The trend of carbon gasified and rate of gas production with combustion-space temperature at constant water-lignite ratio is similar regardless of the time sequence of the data. In the single instance in which the results indicate rate of gas production to decrease with increase in combustion-space temperature (fig. 8), the test periods at lower temperatures were made last, so that the observed effect could not be caused by a trend to buildup of ash deposits with time.

In run 14, water-lignite ratio was the main variable affecting gasification rate. In obtaining the data of run 14, the complete sequence at the lowest water-lignite ratio was obtained first, then the sequence at the second ratio, etc. Thus the test periods most widely separated in time also involve a change in water-lignite ratio. The large effect of water-lignite ratio does not permit evaluation of any secondary effects that may be present in comparing results from the most widely separated test periods in run 14.

Runs 15 and 16

The specific objective of these two runs was to evaluate gasification characteristics of the continuous annulus arrangement of the gasification retort for comparison with data previously obtained from operation with the divided annulus. Data were obtained over a range of values of lignite feed rate, steam feed rate, and temperature distribution along the length of the combustion space. Run 15 was terminated after 466 hours of operation when the lignite elevator failed. Run 16 was completed on schedule after 637 hours of operation. Experiments during run 15 and the first seven test periods of run 16 were made as usual with Dakota Star lignite. Baukol-Noonan lignite, obtained from the University of North Dakota power plant, was used during the last five test periods of run 16.

Influence of Lignite Feed Rate on Gasification Using Continuous Annulus

Data on tests run with the continuous annulus arrangement at constant temperature distribution in the heating space and constant water-lignite ratio but varying lignite feed rates are presented in table 9. The test periods are divided into four series, each at a fixed combustion-space-temperature distribution. In each of these series, lignite was charged to the retort at approximately the same 3 feed rates - nominally 450, 550, and 650 pounds of natural lignite per hour. Water-lignite ratio was maintained approximately constant throughout the series of tests at 1.5 to 1.6 pounds of total water available per pound of m.a.f. lignite.

In general, data of table 9 show the same type of relationship of gasification characteristics to lignite feed rate as was observed in previous comparable tests with the divided annulus arrangement (3). An increase in lignite feed rate - at constant water-lignite ratio and combustion-space temperatures - caused a decrease in the percent of added carbon that was gasified. However, the decrease in percent carbon gasified was in all cases less than proportionate to the increase in lignite feed rate, so that the overall rate of gas production showed an increase. This indicates that the initial fractions of carbon in the lignite are gasified more easily than subsequent portions. This would be expected, since the first phase of gasification presumably consists of release of volatiles and tar, which are released relatively readily. In normal operation these volatiles are further cracked with steam in passing down through the remainder of the retort.

TABLE 9. - Influence of lignite feed rate on performance of gasifier using continuous annulus

Run and period Lignite	16-A Dakota Star	16-B Dakota Star	16-C Dakota Star	15-A Dakota Star	15-B Dakota Star	15-C Dakota Star	16-F Dakota Star	16-E Dakota Star	16-D Dakota Star	16-I Baukol-Noonan	16-J Baukol-Noonan	16-K Baukol-Noonan
Combustion space temperatures, °F.:												
Thermocouple No. 1	1,926	1,924	1,926	1,921	1,924	1,924	1,850	1,849	1,851	1,850	1,852	1,850
2	1,901	1,899	1,897	1,851	1,853	1,850	1,851	1,855	1,856	1,851	1,851	1,846
3	1,692	1,650	1,634	1,735	1,742	1,730	1,579	1,598	1,602	1,707	1,695	1,680
4	1,601	1,600	1,602	1,598	1,600	1,601	1,599	1,605	1,598	1,599	1,600	1,599
Lignite feed rate:												
As charged ... lb./hr.	454	540	681	478	566	638	427	537	637	443	536	663
M.a.f. basis ... do.	260	308	386	280	332	368	251	309	377	257	308	388
Total water available:1/												
Lb./lb. of m.a.f. lignite	1.59	1.66	1.60	1.50	1.50	1.55	1.59	1.61	1.60	1.54	1.60	1.51
Gas made:2/												
M cu. ft. per hour	11.4	12.6	13.9	10.7	12.0	12.9	10.1	11.2	13.0	9.3	10.3	11.5
M cu. ft. per ton of m.a.f. lignite	88.0	81.6	71.8	76.8	72.1	70.3	80.2	72.7	70.7	72.5	66.8	59.2
H_2-CO ratio of product gas	2.41	2.53	2.60	2.54	2.76	2.93	2.62	2.86	2.82	3.05	3.40	3.11
Carbon gasified ... percent	81.9	75.1	68.3	72.0	67.6	65.9	75.5	66.7	66.5	65.2	60.3	54.0
Inner tube wall temperatures, °F.:												
Thermocouple3/ A	1,232	1,225	1,192	1,223	1,205	1,218	1,235	1,181	1,186	1,191	1,153	1,120
B	1,212	1,206	1,177	1,211	1,188	1,205	1,216	1,164	1,175	1,131	1,135	1,104
D	1,147	1,135	1,114	1,099	1,023	1,023	1,146	1,091	1,101	1,096	1,061	1,031
F	1,105	976	920	865	778	744	1,015	943	899	938	875	805
G	847	802	719	752	680	654	864	762	698	775	701	634

1/ Includes process steam and water equivalent to total oxygen in the lignite calculated from the ultimate analysis.
2/ Gas volume, 60. F., 30 inches Hg dry.
3/ Distance from bottom of heated space, ft.:
A - 1.31, B - 3.31, D - 7.31, F - 11.31, G - 13.31.

Temperatures at measurement locations along the inner tube of the gasification retort also dropped as lignite feed rate was increased (table 9). Lignite near the inner wall is farthest from the main heat source. At higher feed rates, the lignite moved down through the retort more rapidly and was at a lower temperature at any one of the fixed measurement positions.

In figure 10 data on percent carbon gasified, hourly gas production, and H_2-CO ratio of the product gas as functions of lignite feed rate are plotted and compared for the divided and continuous annulus arrangements of the gasification retort. All the data of figure 10 were obtained at the same combustion-space-temperature distribution. Total water available was approximately constant at 1.5 to 1.6 pounds per pound of m.a.f. lignite. Data for the continuous annulus arrangement are from periods 15-A to 15-C (table 9). Most of the data on the divided annulus are from run 11, periods 11-A through 11-E. Additional data are given for 3 test periods (13-H, 13-I, 13-N) in run 13 and 1 test period (14-E) in run 14, which were made at the same combustion-space temperatures and within the same range of water-lignite ratios.

In general, the results are similar for the two design modifications within the apparent precision of the experiments. As feed rate is increased, carbon gasified and rate of gas production tend to be higher for the continuous annulus than for the divided annulus. H_2-CO ratios for the divided annulus, including results of test periods from three separate runs, show considerable scatter but appear to be in the same range as the results for the continuous annulus. Ratios are about the same despite the fact that in the divided annulus arrangement from one-half to three-fourths of the process steam was fed to the bottom of the retort, so that steam concentrations in the upper part of the retort were substantially less than in the continuous annulus arrangement. This suggests that in the divided annulus arrangement steam from the lower reaction zone participates in "shifting" composition of gas from the upper reaction zone as the two gas streams meet near the gas offtake.

Influence of Water-Lignite Ratio on Gasification Using Continuous Annulus

In figure 11, data are given for a series of five test periods (15-C through 15-G) at approximately the same lignite feed rate and combustion-space temperatures, but with varying rates of addition of process steam. Lignite feed rate for the 5 tests was equal to 615 ± 23 pounds of natural lignite per hour. Process steam was added at a series of rates up to a maximum of 250 pounds per hour, corresponding to a ratio of total water available to m.a.f. lignite of 1.55.

The general trend of the results is similar to that observed in previous tests (run 14) with the divided annulus at the same combustion-space temperatures but at somewhat lower lignite feed rate. Tests with the continuous annulus were in a comparatively low range of water-lignite ratios, and one test of the series was made without adding process steam. Within the precision of the data, slopes of the best straight lines for carbon gasified and rate of gas production versus water-lignite ratio are about two-thirds greater than was found in run 14 for the divided annulus at water-lignite ratios of 1.55 to 2.65 and a nominal lignite feed rate of 500 pounds per hour.

During run 15 the gasifier was operated for two test periods without adding process steam. Data for one of the test periods are plotted in figure 11 as part of the series at various water-lignite ratios and at a nominal lignite feed rate of 600 pounds per hour. Lignite feed rate for the other test period without addition of process steam was about 10 percent higher. The same combustion-space-temperature distribution was used.

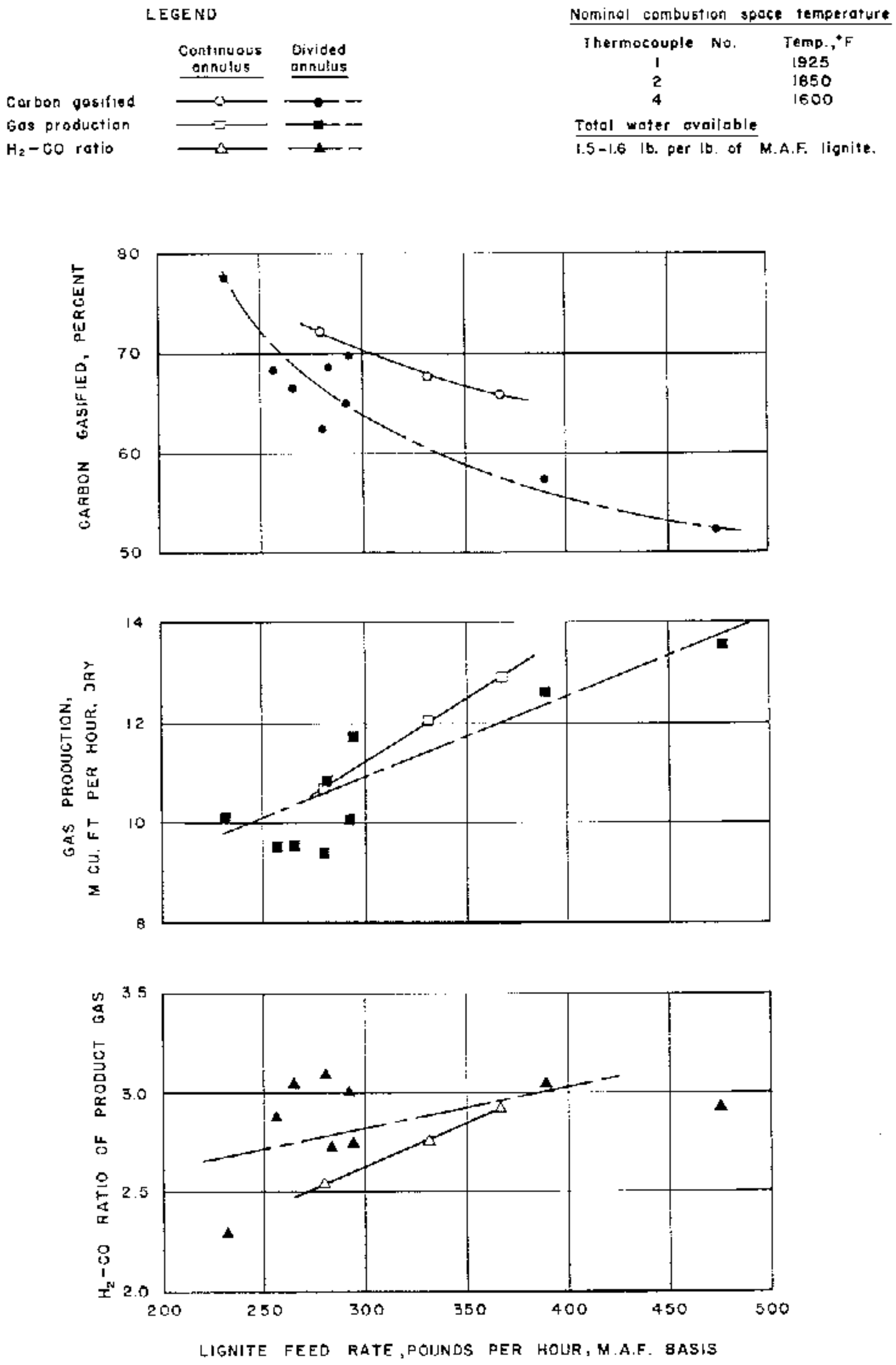

Figure 10. - Influence of lignite feed rate on gasification, divided and continuous annulus.

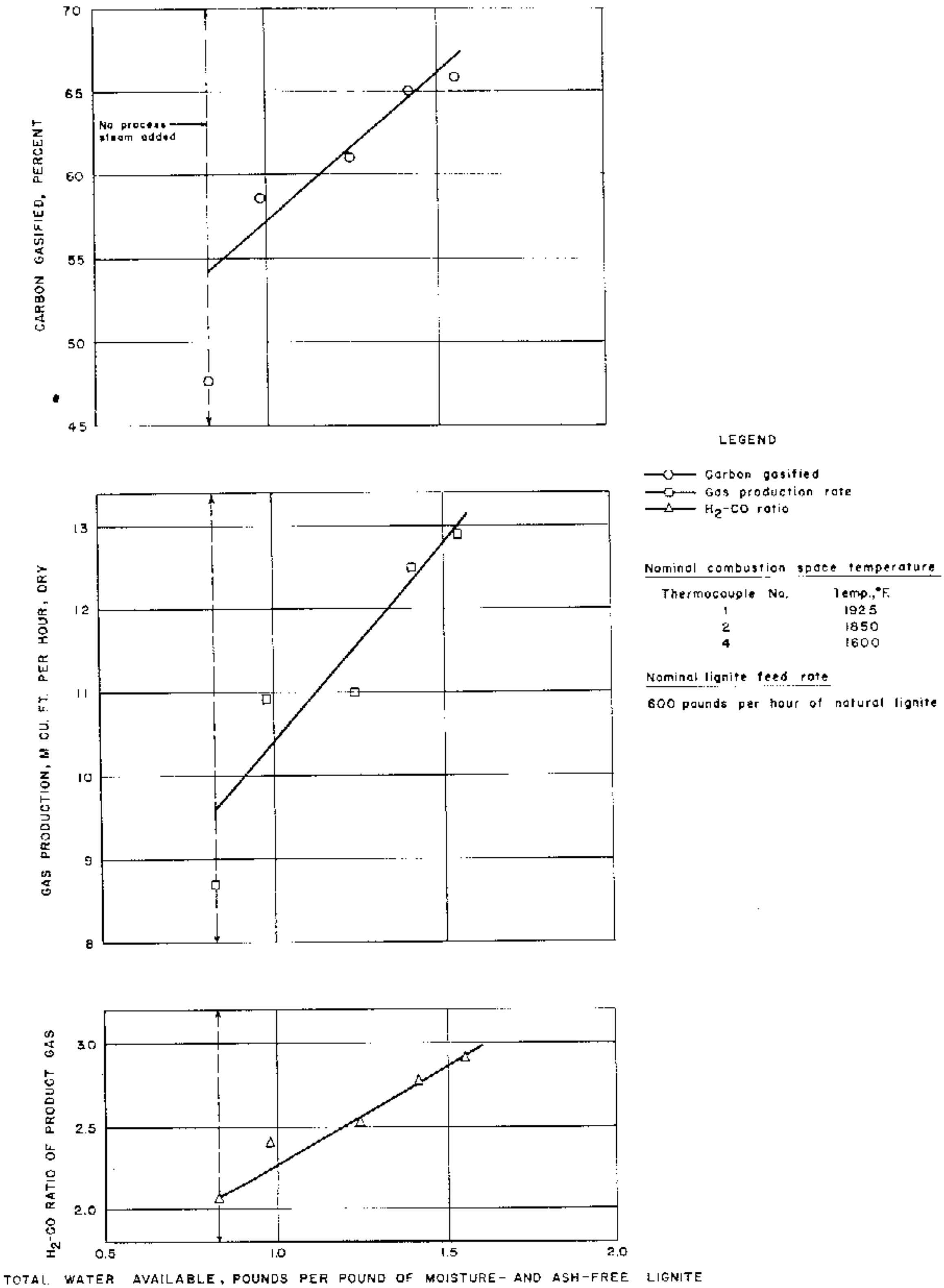

Figure 11. - Influence of total water available on gasification in continuous annulus.

Data for both of these test periods are listed and compared in table 10. Trends in the variables are about as expected within the normal precision of the data. Percent carbon gasified is approximately the same for the two test periods, although this trend obviously could not continue over wider ranges of lignite feed rate. Gas yield increased about in proportion to increase in lignite feed rate. H_2-CO ratio of the product gas was slightly higher at the higher feed rate.

TABLE 10. - Operation of continuous annulus arrangement without addition of process steam

Run and period	15-G	15-H
Combustion space temperatures, °F.:		
Thermocouple No. 1	1,924	1,927
2	1,848	1,851
3	1,749	1,750
4	1,599	1,600
Lignite feed rate:		
As charged ... lb./hr.	591	668
M.a.f. basis ... do.	351	383
Total water available:		
Lb/lb. m.a.f. lignite 1/	0.83	0.87
Gas made:		
M cu.ft. 2/ per hour	8.7	9.5
M cu.ft. 2/ per ton of m.a.f. lignite	40.5	40.2
H_2-CO ratio of product gas	2.06	2.36
Carbon gasified ... percent	47.7	47.2
Inner tube wall temperatures, °F.:		
Thermocouple 3/ A	1,214	1,150
B	1,186	1,106
D	1,000	846
F	718	624
G	619	533

1/ Water equivalent to total oxygen in the lignite, calculated from the ultimate analysis.
2/ Gas volume, 60° F., 30 inches Hg, dry.
3/ Distance from bottom of heated space, ft.:
A - 1.31, B - 3.31, D - 7.31, F - 11.31, G - 13.31

Comparison of Gasification Characteristics of Two Lignites

Dakota Star lignite was used for all test periods in runs 14 and 15 and run 16 through period 16-G. In the latter part of run 16, a series of test periods was run on gasification of lignite from the Baukol-Noonan mine, Noonan, N. Dak.

In figure 12 carbon gasified, hourly gas production, and H_2-CO ratio of the product gas of Dakota Star and Baukol-Noonan lignite are compared as a function of lignite feed rate. All data of figure 12 were obtained at a single combustion-space-temperature distribution and at approximately the same water-lignite ratio. Test periods included are 16-D to 16-F for Dakota Star lignite and 16-I to 16-K for Baukol-Noonan lignite.

At a given lignite feed rate, the results plotted in figure 12 indicate that percent carbon gasified and rate of gas production were 8 to 12 percent lower for the test periods with Baukol-Noonan lignite than for those with Dakota Star lignite. H_2-CO ratio of the product gas was higher for tests with Baukol-Noonan lignite, as

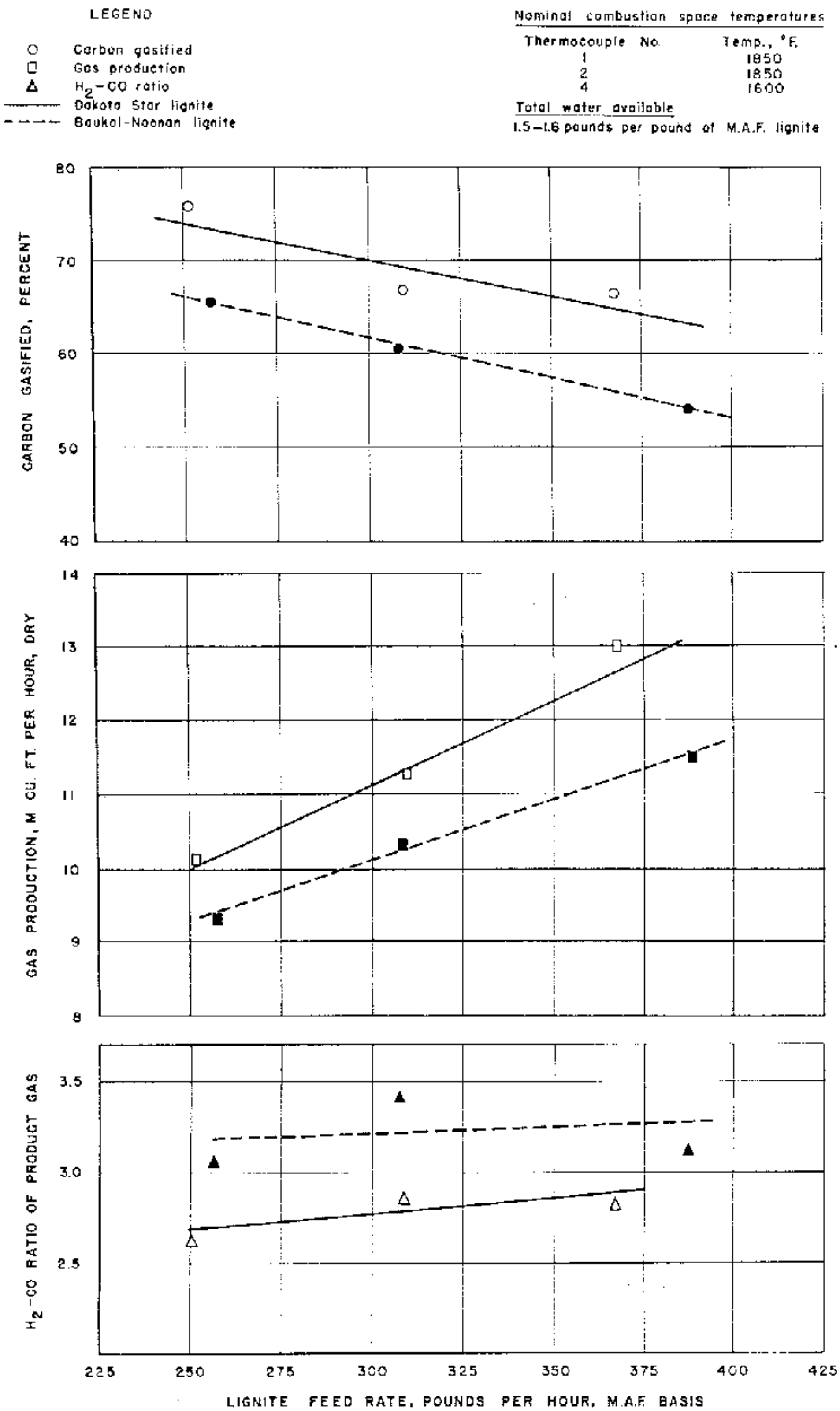

Figure 12. - Gasification characteristics of two lignites as a

a result of the lower volume of dry gas made and the higher steam concentrations in the total gas leaving the retort.

In figure 13, temperatures along the inner wall of the gasification retort are plotted and compared for the same two series of test periods with Dakota Star and Baukol-Noonan lignite. Inner tube temperatures at all points of measurement were lower for tests with Baukol-Noonan lignite. High percent gasification is indicated to correspond to high inner tube temperatures under otherwise comparable experimental conditions; that is, constant lignite feed rate, water to lignite ratio, and combustion-space-temperature distribution.

Differences in gasification characteristics evidently could be the result of fundamental differences in relative reaction rate between the two lignites tested. The results of figures 12 and 13 suggest clearly, however, that restriction on heat transfer rather than differences in reaction rate was the predominant factor determining gasification characteristics. If heat transfer characteristics were equal and the only differences were in reaction rate, a higher temperature gradient across the retort - and therefore a lower temperature at the inner wall - should be found for the lignite with the higher reactivity, since the gasification reactions are endothermic. Actually the higher overall rates of reaction correspond to higher temperatures at the inner wall, indicating heat transfer, not reactivity differences, to be the controlling phenomenon.

Differences in heat transfer may have been caused by differences in size distribution of the two lignites tested. Average size was about 12 percent lower for the Baukol-Noonan lignite for the test periods compared. Another factor previously considered, which could also affect heat transfer rate, is ash buildup on the inside of the alloy tube.

Most of the gasification data of runs 15 and 16 show no evidence of the restriction of operating capacity with time that would be expected from increase in ash deposits. In run 15, the large effect of change in water-lignite ratio predominates for most test periods, making it difficult to evaluate secondary factors. Run 15 was terminated because of mechanical failure in the lignite feed system. A relatively large amount of ash was collected from the alloy tube wall after run 15 (table 8); however, this is believed to be due in part to several hours' heating of the gasifier at the end of the run at zero rate of char discharge while attempts were made to repair the lignite feed system. Intercomparison of data for runs 15 and 16 (table 9) shows that gasification rate for periods 16-D to 16-F was comparable to rate in periods 15-A to 15-C, although slightly higher combustion-space temperatures were used in periods 15-A to 15-C. On the basis of this comparison, there is no evidence of decline in capacity with time in run 16 up to period 16-F.

There is the possibility, however, that further heat transfer restriction by ash deposit formation may have occurred in the latter part of run 16, periods 16-H through 16-L, because of the relatively low ash-fusion temperature of the second lignite tested. The possible effect of ash-fusion temperature on ash deposition is considered further in discussing results for gasification of seven different lignites in run 17.

Run 17

Lignite from seven different mines was gasified in run 17. Mine locations were listed in a previous section Experimental Conditions and Objectives of Test Runs and are shown in figure 3. Data on proximate and ultimate analysis and size distribution of the lignites are given in tables 1 and 2.

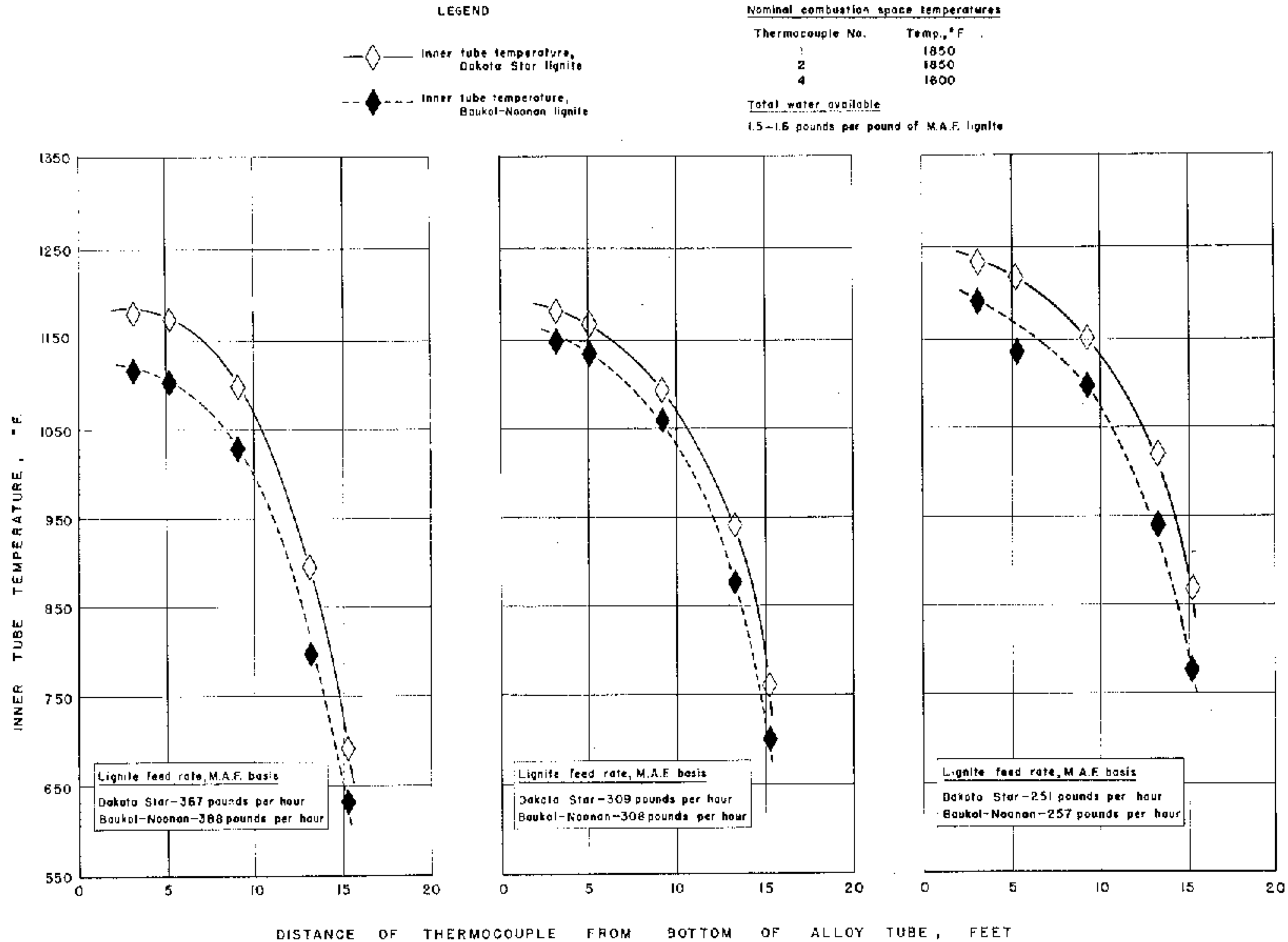

Figure 13. - Temperature of inner tube at various distances from bottom of retort, feed rate and source of lignite as parameters.

Each of the lignites was charged to the gasifier at 2 feed rates, nominally 450 and 550 pounds per hour. Lignite feed rate for individual test periods was maintained within 7 percent of the preselected rate at 450 and within 4 percent at 550 pounds per hour.

A single combustion-space-temperature distribution was maintained throughout run 17 as follows:

Thermocouple No.	1	2	4
Temp., °F.	1,925	1,900	1,600

Variation in temperature at these three measurement points for individual test periods was negligible (± 3° F.). Rate of addition of process steam to the retort was adjusted for change in lignite moisture content and feed rate to maintain an approximately constant water to lignite ratio for all test periods. Water-lignite ratio was held within the range 1.5 to 1.7 pounds of total water available per pound of m.a.f. lignite.

Run 17 was terminated on completion of the scheduled test program after a total of 974 hours of continuous operation. This final run of the series was the longest period of continuous operation ever carried out with the annular-retort gasifier.

Comparison of Gasification of Eight Lignites

Principal experimental data and results for gasification of the seven lignites tested during run 17 are summarized in table 11. Also listed in table 11 are data for gasification of Dakota Star lignite at similar lignite feed rates, combustion-space-temperature distribution, and water-lignite ratio during the first two test periods of run 16.

Comparison of gasification results of table 11 shows a wide variation in carbon gasified and rate of gas production at each of the two levels of lignite feed rate. For the series of test periods at a nominal lignite feed rate of 450 (± 33) pounds per hour, rate of gas production varied from 8.2 to 13.1 M cu. ft. per hour and carbon gasified varied from 66.5 to 86.4 percent. For test periods at a nominal lignite feed rate of 550 (± 21) pounds per hour, rate of gas production varied from 9.3 to 14.1 M cu. ft. per hour and carbon gasified from 58.2 to 79.4 percent.

It is evident that differences in rate of gas production for the test periods listed in table 11 were far larger than could result from change of lignite feed rate in the two test series. The differences are also far larger than would be expected from the relatively small variation in water-lignite ratio during the two test series, on the basis of correlations previously developed (figs. 7 and 11).

Effect of Heat Transfer on Gasification Characteristics

Analysis of the data indicates that the factors affecting change in gasification rate are probably complex. However, as was the case in the comparison of two lignites in run 16, the main differences appear to be those associated with heat transfer.

TABLE 11. - Comparison of gasification characteristics of eight lignites

Run and period	17-A	17-B	17-C	17-D	17-E	17-F	$17\text{-}G_3$	17-H	17-I	17-J	$17\text{-}K_2$	17-L	17-M	17-N	17-O	16-A	16-B
Lignite charged	Kincaid	Kincaid	Baukol-Noonan	Baukol-Noonan	Zap	Zap	Beulah	Beulah	Dickinson	Dickinson	Custer	Custer	Bienfait	Bienfait	Kincaid	Dakota Star	Dakota Star
Feed rate:																	
As charged...lb./hr.	483	552	431	556	436	542	464	529	437	553	446	566	452	542	434	454	540
M.a.f. basis...do...	283	331	244	313	254	332	256	295	228	301	248	314	264	321	253	260	308
Moisture as charged............. percent	35.2	34.2	36.4	36.8	35.0	35.0	35.2	35.8	40.6	37.8	40.0	40.4	36.6	35.0	34.8	36.6	37.2
Ash as charged...do...	6.2	5.9	7.0	6.9	6.7	5.6	9.7	8.4	7.3	7.8	4.5	4.2	4.9	5.7	7.0	5.2	5.7
Average size of lignite........inches	0.93	0.95	0.73	0.74	0.89	0.92	0.60	0.62	0.82	0.76	0.88	0.95	0.94	1.01	1.06	0.90	0.90
Combustion space temperatures, °F.:																	
Thermocouple No. 1...	1,924	1,923	1,924	1,925	1,926	1,925	1,925	1,924	1,926	1,926	1,924	1,923	1,926	1,925	1,925	1,926	1,924
2...	1,900	1,898	1,900	1,898	1,901	1,899	1,898	1,899	1,900	1,900	1,899	1,901	1,898	1,899	1,900	1,901	1,899
4...	1,600	1,597	1,600	1,598	1,599	1,601	1,601	1,600	1,600	1,601	1,601	1,600	1,600	1,600	1,600	1,601	1,600
Total water available:1/																	
Lb. per lb. of m.a.f. lignite.....	1.56	1.53	1.65	1.64	1.61	1.58	1.63	1.66	1.75	1.58	1.60	1.61	1.57	1.57	1.71	1.59	1.66
Gas made:2/																	
M cu.ft. per hour...	13.1	14.1	11.0	12.9	11.1	13.0	9.3	10.0	8.2	9.3	9.7	11.8	10.2	11.6	10.8	11.4	12.6
M cu.ft. per ton of m.a.f. lignite.....	92.4	84.9	90.3	82.4	87.5	80.6	72.6	67.5	72.3	62.0	78.4	75.3	77.0	72.1	85.4	88.0	81.6
H_2-CO ratio of product gas..........	2.12	2.27	2.36	2.83	2.59	2.72	3.38	3.82	3.71	3.92	3.10	3.17	3.13	3.30	2.81	2.41	2.53
Carbon gasified...................percent	86.4	79.4	82.4	73.7	80.2	74.1	66.5	60.7	66.8	58.2	72.3	68.4	58.4	65.0	76.6	81.9	75.1
Inner tube wall temperatures, °F.:																	
Thermocouple3/ A....	1,252	1,245	1,270	1,217	1,224	1,212	1,164	1,141	1,183	1,141	1,184	1,165	1,172	1,157	1,184	1,232	1,225
B....	1,238	1,233	1,254	1,199	1,212	1,195	1,128	1,122	1,169	1,117	1,174	1,146	1,156	1,141	1,174	1,212	1,206
D....	1,120	1,104	1,145	1,047	1,125	1,081	1,029	984	1,055	967	1,058	985	1,039	996	1,082	1,147	1,135
F....	877	844	820	770	885	801	785	731	806	715	756	681	758	691	823	1,005	976
G....	767	740	772	686	755	700	698	659	701	627	649	593	643	588	680	847	802

1/ Includes process steam and water equivalent to total oxygen in the lignite, calculated from the ultimate analysis.
2/ Gas volume, 60. F., 30 inches Hg, dry.
3/ Distance from bottom of heated space, Ft.:
A - 1.31, B - 3.31, D - 7.31, F - 11.31, G - 13.31.