

Composition of Product Gas

Rates of gas generation during runs 14 through 17 varied from 8.2 to 14.3 M cu. ft. per hour, the actual production rate depending upon experimental conditions. H₂-CO ratio of the product gas varied from 2.06 to 4.64. Gas composition data for selected H₂-CO ratios covering the range produced are summarized in table 5. Percent hydrogen in the gas varied relatively little; most of the change in H₂-CO ratio resulted from a shift in concentration of carbon monoxide. Concentration of carbon dioxide increased and that of methane decreased with increasing ratio. Ethane was present only in very small percentages. As a result of the increase in carbon dioxide and decrease in methane concentration, the heating value of the gas decreased with increasing ratio. Gas compositions obtained during these runs were similar at corresponding ratios to those previously reported (4, 5).

TABLE 5. - Typical analyses of product gas at various hydrogen-carbon monoxide ratios

Run and period	15-G	14-E	14-0	16-G
Ratio: H ₂ -CO	2.06	3.02	4.12	4.64
Component, percent: ^{1/}				
CO	26.8	19.0	14.5	13.0
H ₂	55.3	57.4	59.8	60.3
CO ₂	12.5	18.9	21.9	22.9
CH ₄	4.5	3.9	3.0	2.8
C ₂ H ₆	0.1	0.1	0.1	0.3
Illuminants	0.3	0.2	0.2	0.2
N ₂	0.5	0.5	0.5	0.5
Specific gravity (calc.)	0.522	0.544	0.543	0.545
Gross heating value (calc.), B.t.u./cu.ft.	313	288	273	271

^{1/} Air and purge gas free; nitrogen from lignite taken as 0.5 percent.

Sulfur content of the product gas ranged from 22 to 248 grains per 100 cubic feet, of which approximately 2 grains per 100 cubic feet was organic sulfur and the rest hydrogen sulfide. Actual percentages of sulfur transferred to gas from lignite depended upon experimental conditions and original sulfur content of lignite. Data for sulfur concentration in product gas did not reveal any significant variation with retort design (divided versus continuous annulus). As discussed in a previous progress report (3), sulfur balances on the externally heated gasifier tend to be erratic, probably because of difficulties in analyzing the high ash-gasification residue. Sulfur balances in runs 14 through 17 continued to fluctuate widely despite improvement in total material balances.

Concentration of tar vapor in the product gas after the water scrubber, determined by passing a measured volume of scrubbed gas through a tared packed tube, was about 0.03 pound per 100 cu. ft. of gas. Slightly less tar vapor was found when the continuous annulus arrangement was used.

Gasification Residue

Composition and size distribution of the residue or char that was discharged continuously during gasifier operation varied considerably, depending primarily upon the percent of carbon gasified, as discussed in previous reports (3, 4). Tables 6 and 7 present proximate and ultimate analyses and size distribution of the residue for the same test periods for which corresponding data on the lignite feed were given in tables 1 and 2.

TABLE 6. - Proximate and ultimate analyses of gasification residue for selected test periods

Run and period	14-A Dakota Star	14-G Dakota Star	14-O Dakota Star	15-A Dakota Star	15-H Dakota Star	16-E Dakota Star	16-H Baukol- Moonan	16-L Baukol- Moonan	17-C Baukol- Moonan	17-A Kincaid	17-E Zep	17-H Beulah	17-J Dickin- son	17-L Custer	17-N Blount
Carbon gasified ... percent....	62.0	66.0	76.4	72.0	47.2	66.7	75.3	63.4	82.4	86.4	80.2	60.7	58.2	70.7	65.0
Proximate analysis, percent:															
Moisture	2.1	2.0	1.7	3.5	0.4	0.8	0.6	1.0	0.8	0.8	0.8	1.2	0.9	0.7	0.7
Volatile matter	9.4	9.3	9.9	7.7	7.5	9.4	8.7	6.5	7.6	6.1	9.6	8.3	7.0	9.1	7.6
Fixed carbon	55.7	57.5	42.7	48.7	65.7	45.3	41.5	63.1	32.3	29.8	40.1	47.6	53.9	55.9	55.4
Ash/	32.8	31.2	45.7	43.0	26.4	44.5	49.2	29.4	60.3	63.3	49.7	42.9	38.2	34.3	36.3
Ultimate analysis, percent:															
Hydrogen	1.3	1.4	1.2	0.7	0.9	1.0	0.9	1.0	0.7	0.6	1.0	1.1	1.2	1.2	1.3
Carbon	63.6	64.8	51.3	60.8	73.5	57.2	50.0	66.9	39.9	37.5	52.4	56.7	65.3	62.5	61.5
Nitrogen	0.5	0.5	0.4	0.4	0.6	0.6	0.4	0.6	0.3	0.3	0.3	0.4	0.4	0.5	0.6
Sulfur	2.5	2.4	2.4	4.2	2.8	4.1	2.6	1.5	2.3	2.4	4.2	3.3	5.7	2.2	1.7
Oxygen	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ash/	32.8	31.2	45.7	43.0	26.4	44.5	49.2	29.4	60.3	63.3	49.7	42.9	38.2	34.3	36.3
SO ₂ /	5.79	5.37	5.06	9.21	6.89	8.88	5.37	3.31	4.93	5.61	9.76	7.27	12.0	5.61	4.80
C CO ₂ /	2.35	2.60	2.89	2.69	1.56	2.73	2.69	2.01	1.93	1.70	2.28	2.21	1.67	4.01	2.80
Heating value...B.t.u./lb. ...	9,910	10,100	8,030	9,420	11,250	8,910	7,710	10,300	6,090	5,650	8,230	8,760	10,350	9,660	9,420
Ash softening temperature .. °F.	-	-	-	2,520	2,450	2,530	2,470	2,230	2,100	3,150	2,420	2,310	2,490	2,590	2,590

1/ Total ash by conventional analysis, not corrected for sulfur.

2/ SO₂ in ash, reported as percent of original residue.

3/ Determined on original residue.

TABLE 7. - Size distribution of gasification residue for selected test periods

Run and period	14-A Dakota Star	14-C Dakota Star	14-O Dakota Star	15-A Dakota Star	15-H Dakota Star	16-E Dakota Star	16-H Baukol- Noonan	16-L Baukol- Noonan	17-C Baukol- Noonan	17-A Kincaid	17-H Zap	17-J Dickin- son	17-L Custer	17-N Blonfait
Lignite	62.0	66.0	76.4	72.0	47.2	66.7	75.3	63.4	82.4	86.4	80.2	58.2	70.7	65.0
Carbon gasified... percent ...														
U. S. mesh No. 1/	Percent retained													
Screen opening: Inches 2/	Percent retained													
4	26.7	30.3	26.4	16.7	15.5	18.4	14.3	24.8	18.6	13.6	23.5	13.2	16.6	18.1
8	29.5	27.6	22.2	27.5	28.3	26.4	20.0	28.5	18.9	20.9	22.2	21.4	24.7	23.5
16	15.2	14.0	13.2	17.4	20.3	16.2	20.3	14.9	13.3	14.7	13.8	18.2	17.9	15.4
30	8.9	9.9	11.6	13.5	12.1	13.3	11.5	10.5	10.7	11.2	10.4	13.9	9.5	10.5
50	8.4	8.2	10.6	10.1	9.9	14.4	12.1	9.8	13.3	13.4	11.5	14.0	9.1	13.0
100	5.7	4.8	7.2	6.9	6.4	4.6	10.4	6.5	12.0	12.6	9.1	9.6	5.8	10.7
200	2.9	2.3	4.4	3.8	3.6	2.2	5.9	2.8	6.5	7.1	4.5	5.0	3.1	5.3
Not retained	2.7	2.7	4.7	4.1	2.9	4.5	5.5	2.4	6.3	6.5	5.0	4.7	3.3	3.9
Average size	0.137	0.143	0.130	0.108	0.111	0.114	0.093	0.130	0.096	0.090	0.112	0.089	0.122	0.108

1/ Mesh numbers are U. S. Standard Series.

2/ Standard square mesh openings.

3/ Average size of material calculated as sum of fraction retained between 2 screen sizes multiplied by average of retaining screen opening and the one preceding.

Results from conventional ultimate analysis of gasification residues frequently show a sum of constituents exceeding 100 percent, owing chiefly to sulfur retention in the ash, as discussed in an earlier report (4). Oxygen is retained with the sulfur in the form of sulfate. Sulfur in the ash was determined for each test and is given in table 6 (sulfur reported as SO_3). It is evident that most of the sulfur in the original residue was retained in the ash on ignition.

Ash Deposits on Retort Tube

In all runs, in addition to residue removed continuously at the bottom of the retort, there was some buildup of ash deposits on the inner wall of the alloy tube. These ash deposits were removed completely and weighed at the end of each run. The quantity of ash collected from the inner wall of the alloy tube at the end of runs 14, 15, 16, and 17 is shown in table 8.

TABLE 8. - Weight of ash deposits collected from inner wall of 310-alloy tube

Run No.	Residue discharged continuously during gasifier operation, pounds	Total hours of operation	Ash collected from tube wall, ^{1/} pounds
14	60,800	802	52
15	48,400	466	71
16	53,300	637	36
17	74,500	974	109

^{1/} Tube-wall deposits removed and weighed at end of each run.

Probable influence of tube-wall ash deposits on gasifier operation is considered under discussion of results for the individual runs.

Material and Heat Balances

Complete data on material and heat balances for individual periods of runs 14 through 17 are tabulated in the Appendix. Data from representative periods of each run are presented in figures 4 and 5.

For the plot of representative data on material entering and leaving the gasification retort, figure 4, three periods were selected from each of runs 14 through 17. Results for these periods represent the highest, medium, and the lowest recovery obtained in each run. The weight of each individual component varied to some extent, depending upon experimental conditions. Generally, the percentage accounted for as material leaving the gasifier ranged from 93.3 to 100.7 percent of the entering material, with an average recovery of 97.7.

Heat balances at a series of H_2 -CO ratios of the product gas are presented in figure 5. The heat required for external heating of the gasifier ranged from about 28 to 31 percent of the total heat input. Efficiency of the process calculated on the basis of potential heat in product gas and discharged residue was from 73.5 to 77.5 percent, which is in the range previously reported for natural lignite (3). Comparative data indicate that arrangement of the annular reaction space had no significant effect on thermal efficiency. Radiation, convection and unaccounted for losses were generally slightly higher than those previously reported (3). Convection losses were influenced by time of operation of the ventilating system in the pilot-plant building.

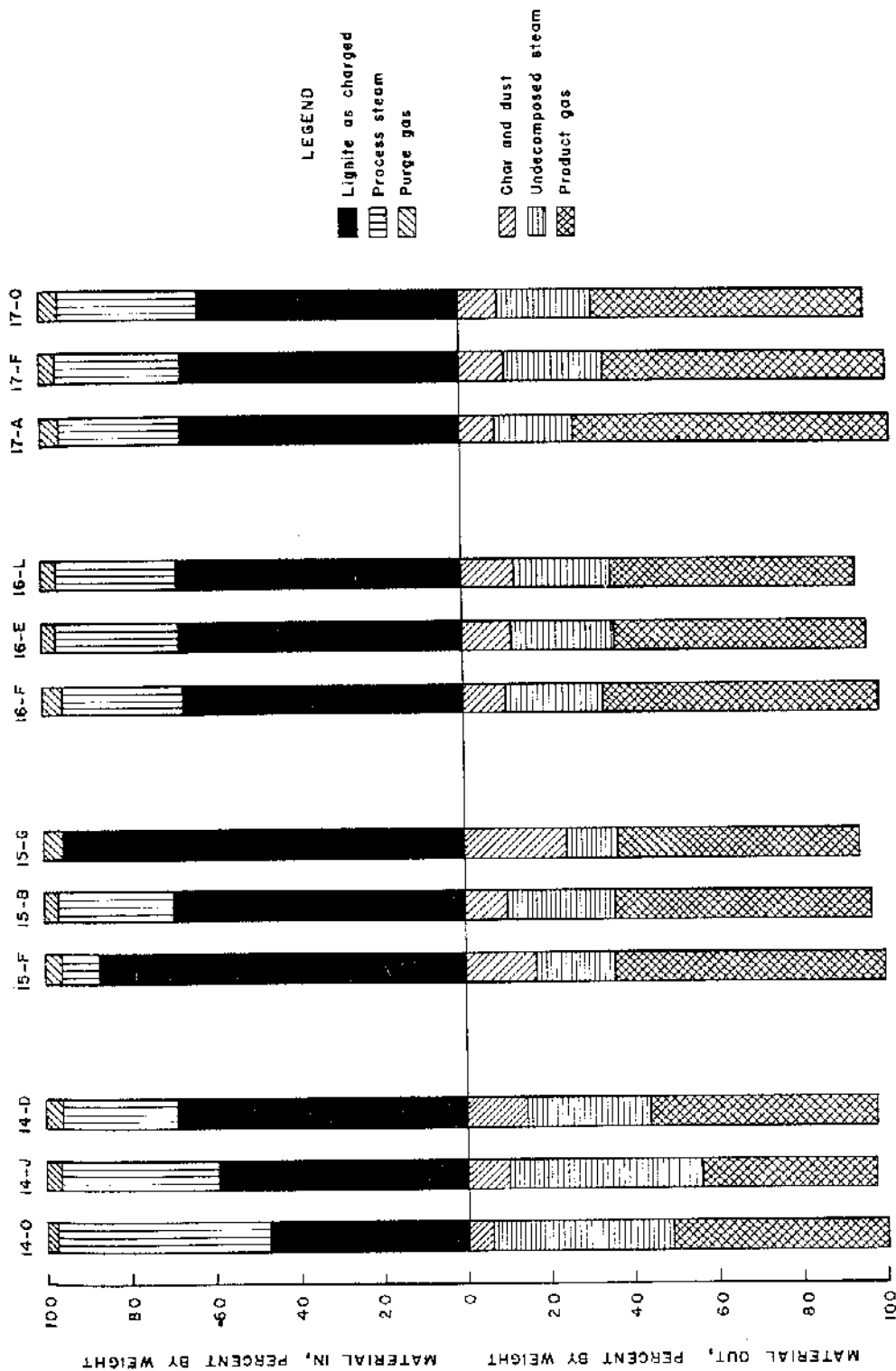


Figure 4. - Material entering and leaving annulus during gasification.

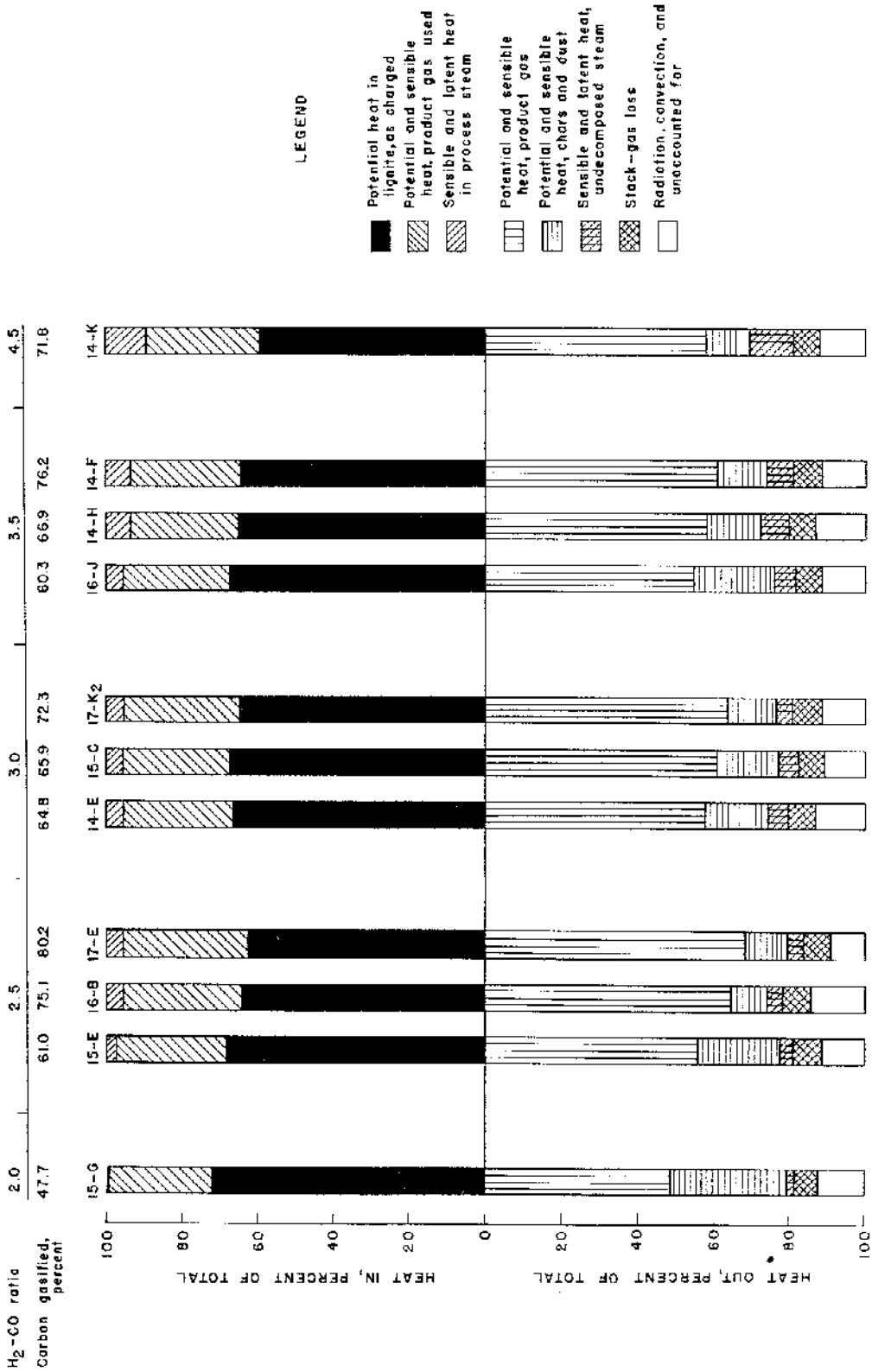


Figure 5. - Heat distribution during gasification as a function of H₂-CO ratio of product gas and carbon gasified.

Thermal Requirements

As in previous runs, results of runs 14 through 17 indicate that thermal requirements for gasification varied over a relatively narrow range, despite wide variation in gasifier operating conditions. Data on thermal requirements for individual tests in runs 14 through 17, expressed as net B.t.u. released in the external heating furnace per standard cubic foot of dry gas made, are given in table 16, Appendix. Limits of variation were from 115 to 156 B.t.u. per cu. ft. A general correlation of rate of gas generation as a function of heat-release rate, including data from runs 14 through 17 and from earlier gasification tests, is presented in Section III of this report Correlating Methods for Overall Gasification Data.

Run 14

The divided annulus arrangement of the gasification retort was used in run 14.

In this run, rate of addition of process steam and temperature distribution in the combustion space were varied at a single, approximately constant lignite feed rate of 500 (\pm 18) pounds per hour. The test schedule included 15 tests covering 3 steam feed rates and 5 combustion-space-temperature distributions. The schedule was designed to permit the separate evaluation of the effect of these two variables - combustion-space-temperature distribution and steam feed rate - on gasifier operation. Gasifier and auxiliary equipment were operated for a total of 802 hours during run 14. The plant was voluntarily shut down for inspection upon completion of the scheduled test program.

Influence of Water-Lignite Ratio on Gasification Using Divided Annulus

Results of experiments at various ratios of total water-lignite are correlated in figures 6 and 7. In addition to process steam, "total water available" includes water equivalent to total oxygen in the lignite, as charged, calculated from the ultimate analysis. Water equivalent to total oxygen was relatively constant at from 0.83 to 0.88 pound per pound of m.a.f. lignite.

Data were obtained at five separate combustion-space-temperature distributions, as indicated on figures 6 and 7.

Four dependent variables characterizing gasifier performance are plotted in figures 6 and 7, as follows: Percent carbon gasified, H₂-CO ratio of product gas, rate of gas production, and rate of heat transfer through the externally heated wall of the gasification retort.

Heat transfer data were obtained by a heat balance method involving differences between large quantities, and the resulting heat transfer rates were, in general, relatively unsatisfactory in precision. However, the data in this series appear to be internally consistent and are presented as an indication of order of magnitude and general trend of heat transfer rate.

Data of figures 6 and 7 show that each of the four variables increased with increase in water-lignite ratio. The general trend with water-lignite ratio is similar at each combustion-space-temperature distribution. As would be expected, maximum percent carbon gasified and highest rate of gas production were obtained at the highest water-lignite ratio and highest combustion-space temperatures.

Nominal lignite feed rate
500 pounds of natural lignite per hour

LEGEND

Carbon gasified
H₂-CO ratio of product gas

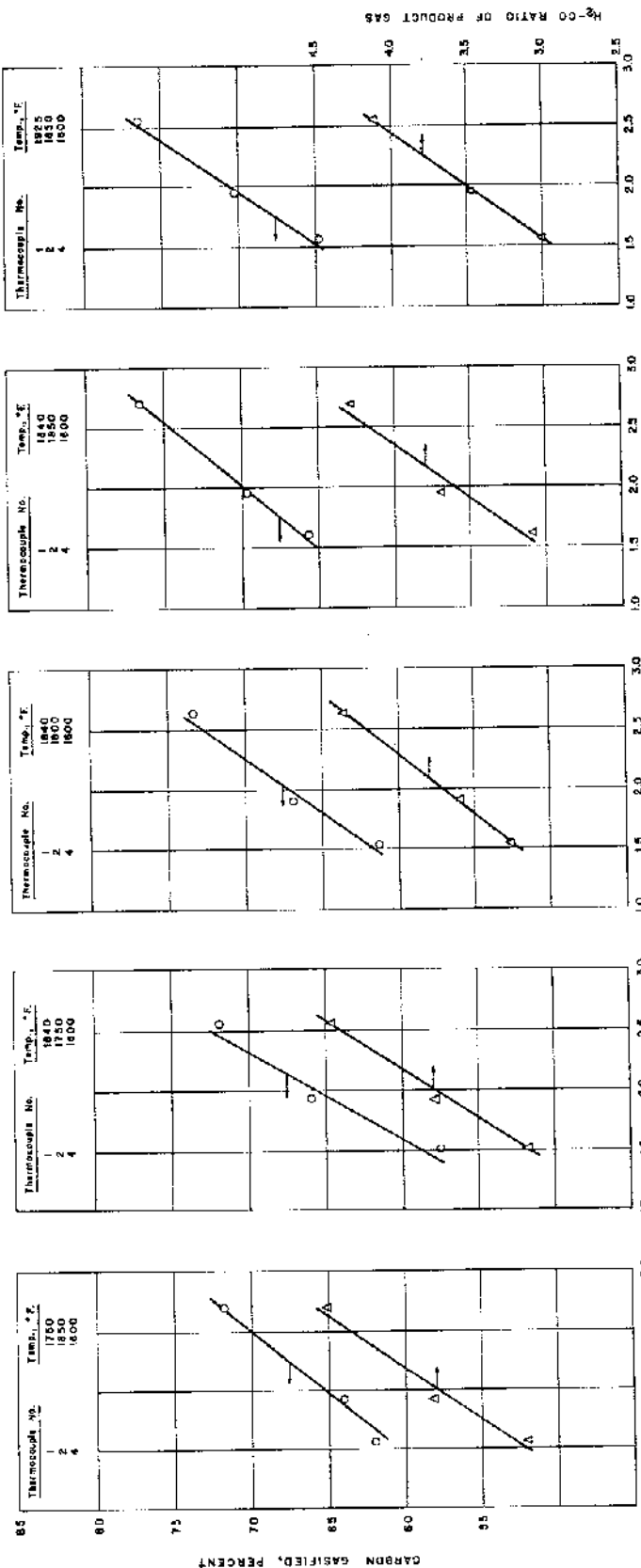


Figure 6. - Influence of total water available on carbon gasified and H₂-CO ratio of product gas, combustion-space-temperature distribution as parameter, divided annulus.

Nominal lignite feed rate
500 pounds of natural lignite per hour

LEGEND

□ Rate of gas production
○ Rate of heat transfer

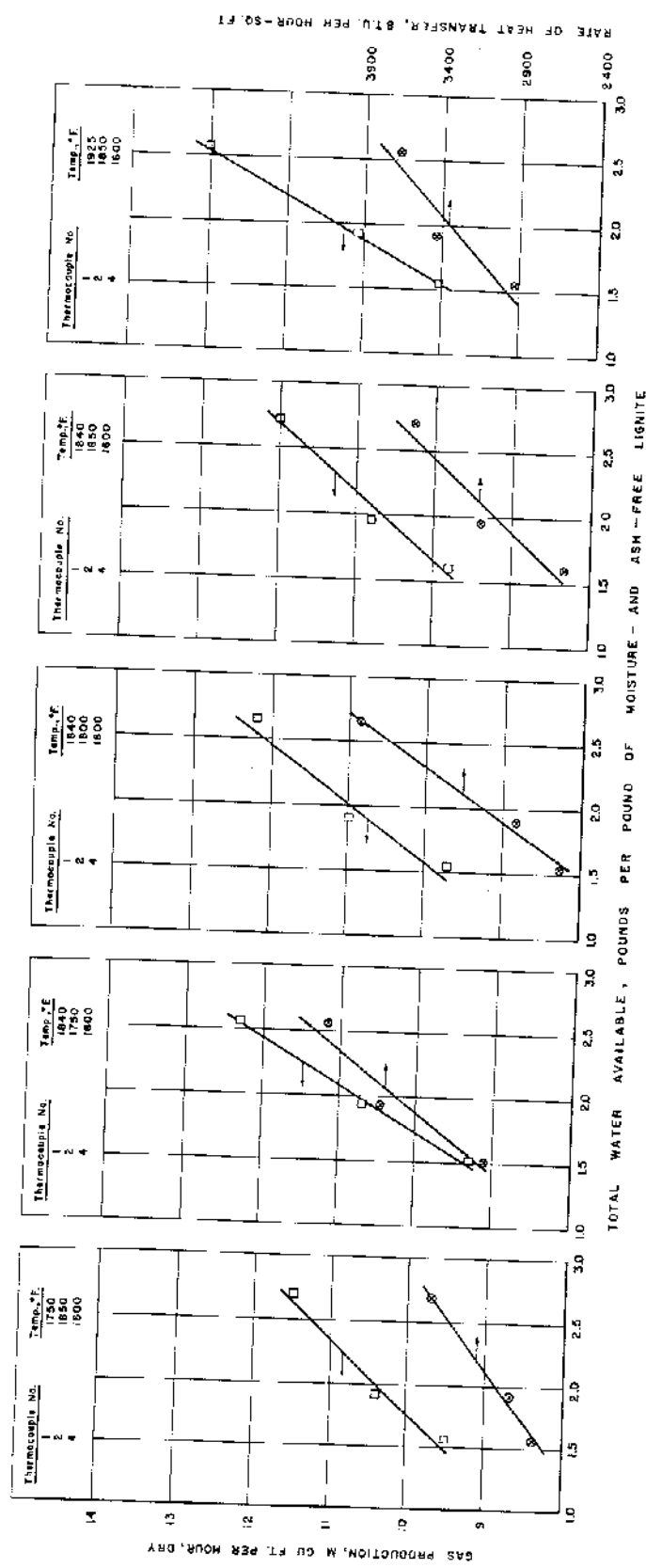


Figure 7. - Influence of total water available on rate of gas production and rate of heat transfer, combustion-space-temperature distribution as parameter, divided annulus.

The range over which water-lignite ratio was varied at each combustion-space-temperature distribution was from about 1.55 to 2.65 pounds of total water available per pound of m.a.f. lignite. In general, an increase in water-lignite ratio from 1.55 to 2.65, or about 70 percent, increased the carbon gasified and the rate of gas production by 20 to 30 percent. The data show an approximate straight-line relationship of percent carbon gasified and rate of gas production to water-lignite ratio in the range investigated, although this relationship obviously could not continue at higher water-lignite ratios, with lignite feed rate held constant. Maximum percent carbon gasified under the operating conditions investigated was 76 percent.

Extrapolation of the curves back to 0.85 pound of water per pound of m.a.f. lignite - corresponding to water available from the lignite with no addition of process steam - indicates that carbon gasified without steam addition would be about 57 percent at the highest combustion-space temperatures.

H₂-CO ratio of the product gas also increased rapidly with increase in water-lignite ratio. At the highest combustion-space temperatures, H₂-CO ratio increased from 3.0 to 4.2 with increase in water-lignite ratio from 1.55 to 2.65. Concentrations of unreacted steam in the total gas leaving the retort increased simultaneously. The increase in H₂-CO ratio evidently was caused by the increased concentrations of steam in the total gas passing through the retort by the mechanism of the water-gas shift reaction.

Although the percent carbon gasified increased significantly with increase in water-lignite ratio, the largest proportion of the total water available passed through unreacted at the higher rates of steam addition. Steam in the total product gas increased from 48 percent of the total water available at a water-lignite ratio of 1.55 to 60 percent at a water-lignite ratio of 2.65. At a water-lignite ratio of 2.65, steam in the total gas leaving the retort was equal to approximately 80 percent of the volume of dry gas generated.

At the lower water-lignite ratios, the amount of unreacted steam in the total product gas exceeded the process steam fed to the retort. At a water-lignite ratio of 2.65, the amount of steam in the total product gas was equal to 87 to 90 percent of the process steam fed to the retort.

To summarize: In the range of operating conditions investigated, increase in the feed rate of process steam caused a significant increase in the percent carbon gasified and the rate of gas generation. However, most of the total water available passed through the retort unreacted. Increasing concentrations of steam in the total gas passing through the retort altered the gas composition and increased H₂-CO ratio by water-gas shift.

Influence of Combustion Space Temperatures on Gasification Using Divided Annulus

Within the range of conditions used in this series of experiments, the effect of combustion-space temperatures on gasification was considerably less than the effect of steam feed rate. To indicate more clearly the effect of combustion-space temperature on the main dependent variables, the data of figures 6 and 7 are re-plotted in figure 8 with combustion-space temperature as the independent variable and water-lignite ratio as the parameter.

Percent carbon gasified and gas-production rates generally increased with increasing combustion-space temperatures. A temperature increase at thermocouple 2 seemed to have more effect on percent carbon gasified than an increase at

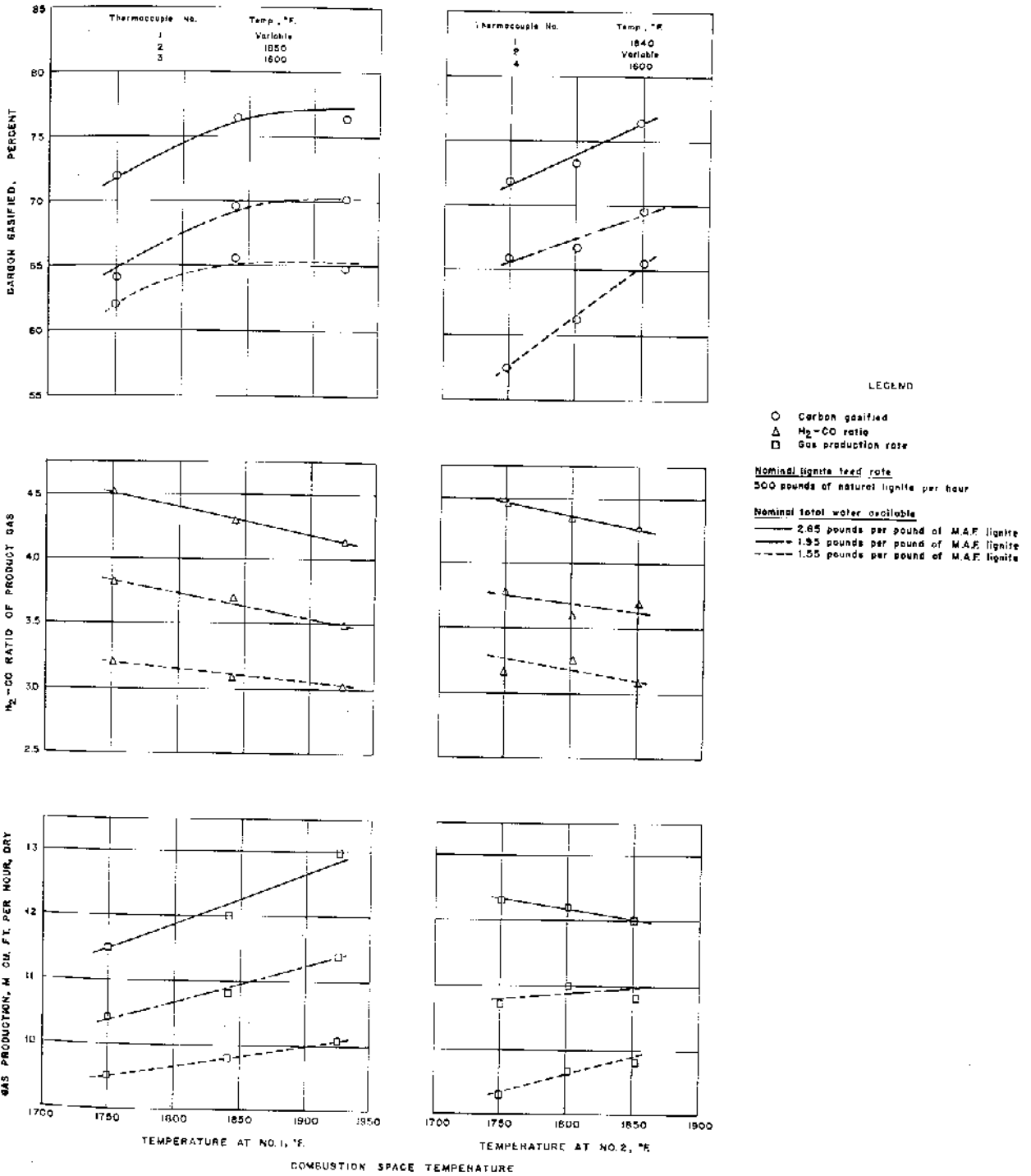


Figure 8. - Influence of combustion-space temperature on lignite gasification, total water to lignite ratio as parameter, divided annulus.

thermocouple 1. Thermocouple 1 is opposite the lower reaction zone of the divided annulus arrangement (see figs. 1 and 2). In this lower zone residual carbon in the char descending from the upper portion of the retort is gasified with steam fed at the bottom of the retort. Thermocouple 2 is opposite the upper reaction zone, where steam and gas generated from the lignite, as charged, are passing downward toward the gas offtake.

Changes of the variables with combustion-space temperature are relatively small and show discrepancies. Hourly gas production rates do not necessarily follow carbon conversion closely, in part because of small variations in the lignite feed rate.

H₂-CO ratio of the product gas decreased slowly with increase in combustion-space temperature at approximately constant water-lignite feed ratio. This trend may be explained by the gradual change in water-gas shift equilibrium constant with temperature, as well as the lower concentration of steam in the gas owing to increased gasification.

On the whole, the influence of combustion space temperature on carbon gasification and rate of gas production, as shown by the data in figure 8, is perhaps less than would be expected. The data appear to indicate that not a great deal of advantage would be gained by increasing these temperatures within reasonable limits. The highest combustion space temperatures used in this series of experiments are close to the maximum temperatures that have been considered acceptable for use in the long-term experimental program for determining useful life of the alloy reaction tube. The data on temperature dependence may reflect in part the unsatisfactory nature of combustion-space temperature as a variable in examining effect of relatively small changes and the failure of this temperature to represent accurately changes in temperature within the gasification retort.

Changes in Composition of Gasification Residue and Attachment of Ash Deposits

To obtain additional information on possible fluctuation in composition of the residue or char discharged from the gasifier during a stabilized test period, 14 samples were collected at 2-hour intervals. Twelve samples were taken during period 14-F and one sample each at the end and beginning of preceding and following transition periods. Fluctuation of ash and sulfur contents of the individual samples is shown in figure 9. The weighted average of ash content was 40.2 percent, whereas the usual composite sample, prepared from individual samples representing 3 percent of the net weight of each char container, showed an ash content of 39.3 percent. Results of this investigation indicated that the established procedure for obtaining representative char samples from a stabilized period was satisfactory despite erratic composition of residue at intervals during the test period.

As discussed in a previous report (3), the observed fluctuations in ash content of the gasification residue during a stabilized test period can be explained by considering that layers of ash that are formed at the externally heated wall of the gasification retort occasionally break loose and are discharged with the residue, increasing its ash content. During the following buildup period the ash content of residue would then be lower.

Data of run 14 were also examined for possible changes in gasification results with time, caused by a trend to permanent buildup of ash deposits (see table 8). Within the precision of the data, no such effect is observable in the results of run 14.

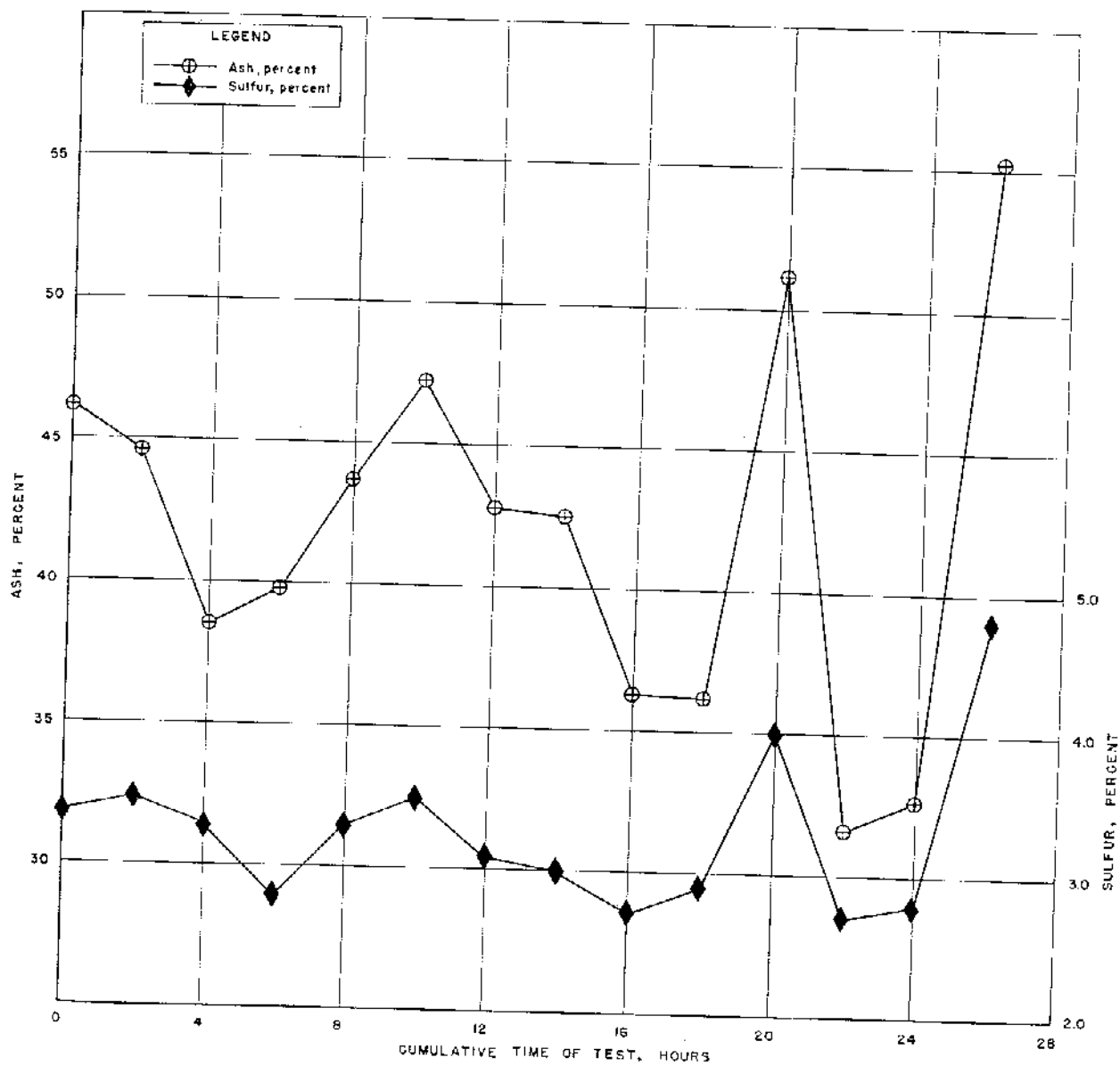


Figure 9. - Fluctuation of ash and sulfur in gasification residue during test period 14-F.