10-inch pipe. Leads to the motor enter the shell through a conically shaped Teflon seal. Helium did not leak around this seal. Standard brushes in the motor wore rapidly in the dry helium atmosphere, however, and were replaced with "high altitude" carbon brushes. These were still in service after 500 hours of operation. A variable transformer is used to control the speed of the motor. The blower normally operates at about 1,000 r.p.m. to circulate helium at 20 std. c.f.m. Gas flow is determined by an orifice meter.

Coal-Gasification Section

Several different lignites were gasified in the gasifier. Lignites were chosen because they are noncoking and therefore were believed least likely to plug the tube coil. Analyses of the coals are given in table 1. The gasification section (fig. 3) consists of equipment for mixing the coal with water, pumping and preheating the slurry, gasifying the coal-steam suspension with heat from hot helium, and exhausting the product gases and residue. As indicated previously, although several different methods were considered for feeding coal to the gasifier, slurry feeding was used in most of the tests.

TABLE 1. - Analyses of coals gasified in helium-heated gasifier

Coal	Proximate, percent				Ultimate, percent					Calorific value, B.t.u./lb.
	Moisture	Volatile matter	Fixed carbon	Ash	Sulfur	Hydrogen	Carbon	Nitrogen	Oxygen	
Lignite[1]	11.54	38.59	40.28	9.59	1.12	3.56	54.76	0.75	18.68	9,057
Subbituminous C[2]	11.65	30.57	29.94	27.84	.50	2.98	40.25	.55	16.23	7,392
Lignite char[3]	4.94	25.53	51.45	18.08	1.51	2.72	58.86	1.22	12.67	9,448

[1]Velva mine, Voltaire, Ward County, N. C.
[2]Healy Bed, Lake de Smet mine, Lake de Smet, Johnson County, Wyo.
[3]Lignite (Milan County, Tex.) carbonized at 930° F. in air in fluidized-type carbonizer; not plastic below 400° F., starts to burn at about 400° F.

Mixing and Pumping Coal-Water Slurry

Figure 8 shows the equipment used to mix and pump the slurry. In the 5-gallon mix tank, air-dried pulverized coal, 70-percent minus 200-mesh, is mixed in batches with water at a dry coal to water ratio of 1 to 3. During gasification, a variable-speed agitator continuously stirs the slurry, which is circulated at about 37 gallons per hour and 2 p.s.i.g. pressure.

Preheating Coal-Water Slurry

In the preheater the water in the slurry is vaporized and the steam-coal suspension is heated to 1,000° F. before passing to the gasifier. Preheaters used with the laboratory-scale gasifier were heated electrically. In a larger unit, helium recycled from the gasifier probably would be used to preheat the slurry.

Preheating the coal was the biggest problem in operating the gasifier. Gasification runs repeatedly were stopped by plugs forming in the preheaters. Figures 9 to 11 show some of the different types of preheaters that were tried.

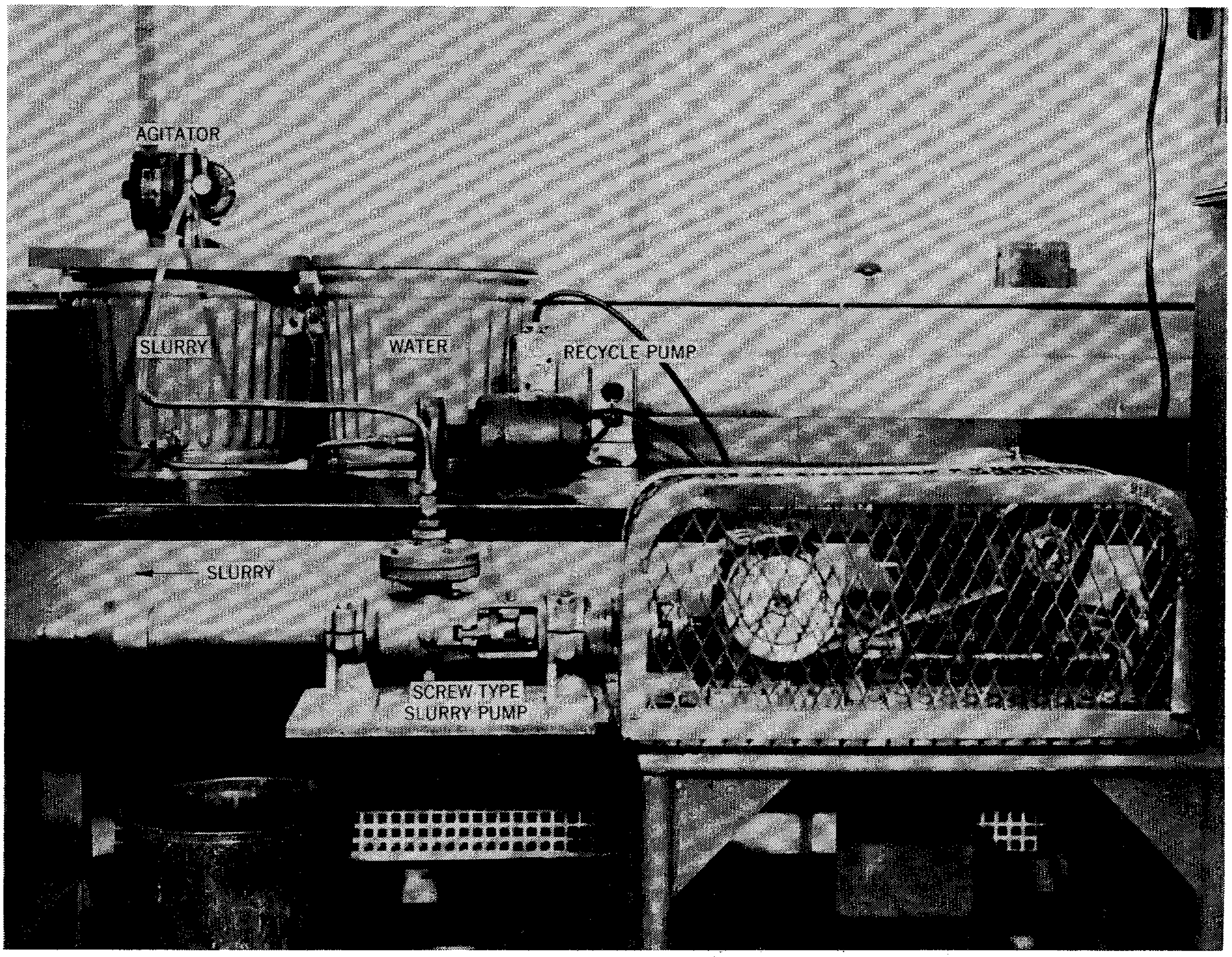

FIGURE 8. - Slurry-Mixing and Pumping Equipment.

The first preheater (fig. 9), a 15-inch-diameter coil made from 26 feet of 3/8-inch-OD type-304 stainless steel tubing, was heated by four silicon carbide heating rods and heated 4 pounds of slurry per hour at 320 p.s.i.g. to 1,000° F. The calculated velocity of the slurry was 0.05 ft./sec.; after vaporization the velocity was more than 30 ft./sec. Salts leached from the coal plugged the tube after about 6 hours. Dissolved solids in water separated from the slurry ran as high as 12,000 p.p.m., even when distilled water was used for the mix. (Bureau researchers had previously experienced this same trouble with a pilot-scale slurry preheater.[12]) Washing the pulverized coal six times decreased the concentration of dissolved solids to 200 p.p.m., but this was not enough to prevent deposition of scale. Increasing the velocity of the steam-coal mixture by increasing the pumping rate to 6-8 lb./hr. failed to correct the difficulty.

[12]Huff, W. R., and Willmott, L. F., Development and Operation of a Pilot Plant for Feeding Bituminous Coal Slurry to a Pressure Gasifier: Bureau of Mines Rept. of Investigations 5719, 1961, 27 pp.

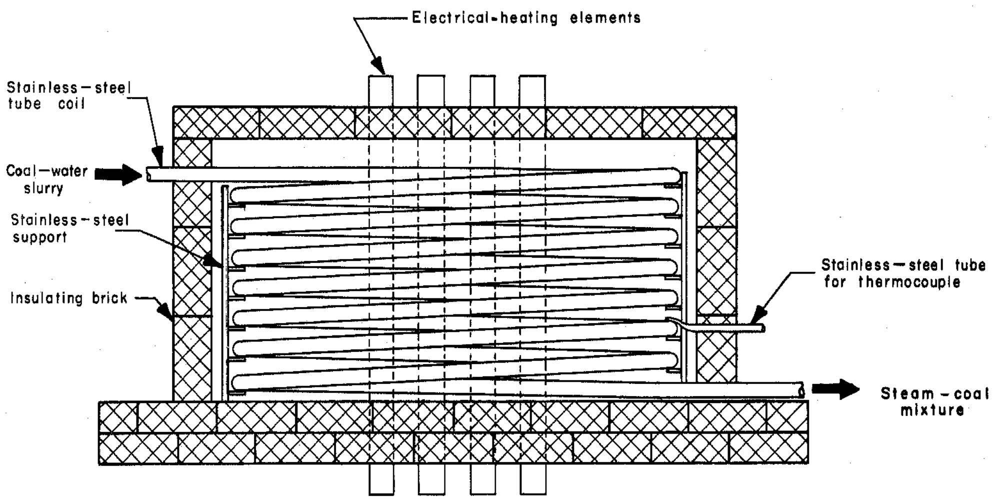

FIGURE 9. - Slurry Preheater With Long-Radius Coil.

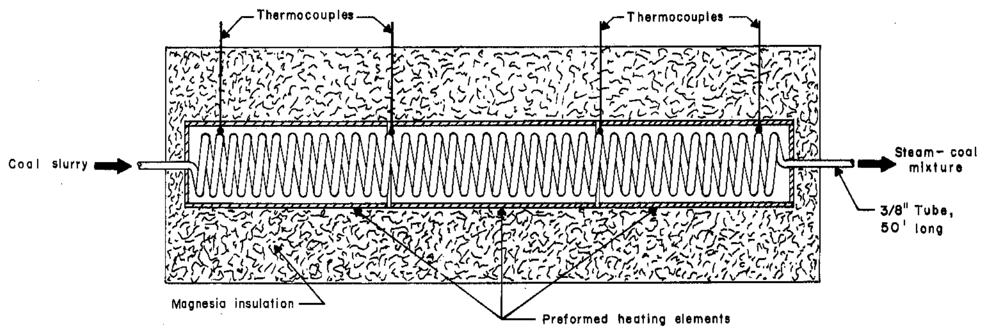

FIGURE 11. - Slurry Preheater With Short-Radius Coil.

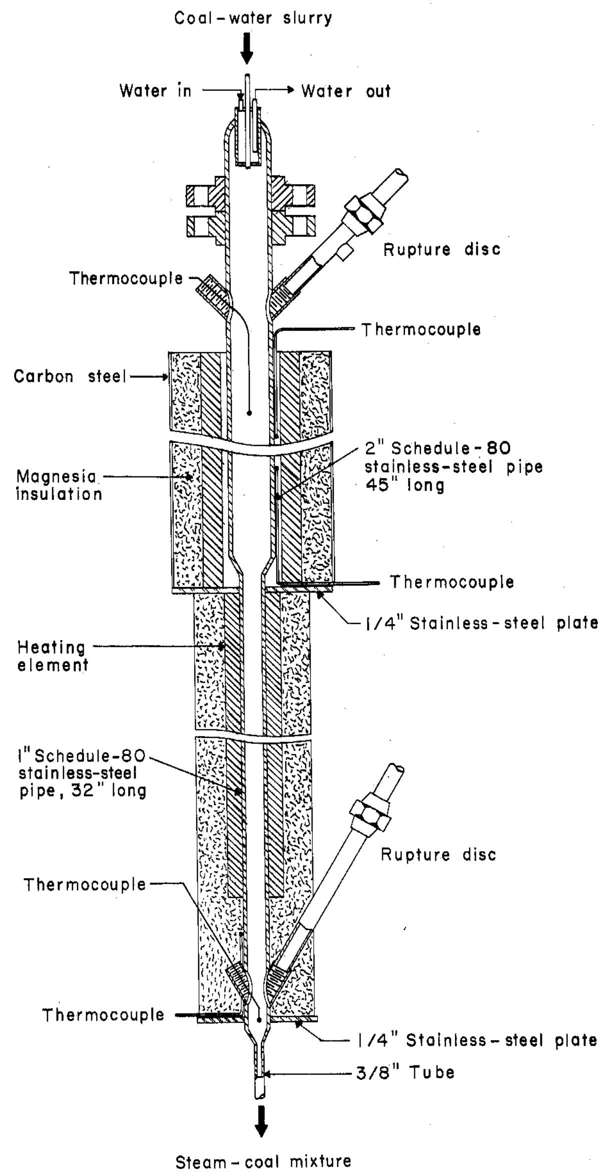

FIGURE 10. - Vertical-Tube Slurry Preheater.

In the next preheater that was tried (fig. 10) the water was flashed into steam about 24 inches from the coal-water inlet as the slurry dropped through the top section of the heater and discharged as steam and partly coked coal from the bottom section at 800° to 1,000° F. This preheater operated satisfactorily as long as 12 hours, but scale invariably plugged the outlet. On one occasion, after the tube had plugged several times, the preheater was dismantled for inspection. The top 24 inches of the flash section was covered inside with a thin layer of coke and scale. The inside of the rest of the preheater appeared clean except for the outlet, which was filled with coke and metallic scale. The presence of metallic scale in the type-304 stainless steel tube indicated temperatures above 1,400° F. Despite the trouble with plugging, this preheater appeared promising. A similar preheater constructed with type-310 stainless steel tube could eliminate scaling.

Another design consisted of two 24-inch long, 3-inch-OD coils (like the one shown in figure 11) in series. Figure 12 is a photograph of these preheaters packed in insulation. The coils were constructed of 3/8-inch OD type-310 stainless steel tubing. The first coil heated the slurry to 400° F. but did not vaporize it; the second coil vaporized and heated the slurry to 1,000° F. The second coil always plugged in considerably less time than the first

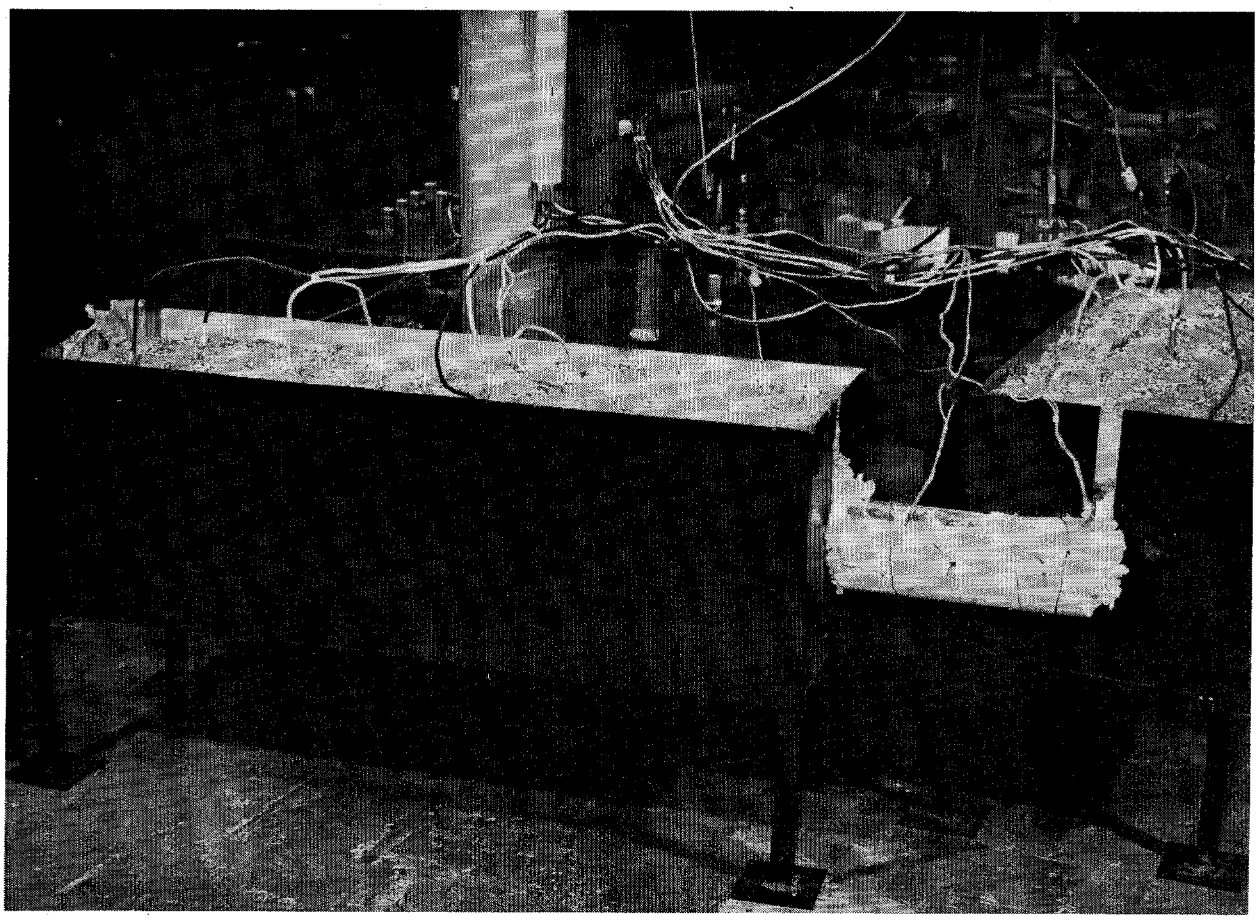

FIGURE 12. - Short-Radius-Coil Slurry Preheater.

preheater made with the 15-inch-diameter coil, usually within about 2-1/2 hours. Greater centrifugal force in the 3-inch-diameter coil may have had a greater tendency to impinge the sticky, semiplastic coal on the wall of the tube.

To determine if centrifugal force was influential in causing the tube to plug, a preheater was constructed with 100 feet of 3/8-inch type-304 stainless steel tubing coiled into a 10-foot-diameter coil. The tube was wrapped with resistance heating wire and insulation, and the temperature gradient along the tube was similar to the gradient maintained along the coils of the preheater shown in figure 12. Slurry was pumped into the tube at 320 p.s.i.g. The velocity of the slurry was 0.05 ft./sec. The velocity of the steam-coal mixture was 30 ft./sec.

Of the several tests made with this preheater, the longest continuous run lasted 12 hours, with the average run lasting about 8 hours. Variations in pressure indicated that many partial plugs formed before complete plugging occurred. In one instance after complete plugging, the coil was cut into sections, and 5 feet of the tubing was found plugged beginning 45 feet from the slurry inlet. The plugged tubing was cut into segments, and the deposit in each segment was removed and analyzed (table 2). Ash from these deposits was consolidated into five samples and analyzed (table 3).

TABLE 2. - Analyses of deposits that plugged the preheater and analyses of the feed coal

Distance from start of plugged section, feet	Proximate,[1] percent			Ultimate,[1] percent		
	Volatile matter	Fixed carbon	Ash	Total carbon	Hydrogen	Sulfur, nitrogen, and oxygen[2]
			Deposits			
0.5	-	-	28.5	55.4	2.9	13.2
1.0	21.0	48.6	30.4	57.0	2.7	9.9
1.5	-	-	13.2	74.2	3.1	9.5
2.0	24.0	62.6	13.4	74.2	3.1	9.3
[3]2.5	36.4	53.5	10.1	73.2	3.3	13.3
3.0	40.0	52.2	7.8	70.7	3.6	17.9
[4]3.5	-	-	7.3	67.4	4.1	21.2
[5]4.0	-	-	13.4	60.9	4.4	21.3
[6]5.0	48.0	45.3	6.7	65.3	4.3	23.7
			Coal fed to preheater[7]			
-	43.6	45.6	10.8	61.8	4.0	23.4

[1]Moisture-free basis.
[2]By difference.
[3]Average tube-wall temperature, 485° F.
[4]Average tube-wall temperature, 470° F.
[5]Average temperature of stream, 340° F.
[6]Average tube-wall temperature, 525° F.
[7]Lignite, Velva mine, Voltaire, Ward County, N.C.

TABLE 3. - Analyses of ash from deposits in the preheater and ash in feed coal[1]

Distance from start of plugged section, feet	SiO_2, percent	Fe_2O_3 and Al_2O_3, percent	CaO, percent	SO_3, percent	MgO, percent	Undetermined, percent
Ash from deposits						
1.0	54.5	14.5	8.2	4.8	3.3	14.7
3.0	21.5	18.4	30.0	6.5	8.9	14.7
4.0	6.8	21.5	41.8	9.6	12.6	7.7
4.5	11.2	[2]46.0	18.3	-	7.2	17.3
5.5	10.6	17.5	39.5	9.0	12.0	1.4
Ash in coal fed to preheater						
-	17.9	23.7	25.0	24.0	6.4	3.0

[1]Moisture-free basis.
[2]Mostly Al_2O_3.

The concentration of ash in the material in the first foot of the plugged section (45 feet downstream from the slurry pump) was 28 to 30 percent, which was higher than the ash content of the material in the last four feet of the plugged section. The ash content was much higher than an ash content from only a plug of coal devolatilized to a char, although charring certainly must have occurred. One foot from the beginning of the plugged section, the volatile matter in the material was about one-half that of the feed coal. The ash in the first foot of the plugged section was high in silica, indicating that siliceous salts were constituents of the material precipitated. Analysis of the ash in the rest of the plugged section showed an increase in calcium and magnesium, and a decrease in silica.

Plugging in the vaporization zone of every preheater indicated that dissolved solids in the slurry water help to cause the trouble, but just how remains unexplained. Failure to develop a successful method for preheating the slurry was a serious limitation to feeding coal in this manner.

Helium-Heated Gasifier

The gasifier is shown in figure 13. The shell is a 69-inch length of 8-inch pipe lined with 3-1/4-inch OD by 3-inch-ID porcelain refractory tube. The gasifier was designed more for quick and easy access than for operating efficiency. Temperatures along the wall of the tube coil (gasifier) are measured by platinum-rhodium thermocouples held by welded clips. The lead wires from the thermocouples pass through fittings mounted on the blind flanges at both ends of the test chamber. Pressure gages are located at each end of the tube coil.

The first tube coil (gasifier) consisted of two concentric coils of 1/4-inch type-310 stainless steel tube. The steam-coal mixture traveled through

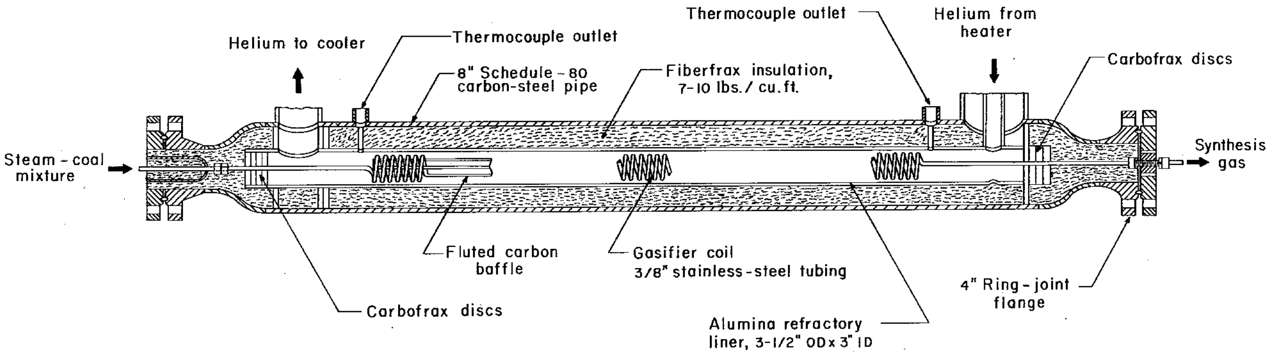

FIGURE 13. - Helium-Heated Coal Gasifier.

the gasifier in the outer coil and then returned to the outlet through the inner coil. The very short radius of the inner coil constricted the 1/4-inch tubing, however, and caused considerable plugging. The single-pass tube coil (gasifier), (fig. 13) was used in all subsequent experiments.

The coil (gasifier), which contains 52 feet of 1/4-inch tubing and is 2-7/8 inches in diameter, performed satisfactorily for 400 hours at a helium temperature of 2,150° F. and steam-coal temperatures up to 1,800° F. Tube-wall temperatures were slightly more than 1,800° F.

Although pressures were approximately equal on each side of the tube wall, unequal pressures would cause the coil to fail from metal creep. For example, in materials-testing experiments the same tubing ruptured in 2 hours at 2,100° F. and 500 p.s.i.g. and in 5 hours at 2,300° F. and 100 p.s.i.g. With balanced pressures, however, the stainless steel tube coil in the gasifier should have a reasonably long operating life at 1,800° F., even with temporary surges in pressure or temperature.

During normal operation, with helium circulating at 20 std. c.f.m., the temperature of the hottest part of the tube coil, near the helium inlet, was about 300° F. less than the inlet helium temperature of 2,150° F. The temperature of the tube coil at the helium exit normally ranged from about 1,040° to 1,170° F. with the helium temperature ranging from 1,090 to 1,270° F. Temperatures as high as 2,500° F. were easily attained in the helium inlet to the gasifier. At 2,500° F., however, the temperature of the tube coil quickly reached 2,200° F.

As indicated previously, the slurry is preheated to 1,000° F. before it is fed to the gasifier. Actually, therefore, the stream entering the tube coil is a mixture of steam, volatile matter, and some form of low-temperature char. During normal gasification at 300 p.s.i.g. the velocity of this mixture in the tube coil ranges from 8 to 11 ft./sec., which corresponds to a residence time of 4.8 to 6.2 seconds at 1,800° F. Apparently, only the volatile matter reacted with the steam as only about 20 to 30 percent of the total carbon in the coal was gasified. Table 4 shows operating data for a typical run. One pound of dry Velva lignite produced 10 to 15 std. c.f. of gas per hour. Table 5 gives a typical analysis of the product gas and an analysis of gas produced in a conventional pressure gasifier.

TABLE 4. - Data from typical run with helium-heated gasifier

Temperatures, ° F.:	
Coal-water slurry to slurry preheater	85
Steam-coal mixture from slurry preheater	940
Wall of gasifier tube-coil:	
Inlet	1,150
Midpoint	1,450
Outlet	1,740
Helium to gasifier	1,880
Helium from gasifier	1,180
Helium from cooler	84
Water to helium cooler	65
Water from helium cooler	82
Product gas to scrubber	780
Pressures, p.s.i.g.:	
Coal-water slurry pump	300
Steam-coal mixture from slurry preheater	300
Gas from gasifier	300
Scrubber	300
Helium loop	310
Process flowrates:	
Helium, std. c.f.m	20
Coal-water slurry,[1] lb./hr	4
Product gas, std. c.f.m	15
H_2O to helium cooler, g.p.h	50
H_2O to scrubber, g.p.h	18

[1] 1 lb. (dry) Velva lignite to 3 lb. water.

TABLE 5. - Typical analyses of gases produced in helium-heated gasifier and conventional pressure gasifier

Gas	Helium-heated gasifier, percent	Conventional pressure gasifier, percent
CO_2	26	12
O_2	1/2	1/2
Ill	1/2	1/2
H_2	60	32
CO	8	50
CH_4	4	1
N_2	1	4
Heating value, B.t.u./std. c.f.	270	300

Normal power input to the heater during gasification was 12.7 kw.-hr., or 43,000 B.t.u./hr. Approximately 5,000 B.t.u. were transferred to the coal-steam mixture, 19,600 B.t.u. were removed by the cooler, and 15,000 B.t.u. were lost by radiation from the loop, leaving about 6,000 B.t.u. unaccounted for.

Product-Recovery Train

The product-recovery train functioned satisfactorily. Synthesis gas, ash, and unreacted coal from the gasifier pass through 10 feet of 1/2-inch pipe that is heated and insulated to prevent tars from condensing before the gas enters the scrubber. Scrubbed gas passes through a 1/2-inch pipe to a wet-test meter and a 3-cubic-foot gasholder.

The scrubber is a 3-foot length of 3-inch pipe. Gas enters through a 1/2-inch pipe that extends almost to the bottom of the scrubber. Gas pressure is controlled pneumatically. A piston-type pump furnishes 13 g.p.h. of water from a constant-level feed tank to the scrubber. Water level in the scrubber is maintained at 12 inches by a pneumatically controlled valve. Effluent water flows to the sewer.

DISCUSSION

The test with the laboratory-scale system indicated that coal can be gasified in a tube heated by helium. Operation for sustained periods, however, depends largely on the development of a satisfactory method of feeding the coal without plugging. Efficiency of the system, as represented by the conversion of carbon into gas, was relatively low--20 to 30 percent. Increased efficiencies should be attainable, however, by improving the heat-transfer rate and increasing the residence time at reaction temperatures. Any future efforts by the Bureau probably will be directed to this end and to developing a successful method for preheating coal-water slurries to 1,000° F.

Because the helium-heated tube coil appears suited for heating other process streams, such as the superheating of steam, investigation is warranted of the applicability of the method beyond the conventional range of superheating.