It is shown in table 19 that steam-dried lignite has slightly better gasification characteristics than natural subbituminous coal, whereas natural lignite cannot be gasified as rapidly or as efficiently as natural subbituminous coal, as indicated by runs 10-B and 12-C. In the small plant, gas was made from subbituminous coal at rates as high as 81.5 cubic feet per hour per square foot, whereas the maximum rate with natural lignite was 63.5 cubic feet per hour per square foot. In runs 2E and 3B on natural lignite in the large plant, rates of gasification up to 77.6 cubic feet per hour were attained. It is indicated, therefore, that rates as high as 100 cubic feet per hour per square foot may be attained on the large plant when gasifying steam-dried lignite.

Experience in the pilot plants has indicated that the capacity of the externally heated retort increases almost inversely with the width of the reaction zone. There was some concern, when the plants were first designed, as to the movement of coal into the narrow annulus. It is now indicated that no trouble will be encountered when using a reaction zone 2.0 or 2.5 inches wide in the large plant. If so, capacities of 85 cubic feet per hour per square foot should be reached with natural lignite under the conditions outlined in column "X" of table 20.

The experimental work thus far has not revealed the optimum length of the two reaction zones. This must be determined by further experimentation. In the large plant, the length of the upper reaction zone has been varied from 12 to 9.75 feet and the bottom zone from 3 to 5 feet. From the experience in the small plant, which has a top zone about 7 feet long and a bottom zone about 3 feet long, it is shown that high overall rates of reaction are attained. Therefore, it is believed that the optimum length of the upper zone in the Grand Forks plant will be 9 to 10 feet, and the bottom zone should be 4 to 5 feet in order to attain the highest capacity at a minimum cost. Further experimental work will be necessary to ascertain the best width and length of the reaction zones.

Heat Balances and Rates of Heat Transfer

Heat balances were not made for all runs on the large plant, but these may be calculated from the operating data of table 7 in conjunction with data on properties of the materials used and produced.

Four typical heat balances were made of a testing period during each of the runs. These are given in tables 21 to 24. It is shown that the potential heat in the gas made varied from 44 to 68 percent of the heat in the materials entering, but the total heat in gas plus that in char residues was 83 to 86 percent of the total heat in materials used. Radiation and sensible heat losses are therefore approximately 15 percent.

TABLE 21. - Heat and material balance on run 1-B, Grand Forks pilot plant.[1]

	Percent	Temp., °F.	Mols	Pounds	B.t.u. thousands	B.t.u. percent
In:						
Natural lignite as charged		60		690	[2]4,268	75.8
Process steam, sensible heat		275	31.38	565	54	1.0
Heating gas, potential heat		70	13.78	225	1,310	23.2
Heating gas, sensible heat		70			1	.0
Air to retort		65	33.53	970	2	.0
Total				2,450	5,635	100.0
Out:						
CO_2	23.9	605	6.25			
CO	12.7	605	3.32			
H_2	58.2	605	15.24			
Ill. $C_{2.8}H_{5.6}$	.2	605	.05			
CH_4	4.2	605	1.10			
C_2H_6	.3	605	.08			
N_2	.5	605	.13			
Subtotal	100.0		26.17		[3]114	2.0
Make gas, potential heat		605		428	2,487	44.2
Undecomposed steam, sensible heat		605	35.02	631	159	2.8
Subtotal				1,059	2,760	49.0
Char and dust, potential heat		600		195	2,308	41.0
Char and dust, sensible heat		600			32	.6
Stack gases, sensible heat		720		1,195	250	4.4
Radiation from system					285	5.0
CO_2 lost						
Unaccounted for				1		
Total				2,450	5,635	100.0

1/ Net heat basis, hourly operation. Gas volumes are dry at 60°F. and 30 in. Hg.

2/ Potential net heat in coal is equal to gross heat minus 18,350 times mol fraction of total hydrogen.

3/ Sensible heat in make gas.

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TABLE 22. - Heat and material balance on run 2-E, Grand Forks pilot plant 1/

	Percent	Temp., °F.	Mols	Pounds	B.t.u. thousands	B.t.u. percent
In:						
Natural lignite as charged		60		729	2/4,551	69.5
Process steam, sensible heat		275	13.88	250	24	.4
Heating gas, potential heat		72	18.60	287	1,968	30.0
Heating gas, sensible heat		72			2	.0
Air to retort		70	50.10	1,450	5	.1
Total				2,716	6,550	100.0
Out:						
CO_2	15.6	695	6.30			
CO	22.9	695	9.25			
H_2	56.7	695	22.89			
Ill. $C_{2.8}H_{5.6}$	.8	695	.32			
CH_4	3.9	695	1.57			
C_2H_6	.0	695	.00			
N_2	.1	695	.04			
Subtotal	100.0		40.37		3/208	3.2
Make gas, potential heat .		695		623	4,444	67.9
Undecomposed steam, sensible heat		695	11.43	206	61	.9
Subtotal				829	4,713	72.0
Char and dust, potential heat		685		123	1,197	18.3
Char and dust, sensible heat		685			22	.3
Stack gases, sensible heat		595		1,737	278	4.3
Radiation from system					337	5.1
CO_2 lost		695		9	1	.0
Unaccounted for		695		18	2	.0
Total				2,716	6,550	100.0

1/ Net heat basis, hourly operation. Gas volumes are dry at 60°F. and 30 in. Hg.

2/ Potential net heat in coal is equal to gross heat minus 18,350 times mol fraction of total hydrogen.

3/ Sensible heat in make gas.

TABLE 23. - Heat and material balance on run 3-G, Grand Forks pilot plant.[1]

	Percent	Temp., °F.	Mols	Pounds	B.t.u. thousands	B.t.u. percent
In:						
Natural lignite as charged		60		539	[2]3,441	70.2
Process steam, sensible heat		240	8.33	150	12	.3
Heating gas, potential heat		81	14.06	219	1,443	29.4
Heating gas, sensible heat		81			2	.0
Air to retort		80	34.73	1,005	6	.1
Total				1,913	4,904	100.0
Out:						
CO_2	14.3	665	4.45	......	......	
CO	25.4	665	7.90	......	......	
H_2	55.4	665	17.26	......	......	
Ill. $C_{2.8}H_{5.6}$	0.3	665	.09	......		
CH_4	3.5	665	1.09	......	......	
C_2H_6	0.1	665	.03	......	......	
N_2	1.0	665	.31	......	......	
Subtotal	100.0		31.13		[3]145	3.0
Make gas, potential heat .		665		485	3,197	65.2
Undecomposed steam, sensible heat		665	6.05	109	31	.6
Subtotal			......	594	3,373	68.8
Char and dust, potential heat		560	......	93	912	18.6
Char and dust, sensible heat		560	...	......	16	.3
Stack gases, sensible heat		645		1,224	226	4.6
Radiation from system					377	7.7
CO_2 lost		665	......	2		
Unaccounted for			......			
Total				1,913	4,904	100.0

1/ Net heat basis, hourly operation. Gas volumes are dry at 60°F. and 30 in. Hg.

2/ Potential net heat in coal is equal to gross heat minus 18,350 times mol fraction of total hydrogen.

3/ Sensible heat in make gas.

TABLE 24. - Heat and material balance on run 4-H, Grand Forks pilot plant.1/

	Percent	Temp., °F.	Mols	Pounds	B.t.u. thousands	B.t.u. percent
In:						
Natural lignite as charged		60		614	2/3,937	69.6
Process steam, sensible heat		420	19.43	350	58	1.0
Heating gas, potential heat		84	16.45	257	1,652	29.2
Heating gas, sensible heat		84			4	.1
Air to retort		77	39.55	1,144	7	.1
Total				2,365	5,658	100.0
Out:						
CO_2	18.0	730	6.31			
CO	19.4	730	6.80			
H_2	59.3	730	20.78			
Ill. $C_{2.8}H_{5.6}$	.3	730	.10			
CH_4	2.2	730	.77			
C_2H_6	.4	730	.14			
N_2	.4	730	.14			
	100.0		35.04		3/184	3.2
Make gas, potential heat		730		569	3,659	64.7
Undecomposed steam, sensible heat		730	16.15	291	91	1.6
Subtotal				860	3,934	69.5
Char and dust, potential heat		600		104	1,061	18.8
Char and dust, sensible heat		600			17	.3
Stack gases, sensible heat		570		1,401	225	4.0
Radiation from system					421	7.4
CO_2 lost						
Unaccounted for						
Total				2,365	5,658	100.0

1/ Net heat basis, hourly operation. Gas volumes are dry at 60°F. and 30 in. Hg.

2/ Potential net heat in coal is equal to gross heat minus 18,350 times mol fraction of total hydrogen.

3/ Sensible heat in make gas.

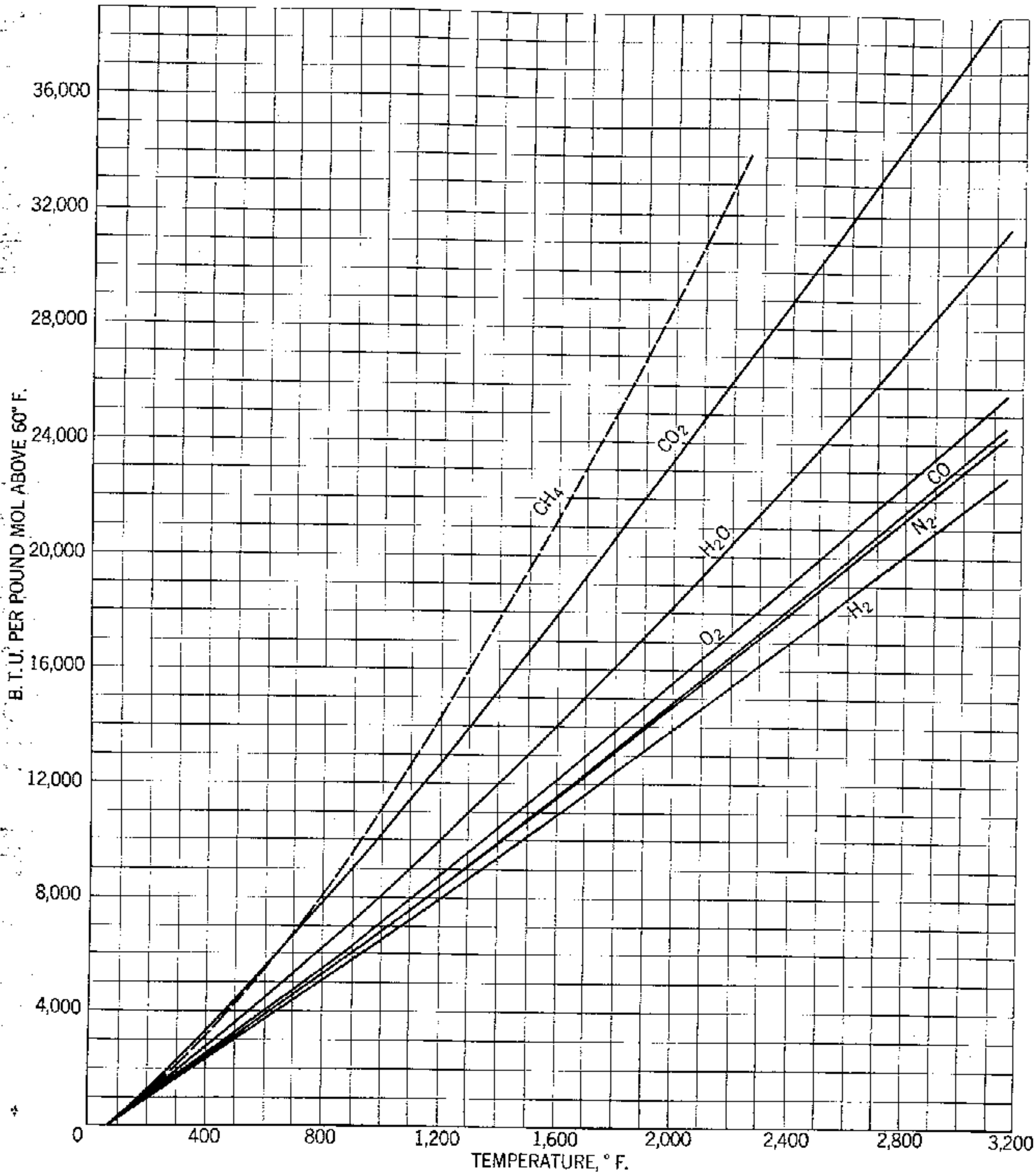

Figure 27. - Molal heat content of gases 60° to 3,000° F.
Bureau of Standards RP 1634.

In a commercial plant, the char residues would be used to make producer gas for heating the retort or for steam raising. If it is assumed that steam is produced at 85 percent efficiency and a producer operating on the char will have 80 percent efficiency, the over-all efficiency of gasification under the conditions described in run 2-E is 72.0 percent. This represents the probable efficiency of the Grand Forks plant when operating on natural lignite having 37 percent moisture. If the lignite is steam dried to 8.0 percent moisture, the comparable calculated over-all efficiency is 76 percent. It is concluded from these comparisons and other calculations that if the latent heat in steam is not considered, the over-all efficiency of the process of gasification on natural lignite will be about 82 percent, and the losses of sensible and potential heat from the generator and producer will be 18 percent.

The maximum rate of transfer of heat in the Grand Forks plant was 5,800 B.t.u. per hour per square foot of heated surface. The heated area is 200 square feet. This was attained during run 2-E. The other runs made at lower capacities indicate heat transfer rates of 3,100 to 5,000 B.t.u. per hour per square foot. Higher rates of heat transfer were attained in the small pilot plant at Golden when employing a 2-inch reaction zone. From the operating data of table 6, the following rates of heat transfer are calculated for the several runs:

Run	Rate of heat transfer, B.t.u. per hour per square foot
10-A	5,580
10-B	6,043
12-A	4,850
12-C	5,240

The higher rate of heat transfer obtained on the small pilot plant is due to the narrower width of the reaction zone. The several tests on both pilot plants have shown that the capacity, which is proportional to the rate of heat transfer, is about inversely proportional to the width of the reaction zone. When the width of the reaction zone in the small plant was decreased from 2.75 to 2 inches, the capacity increased from about 66 to 81 cubic feet per hour per square foot. Likewise, when the width of the reaction zones on the Grand Forks plant was changed from 4 to 3 inches, the capacity changed from 50 to about 75 cubic feet per hour per square foot under comparable conditions. Therefore, it is expected that the capacity of the Grand Forks plant will be increased to about 90 cubic feet per hour per square foot, and the rate of heat transfer will increase from 5,800 to 7,000 B.t.u. per hour per square foot by decreasing the width of the reaction zone from 3 to 2.5 inches.

Figure 27 gives data on the sensible-heat content of gases based upon information published in the Bureau of Standards Research Paper 1634. The heats of reaction given in figure 26 were also calculated from the same data. These figures are included in this report for reference purposes because the data differ somewhat from similar thermal constants reported in the literature.

OPERATING PROBLEMS

Coal Handling and Charging

Ordinarily, coal handling is not considered an operating problem because in most instances adequate mechanical systems are readily available. However, lignite has different physical properties than the higher-rank coals, and troubles were experienced in transporting this fuel in chain-type enclosed conveyors. Figure 18 shows the design of the coal-conveying system, which provides a linked chain with "V"-shaped vanes for conveying the coal in a small rectangular passage. The particular design of vane did not operate satisfactorily on lignite, because this fuel wedged along the sides of the vane and created a severe braking action. Considerable experimentation was necessary to find out the proper shape of vane for moving lignite. It was found that flat vanes spaced at 10-inch intervals were best, and it was also observed that the space between the vanes should not be completely filled. When these modifications were installed, it was indicated that the system would function satisfactorily, but up to the time of writing this report the conveyor had not been tested under active operating conditions.

Charging coal to the retort continuously is a difficult problem, especially when the rate of charging is 600 to 1,000 pounds an hour and the internal pressure in the retort is 20 to 30 inches of water. It is important that the charging system be gas-tight. The temporary solution adopted employed a charging hopper that could be sealed from the retort and charged intermittently. This hopper is illustrated in figure 18. The system was satisfactory, but it required considerable attention and extra labor. It could not be considered satisfactory for a commercial plant. A major difficulty was encountered with this method of charging, which resulted from the internal condensation of steam, which affected the gasification balance in the generator and generally upset smooth operating conditions. When a fresh charge of coal was sealed in the charging hopper, steam would rush into the charging hopper when the connecting feed valves to the retort were opened. Less steam would therefore be available in the reaction zone, causing an equilibrium shift, and for several minutes the system would be out of balance. This condition was remedied to some extent by introducing purge gas into the charging hopper to equalize the pressure before opening the connecting valves.

During the course of experimentation on the large plant it became increasingly evident that coal had to be charged in a steady stream to avoid unbalancing the gasification system.

Char Discharging

The continuous removal of char from the lower reaction zone has not been a serious problem. The scraper illustrated in figure 17 has operated satisfactorily, and it appears to be a good solution for commercial operation. This scraper revolves just beneath the annular space and shaves an increment of char from each section as the blades rotate. The rate of char removal is governed by the speed at which the scraper is made to rotate.

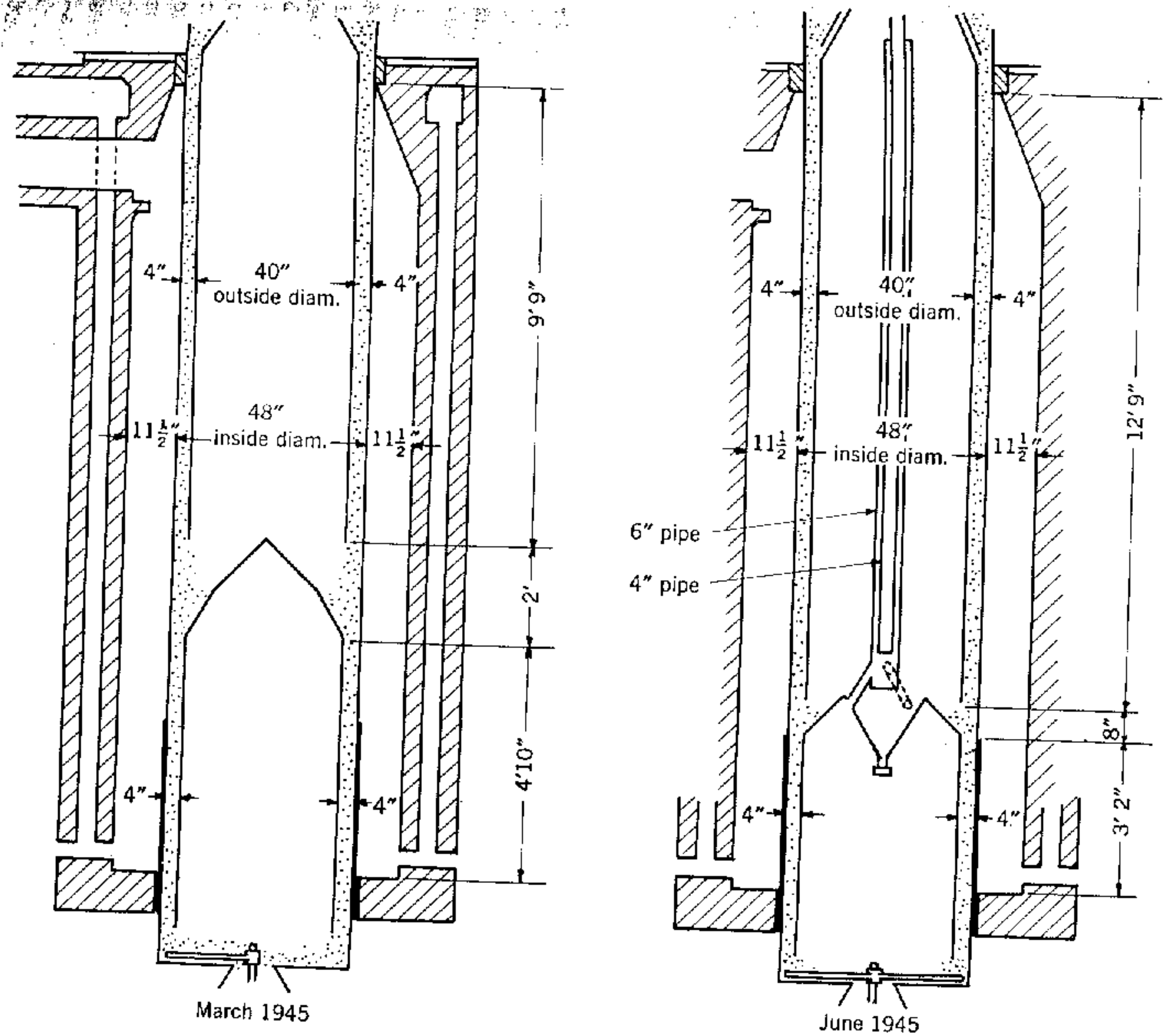

Figure 28. - Grand Forks pilot plant retort designs.

The char is moved into the central discharge outlet and into a receiver. During the early tests this receiver was emptied intermittently by cut-off valves and disconnecting the portable receiver. During runs 2, 3, and 4, receiver was emptied by a jet of purge gas, which pneumatically transported the char through a 2-inch pipe into a large receiver outside the retort building. This method is satisfactory, but occasionally stoppages were caused by large pieces of slate and shale wedged in the ejector throat. Release was usually easily effected by a slight jar or vibration.

Gas Cooling and Scrubbing

The cooling and scrubbing of gas was accomplished successfully by a wash box connected with a small water scrubber, as illustrated in figure 9. The gas leaving the retort carried variable amounts of fine dust but no tar. The dust was knocked down in the wash box and, by the descending water spray in the scrubber, was carried into the sump tank, where the solids separated and the water passed out through a separator. The solids were drained and shoveled from the sump tank periodically. During run 3, the solids from the sump tank were passed through a vacuum filter press and it was feasible to recover all dusts with no difficulty. The cooling and scrubbing system outlined in figure 9 has been satisfactory for handling the gases made in the plant, and it is indicated that the purification system will treat 20,000 cubic feet of water gas adequately.

Gas Generation and Retort Changes

The first arrangement of the annular reaction zone tested during the preliminary run in March 1945 is described in figure 28. The width of the reaction zones was 4 inches. The length of the upper zone was 10.75 feet and the lower zone was about 5 feet. Saturated steam was introduced directly in the lower reaction zone. No special provisions were made to remove char dusts that moved into the central zone, and the preliminary test was made primarily to obtain operating experience. Three fundamental troubles developed. It was evident that the length of the upper zone was too short when employing the 4-inch reaction zone. All tar was not decomposed, and this contaminated the scrubber water going to the sewer. Before the test was completed, future troubles were foreseen due to building up of fine char dusts in the central gas offtake. A major trouble was caused by the introduction of wet steam to the lower annulus. The free moisture wetted the char in the lower part of the annulus, and in some periferal sections the char failed to move down. This uneven flow of char caused a concentration of high-ash material in sections of the lower annulus, which insulated the metal wall and permitted it to overheat. After the test, examination showed that several sections of the lower zone were packed rather solidly with ash and the retort tube had warped in places. All these difficulties were traced to the use of wet steam for the lower reaction zone. Previous experience from handling chars in the small plant had shown they will move freely so long as they are dry. The preliminary test revealed the need for three changes in the system which were made before the first regular test.

After the changes were made in the retort system, the plant was started in June 1945 for run 1 with the arrangement shown in figure 28. Steam for the lower reaction zone was introduced from the top of the retort and was preheated before entering the reaction zone. The length of the upper zone was increased to 12.75 feet, and the length of the lower zone was decreased to 3.2 feet, as shown. Alterations were also made in the char-removal scraper. Provisions were made to collect some of the blown-over char in the central section, from which it could be withdrawn by a high-vacuum suction line. This arrangement of the retort performed well, and much was learned about the method of gasification during this test.

After several days' operation, it was observed that the pressure drop through the central zone was increasing steadily, even though considerable char was removed by the suction-discharge line. After 10 days' operation, the pressure drop had increased to more than 20 inches of water, and it was estimated that the char had built up to a height of about 3 feet in the central zone. Otherwise the retort operated satisfactorily and no troubles were experienced with char removal. No tar was formed during this test, even though the temperatures were decreased about 200°F. This test revealed that some further changes in the retort arrangement were necessary to gain higher rates of capacity. From observations at Golden, it was indicated that a narrower reaction zone was necessary; also, the volume of the combustion chamber should be less in order to increase convection heat transfer and to reduce radiation. With a narrower reaction zone, an upper zone shorter than 12.75 feet could be employed with an attendantly longer lower zone.

The retort arrangement was revised for run number 2, which was made in December 1945. The unit was changed, as shown in figure 29. Provisions were made to remove blown-over char down through the center of the bottom discharging system, and a large reservoir was built in the central zone. The steam was introduced through a bundle of pipes, as shown, which were connected individually into the space leading to the lower reaction zone. The length of the upper annulus was shortened, and the width of the reaction zone was reduced to 3 inches. In addition, the width of the combustion chamber was reduced from 11.5 to 7 inches. During this period the outer metallized steel retort tube was replaced with the special steel alloy retort, and other improvements were made in the plant. Experimental work was conducted to find a better design for the center gas offtake, and the improved offtake, having an opening of 2.56 square feet, was installed.

The December test revealed considerable improvement in the smoothness of operation of the plant. No major troubles developed, but it was observed that, when making gas at rates exceeding 14,000 cubic feet per hour, the char blown into the center offtake pipe became excessive and increased rapidly as the gasification capacity was increased. When making less than 14,000 cubic feet per hour, the char blown into the center offtake was not troublesome and could be handled by suitable mechanical means. As capacities of 15,000 to 16,000 cubic feet per hour were reached, more fine dust traveled away with the gas, but it did not create a problem in the scrubbing system. The char-removing scraper performed its function without noticeable difficulties.

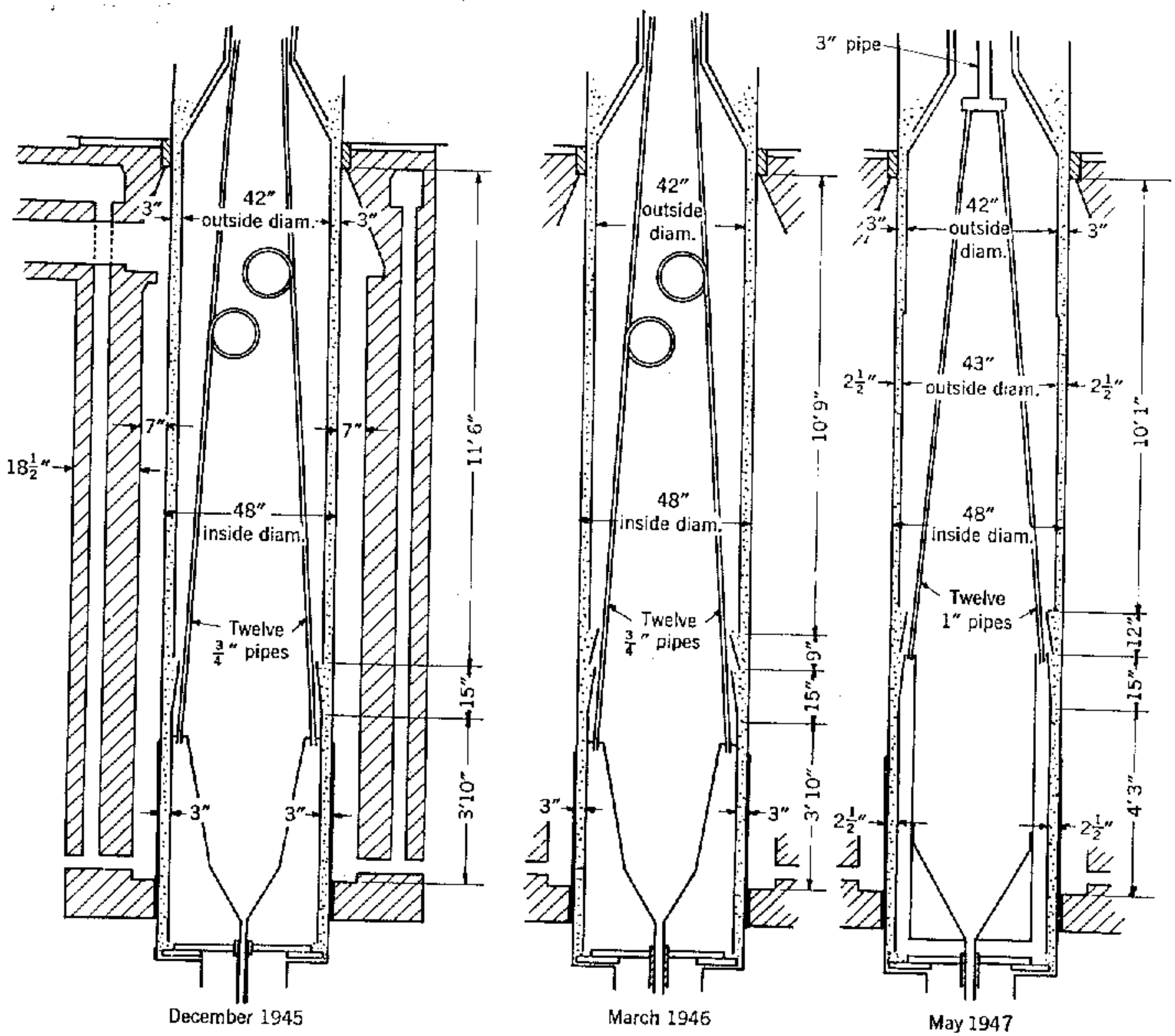

Figure 29. - Grand Forks pilot plant retort designs.

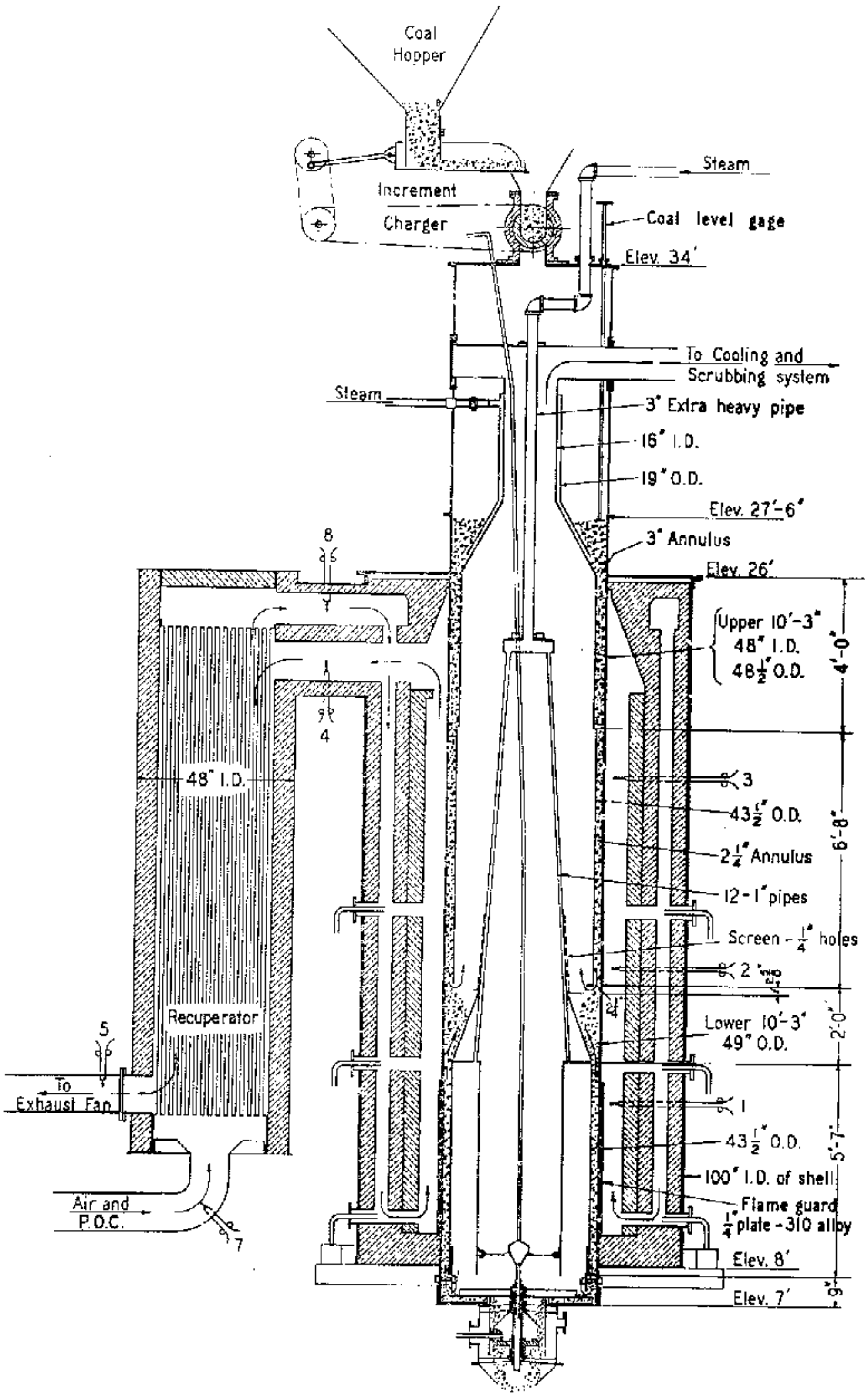

Figure 30. - Arrangement of generator for Grand Forks, N. Dak. pilot plant, 1948.

For test 3, which was made in March 1946, the center gas offtake was enlarged from 2.56 to 4 square feet, as shown in figure 29. Except for minor improvements in the char-extraction system, no other changes were made in the plant. The enlarged gas offtake improved operating conditions somewhat, but blown-over char became significant when making more than 15,000 cubic feet per hour. An increase in the gas made from 12,000 to 15,000 cubic feet per hour caused the blown-over fuel to increase from 2.4 to 6.5 pounds per hour. In the previous test with the smaller offtake, the blown-over char amounted to about 30 pounds per hour when making 15,000 cubic feet of gas per hour.

The experimental work thus far indicates that the retort arrangement shown as the right-hand diagram of figure 29 will be best for highest capacity with moderate blown-over char. This arrangement provides for a 2-1/2-inch reaction zone, a shorter upper reaction zone, and a longer lower reaction zone than were employed during the March 1946 run. The design of the generator with the 2-1/2-inch reaction zones is shown in more detail in figure 30, which also indicates a method for charging the retort. The piston charger, as shown, was built and tested in the shop, but it was not used for charging because of the possibility of gas leaks and irregularities in operation.

Figure 30 shows the arrangement of the generator for testing during 1947 and 1948. The width of the annulus is reduced to 2.25 inches, and suitable alloy parts have been specified. The outer retort is a heat-resisting alloy casting having 25 percent chromium, 20 percent nickel, and 1.25 silicon (type HK). The wall thickness is 3/4-inch. The inner retort is type 430 alloy steel containing 17 percent chromium, and the recuperator is type 309 alloy of 25 percent chromium and 12 percent nickel. With the reduced width of the reaction zone, the maximum temperatures necessary with this arrangement should not exceed 1900° F. when making gases having H_2/CO ratios of 2.0 to 2.5 at rates of 80 cubic feet per hour per square foot of retort area.