so that the later ash balances generally showed 80 to 100 percent ash recovery. No corrections have been made for the dust content of the exhaust gases going out of the stack; data in table 6 show this quantity to be small.

Comparison of product-gas flow data and residue data

Two general methods are used to determine carbon gasification and other material balance items, namely, calculations based on direct measurement of product-gas flow and calculations based on residue collection. This was found to be a useful procedure, particularly in the early stages of the program. Data on the nature of the residues obtained are necessary to determine proper design of scrubbing and waste-disposal equipment. By extending the waste sampling procedure to determine amounts also, an independent check on the results from flow meter calculation is obtained, which detects errors in flow measurements that may not otherwise be noted. Columns 27 and 28 of table 1 compare the carbon gasification by these two methods and thus show the overall result of errors in measurements. The same data are expressed graphically in figure 22. Except in the highest gasification ranges, the carbon gasified, based on residue data, is seen to be, on the average, slightly higher than that based on gas-flow data.

Table 1 indicates that flow data were used as standard for 58/85, or 68 percent, of the 85 runs (or periods) reported, residue data were standard for 13/85, or 15 percent, and average data for 14/85, or 17 percent. However, if the comparison is restricted to the 26 complete runs for which both flow and residue data are available, it is found that flow data were used as the standard for 9 runs, or 35 percent, residue data for 3 runs, or 11 percent and average data for 14 runs, or 54 percent. The reason for this apparent contradiction is that separation of residue quantities by periods was generally imperfect, and the individual-period results calculated from residue data tend to be less accurate than those calculated from flow data. The relative accuracy of residue data increased when applied to an entire run, as evidenced by the fact that results based on residue data or the average of flow and residue data were the standard for 17 out of these 26 runs.

Other measurements

No special problems were encountered in the normal measurements of temperatures and pressures required for determining reactant and product flows. For this particular series of test runs, however, the values shown in table 1, column 18, for product-gas flow through the slag throat are of low accuracy. Initially, the major interest in this flow was for control purposes, that is, to keep the slag throat just hot enough for satisfactory slag flow, and readings of pressure differential across the orifice plate in the slag-gas vent line were enough to indicate trends. Temperatures and moisture contents of the vent gas at the orifice plate were only approximated, and the time intervals corresponding to pressure readings were not recorded. Inasmuch as the vent gas was reintroduced into the main product-gas stream, inaccuracies in vent-gas measurements did not affect the overall measurement of product gas. These inaccuracies do have some effect, however, on the calculated residence time in the gasifier (column 35) and the distribution of the sensible heat in the product gas (columns 47-50).

The accuracies of the various heat-balance items of table 1 increased during the course of this investigation - as gasifier operation stabilized and more time was devoted to measurements of cooling water, etc., and to examining apparent inconsistencies. The values shown should be reasonably accurate for indicating design trends, but individual points apparently out of line with the prevailing values should not be given undue weight.

DISCUSSION OF RESULTS

As was mentioned earlier, several cooling-coil arrangements and nine designs of reactant burners were used during this investigation. Also, as was stated previously, the emphasis on development of an operable process placed two limitations on the range and nature of the test conditions reported on here. Time did not allow for a large number of check tests under absolutely similar conditions and, since the gasifier was to be operated under slagging conditions on this particular fuel, the lower oxygen to carbon ratios (under 10.7 std. c.f. per lb.) were not investigated. To single out the specific effects on changes in reactant ratios, it was desirable to minimize the effects of the above design changes, as well as changes in coal-feed rates and methods of heating reactants. A study of the results showed that runs 13 through 23 provided the best data for singling out the effects of oxygen-carbon and steam-carbon ratios - in that no changes were made in cooling-coil arrangement or method of heating reactants, and only two designs of reactant burners (designs 5 and 6) were used. Coal-feed rates varied from 329 to 627 lb. per hr., but this was thought to have less effect than changes in reactant ratios. The points shown on the plots in this section have been limited to results from these runs.

Effect of oxygen-carbon ratio

Figure 23, based on data from table 1, has been prepared to indicate the effect of oxygen-carbon ratio, that is, standard cubic feet of oxygen supplied per pound of carbon in the coal, on the percentage of carbon gasified for runs 13 through 23. The solid line shows a substantial increase in carbon gasification with increase in oxygen-carbon ratio, and the general shape of the curve holds for the four steam-carbon ratios shown. Most of the triangles fall above the line and most of the squares below the line, indicating that, for a given oxygen-carbon ratio, somewhat better carbon gasification was achieved for the low steam-carbon ratios (0.5-0.70 lb. per lb.) than for the higher ratios (1.00-1.50 lb. per lb.). The points representing the highest steam-carbon ratios (1.51-1.65 lb. per lb.) coincide with high oxygen-carbon ratios because it was generally found necessary to supply extra oxygen along with extra steam to maintain temperatures high enough for satisfactory slag flow.

Figure 24 shows the effect of the oxygen-carbon ratio on the carbon requirement per thousand standard cubic feet of CO + H_2 for four ranges of steam-carbon ratios. As was expected, the carbon requirement decreases with increase in oxygen-carbon ratios. Also, for a given oxygen-carbon ratio, the carbon requirement is lowest for the lowest steam-carbon ratio. For example, for an oxygen-carbon ratio of 12 std. c.f. per lb., the carbon requirement is only 27.0 at the lowest steam-carbon ratio (0.50-0.70 lb. per lb.), and is 28.9 pounds at the next higher steam-carbon range (0.80-0.86 lb. per lb.).

Figure 25, also based on data from table 1, indicates the effect of the oxygen-carbon ratio on the oxygen requirement - for four ranges of steam-carbon ratios. Separate ordinates have been used to avoid confusion of points. It is seen that, for the ranges of oxygen-carbon ratios covered, the oxygen requirement increases with increase in oxygen-carbon ratio. The range covered is insufficient to show whether the curves pass through minimums at lower oxygen-coal ratios and whether the oxygen requirements increase with still lower oxygen-carbon ratios. The program for future testing work with the bituminous coals contemplates a series of tests in the lower oxygen to carbon ratios. Such tests would of course be in the nonslagging range and would also serve to check the operability of the gasifier under such conditions.

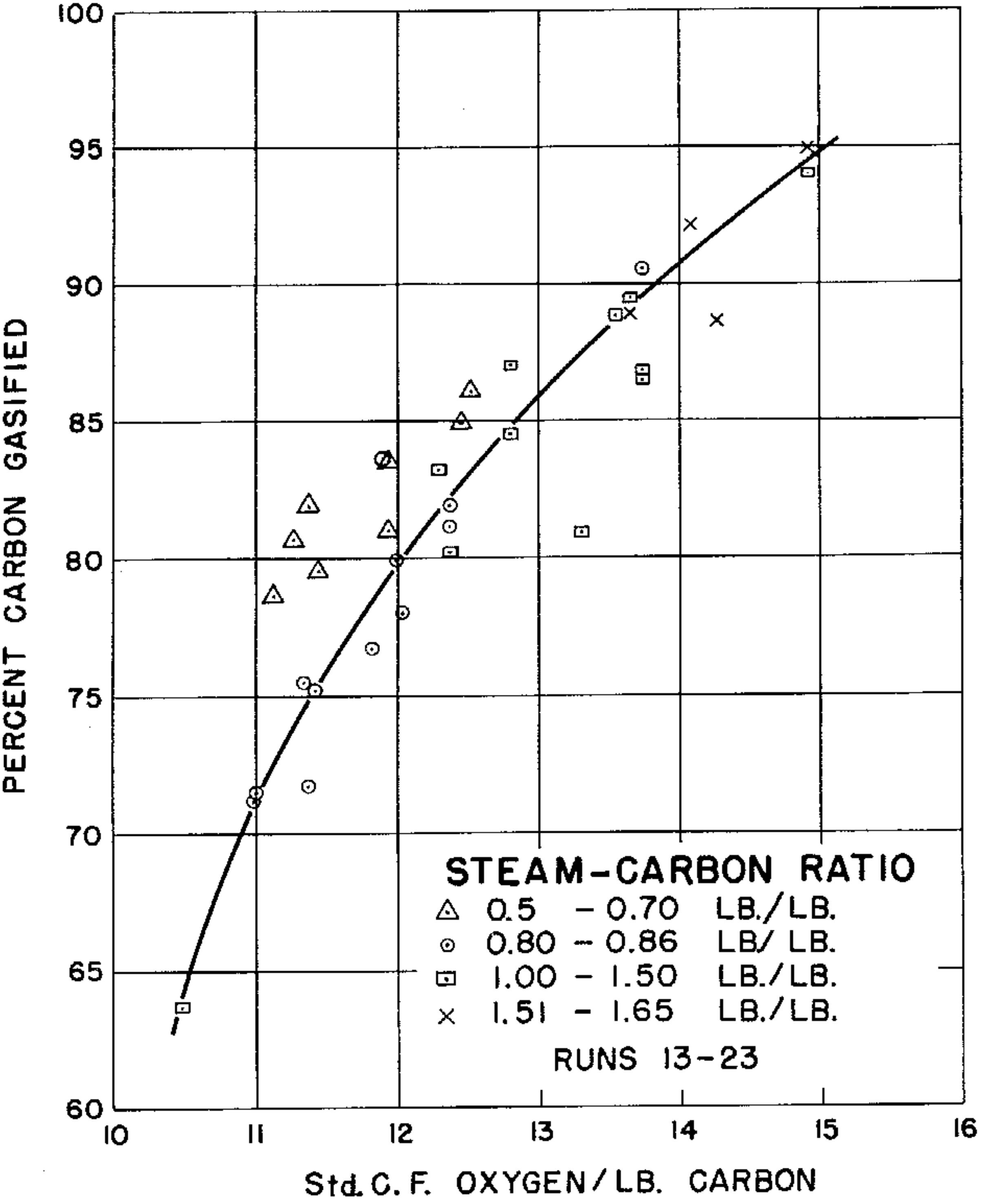

Figure 23. - Effect of reactant ratios on carbon gasified.

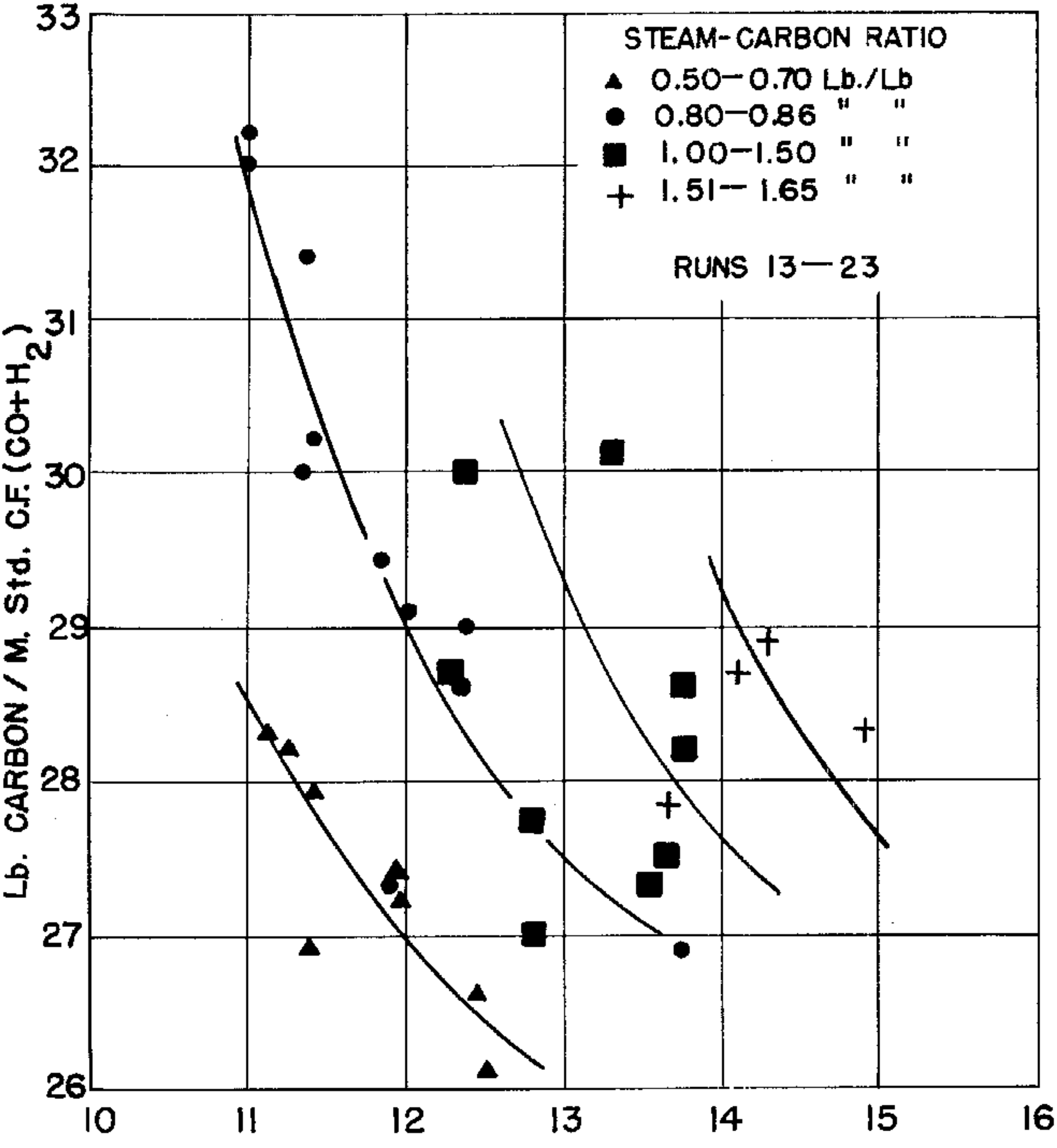

Figure 24. - Effect of reactant ratios on carbon requirement.

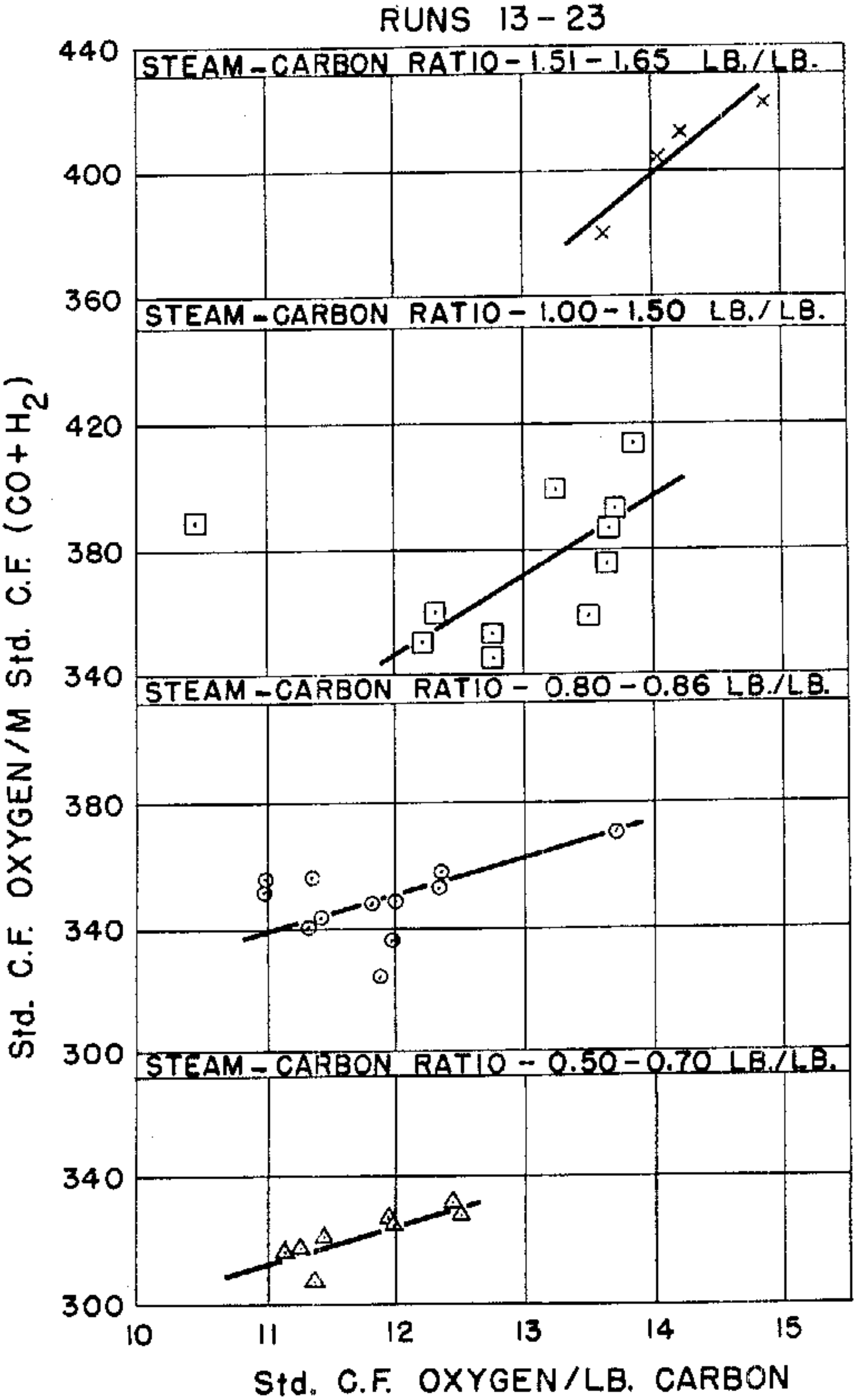

Figure 25. - Effect of reactant ratios on oxygen requirement.

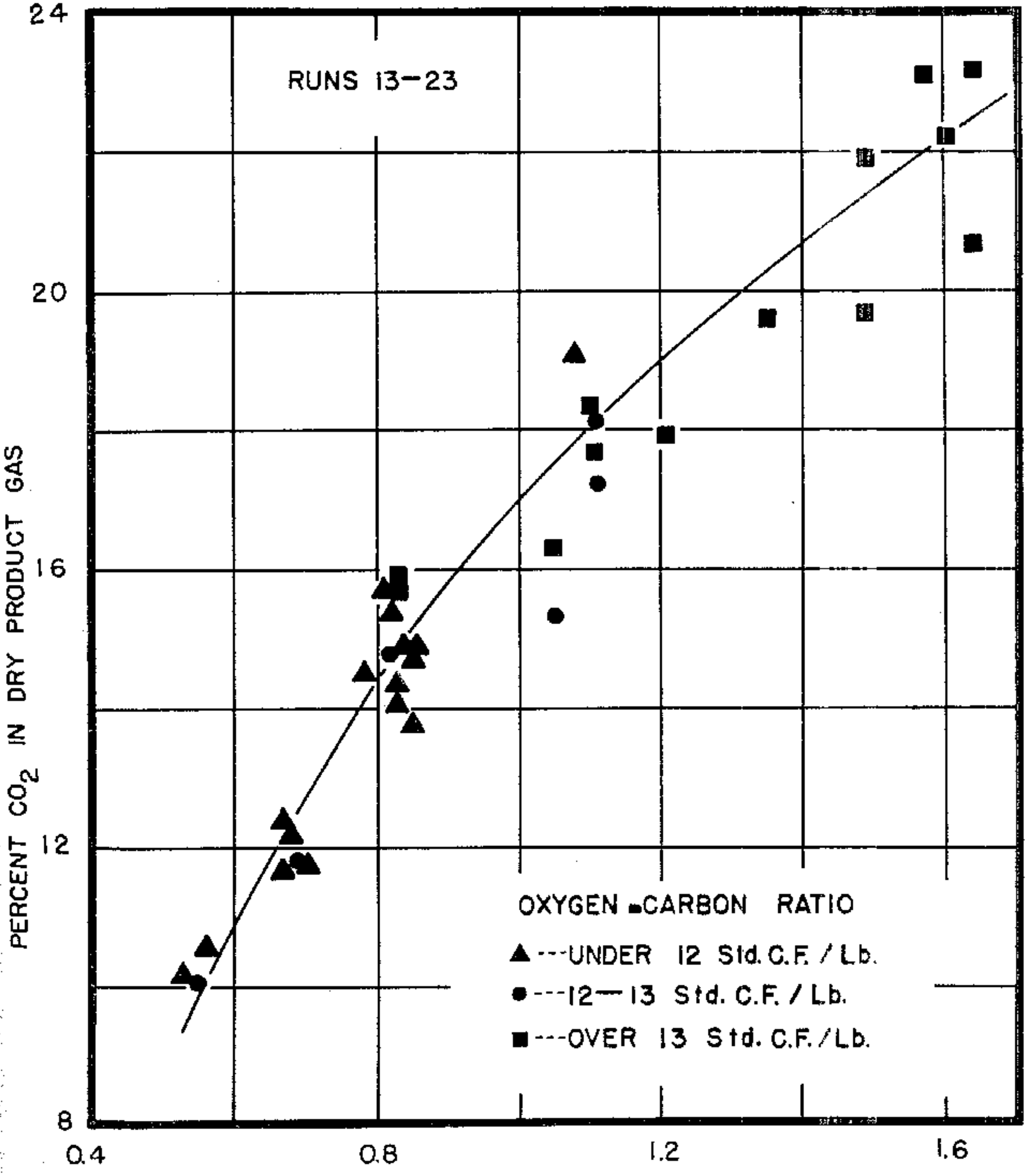

Figure 26. - Effect of steam-carbon ratio on CO_2 content of product gas.

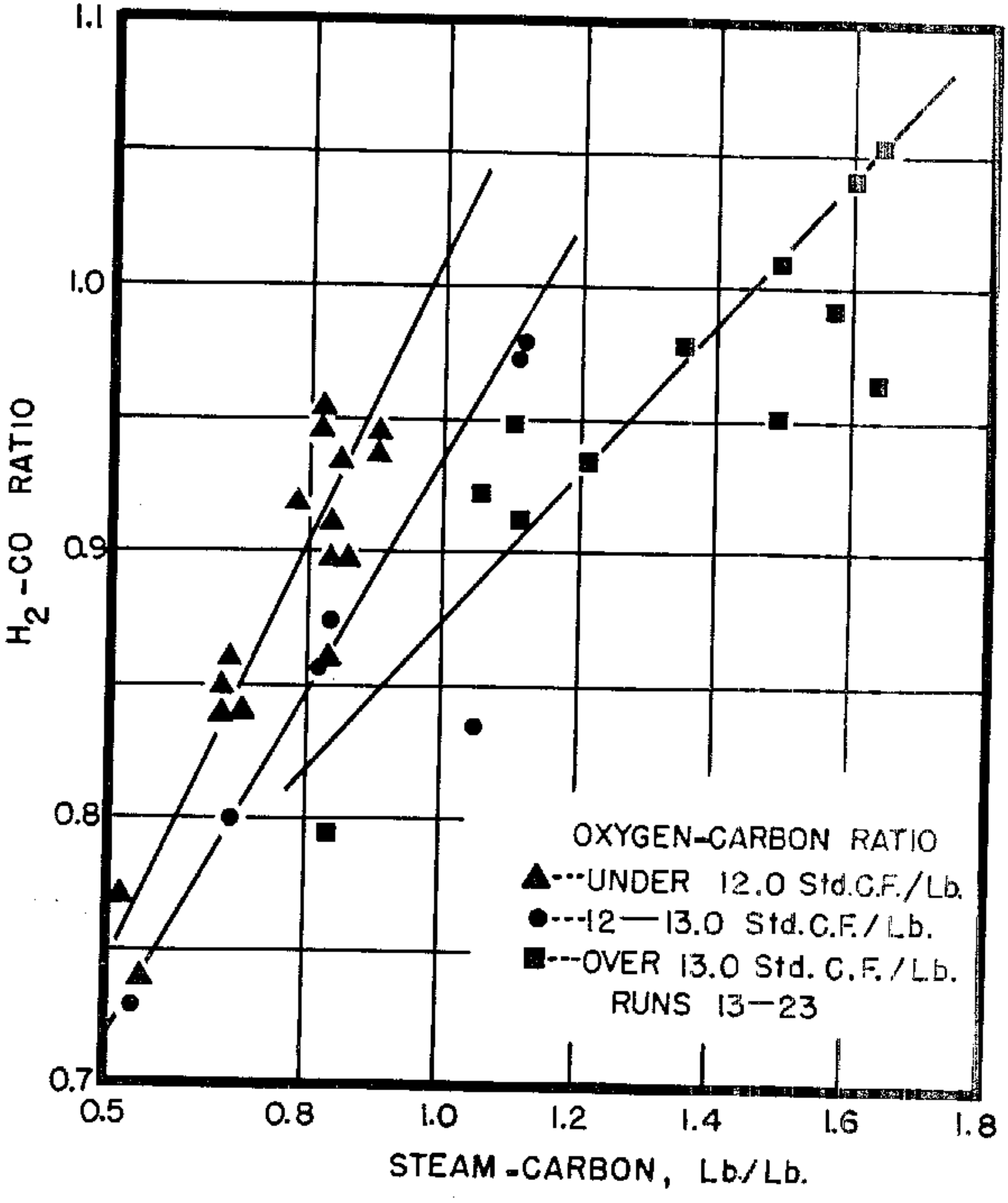

Figure 27. - Effect of reactant ratios on H_2-CO ratio in product gas.

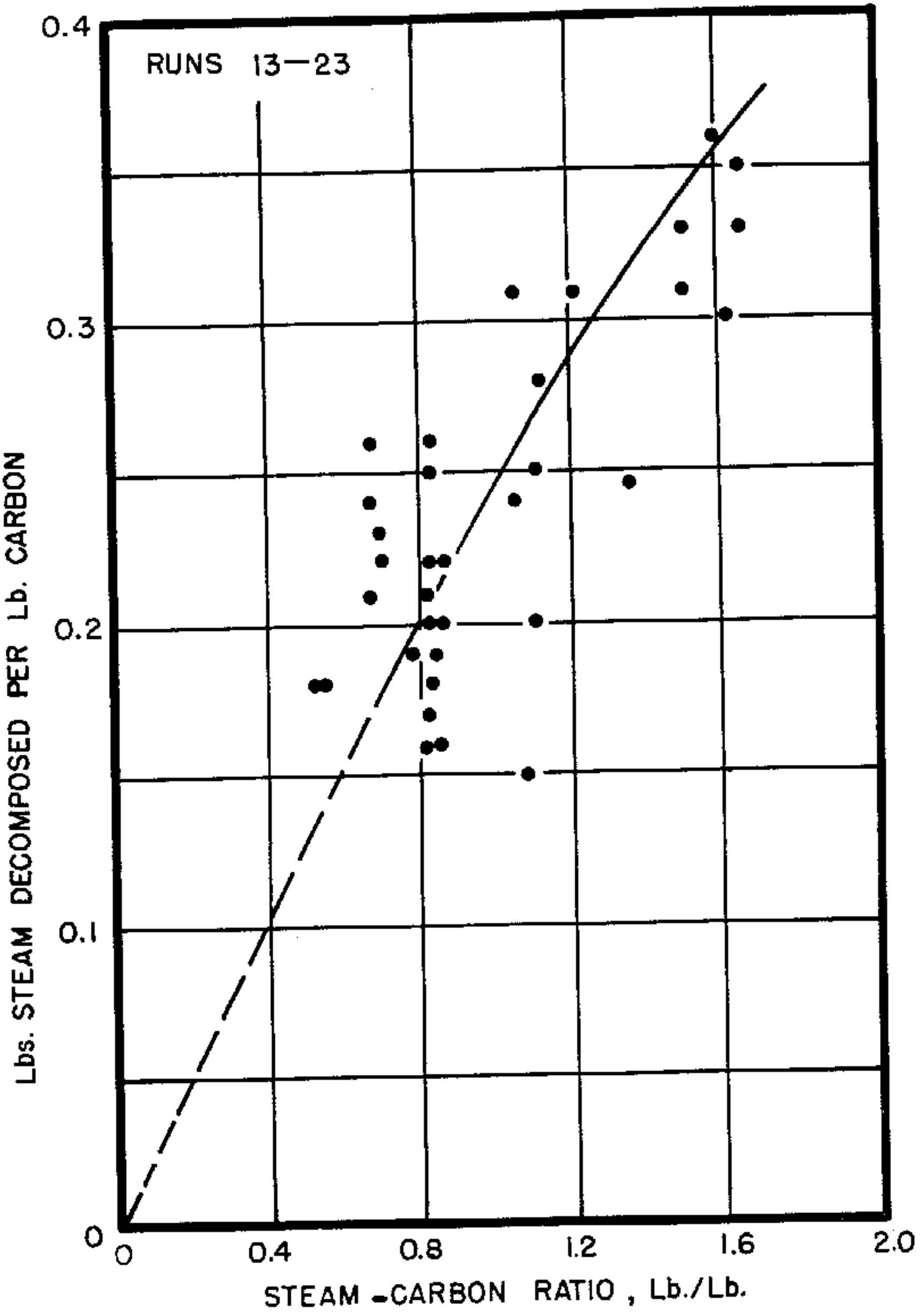

Figure 28. - Effect of steam-carbon ratio on steam decomposition.

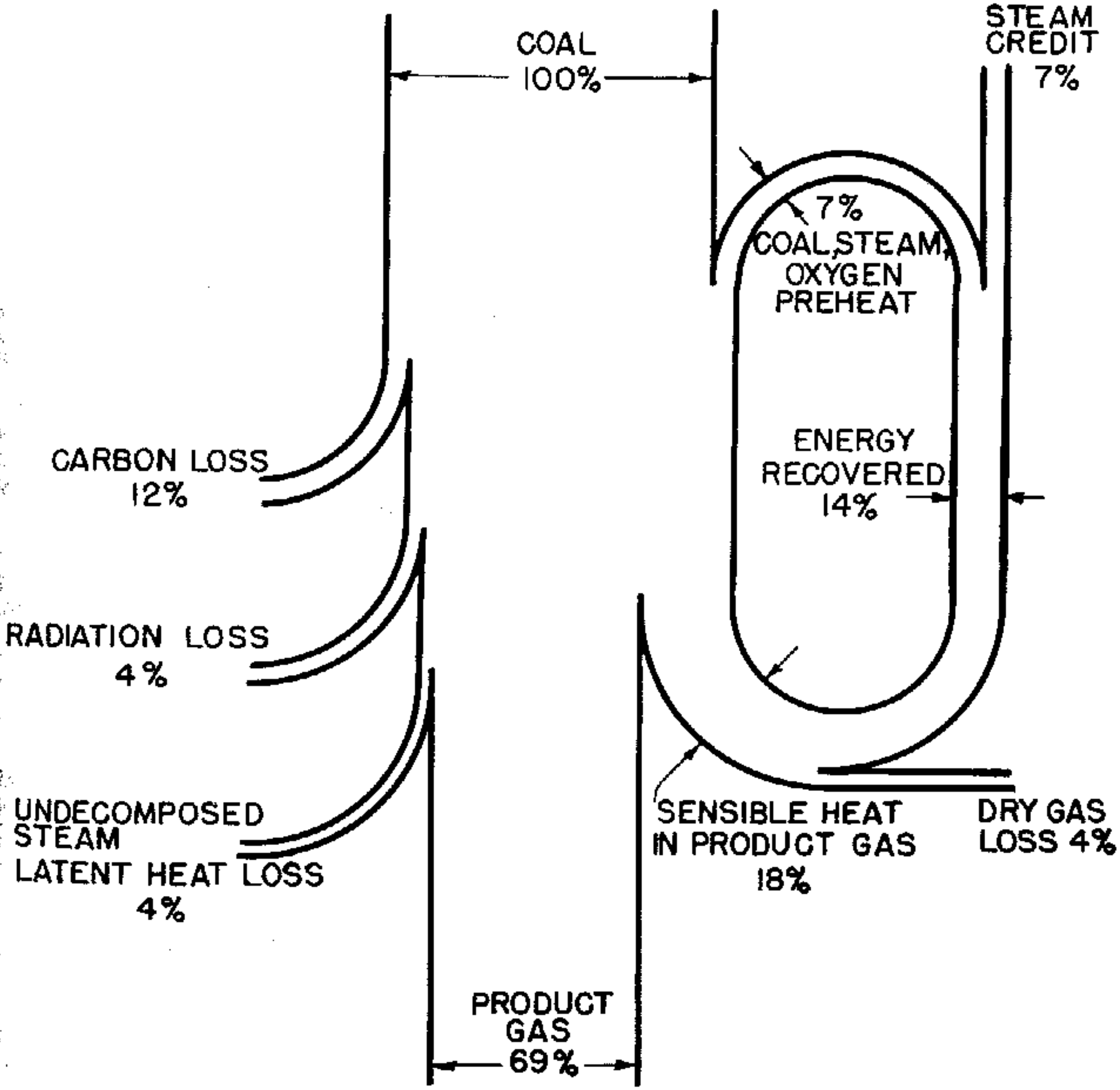

Figure 29. - Heat-flow distribution; atmospheric pressure gasifier 4.

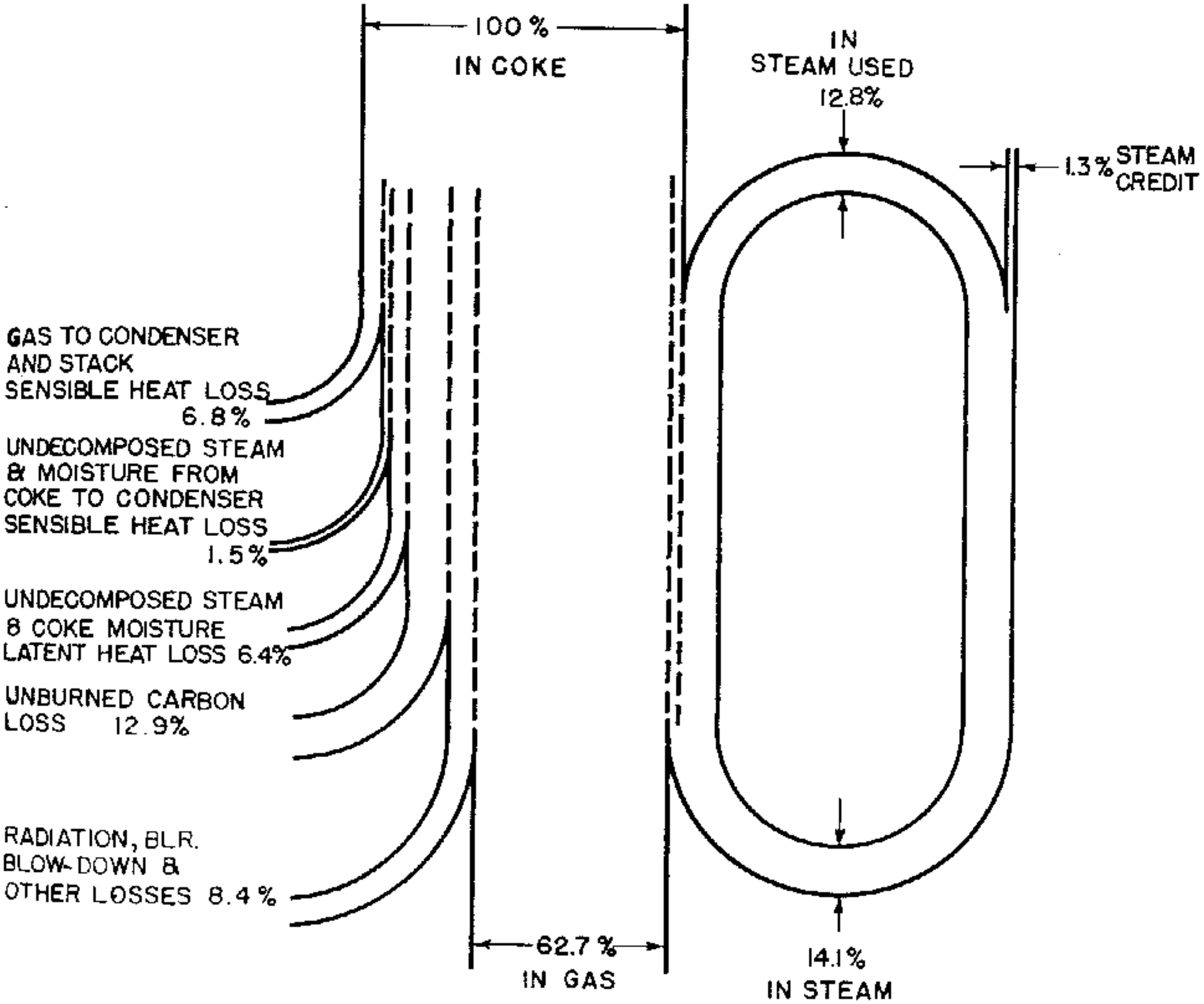

Figure 30. - Heat-flow distribution; standard blue-gas set.

Effect of steam-carbon ratio

Figure 26 shows the considerable increase in carbon dioxide of the dry product gas with increase in steam-carbon and oxygen-carbon ratios, namely, from about 10 percent with a steam-carbon ratio of 0.5 lb. per lb. and an oxygen-carbon ratio under 12 std. c.f. per lb. to about 22 percent for a steam-carbon ratio of 1.6 lb. per lb. and an oxygen-carbon ratio of over 13 std. c.f. per lb.

Since the high oxygen-carbon ratios were used with the high steam-carbon ratios to provide the necessary reaction temperature, it is not possible to determine how much of the high carbon dioxide percentage is due to each. The high steam-carbon ratio moves the water gas shift equilibrium toward the carbon monoxide plus hydrogen side of the reaction, and some of the extra oxygen burns carbon monoxide to carbon dioxide. However, stoichiometry indicates in the example cited above that probably less than a third of the increase in carbon dioxide percentage is due to the burning of carbon monoxide by extra oxygen. Since the quantity of valuable $CO + H_2$ per lb. coal in the product gas may be assumed to be approximately proportional to 100 percent minus percent CO_2, an important advantage of low steam-carbon and oxygen-carbon ratios is illustrated, namely, to reduce the amount of dilutent carbon dioxide.

Figure 27 shows the large increase in H_2-CO ratio with increase in steam-carbon ratio for three ranges of oxygen-carbon ratio. Separate curves are evident for each oxygen-carbon ratio. These curves illustrate a possible advantage of the higher steam-carbon ratios if a H_2-CO ratio of 1.0 or greater is desired. For example, using the middle line based on an oxygen-carbon ratio of 12-13 std. c.f. per lb., a steam-carbon ratio of 0.5 lb. per lb. gives a H_2-CO ratio of only 0.72, and a steam-carbon ratio of about 1.15 lb. per lb. is required to give a H_2-CO ratio of 1.0.

The optimum steam-carbon ratio is influenced by the H_2-CO ratio desired in the synthesis gas and the relative reactants costs per unit of gas of this composition, using various steam-carbon ratios. A savings in material requirements per M std. c.f. of $(CO + H_2)$ produced, achieved by reducing the CO_2 concentration with a low steam-carbon ratio, may be more then offset by the extra cost of shifting the H_2-CO ratio.

Figure 28 has been included to show the effect of steam-carbon ratio on steam decomposition, using data appearing in table 1 and calculated from hydrogen and oxygen balances. (The generally good agreement between calculated and experimental moisture contents was given earlier in table 4.) The solid line indicates that the quantity of steam decomposed per pound of carbon is approximately proportional to the steam-carbon ratio and amounts to about 25 percent of the process steam introduced. This confirms results on atmospheric gasifier 2.[20]

PROCESS HEAT BALANCE

Using operating results, which it is indicated would be obtained in large-scale units, a heat balance for this process has been prepared and is shown in figure 29. It is interesting to compare this with a similar heat balance for the standard blue gas process using coke as a fuel (fig. 30). Those data are taken from another publication.[21]

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[20] See work cited in footnote 4, p. 36.

[21] Morgan, J. J., Manufactured Gas: Vol. 1, 1926, pp. 246-247.

Full scale operation of this process should give a more favorable comparison than indicated here.

To date, the methods used to introduce the reactants have been substantially the same, that is, the coal has been fed into the reactor in a dense-phase fluidized state and mixed with the steam and oxygen introduced through small ports at high velocities. As has been shown previously, the nature of the reactant burner used in relation to a given reaction space has a considerable effect on the materials requirement per thousand cubic feet of CO + H_2 produced. There is a large field for development in burner design and also in methods of introducing the coal or conveying it from the mill to the burner. Coincidental with this there is the need to develop burner designs that will allow for considerable turndown without material reduction in efficiency and will also have mechanical features permitting long life.

In using lower rank coals it is indicated that heat recovered from the process may be used to advantage to preheat them before their admission to the reaction zone. Such preheating, in the range 700 -900 F., may, by a process of partial gasification in low cost tubular style heaters, so prepare the coal that the time needed for the reaction is lessened or the capacity of a given reaction space, in throughput per unit of time, is greatly increased. Experiments on such preheating of these coals, both in the dense and dilute fluidized phase are underway.

Experience in other industries where slags of varying composition are dealt with has shown that for gasifiers of this type there may not be one refractory suitable for all coals. In the course of the experimental program it is expected that a considerable variety of refractories will be tried out.

PROCESS COST EVALUATION

The present status of the experimental work does not allow for more than a tentative projection of the probable cost of synthesis gas made by this process. The probable range of reactant requirements per M. c.f. of CO + H_2 produced, which will be affected by the H_2-CO ratios needed in the synthesis and by the rank of the coal used, can be set reasonably well. The magnitude of the heat losses per pound of coal used in full-scale reactors can be estimated within reasonable limits. Although exact data on refractory life in those reactors have not been obtained, a projection based on the experience to date, both in the pilot plant described here and others of a similar nature, indicates that this will not be a major objection to the process.

Such cost evaluations have been made,[22] and further elaboration in this report does not seem necessary. Assuming costs for coal, oxygen, and steam in the ranges shown in figure 31, it is indicated that the materials cost per thousand cubic feet of CO + H_2 produced will be about 20 to 25 cents.

Figure 31 provides a graphical method of determining the total cost of reactants per thousand standard cubic feet of (CO + H_2) from the individual reactant requirements and prices. In the example shown, the assumed requirements of 40 pounds of coal, 20 pounds of 1,000° F. steam, and 355 std. c.f. of oxygen per thousand standard cubic feet of (CO + H_2) are based on those given in table 1 for test run 33. The assumed prices at the gasifier of \$5.50 per ton of coal, \$0.40 per 1,000 pounds of 1,000°F. steam, and \$6,50 per ton for oxygen are based on data presented in the previous reference.[23]

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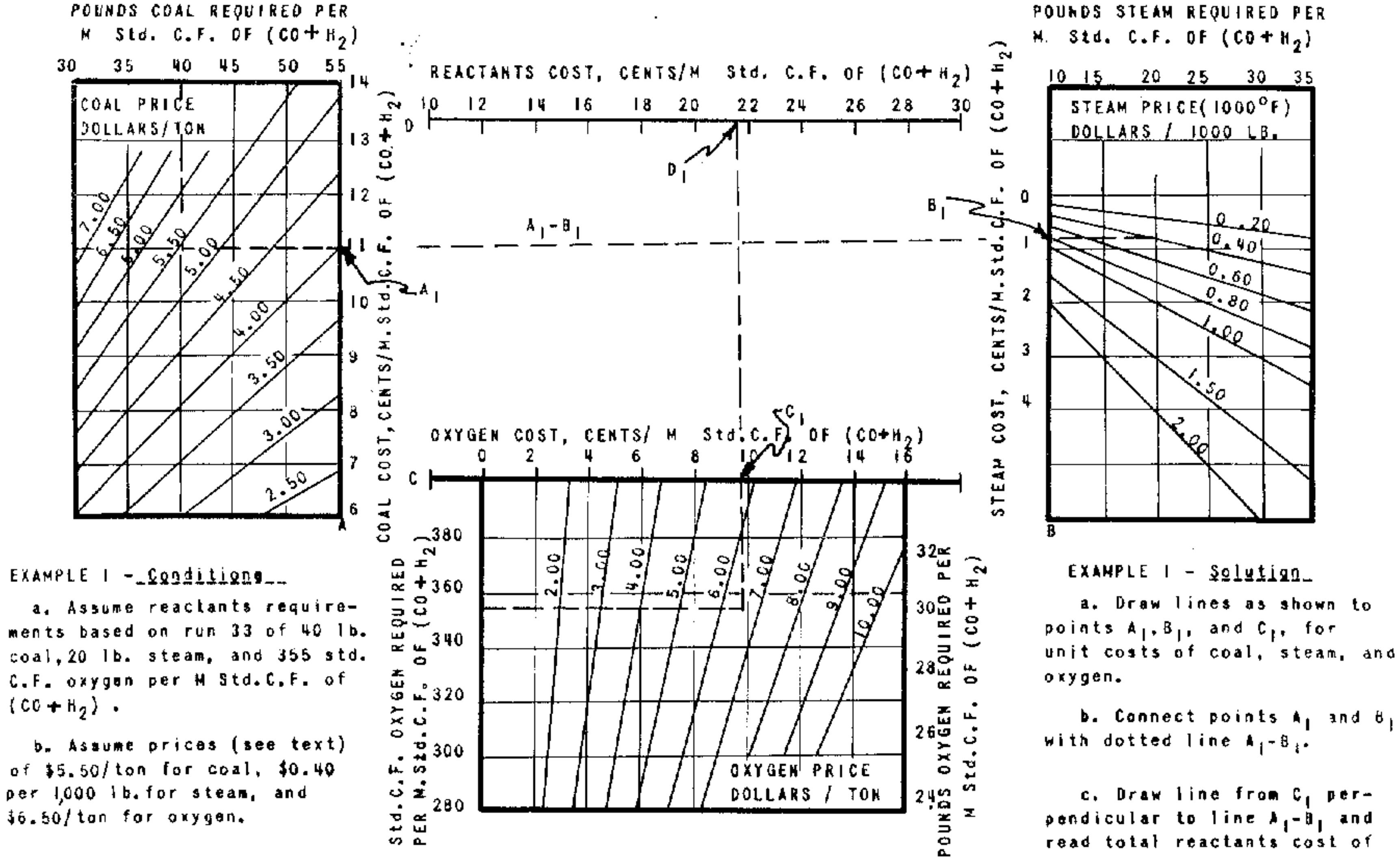
[22] See footnote 5.

[23] See work cited in footnote 5, table 3. The steam price of \$0.25 per million B.t.u. has been taken as equivalent to approximately \$0.40 per 1,000 pounds of 1,000° F. steam.



EXAMPLE I - Conditions

a. Assume reactants requirements based on run 33 of 40 lb. coal, 20 lb. steam, and 355 std. C.F. oxygen per M Std.C.F. of $(CO + H_2)$.

b. Assume prices (see text) of $5.50/ton for coal, $0.40 per 1,000 lb. for steam, and $6.50/ton for oxygen.

EXAMPLE I - Solution

a. Draw lines as shown to points A_1, B_1, and C_1, for unit costs of coal, steam, and oxygen.

b. Connect points A_1 and B_1 with dotted line A_1-B_1.

c. Draw line from C_1 perpendicular to line A_1-B_1 and read total reactants cost of 21.5 cents at point D_1.

Figure 31. - Nomograph for determining reactant costs per M std. c. f. of $(CO + H_2)$.

The actual prices of coal, steam, and oxygen will depend on the locality and the size and type of installation. The reader can select reactant requirements based on those of table 1 or on what appear reasonable for his contemplated application and use reactant prices bases on those prevailing in his locality. Then, using figure 29, he can determine graphically the resulting total cost of reactants per M std. c.f. of (CO + H_2).

DEVELOPMENT OF EXPERIMENTAL PROGRAM

Since the completion of the last test on which data are given in this report, test 34, about 20 more tests have been made. After test 34 the gasifier design was stabilized approximately as shown in figure 5. A variety of coals have been tested, including a subbituminous C coal, an anthracite, and a western bituminous coal. Also, tests have been made on the production of gas using large percentages of nitrogen in the reactants.

As has been mentioned before,24/ the process has been adapted to full-scale operation elsewhere but a considerable field of investigation remains to develop the most efficient equipment construction possible and to determine the optimum conditions for the gasification of any particular fuel.

The process has indicated an adaptability to a large range of fuel types, but as yet it is not possible to predict, without actual test runs, the best reactant feed ratios for any one fuel. Consequently, it is expected that for some time the program will be devoted to testing a wide range of coal types or ranks, and will include a study of variables, for example, preheating of reactants, heat losses, and reactant ratios.