RESULTS OF TESTS

General

All operating data and general observations during the five runs of the commercial-scale pilot plant from December 1946 through December 1948 are presented in this report.

After run 4 the retort unit was not dismantled or changed. Run 5 was begun on December 13, 1946, and the specific objective was to make gas with a high hydrogen-carbon monoxide ratio. Erratic operation dictated a shut-down on December 28, after which the unit was dismantled for examination. Appreciable deposits of ash were found on the inside of the outer retort tube near the gas offtake and in the lower reaction zone. In the same general region considerable corrosion and deposits of scale were observed both inside and outside the retort tube. Corrosion was particularly severe at the welded seams. Measurement of the tube showed that the diameter had increased slightly in this region.

The retort tube was reconditioned and inverted for run 6, which was begun September 8, 1947, and continued until October 4. In nine test periods the conditions to make gas with a high hydrogen-carbon monoxide ratio were determined. This ratio was varied from 4 to 9 at gas production rates from 7 to 12 M cu. ft. per hour. Examination of the retort tube after the run revealed no important additional corrosion except at the welded seams near the gas offtake. Corroded welds were repaired with 310 alloy before run 7.

For run 7, which was begun December 6, 1947, and ended December 23, the retort unit was arranged with a continuous annulus (<u>see</u> fig. 4). Again the objective was to produce gas with a high hydrogen-carbon monoxide ratio. The actual ratio ranged from 3 to 6 at gas-production rates from 7 to 11 M cu. ft. per hour. The retort tube was in good condition after run 7 and required no maintenance except cleaning before it was reinstalled for run 8.

Run 8 was begun January 16, 1948, with the same continuous annulus arrangement of the retort as in run 7. Furnace temperatures were raised and other operating conditions changed to make a gas with a hydrogen-carbon monoxide ratio between 2.3 and 3.3 at production rates from 7 to 11 M cu. ft. per hour. When the run ended on February 13, the outer retort tube showed no additional corrosion, but measurements indicated some progressive increase in diameter.

A new centrifugally cast HK-alloy tube was installed for run 9 with a nominal 2-1/4-inch divided annulus (<u>see</u> fig. 4). Heating was begun April 30, 1948, but operation became so erratic that the plant was shut down on May 4. No successful test was completed; accordingly, no operating data for this run are presented.

A summary of all operation of the plant is given in table 1. The hours of operation have been calculated as the time from ignition of the gas burners until they were turned off. In 3,857 hours of operation 756 tons of lignite have been gasified to produce 32,975 M cu. ft. of gas. Subtotals in the table show the results with each retort tube.

TABLE 1. - Summary of operation of commercial-scale pilot plant, February 1945 through December 1948

Run No.	Retort tube[1]	Date		Time operated, hr.[2]	Lignite processed, tons	Gas made, M cu. ft.[3]
		From	To			
Preliminary	1	2/27/45	3/7/45	192	[4]22.5	[5]731
1	1	6/13/45	6/24/45	257	55.4	1,626
Subtotal	1			(449)	(77.9)	(2,357)
2	2	12/6/45	12/16/45	258	56.0	2,569
3	2	3/6/46	3/25/46	418	94.4	4,121
4	2	4/16/46	5/16/46	[6]736	[6]187.9	8,690
5	2	12/13/46	12/28/46	369	54.1	2,300
Subtotal	2			(1,781)	(392.4)	(17,680)
6	3	9/8/47	10/4/47	625	118.4	5,680
7	3	12/1/47	12/23/47	475	74.1	3,273
8	3	1/26/48	2/13/48	429	78.9	3,586
Subtotal	3			(1,529)	(271.4)	(12,298)
9	4	4/30/48	5/4/48	98	14.2	640
Grand total	All types			3,857	755.9	32,975

[1] 1, Spray-coated tube; 2, alloy-clad tube; 3, reconditioned alloy-clad tube; 4, cast HK-alloy tube

[2] Time to the nearest hour from lighting burners until they were shut off.

[3] Up to and including run 6, gas production was measured with an orifice meter; a positive-displacement meter was used in all succeeding runs.

[4] Weight estimated from volume measurement.

[5] Estimated; volume was measured for only part of period.

[6] Includes 72 hours when 7.6 tons of char was used.

Lignite Tested

Dakota Star lignite for all runs was purchased from the mine at Hazen, Mercer County, N. Dak., in carlots of Stoker-Nut Size, 1-1/2 by 3/8 inch. It was used as received, except for rescreening to 1-1/2 by 1/2-inch size, in all tests reported herein. Typical analyses are given in table 2, which show about 35 to 37 percent moisture, 6 to 7 percent ash, and 0.6 to 0.9 percent sulfur. For all practical purposes, this lignite is quite uniform in composition, and test results are comparable in this respect. Experience during earlier runs (2) had shown that this size would flow freely through a 3-inch anulus, and this fact was verified in these tests.

In runs 5 and 8 a single composite sample was prepared to represent the run, but individual samples were prepared for each period of runs 6 and 7. Complete analyses for all samples are given in table 11 in the appendix.

TABLE 2. - Typical analyses of natural lignite gasified in commercial-scale pilot plant

Run and period number	[1] 5	6C	6I	7D	7E	[1] 8
Proximate analysis, percent:						
Moisture	36.2	36.0	34.3	36.1	37.1	35.9
Volatile matter	27.3	28.3	28.4	27.7	27.0	27.6
Fixed carbon	30.1	29.4	31.1	30.4	29.4	30.3
Ash	6.4	6.3	6.2	5.8	6.5	6.2
Ultimate analysis, percent:						
Hydrogen	6.7	6.9	6.7	6.8	6.8	6.8
Carbon	41.4	41.4	42.6	41.8	41.0	41.5
Nitrogen	0.6	0.6	0.6	0.6	0.6	0.6
Sulfur	0.7	0.7	0.9	0.6	0.7	0.7
Oxygen	44.2	44.1	43.0	44.4	44.4	44.2
Ash	6.4	6.3	6.2	5.8	6.5	6.2
Heating value, B.t.u. per lb.	6,960	6,990	7,190	7,040	6,880	6,970
Ash-softening temperature, °F.	2,310	2,360	2,360	2,280	2,260	2,260

[1] Composite sample representing all test periods in these runs.

Operating Results

A condensed summary of typical operating results is given in table 3, arranged in ascending order of H_2:CO ratio in product gas. Although reported on an hourly basis, these results represent average performance during the whole test period. Complete operating results for all test periods are given in table 12 in the appendix.

TABLE 3. - Typical results on gasification of natural lignite in commercial-scale pilot plant

Run and period number	8E	8D	7C	6A	5D	7G	5C	6H
Ratio H_2:CO in gas	2.30	3.32	3.91	4.04	5.05	5.95	7.02	8.99
Lignite charged...lb. per hr.	346	436	492	323	380	353	295	375
Gas made...M cu. ft. per hr. (SGC)[1]	7.39	10.54	10.64	7.11	7.17	8.97	7.08	9.06
Lignite per M cu. ft. of gas...lb.	46.8	41.3	46.2	45.5	53.0	39.3	41.7	41.3
Char removed...lb. per hr.	49.4	58.8	62.6	43.7	68.7	47.3	31.6	52.6
Carbon gasified...percent	67.2	72.8	65.8	65.7	56.7	74.3	69.0	67.0
Steam to upper reaction zone, lb. per hr.	100	300	350	96	145	455	220	535
Steam to lower reaction zone, lb. per hr.	([2])	([2])	([2])	155	245	([2])	395	465
Undecomposed steam..lb. per M cu.ft.	11.4	20.5	25.1	27.0	52.6	39.8	76.5	99.7
Heat used, B.t.u. per cu. ft. of gas made, net	147.3	120.0	121.1	103.0	141.9	122.4	145.0	77.8
Heating value of gas, B.t.u. per cu. ft., calculated gross	294	277	282	265	270	270	263	252
Temperatures, °F.:								
Bottom of combustion chamber	1,950	1,850	1,778	1,778	1,771	1,650	1,748	1,666
Outlet of combustion chamber	1,501	1,401	1,381	1,432	1,301	1,284	1,303	1,269

[1] Saturated gas at 60° F. and 30 in. of mercury.
[2] Continuous annulus; no lower reaction zone.

Table 3 shows that 40 to 53 pounds of natural lignite was required per M cu. ft. of gas, which when cleaned and cooled had a heating value of 250 to 295 B.t.u. per cubic foot. Lower heating values correspond to higher hydrogen-carbon monoxide ratios, the range of which was from 9 to 2.3. Inasmuch as char may be a useful byproduct of this process, the greatest possible percentage of gasification of the lignite was not an objective.

Other data on the static pressures, retort dimensions, and steam rates are not summarized but are reported in table 13 in the Appendix.

Analyses of Product Gas

Typical average gas analyses from the tests are presented in table 4, with the heating values from the recording calorimeter and those calculated from the analyses. The analyses are arranged to show changes as the hydrogen-carbon monoxide ratio increases. Complete analyses, heating values, and specific gravities of the product gas from all tests are given in table 14 in the Appendix. In addition, table 14 includes the average analyses calculated to an air- and purge-gas-free basis, except in run 5, when the volume of purge gas was negligible. The correction for air is made first and assumes that any oxygen is present as air. It is eliminated, with the equivalent amount of nitrogen in air. In the correction for purge gas it is assumed that the normal nitrogen content of the product gas is 0.5 percent and that any excess nitrogen is derived from air-free products of combustion containing 17 percent carbon dioxide and 83 percent nitrogen.

Results from the continuous record of the carbon dioxide analyzer are not presented, but these agree well with the carbon dioxide content in the average analyses.

TABLE 4. - Typical analyses of product gas from commercial-scale pilot plant

Run and period number	8E	8D	7C	6A	5D	7G	5C	6H
Ratio H_2:CO	2.30	3.32	3.91	4.04	5.05	5.95	7.02	8.99
Constituent, percent by volume:								
CO_2	13.4	18.8	20.5	21.6	23.7	23.7	25.3	26.8
Ill.	0.1	0.2	0.2	0.1	0.2	0.2	0.2	0.2
O_2	0.2	0.2	0.1	0.1	0	0.1	0.1	0.2
CO	24.3	17.6	15.0	14.2	11.9	10.2	8.8	6.8
H_2	55.8	58.4	58.6	57.3	60.1	60.7	61.8	61.1
CH_4	2.6	2.9	3.1	3.3	3.3	2.5	2.3	2.6
C_2H_6	0.6	0.2	0.7	0.1	0.2	0.8	0.6	0.3
N_2	3.0	1.7	1.8	3.3	0.6	1.8	0.9	2.0
Gross heating value, B.t.u. per cu. ft.:								
Calorimeter	293	281	274	270	269	263	257	246
Calculated	294	279	282	265	270	270	263	252

Analyses of Char

Characteristics of the char were determined from proximate and ultimate analyses of composite samples, including proportional amounts of char, blow-over dust, and solid residues recovered in the sump of the water scrubber. Previous experience had indicated that no vital information would become available from analyses of each kind of residue. No determination of size consist was made on any residue.

Typical analyses of these composite samples with different ash contents are given in table 5. The ash ranges from 25 to nearly 47 percent and, as would be expected, increases somewhat as the prrcentage of carbon decreases. Complete information for all test periods is presented in table 15 in the Appendix.

Some of the results in tables 5 and 15 show that the conventional methods of proximate and ultimate analysis do not yield satisfactory results when applied to char. For many high-ash chars the sum of the constituents in the normal ultimate analysis, except oxygen, exceeds 100 percent. Much of the sulfur and some of the carbon in the char remain in the ash during ignition of the analytical sample. Beginning with run 6 and continuing thereafter, the amounts of these elements so retained were determined, and the results are included in the tables as equivalent percentages of sulfur trioxide and carbon dioxide in the original char. Although some effects of this condition are known (high ash, low fixed carbon, sulfur reported twice), no corrections of any kind have been made to the results in tables 5 and 15, although no oxygen is reported in the ultimate analyses for run 6 and subsequent runs.

TABLE 5. - Analyses of chars from commercial-scale pilot plant

Run and period number	6H	6G	8E	8G	7G	6C
Proximate analysis, percent:						
Moisture	1.5	1.4	0.3	0.5	0.6	0.8
Volatile matter	12.3	11.8	6.9	8.8	10.8	10.8
Fixed carbon	60.8	56.6	58.3	50.6	46.1	41.8
Ash1/	25.4	30.2	34.5	40.1	42.5	46.6
Ultimate analysis, percent:2/						
Hydrogen	1.8	1.6	0.8	0.9	1.0	1.2
Carbon	66.8	62.7	67.3	62.0	56.1	51.5
Nitrogen	0.6	0.5	0.4	0.4	0.4	0.4
Sulfur	0.6	0.8	3.1	3.7	2.7	2.5
Ash1/	25.4	30.2	34.5	40.1	42.5	46.6
$SO_3$3/4/	2.87	1.84	7.2	6.2	6.09	5.92
$CO_2$3/	4.63	4.38	2.3	3.2	4.94	3.83
Heating value, B.t.u. per lb.	10,410	9,740	10,370	9,650	8,660	8,120
Carbon gasified, percent	67.0	71.9	67.2	71.0	74.3	73.9

1/ Ash uncorrected for sulfur and carbon reported as SO_3 and CO_2.
2/ Oxygen omitted, see text for explanation.
3/ In ash; reported as percent of original char.
4/ Total sulfur in ash reported as equivalent SO_3 regardless of chemical form of sulfur; some results indicate more sulfur in ash than in original char.

DISCUSSION OF RESULTS

Operating Results

In earlier experiments (2) product gas was generated at a rate of over 15 M cu. ft. per hour, but production in the tests reported herein never exceeded 12 M cu. ft. per hour. (See table 12.) Although no attempt was made to reach maximum production, it appears probable that maximum rates were approximated in some periods when the hydrogen-carbon monoxide ratio exceeded 6 or 7 because of the large volume of excess steam required to achieve high ratios. From figure 9 it is apparent that, at a ratio of 5, the volume of excess steam approximately equals the volume of gas and that this condition becomes more unfavorable at higher ratios. As excess steam leaves the retort in a gaseous state and there is a maximum capacity for total flow through the offtake, the volume of product gas that can flow through the offtake simultaneously with the excess steam is limited. This limitation, together with excess steam losses, will tend to make high-ratio gas cost more than low-ratio gas.

Operating results in table 6 show that undecomposed steam in the product gas is nearly equivalent to the process steam admitted to the generator. This confirms the observation that the principal effect of an increase in process steam is to increase the hydrogen-carbon monoxide ratio rather than to increase gas production. For example, comparison of the results for runs 8E and 7G, in which the coal rate is virtually constant, shows that a fourfold increase in steam rate increased the volume of

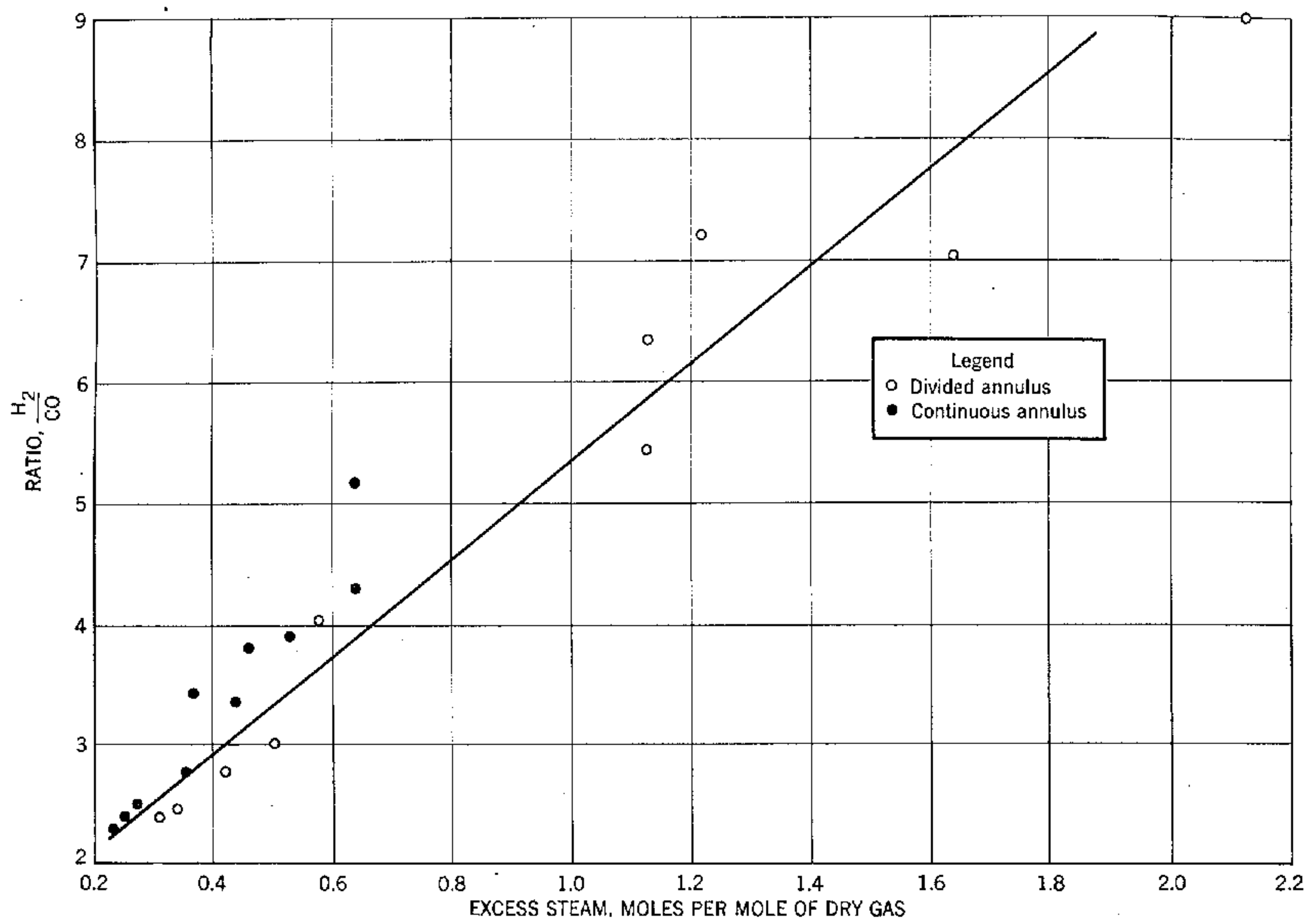

Figure 9. - Relation between ratio of hydrogen to carbon monoxide and excess steam at 60 to 70 percent gasification of carbon in lignite.

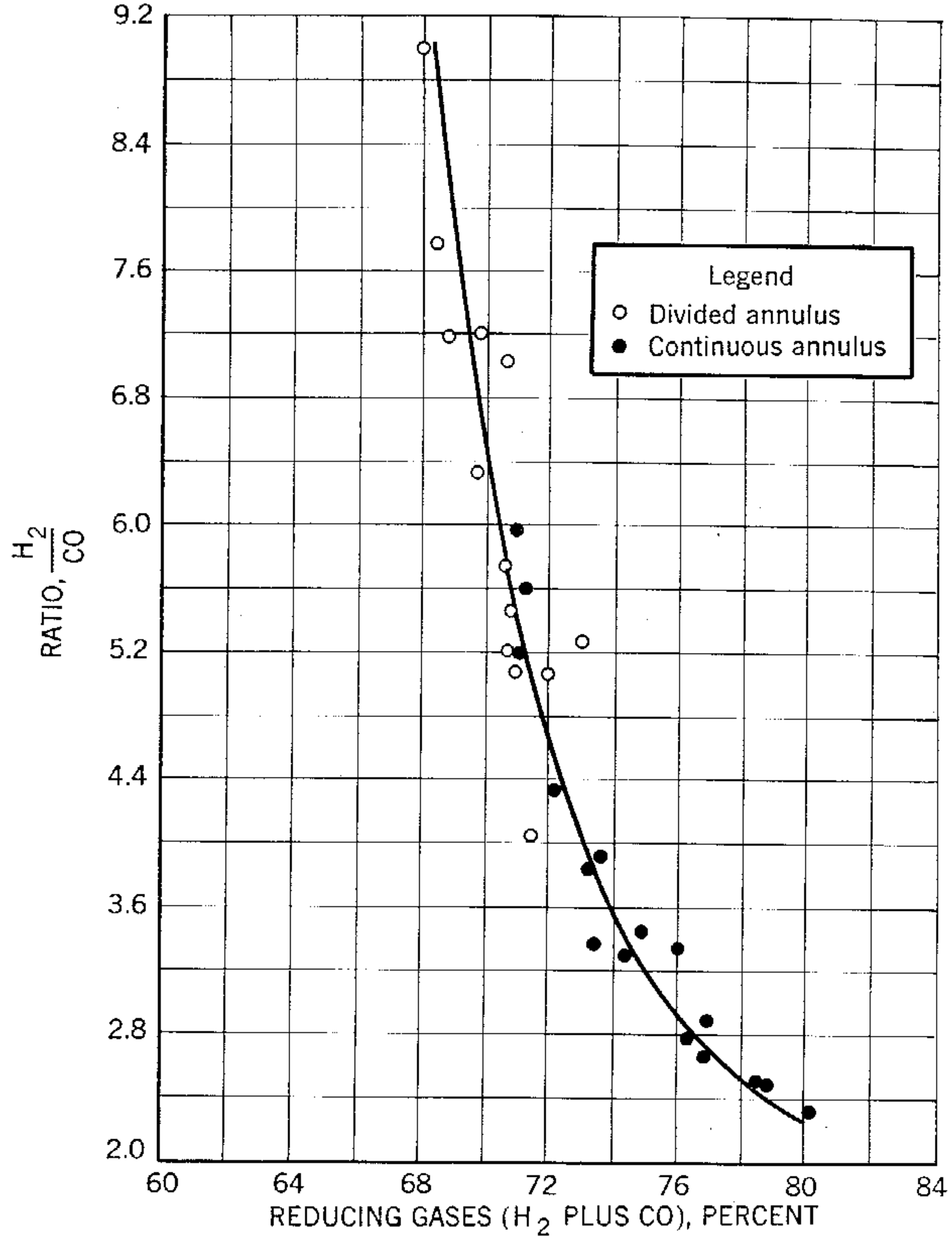

Figure 10. - Relation between ratio of hydrogen to carbon monoxide and percentage of reducing gases.

gas by approximately 20 percent. In contrast, a change in lignite rate has a much more pronounced effect on gas volume.

TABLE 6. - Operating results on commercial-scale pilot plant

Run and period number	8E	8D	7C	6A	5D	7G	5C	6H
Ratio, H_2:CO	2.30	3.32	3.91	4.04	5.05	5.95	7.02	8.99
Coal rate lb./hr./sq.ft.1/	1.65	2.08	2.34	1.54	1.81	1.68	1.40	1.79
Steam rate, lb./hr./sq.ft.:								
Upper reaction zone2/	0.48	1.43	1.67	0.46	0.69	2.17	1.05	2.55
Lower reaction zone2/	(4)	(4)	(4)	0.73	1.17	(4)	1.88	2.21
Total2/	0.48	1.43	1.67	1.19	1.86	2.17	2.93	4.76
Undecomposed in gas3/	0.40	1.03	1.27	0.91	1.80	1.70	2.58	4.30
Gas made, S.G.C.:5/								
Cu.ft./hr./sq.ft.	35.2	50.2	50.7	33.9	34.1	42.7	33.7	43.1
Cu.ft.lb./lignite	21.3	24.1	21.7	22.0	18.8	25.4	24.1	24.1
CO + H_2 cu. ft./hr./sq.ft.	28.2	38.2	37.4	24.2	24.5	30.2	23.8	29.2

1/ All unit data are based on a heated area of outer retort tube of 210 sq. ft.

2/ Data for two reaction zones and total include only steam supplied to generator and neglects any water in lignite, as well as any formed by reaction during gasification.

3/ Total steam in product gas, regardless of source.

4/ Continuous annulus; no lower reaction zone.

5/ Saturated gas at 60° F. and 30 in. of mercury.

Comparison of the results in table 6 shows a wide range in performance of the plant and indicates that considerable flexibility in operation is possible. The plant has operated smoothly at production rates as low as 6.5 M cu. ft. per hour and as high as 11.9 M cu. ft. per hour (runs 7F and 6D, respectively, table 12 in Appendix). Experience suggests that lower and higher production rates could be reached.

Another point of interest is the effect of operating conditions on the yield of reducing gases. The curve of figure 10 correlates the percentage of reducing gases, the sum of hydrogen and carbon monoxide, to the ratio. It shows the proportion of reducing gases is decreased considerably at higher ratios. When this fact is considered, together with the lower capacity of the plant at higher ratios, it is evident that the greatest volume of reducing gases can be produced for the least cost at the lower ratios.

Hydrogen-Carbon Monoxide Ratio

Most of the gas produced in this plant appears to be formed by reactions of steam and carbon, and its composition can be represented closely by some combination of the following reactions:

$$C + H_2O = CO + H_2,$$

$$C + 2H_2O = CO + 2H_2,$$

$$C + CO_2 = 2CO.$$

These reactions suggest that considerable variation in the hydrogen-carbon monoxide ratio can be achieved. In previous experiments (2) gas with ratios up to 5 was produced, but in these tests the highest ratio was 9.

With the divided annulus in runs 5 and 6 these ratios ranged from 4 to 9. Increased steam rates appeared most effective in increasing the ratio, but usually furnace temperatures were deliberately reduced simultaneously. Figure 9[9] shows the relation between the ratio and excess steam expressed as moles per mole of dry gas when 60 to 70 percent of the carbon in the lignite was gasified and confirms the importance of excess steam. The individual points in figure 9 suggest that slightly less excess steam is required in the continuous annulus to produce gas with the same ratio. It is hoped that this indication can be confirmed or denied by future experiments, in which gas with higher ratios is produced in the continuous annulus. Any effect of furnace temperature on the ratio is nor markedly evident, although it is usual to increase this temperature when operating to produce gas with a lower ratio.

Tests in the continuous annulus at higher steam rates had been planned but were abandoned when the pressure in the charging dome exceeded approximately 60 inches of water. The maximum design pressure delivered by the purge-gas pump was 90 inches of water, and it seemed unwise to experiment with steam rates that required a higher pressure than 60 inches of water in the charging dome. In consequence, the highest steam rates were not as high as in runs with the divided annulus.

Hydrogen

The gasification reactions show that hydrogen in the product gas should range between 50 and 67 percent. Actually the hydrogen varied between 57 and 62 percent when corrected to an air- and purge-gas-free basis. This is shown in figure 11, where the percentages of hydrogen, carbon monoxide, and carbon dioxide are plotted against the hydrogen-carbon monoxide ratio. From these curves it is evident that relative changes in percentages of carbon monoxide are greater than relative changes in either of the other two constituents; consequently, changes in hydrogen-carbon monoxide ratio are due to changes in the percentage of carbon monoxide.

If the reactions of lignite with steam were the only source of hydrogen, its percentage should equal the sum of twice the percentage of carbon dioxide plus the percentage of carbon monoxide. The actual percentage of hydrogen always exceeded this sum, sometimes by as much as 4 percent (see table 4). This excess hydrogen probably is derived from carbonizing lignite or from cracking the hydrocarbons produced during carbonization because plant conditions are maintained to gasify approximately all of the tar.

The relationships in figure 11 also have been helpful in adjusting the plant to produce gas at a preselected hydrogen-carbon monoxide ratio. It is usually sufficient to ascertain the percentage of carbon dioxide corresponding to the desired ratio and to adjust the operating variables to produce this percentage of carbon dioxide, as indicated by the continuous analyzer. The actual ratio is determined from the gas analysis but does not vary appreciably from that selected.

Heat and Material Balances

Heat and material balances based on gross heating values and average hourly results are given in tables 7 through 10 for four test periods. The first consideration in selecting these periods was that the lignite feed rate was about 325 pounds per hour. The second was that the hydrogen-carbon monoxide ratios represented approximately the range for these tests. These balances show that the potential heat in the product gas ranges from 52 to 58 percent of the heat in the entering materials and that the lower percentages correspond to the higher ratios. Such a correlation is indicated also by the heat losses in the undecomposed steam. These increase noticeably at higher ratios, because a relatively large excess of steam is required to

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[9] Some data in figure 9 for the lower ratios in the divided annulus are results of previous experiments (2).

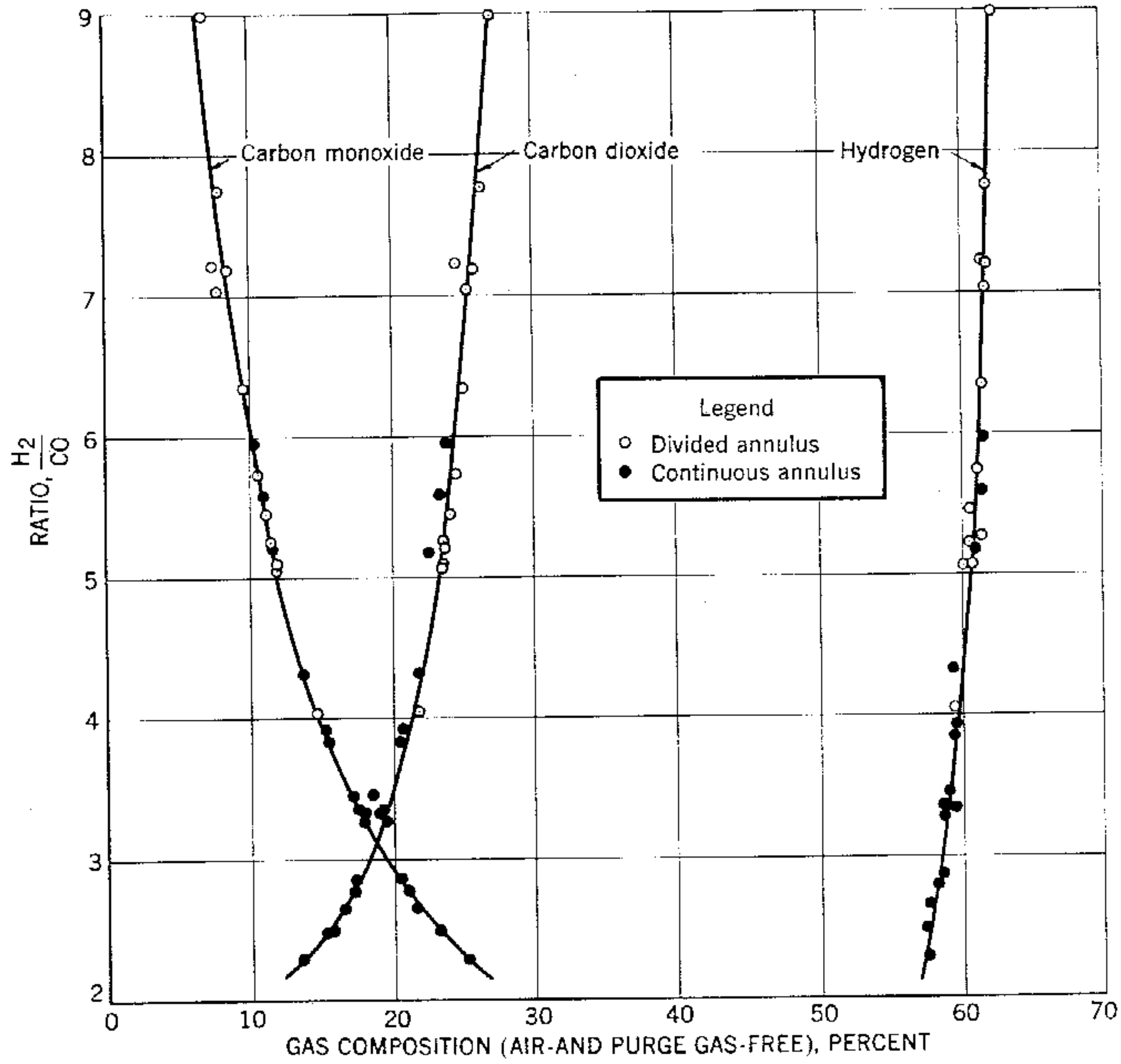

Figure 11. - Relation between ratio of hydrogen to carbon monoxide and gas composition.

achieve high ratios. Radiation and unaccounted for heat losses are relatively constant in amount, a result that might be expected because the temperature conditions in the furnace and recuperator systems do not vary greatly. With the exception of period 7E (table 9), the radiation losses decrease as the temperature in the furnace system decreases.

All the material balances show a negligible loss.

TABLE 7. - Heat and material balances for period 8E, commercial-scale pilot plant[1]

(Ratio H_2:CO = 2.30)	Temperature, °F.	Material balance, lb.	Heat balance	
			M B.t.u.	Percent
In:				
Natural lignite: Potential heat	(2)	346	2,421	64.8
Process steam[3]	[4]270	100	115	3.1
Heating gas: Potential heat	(2)	159	1,203	32.1
Air to furnace	(2)	725	(2)	(2)
Total		1,330	3,739	100.0
Out:				
Product gas: Potential heat	-	-	2,173	58.2
Sensible heat	654	287	87	2.3
Undecomposed steam[3]	654	84	112	3.0
Char and dust: Potential heat	-	-	726	19.3
Sensible heat	[4]1,000	70	18	.5
Stack gases: Sensible heat dry gases	633	758	113	3.0
Water formed during combustion[3]	633	126	167	4.5
Radiation and unaccounted for	-	4	343	9.2
Total		1,330	3,739	100.0

[1] Gross heat basis, hourly averages, and above 60° F.

[2] Assumed atmospheric; sensible heat considered negligible.

[3] Enthalpy of steam above 60° F. calculated as 1,020 + 0.48t B.t.u. per lb.

[4] Assumed.

TABLE 8. - Heat and material balances for period 6A, commercial-scale pilot plant1/

(Ratio H_2:CO = 4.04)	Temperature, °F.	Material balance, lb.	Heat balance	
			M B.t.u.	Percent
In:				
Natural lignite: Potential heat	(2)	323	2,268	67.2
Process steam3/	248	251	286	8.5
Heating gas: Potential heat	(2)	126	821	24.3
Air to furnace	(2)	767	(2)	(2)
Total		1,467	3,375	100.0
Out:				
Product gas: Potential heat	-	-	1,884	55.8
Sensible heat	641	290	84	2.5
Undecomposed steam3/	641	192	255	7.6
Char and dust: Potential heat	-	-	616	18.3
Sensible heat	1,087	66	17	.5
Stack gases: Sensible heat dry gases	602	797	113	3.3
Water formed during combustion3/	602	96	126	3.7
Radiation and unaccounted for	-	24	280	8.3
Total		1,467	3,375	100.0

1/ Gross heat basis, hourly averages, and above 60° F.
2/ Assumed atmospheric; sensible heat considered negligible.
3/ Enthalpy of steam above 60° F. calculated as 1,020 + 0.48t B.t.u. per lb.

TABLE 9. - Heat and material balances for period 7E, commercial-scale pilot plant1/

(Ratio H_2:CO = 5.59)	Temperature, °F.	Material balance, lb.	Heat balance	
			M B.t.u.	Percent
In:				
Natural lignite: Potential heat	-	324	2,229	58.9
Sensible heat	(2)	-	(2)	(2)
Process steam3/	4/270	350	403	10.6
Heating gas: Potential heat	-	177	1,154	30.5
Sensible heat	(2)	-	(2)	(2)
Air to furnace	(2)	741	(2)	(2)
Total		1,592	3,786	100.0
Out:				
Product gas: Potential heat	-	-	2,158	57.0
Sensible heat	675	331	102	2.7
Undecomposed steam3/	675	276	371	9.8
Char and dust: Potential heat	-	-	546	14.4
Sensible heat	4/1,000	59	15	0.4
Stack gases: Sensible heat dry gases	480	781	81	2.1
Water formed during combustion3/	480	137	171	4.5
Radiation and unaccounted for	-	8	342	9.1
Total		1,592	3,786	100.0

1/ Gross heat basis, hourly averages, and above 60° F.
2/ Assumed atmospheric; sensible heat considered negligible.
3/ Enthalpy of steam above 60° F. calculated as 1,020 + 0.48t B.t.u. per lb.
4/ Assumed.

TABLE 10. - Heat and material balances for period 5B, commercial-scale pilot plant1/

(Ratio H_2:CO = 1.21)	Temperature, °F.	Material balance, lb.	Heat balance M B.t.u.	 Percent
In:				
Natural lignite: Potential heat.......	-	325	2,262	56.5
Sensible heat........	(2)	-	(2)	(2)
Process steam3/........................	273	503	579	14.4
Heating gas: Potential heat...........	-	174	1,166	29.1
Sensible heat...........	(2)	-	(2)	(2)
Air to furnace.........................	(2)	745	(2)	(2)
Total...........................		1,747	4,007	100.0
Out:				
Product gas: Potential heat...........	-	-	2,102	52.5
Sensible heat...........	655	314	93	2.3
Undecomposed steam3/..................	655	445	593	14.8
Char and dust: Potential heat.........	-	-	701	17.5
Sensible heat..........	4/1,000	63	16	0.4
Stack gases: Sensible heat dry gases..	480	788	82	2.0
Water formed during combustion3/..........	480	131	164	4.1
Radiation and unaccounted for..........	-	6	256	6.4
Total...........................		1,747	4,007	100.0

1/ Gross heat basis, hourly averages, and above 60° F.
2/ Assumed atmospheric; sensible heat considered negligible.
3/ Enthalpy of steam above 60° F. calculated as 1,020 + 0.48t B.t.u. per lb.
4/ Assumed.

Rates of Heat Transfer

These balances supply the data necessary for calculating the rates of heat transfer through the metal retort wall. In these four experiments this rate ranged from about 1,500 to over 3,000 B.t.u. per square foot per hour. Higher rates were reached in some experiments, but no attempt was made to reach the highest rates achieved in earlier tests (2).

BEHAVIOR OF RETORT TUBES

General

The relatively severe conditions to which the metal retort tube is exposed in this gas plant is unusual in commercial processes, and information about the behavior of the tube is an important objective of the investigation. Table 1 shows that the commercial-scale pilot plant had been operated for 3,857 hours by the end of run 9, during which time three retort tubes were used. Observations on the behavior of each are considered in the following discussion.

Spray-Coated Retort Tube

The two chief considerations in selecting the first retort tube were promptness of delivery and resistance to corrosion. This tube was fabricated by welding together three pieces of mild-steel pipe 48 inches in internal diameter. The upper part was about 12 feet long by 1/2 inch thick, and the lower part was 8-1/2 feet long by 3/4 inch thick. After fabrication, the tube was treated by metcolizing process 45 on