Columns 36 to 40 show gasifier temperatures, the first one for product gas at the crossover level (after passing through the heat-trap coils) and the next four at various locations in the refractory lining. Columns 41 to 45 give heat-input items, and columns 46 to 61 give heat-output items.

The cold thermal efficiency of the process (heat of combustion of product gas related to the heat of combustion of coal charged) is indicated in column 62 and calculated heat losses through the refractory in columns 63 and 64. The total preheat to reactants and the sum of the heat losses from the gasification zone, both expressed per pound of coal charged, are given in columns 65 and 66.

Coals charged

Table 2 presents ultimate analyses, calorific values, and ash fusibilities of the various batches of Sewickley-bed coal used during runs 1 through 34. All determinations were made on samples representing averages of the coal batches (generally 5 to 8 tons each) as received at the station. The total carbon content varied from 70.3 to 72.5 percent in the data used.

The total sulfur content varied over a relatively wide range of 1.1 to 3.2 percent. The relationship between sulfur in coal and sulfur in product gas is shown later under Sulfur Data.

The ash-fusibility temperatures were remarkably consistent. Except for the initial deformation temperature of the ash from Batch 31 coal, the spreads for initial-deformation, softening, and fluid temperatures were under 100° F. each. All fusibility determinations were made in a Baker-Brunjes ash-fusion-point furnace in a reducing atmosphere of hydrogen to conform as closely as possible to conditions in the gasifier.

Two finenesses of grinding were used. The finer size of coal, nominally 90 percent through a 200-mesh screen, was employed for runs 1 through 18, and the coarser size, nominally 70 percent through 200-mesh, for runs 19 through 34. The following tabulation presents average screen analyses for the two sizes, weighted according to the number of test runs made with each batch of coal:

Weighted average screen analyses of Sewickley-bed coal

Screen size		Size distribution, weight-percent	
		Runs 1-18	Runs 19-34
minus 20	plus 50	0.1	0.3
minus 50	plus 100	1.1	4.4
minus 100	plus 140	3.2	10.6
minus 140	plus 200	8.3	14.0
minus 200		87.3	70.7
		100.0	100.0

Coal batch number	Gasification-run numbers	Ultimate analysis (as-rec'd.), percent[1]							Calorific value, B.t.u./lb.		Ash-fusibility temp., °F.[2]		
		Moist.	H	C	N	O	S	Ash	Gross	Net	Initial deform.	Softening	Fluid
13	1-2	1.6	4.9	70.2	1.5	5.5	2.8	13.5	12,620	12,150	2,265	2,295	2,340
14	3-4	1.7	5.1	68.2	1.3	5.7	2.5	15.5	12,460	11,970	2,170	2,250	2,330
15	5-7	1.2	5.1	72.3	1.5	5.1	3.2	11.6	13,360	12,870	2,170	2,230	2,320
16	8-9	1.1	4.8	72.2	1.5	6.6	2.3	11.5	13,285	12,830	2,215	2,245	2,315
18	10-12	1.3	4.6	70.3	1.6	5.9	2.3	14.0	12,770	12,320	2,220	2,265	2,380
19	13-14	1.2	4.7	71.3	1.6	6.4	2.1	12.7	12,970	12,530	2,240	2,250	2,360
21	15-18	1.7	4.5	71.3	1.4	5.7	1.1	14.3	12,675	12,240	2,260	2,300	2,350
22	19-20	1.3	4.7	70.9	1.5*	5.0	2.6	14.0	12,740*	12,295	2,250	2,305	2,365
23	21-22	1.1	4.8	70.8	1.4	5.9	2.7	13.3	12,910	12,460	2,265	2,295	2,315
24	23A-23F	1.1	4.8	71.8	1.4*	5.4	2.4	13.1	12,910*	12,460	2,240	2,290	2,360
24-25	23G	1.4	4.8	71.4	1.4	5.3	2.2	13.5	12,810*	12,360	-	-	-
25	24-28B	2.0	4.6	70.5	1.4	5.1	1.8	14.6	12,550*	12,110	2,220	2,250	2,360
25-26	28C	2.1	4.7	70.7	1.4	5.2	2.0	13.9	12,640*	12,180	-	-	-
26	28D-29	2.3	4.7	71.0	1.1	5.4	2.2	13.0	12,750*	12,290	2,210	2,270	2,370
27	30-31	1.9	4.8	72.5	1.1	5.8	1.2	12.4	12,900*	12,435	2,200	2,260	2,360
30	33-34Q	1.0	4.8	70.4	1.4	5.8	1.8	14.8	12,620	12,165	2,220	2,280	2,390
30-31	34R	1.1	4.7	71.1	1.4	6.0	1.7	14.0	12,730	12,290	-	-	-
30-31	34T	1.1	4.4	72.2	1.4	6.2	1.4	13.0	12,890	12,465	-	-	-
30-31	34U	1.0	4.8	70.5	1.4	5.8	1.8	14.7	12,630	12,180	-	-	-
31	34S	1.4	4.4	72.4	1.4*	6.3	1.4	12.7	12,930*	12,510	2,050	2,260	2,350

1/ An asterisk (*) indicates items (nitrogen or gross calorific value) estimated from similar analyses. Oxygen was determined by difference, not calorific values were calculated from gross values, and analyses of mixtures of two coal batches were calculated from those for the individual batches. The volatile-matter content (not shown) ranged from 30 to 36 percent and averaged 33 percent.

2/ Ash fusibility determinations were made in a Baker-Brunjes ash-fusion-point furnace, using the method specified for a reducing atmosphere in that furnace. A platinum, platinum-rhodium thermocouple was used for temperature measurements, and a stream of hydrogen provided the reducing atmosphere.

TABLE 3. - Weights, analyses, and calorific values of residues recovered[1]

| Run No. | Residue weight and distribution by type | | | | Ultimate analysis of carbonaceous residue (total residue except slag), percent | | | | | | | Net calorific value of carbonaceous residue B.t.u./lb. | Ash content of slag, percent |
	Total recovered residue, lb./hr.	Entrained carbonaceous residue leaving at top of gasifier, percent	Entrained carbonaceous residue recovered at slag tap, percent	Slag from slag tap, percent	Moist.	H	C	N	O	S	Ash		
10	116.2	77.6	3.2	19.2	1.6	0.2	54.2	0.4	1.1	1.7	40.8	8,060	100.0
11	157.1	89.7	5.3	5.0	1.7	.2	61.3	.5	1.0	1.7	33.6	9,170	98.9
12	193.5	94.2	.9	4.9	4.0	.2	59.0	.5	1.4	1.3	33.6	8,695	97.1
13	99.3	63.3	.7	36.0	2.3	.3	59.9	.3	.5	1.2	33.6	7,320	100.0
14	87.1	74.5	.8	24.7	.9	.4	49.9	.4	.1	1.1	45.5	7,480	100.0
15	63.1	63.7	1.1	35.2	1.0	.6	50.5	.4	.0	1.1	46.6	6,685	100.0
16	110.1	75.9	1.2	22.9	1.9	.3	45.7	.4	.9	1.2	51.3	8,120	99.8
17	88.6	78.7	1.5	19.8	1.2	.3	55.1	.3	.3	.7	40.7	8,460	97.1
18	204.1	89.0	2.3	8.7	1.1	.2	57.6	.5	.3	.8	39.5	9,350	97.2
19	74.0	70.3	2.4	27.3	1.6	.3	63.1	.4	.8	.7	33.6	8,335	99.4
20	98.9	78.3	1.5	20.2	1.2	.3	57.4	.4	.7	1.5	39.1	9,480	91.7
21	88.4	81.0	1.1	17.9	1.9	.3	64.4	.5	.6	1.8	31.2	8,530	100.0
22A-H	123.4	87.0	.7	12.3	4.0	.4	58.0	.4	2.1	.8	36.5	8,850	98.5
23	157.3	77.3	1.0	21.7	5.7	.3	57.7	.5	.9	1.9	33.6	8,530	91.9
25	138.2	67.2	3.5	29.3	1.7	.5	61.0	.3	.2	1.1	35.2	8,860	96.5
28	144.7	71.8	11.8	16.4	4.2	.5	58.4	.5	.8	1.2	34.4	8,600	98.4
29	133.6	81.1	3.5	15.4	2.2	.4	62.1	.4	.4	1.2	33.3	9,060	99.6
30	126.5	68.4	21.9	9.7	1.6	.5	62.0	.6	.8	1.2	33.3	9,130	99.6
31	105.8	67.2	14.2	18.6	1.1	.6	62.0	.4	.5	1.2	36.4	8,720	99.7
33	124.1	63.6	8.0	28.4	.6	.4	59.8	.4	.2	1.2	35.5	8,830	100.0
34C-H	126.1	75.9	9.1	15.0	1.4	.3	60.8	.3	.8	1.1	31.9	9,495	99.4
34I-N,T	134.1	70.3	10.4	19.3	1.5	.2	64.2	.3	.9	1.1	36.2	8,795	99.6
34 O,P,R,S	130.5	70.9	8.4	20.7	1.4	.2	59.6	.3	.5	1.3	37.9	8,570	100.0
34Q	129.2	74.5	6.3	19.2	1.8	.2	58.7	.3	.6	.9	37.5	8,570	100.0
34U	120.8	65.1	15.1	19.8	2.6	.2	60.5	.3	.6	.9	34.9	8,820	99.6

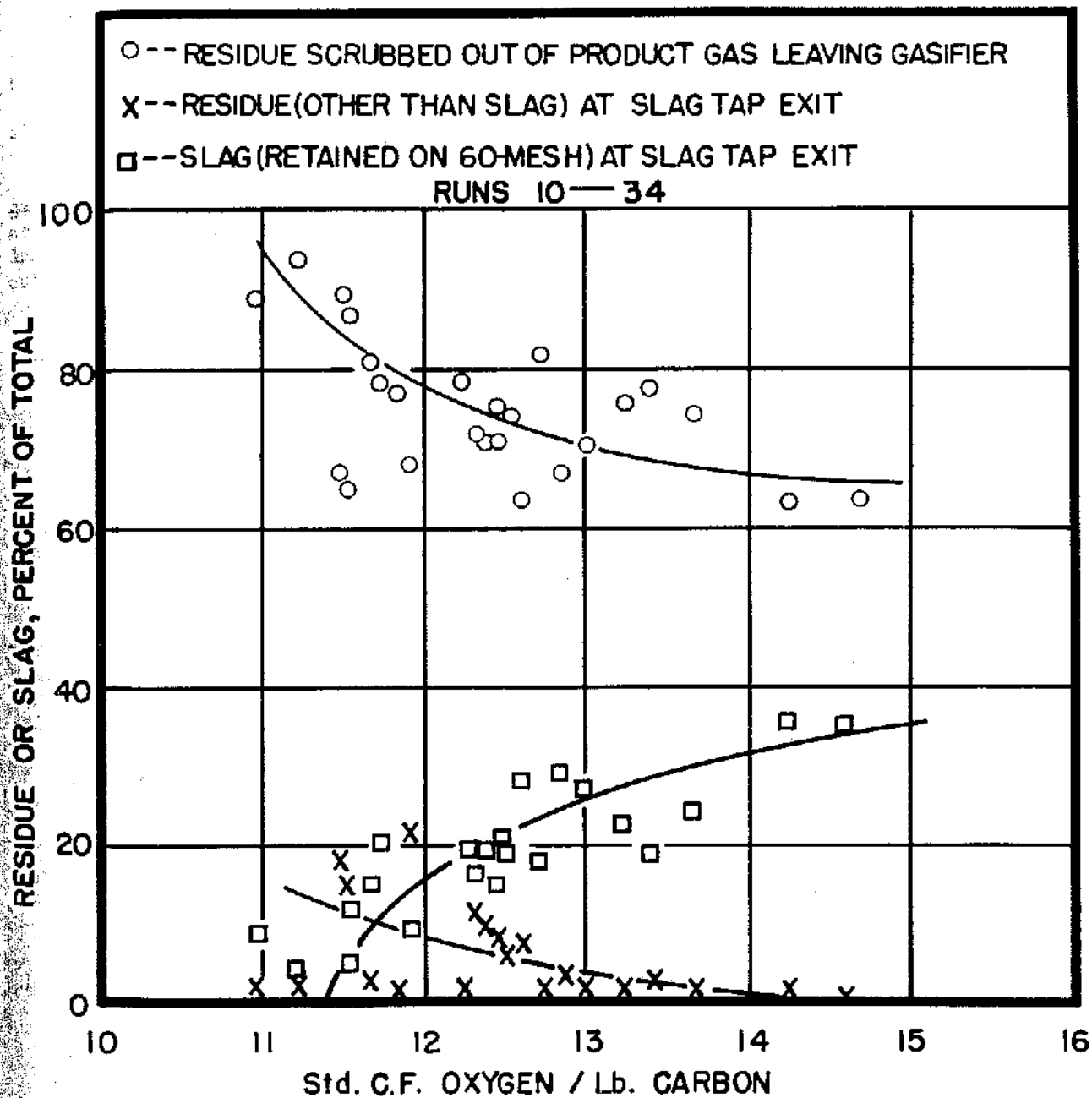[1] Residue weights and ultimate analyses on air-dry basis.

Figure 21. - Effect of oxygen-carbon ratio on residue and slag distribution.

Types of residues recovered

Table 3 shows total weights, weight distributions, ultimate analyses, and calorific values of the residues recovered during runs 10 through 34. The corresponding data have been omitted for earlier runs because the runs were less stable, the methods of collecting residue were not as well established, and the residue information obtained was of less value for design purposes. Residues have been divided into the following categories:

1. Entrained carbonaceous residue scrubbed out of the product gas leaving the gasifier. This includes material removed in the fogging chamber and the water scrubber and collected (or sampled) at the sludge tanks plus that removed at the dust-train seal pots. It does not include dust remaining in the exhaust gases going out the stack.

2. Entrained carbonaceous residue leaving the gasifier through the slag tap and collected (or sampled) at the slag pot. This includes material finer than 60-mesh sampled in the overflow water leaving the slag pot.

3. Slag (generally material coarser than 60-mesh) leaving the gasifier through the slag tap and collected in the slag pot.

The ash content of the carbonaceous residue, that is, total residue except slag, is seen to range from 31 to 51 percent, whereas the ash content of the slag generally ranged from 95 to 100 percent. Residue weights and analyses were used for calculating carbon, hydrogen, oxygen, and ash balances and for certain heat-balance items.

Figure 21 shows the effect of oxygen-carbon ratio on the weight distribution of the residues for these runs. As was expected, the percentage of residue collected as slag increased from under 5 percent to about 30 percent with increase in oxygen-carbon ratio. Also, the amount of carbonaceous residue collected at the slag-tap exit decreased materially.

Moisture tests and steam-decomposition results

The percentages of process steam decomposed, shown earlier in table 1, column 30, were averages calculated from hydrogen and oxygen balances. To check these values experimentally, samples of product gas from the top of the gasifier were passed through jars cooled in ice water and the condensed steam was weighed.

The following tabulation compares the experimentally determined moisture contents with averages calculated from hydrogen and oxygen balances, using flow data and residue data:

TABLE 4. - <u>Comparison of experimentally determined moisture</u>
<u>content of product gas with values calculated</u>
<u>from flow and residue data</u>

Run No.	Flow method, average	Residue method, average	Average of flow and residue	Experimental results
15C	35.0	35.5	35.3	35.6
16B	25.4	28.5	27.0	26.9
18	23.5	24.4	24.0	21.5
19C	28.8	28.3	28.6	27.8
19D	23.6	21.0	22.3	22.7
20A	31.0	26.4	28.7	29.1
20B	26.5	22.1	24.3	24.5
20C	23.6	21.3	22.4	21.9
23A	18.0	16.9	17.4	18.3
23B	16.1	11.7	13.9	15.6
Avg.	25.15	23.61	24.39	24.39

The good agreement between experimentally determined and calculated moisture contents indicates the general reliability of the steam-decomposition results calculated from material balances.

Data on sulfur content of gas

Table 5 lists the total sulfur content of the coal and the H_2S and organic sulfur contents of the product gas for the runs for which sulfur data were obtained. Sulfur in coal was determined from batch coal samples (as-received basis) through run 31 and from samples obtained at the feeder to represent coal charged to the gasifier for the indicated periods of run 34.

Inspection shows that the H_2S content of the product gas increases with increase in sulfur content of the coal. The best correlation is observed for the data from run 34 where the coal samples actually typify coal fed to the gasifier. The increase in H_2S content is seen to be linear and to amount to about 175 grains of H_2S per 100 std. c.f. of gas for each percent of total sulfur in the coal.

Data from the other runs, except 16 through 18, confirm the general relationship of H_2S to total sulfur in coal, but the spread of points is greater. A logical explanation is that the sulfur content reported as representing the average for a batch of coal may not agree with the sulfur content of the coal fed to the gasifier. The test procedure has been modified (commencing with run 34) so that coal samples are now obtained at the feeder and should represent coal fed to the gasifier rather than averages of coal batches received at the station.

Organic sulfur data from the same test runs show that the organic sulfur concentration in the product gas also increases with increase in total sulfur of the coal. The values for run 34 (for which the data were most reliable) range from 7 to 9 grains sulfur per 100 std. c.f. of gas per percent of total sulfur in the coal. Organic sulfur contents appear to be affected more (proportionally) by changes in experimental conditions. In general, 70 to 80 percent of the coal sulfur appears in the gas as H_2S and organic sulfur.

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TABLE 5. - Sulfur content of coal and H₂S and organic sulfur contents of product gas for runs 13 to 20 and 30 to 34

TABLE 5. - Sulfur content of coal and H_2S and organic sulfur contents of product gas for runs 13 to 20 and 30 to 34

Run No.	Sulfur content of coal, percent[1]	H₂S in gas, grains H₂S /100 std. c.f.	Organic S in gas, grains S /100 std. c.f.
13	2.1	330	7.0
14A	2.1	300	13.2
14B	2.1	330	10.4
14C	2.1	315	-
15	1.1	160	5.8
16A	1.1	120	4.8
16B	1.1	125	5.4
17	1.1	130	6.9
18	1.1	130	6.4
19A	2.6	450	18.1
19B	2.6	490	22.2
19C	2.6	445	17.8
19D	2.6	485	19.5
20A	2.6	415	-
20B	2.6	415	14.2
20C	2.6	440	14.2
30A	1.2	205	10.3
30B	1.2	225	12.2
30C	1.2	230	12.9
31	1.2	200	12.8
34N	2.6	490	20.1
34O	2.5	435	22.7
34P	1.9	325	13.2
34Q	2.7	485	20.0
34U	2.0	350	14.5

1/ Coal analyses for runs 13 to 31 were made from samples of coal batches received at the station. Analyses for run 34 were made on samples obtained at the feeder to represent coal fed to the gasifier.

Data on dust content of gas

Table 6 shows the experimentally determined dust concentrations leaving the water scrubber and their relationships to the total weight of residue for the test runs during which dust-concentration data were obtained. These dust quantities, amounting to 0.1 to 0.7 lb. per hr. and averaging less than 0.4 percent of the total gasifier residue (other than slag), indicate a removal efficiency of over 99 percent for the fogging chamber and water scrubber. These amounts of dust remaining in the gas are small enough so that they can be neglected in material-balance and heat-balance calculations. Later tests, during which dust samples were taken at the gasifier outlet as well as the scrubber outlet, confirmed the removal efficiency of over 99 percent.

Even though the dust concentration leaving the scrubber was very small compared to that leaving the gasifier, it was enough to interfere with the continued operation

of the product-gas meters and to be objectionable in a synthesis gas. During run 34L the Cottrell electrostatic precipitator (mentioned earlier) reduced the dust concentration from the 15.7 grains leaving the water scrubber (see table 6) to 0.92 grains per 100 std. c.f. of product gas, a removal of 94 percent. Later tests (not reported here) showed removal of 97 to over 99 percent of the dust in the gas leaving the water scrubber when using the Cottrell precipitator.

TABLE 6. - Dust concentrations leaving scrubber for test runs on atmospheric gasifier 4

Run No.	Dust concentration leaving water scrubber		Percent of total residue (other than slag)[2]
	Grains/100 std. c.f. product gas	Pound hr.[1]	
10	11.0	0.23	0.2
12	3.6	.07	0
19C	11.7	.19	.4
22B	32.0	.50	.5
22F	29.4	.70	.7
33A	30.0	.60	.6
33A	18.0	.36	.4
34L	15.7	.32	.3
34M	8.8	.18	.2
34U	10.5	.20	.2

[1] Product-gas flows from table 1 were used in converting to pounds dust per hour.
[2] Based on residue quantities given in table 3.

The experimental moving-bed coke filter also was used (after the water scrubber) during some of the gasification runs reported here. To determine the highest gas purity obtainable with the filter, it was operated during run 33 with a large amount of dust in the coke bed, and a consequent high pressure drop (7 inches of water at a flow of 1,000 std. c.f. per hr. per sq. ft. cross sectional area). The dust concentration was reduced from 30 to 0.14 grain per 100 std. c.f., a 99.5-percent removal. During run 34M it was operated with a clean bed (pressure drop of 0.2 inch of water at a flow of 1,000 std. c.f. per hr. per sq. ft.), and the dust concentration was reduced from 8.8 to 0.48 grain per 100 std. c.f., a removal of 94.5 percent. Investigation on relative effectiveness of dry, moist, and wet coke beds and on improved methods of moving the coke bed are continuing.

Reactant-injection-burner design data

Table 7 presents design data for the eight reactant-injection burners used for the test runs reported. Column 1 gives the run (or period) for which the calculations were made, column 2 gives the burner-design number, and columns 3, 4, and 5 give calculated velocities of coal, steam, and oxygen at the burner ports. These calculated values are based on actual feed rates and temperatures shown earlier in table 1.

Column 6 shows the average quantity of sweep gas (inert gas or nitrogen) for each burner, added at the sight glasses in the coal-feed lines to give the desired coal velocities through the burners. During the first 9 runs, oxygen, amounting to approximately 20 percent of the total oxygen feed, was used as sweep gas.

TABLE 7. - Reactant-injection-burner design data[1]

Run No.	Burner design No.	Coal velocity, ft./sec.[2]	Steam velocity, ft./sec.[3]	Oxygen velocity, ft./sec.[4]	Average sweep gas to each burner, std. c.f./hr.[5]
1	2	3	4	5	6
4	2	185	142	46.0	-
5	2	185	130	37.7	-
6	2	186	232	36.2	-
7	2	210	252	35.7	-
9	2	195	254	32.2	-
10	3	72.9	232	232	100
11	4	67.3	220	220	100
12	4	55.2	192	192	97
13	5	52.6	318	318	71
14B	5	36.1	271	271	66
15A	5	47.4	192	192	52
16A	5	37.9	224	224	53
17	5	64.2	175	175	52
18	5	51.0	202	202	83
19A	5	51.3	163	163	83
20A	5	52.4	166	166	83
21	6	59.7	745	745	85
22A	6	48.1	935	935	66
23A	6	18.1	977	977	34
24A	7	16.0	724	724	25
25A	7	28.9	876	876	32
26A	7	28.9	1,050	1,050	29
27A	7	16.4	1,010	1,010	29
28A	6	41.3	651	651	31
29A	6	43.7	918	918	37
30A	9	19.3	920	920	27
31	9	19.9	660	660	34
33	9	21.6	770	770	41
34C-H	9	22.2	770	770	38

[1] Velocities are calculated values based on actual reactant feed rates.

[2] See columns 5 and 8 of table 1 for coal-feed rates and inlet temperatures.

[3] See columns 6 and 9 of table 1 for steam-feed rates and inlet temperatures.

[4] See columns 7 and 10 of table 1 for oxygen-feed rates and inlet temperatures.

[5] During runs 1 through 9 the coal was swept with oxygen from the sight glasses to the gasifier.

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ACCURACY OF RESULTS

In considering the data presented in table 1 and the various graphs showing the indicated effect of variables on the results, the reader should bear in mind that the major effort to date in this experimental program has been to develop an operable process. This has meant that check tests have not been possible except in a very few cases. As will be noted from the data given in table 7, the design characteristics of the reactant injection burners have varied considerably. Also, as shown in the discussion of the modifications made to the gasifier, particularly as regards the addition of various cooling coils, the heat loss per unit of fuel charged or per unit of product-gas output has not been constant for the tests reported here.

These two factors, changes in burner design and variable heat losses, account for a considerable portion of the scatter shown in the data plots for runs having similar reactant ratios. As noted later in the report, the gasifier design has been stabilized, as shown in figure 5. However, burner design has not been stabilized to date, and development on the burner is continuing. Also, further investigations are being carried out to increase the amount of preheat added to the reactants.

Probable accuracy of measurements

Much of what was said concerning flow measurements for gasifier 2[19]/ also applies to atmospheric gasifier 4. The most important measurements continue to be the flow measurements of input reactants, product gas, and residues. Measurement accuracy was improved considerably during this investigation. The instantaneous coal rates are approximated by reading the "delta P" across the calibration-coil coal feedline and are verified by the weigh hoppers, feeding back any coal that remains at the end of the run. The oxygen rate is measured at 200 p.s.i.g. by a precalibrated orifice and differential transmitter, and the rate is verified by orifice measurements at 80 p.s.i.g. of the total flow and the flow to each reactant-injection burner. Water flows to the steam generator and superheater, equivalent to steam flows from the superheater, are determined by a precalibrated orifice meter. All these rates should be accurate within 1 or 2 percent for most of the later runs reported.

Product-gas measurements

Product-gas flows are determined by using an orifice-type meter, whose orifice plate is installed in the exhaust line where the gas is at approximately atmospheric pressure and room temperature. A positive-displacement-type Roots-Connersville meter was used in series with the orifice meter for at least part of the later runs. These flows generally checked each other within 1 or 2 percent, but sometimes the magnitude of the discrepancy was as high as 10 percent because of erroneous readings caused by moisture in the orifice-meter impulse lines, gradual plugging of the Roots-Connersville meter from dirty gas, etc. In such cases the reasons for the discrepancy were investigated, and the method that gave the best internal consistency was used as the standard for that run. Also, improvements in metering technique were worked out to minimize troubles from these sources in later runs.

Residue measurements

As was mentioned earlier, samples are collected and analyses are made of the residue scrubbed out of the product gas leaving the gasifier, the residue (other than slag) at the slag-tap exit, and the slag (including plus-60-mesh material) at the slag-tap exit. The accuracy of sampling increased during the course of the investigation
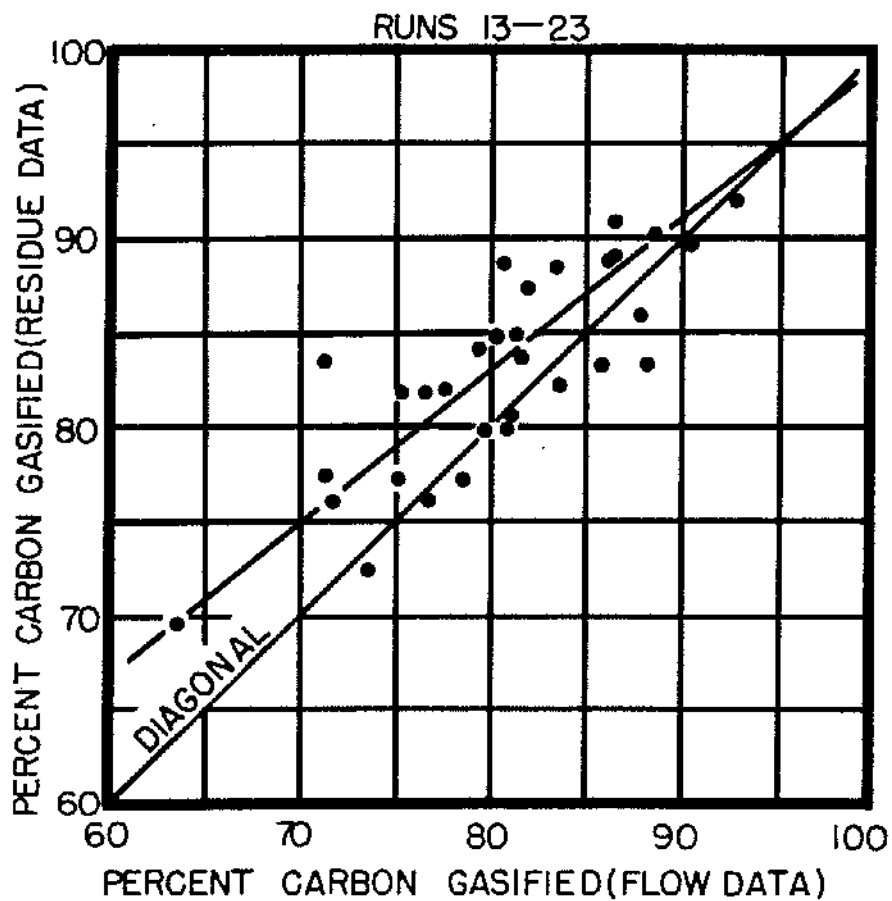
19/ See footnote 4.

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Figure 22. - Comparison of carbon gasified from flow and
residue data.