II. EXPERIMENTAL PILOT UNIT FOR UNDERGROUND GASIFICATION STUDIES WITH HIGHLY SUPERHEATED STEAM AND OXYGEN

INTRODUCTION

This project was undertaken in cooperation with Dr. Albert DeSmaele, Chairman of the Board, SOCOGAZ, Belgium, to study in an experimental pilot unit the underground production of synthesis gas from coal with very highly superheated steam and oxygen. Conditions existing in underground gasification were to be simulated in the two units to be constructed at Morgantown. Later, after all plans had been completed, it was decided to build only one unit at first in order to make the preliminary investigations. The decision called for constructing a second unit after the completion of a run in the first one. Thus, the expected operating difficulties due to shortcomings of the first unit were to be eliminated from the second unit.

As underground gasification is essentially gasification of coke walls resulting from the devolatization (carbonization) of coal seams by intense heat, it was decided to study the gasification of run-of-oven, high-temperature coke cemented together into a strong circular wall about 2 feet thick.

APPARATUS AND OPERATING PROCEDURE

The pilot unit constructed is a cylindrical steel chamber 10 feet long and 4 feet in diameter, holding about 3 tons of coke, with a 4-inch diameter channel along its axis in the middle. A large (2-million B.t.u. per hr.) capacity burner of special design, using natural gas and oxygen, was constructed to blast the charge from the top. The products of combustion - steam and CO_2 - could be mixed with enough additional steam in such a way that all of these reactants were introduced through the 4-inch channel at 4,000° F. The products of gasification moved downward into an 8-inch stack. The immediate objective was to vary the steam and oxygen to carbon ratios, and thereby the temperature of the reactants, to determine the optimum choice of operating variables for efficient and economical gasification of coal in underground seams.

To build a circular coke wall of maximum strength and bulk density, it was necessary to find a proper cement mixture of low inorganic content for the coke charge. The agglutinating powers of the cement mixtures were determined in 13 block tests. Each block was built up in a 2 by 2 by 2-foot steel box (with removable side walls) from layers of lump coke. The interstices

3937

were filled with minus 2-inch pieces and coke breeze soaked in a thin water paste of various cements and plastic fire clay, and each dried block was then tested for its strength.

The shatter tests made by repeated droppings of a 50-pound steel block from a 6-foot height over each coke block proved the superior strength of coke walls of the following composition:

	Percent
Over 2-inch size lump coke	45
1/4-inch to 2-inch pieces of coke ...	24
Coke breeze (minus 1/4-inch size) ...	26
Portland cement	4.5
Plastic fire clay	0.5
	100.0

A coke wall of this composition had also the maximum bulk density (51.3 lb. per cu. ft.) with the minimum amount of binding cement. The addition of fire clay was necessary in order to make the surfaces of the coke lumps wettable with cement.

Pictures of a coke block of inferior strength and of one that had the greatest strength and bulk density among the 13 different cement compositions tested are shown in figures 16 and 17. The method of building up the coke wall by layers is seen in figure 16.

The procedure followed in filling the generator chamber was the same as that which furnished the strongest coke block, namely, building up the coke wall by layers. A 3-inch iron pipe covered with paper cardboard (4 inches O.D.) was placed in the center of the empty shell in vertical position, and the coke wall was constructed around it. The pipe was pulled out of the charge after it had dried, leaving a 4-inch channel in the exact center of the charge.

Details of construction of the unit together with natural gas, steam, oxygen, and water supply lines are shown on a flow sheet in figure 18. The appearance of the pilot unit supported on a refractory base with the burner apparatus on the top, rising 16 feet above the ground floor, is shown in figure 19.

The water-cooled burner and steam-superheating head, which furnishes a maximum of 2 million B.t.u. per hour, was tested outside in the open prior to its installation. The flame test, shown in figure 20, indicated that a high-intensity flame of normal shape developed, and the size of the flame could easily be controlled by manual regulation of a valve on the oxygen line. The natural gas was automatically proportioned by means of a diaphragm-type governor with 2.2 times its volume of oxygen. The steam issuing from a 3/4-inch wide annular ring of 12-inch diameter mixed well with the flame, against which it was directed at a slight angle.

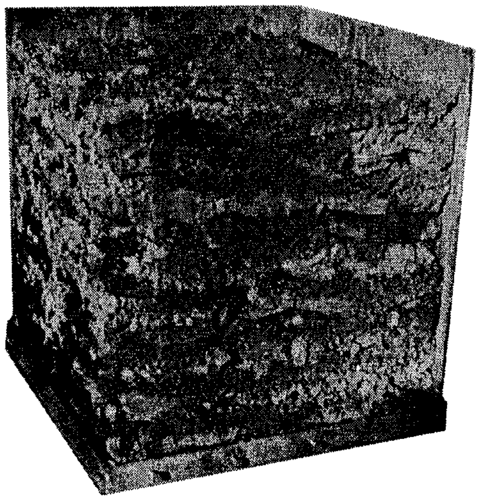

Figure 16. - Cemented coke block of inferior strength. Method of building coke wall by layers.

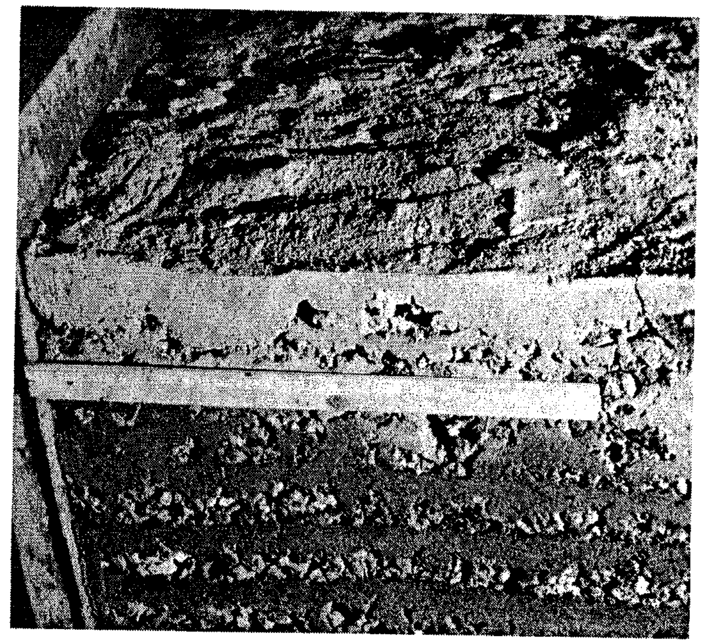

Figure 17. - Cemented coke block of superior strength.

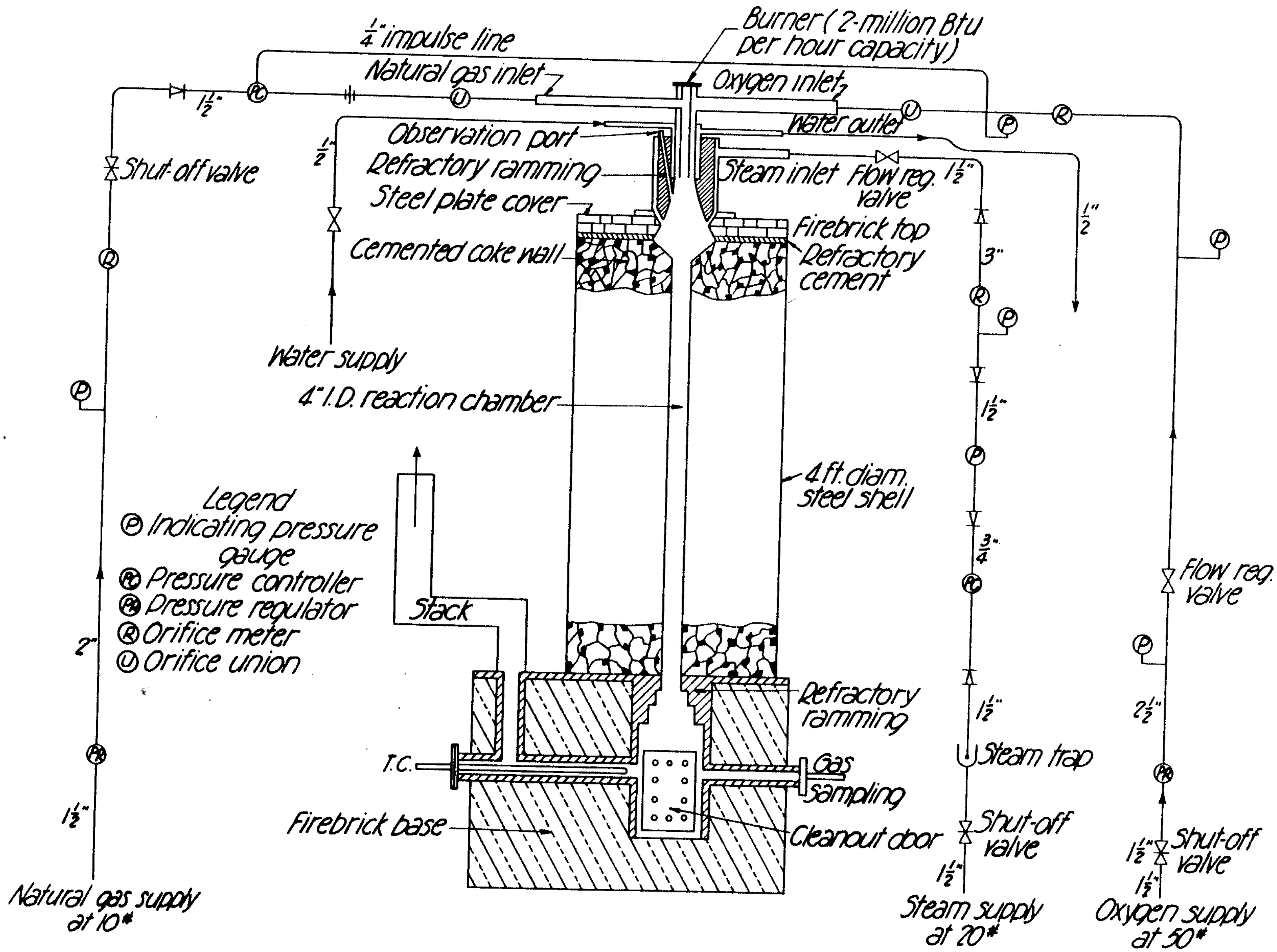

Figure 18. - Flow diagram of pilot unit for study of underground gasification of coke walls.

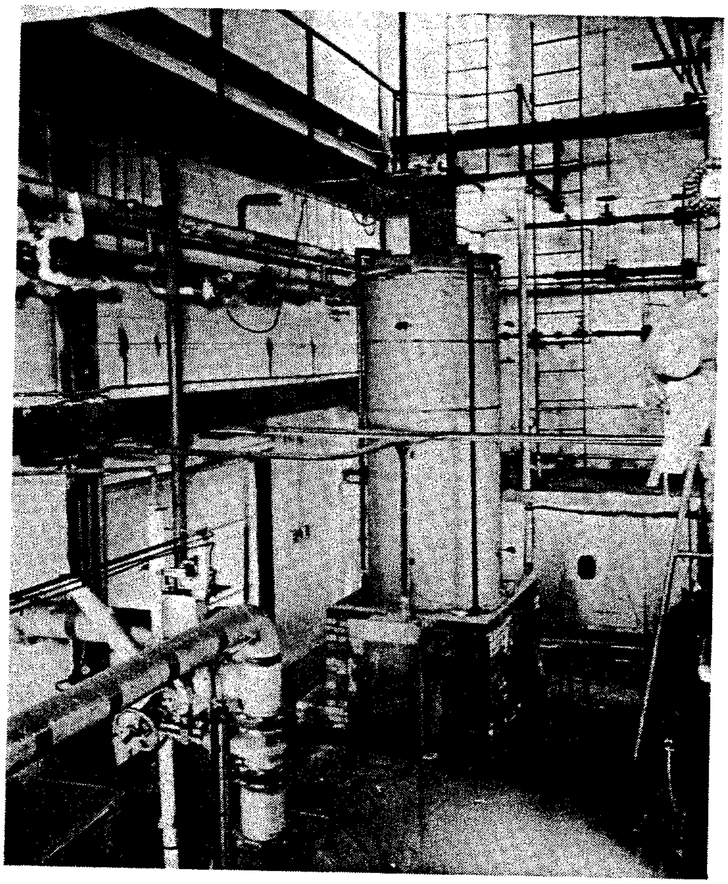

Figure 19. - Pilot unit for study of underground gasification of coke walls.

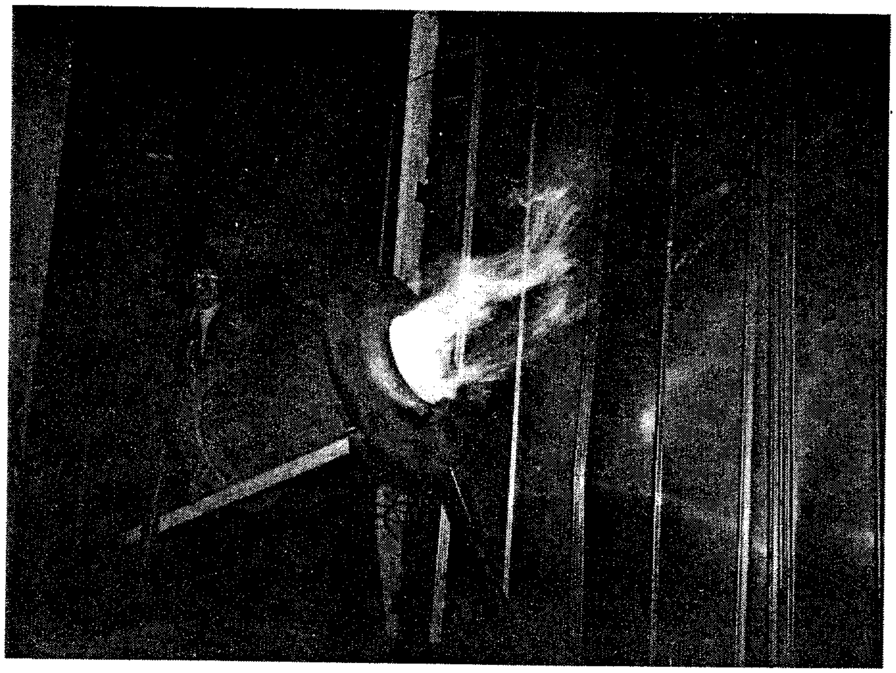

Figure 20. - Flame test with burner and steam superheater used for study of underground gasification of coke walls.

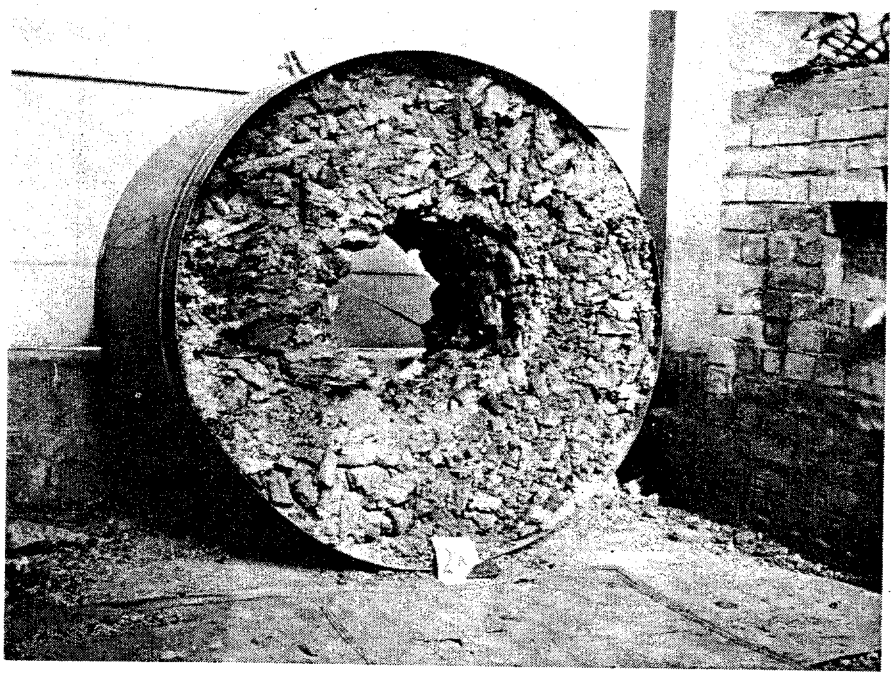

Figure 21. - Middle section of generator after run made for underground gasification studies.

Calculations showed that the natural gas, having a net calorific value of 1,018 B.t.u. (60° F., 30" Hg, dry) and containing 80.3 percent CH_4, 18.5 percent C_2H_6, 1.12 percent N_2, and 0.08 percent CO_2, could be burned at the rate of 1,965 standard cubic feet[23] per hour. Using oxygen at the rate of 4,430 standard cubic feet per hour for a theoretically complete combustion, the theoretical yield of combustion products would be 4,248 standard cubic feet of steam (202.2 lb.), 2,307 standard cubic feet of carbon dioxide, and 22 standard cubic feet of nitrogen, or a total of 6,577 standard cubic feet per hour. The theoretical flame temperature, taking into consideration the extent of the dissociation of H_2O and CO_2, would then be 5,285° F. However, by the admixture of steam (340° F., 100 p.s.i.g.) at the rate of 15,910 standard cubic feet per hour (758 lb.), the theoretical flame temperature would decrease to 4,000° F.[24] Thus, the burner apparatus was capable of delivering hourly 960 pounds of steam (202.2 + 757.8), 2,307 cubic feet of carbon dioxide, and 22 cubic feet of nitrogen at a theoretical temperature of 4,000° F.

OPERATING DATA AND RESULTS

The run was preceded by a preliminary heating period, intending to raise the temperature of the charge gradually to about 1,800° F. by blasting it with a flame, using only one-fourth of the natural gas and oxygen calculated above for a heat release of 2 million B.t.u. per hour and a flame temperature of 4,000° F. Too rapid heating of the circular coke wall was thought to be detrimental, because rapid expansion might cause the concrete wall to decrepitate. The plans called for the admixture of excess steam at the start of the preheating period, so that the temperature of the flame would be about 1,000° F. The flame temperature was to be increased gradually to 1,800° F.

When the temperature of the coke wall had reached 1,800° F., after about 30 hours of preheating, it was found that the rate of blasting could not be increased as planned, because considerable back pressure developed. Through a sight glass on the burner head it was seen that several 4- to 6-inch pieces of coke became dislodged from the circular wall and choked the flow of the make gas at the bottom of the 4-inch channel. Injection of oxygen alone was attempted for a total of 45 minutes with the intention of burning off the obstructing lumps of coke, aiding, meanwhile, the passage of the product gases by the suction of a steam jet installed in the 8-inch stack. For a while it seemed that the channel might clear by this procedure, but additional lumps of coke began to dislodge from the wall until, finally, the run had to be discontinued.

Several 2-foot sections were cut horizontally across the generator after the remaining charge had cooled sufficiently for handling. The middle section is shown in figure 21.

Although the run was incomplete owing to the failure of the coke wall (the high initial strength of which, by all evidence, had decreased rapidly

23/ See footnote 13.

24/ Dissociations of H_2O (2 percent) and CO_2 (20 percent) have been taken into account.

at higher temperatures), it proved the feasibility of gasifying even such unreactive substances as a high-temperature coke containing 23 percent of inert material if the temperature of the reactants is sufficiently high. It is believed that an 8-inch channel in the middle of the charge may have prevented clogging by dislodged pieces of coke, as many of the lumps probably boke loose because of the high velocity of the steam and CO_2 blown downward toward the bottom outlet (680 ft. per second at 2,000° F.).

Although, the original intention was to build a second unit after completion of a run in the first one, further experimental work was deferred indefinitely owing to the urgency of other investigations.

The operating results are incomplete. Several important measurements could not be made because of clogging of the channel in the center of the charge, which necessitated the use of steam jets in the 8-inch pipe line connecting to the stack. The suction thus provided balanced the back pressure developing in the generator, but the steam introduced prevented the determination of the flow rate of the make gas. Similarly, measurements of the flow rates of natural gas, oxygen, and steam by orifice meters failed during a considerable part of the run, as the high back pressures spoiled the readings of the pressure differential across the orifices. Nevertheless, a rough estimate of the flow rates, i.e. inputs of natural gas, oxygen, and steam, was made.

Blasting the charge with oxygen before the final shut-down was also a rather disturbing factor. This, and the fact that an unknown quantity of air leaked into the unit, prevented the stoichiometric calculation of the output of the make gas.

The available operating data and results are given in table 14. The high CO_2 content of the make-gas and low percent steam decomposed are probably due to the extremely short contact (or residence) time of the reactants, approximately 0.015 second at 2,000° F.

CONCLUSIONS

A preliminary run of 31 hours' duration in an experimental pilot unit, constructed for the study of underground gasification of coke walls with oxygen and very highly superheated steam, proved that the production of synthesis gas is possible even from such unreactive substances as high-temperature coke containing 23 percent inert material. Although the run was discontinued because of the failure of the cemented circular coke wall, the feasibility of gasification was demonstrated.

TABLE 14. - Experimental pilot unit for underground gasification studies with very highly superheated steam and oxygen. Operating data and results

Composition of coke wall, percent	
Moisture	0.5
Ash	18.0
V.M.	3.2
F.C.	73.3
Portland cement	4.5
Plastic fire clay	.5
Total	100.0

Composition of natural gas burned, percent	
CO_2	0.08
CH_4	80.30
C_2H_6	18.50
N_2	1.12
Total	100.00

Weight of charge (coke wall): 5,704 lb.
Volume of charge (coke wall): 111.2 cu. ft.
Bulk density of charge (coke wall): 51.3 lb. per cu. ft.

Period	Duration, hours	Input: Natural gas, cu.ft./hr.	Input: Oxygen, cu.ft./hr.	Input: Steam, lb./hr.	Analysis of dry gas, percent: CO_2	O_2	Unsat. H. C.	H_2	CO	CH_4	N_2	Total	B.t.u.	Sp.gr.	Percent H_2O in wet gas	Percent steam decomposed
I	30.25	499.8	1,115.3	485.6	33.1	1.7	3.6	44.6	9.2	3.7	4.1	100.0			69.9	20.2
II	.75	0	1,644.4	0	5.3	5.9	1.2	35.0	32.4	2.0	18.2	100.0			nil	nil
Weighted average		487.7	1,128.1	473.9	32.5	1.8	3.5	44.2	9.9	3.7	4.4	100.0	270.6	0.743	68.2	19.7
Total input	31.00	15,119	34,976	14,670												

Composition of residue, percent	
Moisture	0.2
Ash + inerts	29.4
V.M.	3.2
F.C.	72.2
Total	100.0
Total combustible matter (V.M.+F.C.)	75.4
Total carbon	74.7

Gasification data	Total weight, lb.	Combustible matter, lb.	Total carbon, lb.
Charge before run	5,704	4,364	4,210
Residue after run	5,146	3,880	3,850
Amount gasified (difference in weight)	558	484	360
Percent gasification	9.8	11.1	8.5

APPENDIX

OPERATING DATA AND RESULTS ON VARIOUS RUNS

Run No.	Type of coal gasified; name of bed	Size of coal, percent through 200 mesh	Duration of run, hours	Rate of coal feed, lb./hr.1/	Oxygen input, cu. ft./hr.2/	Steam input, lb./hr.3/	Natural gas input, cu. ft./hr.4/	Steam-to-coal ratio, lb./lb.3/ 5/	Oxygen-to-coal ratio, lb./lb.5/	Gas output, cu. ft./hr.
1	Wyoming No. 9	72.0	-	1.85	172.0	5.80	60.40	3.50	0.58	-
3	do.	72.0	0.33	1.85	156.4	4.55	42.10	2.74	4.53	-
5	do.	72.0	.37	4.85	156.4	6.12	42.80	1.41	1.38	-
6	do.	72.0	1.25	4.80	71.0	2.27	0	.53	1.39	73.4
8	do.	72.0	1.88	5.86	71.5	1.98	0	.38	1.15	89.0
9	do.	72.0	1.80	6.67	72.4	2.53	0	.42	1.02	147.0
12	do.	72.0	1.88	4.73	50.7	.32	0	.07	1.01	76.7
13	do.	72.0	4.31	9.79	132.0	1.30	0	.15	1.27	276.0
15	do.	86.3	1.00	15.40	131.3	1.91	0	.14	.80	279.0
17A	do.	72.8	1.25	15.20	146.5	1.72	0	.13	.91	-
22	do.	78.6	1.11	14.80	142.8	3.50	0	.17	.91	294.1
23A	do.	78.6	1.00	15.00	129.1	1.46	0	.11	.81	303.8
24	do.	78.6	2.50	15.00	116.9	1.04	0	.08	.73	314.6
27E	do.	78.6	2.40	20.00	122.8	1.35	0	.09	.58	-
27F	do.	78.6	1.08	29.60	115.6	1.86	0	.07	.37	-
29	do.	91.1	2.10	16.25	116.3	.86	0	.06	.67	297.6
31C	do.	91.1	1.50	19.20	139.7	1.01	0	.06	.68	-
33A	do.	91.1	1.10	15.90	123.1	.12	0	nil	.73	292.9
34A	do.	91.1	1.85	17.20	190.1	.91	0	0.05	1.03	-
36	do.	91.1	4.13	18.00	97.0	.95	0	.06	.50	245.1
37	do.	91.1	6.00	16.10	79.1	.86	0	.05	.46	235.1
40	Sewickley	71.3	3.20	19.44	253.2	4.12	36.30	.25	.87	-
43	do.	71.8	.83	31.00	252.5	4.37	36.40	.16	.54	838.2
44	do.	71.3	1.92	28.90	252.5	4.69	39.90	.19	.56	792.0
46	do.	71.3	2.95	44.60	282.6	.80	0	.02	.62	884.2
47	do.	89.1	3.00	34.05	282.6	.68	0	.02	.82	810.7
48	do.	89.1	4.00	35.40	322.7	.71	0	.02	.90	800.3
49	do.	89.1	3.20	37.50	284.0	.76	0	.02	.75	762.0
50	do.	89.1	3.08	40.50	304.2	.81	0	.02	.74	919.4

1/ On moist basis, as charged.

2/ All gas data refer to 60° F., 30 in. Hg, dry.

3/ Consists of steam originating (a) from moisture in coal and (b) steam injected. In certain runs, where the input of the natural gas is indicated, (c) steam formed as a result of the combustion of natural gas was included in the total steam input.

4/ Natural gas was injected for the experimental purpose of supplying superheated steam and CO_2 by the combustion of natural gas with sufficient amount of added oxygen.

5/ Lb. per lb. dry, ash-free coal.

Run No.	Oxygen input, cu. ft./MCF gas	Oxygen input, cu. ft./MCF $CO + H_2$	Steam input, cu. ft./MCF gas	Coal feed, lb./MCF gas 1/	Residue output, lb./hr. 1/	Percent of raw coal gasified	Percent of fixed carbon gasified 6/	B.t.u. in gas per each 100 B.t.u. in coal charged 7/	B.t.u. in gas plus residue per each 100 B.t.u. in coal charged 8/	Yield of $CO + H_2$, cu. ft./ton 9/
1	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-	-
6	966.0	1,412	649.2	65.5	0.85	82.2	77.6	31.6	-	22,310
8	803.0	1,706	466.7	65.8	-	-	-	31.1	-	15,240
9	493.0	1,057	361.1	45.4	-	-	-	27.3	-	21,750
12	661.0	1,047	86.0	61.6	-	-	-	55.2	-	21,510
13	478.0	706.0	98.9	35.5	-	-	-	57.4	-	40,215
15	470.6	795.0	143.7	55.2	-	-	-	32.4	-	22,600
17A	-	-	-	-	-	-	-	-	-	-
22	485.5	684.9	158.2	50.3	4.10	74.3	64.9	36.8	-	30,000
23A	425.0	560.6	100.5	49.4	4.09	74.6	63.0	41.4	-	32,522
24	371.6	506.9	69.2	48.0	4.65	69.3	56.0	46.1	-	32,536
27E	-	-	-	-	-	-	-	-	-	-
27F	-	-	-	-	-	-	-	-	-	-
29	390.7	510.1	64.3	54.6	8.50	48.1	23.7	39.2	-	29,381
31C	-	-	-	-	-	-	-	-	-	-
33A	420.3	548.9	8.6	54.3	4.40	73.0	59.8	45.7	74.3	22,670
34A	-	-	-	-	-	-	-	-	-	-
36	395.8	587.2	81.0	73.4	8.30	55.0	34.0	27.2	-	19,220
37	336.5	486.0	76.7	68.5	9.90	38.8	12.6	36.8	-	21,450
40	-	-	-	-	8.59	-	-	-	-	-
43	203.5	230.0	109.5	37.0	11.80	62.9	55.7	60.0	-	48,800
44	205.4	230.8	124.3	36.5	8.50	70.6	62.4	60.8	81.9	56,800
46	319.6	353.5	17.8	50.4	21.20	51.8	35.5	48.0	87.0	36,575
47	348.6	393.4	17.6	42.0	10.70	68.8	64.5	56.3	86.5	43,600
48	403.3	456.7	18.6	44.2	11.25	68.3	61.2	54.5	77.9	40,750
49	372.7	424.5	20.9	49.2	14.00	63.3	54.2	51.4	78.4	35,660
50	330.9	367.2	18.5	44.1	13.60	66.7	58.4	54.4	79.1	41,790

1/ See footnote 1 on page 39.
6/ F. C. input minus F. C. output, divided by F. C. input.
7/ B.t.u. output in gas divided by B.t.u. input in coal.
8/ B.t.u. output in gas plus residue divided by B.t.u. input in coal.
9/ Per ton of dry coal.

Run No.	Average wall temperature at middle of generator, °F.	Analysis of gas made, percent								Cal. value of make gas, B.t.u.10/
		CO_2	O_2	Unsat. HC	H_2	CO	CH_4	N_2	Total	
1	-	23.3	0.7	0.2	37.8	34.6	0.3	3.1	100	241
3	-	39.0	.8	.2	32.9	23.5	1.4	2.2	100	200
5	-	31.1	.7	.3	34.9	28.8	1.4	2.8	100	225
6	-	23.4	1.3	.1	32.6	35.8	2.0	4.8	100	243
8	-	43.3	.0	2.0	31.7	15.4	7.6	.0	100	262
9	-	44.1	.6	.3	28.2	18.4	8.4	.0	100	241
12	-	28.9	.9	.5	18.6	44.5	2.1	4.5	100	234
13	-	26.0	1.4	.4	30.4	37.4	2.0	2.4	100	246
15	1,924	33.7	.4	.7	29.4	29.8	1.9	4.1	100	222
17A	1,762	21.6	.0	.7	35.8	35.6	5.2	1.1	100	295
22	1,778	27.2	.0	.2	23.5	47.4	1.7	.0	100	231
23A	1,836	17.5	.6	.2	27.1	48.7	.9	5.0	100	254
24	2,010	23.4	.0	.5	26.1	47.2	2.8	.0	100	274
27E	1,888	20.3	.0	1.0	22.1	49.0	6.5	1.1	100	312
27F	2,159	16.8	.0	.9	24.5	51.3	5.4	1.1	100	314
29	1,890	19.3	1.0	.6	27.0	49.6	2.5	.0	100	277
31C	2,126	18.0	.0	.8	27.5	50.5	3.2	.0	100	297
33A	2,255	17.0	.5	.9	25.5	51.1	5.0	.0	100	313
34A	2,223	27.1	.0	.5	21.8	44.4	1.8	4.4	100	240
36	1,931	21.5	.8	1.0	32.7	40.8	2.1	1.1	100	275
37	1,771	18.1	.3	1.9	30.5	38.7	6.3	4.2	100	319
40	1,890	29.2	.0	1.3	34.3	31.2	1.6	2.4	100	249
43	2,183	6.3	.2	.5	36.3	52.2	2.2	2.3	100	317
44	1,997	7.1	.2	.9	33.3	55.7	1.8	1.0	100	321
46	1,927	7.1	.0	.9	35.0	55.4	.6	1.0	100	313
47	1,824	8.9	.0	.7	30.6	58.0	.8	1.0	100	306
48	1,901	8.8	.0	1.1	29.2	59.1	.8	1.0	100	312
49	1,876	7.3	.3	2.2	28.6	59.2	1.4	1.0	100	334
50	1,870	6.8	.0	.6	30.9	59.2	1.5	1.0	100	316

10/ B.t.u. per cu. ft. (60, 30, dry, gross).

Run No.	Dry residue output, lb./MCF gas	Analysis of dry carbonaceous residue, percent					Gross cal. value of dry residue, B.t.u.
		Ash	V.M.	F.C.	Total C	S	
1	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-
6	11.3	15.5	15.5	67.2	-	-	-
8	-	10.8	-	-	-	-	-
9	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-
13	-	22.7	-	-	-	-	-
15	17.0	24.9	27.0	72.7	-	-	-
17A	-	12.0	4.0	84.0	-	-	-
22	13.9	13.7	8.9	77.4	-	-	-
23A	13.5	16.4	3.2	80.4	-	-	-
24	14.8	17.9	10.3	71.8	-	-	-
27E	-	-	-	-	-	-	-
27F	-	-	-	-	-	-	-
29	28.6	10.2	9.1	80.7	-	-	-
31C	-	-	-	-	-	-	-
33A	15.0	13.5	6.1	81.4	-	-	-
34A	-	-	-	-	-	-	-
36	33.9	13.1	9.1	77.8	-	-	-
37	42.1	11.5	11.6	76.7	-	-	-
40	-	26.8	10.7	62.5	-	-	-
43	13.8	32.4	5.9	61.7	-	-	-
44	10.7	30.6	2.7	66.7	64.9	2.9	10,330
46	21.0	25.9	4.7	69.4	71.5	2.4	10,420
47	13.1	35.8	5.0	59.2	-	-	9,580
48	14.0	33.3	3.5	63.2	-	-	9,580
49	18.1	29.5	5.8	64.7	68.2	2.2	9,580
50	14.7	32.5	2.7	64.8	-	-	9,768

Analysis of coals gasified in various runs (moisture-free basis), percent

Fuel charged	Wyoming No. 9 coal		Sewickley coal
Serial numbers of runs	1 - 28	29 - 39	40 - 51
Volatile matter	41.5	38.7	34.7
Fixed carbon	53.5	56.2	53.0
Ash	5.0	5.1	12.3
Hydrogen	5.7	5.2	4.9
Carbon	74.3	71.5	73.0
Nitrogen	1.4	1.5	1.6
Oxygen	12.8	15.9	5.3
Sulfur	.8	.8	2.9
B.t.u.11/	13,175	13,215	13,200
Ash-softening temperature, °F. ...	2,340	2,340	2,210
Moisture in coal as charged	5.9	4.5	2.0

11/ Gross B.t.u. per lb. of dry sample.