are essentially segments of a continuous curve. The same is true for a heat loss of 900 B.t.u./lb. of coal. At 150 p.s.i.g., however, the lines of constant heat loss are no longer segments of a continuous curve. In this case, increasing the coal-feed rate lowered the level and decreased the slope of the curves. In other words, the trends shown for an operating pressure of 150 p.s.i.g. (fig. 7) where the 1,000 lb./hr. curve falls between the 400 and 700 lb./hr. curves, are due largely to the effects of heat loss. Figure 9 shows that conversion of carbon was virtually independent of residence time at 300 p.s.i.g.; conversion decreased when the residence time at 150 p.s.i.g. was decreased by increasing the coal-feed rate.

Oxygen and Coal Requirement

Figures 10 and 11 give the oxygen and coal requirement for both the water-cooled gasifier (2 cu. ft.) and the refractory-lined gasifier (3 cu. ft.) at pressures of 150 and 300 p.s.i.g. and coal-feed rates of 270 and 500 lb./cu. ft./hr. of reaction space. The long sweeping curves show the results at the variable heat loss occurring in the tests. The short intersecting lines represent lines of constant heat loss. Except for the water-cooled gasifier at 150 p.s.i.g., higher coal-feed rates (shorter residence time) reduced the oxygen and coal requirements. More heat was lost when the gasifier was operated with lower coal-feed rates. This corresponds to the relationship found for carbon gasified (fig. 9). When heat loss is taken into account, basic raw material requirements were either unaffected or decreased by an increase in residence time, as reflected by decrease in coal-feed rate or increase in pressure (figs. 12 and 13).

When the effect of variation in heat loss is separated (fig. 10), there is less change in oxygen requirement with change in oxygen-to-coal ratio. At constant heat loss, the oxygen-to-coal ratio has little effect on the oxygen requirement. Most of the increase in oxygen requirement shown by the long lines was not caused by the rise in the oxygen-to-coal ratio itself but by the increase in heat loss accompanying the rise in oxygen-to-coal ratio.

For coal requirement, the effect was just the opposite. When the coal requirement is calculated on the basis of constant heat loss, the rate of decrease of coal requirement with an increase in oxygen-to-coal ratio is greatly speeded. The effect is shown by the intersecting lines for constant heat loss (fig. 11).

The curves of figures 12 and 13 show the rate at which the oxygen and coal requirements increase as heat loss rises. Slopes of each of the curves can be found by differentiating the correlation equations with respect to heat loss (app. C). The increase in the oxygen requirement per increase in heat loss of 1 B.t.u./lb. of coal is then:

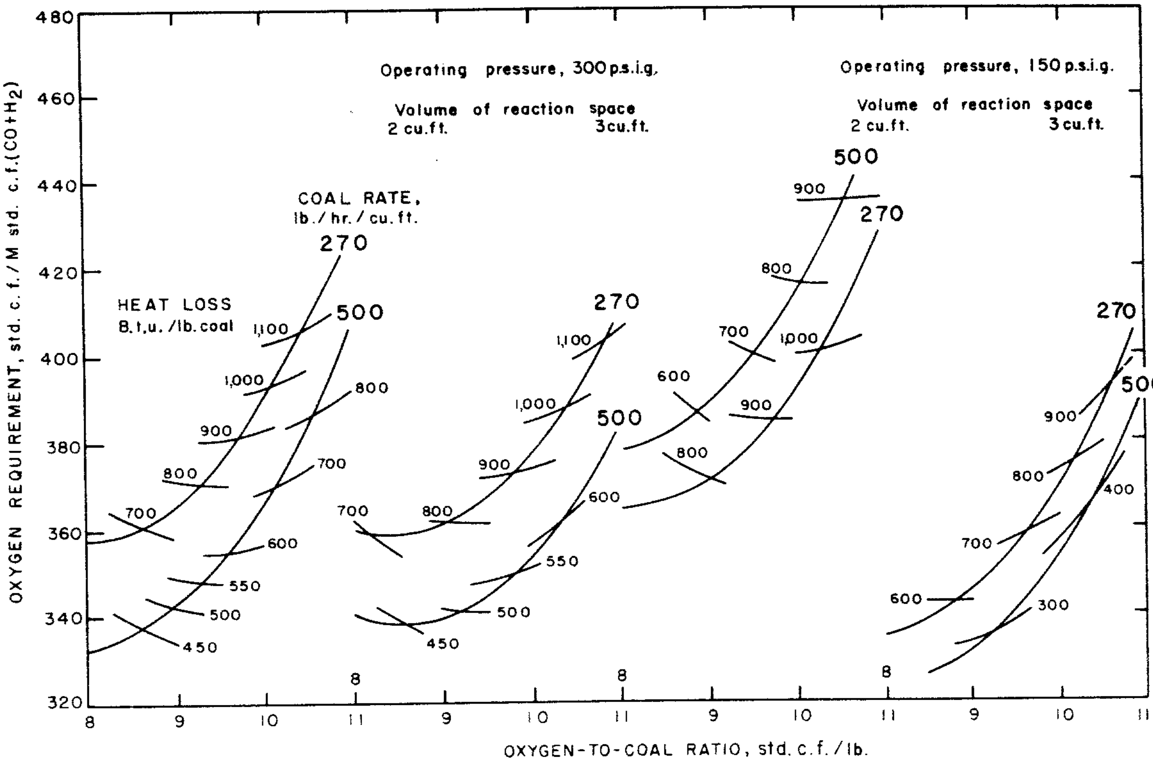

FIGURE 10. - Effect of Oxygen-to-Coal Ratio on Oxygen Requirement at Constant Heat Loss and at Variable Heat Loss.

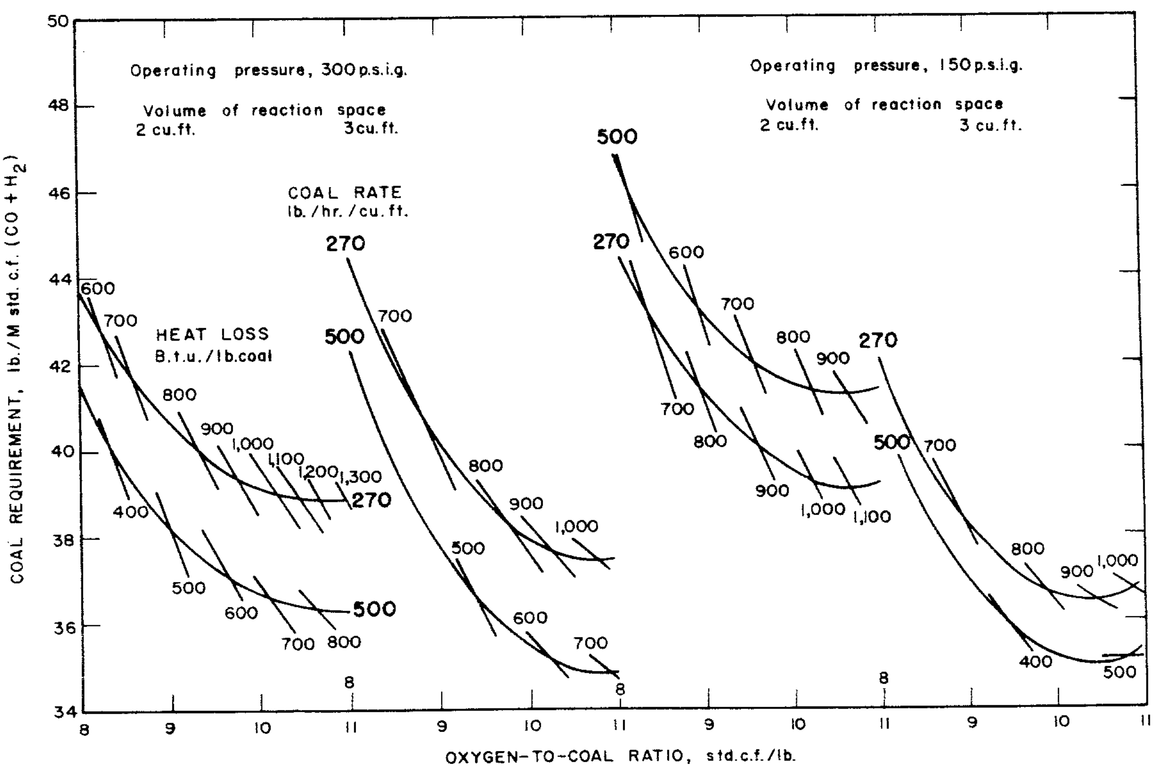

FIGURE 11. - Effect of Oxygen-to-Coal Ratio on Coal Requirement at Constant Heat Loss and at Variable Heat Loss.

$$\Delta O_r = 0.40 - p/4{,}600 + R/2{,}400 - (O/C)/17.5 + HL/4{,}300, \qquad (1)$$

where

ΔO_r = increase in oxygen requirement, std. c.f./M std. c.f. $CO + H_2$,

p = pressure, p.s.i.g.

R = coal-feed rate, lb./hr./cu. ft. of reaction space,

O/C = oxygen-to-coal ratio, std. c.f./lb.,

and HL = heat loss, B.t.u./lb. of coal.

The increase in coal requirement per increase in heat loss of 1 B.t.u./lb. of coal is:

$$\Delta C_r = 0.0505 - p/31{,}500 + R/24{,}000 - (O/C)/155 + HL/43{,}000, \qquad (2)$$

where

ΔC_r = increase in coal requirement, pounds of coal/M std. c.f. $CO + H_2$.

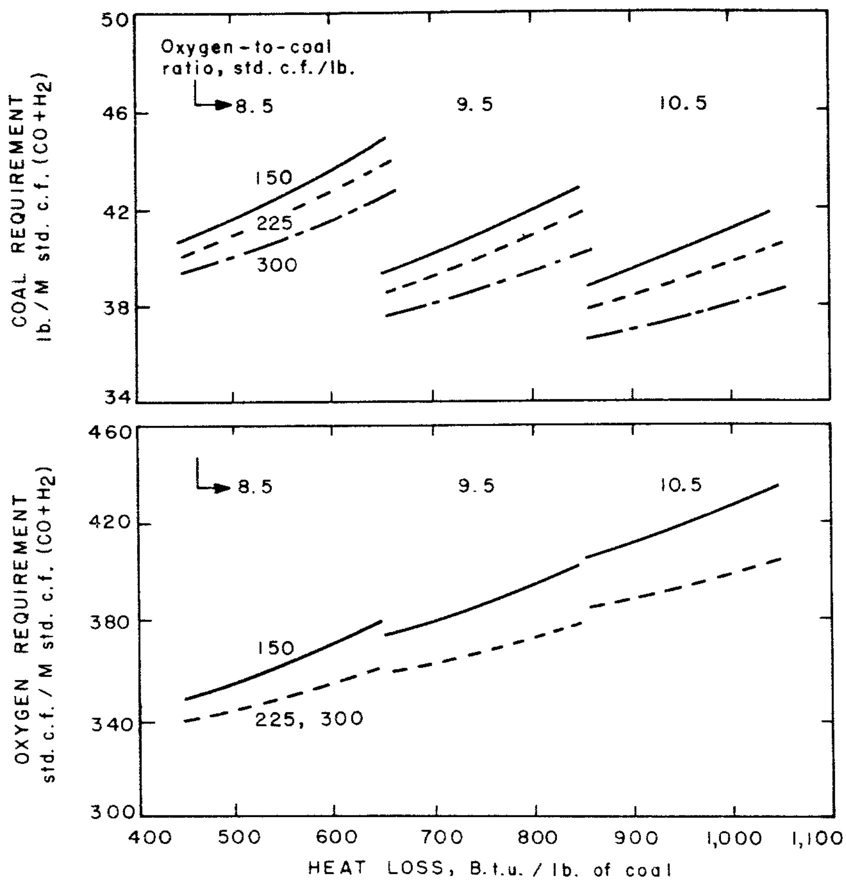

FIGURE 12. - Oxygen and Coal Requirement as a Function of Heat Loss at Coal Rate of 1,150 Pounds per Hour. Pressures are 150, 225, and 300 p.s.i.g.

Because these results were obtained from an empirical equation, the values of the variables have to fall within the ranges occurring in the tests. Inasmuch as residence time is directly proportional to the pressure and inversely proportional to the coal-feed rate, the negative sign for the pressure term and the positive sign for the coal-feed rate term in equation (2) suggest that these two terms are measuring the effect of residence time, and that for longer residence times, heat loss has less effect on material requirements. A negative sign for the oxygen-to-coal ratio is an expected result because, at higher oxygen-to-coal ratios, proportionately more coal is gasified with oxygen and less gas is formed by reaction of carbon with steam.

Evaluation of Fraction of Heat Loss Equivalent to Decrease in $CO + H_2$ in Product Gas

If the amount of heat lost from the gasifier is reduced, more energy is available for the endothermic gasification reaction. This energy can produce more $CO + H_2$, can increase the temperature of the gas, or both. Thus, heat loss can deprive the system of energy in two ways. It can reduce the amount of heat available to carry on the reaction, thereby decreasing the quantity of $CO + H_2$, or it can decrease the sensible heat in the gas.

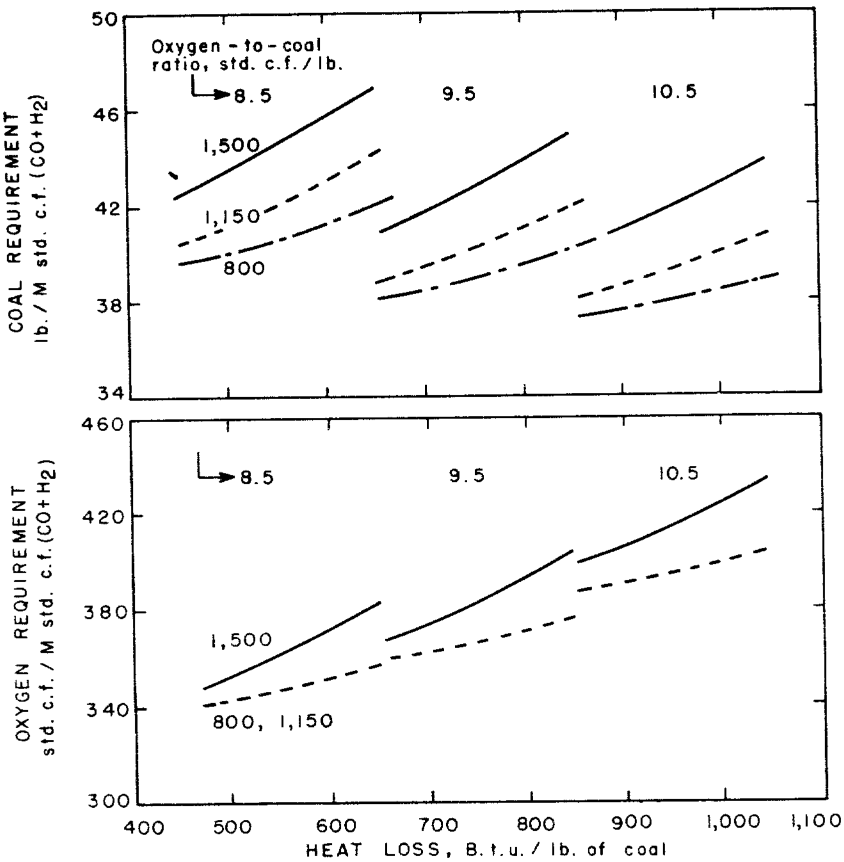

FIGURE 13. - Oxygen and Coal Requirement as a Function of Heat Loss at Operating Pressure of 225 Pounds per Square Inch Gage. Coal rates are 800, 1,150 and 1,500 pounds per hour.

The fraction of the heat loss that removes energy from the reaction represents the amount of heat loss equivalent to the decrease in $CO + H_2$ output. This fraction is equal to the heat required to convert carbon and steam (or carbon and CO_2) to $CO + H_2$, multiplied by the increase of the coal requirement with increase in heat loss (ΔC_r from equation (2)), divided by the square of the coal requirement. The average heat of reaction for the CO-to-H_2 ratio generated in the gasifier is about minus 80 B.t.u./std. c.f. of $CO + H_2$ produced. The heat loss equivalent to $CO + H_2$, on the basis of 1,000 std. c.f., is then given by either of the following equations:

$$f = (80{,}000)\ (\Delta C_r)/(C_r)^2, \qquad (3)$$

$$f = \left[(80{,}000)\ (\Delta O_r)/(O_r)^2\right]\left[O/C\right], \qquad (4)$$

where

f = fraction of heat loss equivalent to $CO + H_2$,

ΔC_r = change in the coal requirement with heat loss, from equation (2),

C_r = coal requirement, lb./M std. c.f. of $CO + H_2$,

ΔO_r = change in oxygen requirement with heat loss, from equation (1),

O_r = oxygen requirement, std. c.f./M std. c.f. $CO + H_2$,

and O/C = oxygen-to-coal ratio, std. c.f./lb.

Thus, f can be found from the correlation equation in which heat loss is included as an independent variable (fig. 14), where f is a function of the heat loss, and oxygen-to-coal ratio, coal-feed rate, and pressure are parameters. At constant oxygen-to-coal ratio, f increases as heat loss rises. When the heat loss is constant, f decreases as the oxygen-to-coal ratio increases. At higher heat losses, more of the available potential energy would be expected to be abstracted from the reaction because of the lower reaction rate. At constant heat loss, increasing the oxygen-to-coal ratio would be expected to increase the fraction of heat loss (1 minus f) attributable to an increase in gas temperature.

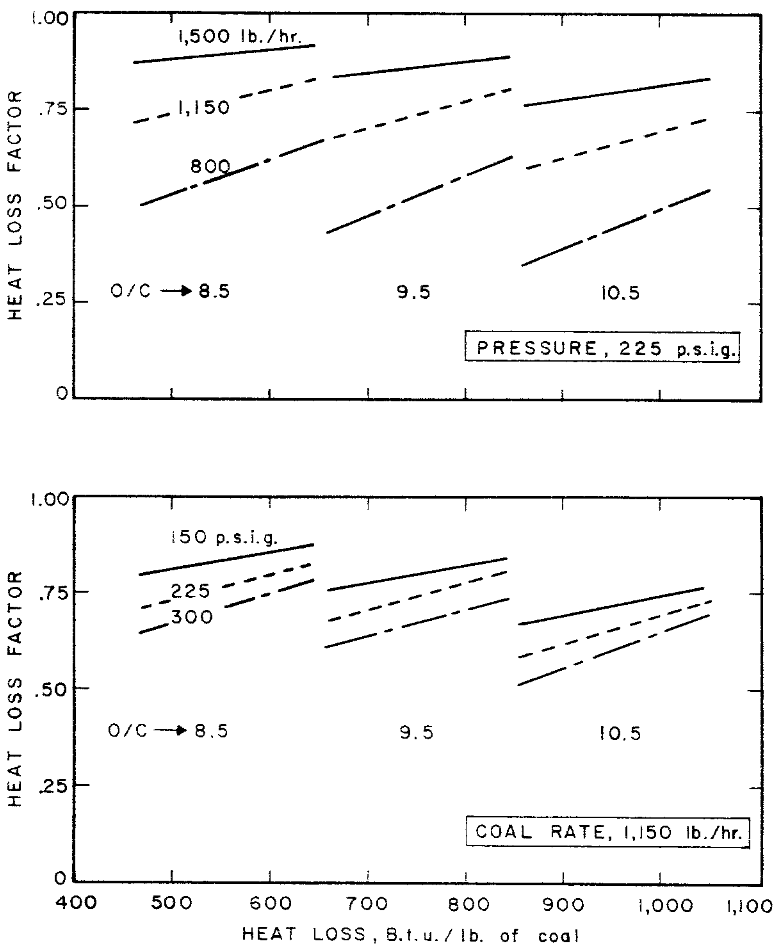

FIGURE 14. - Heat Loss Factor as Function of Heat Loss and Oxygen-to-Coal Ratio at Constant Operating Pressure and Constant Coal Rate.

Optimum Capacity of the Gasifier

If the residence time is increased, gasification reactions proceed nearer to completion, and more $CO + H_2$ is produced. As a result, less coal and oxygen is required to produce a unit quantity of $CO + H_2$, reducing, of course, the corresponding unit cost of these basic materials. One way to increase the residence time is to use a larger gasifier; however, a larger gasifier has more surface to radiate heat, and the greater heat loss increases the unit cost of the coal and oxygen. Thus, the two factors are in opposition. Ignoring the relatively small additional cost of a larger gasifier and considering only the cost of oxygen and coal per unit quantity of product gas, the size of the gasifier theoretically can be increased until the incremental decrease in unit cost per increase in residence time equals the incremental increase in cost per increase in heat loss at longer residence times. The $CO + H_2$ output under these conditions is defined as the optimum capacity of the gasifier.

Optimum gasifier capacity can be estimated by finding this point of equality. It is the point at which the increase in unit cost per increase in residence time equals the increase determined by multiplying the unit cost caused by greater heat loss by the change in heat loss with residence time. Because residence time is inversely proportional to the coal-feed rate, the latter can be used in place of residence time as the basis of calculation. Using a proportionality constant, a, that relates the cost of oxygen to that of coal, the desired relationship can then be expressed in terms of oxygen and coal requirement:

$$\frac{dC_r}{dCR} + a\,\frac{dO_r}{dCR} + \left[\frac{dC_r}{dHL} + a\,\frac{dO_r}{dHL}\right]\frac{dHL}{dCR} = 0, \qquad (5)$$

where

C_r = coal requirement, lb./M std. c.f. $CO + H_2$,

CR = coal-feed rate, lb./hr.,

a = cost of 1 cu. ft. of oxygen divided by cost of 1 lb. of coal,

O_r = oxygen requirement, std. c.f./M std. c.f. $CO + H_2$,

and HL = heat loss, B.t.u./lb. of coal.

By means of equation (5), the optimum capacity of the gasifier at each of various combinations of operating conditions was estimated from the correlation equations that included heat loss as a variable. Table 4 gives these optimum conditions and values. (In table 4, the column headed "economic factor" lists calculated values that represent the combined cost of coal and oxygen, with "a" in equation (5) assumed as 0.1. The lower the economic factor, of course, the lower the combined cost of these two raw materials.) The lowest value for the economic factor was at the highest operating pressure, 300 p.s.i.g.

Estimation of Oxygen and Coal Requirements at Lower Levels of Heat Loss

Coal and oxygen requirements for gasification at lower levels of heat loss can be estimated by extrapolating the curve showing the change of the material requirement with heat loss at the higher heat-loss value. Figures 12 and 13 show that the variation of the material requirements with heat loss is roughly linear; hence, extrapolation of these curves should give a reasonably good estimate.

TABLE 4. - Optimum gasifier capacity[1]

Pressure, p.s.i.g.	Oxygen/ coal ratio, std. c.f./lb.	Heat loss, B.t.u./lb. of coal	Materials required/M std. c.f. of $CO + H_2$		Economic factor[2]	Optimum capacity, M std. c.f. $CO + H_2$/cu. ft./hr.	Coal-feed rate at optimum capacity lb./cu. ft./hr.
			Coal, lb.	Oxygen, std. c.f.			
150	8.5	410	40	340	74	8.5	345
150	9.5	445	37	350	72	10	360
150	10.5	555	36	380	74	10	365
225	8.5	410	40	340	74	10	390
225	9.5	445	37	350	72	11	410
225	10.5	510	35.5	375	73	12	430
300	8.5	365	39	330	72	11	430
300	9.5	415	36	340	70	13	460
300	10.5	495	34.5	365	71	14	495

[1] $CO + H_2$ output at operating conditions that makes the overall cost of coal and oxygen requirement a minimum.
[2] Coal requirement plus 1/10 of oxygen requirement.

This procedure for estimating the material requirements at lower heat loss may be thought of in another manner. If the heat loss is decreased by ΔHL, the fractional increase in $CO + H_2$ produced is $(\Delta HL)\ C_r\ f/H$, where C_r is the coal requirement, f is the average fraction of the heat loss converted to $CO + H_2$, and H is the heat required for the reaction to produce 1,000 std. c.f. of $CO + H_2$. Then the coal requirement at the lower heat loss is

$$C_r/\ (1 + (\Delta HL)\ C_r\ f/H).$$

Table 5 gives an estimate of the material requirements at a heat loss of 100 B.t.u./lb. of coal.

TABLE 5. - Estimated coal and oxygen requirements at optimum gasifier capacity projected to a constant heat loss of 100 B.t.u./lb. of coal

Pressure, p.s.i.g.	Oxygen-to-coal ratio, std. c.f./lb.	Coal and oxygen required/ M std. c.f. $CO + H_2$	
		Coal, lb.	Oxygen, std. c.f.
150 and 225	8.5	36	300
150 and 225	9.5	34	320
150 and 225	10.5	33.5	350
300	8.5	36	300
300	9.5	34	320
300	10.5	33	340

Determination of Temperature of Gas From the Gasifier

Efforts to measure the temperature of gas from the reaction zone with thermocouples have been unsuccessful. Slag and hot, high-speed gases erode or break metal and ceramic protecting tubes. (Protecting tubes are required to avoid condensation of water vapor on the thermocouple where it passes through the shell coils to the outer shell of the gasifier.) Exit-gas temperature can be calculated from a heat balance, however, by either of two methods. A heat balance can be made across the gasifier between the inlet and the end of the refractory section or between the end of the refractory section and the scrubber outlet. The first method was used to determine the temperatures reported in Report of Investigations 5573.[9] The difference in the results of the two methods gives the heat unaccounted for in the normal heat balance over the entire process. Although both positive and negative values were obtained for heat unaccounted for in individual tests, the average for the entire series of tests was approximately zero. As a result, the temperature of the gas from the gasification section was determined from an average heat balance calculated from average values for coal analysis, volumes of methane and illuminants produced, and an average value for the water-gas equilibrium constant. Details of the heat balance calculations are given in appendix E.

As determined from the heat balance, the temperature of the synthesis gas from the gasification section is a function of the oxygen-to-coal ratio, steam-to-coal ratio, heat loss, and percent of carbon gasified. Because the carbon gasified was determined as a function of the independent variables, the exit-gas temperature can be determined the same way. Because heat loss is involved in both the heat balance and the carbon gasified equation, the effect of heat loss on the exit-gas temperature can be found.

Figure 15 shows the exit-gas temperature as a function of heat loss with steam-to-coal ratio, oxygen-to-coal ratio, and coal-feed rate as parameters. (Pressure had no effect on heat loss or exit-gas temperature.)

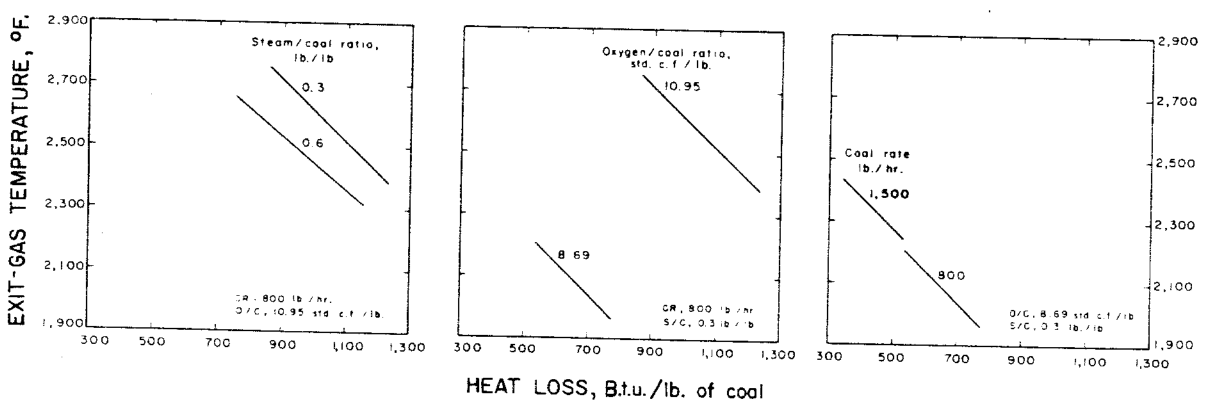

FIGURE 15. - Effect of Heat Loss on Exit-Gas Temperature. Steam-to-coal ratio, oxygen-to-coal ratio, and coal rate are parameters.

[9] Work cited in footnote 8, p. 10.

The curves of figure 15 are virtually parallel, an increase in heat loss of 100 B.t.u./lb. of coal always decreased the exit-gas temperature by 80° to 100° F. The left-hand graph of figure 15 shows that decreasing the steam-to-coal ratio by 0.3 slightly increased the heat loss, and that decreasing the steam-to-coal ratio by 0.3 at constant heat loss increased the exit-gas temperature by about 150° F. The center graph shows that increasing the oxygen-to-coal ratio increases both the heat loss and exit-gas temperature; the change in exit-gas temperature at constant heat loss is more than 300° F./std. c.f./lb. change in oxygen-to-coal ratio. The right-hand graph shows that changing the coal rate had little effect on exit-gas temperature, as the two segments representing different coal rates lie almost in a straight line.

Table 6 gives the exit-gas temperatures for the same operating conditions and for the optimum capacities given in table 4.

TABLE 6. - Exit-gas temperatures at conditions of optimum gasifier capacity

Pressure	Oxygen-to-coal ratio	Exit-gas temperature, °F.
150	8.5	2,150
150	9.5	2,400
150	10.5	2,720
225 and 300	8.5	2,190
225 and 300	9.5	2,450
225 and 300	10.5	2,770