Two things have been observed in the operations of the unit which indicate that very strong centrifugal forces are developed when tangential injection for the high-temperature steam is used. Ordinary thin-walled thermocouple protecting tubes are bent in the direction of rotation, and slag erosion where the Thermolith cement was used has been very extensive. At a steam rate of 800 pounds per hour and at a temperature of 3,000°F., the velocity of the steam entering the generator is approximately 700 feet per second. The velocity of the coal-oxygen feed stream of course varies with the oxygen:coal ratio used but is approximately 200 feet per second. Hence, the gases revolve inside the generator at a high rate.

## Dust-Removal and Residue Data

The data on the residue collected in the dust-removal train and size analyses of the coals used are given in tables 6 and 7. These have been grouped by run series, since the variations in the ash content and size within any series were not significant. The data on the amounts of very fine material leaving the stack are not too accurate on account of difficulties in sampling. In the tables the material designated as "Weir tank and cyclone separator" is that collected in the sludge tank where the sludge-bearing water from the wet cyclone and the wash box was allowed to partly settle out, metered over a weir, and the overflow periodically sampled for sludge content.

While these tests were not a fair indication of what can be expected for the performance of properly designed collectors, since the Aerotecs used were over capacity, the results are reported as giving an indication of what may be expected when pulverized coal is gasified under the test conditions reported.

## Data on Sulfur Content of Gases

For reasons previously given, it has not been possible to secure adequate check runs or runs in which all but one variable could be rigidly controlled. This is reflected in all the data and is particularly pertinent in any discussion of the amounts and kinds of sulfur found in the gas.

The analyses of the gases made in the pilot-plant generator to date indicate that no unusual forms of sulfur exist and that the demands made in the purification process will be similar to those encountered in the manufacture of water gas from coal in fixed beds.

There are definite trends indicating that the use of high steam:coal ratios at the higher steam temperatures reduces significantly the proportion of the coal sulfur which appears as organic sulfur in the gas. This reduction in organic sulfur content, if borne out by future work, will constitute a distinct credit as regards purification costs.

TABLE 6. - Weight distribution and chemical analyses of residues from pilot-plant runs 1 - 31

| Run numbers | 1-14 | 15-25 | 26-27 | 28-31 |
|---|---|---|---|---|
| Coal | Sewickley | Sewickley | Sewickley | Wyoming |
| Temperature range of inlet steam, °F. | 2,700-3,400 | 230-250 | 1,600-2,000 | 1,600-2,000 |
| Residue leaving generator (collected, over weir, and exhausted out stack): | | | | |
| Total weight, dry basis, lb. per 100 lb. coal | 20.0 | 19.9 | 19.9 | 7.2 |
| Distribution, weight percent: | | | | |
| Aerotec No. 1 | 11.8 | 23.2 | 23.3 | 27.0 |
| Aerotec No. 2 | 5.8 | 7.6 | 7.7 | 5.8 |
| Aerotec No. 3 | 2.0 | 2.9 | 3.3 | 2.8 |
| Weir tank and cyclone separator | 72.4 | 59.1 | 60.7 | 59.4 |
| Exhaust stack | 8.0 | [1]7.2 | [1]5.0 | [1]5.0 |
| | 100.0 | 100.0 | 100.0 | 100.0 |
| Ash content, dry basis, percent: | | | | |
| Aerotec No. 1 | 31.6 | 44.9 | 43.2 | 42.3 |
| Aerotec No. 2 | 18.6 | 39.0 | 33.1 | 43.0 |
| Aerotec No. 3 | 14.9 | 33.7 | 27.0 | 39.3 |
| Weir tank and cyclone separator | 36.1 | 39.8 | 36.0 | 32.9 |
| Exhaust stack | [1]17.3 | [1]33.7 | [1]27.0 | [1]39.3 |
| Weighted average ash content | 32.9 | 40.4 | 36.7 | 36.5 |
| Weighted average volatile matter content, percent | [1]6.0 | 3.5 | 2.8 | 3.3 |
| Weighted average fixed carbon content, percent | 61.1 | 56.1 | 59.7 | 60.2 |
| Estimated average total carbon content, percent | 64.1 | 57.9 | 61.1 | 61.9 |
| Ash in residue leaving generator, weight percent of ash input in raw coal | 47.3 | 59.6 | 68.5 | 40.9 |

---

[1] Estimated values.

TABLE 7. - Screen analyses of coals used and residues collected for pilot-plant runs 1 - 31.

| Run numbers........ | | 1-14 | 15-25 | 26-27 | 28-31 | | |
|---|---|---|---|---|---|---|---|
| Coal............... | | Sewickley | Sewickley | Sewickley | Wyoming | | |
| Coal-batch numbers averaged......... | | I-IV | IV-VI | VII | Wyo 2 | Wyo 1 | Ave Wyo |
| Source | Screen size | Size distribution, weight percent[1] | | | | | |
| Raw-coal feed | + 50 | 0.1 | 0.1 | 0.2 | 0.4 | [2]0.3 | 0.4 |
| | - 50 +100 | 1.6 | 1.4 | 1.8 | 2.5 | 1.6 | 2.0 |
| | -100 +150 | 2.8 | 3.3 | 3.2 | 3.8 | [2]4.0 | 3.9 |
| | -150 +200 | 6.4 | 5.9 | 6.0 | 5.4 | [2]6.6 | 6.0 |
| | -200 | 89.1 | 89.3 | 88.8 | 87.9 | 87.5 | 87.7 |
| Aerotec No. 1 | +100 | 5.9 | .5 | 1.5 | | | .0 |
| | -100 +150 | 5.7 | .5 | 1.5 | | | .0 |
| | -150 +200 | 32.4 | 2.9 | 3.7 | | | .0 |
| | -200 +325 | 26.2 | 7.7 | 17.7 | | | 1.3 |
| | -325 | 29.8 | 88.4 | 75.6 | | | 98.7 |
| Aerotec No. 2 | +100 | 5.7 | 2.0 | 8.3 | | | .7 |
| | -100 +150 | 15.6 | 2.7 | 4.5 | | | 1.0 |
| | -150 +200 | 46.8 | 7.7 | 5.8 | | | 1.0 |
| | -200 +325 | 18.1 | 33.5 | 49.9 | | | 29.6 |
| | -325 | 13.8 | 54.1 | 31.5 | | | 67.7 |
| Aerotec No. 3 | +100 | 14.0 | .9 | .1 | | | 1.3 |
| | -100 +150 | 13.3 | 2.9 | 4.2 | | | 1.5 |
| | -150 +200 | 36.2 | 14.5 | 14.1 | | | 3.0 |
| | -200 +325 | 22.2 | 27.3 | 55.8 | | | 34.7 |
| | -325 | 14.3 | 54.4 | 25.8 | | | 59.5 |
| Weir tank and cyclone separator | +100 | 7.7 | 4.2 | 2.9 | | | 4.2 |
| | -100 +150 | 6.2 | 5.2 | 6.8 | | | 7.1 |
| | -150 +200 | 14.7 | 9.3 | 10.5 | | | 7.7 |
| | -200 +325 | 32.5 | 20.7 | 21.7 | | | 18.8 |
| | -325 | 38.9 | 60.6 | 58.1 | | | 62.2 |

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[1] Size distribution, weight percent, for each group of runs is an average of the batches used in that group, weighted according to the number of runs on coal from each batch.

[2] Approximate values for these size ranges on batch "Wyo 1", as the screens used did not conform to the indicated ranges. Batch "Wyo 1" was the special shipment of finely pulverized coal from the Louisiana, Mo. station, and its size distribution was taken from data for the Louisiana, Mo., run 17.

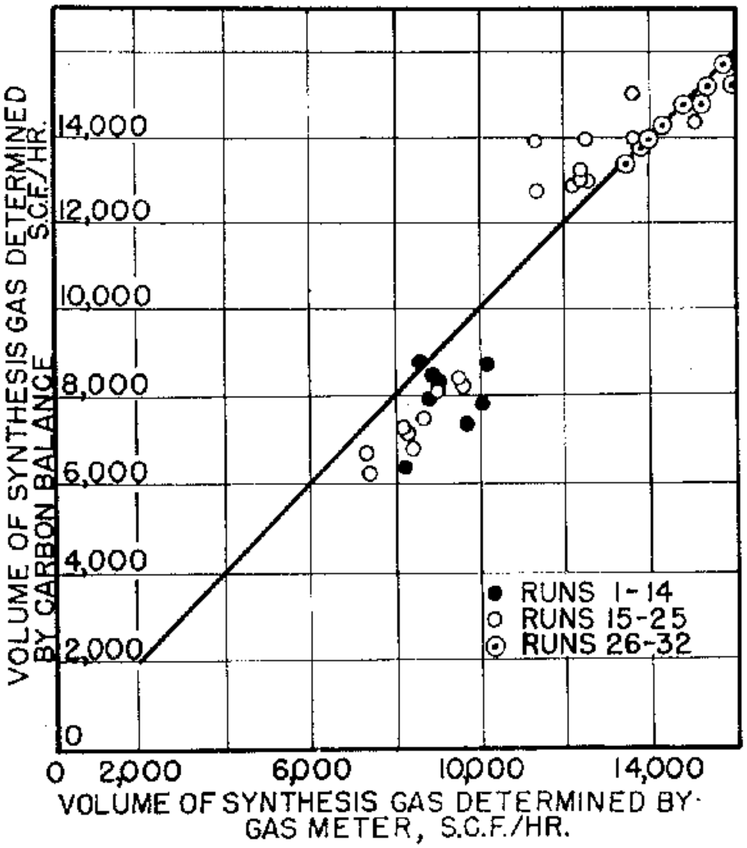

Figure 35. - Volume of synthesis gas as measured by gas meter compared with that by carbon balance.

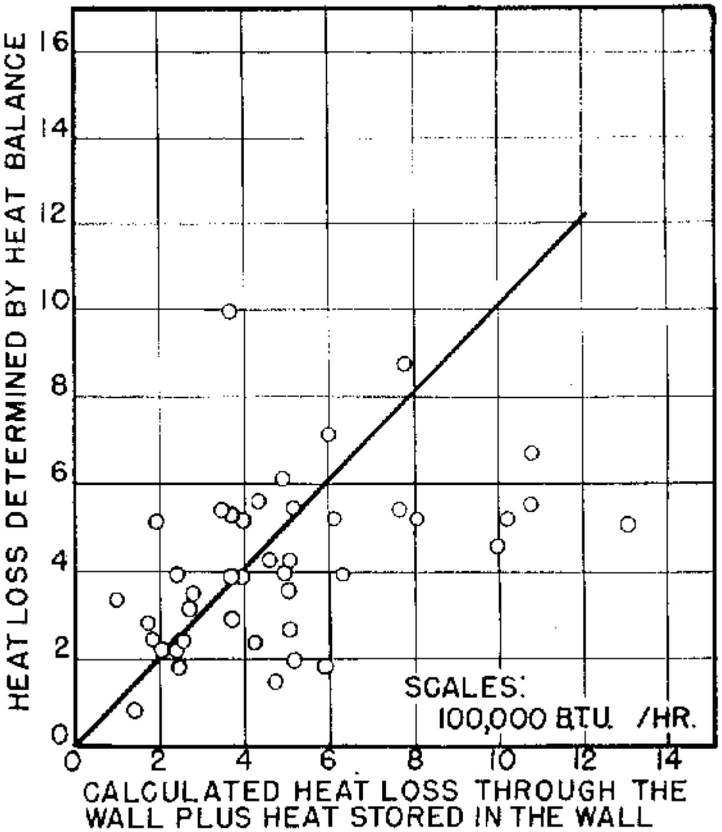

Figure 36. - Heat loss determined by heat balance compared with that determined by conduction through wall plus heat stored in wall.

## ACCURACY OF RESULTS

The uncertainties encountered in the residue measurements make the carbon balance based on this measurement less accurate than the carbon balance based on the gas measurements when the Roots-Connersville meter was used. Causes of errors in the residue data are as follows:

(1) Since not all the dust was removed in the train, the remaining dust was measured by sampling the exit-gas stream.

(2) The dust washed out of the gas in the cyclone separator and the wash box required another sampling determination. It is generally recognized that no satisfactory method exists for determining accurately the dust content of a stream by aliquot sampling.

(3) Since the generator had not reached equilibrium conditions at the start of the run, the initial carbon gasification was probably less than that at equilibrium, and since the collection hoppers could not be opened during the course of the run, the rate of residue collection was greater in the initial period than after equilibrium conditions had been reached.

(4) Since the slag from a series of runs was accumulated in the base of the generator, and since as previously reported there is evidence of carbon occlusion in the slag, some small amount of carbon remained in the generator at the end of each run.

Figure 35 shows the volume of synthesis gas as measured by gas meter compared with that determined from residue measurement and carbon balance. The results of the two methods agree within the accuracy of the experimental data. The gas-volume measurements are believed to be reasonably accurate. Orifice meters were calibrated against the Roots-Connersville meter, and the steam meter was checked by weighing the condensed steam. Furthermore, the total oxygen flow from the Cascade unit agreed with the sum of the flows of the separate oxygen streams.

In runs 1 through 14, since only ash and combustible material were measured, it was assumed that the residue consisted of ash, carbon, and 3 percent other constituents. In the later runs, the residue was analyzed for volatile matter, fixed carbon, and ash, and the carbon content was assumed to be the fixed carbon plus half the volatile matter. From the analyses made in the later runs, the assumptions for the first runs were found to be reasonable.

The undecomposed steam in the synthesis gas was calculated from both the hydrogen and oxygen balances. In general, the value obtained from the hydrogen balance was higher than that obtained from the oxygen balance, the over-all average value being 5 percent higher. It is possible that the volatile matter in the residue, which accounted for 2 to 6 percent of the total weight of dry residue, contained some hydrogen. Residue, however, from run 31 - the only residue analyzed for hydrogen - showed a negligible 0.04 percent hydrogen. Even if the average hydrogen content in these residues was 0.5 percent, the average resultant error in the undecomposed steam determination should not exceed 2 percent. On account of the relatively small magnitude of this probable error and the lack of data on hydrogen in residue for other runs no correction has been made for hydrogen in the residue.

The measurement of undecomposed steam, made by withdrawing samples of gas from the generator outlet and weighing the absorbed moisture, gave erratic results. These results checked those calculated from hydrogen and oxygen balances for about one third of the runs and were much lower for the remaining runs. In general, low values for the steam measurement were obtained when low values for the dust measurement were obtained, suggesting that the probable cause was failure to obtain accurate aliquot portions. Because of these low values, the undecomposed steam was calculated from the hydrogen and oxygen balances.

Attempts to determine undecomposed steam by withdrawing a sample of gas from the generator outlet to a 4-inch-I. D. cylinder, cooling the gas in the cylinder, and calculating the percentage of steam by pressure-temperature relationships also gave inconsistent results. The dust in the gas caused valve leakage, and as a consequence reliable check results were not obtained.

The measured values for the exit synthesis-gas temperature are slightly low. When checked with a high-velocity thermocouple, the exit-gas temperature was found to be about 25°F. low.

The inlet superheated-steam temperatures are believed to be reasonably accurate. For the high-temperature steam runs they were determined by heat balances on the Royster stoves, as protecting tubes would not stand up against the temperatures in the steam stream, and data on the relationships between pebble-bed temperature and superheated-steam temperature were insufficient to give accurate results. The corresponding low-and intermediate-range steam temperatures were measured by a thermometer and a thermocouple, respectively, in the steam inlet line to the generator, and these results have the usual accuracy of thermometer and thermocouple measurements.

Since the runs were started at generator temperatures below those obtaining after the operation became steady, some heat was stored in the generator brickwork. The runs were started at the lower temperature because the generator heat-up burner was of insufficient capacity to obtain the desired temperature, and because it was necessary to pass "purging" steam through the generator and purification train prior to starting the coal-oxygen feed. Figure 36 shows a plot of the heat loss determined from the generator heat balance compared with that calculated for conduction through the generator brickwork and storage in the brickwork. The agreement is reasonable and probably within the accuracy of the experimental data when it is considered that the heat loss calculated from the heat balance is a small difference between large numbers.

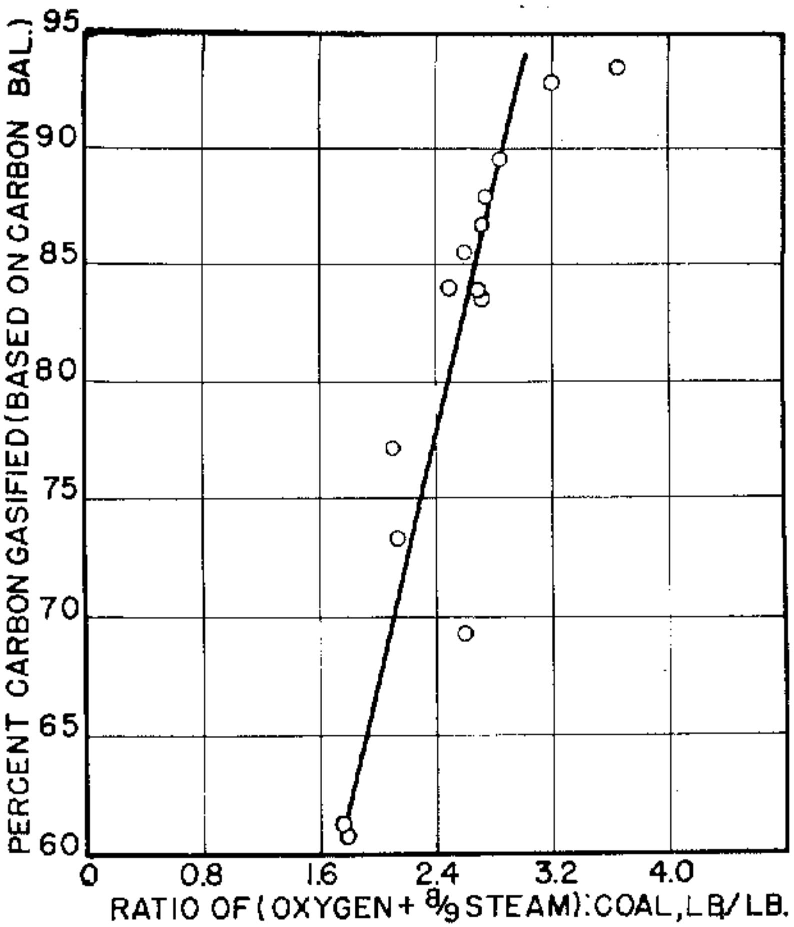

Figure 37. - Effect of ratio of (oxygen + oxygen equivalent of steam): coal on percentage of carbon gasified for runs 1-14.

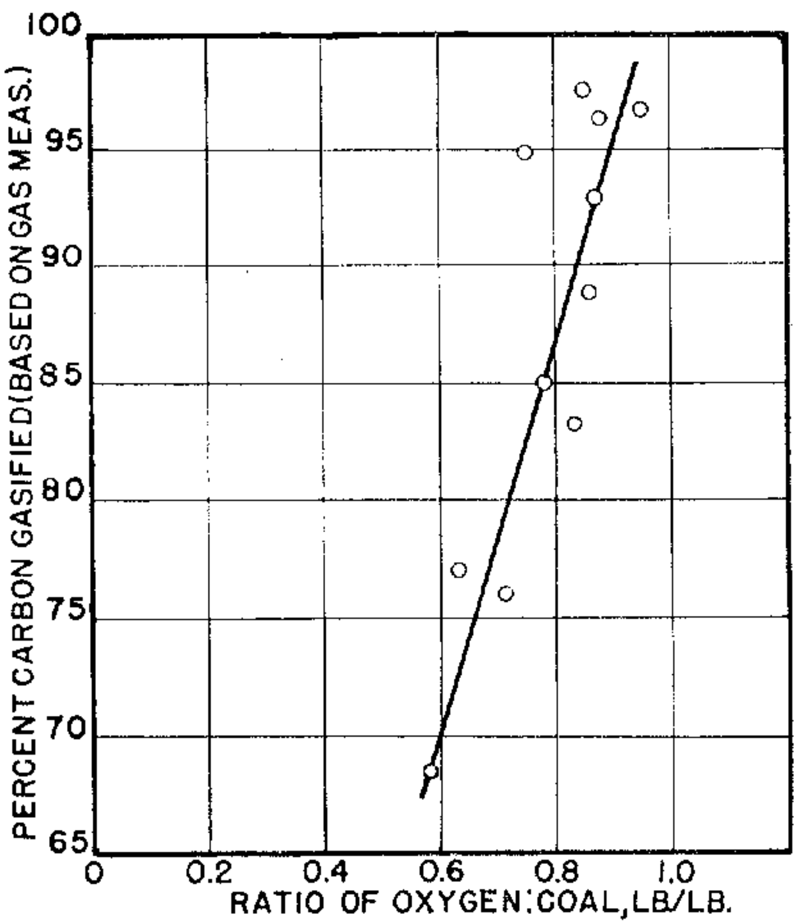

Figure 38. - Effect of ratio of oxygen:coal on percentage of carbon gasified for runs 15-25.

A source of error in some of the runs resulted from varying the reactant feed rates during the run period, as it was not always possible to set up desired conditions in advance. The percentage error introduced by this procedure was not large in any case. Neither the error in the heat balance due to these conditions nor the heat loss indicated would exist in a larger unit operating at steady load conditions.

## DISCUSSION OF RESULTS

It was shown earlier (fig. 34) that the percentage of coal ash remaining as slag increases in an almost straight-line relationship with the percentage of carbon gasified. A possible explanation of this phenomenon is that some of the coal particles are held on the wall of the generator in molten ash and gasified by the swirling gases moving past the surface. If the reaction were being carried on in a complete entrainment system, no ash would be deposited in the generator, and increasing percentages of carbon gasified would be coupled with increasing percentages of ash in the material carried over in the gas stream. No such linear relationship is found when the ash content of the residues is compared with gasification efficiencies.

The presumed hypothesis would also explain the continued formation of gas after the coal feed is shut off. Calculating centrifugal force exerted on the particle by the rotation of the gas, it appears that all except the very fine particles are driven to the generator wall. Coal gasification by this method or under these conditions has two distinct advantages: (1) By slagging out most of the ash, the dust-removal and waste-disposal problems are greatly simplified, and (2) since larger particles are held in the slag until gasified, the cost of coal preparation may be reduced. That is, it may not be necessary to pulverize the coal as finely as that used in these tests (90 percent minus 200-mesh).

Figures 37 and 38 show that the percentage carbon gasified increases greatly with the oxygen:coal ratio for the low-temperature steam runs and the (oxygen plus oxygen content of steam):coal ratio for the high-temperature steam runs. In the low-temperature steam runs, the entering steam velocity was very low, resulting in a low rate of rotation, in the high-temperature steam runs, a high entering steam velocity produced high rotation rates. Increased rotation rate in the high-temperature steam runs moved the gas past the coal particles more rapidly, so that the diffusional resistance was decreased. Since the coal particles were not surrounded by the products of the reaction of coal and oxygen, the reaction of carbon with steam could take place to a greater extent; and hence the percentage of carbon gasified was a function of the ratio of (oxygen plus steam):coal. In the low-temperature steam runs, the reaction of carbon with steam was not favored to the same extent, because the products of the reaction of carbon and oxygen were not so well separated from the carbon particles and hence the carbon gasified was a function of the ratio of oxygen alone to coal. The effect of the increase of the rotation rate in the high-temperature steam runs over that in the low-temperature steam runs was also shown in figure 34, where, at the same percentage of carbon gasified, the amount of ash removed as slag is greater for the high-temperature steam runs than for the low-temperature steam runs.

Figures 39 and 40 show the variation of the oxygen requirement with steam temperature for the high-temperature steam runs for two steam:coal ratios at zero heat loss. The solid lines show the calculated effect of steam temperature taken from figure 3, using the assumptions previously given. The points were determined from the experimental data, using the oxygen:coal ratio recorded in the run and recalculating the steam:coal ratio to the nearest ratio plotted. The composition of the gas was determined by using material balances, by assuming that the water-gas shift reaction reaached equilibrium at the measured exit-gas temperature, and by using a heat balance assuming no loss. The points show approximately the expected slope but lie above the calculated line largely because the measured percentage of carbon gasified is less than that assumed in calculating line A.

Figure 41 shows how the oxygen requirement increases with the increasing steam:coal ratio for the low-temperature steam runs. The solid line was calculated for 90 percent carbon gasification and 1,000 B.t.u. per pound of coal heat loss, the approximate average obtained in all the runs. The agreement is reasonable, the departure from the line again reflecting the lower carbon gasification obtained in the runs than that assumed in the calculation. The reason for the increase in the oxygen requirement with steam:coal ratio is that, as more steam is added, more heat is required for the increased amount of steam decomposed and the increased amount of heat in the sensible heat of the exit gas. Since only a small amount of heat is available from the reaction of carbon with oxygen to form CO, the greatest oxygen economy is obtained at low values of the steam:coal ratio.

Figure 42 shows the increase in the steam decomposition per pound of coal with an increase in the steam:coal ratio. It may be seen that the steam decomposition varies linearly and that the rate of increase corresponds to a steam decomposition of 25 percent for all three ranges of steam temperature. This value for steam decomposition agrees with that obtained by a heat balance. Thus in the high-temperature steam runs, 3 pounds of steam are used to supply heat for the reaction per pound of the steam taking part in the reaction.

If it is assumed that only three reactions take place in the generator - the reaction of carbon with oxygen to form carbon monoxide, that of carbon with steam to form carbon monoxide and hydrogen, and the water-gas shift reaction - it is possible to estimate the amount of steam actually reacting with carbon, that is, separately from that taking part in the shift. Thus, the mols of steam decomposed by the shift are equal to the mols of carbon dioxide formed. With these assumptions, the mols of hydrogen in the gas minus the hydrogen from the coal minus the mols of carbon dioxide equal the mols of steam reacting with carbon of the coal to produce carbon monoxide and hydrogen. Thus, it is possible, by this rather overly simplified method of analysis, to estimate the fraction of the steam decomposed which actually produces carbon monoxide and hydrogen. This fraction of steam decomposed, averaged for the high-temperature steam runs, is approximately 0.4. On the above basis for each pound of coal gasified, the pounds of steam reacting with carbon to produce synthesis gas are about 0.3 pound greater for the high-temperature steam runs than for the low-temperature steam runs.

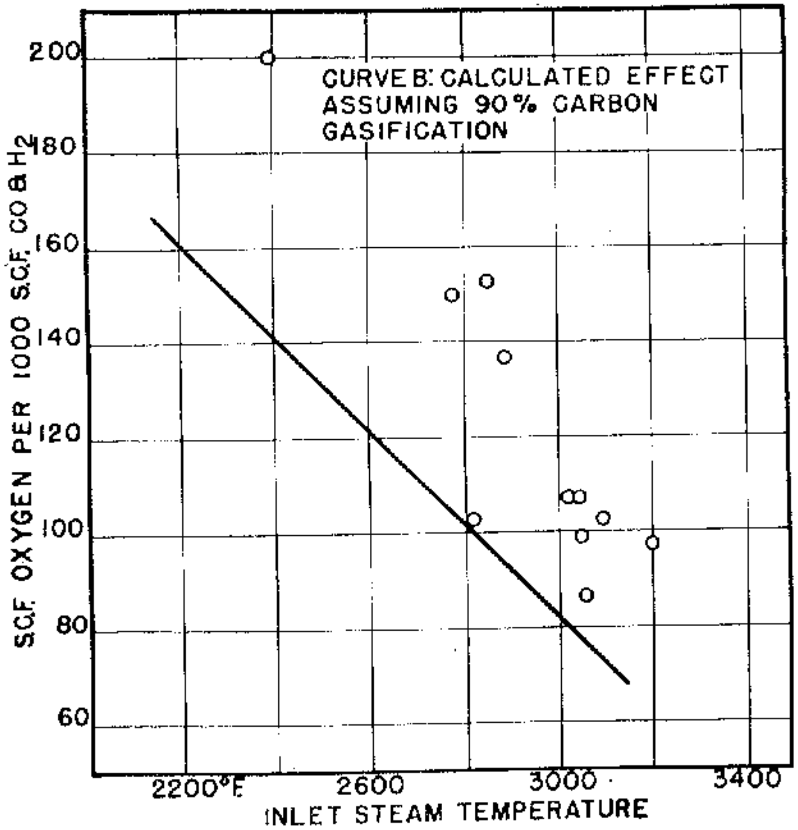

Figure 39. - Effect of steam temperature on oxygen requirement for gasification of Sewickley coal at steam:coal ratio of 2.5.

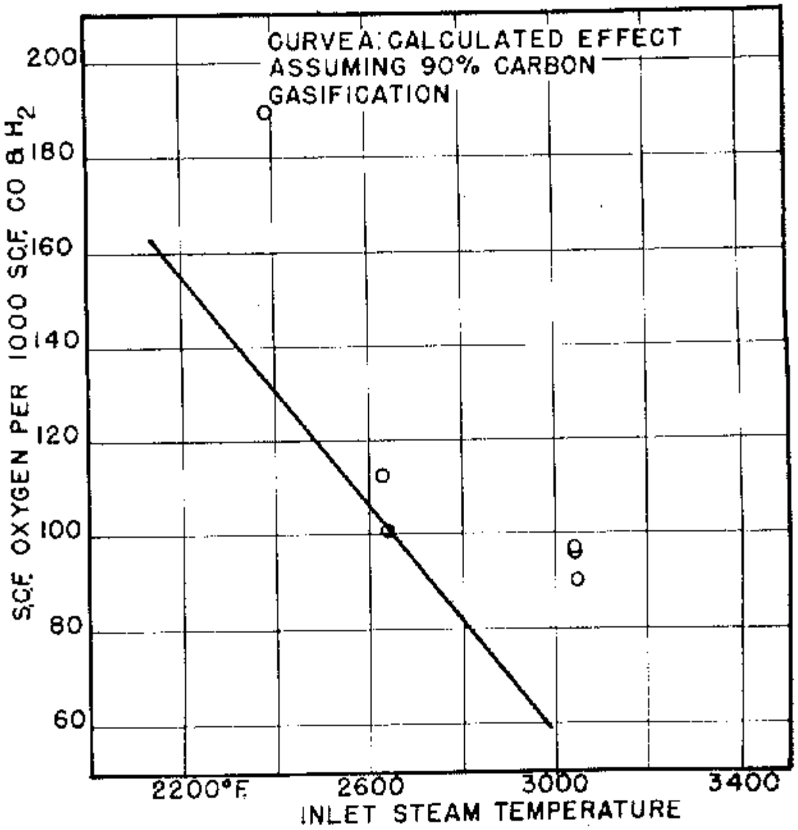

Figure 40. - Effect of steam temperature on oxygen requirement for gasification of Sewickley coal at steam:coal ratio of 3.0.

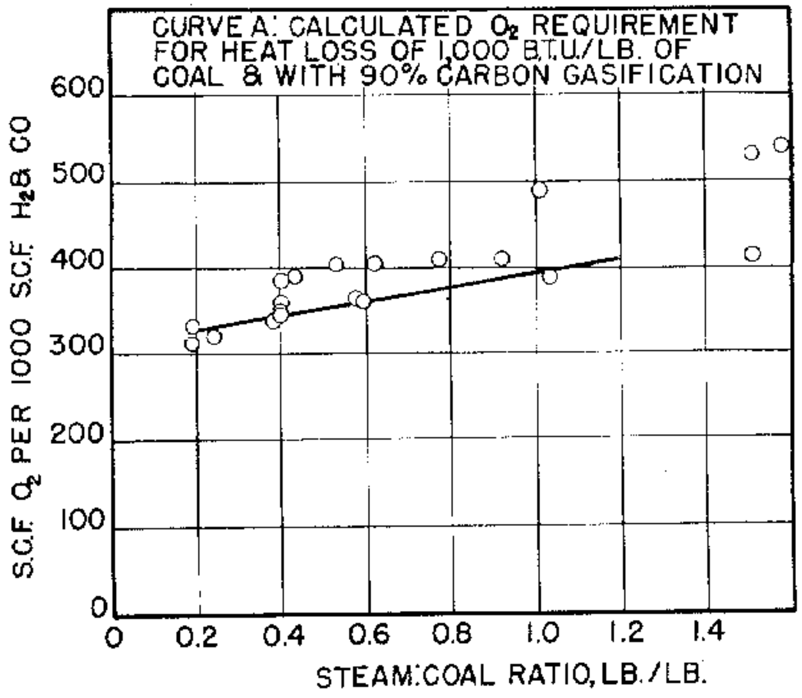

Figure 41. - Effect of steam:coal ratio on oxygen requirement for low-temperature steam runs.

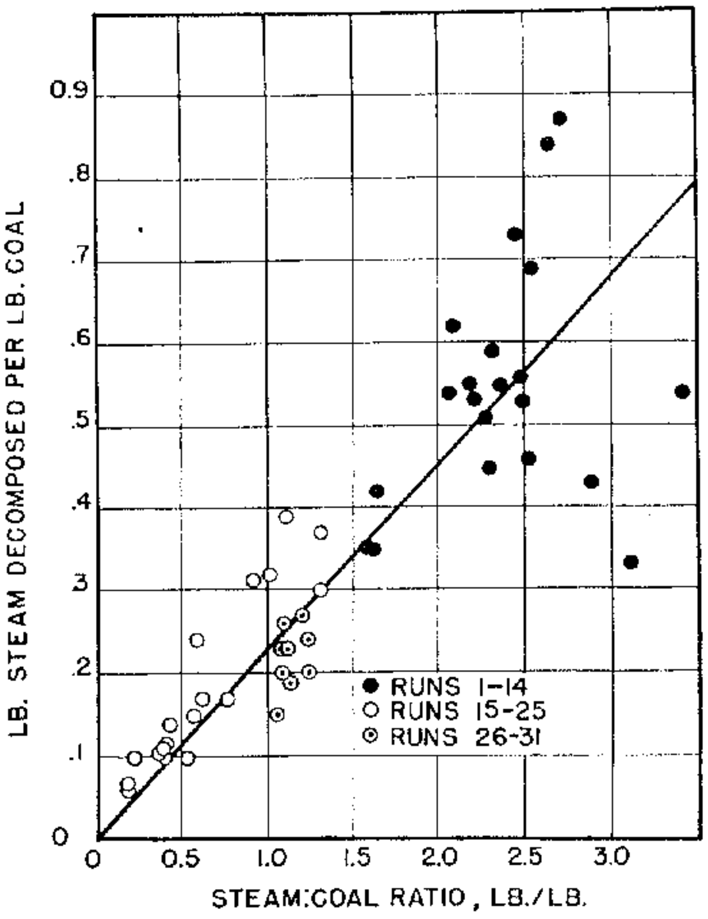

Figure 42. - Effect of steam:coal ratio on steam decomposition.

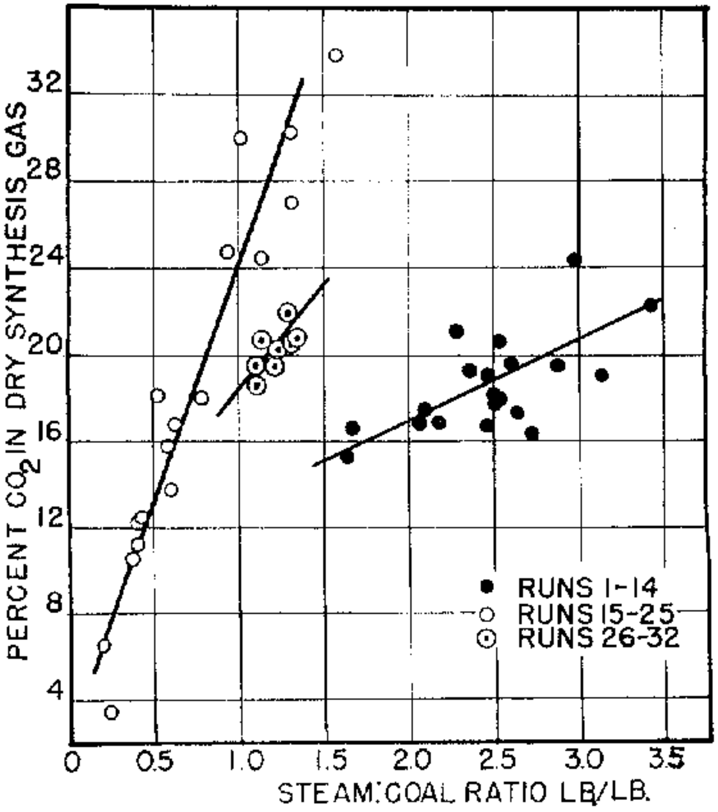

Figure 43. - Effect of steam:coal ratio on percentage carbon dioxide in dry synthesis gas.

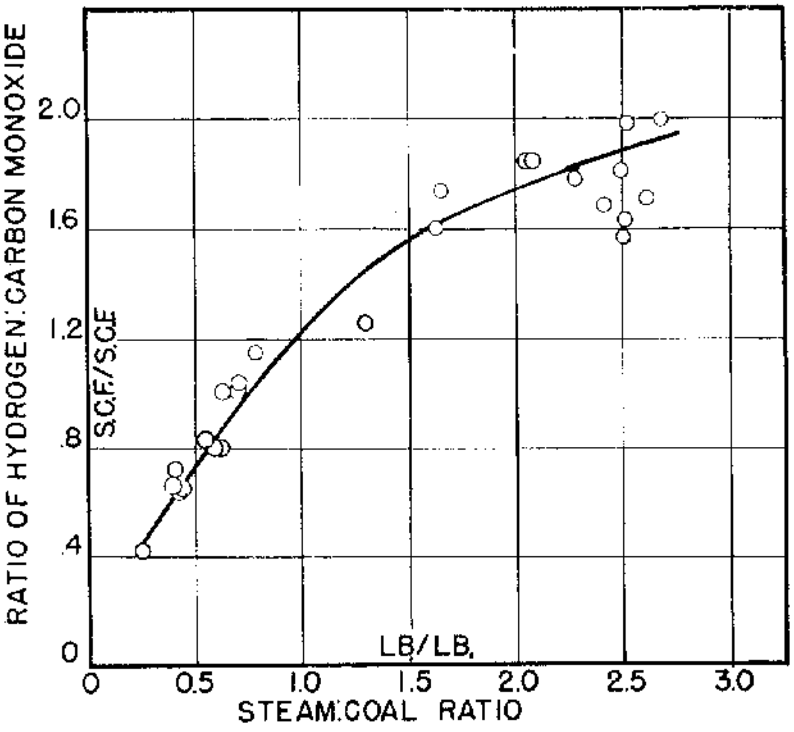

Figure 44. - Effect of steam:coal ratio on hydrogen:carbon monoxide ratio.

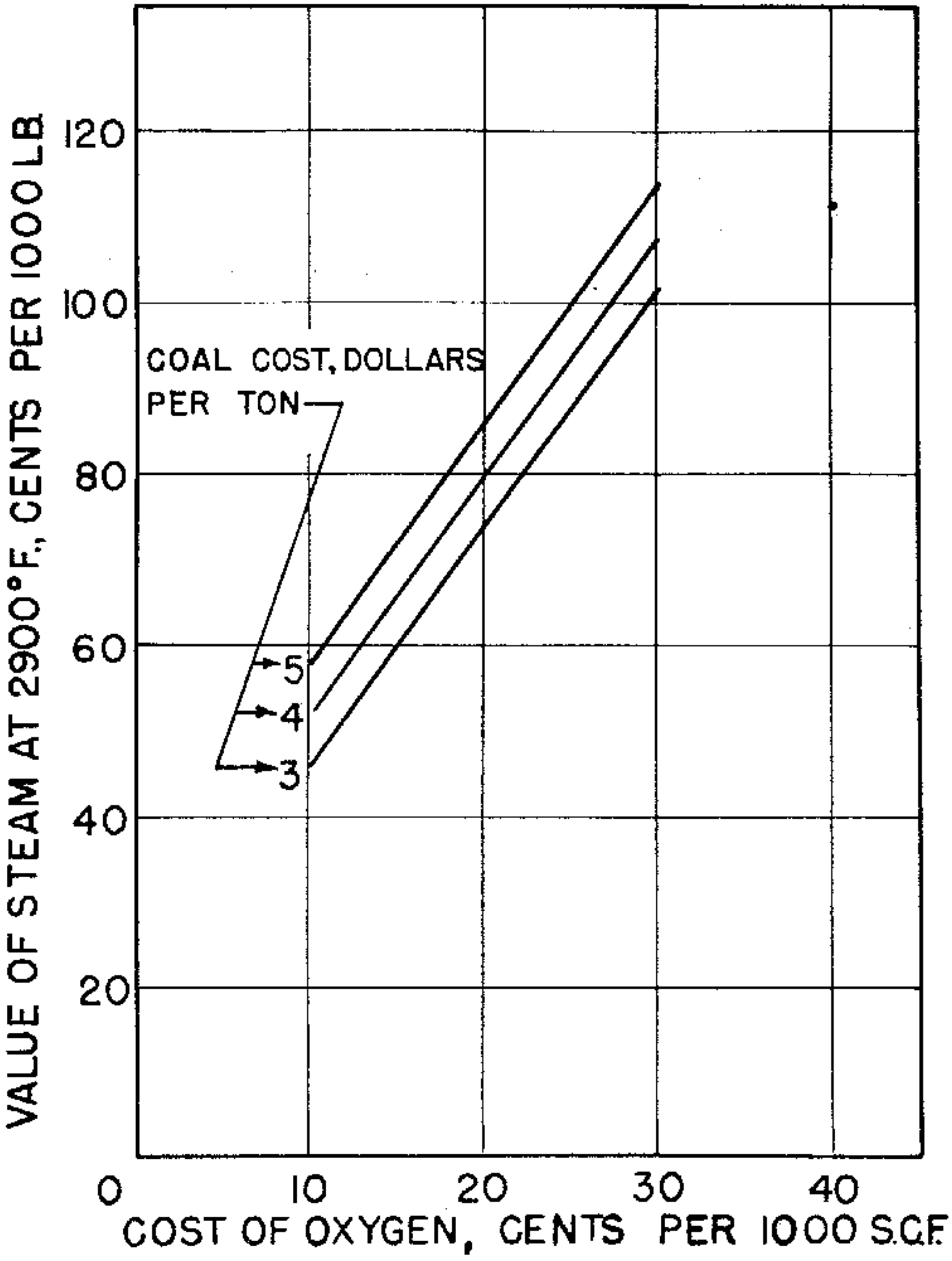

Figure 45. - Value of steam at 2,900° F. for production of synthesis gas.

Figure 43 shows the increase in the percentage of carbon dioxide in the dry synthesis gas with an increase in the steam:coal ratio. In the low-temperature steam runs, the carbon dioxide increases rapidly with the steam:coal ratio. This rise is accounted for by the increase in the oxygen requirement with an increase in the steam:coal ratio as shown in figure 41. As the steam:coal ratio increases, more heat must be generated from the reaction of carbon with oxygen to balance the heat requirement of the increased steam carbon reaction and the increased amount of heat in the exit gas. To supply this additional heat, more carbon dioxide is generated.

In the high-temperature steam runs, the increase in the carbon dioxide with steam:coal ratio may be explained by the equilibrium relations. Since equilibrium is essentially established for the water gas shift reaction at the exit gas temperature, and the ratio of hydrogen to carbon monoxide varies only slightly (1.6 to 2.2. from column 17, table 1), the carbon dioxide increases with the steam:coal ratio.

Figure 44 shows the relation between the steam:coal ratio and the hydrogen:carbon monoxide ratio. At a steam:coal ratio of zero, the hydrogen:carbon monoxide ratio is essentially the molal ratio of hydrogen to carbon in the coal. As the steam:coal ratio increases, more steam is decomposed, and as discussed previously, more $CO_2$ is formed. As the carbon dioxide increases, less carbon is available to form carbon monoxide, and hence the hydrogen:carbon monoxide ratio is increased. Figure 44 shows that a wide range of hydrogen:carbon monoxide ratios are available. One advantage of the high-temperature steam process is that it produces a hydrogen:carbon monoxide ratio of about 1.8, which is that reported to be used by the synthetic liquid fuel plant at Brownsville, Tex.

### Value of 2,900° F. Steam for Production of Synthesis Gas

Figure 45 shows the value of steam at 2,900° F. for use in the production of synthesis gas. Its value is determined by the costs of oxygen and of coal. Figure 45 is based on the average of all the high-temperature steam runs and 11 of the low-temperature steam runs 8 of the latter being omitted because the steam:coal ratio was too high and, hence, the oxygen requirement too high. The averaged data are given in table 8.

TABLE 8. - Requirements per 1,000 S.C.F. of $(CO + H_2)$ produced

| Steam temperature, °F. | Coal, lb. | Steam, lb. | Oxygen, S.C.F. | Thousands of B.t.u. above 400°F. in exit gas |
|---|---|---|---|---|
| 2,904 | 33.4 | 81.2 | 170 | 52.8 |
| 238 | 42.3 | 29.1 | 394 | 42.5 |

The data in the table show that the use of 81.2 pounds of steam superheated to 2,900° F. effects a saving of 225 S.C.F. of oxygen, and 9 pounds of coal and produces an additional 10,000 B.t.u. in the exit gas. If the extra heat in the exit gas is credited at coal cost, the value of the steam may be