1113 ELDER JL

THE SECOND UNDERGROUND GASIFICATION EXPERIMENT AT GORGAS, ALABAMA

POOR QUALITY

ORIGINAL

W. III. c.
BM 182
X

Bureau of Mines
Report of Investigations 4808

THE SECOND UNDERGROUND GASIFICATION EXPERIMENT AT GORGAS, ALA.

BY JAMES L. ELDER, M. H. FIES, HUGH G. GRAHAM,
R. C. MONTGOMERY, L. D. SCHMIDT, AND E. T. WILKINS

United States Department of the Interior—October 1951

THE SECOND UNDERGROUND GASIFICATION EXPERIMENT AT GORGAS, ALA.

By James L. Elder, M. H. Fies, Hugh G. Graham, R. C. Montgomery, L. D. Schmidt, and E. T. Wilkins

* * * * * * * * * Report of Investigations 4808

UNITED STATES DEPARTMENT OF THE INTERIOR
Oscar L. Chapman, Secretary
BUREAU OF MINES
James Boyd, Director

Work on manuscript completed May 1951.

October 1951

THE SECOND UNDERGROUND GASIFICATION EXPERIMENT AT GORGAS, ALA.

by

James L. Elder,[1] M. H. Fies,[2] Hugh G. Graham,[3] R. C. Montgomery,[4] L. D. Schmidt,[5] and E. T. Wilkins[6]

CONTENTS

1/ Chief, Underground Gasification Section, Synthetic Liquid Fuels Branch, Bureau of Mines, U. S. Department of Interior, Gorgas, Ala.

2/ Consulting coal mining engineer, Synthetic Liquid Fuels Branch, Bureau of Mines, U. S. Department of Interior; Manager of Coal Operations, Alabama Power Co.; Consulting Mining Engineer, the Southern Co., Birmingham, Ala.

3/ Mining engineer, Underground Gasification Section, Synthetic Liquid Fuels Branch, Bureau of Mines, U. S. Department of Interior, Gorgas, Ala.

4/ Engineer, Gorgas Underground Gasification Project, Alabama Power Co., Gorgas, Ala.

5/ Chief, Synthesis Gas Branch, Bureau of Mines, U. S. Department of Interior, Morgantown, W. Va.

6/ Principal scientific officer, Fuel Research Station, Department of Scientific and Industrial Research, London, England.

CONTENTS (Cont.)

TABLES

TABLES (Cont.)

ILLUSTRATIONS

ILLUSTRATIONS (Cont.)

INTRODUCTION

The Bureau of Mines and the Alabama Power Co. jointly conducted a first experiment in underground gasification of coal at Gorgas, Ala., during the fall and winter of 1946-47. This preliminary experiment7/ showed that it was not difficult to maintain combustion of coal underground, and that coal in place could be completely gasified. It was noted that the high temperature developed by the gasification of coal in place brought about changes in overlying strata that appeared to be favorable to the process. The high temperatures caused the roof rock to become plastic, to expand, and to settle down on the mine floor directly behind the reacting coke face. These results were promising enough to warrant further investigation of the process. It was believed that if this action could be controlled properly with roofs of similar composition, it would tend to force the gas-making fluids underground against the coal faces. Plans for the second experiment were based in part on this favorable roof action, and the successful operation of the planned initial straightline passages depended on this fact.

Gorgas was chosen as the site for the second experiment for the following reasons: A tract of coal land of sufficient size was available and isolated from the main body of coal; the roof rock was similar in composition to that encountered in the first experiment; and the overlying strata were thick enough to eliminate some of the operating difficulties that had been encountered. In addition, power, water, and machine-shop facilities as well as an adequate supply of labor were available in this area, and the friendly cooperation of the Alabama Power Co. further recommended this site for the planned experiment.

In 1948, the Alabama Power Co. entered into a nonprofit contract with the Government whereby, under the supervision of Bureau of Mines' personnel, the company would construct and operate such parts of the project as directed, and the Government would reimburse them for the direct costs incurred. Further, the Gorgas site, including surface area and the underlying coal bed, was provided by the Alabama Power Co. without cost to the Government.

Both the Bureau of Mines and the Alabama Power Co. are interested in underground gasification of coal, the Bureau from the standpoint of developing low-cost processes for manufacturing synthesis gas to produce synthetic liquid fuels as well as the utilization and conservation of natural resources, and the Power Co. from the standpoint of power generation.

In this second underground gasification experiment it was planned to utilize the principles of the "stream method", wherein the gas-making fluids flow past a

7/ Dowd, James J., Elder, James L., Capp, J. P., and Cohen, Paul, Experiment in Underground Gasification of Coal, Gorgas, Ala.: Bureau of Mines Report of Investigations 4164, 1947, 62 pp.

coal face and make contact with it. The exposed face is the full thickness of the coal bed, and, as the carbonaceous material is gasified, the face recedes. It was decided to use a straight-line passage in the coal bed with inlet and outlet connections to gasify the coal exposed, and to advance the combustion of an area by constructing new inlets or outlets off the line of the original passage as needed. Thus, an area would be gasified in roughly triangular increments. This system was dependent on the roof action in an adjacent burned-out increment, so that the blast medium would always be forced against reacting coal faces. The roof action in the first experiment was thought adequate to make this plan applicable. It was decided to use air as a gasification medium, as it was believed that the information obtained would be fundamental and, by using air, the cost of the gas-making fluids would be reduced materially, as compared to using oxygen.

The primary objectives of this second experiment at Gorgas were to extract the energy contained in unmined coal and to obtain fundamental knowledge relating to underground gasification of coal. In particular:

1. To determine the quantity of coal that can be gasified from a given initial combustion zone and the shape and extent of the burned-out area formed by this gasification.

2. To determine the quality and quantity of the air-blow product gas generated at the conditions of the experiment.

3. To determine the operational characteristics of the system as designed and constructed, including such fundamental factors as the optimum length of passage, the optimum rate of fluid flow, and the pressure drop encountered.

4. To obtain information regarding the action of heat on the overlying strata.

5. To obtain fundamental technical and economic information with regard to the choice of plant sites, installations, and operating procedures, including the installation and testing of air inlets and gas outlets, both as vertical boreholes to the coal bed and as stoppings in the coal bed near the outcrop.

SUMMARY AND CONCLUSIONS

The second experiment in underground gasification of coal at Gorgas was operated continuously for 22-1/2 months without any great difficulty. As shown in figure 1, the initial development consisted of 1,100 feet of double entry between borehole II and the entry seal driven horizontally in the coal bed and a single entry 300 feet long connecting borehole II with borehole I. These entries provided a passage for the gas-making fluids along the coal faces. Five large-diameter boreholes on 300-foot centers were drilled from the surface to the entries, and subsequently two additional large-diameter boreholes were drilled near the perimeter of the reacting zone in order to introduce air at the horizon of the coal bed and to remove gas and products of combustion. An air blast of approximately 7,500 c.f.m. usually was employed, but at times a reduced blast rate was used. The operational characteristics of the installation were studied, and records were kept of the volume of air admitted to the system, temperatures at various points underground, and other pertinent data.

One objective was to determine the quantity of coal that can be gasified from an initial opening in the coal bed. During the operation, 10,485 tons of moisture- and ash-free coal was consumed, underlying an area of 83,690 square feet, or 1.92

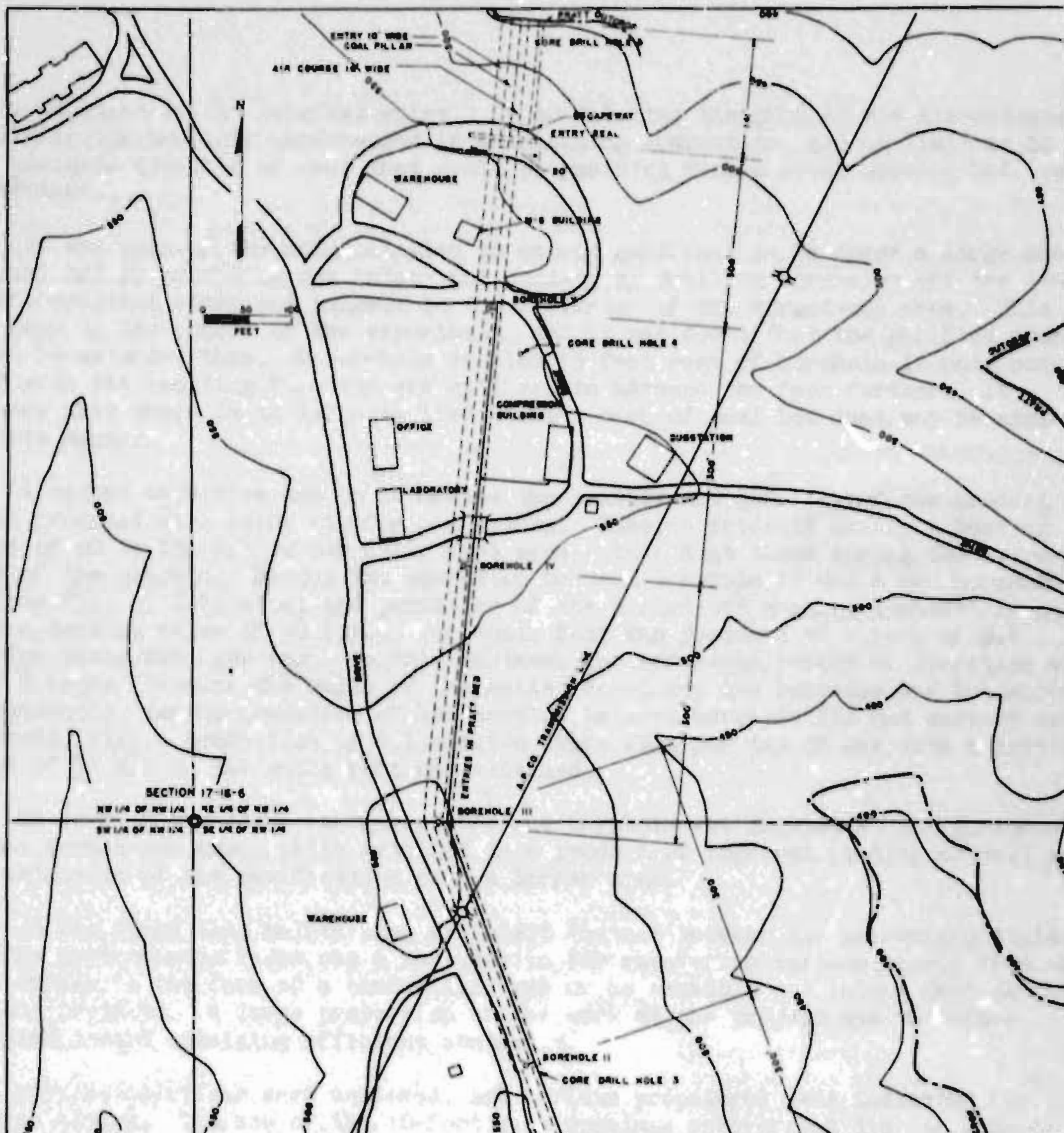


Figure 1. - Plant lay-out; plan of underground gasification project.

acres adjacent to the original entry. Up to the time the project was discontinued, no difficulty had been experienced in maintaining combustion, and no limit as to the ultimate quantity of coal that could be gasified from a given opening had been determined.

It was part of the original plan to extend gasification to cover a large area of coal bed by providing new inlets and outlets by drilling boreholes off the line of the original entry and tangent to the perimeter of the burned-out area. This was done in the course of the experiment, and it was found that the gasified area could be extended thus. A borehole drilled 75 feet east of borehole II made contact with the reacting face and was utilized to advance the face further. It appears that there is no definite limit to the area of coal bed that may be exploited in this manner.

A second objective was to determine the quality and quantity of the product gases produced when using air for combustion. Gaseous products having a heating value of 90 to 150 B.t.u. per cubic foot were obtained at times during the operation of the project. During the operation between borehole II and a new borehole VI (see fig. 6) drilled at the perimeter of the burned-out area, a combustible gas with a heating value of 90 B.t.u. per cubic foot was produced at a rate of 9.4 million cubic feet per day. In this instance the effective period of operation was only 8 hours, because the walls of the outlet fused and the borehole was destroyed. Subsequently, during operation of the section between borehole III and another new borehole, VII, a production of 6.7 million cubic feet per day of gas with a heating value of 72 B.t.u. per cubic foot was attained.

In each of the above instances, the new borehole was drilled at the perimeter of the burned-out area, which resulted in a product of improved quality as well as the extension of the gasification over a larger area.

It was found that maintaining efficient contact between the gas-making fluids and the carbonaceous faces was a perequisite for recovering maximum energy from the coal either in the form of a combustible gas or as sensible and latent heat in the gaseous products. A large proportion of the work at the project was therefore directed toward obtaining efficient contact.

Partial solutions were achieved, and various procedures were indicated for further attack. The use of the 10-foot wide openings underground did not promote efficient contact between the coal faces and the gas-making fluids. The dimensions of the original openings should have been smaller in order to obtain a better product. Some success was achieved in forcing contact between the coal faces and the gas-making fluids by filling void spaces underground with fluidized solids. During periods in which this procedure was used, contact efficiency probably was increased fourfold. Furthermore, utilization of new inlets and outlets near fresh coal faces and off the line of the original underground openings provided better contact. As has been shown in the body of the report, the rate of combustion of coal was increased from 9 to 18 and thence to 30 to 45 tons per day. These increases in the rate of coal consumption paralleled increases in the quality of the gaseous products obtained.

Another purpose of the experiment was to determine the optimum rate of air input for a given system. Consideration of the results obtained and a study of the moisture inflow to the system indicates that the fluid flow must be maintained at such a quantity that the heat losses from the evaporation and dissociation of moisture do not become excessive. No criterion as to the permissable limit of heat loss due to moisture was established, but it is believed that the volume of fluid flow through the system must be maintained large enough so that the heat loss from this cause does not exceed 5 to 15 percent of the heat of combustion of the coal consumed. If the fluid flow was reduced in quantity, the heat loss from this source tended to increase beyond these figures, and an adequate temperature level could not be maintained. During periods of operation when the rate of fluid flow was relatively low. the percentage moisture content of the effluent gases was high, and heat losses from the system were excessive. Under such conditions the operating characteristics of the system deteriorated rapidly.

Heat balances obtained during the operation consistently show maximum energy recovery in the effluent gases during prolonged periods of operation in one direction at the highest air-input rates available at the project. This stands out during a long cycle operation in the course of the period October 5 to December 22, 1949, and during a period when operating between boreholes V and III just before cooling was started. In the first of the above periods, the heat loss to underground strata during prolonged cycles at high discharge temperatures and maximum air-input rates averaged approximately 20 percent, whereas with intermediate air-input rates the loss amounted to 26 percent, and with low input air rates the loss was 36 percent. These figures indicate that high rates of coal consumption and high rates of fluid flow are desirable in underground gasification.

The action of the immediate roof in regions outside the original underground passages where the coal was burned out has not yet been completely assessed. The information available indicates that this roof came down behind the reacting coal faces and tended to force the fluid flow toward the face. It was expected that bloating of the roof rock would completely fill the space where coal had been consumed. Although definite evidence is lacking, there are indications that partial bloating occurred. The gradual increase in back pressure during each of the operating periods shows that the passageways between the inlet and outlet boreholes became more constricted with the time in spite of the fact that the volume of coal consumed increased with time; however, in every instance, holes drilled into the burned-out area admitted air or water and emitted gas. It was evident that in places where the coal was burned out a restricted flow of gas existed. Prolonged exposure of the strata above the coal bed to heat caused cracking and added to the permeability of the burned-out area. In all cases the growth of the burned-out area resulted in deterioration in operating characteristics.

The measured rate of advance in the area between boreholes I and II ranged between 1.25 and 2 inches per day. It was likely that this rate was exceeded in the area between boreholes VII and III; however, the rates here were not measured. Theoretically, the total heat lost to the strata should decrease with increasing rate of advance of the reacting face. The source of heat is the reaction, and, with a higher rate of advance, less total time would be available for heat to penetrate into the rock above and below the coal bed.

The operation at Gorgas indicated that the optimum conditions for underground gasification employing the stream method required high rates of reaction and rapid movement of the coal faces underground in order to minimize heat losses from the system. In addition, the operation consistently indicated that when fresh coal faces were exposed near the inlet or outlets to the system, the best contact efficiency and the best energy recovery, either in the form of a combustible gas or as heat, were obtained.

Studies were made of leakage from the underground system during various periods of operation. These indicate that leakage increased gradually with time up to approximately 50 percent of the total fluid input and remained fairly constant at this figure. There were indications that the increase in leakage was influenced by subsidence of the strata overlying the burned-out region causing cracks through which the gas escaped. Several initial leaks were found in early operations, but these accounted for only a small proportion of the leakage that eventually occurred. The figure of 50 percent was exceeded when higher pressures were placed upon the underground system by closing off or choking the gas outlets. It was possible that long exposure to heat and subsequent drying of strata increased leakage. Further, the applied air pressure could force moisture back into the capillaries of the strata and thus reduce the sealing effect of water.

An objective of the experiment was to determine the optimum length of underground passage that could be used. It was found that quadrupling the surface area of the coal faces initially available increased the rate of consumption of coal by a factor of approximately 2.5. This was based upon a comparison of the operation between boreholes I and II, before any fluidized sand was injected underground, and the operation between boreholes III and V.

Various types of equipment and construction were tested during the experiment. It was found that the installation of a water jacket between the borehole casing and the concrete surface seal was very effective for handling hot gases, and exit boreholes were operable for long periods. Refractory-lined boreholes where hot gases were handled were not superior to unlined boreholes, and the extra cost of using refractories in future installations does not appear justified. Using pressure-grouting techniques in areas surrounding an outlet hole as a means of decreasing porosity of the stratum that was traversed by the opening appears to be advantageous. This technique can be used also in decreasing leakage over limited areas, as the grout will fill horizontal and vertical cracks intercepted by the hole.

The construction of the entry seal was adequate for the service required. Leakage from this seal was not excessive, but a more satisfactory construction calls for inletting the seal to a greater depth in the bottom rock and improving the application of pressure-grouting techniques. The use of supporting brickwork around the base of the boreholes serving as inlets and outlets might help in prolonging the life of the openings in question, however, there was little difference between the service obtained at borehole VII, where it was not possible to use this construction, and the service of the brick-supported boreholes, I to V.

The technical feasibility of a process must first be proved by experiment and trial before a definite economic evaluation can be made. Processes for the underground gasification of coal are still in the experimental stages, but several results that appear to be favorable from an economic viewpoint have been obtained. The quantity of coal that can be gasified from an initial opening in the coal bed is presumably limited, but to date no definite limit has been reached. More than 5,000 tons of coal from a bed 42 inches thick have been gasified from the ribs of an initial 300-foot entry in the coal bed. It has been possible to enlarge the area of coal consumed by constructing new inlets/outlets near the combustion faces. The energy of the coal can be brought out of the ground as sensible and latent heat of the effluent gases, and qualitatively it has been shown that this energy can be utilized in a gas turbine. Combustible gases can be produced underground on the coal ribs, but inadequate control of contact between the carbon faces and the gas-making fluids has so far prevented obtaining this gas above ground for more than a few days at a time.

Installations for the underground gasification of coal can be intended for any of the following three uses:

1. Complete combustion of coal underground with air, and utilization of the heat energy in gas turbines or in raising steam. By this method an over-all thermal efficiency from coal consumed to electric power generated should run from 15 to 20 percent of the heat of combustion of the coal. This may be compared to the operation of a steam-generating power plant using 1 pound of coal for the production of 1 kilowatt-hour, plus the mining of the coal wherein 1 pound is left underground for every pound produced. Here the over-all thermal efficiency is approximately 12.5 percent.

2. The production of producer gas by gasification of the coal with air and utilization of the combustible gas in gas turbines, for raising steam or for other applications requiring heat located near the pit mouth. To date a continuous supply of gas has not been produced because of loss of efficient contact.

3. The production of synthesis gas by gasification of the coal with oxygen and steam and the subsequent utilization of the gas in the manufacture of synthesis liquid fuels or organic chemicals. No experiments were made with an oxygen-steam blast during the second Gorgas experiment. It may be possible that this method will be more generally satisfactory than (2) because of the high rates of combustion and consequent high temperature levels that should result.

A new installation is being constructed at Gorgas for additional investigation of the process of underground gasification. The American bed, which lies under the Pratt in this area, will be gasified, and an electrical system of connecting inlets/outlets in the coal bed will be tried. The additional cover over the American bed and the greater distances to its outcrops should aid in preparing a system that will be much tighter with respect to gas leakage. The electrical system of connecting inlets/outlets should reduce site-development costs greatly and eliminate all underground labor. It will also result in the preparation of a high-temperature fuel bed at the beginning of gasification operations and reduce the time to heat a new system. Several geometrical changes will be made in the shape of the underground passages in an effort to increase contact efficiency and improve control of the system.

ACKNOWLEDGMENTS

The authors wish to express their appreciation of the assistance and cooperation given by the following: Dr. A. C. Fieldner, chief fuels technologist, formerly chief of the Fuels and Explosives Division, and Dr. W. C. Schroeder, chief of the Synthetic Liquid Fuels Branch, each of the Bureau of Mines, who took an active part in planning and organizing the work carried out at the Gorgas project. T. W. Martin, chairman of the Board, and J. M. Barry, president, of the Alabama Power Co., were extremely cooperative in placing the facilities of the company at the service of the Bureau in conducting this work. H. M. Johnstone, manager of the Gorgas Mines of the Alabama Power Co., materially aided with the construction, operation, and maintenance of the project. J. P. Capp, W. H. Eddy, J. R. Gray, and M. C. Slone, of the Bureau of Mines, and W. L. Ruckes, W. J. Lough, G. C. Woods, and J. H. Wakefield, of the Alabama Power Co., aided technical planning of the operation or acted as shift supervisors. H. M. Cooper, W. A. Selvig, and L. A. Turnbull, all of the Central Experiment Station, Bureau of Mines, Pittsburgh, Pa., respectively supervised the analysis of the coal samples, the rock and ash samples, and aided in planning the

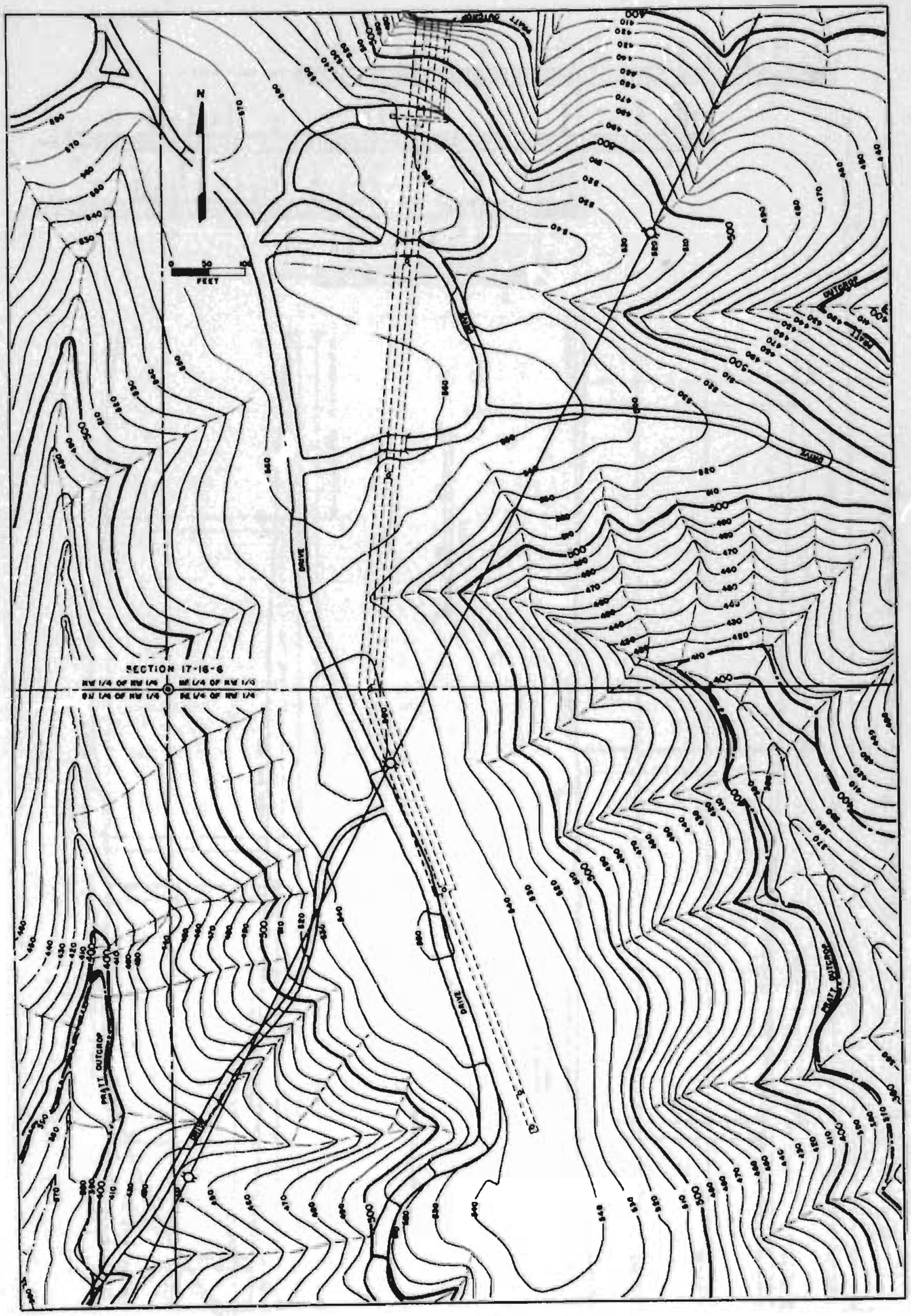


Figure 2. - Topographic map.

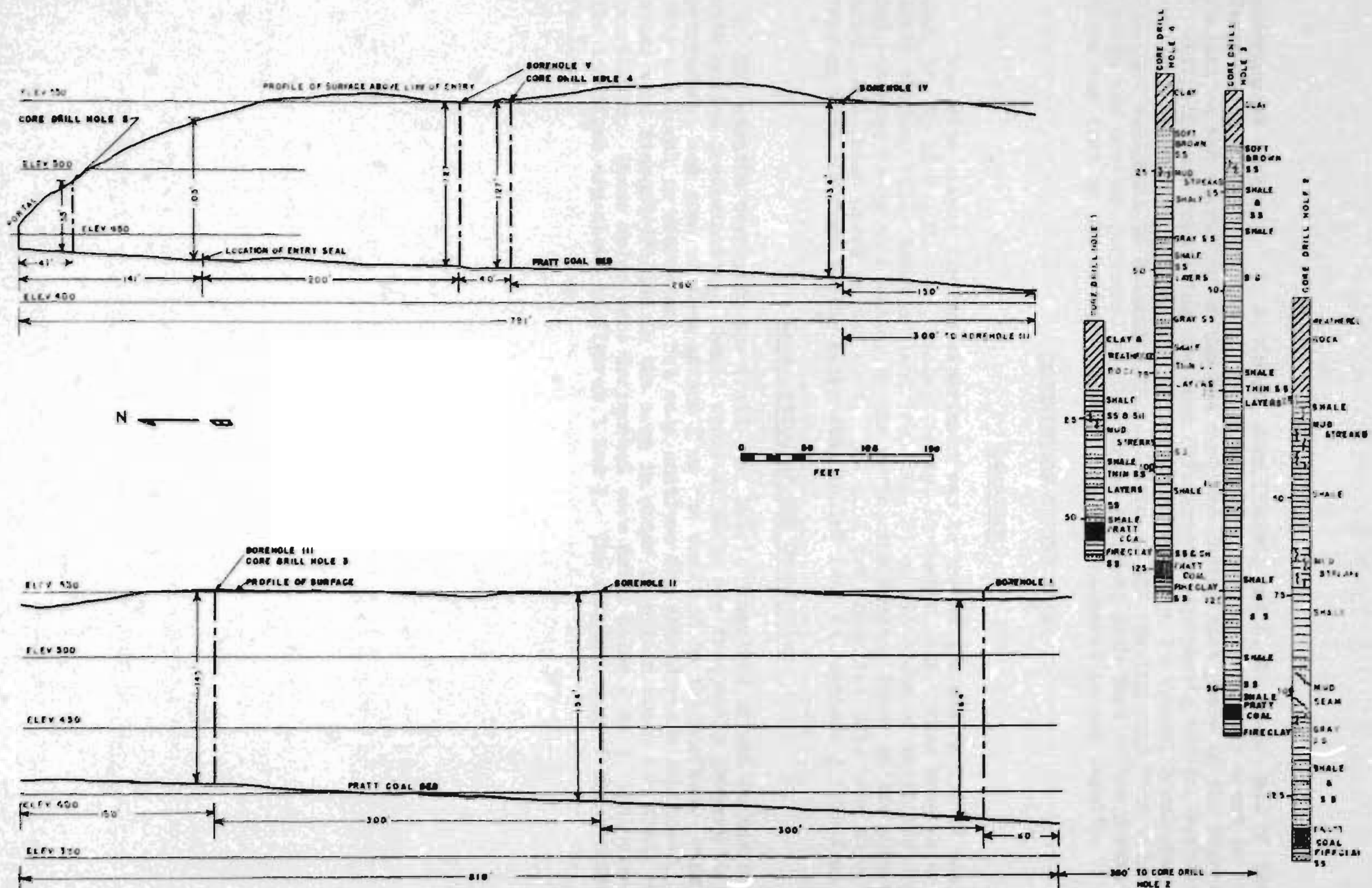


Figure 3. - Profile of site and core-drill log.

underground workings. J. P. McGee, John Holden, and A. E. Sands, all of the Morgantown, W. Va., station of the Bureau of Mines, respectively aided in the installation and operation of the gas turbines during that phase of the experiment, in designing and installing the sand fluidization equipment, and in organizing and training laboratory personnel. The Southern Research Institute, Birmingham, Ala., designed equipment to determine the location of the burning coal face underground. Thanks are due the personnel at the Gorgas project, both that of the Bureau of Mines and that of the Alabama Power Co. for its cooperation and loyalty.

DESCRIPTION OF THE AREA

Location

The site chosen for the experiment was in the NE 1/4 and SE 1/4 of the NW 1/4, sec. 17, T. 16 S., R. 6 W., Walker County, at Gorgas, Ala. This area is an irregularly shaped, hilly tract of land (see fig. 2) on all sides of which the Pratt coal bed outcrops owing to a valley on the north, the Warrior River on the east and south, and Baker Creek on the west. The coal bed underlies this area at a depth ranging from 100 feet at the entry seal to 162 feet at borehole I (see fig. 3).

Description of the Overburden

The stratum overlying the Pratt coal bed is comprised of shales and sandstones, with shales predominating. Small vertical slips are frequently present in the overburden, and some of them extend from the coal bed to the surface. Generally they are local in character, but some continue for considerable distances. Four holes were diamond-drilled in the area in order to obtain cores for study of the overburden. These holes were designated core drill holes 2 to 5, inclusive, and the locations are shown in figures 1 and 3. The complete log of these holes follows:

LOGS

Hole 2

Depth From- Ft.	Depth From- In.	Depth To- Ft.	Depth To- In.	Thickness Ft.	Thickness In.	Material
0	0	24	0	24	0	Soft brown sandstone.
24	0	91	9	67	9	Shale.
91	9	92	6	0	9	Sandy shale.
92	6	102	0	9	6	Weathered shale.
102	0	107	9	5	9	Broken shale and sandstone.
107	9	112	0	4	3	Gray sandstone with shale streaks.
112	0	121	11	9	11	Sandy shale.
121	11	124	3	2	4	Sandstone with shale streaks.
124	3	131	8	7	5	Dark shale.
131	8	133	7-1/2	1	11-1/2	Sandy shale.
133	7-1/2	134	3-1/2	0	8	Coal.
134	3-1/2	134	5-1/2	0	2	Bone.
134	5-1/2	137	5-1/2	3	0	Coal.
137	5-1/2	137	6-1/2	0	1	Bone.
137	6-1/2	138	4-1/2	0	10	Fire clay.
138	4-1/2	138	6	0	1-1/2	Bone.
138	6	140	8	2	2	Shale.
140	8	141	6	0	10	Sandstone with black streaks.

Hole 3

Depth From- Ft.	Depth From- In.	Depth To- Ft.	Depth To- In.	Thickness Ft.	Thickness In.	Material
0	0	14	0	14	0	Red clay.
14	0	16	0	2	0	Soft brown sandstone.
16	0	32	0	16	0	Dark-gray sandstone with thin shale streaks.
32	0	41	0	9	0	Gray sandy shale.
41	0	56	0	15	0	Dark-gray sandstone with thin shale streaks.
56	0	61	0	5	0	Fine-grain light-gray, sandy shale.
61	0	80	6	19	6	Light-gray, sandy shale.
80	6	100	9	20	3	Gray shale, slightly sandy.
100	9	143	8	42	11	Sandy shale with streaks of gray sandstone.
143	8	148	4	4	8	Dark shale.
148	4	149	6	1	2	Gray sandstone.
149	6	150	2	0	8	Dark shale.
150	2	154	7	4	5	Sandy shale.
154	7	155	2-1/2	0	7-1/2	Coal.
155	2-1/2	155	4-1/2	0	2	Bone.
155	4-1/2	158	3	2	10-1/2	Coal.
158	3	158	4	0	1	Bone.
158	4	160	0	1	8	Blue shale.
160	0	161	11	1	11	Blue shale.
161	11	163	4	1	5	Gray sandstone with thin streaks of shale.

Hole 4

Depth From- Ft.	Depth From- In.	Depth To- Ft.	Depth To- In.	Thickness Ft.	Thickness In.	Material
0	0	14	0	14	0	Clay and dirt.
14	0	20	0	6	0	Soft brown sandstone.
20	0	23	4	3	4	Gray sandstone.
23	4	26	2	2	10	Very soft brown sandstone.
26	2	32	9	6	7	Sandy shale.
32	9	33	5	0	8	Gray sandstone.
33	5	35	3	1	10	Dark shale with sand streaks.
35	3	35	5	0	2	Gray sandstone.
35	5	41	6	6	1	Dark shale with sand streaks.
41	6	42	9	1	3	Gray sandstone with shale streaks.
42	9	43	9	1	0	Sandstone.
43	9	52	9	9	0	Sandy shale.
52	9	61	1/2	8	3-1/2	Shale with sandstone streaks.
61	1/2	62	5	1	4-1/2	Gray sandstone.
62	5	71	9	9	4	Dark shale with sandstone streaks.
71	9	81	6	9	9	Shale with sandstone streaks.
81	6	91	5	9	11	Blue shale with sandstone streaks.
91	5	95	10-1/2	4	5-1/2	Blue shale with sandstone streaks.
95	10-1/2	96	8	0	9-1/2	Sandstone.
96	8	98	11	2	3	Blue shale with sandstone streaks.
98	11	99	11	1	0	Sandstone.
99	11	101	2	1	3	Blue shale with sandstone streaks.
101	2	111	1	9	11	Shale with sandstone streaks.
111	1	115	9	4	8	Shale with sandstone streaks.
115	9	120	5	4	8	Dark shale.
120	5	120	10	0	5	Gray sandstone.
120	10	122	8	1	10	Sandy shale.
122	8	123	4	0	8	Coal.
123	4	123	7	0	3	Bone.
123	7	126	6	2	11	Coal.
126	6	127	6	1	0	Shale.
127	6	129	8	2	2	Sandy shale.
129	8	132	4	2	8	Sandstone.

Hole 5

Depth From- Ft.	Depth From- In.	Depth To- Ft.	Depth To- In.	Thickness Ft.	Thickness In.	Material
0	0	10	0	10	0	Overburden and brown sandstone.
10	0	17	10	7	10	Weathered sandstone.
17	10	22	9	4	11	Shale.
22	9	24	0	1	3	Blue shale.
24	0	29	10	5	10	Shale with sandstone streaks.
29	10	32	7	2	9	Blue shale.
32	7	33	5	0	10	Shale.
33	5	41	10	8	5	Shale with sandstone streaks.
41	10	47	2	5	4	Black shale.
47	2	48	10	1	8	Sandstone with shale streaks.
48	10	51	6	2	8	Sandy shale.
51	6	52	2	0	8	Coal.
52	2	52	4	0	2	Bone.
52	4	55	4	3	0	Coal.
55	4	58	8	3	4	Shale.
58	8	60	7	1	11	Sandy shale.

Geology

The coal measures of Alabama occur in the Pottsville formation of the Pennsylvania period. The rocks associated with the coal beds are shales and sandstones. At the experimental site, the core-drill records show relatively few thin beds of sandstones interspersed with the predominating shales. Bedding planes are parallel, and there are no faults or unconformities at the site. Visual inspection of core samples (see fig. 3) show the shale to be closely laminated, of an invisible grain size, and a dark slaty color. The sandstones are strong and are not laminated; they have sharply defined upper and lower bed faces, a fine visible grain structure, and a light-gray color. A concentration of sandstone beds is noted between 20 and 40 feet above the Pratt coal. Another such concentration appears 20 to 35 feet below the surface at the hill top.

Laboratory permeability tests were made on core samples of roof rock. The results of these tests are given below:

Type of rock	Permeability	Distance above top of coal bed
Sandstone	Impervious	1 ft. 11 in.
do.	do.	2 ft. 0 in.
do.	do.	2 ft. 1 in.
Shale	do.	2 ft. 5 in.
do.	do.	2 ft. 7 in.
do.	do.	2 ft. 8 in.
do.	do.	2 ft. 11 in.
do.	do.	3 ft. 1 in.

Siderite ($FeCO_3$) was found in the bottom rock, 1 foot 7 inches and lower, below the coal bed, and 6 feet 11 inches and higher in the rock above the coal bed. This mineral occurred as bands less than 1/2 inch thick and as nodules embedded in shale.

In general, the rocks are only fairly resistant to erosion and thereby contribute to the topography of the region, which is that of a dissected peneplain. It is characterized by steep-sided, narrow ravines and gullies. The hilltops are relatively flat, and weathering of the surface rocks on them has progressed to a depth of approximately 25 feet. The hilltops lie at an elevation of 500 to 600 feet above sea level, and the base of erosion is the Warrior River, which at Gorgas is approximately 250 feet above sea level.

Where the stratum along hillsides has been exposed by excavation, numerous mud seams can be seen. These are joint planes that have been opened by slumping of the hillside and refilled by deposited clayey material. The mud seams offer little restriction to the flow of fluids. Although several mud seams were encountered in core-drill holes 2 and 5, on the hillsides, no cracks whatever were observed in cores from core-drill holes 3 and 4 below the limits of weathering. This fact led to the assumption that the stratum back from the outcrops and under cover 50 or more feet thick was undisturbed and should prove relatively gas-tight.

Description of the Coal Bed

The Pratt bed dips approximately 1°55' in the direction a little east of south. In this area the coal ranges in thickness from 40 to 44 inches. Vertical face cleats in the coal are closely spaced, averaging 20 cleats to the foot and running S. 50° W. Starting at the top, the coal bed can be described as follows:

Inches	
7	Bright coal
2	Bone
7	Coal
1/2	Bone or fusain
24	Coal with streaks of bone or fusain

Analysis of the Coal

Standard channel samples of the coal were obtained at five locations within the experimental mine and were sent to the Central Experiment Station of the Bureau of Mines for analysis. The coal is high-volatile A bituminous, rated as "good coking." The analyses are given in table 1.

Two benched channel samples were obtained from the mine, and the analyses given in table 2 show that the maximum sulfur concentration occurs in the top benches of the coal bed.

In one instance the forms of sulfur in the coal were determined, and these results are given in table 3.

Analyses of samples taken of the immediate floor and roof at various locations in the gasification mine are given in table 4.

Laboratory Test of Roof Rock

In addition to the analyses of the roof rock given in table 4, additional tests were made to determine the effect of heat on this material. When a sample was heated to 2,400° F., a considerable degree of expansion occurred, but there was no evidence of flowing. Heating another sample to 1,500° F. and holding it at this temperature for 30 minutes resulted in a decrease in weight of approximately 0.6 percent and an increase in volume of 1.7 percent. The test samples at temperatures up to 2,400° F. gave a permanent expansion, and there was no evidence of cracking or crumbling in the small test pieces. The large sample from which the test specimens were obtained showed some evidence of cracking along the bedding planes during handling, presumable due to drying.

A small diamond-drill core sample of roof rock was tested by mounting in a refractory shell about 1-3/4 inches thick and placed on top of a gas furnace in such a way that the bottom surface of the roof sample was exposed to the full furnace temperature. The furnace temperature was raised to 2,080° F. over a period of 2-1/2 hours. A few chips were observed cracking loose from the bottom of the sample when the temperature reached 2,100° F. As the temperature was increased, a larger chip was dislodged. When the temperature reached 2,375° F., the bottom of the sample fused, and no further changes were noted. In general, this sample of roof rock withstood high temperature better than did a large slab that was tested prior to the first experiment[8/], under similar conditions except for size of the sample.

8/ Work cited in footnote 7.

TABLE 1. - Chemical analysis of Pratt-bed coal, underground gasification mine

Laboratory No.	Condition[1/]	Proximate, percent: Moisture	Proximate, percent: Volatile matter	Proximate, percent: Fixed carbon	Ultimate, percent: Ash	Ultimate, percent: Hydrogen	Ultimate, percent: Carbon	Ultimate, percent: Nitrogen	Ultimate, percent: Oxygen	Ultimate, percent: Sulfur	Calorific value, B.t.u.	Fusibility of ash, temperature, °F.: Initial deformation	Fusibility of ash, temperature, °F.: Softening	Fusibility of ash, temperature, °F.: Fluid	Real specific gravity
D-13570[2/]	1	5.3	32.2	53.3	9.2	5.3	72.5	1.6	10.1	1.3	13,010	2,520	2,650	2,710	1.34
	2	-	34.0	56.3	9.7	5.0	76.5	1.7	5.8	1.3	13,740				
	3	-	37.6	62.4	-	5.5	84.7	1.8	6.5	1.5	15,210				
D-13571[2/]	1	4.0	31.9	50.6	13.5	5.0	69.1	1.4	9.3	1.7	12,420	2,470	2,620	2,780	1.38
	2	-	33.2	52.8	14.0	4.8	72.0	1.5	5.9	1.8	12,930				
	3	-	38.6	61.4	-	5.6	83.7	1.7	7.0	2.0	15,040				
D-13572[2/]	1	2.2	32.7	52.6	12.5	5.0	71.5	1.5	7.4	2.1	12,850	2,420	2,520	2,700	1.37
	2	-	33.4	53.8	12.8	4.9	73.1	1.6	5.5	2.1	13,130				
	3	-	38.3	61.7	-	5.6	83.8	1.8	6.4	2.4	15,050				
D-13573[2/]	1	4.1	31.9	54.0	10.0	5.2	72.8	1.6	8.8	1.6	13,020	2,520	2,610	2,780	1.35
	2	-	33.3	56.2	10.5	5.0	75.9	1.6	5.3	1.7	13,590				
	3	-	37.2	62.8	-	5.5	84.8	1.8	6.0	1.9	15,170				
D-13574[2/]	1	2.6	33.6	54.8	9.0	5.2	75.2	1.6	7.3	1.7	13,490	2,420	2,570	2,590	1.33
	2	-	34.5	56.3	9.2	5.1	77.1	1.7	5.2	1.7	13,850				
	3	-	38.0	62.0	-	5.6	85.0	1.8	5.7	1.9	15,250				

1/ 1. Sample as-received; 2. Dried at 105° C.; 3. Moisture- and ash-free.
2/ Location of coal samples (see fig. 1). D-13570, 58 ft. northwest of borehole I on left rib.
D-13571, 50 ft. northwest of borehole II on left rib of air course. D-13572, 50 ft. north of borehole III on left rib of air course.
D-13573, 49 ft. north of borehole IV on left rib of air course. D-13574, 50 ft. north of borehole V on left rib of air course.

TABLE 2. - Chemical analysis of benched channel samples of Pratt-bed coal, underground gasification mine

Laboratory No.	Bench[1/] reading from top of bed, thickness in inches	Proximate, percent: Moisture	Proximate, percent: Volatile matter	Proximate, percent: Fixed carbon	Ultimate, percent: Ash	Ultimate, percent: Hydrogen	Ultimate, percent: Carbon	Ultimate, percent: Nitrogen	Ultimate, percent: Oxygen	Ultimate, percent: Sulfur	Calorific value, B.t.u.	Fusibility of ash, temperature, °F.: Initial deformation	Fusibility of ash, temperature, °F.: Softening	Fusibility of ash, temperature, °F.: Fluid	Real specific gravity
D-13576[2/]	6	1.6	35.1	50.1	13.2	5.1	70.5	1.5	6.7	3.0	12,820	2,100	2,280	2,540	1.38
D-13577[2/]	2	3.7	15.3	22.3	58.7	-	28.2	-	-	1.0	-	2,840	2,890	2,910	+ 2.00
D-13578[2/]	7	2.0	34.7	53.4	9.9	5.2	73.9	1.6	7.8	1.6	13,350	2,710	2,760	2,820	1.35
D-13579[2/]	19	2.2	36.0	58.2	3.6	5.5	79.8	1.7	7.9	1.5	14,380	2,230	2,340	2,750	1.30
D-13580[2/]	8	2.8	33.8	53.7	9.7	5.2	74.0	1.6	7.9	1.6	13,290	2,260	2,520	2,600	1.35
Total	42														
D-13581[2/]	9	1.7	34.8	51.6	11.9	5.1	71.4	1.6	5.9	4.1	13,100	1,940	2,050	2,490	1.37
D-13582[2/]	2	2.7	17.3	29.3	50.7	-	36.9	-	-	1.0	-	2,760	2,860	2,910	+ 1.86
D-13583[2/]	7	2.4	32.8	52.2	12.6	5.0	70.8	1.5	7.1	3.0	12,800	2,080	2,470	2,570	1.39
D-13584[2/]	1	2.9	14.7	24.2	58.2	-	30.3	-	-	.2	-	2,800	2,870	2,910	+ 1.96
D-13585[2/]	19	2.0	34.8	58.8	4.4	5.5	79.8	1.7	7.2	1.4	14,310	2,230	2,360	2,600	1.30
D-13586[2/]	6	3.1	33.3	53.2	10.4	5.2	73.1	1.6	8.3	1.4	13,150	2,380	2,550	2,750	1.35
Total	44														

1/ Sample as-received.
2/ Location of coal samples (see fig. 1), D-13576 to D-13580, inclusive, 42 ft. north of borehole II on left rib of air course.
D-13581 to 13586, inclusive, 48 ft. north of borehole IV on left rib of air course.

TABLE 3. - Sulfur forms found in Pratt-bed coal, underground gasification mine

Laboratory No.	Condition 1/	Sulfur forms, percent			
		Sulfate	Pyritic	Organic	Total
C-97398 2/	1	0.01	0.58	0.50	1.09
	2	.01	.59	.51	1.11
	3	.02	.72	.61	1.35

1/ 1, Sample as-received; 2, dried at 105° C.; 3, moisture- and ash-free.
2/ Drill core, hole 3; this core was obtained at the exact location of borehole 11 (see figs. 1 and 3).

Site Preparation

Locating the Pratt Coal Outcrop

In the spring of 1948, a bulldozer was used to uncover the Pratt coal outcrop in the immediate vicinity of the project to aid in determining the best location available for the underground workings. The uncovering of the outcrop and the data from the diamond-drill holes established the continuity of the Pratt coal bed and showed that it was completely isolated from the main body of coal. It was the general opinion of all concerned that complete isolation of the body of coal that was to be utilized was desirable, although no difficulty was anticipated with respect to extinguishing the fire.

CONSTRUCTION

Access Roads and Buildings

After uncovering the coal outcrop, the bulldozer was used for clearing the land on top of the hill so that the necessary office, laboratory, and storage buildings, could be erected and the equipment installed. Access roads were built from the project site to the public highways leading to the Gorgas Steam Plant.

A prefabricated-steel office building, laboratory, and warehouse were built. Wood-frame buildings with galvanized sheet-steel siding were erected to house the compressor equipment and for instrument houses, pump house, and additional warehouse space.

Mining

Figure 1 shows the plan of the underground openings. The outcrop at the north end of the project was faced up with a bulldozer, and an entry and air course were driven 10 feet wide each and separated by a 10-foot coal pillar. The coal was drilled, shot without undercutting, and hand-loaded into chain-and-flight conveyors, which were extended between move-ups by 6-foot lengths until their maximum length of 300 feet was reached. A 30-inch belt conveyor was installed, and the chain-and-flight conveyors were loaded directly on the belt. The belt was extended as required and led directly into a bin (see fig. 4) at the outcrop. The coal was loaded directly from the bin into trucks. During mining an average advance of 20 feet per shift was achieved in each entry.

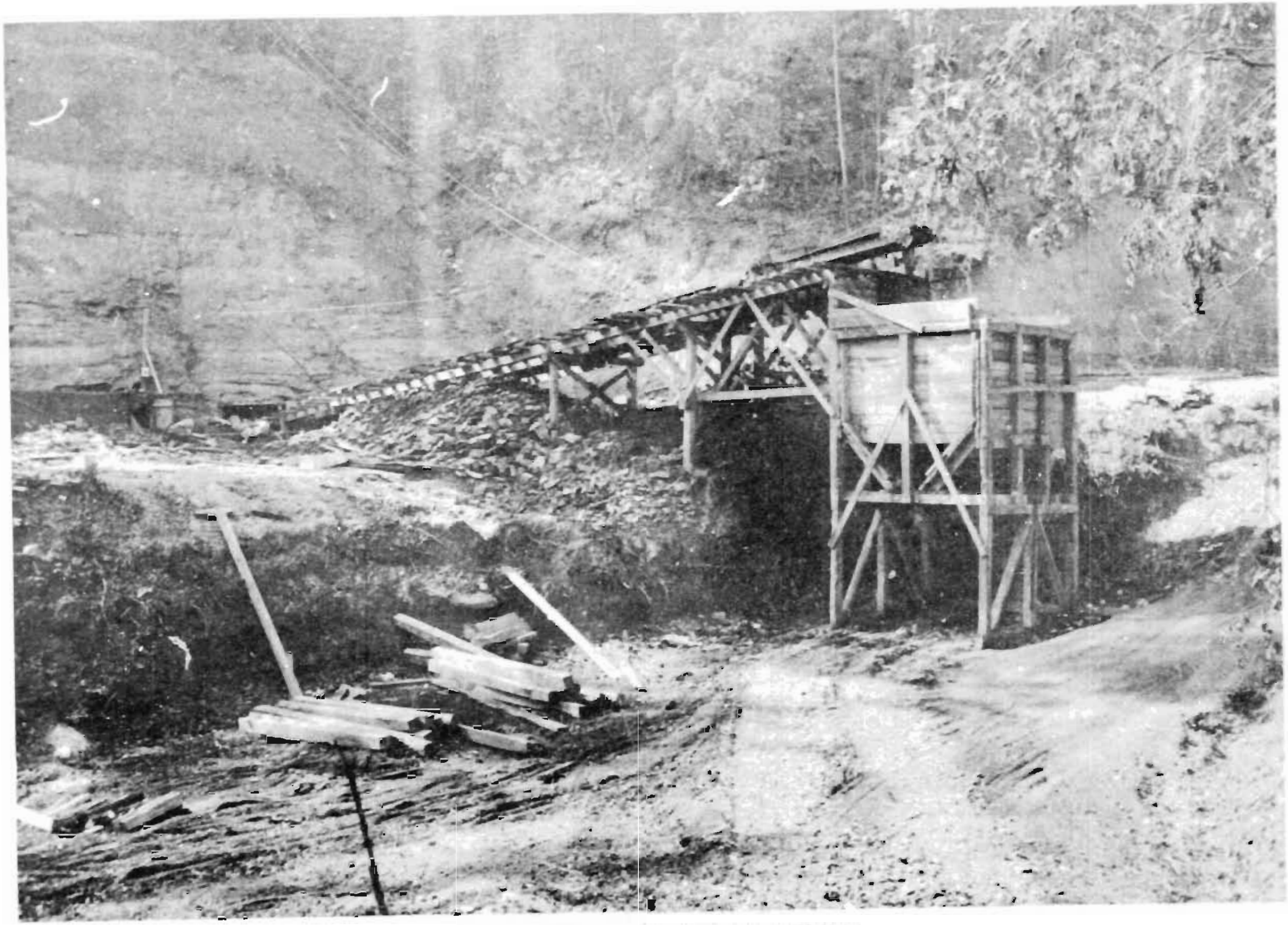


Figure 4. - Mine portal, conveyor, and line.

TABLE 4. - Chemical analysis of immediate roof and floor adjacent to Pratt-bed coal, underground gasification mine

Laboratory No.	Roof samples1/					Floor samples1/	
	D-13589	D-13590	D-13591	D-13592	D-13593	D-13587	D-13588
Real specific gravity	2.69	2.53	2.71	2.65	2.64	2.60	2.67
Proximate2/, percent:							
Moisture	2.0	1.2	1.3	1.7	1.2	2.5	.7
Volatile matter	6.6	9.0	6.7	6.5	5.4	8.0	6.9
Fixed carbon	.1	9.1	.7	2.2	1.5	1.9	.1
Ash	91.3	80.7	91.3	89.6	91.9	87.6	92.3
Ultimate2/, percent:							
Ash	91.3	80.7	91.3	89.6	91.9	87.6	92.3
Carbon	1.7	9.6	1.9	3.1	2.7	4.5	1.8
Sulfur	.1	7.0	1.2	2.3	1.1	.3	.1
Analysis of ash:							
Loss on ignition at 800°C.	.2	.1	.3	.3	.1	.3	.2
SiO_2	64.2	67.9	62.4	66.2	72.9	61.3	61.9
$Al_2O_3$3/	21.8	13.2	22.1	19.6	16.0	25.6	25.2
Fe_2O_3	7.0	14.2	7.8	7.1	5.9	5.5	5.5
CaO	.5	1.0	.5	.3	.4	.3	.3
MgO	2.0	1.0	2.0	1.6	1.4	2.2	2.2
SO_3	.2	.5	.3	.3	.2	.2	.2
$Na_2O + K_2O$4/	4.1	2.1	4.6	4.6	3.1	4.6	4.5
Fusibility of ash, temperature, °F.:							
Initial deformation	2,360	2,130	2,320	2,310	2,310	2,380	2,360
Softening	2,450	2,210	2,460	2,450	2,470	2,550	2,550
Fluid	2,590	2,590	2,610	2,700	2,680	2,800	2,800

1/ Location of samples (see fig. 1): D-13589, 59 ft. northwest of borehole I, 10 in. of roof rock sampled. D-13590, 50 ft. north of borehole II, 10 in. of roof rock sampled. D-13591, 50 ft. north of borehole III, 10 in. roof rock sampled. D-13592, 50 ft. north of borehole IV, 13 in. of roof rock sampled. D-13593, 50 ft. north of borehole V, 11 in. roof rock sampled. D-13587, 50 ft. northwest of borehole II, floor rock sample from 0 to 6 in. D-13588, 50 ft. northwest of borehole II, floor rock sample from 6 to 12 in.

2/ Sample as received.

3/ The Al_2O_3 includes a small quantity of manganese oxide (Mn_3O_4) and any titanium dioxide and phosphorus pentoxide that may be present.

4/ By difference.

When the entry and air course had reached a point 141 feet from the pit mouth, headings 4 feet wide were driven for 25 feet from the west rib of the entry and the east rib of the air course. A 4-foot crosscut was driven through the coal pillar connecting these headings. Thus, a place 80 feet long and 4 feet wide was excavated. It was extended 2 feet into the bottom rock and 6 feet into the roof rock, and the entry seal wall was constructed (see fig 5). An escapeway was constructed later to simplify changing of the explosion disks at the entry seal.

Mining of the entries presented nothing unusual. The roof rock was heavy and required close timbering for approximately the first 125 feet from the portal. Inby this point the roof was firm, and the draw rock was supported by safety posts. Ordinarily, 2 to 4 inches of roof fell as the coal was shot. The floor rock was hard. Influx of water from the roof occurred at two points inby the location of the entry seal. At each of these points a considerable volume of water was found initially, but after a few days the inflow nearly ceased. The floor was ordinarily wet, and water frequently appeared in shot holes drilled in the lower half of the coal bed.

Ventilation was provided by a small, electrically driven mine fan exhausting at the air course portal and by two portable, electric, auxiliary fans with collapsible tubing set 15 feet outby the last crosscut. The portable blowers delivered approximately 3,200 cubic feet of air per minute to the entry faces. All safety precautions consistent with good coal-mining practice were observed during the mining and underground construction work.

The entry seal (see fig. 5) consists of a three-course wall of firebrick backed with steel buckstays. The top and inby sides of this wall were pressure-grouted to the roof and surrounding stratum by means of neat cement admitted through the four 6-inch boreholes shown. After grouting the wall, the inby and outby exposed surfaces were grouted with a refractory cement applied with a cement gun. Later, the air space along the outby face of the seal was filled with concrete made from cement, rock dust, and sand. The 24-inch outlet pipes were set in concrete, as shown, and the explosion disks were set in flanges anchored to the concrete surrounding the outlet pipes.

A fan and fan house were erected and connected to the escapeway in such a way that at all times men could travel underground to the entry seal without danger of interruption of air supply. The portals of the air course and entry were fitted with doors and regulators so that the air flow could be controlled as desired when work at the entry seal was necessary.

The roof of the entry from the portal to borehole I was supported by 60-pound steel rail set in hitches in the top coal and secured by wedges of stone or brick. The steel rails were approximately 13 feet long and were placed on 2-foot centers. The air course was timbered with wood safety posts, and, where necessary, 3 by 8-inch wooden cross collars were used.

Drilling

The over-all plan of the project is shown in figure 1. The entry and air course were connected with the surface installation by means of the large boreholes, I to V, inclusive. In addition to the original boreholes shown in figure 1, two other large boreholes were drilled later at other locations. A number of test holes were also drilled before the start of the experiment and additional holes were drilled during the course of the operation. All of the holes drilled, except the 6-inch pressure-grout holes, are shown in figure 6, and the specifications of each are given in table 5.

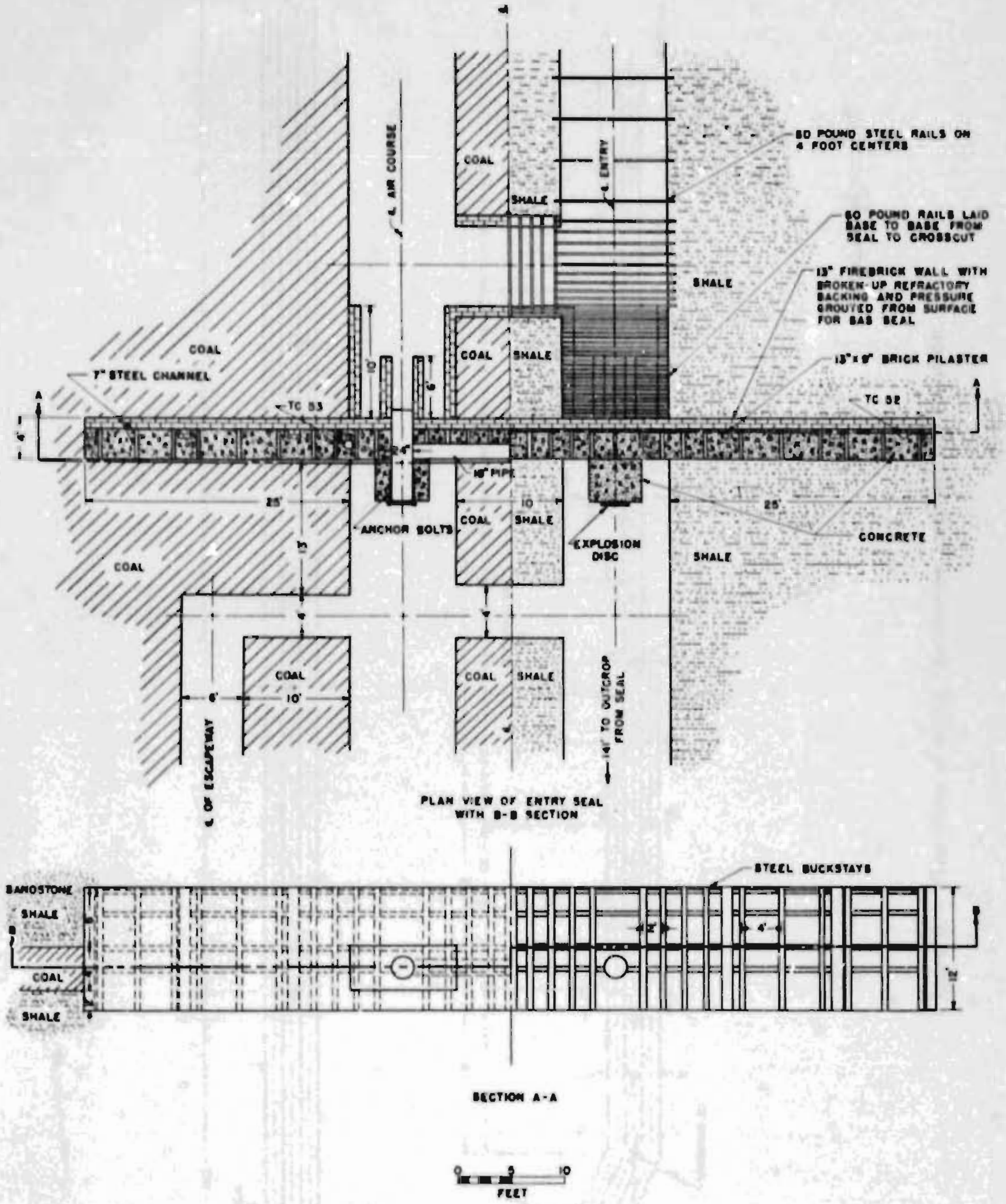


Figure 5. - Entry seal.

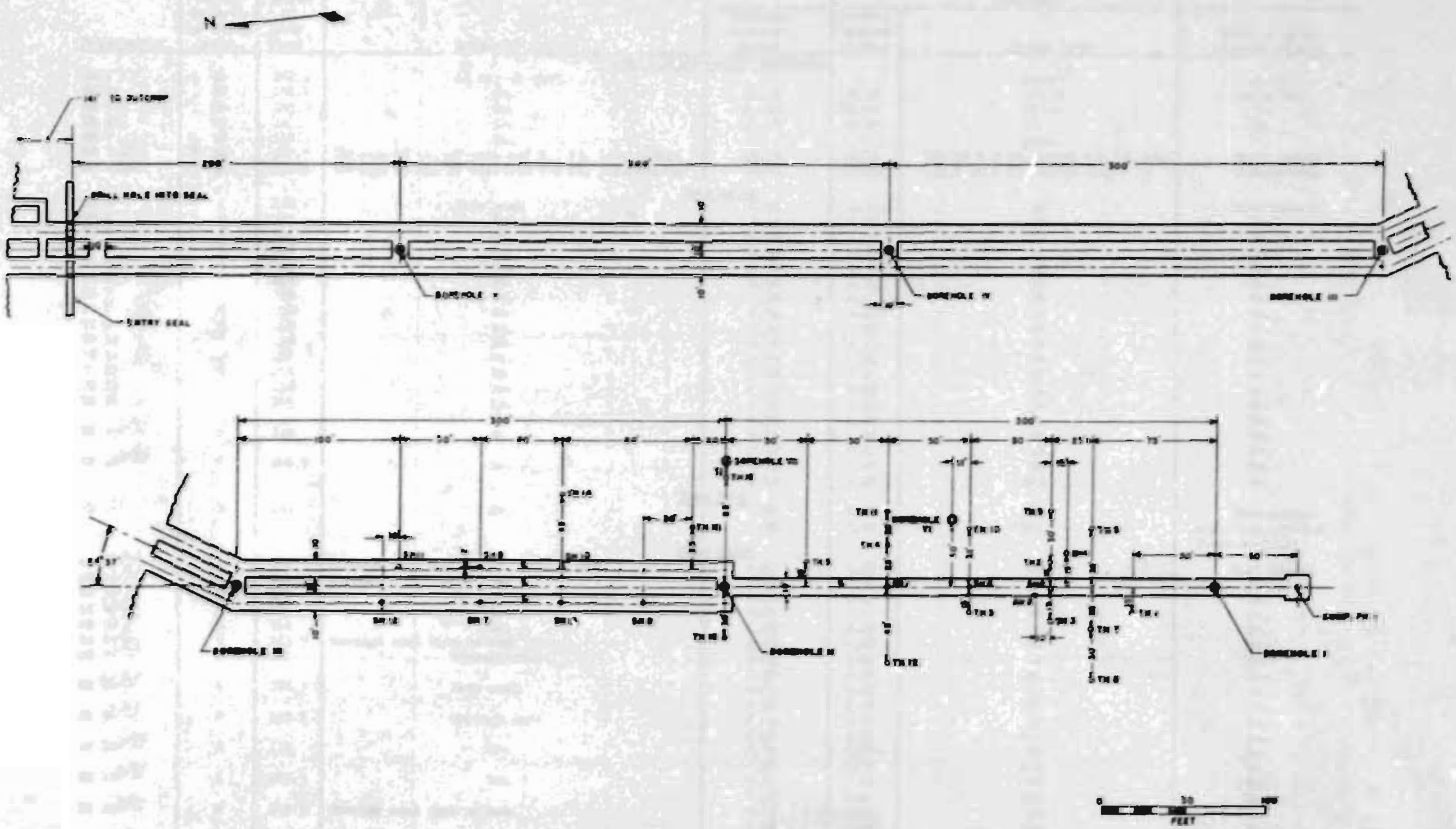


Figure 6. - Plan view of entry, air course, and drilling location.

TABLE 5. - Specifications of the churn-drill holes, gasification project

Designation	Nominal diameter of hole, inches	Depth of hole, feet	Bottom of hole	Casing[1/] External diameter, inches	Casing[1/] Internal diameter inches	Casing[1/] Depth, feet	Type of grout around casing
			Large inlet-outlet boreholes				
BH I	18	162.1	At top of coal	-	-	None[2/]	None[2/]
BH II	28	154.0	do.	20.00	19.50	154.0	Refractory
BH III	28	145.0	do.	20.00	19.50	145.0	Do.
BH IV	28	136.3	do.	20.00	19.50	136.3	Do.
BH V	18	118.3	do.	-	-	None	-
BH VI[3/]	14	166.5	Through 42 in. of coal and 1.5 ft. into bottom.	10.75	10.19	157 or 4.5 ft. above top of coal	Neat cement
BH VII[3/]	18	151.5	Through 45 in. of coal and 5.0 ft. into bottom.	12.75	12.00	141.8 or 1 ft. above coal.	Cement sand
			Test holes				
TH 1	6	161	Into coal	4.50	4.03	30	Neat cement
TH 2	6	162	do.	4.50	4.03	30	Do.
TH 3	6	161	do.	4.50	4.03	30	Do.
TH 4	6	158	do.	4.50	4.03	30	Do.
TH 5	6	158	do.	4.50	4.03	30	Do.
TH 6	6	162	do.	4.50	4.03	30	Do.
TH 7	6	162	do.	4.50	4.03	30	Do.
TH 8	6	159	do.	4.50	4.03	30	Do.
TH 9	6	160	do.	4.50	4.03	30	Do.
TH 10	6	159	do.	4.50	4.03	30	Do.
TH 11	6	158	do.	4.50	4.03	30	Do.
TH 12	6	158	do.	4.50	4.03	30	Do.
TH 13	6	156	do.	4.50	4.03	30	Do.
TH 14	6	145	do.	4.50	4.03	30	Do.
TH 15[3/4/]	6	149	do.	2.38	2.07	141	Do.
				6.63	6.07	30	Do.
TH 16[3/4/]	6	146.5	do.	2.38	2.07	130	Do.
				6.63	6.07	30	Do.
				3.50	3.07	140	Do.
			Pump hole				
PH 1[4/]	6	166	do.	6.63	6.07	20	Neat cement
				3.50	3.07	166	None; 3-in. casing loose in hole.
			Sand holes				
SH 1[3/4/]	6	163	Through coal and 2.5 ft. into bottom.	6.63	6.07	28.7	Neat cement
SH 2[3/4/]	6	154.7	Stopped 6 ft. above coal.	6.63	6.07	32.3	Do.
SH 3[3/4/]	6	164	Through coal	6.63	6.07	30	Do
SH 4[3/4/]	6	165	do.	6.63	6.07	30	Do.
SH 5[3/4/]	6	164	do.	6.63	6.07	30	Do.
SH 6[3/4/]	6	163.5	Through coal into bottom.	6.63	6.07	30	Do.
SH 7[3/4/]	6	147	Through coal	6.63	6.07	30	Do.
SH 8[3/4/]	6	146.5	Into coal	2.38	2.07	135	Do.
				6.63	6.07	30	Do.
SH 9[3/4/]	6	157.8	Through coal	2.38	2.07	132	Do.
				6.63	6.07	30	Do.
SH 10[3/4/]	6	150	do.	2.38	2.07	134.7	Do.
				6.63	6.07	30	Do.
SH 11[3/4/]	6	149.5	do.	2.38	2.07	130	Do.
				6.63	6.07	30	Do.
SH 12[3/4/]	6	150.5	Through coal into bottom.	2.38	2.07	135	Do.
				6.63	6.07	30	Do.
SH 13[3/4/]	6	145.5	3 ft. above coal	2.38	2.07	140	Do.
				6.63	6.07	30	Do.
				2.38	2.07	140	Do.
			Holes for grouting entry seal				
1[4/]	6	97	Into coal	6 inch galvanized sheet-metal well casing.		19.5	Filled hole with neat cement during later construction.
2[4/]	6	101	do.			18	
3[4/]	6	100	do.			20	
4[4/]	6	100	do.			20	

1/ Standard pipe was used for casing except as noted. 2/ 30 feet of 16-inch pipe was placed in hole at a depth between 30 and 60 feet; neat cement grout was run into annulus to plug vertical cracks in strata between these elevations. 3/ These holes were drilled after operation of the project had continued for varying lengths of time, and the hole was usually bottomed in a burned-out area or in carbonized coal. 4/ These holes were started with an 8-inch bit in order to place the 6-inch casing.

Table 6 gives a survey of the deviation in diameter obtained in churn-drilling a 28-inch-diameter hole through strata of the nature found at the project site.

To aid in estimating the construction time required for churn-drilling holes, a record of the average rate of drilling was kept. These rates are given in table 7 and include setting-up time for the drill rig.

TABLE 6. - Variation in diameter of borehole II with depth

Depth from surface, feet	Diameter, inches1/	Depth from surface, feet	Diameter, inches1/
25.................	29	90.................	29.5
30.................	29	95.................	30
35.................	29	100.................	29.5
40.................	30	105.................	30
45.................	30	110.................	30
50.................	29	115.................	29
55.................	29	120.................	31
60.................	29	125.................	31
65.................	29	130.................	30.5
70.................	29.5	135.................	31.5
75.................	29.5	140.................	32
80.................	29.5	145.................	31.5
85.................	29.5		

1/ Bit gaged at 28 inches.

TABLE 7. - Rate of churn drilling holes of various diameter at Gorgas

Nominal diameter of hole, inches	Footage considered	Rate of drilling, feet per hour		
		Average	Maximum	Minimum
28	438	0.57	1.46	0.38
18	283.5	1.67	2.02	1.48
6	6000	3.80	7.30	1.83

Before drilling the large boreholes I to V, inclusive, the area through which each hole was to be drilled was pressure-grouted with cement. The arrangement of the pressure-grout holes is shown in figure 7. Grout was applied in the unlined holes from 30 feet below the surface to the coal bed. The cement usage and other details of pressure grouting are given in table 8. This shows that after two or three holes had been grouted at each location, the last one or two holes refused grout in each case, (20 bags were required to fill the hole) and the area was therefore presumed to be tight and the cracks in the strata filled.

Reference to table 5 indicates that refractory cement was used to grout the 20-inch casing at boreholes II, III, and IV. In each instance a castable refractory of high alumina content was used for filling the first 10 feet of the annulus adjacent to the top of the coal bed. Castable refractories of lower alumina content were used for filling the remainder of the annulus, and the type of refractory at each of the three boreholes was varied to obtain a comparison as to their individual characteristics for this service.

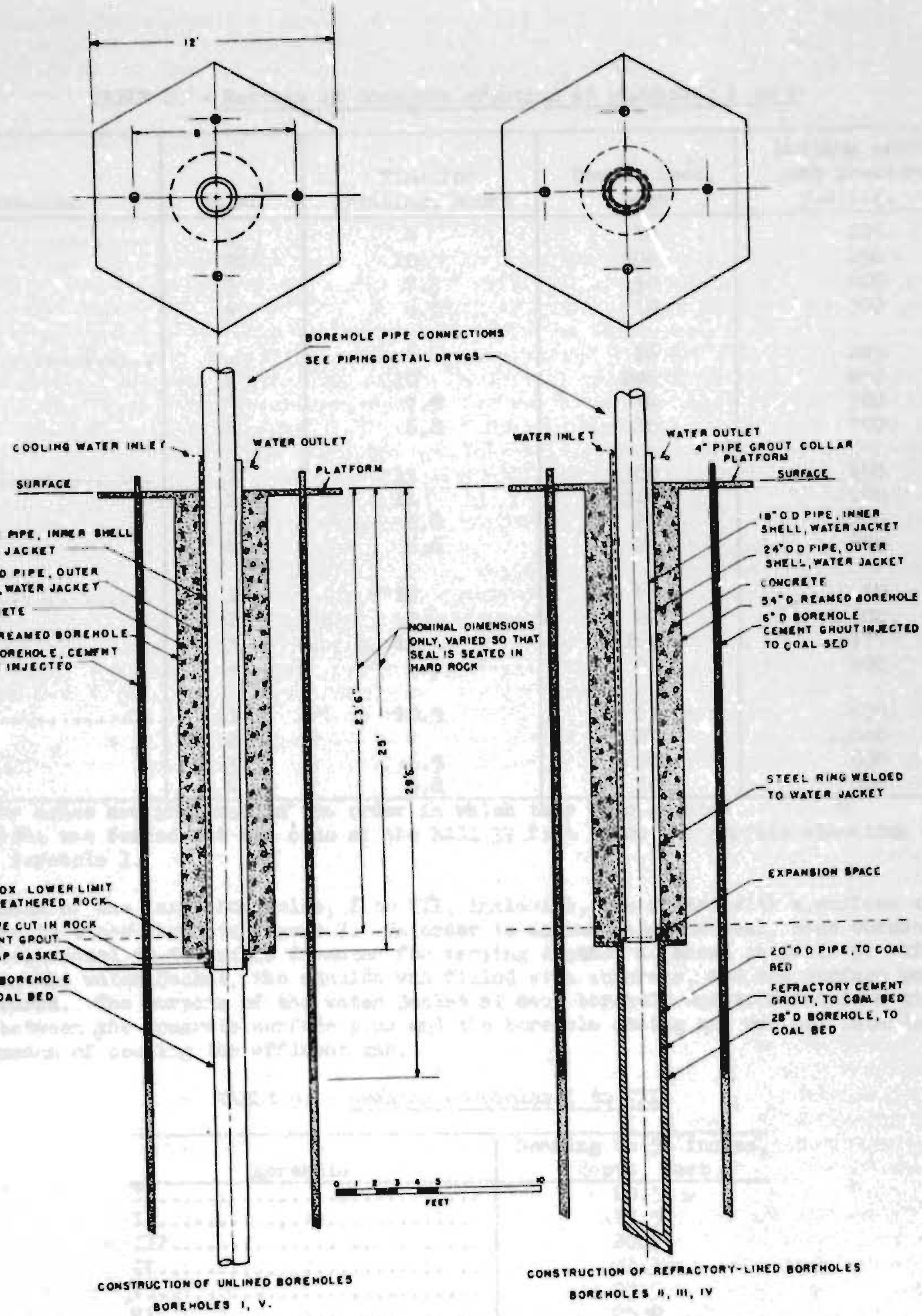


Figure 7. - Borehole installation, including water jacket and surface seal.

TABLE 8. - Results of pressure grouting at boreholes I to V

Location	Hole[1/]	Time for grouting, hours	Cement used, bags	Maximum grout pump pressure, p.s.i.g.
BH I.............	1	4	19	225
	2[2/]	10	204	250
	3	7.3	30	600
	4	6.5	19	500
BH II............	1	4	16	225
	2	10	296	450
	3	7.5	34	500
	4	6.8	26	700
BH III...........	1	13	300	450
	2	11	300	700
	3	6.8	25	700
	4	6.8	27	800
BH IV............	1	12	63	50
	2	7	22	1,000
	3	11	163	175
	4	6.8	22	800
BH V.............	1	10.5	67	600
	2	7	27	1,000
	3	6.5	20	800
	4	6.8	20	800

1/ The holes are numbered in the order in which they were grouted.

2/ Grout was forced out the side of the hill 37 feet below the surface elevation at borehole I.

Each of the large boreholes, I to VII, inclusive, was fitted with a surface seal similar to those shown in figure 7. In order to accommodate the seal, each borehole had been reamed to 54 inches diameter for varying depths, as shown in table 9. After placing the water jacket, the annulus was filled with concrete, and the surface pad was poured. The purpose of the water jacket at each borehole was to maintain a tight seal between the concrete surface plug and the borehole casing and was not intended as a means of cooling the effluent gas.

TABLE 9. - Reaming boreholes I to VII

Borehole	Reaming to 54 inches, depth, feet
I..........................	20.5
II.........................	17.5
III........................	20.5
IV.........................	21.3
V..........................	23.5
VI.........................	25.0
VII........................	22.0

Boreholes II to V were drilled into crosscuts, which interconnected the underground passages. Borehole I was drilled into the single entry at the southern end of the project, and boreholes VI and VII were drilled into the coal bed near the burning coal faces during operation. At the elevation of the coal bed, boreholes I to V were supported by fire-brick structures similar to that shown in figure 8. The purpose of these structures was to support the roof rock adjacent to the borehole and to prevent plugging of the bottom opening.

Surface Equipment

A 20-inch-diameter air-blast manifold was installed to connect the large boreholes with the compressor units (see figs 9 and 10). The manifold is shown in figure 9, and a more detailed plan is shown in figure 11. The connections to the boreholes were valved, so that each could be used either as an air inlet or a gas outlet. The air-inlet valves were 20-inch, worm-gear, cast-iron plug valves, and the hot-gas outlets were flapper-type valves fabricated at the project and operated as indicated in figure 11. The faces of the latter valves were gasketed with asbestos and fitted with cables for opening and closing from the ground. When closed, they were bolted to the stack to minimize leakage. Each of the boreholes was fitted with an internal water spray, thermocouples, and sampling connections. The thermocouples normally were located at the gas-sampling point and 40 feet below ground level. At times, thermocouples were placed at the elevation of the coal bed and at various other depths.

Recording flow meters were installed in the air manifold as well as temperature- and pressure-measuring devices. The primary air source for the project was a reciprocating compressor powered by an 800-horsepower synchronous motor having a rated capacity of 7,200 c.f.m. of free air at a discharge pressure of 30 pounds per square-inch gage (see fig. 12). Auxiliary air-compression equipment consisted of two rotary, positive-pressure, lobe-type blowers, one of which was powered by a 100-horsepower motor and had a rated capacity of 1,600 c.f.m. of free air at 10 pounds per square-inch gage. The other unit had a rated capacity of approximately 7,000 c.f.m. of free air with a discharge pressure of 2 pounds per square-inch gage and was powered by a 75-horsepower motor.

Two skid-mounted gas-sampling rigs were built and connected to the outlet stacks as desired. These units included a primary condenser, a coke filter tower, secondary tubular condenser, a gas pump, an after condenser, and flow-measuring equipment as shown in figure 13. The gas leaving the units was piped to the laboratory, where iron-oxide boxes, a 100-cubic-foot gas holder, and a pressure regulator were installed. From the iron-oxide boxes, the gas sample was piped to a recording calorimeter and to a recording gravitometer in the laboratory building. The gas was analyzed on either grab or continuous samples by means of Bureau of Mines precision-type Orsat equipment.

Electrical power for the project was obtained from a 44-kv. transmission line of the Alabama Power Co., which passed over the site. A 1,000-kw. substation was installed and delivered current at a primary voltage of 2,300 for use at the project. All motors of 75 horsepower or larger were direct-connected to 2,300-volt service. Secondary transformers were installed where a voltage of 110, 220, or 440 was required by the various installations.

To provide the water needed, two 150-gallon-per-minute, 400-foot-head, centrifugal pumps were installed at the Warrior River, approximately 3/4 mile from the site of the experiment. Water was required for cooling product gas, for circulating in the water jackets of the borehole seals, for cooling the reciprocating compressor, and for various other purposes. The river pumps delivered the water to a 3,000-gallon tank on the site. An automatic float switch was installed to control operation of the pumps.

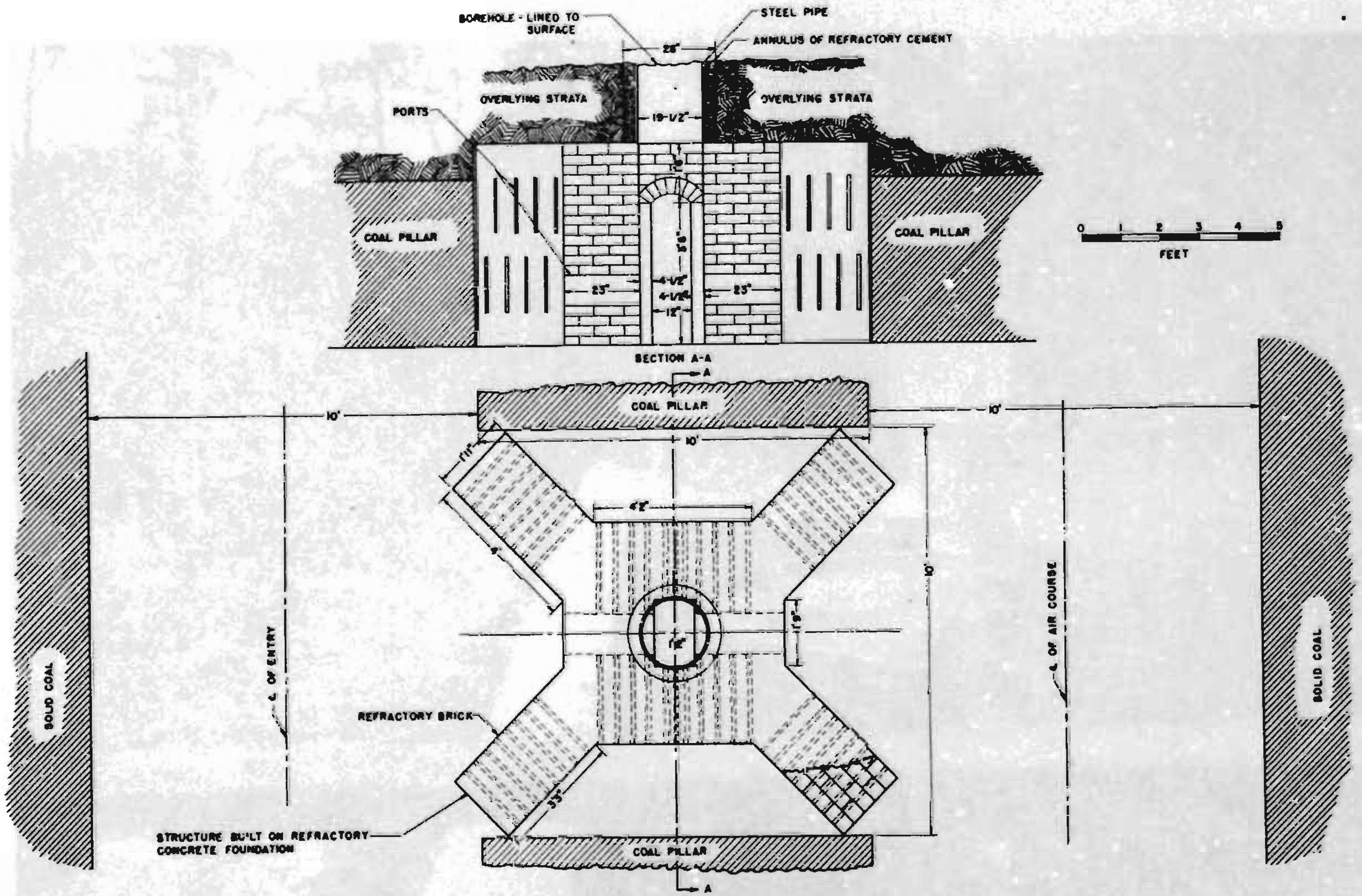


Figure 8. - Firebrick supporting structure at base of borehole III.

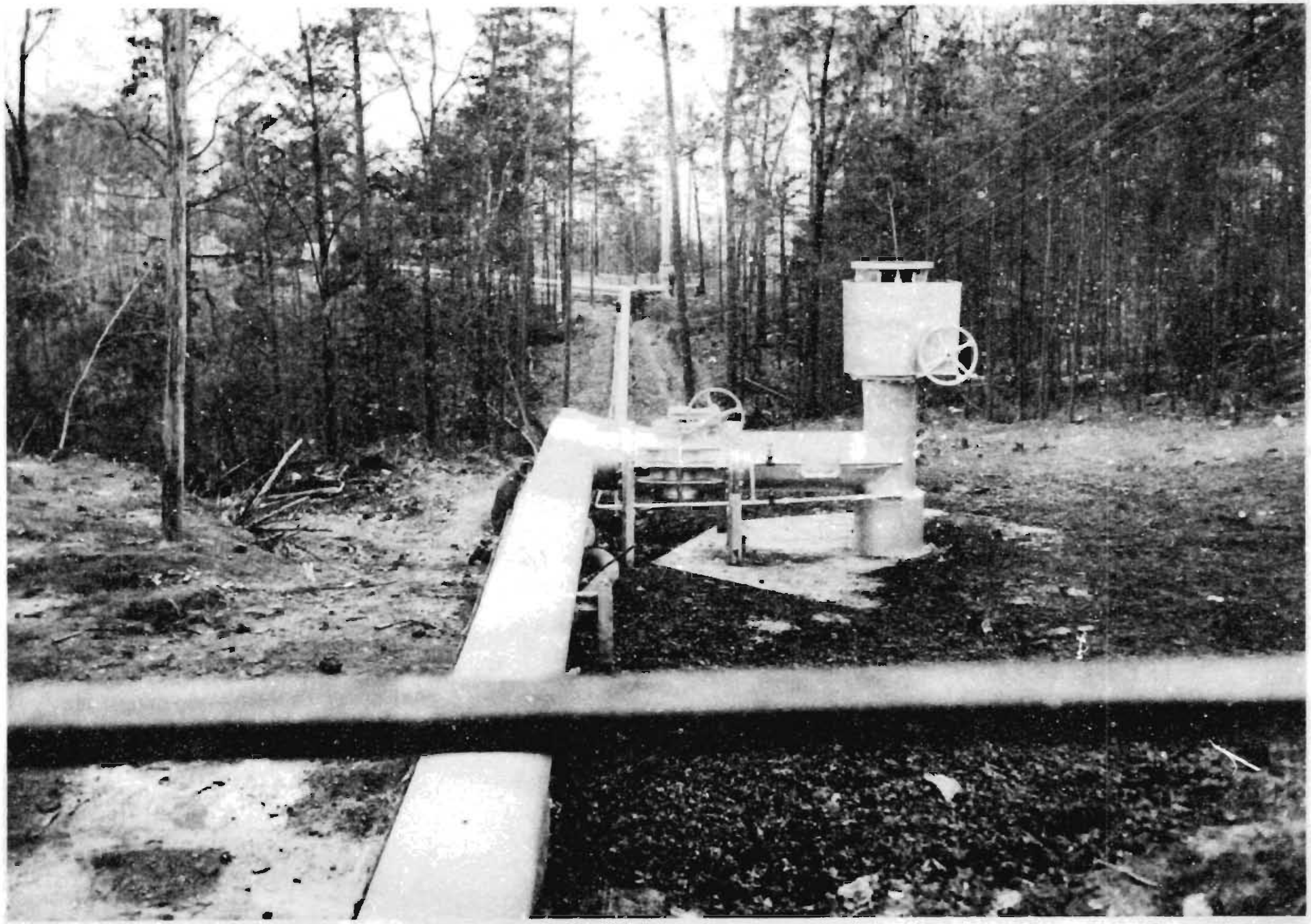


Figure 9. - 20-inch air manifold.

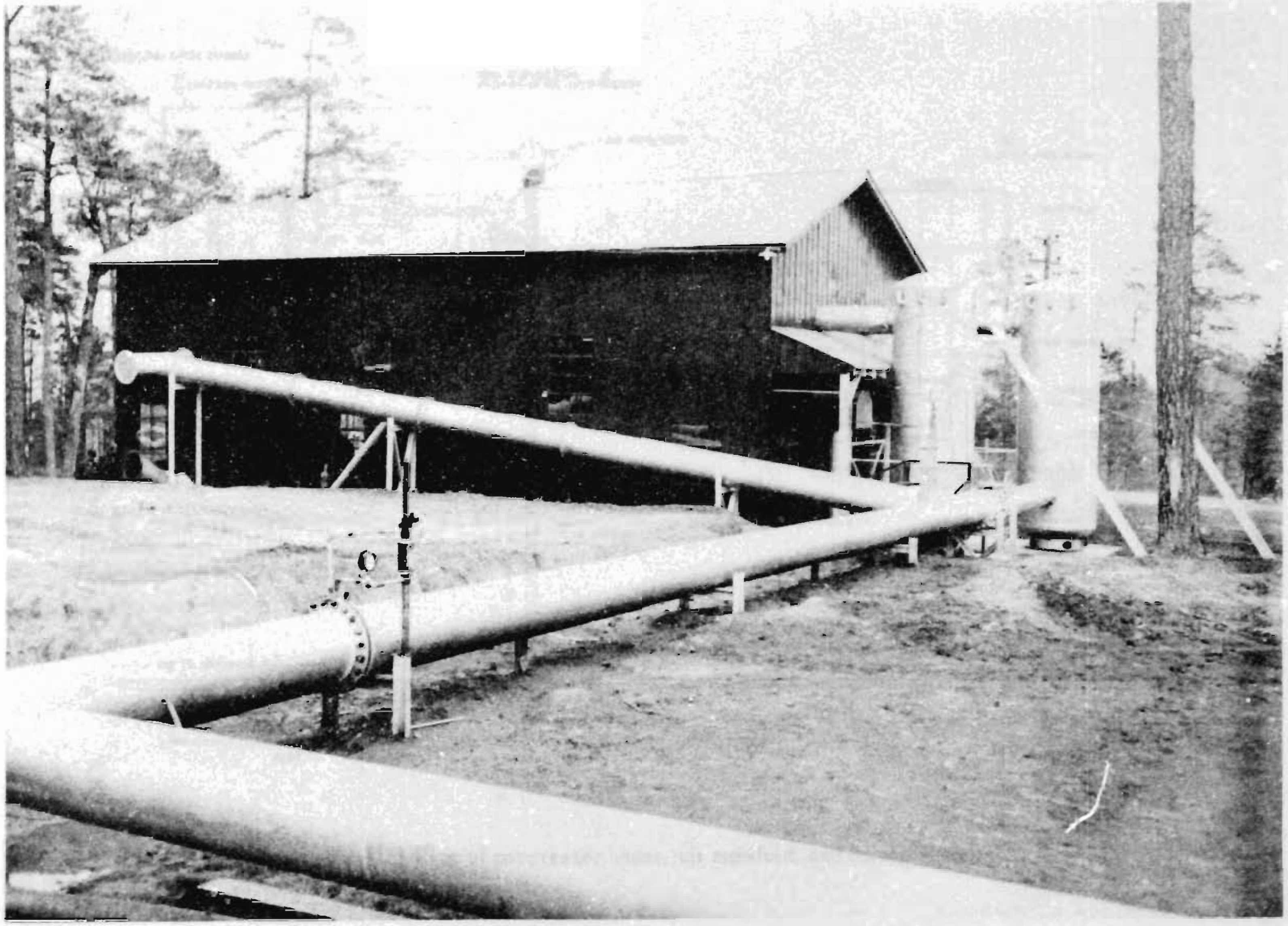


Figure 10. - Manifold and compressor house.

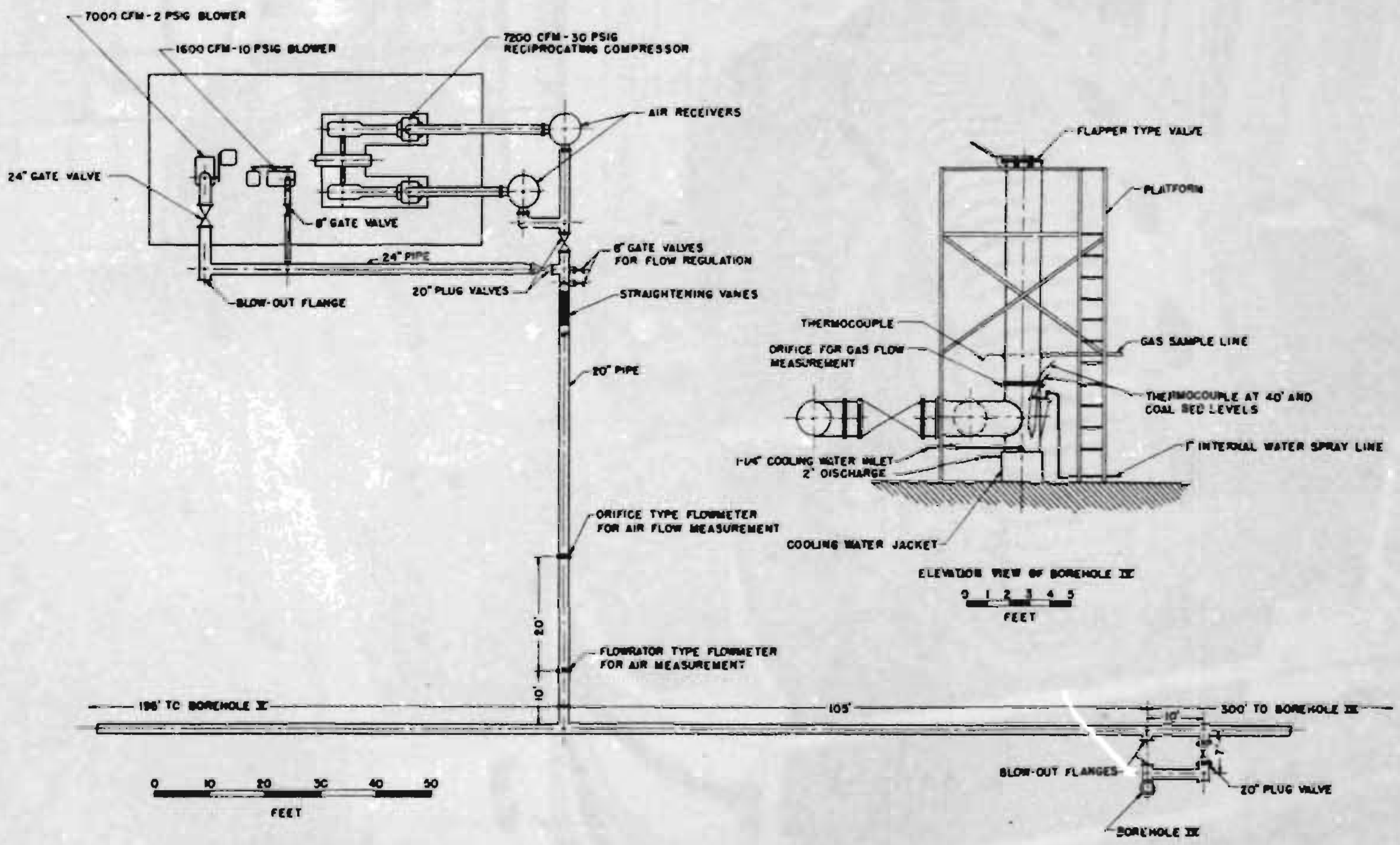
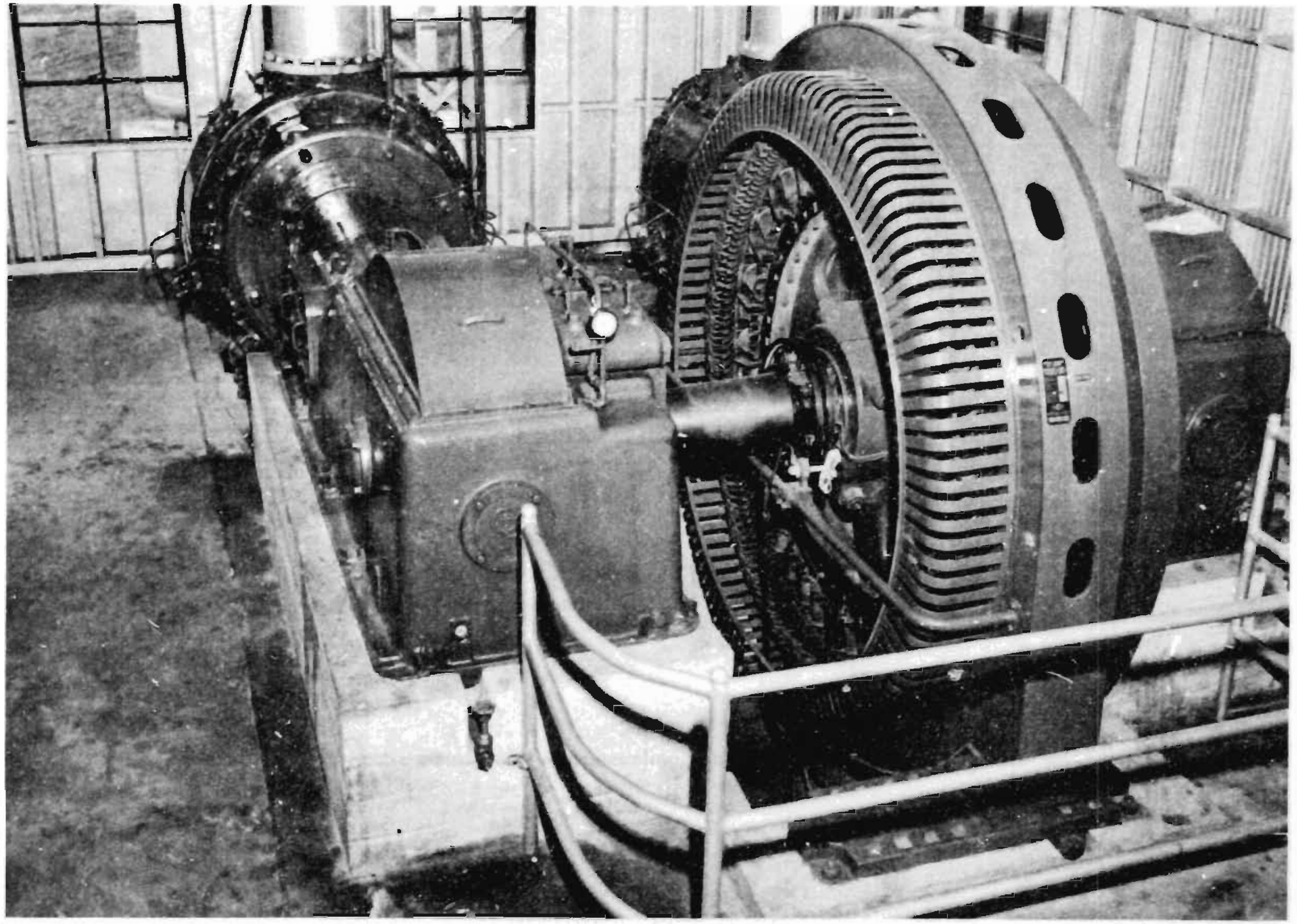


Figure 11. - Plan of compressor house, air manifold, and borehole piping.



F.gure 12. - 7,200 c.f.m. air compressor.

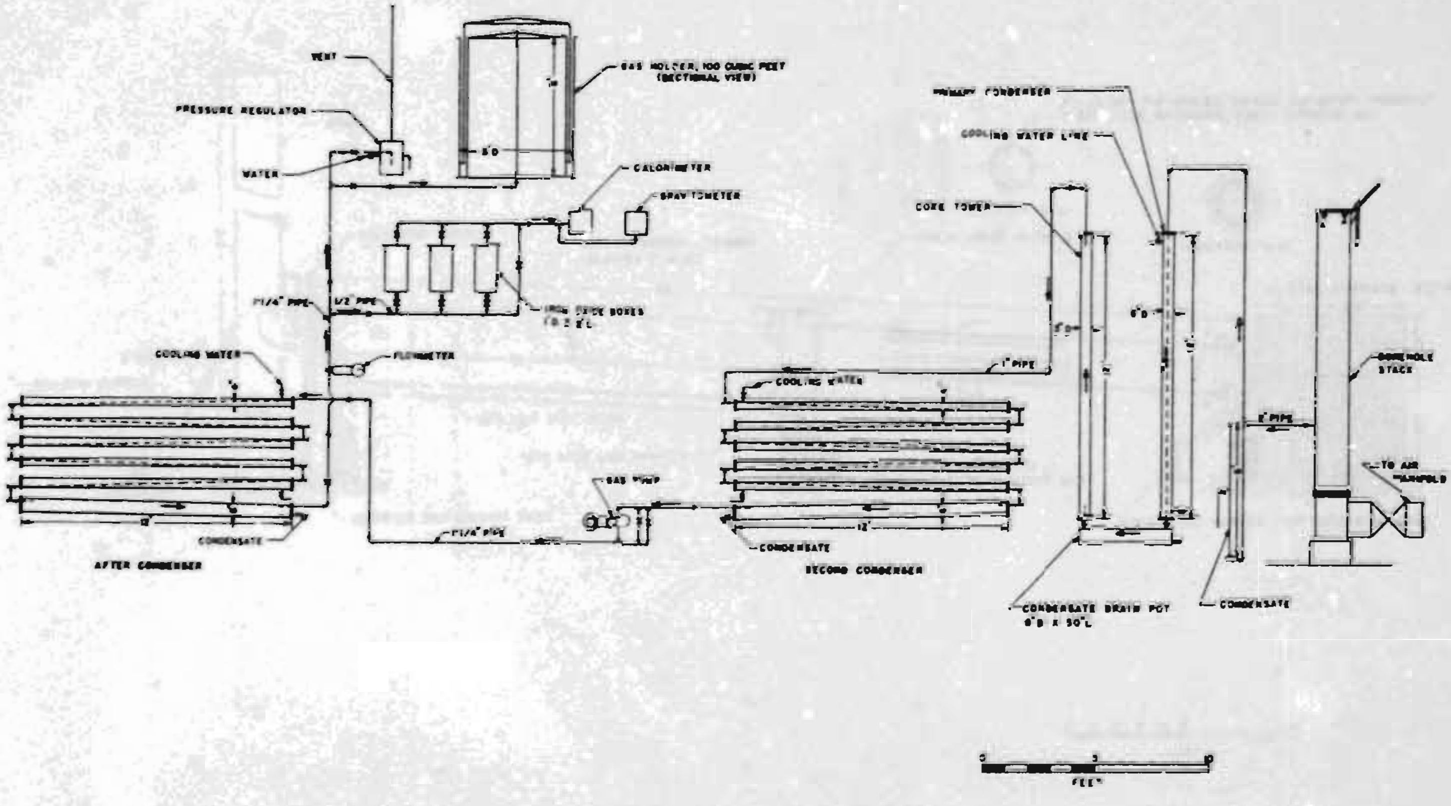


Figure 13. - Schematic arrangement of gas-cooling, cleaning, and sampling equipment.

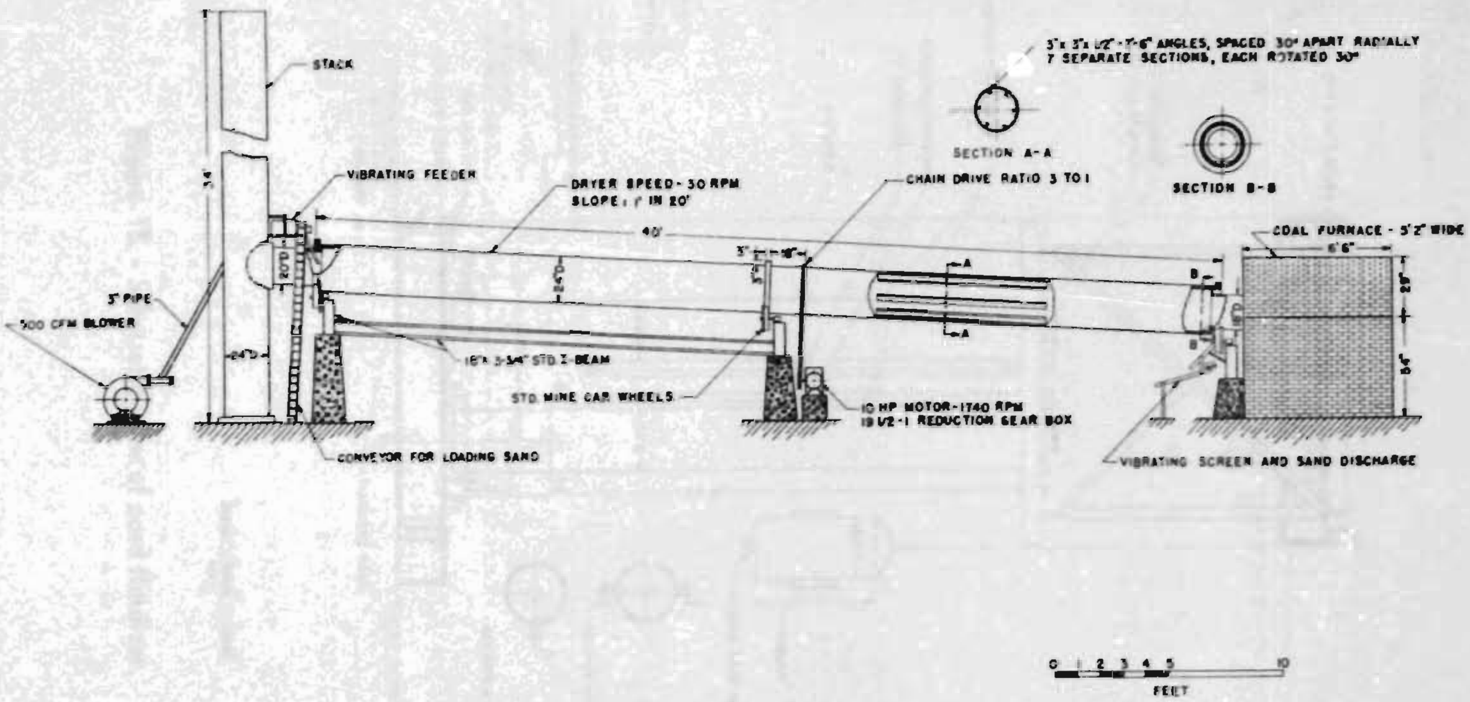


Figure 14. - Rotary sand dryer.

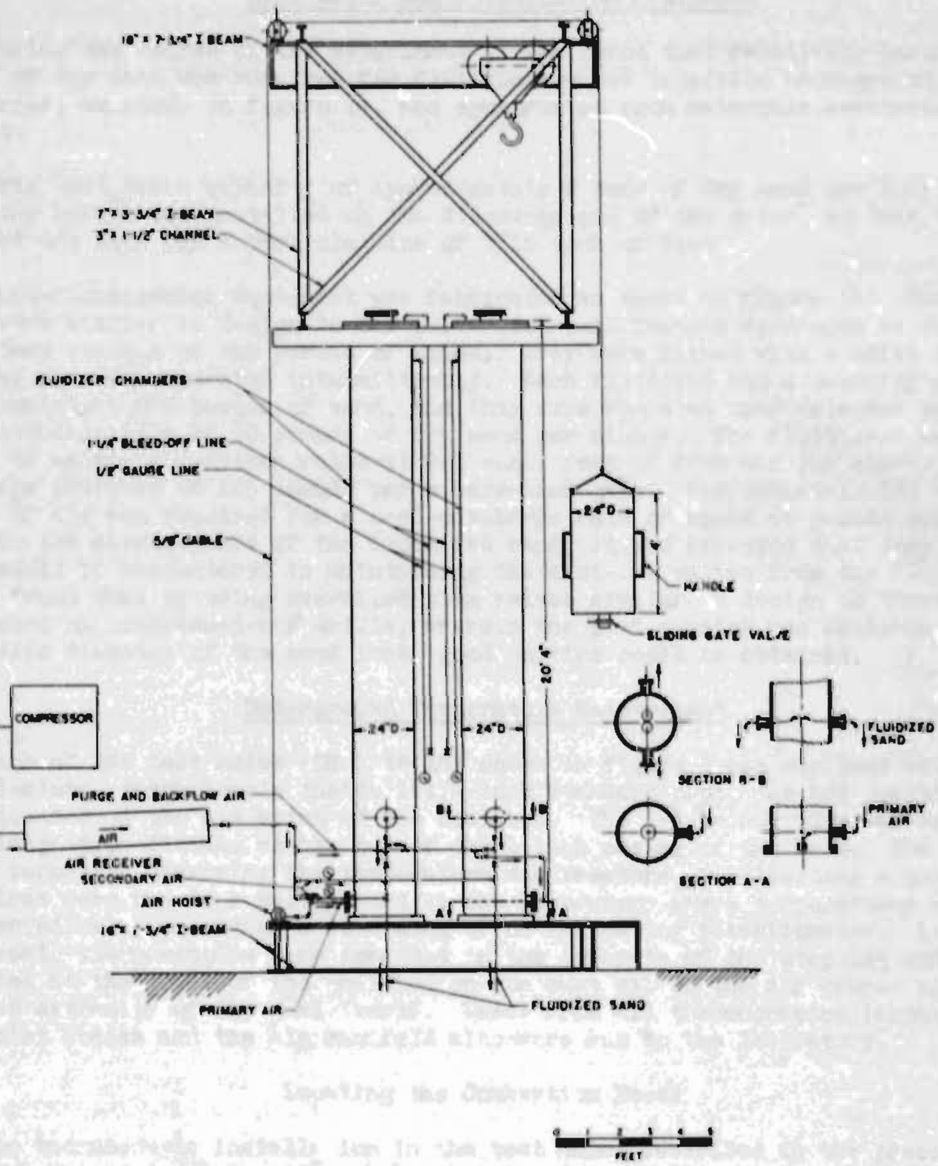


Figure 15. - Schematic view of sand fluidizer.

A 125-horsepower horizontal steam boiler was installed at the site to provide steam for purging the system or for such other purposes as might be desired.

Sand Drier and Fluidization Equipment

During the course of the experiment it was found that relatively large quantities of dry sand was required for fluidization and injection underground, and a sand drier, as shown in figure 14, was constructed from materials available at the project.

This unit has a capacity of approximately 2 tons of dry sand per hour. The vibrating screen was installed on the discharge end of the drier, so that the finished dry sand had a particle size of 1/10 inch or less.

Sand-fluidization equipment was fabricated as shown in figure 15. These units were similar in design to the pulverized-coal feeders developed at the Morgantown station of the Bureau of Mines. They were fitted with a hoist for charging and were operated intermittently. Each fluidizer had a capacity of approximately 5,000 pounds of sand, and they were operated over extended periods at a discharge rate of 60 pounds of dry sand per minute. The fluidizers were connected to an air compressor rated at 225 cubic feet of free air per minute, with a discharge pressure of 125 pounds per square-inch gage. Approximately 125 to 150 c.f.m. of air was required for a sand-discharge rate of about 60 pounds per minute. Owing to the abrasiveness of the fluidized sand, it was expected that some difficulty would be encountered in maintaining the shut-off valves from the fluidizer. It was found that by using oversized plug valves similar in design to those commonly used on compressed-air drills, wherein the port opening was equivalent to the inside diameter of the sand line, good service could be obtained.

Underground Temperature Measurement

Each of the test holes (TH 1 to 16) shown in figure 6 was equipped with a chromel-alumel thermocouple inside 1-1/4-inch standard pipe, the hot junction being located at the elevation of the coal bed. The 1-1/4-inch pipe was welded to a flange-type fitting at the top of the 4-inch casing of the hole. The installation permitted measuring the temperature and pressure or collecting a gas sample. Lead wires were run to a switchboard in the laboratory where temperatures could be read periodically on either a recording or an indicating potentiometer. At the entry seal, thermocouples were imbedded in the concrete of the stopping and were installed at the level of the coal bed on the east rib of the air course and near the west extremity of the seal itself. Leads from all thermocouples installed in the outlet stacks and the air manifold also were run to the laboratory.

Locating the Combustion Faces

The thermocouple installation in the test holes described in the preceding paragraph was used for locating the combustion faces underground. A second method of locating the combustion faces also was provided.

On the west rib of the single entry, at a point 100 feet north of borehole I, a 2-inch hole was drilled horizontally in the coal bed normal to the line of the entry and to a depth of 30 feet. A similar hole was drilled 100 feet north of borehole III on the west rib of the entry. Stainless-steel capsules with rupture-disk assemblies were charged with 39 grams of mercury, sealed, and placed in these horizontal holes at 5-foot intervals. Between the capsules, the hole was filled with refractory cement. The capsules were designed to explode at a pressure of about 1,300 pounds per square inch and a temperature of 1,350° F. A special sampling system was installed at No. I and No. II boreholes, so that a sample of the issuing gases was sent through a cooler, a liquid trap, a pressure regulator, a filter, a flow meter, and thence to a recording-type, photo-electric mercury detector. When the combustion face reached a mercury capsule, the capsule exploded, and the detector indicated the presence of mercury vapor in the effluent gases.

Gas-Turbine Installation

It was decided to install two aircraft-type turbo superchargers to obtain some information on the possibilities of operating gas turbines in connection with underground gasification. At borehole III, the gas-turbine installation shown in figure 16 was constructed. It consisted of five cyclone-type knock-out chambers acting in parallel for the removal of dust and clinker from the effluent gas. The discharge from the knock-out chambers was connected to the intakes of two gas turbines connected in parallel. In each turbo-compressor, the turbine and the air compressor were mounted on the same shaft. Two stages of compression were obtained as air was admitted to one compressor unit, nd this discharged into the intake of the second. The discharge from the second compressor was added to the air stream entering the underground system or discharged to the atmosphere. All units comprising the gas-turbine installation were mounted on concrete foundations. The knock-out chambers and the hot-gas handling lines were insulated with 2 inches of magnesia asbestos lagging. Steel barricades were erected around the turbo-compressor units, and an adequate oil-cooling and storage system was installed. The gas discharge from the gas turbines was vented to the atmosphere through a 20-inch stack. Bellows-type expansion units were provided in all gas lines leading to the turbo-compressor units.

OPERATION

Operation of the project was divided into several periods. Various problems developed, and certain operational changes were made. In each instance the changes were planned either to correct difficulties encountered or to obtain information regarding the effect of certain variables on the process.

Firing the Project

Each rib of the 300-foot single entry between boreholes I and II was undercut to a depth of 15 inches, and the loose coal obtained was piled against the ribs. Approximately 15 tons of coal was placed around the base of borehole I and along the ribs of the entry. Several cords of pine wood was stacked on top of the coal, and a number of thermite fire bombs was placed in the pile of fuel. One hundred gallons of fuel oil was poured down borehole I. The 1,600-cubic foot-per-minute compressor was started; the air valve at I and the stack valve at II were opened. At 3:00 P.M. on March 18, 1949, a thermite bomb was dropped down borehole I, and operation of the project began.

First Operating Period, March 18 to June 21, 1949

It was originally planned to operate the project by using a unidirectional flow in the 300-foot length of single entry between boreholes I and II. Air was admitted at borehole I, and the effluent gas was sampled and vented at borehole II. It was planned to use a low air input at the start and gradually increase the flow to the optimum rate. The purpose of the low initial air flow was to set up a stable combustion zone near the base of borehole I and to carefully build it up by gradually

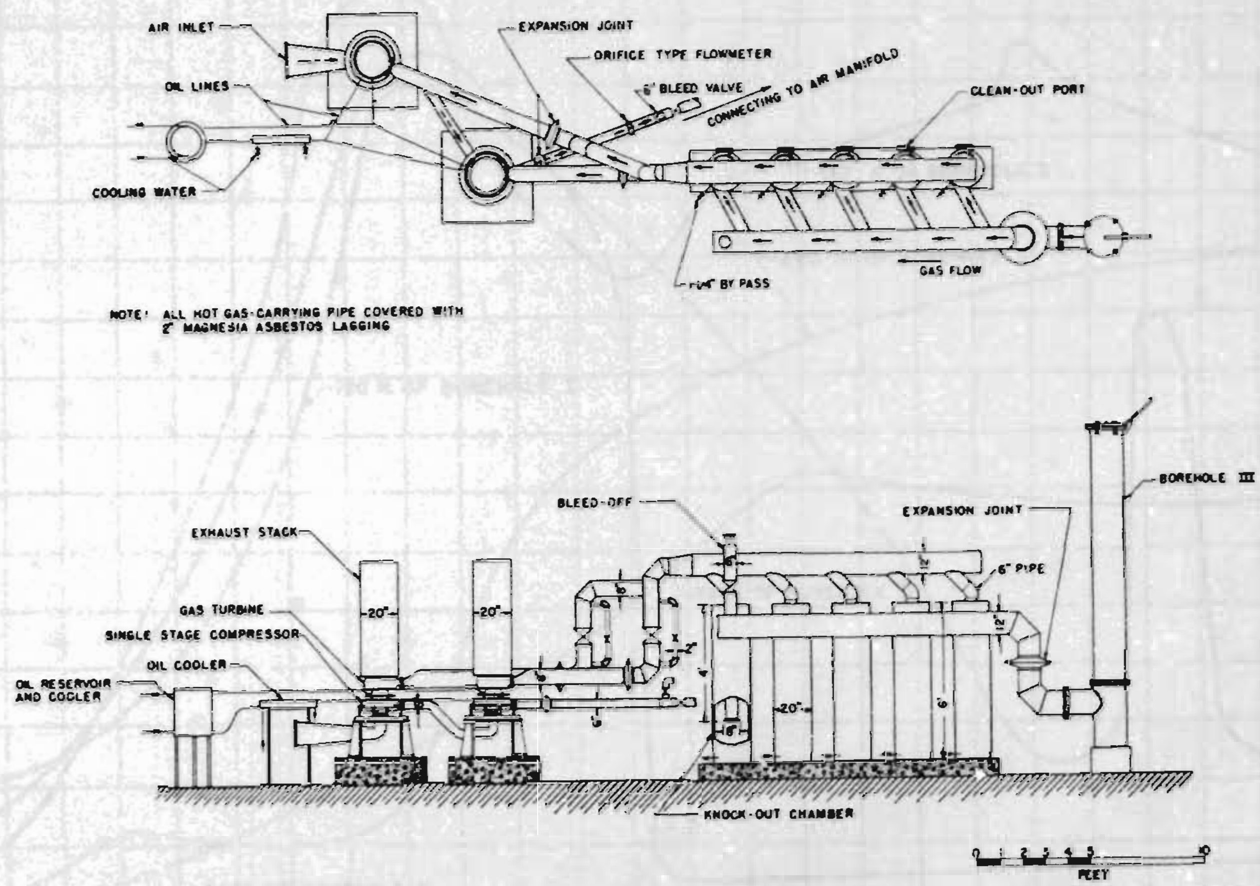


Figure 16. - Gas-turbine installation.

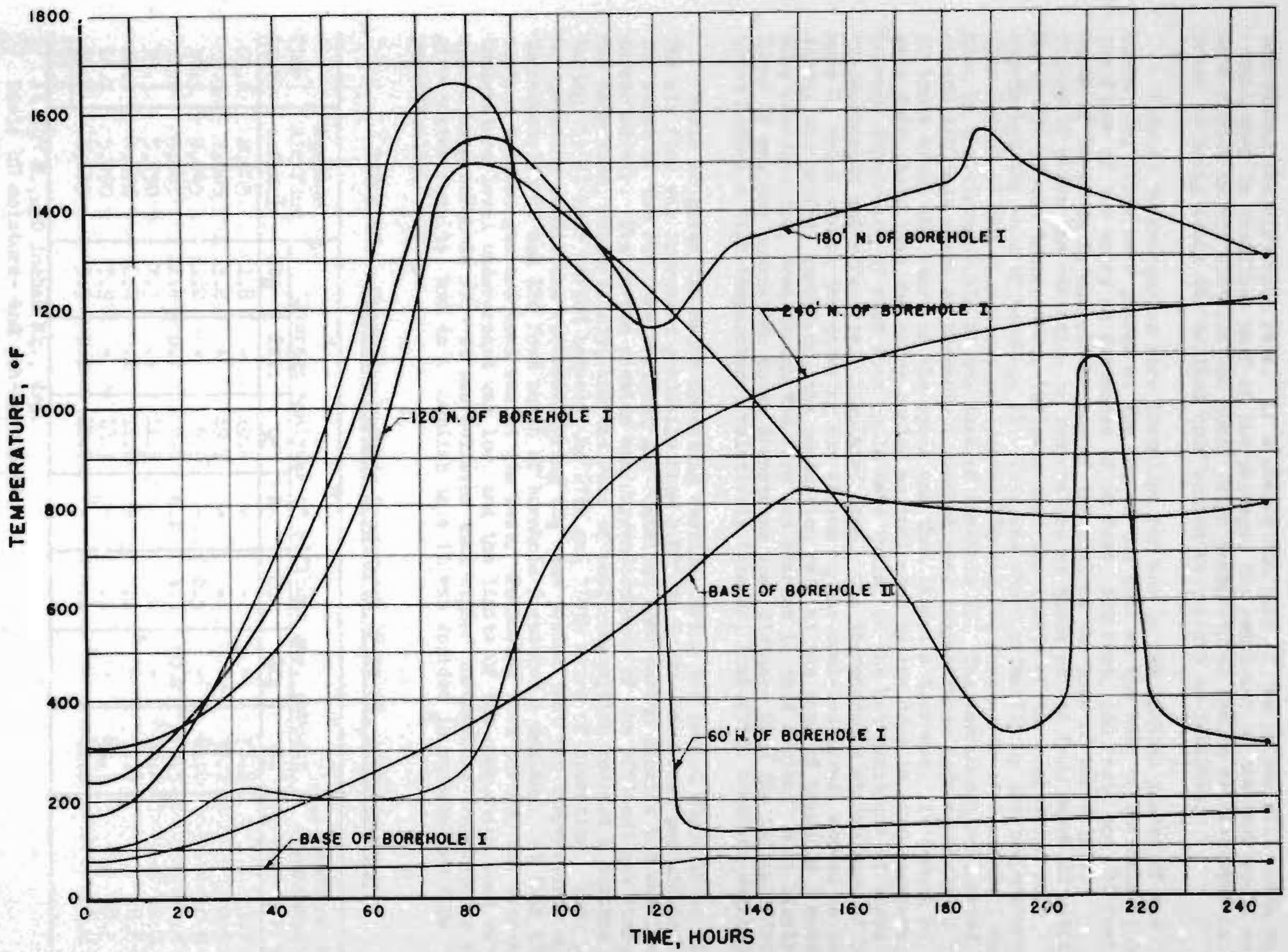


Figure 17. - Temperature at elevation of coal bed during cycle I.

increasing the air-input rate. If a combustion zone of the proper size could be established in the first half of the passage, the remainder of the path would serve as a reduction and distillation zone. High temperatures had to be developed in order to bring about the desired roof action as quickly as possible.

Special thermocouples were installed for use in the initial phases of the operation. They were placed at the top of the coal at the base of borehole I; on the floor of the entry at distances of 60 feet, 120 feet, 180 feet, and 240 feet north of borehole I; and at the top of the coal at the base of borehole II. Figure 17 shows the variation in temperature at these points from March 18 until March 29. These temperatures indicate that the limits of the combustion zone approached the base of borehole II. This was shown primarily by the temperature-time curves of the thermocouples located 180 and 240 feet north of borehole I and also by the thermocouple at the base of borehole II. The thermocouples located 60 and 120 feet north of borehole I reached peak temperatures approximately 70 to 90 hours after the start of the cycle and then showed a decrease. It cannot be said definitely that the entry cooled as indicated by the drop in these temperatures, because quantities of roof rock could have fallen on the hot junctions of these thermocouples and effectively insulated them. The thermocouple at the base of borehole I, which was in the entering air stream at the coal-bed level, showed no change during the period; therefore, the combustion rate at the base of borehole I must have remained low, even though the fire was started in this region. Most likely, the locus of maximum combustion moved downstream some distance from the initial firing point before a high-temperature, relatively intense, combustion zone was established.

Table 10 gives the major operating results during the period March 18 to 29. The air flow was increased gradually from 2,025 to 5,290 cubic feet per minute. At the start of the run, the effluent gas contained some carbon dioxide but was largely unreacted air. The carbon dioxide and oxygen contents of the effluent gas increased and decreased, respectively, and the rate of coal consumption reached a maximum during the 51-hour period between the 67th and 118th hours of operation. This peak in operating conditions occurred during the same period that the temperatures on the thermocouples 60 and 120 feet north of borehole I reached a maximum. At this time, contact between gas and coal was at its best. Following this period, the over-all temperature level underground was low, and the limits of the combustion zone were approaching borehole II. It was believed that higher underground temperatures would give better results, and to accomplish this it was decided to reverse the flow periodically.

TABLE 10. - Operating results from March 18 to 29, 1949, cycle 1

Time, hours	Average air flow c.f.m.1/	Average analyses of effluent gas, percent							Rate of coal consumption, tons per day2/
		CO_2	Ill.	O_2	H_2	CO	CH_4	N_2	
25.6	2,025	1.8	-	19.4	-	-	-	78.8	1.5
3.5	2,805	3.2	-	19.7	-	-	-	77.1	2.3
38.3	3,245	11.2	-	6.9	-	0.5	-	81.4	10.0
51.2	3,665	11.4	0.7	5.8	0.1	1.3	0.2	80.5	14.3
93.3	5,250	7.3	.4	11.5	-	.4	-	80.4	11.7
10.3	4,670	6.2	.1	11.8	-	.1	-	81.8	8.6
16.7	5,290	5.9	-	12.3	-	.1	-	81.7	8.3
18.7	4,115	5.5	0.1	12.7	-	.1	-	81.6	6.2
257.6									

1/ At 60° F., 30 inches Hg., dry.
2/ Basis of moisture- and ash-free coal.

In the course of this first operating cycle, the over-all resistance to flow increased. The change was small, and the effect was masked by the variation in quantity of input air and the temperature level underground. Some roof must have fallen to account for the total increase.

Following this first cycle, the flow was periodically reversed; borehole II and borehole I were alternately made the inlet and outlet. The effluent-gas temperatures were chosen as a basis upon which to effect these periodic reversals in flow. The average operating conditions for the remainder of the period March 29 to June 21 are summarized in tables 11 and 12. In these tables the results obtained during individual cycles are averaged by weeks and direction. Table 11 summarizes the results when blowing in at borehole I and removing the gaseous products at borehole II. Table 12 summarizes the results obtained when blowing from borehole II to borehole I.

In the course of the 15 weeks of operation given in table 11, the carbon dioxide and oxygen content of the effluent gases remained nearly constant, although with the passing of time there was a slight decrease in carbon dioxide content and a slight increase in oxygen content. The heating value of the product gases remained low for the entire period. The maximum temperature of the effluent gases for each cycle was periodically raised from 700° to 1,100° F., and this temperature was the criterion used in limiting the time for each cycle. As the discharge temperature was raised, the operating time required to reach that temperature first increased and then decreased to the previous value, indicating that the over-all temperature level of the underground system was gradually increasing.

In the sixth week of operation, an attempt was made to raise the temperature level by spraying fuel oil into the entering air at borehole II. About 500 gallons of oil was added to the input air during two consecutive cycles in the direction borehole II to I. Adding the fuel oil caused the temperature to rise at the base of the inlet borehole; but there was no other apparent effect upon operating conditions, and the use of oil was discontinued.

When mining of the underground entries was completed, it was found that water regularly flowed into these passages. This water drained south to the pump hole, where it accumulated. It was then pumped from this sump and measured. The water inflow during the period preceding the first operating period averaged 1.7 gallons per minute. From March 18 until June 21 the sump was periodically pumped dry, and for the entire period the water averaged 0.2 gallon per minute. It was presumed that of the water entering the mine, 1.5 gallons per minute, was evaporated in the combustion zone and was evolved with the gaseous products. This quantity was approximately equivalent to 0.04 mol of water per mol of dry gas. In tables 11 and 12, the value of 0.1 mol of water per mol of dry gas has been assumed. This assumption was based on later analytical determinations of the water actually associated with the effluent gas, bearing in mind that 40 percent of this figure can be justified from normal inflow of water and evaporation in the combustion zone. After June 21, temperatures rose to such a high level in the vicinity of the water sump that the deep well pump had to be removed.

TABLE 11. - Operating results, March 18 to June 21, 1949. Direction of flow, borehole I to borehole II

Week and cycles averaged 1/	Length of cycle, hours	Av. air flow, c.f.m. 2/	Average analysis of effluent gas: Percent CO_2	Ill.	O_2	H_2	CO	CH_4	N_2	Heating value, B.t.u. per cu. ft. 2/	Mol water per mol dry gas	Temperature of effluent gas: Av. temp., °F.	Max. temp., °F.	Average rate of coal consumption, tons per day 3/	Heat balance 4/, percent of heat of combustion of coal consumed: Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor	Unaccounted for and presumed stored underground, by difference
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4 - 2	16.9	4,130	7.0	0.2	11.6	-	0.2	-	81.0	4.6	5/0.1	513	700	8.3	20.0	10.6	13.2	56.2
5 - 11	7.6	5,285	5.9	.2	12.6	-	-	-	81.3	4.0	5/ .1	531	767	8.7	25.2	11.2	16.1	47.5
6 - 5	18.2	3,665	4.8	.2	14.2	-	0.2	-	80.6	4.6	5/ .1	503	666	5.2	27.3	15.1	18.7	38.9
7 - 3	17.1	7,296	4.4	.2	14.8	-	.2	-	80.4	6.0	5/ .1	592	1,290	9.7	35.2	21.0	20.7	23.1
8 - 5	19.1	7,622	4.0	.4	15.1	0.1	.2	0.1	80.1	9.9	5/ .1	736	1,039	10.4	43.8	33.9	21.4	.9
9 - 7	12.2	7,489	3.8	.3	14.9	-	.2	-	80.8	6.6	5/ .1	626	906	9.1	40.8	25.2	22.8	11.2
10-11	7.8	7,702	4.2	.2	14.4	.4	.4	0.2	80.6	8.6	5/ .1	646	921	10.6	37.5	29.0	20.3	13.2
11- 9	7.3	7,554	5.1	.1	13.4	.5	.4	.1	80.4	5.9	5/ .1	714	1,001	11.8	37.0	17.6	18.4	27.0
12- 3	8.7	7,275	5.3	.3	12.2	1.0	.2	.1	80.9	11	5/ .1	782	1,109	11.9	39.2	31.4	18.1	11.3
13- 7	8.5	7,216	5.4	.4	13.5	.6	.3	.6	79.2	17	5/ .1	767	1,122	13.8	33.2	41.9	15.5	9.4
14- 5	10.0	7,186	5.2	.6	13.4	.6	.4	.2	79.6	17	5/ .1	745	1,099	13.5	32.6	42.5	15.7	9.2
15- 2	13.8	7,200	5.0	.1	13.8	.4	.1	.4	80.2	8.0	5/ .1	764	1,140	10.9	41.2	24.6	19.4	14.8
																		6/21.9

1/ The first figure is the operating week, March 13-19, 1949 = 1; the second figure is the number of operating cycles in this direction during the week, the results of which are averaged. 2/ At 60° F., 30 inches Hg. dry. 3/ Basis of moisture- and ash-free coal. 4/ Heat balance is based on 60° F. 5/ Assumed during this period. 6/ Average.

TABLE 12. - Operating results, March 18 to June 21, 1949. Direction of flow, borehole II to borehole I

Week and cycles averaged 1/	Length of cycle, hours	Av. air flow c.f.m. 2/	Average analysis of effluent gas: Percent CO_2	Ill.	O_2	H_2	CO	CH_4	N_2	Heating value, B.t.u. per cu. ft. 2/	Mol water per mol dry gas	Temperature of effluent gas: Av. temp., °F.	Max. temp., °F.	Average rate of coal consumption, tons per day 3/	Heat balance 4/, percent of heat of combustion of coal consumed: Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor	Unaccounted for and presumed stored underground, by difference
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1 - 0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2 - 0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3 - 1	145.1	2,560	5.6	0.3	12.3	-	0.2	-	81.4	6.6	5/0.1	768	866	4.3	37.7	18.1	17.3	26.9
4 - 2	15.5	4,190	7.0	.2	11.8	0.1	.1	-	80.8	4.6	5/ .1	433	700	8.3	17.4	11.1	13.4	58.1
5 - 11	7.4	5,220	6.4	.2	12.6	-	.2	-	80.6	4.6	5/ .1	426	680	9.7	18.8	12.3	14.8	54.1
6 - 5	10.7	5,410	4.6	.1	14.3	-	.1	-	80.9	2.3	5/ .1	464	710	7.0	27.6	8.2	20.1	44.1
7 - 4	15.3	7,452	4.0	.2	14.8	-	.2	-	80.8	4.6	5/ .1	457	843	9.1	28.5	17.5	21.2	32.8
8 - 5	13.8	7,450	4.0	.2	15.4	-	.2	0.1	80.1	5.6	5/ .1	521	880	9.3	32.7	21.0	21.5	24.8
9 - 6	10.7	7,550	4.0	.3	15.3	-	.2	-	80.2	6.6	5/ .1	515	903	9.6	31.6	24.2	21.0	23.2
10- 10	7.2	7,718	4.7	.2	14.8	0.3	.3	0.2	79.5	8.0	5/ .1	573	949	11.6	30.5	25.0	19.0	25.5
11- 11	6.4	7,550	5.4	.2	13.7	.5	.4	.3	79.5	9.9	5/ .1	667	1,091	13.2	31.6	26.7	16.4	25.3
12- 7	7.8	7,285	5.8	.3	13.6	.7	.3	.3	79.0	12	5/ .1	554	938	13.8	23.7	30.0	14.5	31.8
13- 6	8.3	7,302	6.0	.3	12.9	.8	.3	.2	79.5	15	5/ .1	605	1,110	13.9	26.0	29.7	14.7	29.6
14- 5	8.0	7,268	6.5	.5	12.8	.6	.2	.5	78.9	18	5/ .1	605	939	16.1	22.5	38.6	12.7	26.2
15- 1	9.8	7,220	5.4	.0	12.8	.0	.0	.2	81.6	2.0	5/ .1	599	1,100	10.6	31.9	6.1	18.2	43.8
																		6/34.3

1/ The first figure is the operating week, March 13-19, 1949 = 1; the second figure is the number of operating cycles in this direction during the week, the results of which are averaged. 2/ At 60° F., 30 inches Hg. dry. 3/ Basis of moisture- and ash-free coal. 4/ Heat balance is based on 60° F. 5/ Assumed during this period. 6/ Average.

Table 11 also indicates that the average rate of coal consumption increased with time during the period. Heat balances on the system showed that the energy originally contained in the coal was being brought out principally as sensible and latent heat in the product gases. The heat of combustion of these gases varied between 10 and 42 percent of the energy originally contained in the coal and this percentage increased with time. The heat lost to the surrounding underground strata decreased from 56 percent at the beginning of the period to between 10 and 14 percent at the end. A numerical average of these figures as given in column 19 of table 11 indicates that approximately 22 percent of the heat of combustion of the coal was absorbed by the surrounding strata.

Results of the cycles for flow in the direction borehole II to borehole I are given in table 12. With the exception of heat balances, the results are similar to those given in table 11. Again, the heat balances show that the coal energy was brought out of the ground largely as sensible and latent heat in the product gases. The heat of combustion of the dry gas was low, and the total energy delivered above ground in the course of this period increased with time. The major difference caused by the reversed direction of flow was the quantity of heat lost to the underground surroundings. A numerical average of the values given in column 19 of table 12 indicates that about 34 percent of the heat was stored underground in contrast to the 22 percent heat loss when blowing in the opposite direction.

In this period of operation, 877 tons of moisture- and ash-free coal was consumed, as calculated from the material balances obtained on the system. This figure is based on the total quantity of air admitted, analysis of the coal in the region between boreholes I and II, and analysis of the effluent gases. No correction has been applied for possible leakage from the underground system. This factor will be discussed later.

A gradual increase in flow resistance through the system was noted during the course of this 15-week operating period. From the 8th to the 15th week, the input air rate was maintained at the maximum capacity of the reciprocating compressor for most of the time. Under this condition, the back pressures may be compared readily. This comparison is shown in table 13.' The apparent increase can be attributed to two factors: (1) the increase in over-all temperature level of the underground system required additional pressure to overcome expansion of gases underground, and (2) falls and fusion of roof rock tended to block the underground passages. It is believed that the second effect predominated, because this particular roof should have fused and become plastic at combustion temperatures.

The results demonstrated that the roof action along the 10-foot-wide single entry was not sufficient to provide efficient contact between the air and the coal faces. Gas produced at the coal faces was mixing and burning upon meeting air that had not contacted carbon. It is shown in tables 11 and 12 that large amounts of air was passing through the system without reacting with carbon or gas. In several instances cycles were run at reduced air-input rates without any appreciable change in the characteristics of the system. This further substantiated the belief that quantities of air was traveling through porous strata without contacting carbon. In a system containing parallel flow paths of constant dimensions, the proportion of the total flow following any path does not change with the total flow through the system.

TABLE 13. - Back-pressure development during the initial operating period from March 18 to June 21, 1949

Resistance to flow[1], pounds per square inch gage

Week	8	9	10	11	12	13	14	15
Direction of flow								
BH I to BH II..............	3.7	3.9	4.1	4.5	4.8	4.8	4.9	5.0
BH II to BH I..............	3.6	3.8	3.8	4.4	4.6	4.7	4.7	4.7
Average for both directions.	3.7	3.9	4.0	4.5	4.7	4.8	4.8	4.9

1/ The back pressures reported are for all cycles in which the input-air rate was over 7,000 cubic feet per minute.

Two tests were made to determine permeability characteristics of the coal and the overlying strata. In each instance the technique was similar. A constant pressure of 10 pounds per square-inch gage was applied to the underground system, and test holes 1, 3, 4, 6, 7, 8, 9, 10, 11, 12, and, at times, 5 were opened, and gas was allowed to bleed off to the atmosphere. The bottom-hole temperature and the flow and analysis of the effluent gas issuing at each test hole were measured periodically. These measurements were made over a period of 4 hours in the first test and 8 hours in the second.

The results obtained during the second test on May 10, 1949, are summarized in table 14. Test hole 5 was in the combustion zone, and test hole 4 was near, although the low flow indicates it was not yet in the combustion zone. Test holes 1, 6, and 7 were close to the combustion zone, as evidenced by the bottom-hole temperatures, but were still in coal. Test hole 8 was relatively far removed from the reaction zone but was connected by some fissure, as indicated by the relatively high gas flow. Test holes 9, 10, 11, and 12 were still relatively far from the reaction zone but had some connection with it. The effluent gases were mixtures of coal-distillation products, producer gas, air, and products of combustion.

It was possible to collect samples of light oil and tar being evolved at several of the holes, and this was done on subsequent occasions. The test showed that there was some possibility of gas flow through the laminations of the coal bed, but the resistance to flow was high. It did not prove that the entire path of travel was in coal, but in each instance a portion of the path was through coal.

While the system was under pressure, the adjacent hillside was examined to determine whether leakage existed. At a point about 300 feet west of borehole II, at the elevation of the Pratt coal outcrop, a very small volume of gas was escaping. The gas flow was below the coal bed, through the coal bed, and through strata just over the coal bed.

TABLE 14. - Results obtained during strata permeability test of May 10, 1949

Test-hole No.	Elapsed time, hours	Analysis of effluent gas								Bottom-hole temperature, °F.	Average effluent gas flow s.f.m.[1]
		Percent							Heating value, B.t.u. per cu. ft.[1]		
		CO_2	Ill.	O_2	H_2	CO	CH_4	N_2			
TH 1.................	1	9.3	0.1	0.9	0.2	0.6	1.8	87.1	23	182	30
	5	13.5	0	7.1	.7	.6	3.8	74.3	43	189	
	8	13.5	.1	7.3	1.7	.6	3.6	73.2	46	170	
TH 4.................	1	20.7	1.1	.3	1.9	2.1	18.4	55.5	221	1,291	
	5	24.9	1.8	.6	12.3	3.5	29.2	27.7	383	1,276	2.8
	8	24.5	0.8	.4	16.8	3.1	21.7	32.7	300	1,272	
TH 5.................	1	-	-	-	-	-	-	-	-	-	
	5	-	-	-	-	-	-	-	-	-	No reading[2]
	8	16.4	.3	4.7	21.8	8.1	9.2	39.5	196	-	
TH 6.................	1	19.0	.1	1.4	8.0	2.1	17.6	51.8	213	99	
	5	19.8	.7	1.4	9.2	2.0	16.5	50.4	217	102	5.5
	8	18.6	.8	1.2	5.2	1.2	20.7	52.3	246	100	
TH 7.................	1	19.3	1.0	1.4	5.5	1.8	22.0	49.0	266	127	
	5	19.3	1.0	3.0	11.5	2.0	21.8	41.4	284	129	8.6
	8	21.2	.6	2.8	6.9	1.5	25.5	41.5	297	116	
TH 8.................	1	8.8	.2	5.4	13.3	1.7	3.6	67.0	89	109	
	5	18.9	.3	3.6	4.9	1.3	8.9	62.1	116	115	19
	8	20.8	.1	3.0	4.0	0.6	9.3	62.2	111	103	
TH 9.................	1	15.5	.8	.3	4.3	4.7	20.2	54.2	250	50	
	5	18.2	.8	4.3	13.7	3.7	21.9	37.4	294	53	2.8
	8	17.7	1.0	2.8	23.0	4.4	25.0	26.1	362	47	
TH 10................	1	6.8	.2	8.5	.8	.4	1.9	81.4	39	91	
	5	18.4	.6	1.8	7.8	6.0	7.6	57.8	134	91	6.7
	8	-	-	-	-	-	-	-	-	84	
TH 11................	1	-	-	-	-	-	-	-	-	53	
	5	22.9	.5	.8	7.8	3.4	12.6	52.0	172	55	3.3
	8	21.2	.2	.9	7.6	2.7	12.5	54.9	164	50	
TH 12................	1	15.3	.2	2.0	.7	2.5	15.5	63.8	171	59	
	5	23.0	1.0	.4	6.5	5.2	23.4	40.5	295	63	3.3
	8	23.2	1.2	1.0	12.9	3.3	31.4	27.0	394	60	
											[3]72

1/ At 60° F., 30 inches Hg., dry.
2/ The flow at TH 5 can be estimated at 300 s.f.m.
3/ Average total flow excluding TH 5.

Second Operating Period, June 21 to October 5, 1949

The first operating period indicated that contact between the gas-making fluids and the coal faces was incomplete. This was largely responsible for the low over-all temperature level underground and resultant poor utilization of the coal. It was decided to drill holes along the line of the original entry connecting boreholes I and II and to inject a fluidized solid into the void spaces believed to exist in an effort to improve contact between air and coal faces.

Sand holes 1 to 6, inclusive, were drilled at the locations shown in figure 6 according to the over-all specifications given in table 5. Sand holes 1, 2, and 6 were thus on the center line of the original entry, 5 was on the west rib line of the entry, and 3 and 4 were bottomed in a region where the coal had been consumed. The drilling of these holes furnished the first direct evidence of the characteristics of the burned-out area, and a resume of drilling notes from each hole follows:

Drill Notes

Sand hole 1, SH 1

Distance above Pratt coal, feet	Elevation of top of coal 392.3 feet Remarks
7.6	No effect of heat or caving observed above this point. Lost water, steam issued from hole.
5.6	Bit fell suddenly after several blows at 7.6 ft., indicating a cavity overlain by a slab of rock.
2.6	Drilled with constant stream of water. Enough water retained in hole to bail cuttings. Cuttings were bright red, result of heat and oxidation.
0.4	Drilled through caving material. Cuttings red.
-5.5	Slow drilling due to caving through horizon of coal bed. No voids observed. Cuttings fireclay (bottom rock) and red rock. Bottom of hole.

Sand hole 2, SH 2

	Elevation of top of coal 387.5 feet Remarks
9.0	No effect of heat or caving observed above this point. Hot steam issued from hole. Water run into hole induced down draft of air. Red smoke observed issuing in puffs from borehole II.
8.7	Measured 4-inch void space when bit lowered in hole.
6.7	Drilled at a normal rate with constant stream of water in hole.
5.3	Drilled at very slow rate. Three hours further drilling failed to make progress. Driller's opinion bit deflecting from inclined slab. Bit corners rounded. Bottom of hole.

Sand hole 3, SH 3

Distance above Pratt coal, feet	Elevation of top of coal 386.2 feet Remarks
95.5	Inleakage of air or gas, indicated by bubbling.
70.5	Increased inleakage observed over preceding 5 feet.
25.5	Cuttings show no effect of heat.
20.5	Thermocouple in hole measured temperature 82° F. A few brown particles in cuttings.
15.5	Surface temperature of bit when withdrawn from hole 120° F. Cuttings normal shale color.
10.5	Bit temperature 162° F. A few red particles in cuttings.
7.5	Bit temperature, also bailed-water temperature 190° F. Loss of water noted. Cuttings contain brown and red particles.
2.5	Steam (from drilling water) issuing from hole. Bit temperature 203° F. Fine cuttings, many red and brown particles.

Sand hole 3, SH 3

	Remarks
0.3	Very fine cuttings, appearance similar to crushed coke, light-reflecting surfaces.
-1.2	Break through of gas into hole, rapid loss of water. Cuttings black, shiny, cellular, fine. Fast drilling.
-5.0	Slow drilling. Hard material. Bottom of hole.

Sand hole 4, SH 4

	Elevation of top of coal 385.2 feet Remarks
55.7	Slight inleakage of air or gas.
35.7	Increased inleakage noted.
25.7	Weak, light-gray shale, no indication of heat effects.
20.7	Cuttings as above; bit temperature 120° F.
15.7	Cuttings as above.
10.7	Cuttings very coarse, many red particles. Bit temperature 190° F.
5.7	Fine, dark-gray shale, few red particles. Bit temperature 203° F., caving into hole.
4.2	Started to lose water.
0.7	Fine, dark-gray shale, few red particles. Bit temperature 214° F.
-2.8	Lost all water.
-3.5	Coarse, lightweight, black, cellular cuttings slightly attracted by magnet. Hole had filled 3 feet when bit returned.
-4.5	Cuttings as above. Hard drilling. Bailed 7 feet of water. Bottom of hole.

Sand hole 5, SH 5

Distance above Pratt coal, feet	Elevation of top of coal 386.6 feet Remarks
30.2	Bit lukewarm.
25.2	Cuttings light-gray, coarse shale. Bit temperature 100° F.
20.2	Cuttings as above. Bit temperature 105° F.
15.2	Dark-gray, coarse cuttings, slight discoloration. Bit temperature 150° F.
10.2	Dark-gray, coarse, many red particles. Bit temperature 182° F.
5.2	Coarse cuttings, mixture of black and red particles. Bit temperature 190° F. Slight inflow of gas.
4.2	Lost water.
3.7	Steam and gas issued from hole.
0.7	Large volume gas and steam.
-3.5	Soft or loose material.
-3.6	Bottom of hole, hard material.

Sand hole 6, SH 6

	Elevation of top of coal 389.3 feet Remarks
26	Cuttings show brown discoloration.
21	Cuttings as above, bit warm.
16	Cuttings contain red particles. Bit temperature, 140° F.
11	Few red particles. Bit temperature 175° F.
8	Hard drilling. Many red particles. Bit temperature 190° F.
5.5	Hard drilling. Steam issuing from hole. Bit temperature 190° F.
0.5	5 feet fast drilling. Bit temperature 200° F. No gas flow.
-3.5	Bottom of hole.

The drilling notes from SH 1 and 2 indicate the presence of voids at horizons up to 9 feet above the top of the coal, which no doubt were caused by the roof action along the line of the single, 10-foot wide entry. SH 6 also was drilled along the line of the single entry, but not until sand filling of the voids at SH 1 and 2 had been completed. Definite indications of the presence of voids was not obtained, and the lack of gas leakage at a horizon only 6 inches above the top of the coal bed indicated that some success had been achieved in injecting fluidized sand.

The drilling notes from SH 3 and SH 4 do not indicate the presence of voids in the overlying strata. Small cracks in the strata were indicated at horizons 50 to 100 feet above the top of the coal bed. Samples of the drill cuttings were taken at regular intervals near the top of the coal bed, and the analyses of these cuttings are given in table 15. It must be remembered that cuttings removed from a churn-drill hole are not exactly representative of the strata through which the bit passes. Sloughing off of material above the sampling point and incomplete bailing tend to contaminate the sample. The samples were obtained by using all possible precautions to minimize these effects, and the analyses yielded qualitative information as to the action taking place underground.

TABLE 15. - Analysis of drill cuttings, sand holes 3 and 4

Sampling point, distance above top of coal,1/ feet	Volatile loss,2/ percent	Ultimate analysis, percent3/				
		Hydrogen	Carbon	Nitrogen	Sulfur	Ash
		Sand hole 3, SH 3				
25	5.7	-	-	-	-	-
20	4.7	-	-	-	-	-
15	6.1	-	-	-	-	-
10	6.2	-	-	-	-	-
5	3.3	-	-	-	-	-
0	0.0	-	-	-	-	-
- 2	1.6	-	-	-	-	-
- 3.9	10.7	0.2	11.1	0.3	0.9	87.9
- 4	23.0	0.3	21.9	0.4	1.1	75.6
		Sand hole 4, SH 4				
25	6.7	-	-	-	-	-
20	5.5	-	-	-	-	-
15	5.9	-	-	-	-	-
10	4.7	-	-	-	-	-
5	0.3	-	-	-	-	-
0	0.0	-	-	-	-	-
- 4	26.3	0.3	26.2	0.4	0.8	71.5
- 5	9.7	0.2	11.4	0.2	0.6	87.7

1/ The original thickness of the coal bed ranged between 3.5 and 3.75 feet.
2/ The sample was dried at 215° F. to remove moisture, then reheated to 500° F. to remove loosely combined moisture, etc. (all samples lost up to 0.2 percent on reheating to 500° F. except two, which lost 0.3 and 0.4 percent), then reheated to 1,500° F. and this final loss reported as volatile loss.
3/ As-received basis. Each analysis adds to just over or just under 100 percent without consideration of the presence of oxygen. Each sample contained a small quantity of hydrochloric acid soluble sulfide. These factors may be due to the reducing conditions existing in the region where the samples were obtained.

The analyses indicated that virtually all carbon had been gasified, although some remained near the level of the bottom of the coal bed.

The drilling notes and the analytical data of table 15 indicate that physical changes in the strata due to heat effects had occurred at horizons ranging from 7.6

to 15 feet above the coal and in SH 6, which was drilled much later than SH 1 or 2, at a horizon 26 feet above the coal. Visual examination of the cuttings did not indicate any bloating or expansion of the roof rock. SH 3 and SH 4, which were off the line of the entry, did not lose water at the coal-bed horizon during drilling. The bit went through material that was easily drilled, and no voids were found; these facts indicate that the roof in this area may have fused and come down behind the reacting coal face, as was expected.

Sand Injection

Upon completing sand holes 1 and 2, a quantity of sand was dried, screened, fluidized (see figs. 14 and 15), and injected into the underground voids at these locations. Operation of the project was continued as sand was injected.

Sand was chosen for filling the voids, because the cost was reasonable, it was easy to handle, and it had adequate refractory properties.

Standard 1-inch pipe was placed in the sand hole to a point 1 foot above the bottom. The 1-inch pipe was sealed in the hole by means of a flanged connection at the top of the surface casing. To help keep the hole open and to blow sand back into crevices, an air line was connected to the surface casing, and air was passed down the annulus between the sand line and the strata. Sand was injected until the hole plugged frequently; the sand line was then shortened 1 foot, and the process was continued. A sand hole was abandoned only when there was no longer any possibility of injecting a reasonable quantity of sand at any horizon intercepted by the hole.

It was found advisable to inject sand during periods when the project was operated at full blast rates, because under these conditions the stream of gas and air tended to carry sand away from the hole. Moisture collection in a sand hole tended to cause plugging, and at times it was necessary to vent hot gas at the sand holes in order to dry them.

On June 21, 1949, sand injection was started at SH 1. Injection at the various holes was continued as rapidly as possible throughout the second operating period ended October 5. SH 1 to 6 and test holes 1 to 5 were ultimately used for sand injection in the area between boreholes I and II, and solids were injected underground until March 3, 1950. Table 16 gives a summary of the quantities of solids injected in this area to October 5, 1949, and also to March 3, 1950.

Sand holes SH 1, 2, and 6, along the line of the entry, took 86 percent of the total solids injected underground, whereas sand holes SH 3, 4, and 5 and the test holes TH 1 to 5, inclusive, which were in areas originally underlain by coal, refused to admit a large quantity of sand. This, again, shows that the voids underground existed primarily along the line of the original entry. Most of the sand was injected at horizons relatively close to the top of the coal bed. The one exception was test hole TH 1, which received solids at a horizon 100 feet above the coal bed.

In February and March 1950, rock dust (pulverized limestone) was substituted for sand and injected at sand holes SH 3 and 5. The object of these tests was to determine whether a very small particle size would facilitate penetration of underground crevices. The results indicated that a larger quantity of rock dust could be injected at a given horizon, but it was not believed that the increase was significant.

TABLE 16. - Sand injected between boreholes I and II

Hole	Location	Sand injection, pounds Cumulative total through -			
		July 30, 1949, 6th week	Aug. 27, 1949, 10th week	Oct. 5, 1949, 16th week	Mar. 3, 1950
SH 1	Center of entry: 200 feet north of BH I..........................	131,540	131,540	131,540	131,540
SH 2	Center of entry: 100 feet north of BH I..........................	-	131,340	141,410	151,140
SH 3	19 feet west of center of entry: 100 feet north of BH I..........	-	-	-	13,050
SH 4	19 feet east of center of entry: 90 feet north of BH I...........	-	-	-	1,320
SH 5	West rib of entry: 110 feet north of BH I......................	-	-	-	6,450
SH 6	Center of entry: 150 feet north of BH I..........................	-	-	-	15,020
TH 1	15 feet west of center of entry: 50 feet north of BH I...........	-	-	420	8,750
TH 2	15 feet east of center of entry: 100 feet north of BH I..........	-	-	3,960	3,960
TH 3	15 feet west of center of entry: 150 feet north of BH I..........	-	-	6,270	6,270
TH 4	25 feet east of center of entry: 200 feet north of BH I..........	-	-	4,130	4,130
TH 5	15 feet east of center of entry: 250 feet north of BH I..........	-	-	4,460	4,460
	Total solids injected, pounds...	131,540	262,880	292,190	346,090
	Percent of total solids injected	38	73	85	100
	Volume of solids injected3/, cu.ft.	1,450	2,890	3,210	3,800
	Percent of volume of original entry4/	13.8	27.5	30.6	36.2

1/ Includes 11,880 pounds of rock dust.
2/ Includes 2,160 pounds of rock dust.
3/ Measured bulk density of dry sand, 91 pounds per cubic foot.
4/ Original entry volume: 10,500 cubic feet.

Solids injection in this area was 85 percent complete by October 5, the end of the second operating period. At this time, enough solids had been injected to fill 30.6 volume percent of the original entry. Table 17 shows the effect of sand injection on the resistance to flow through the system. The resistance to flow increased steadily as solids were injected, and during the 16 weeks of this operating period flow resistance doubled.

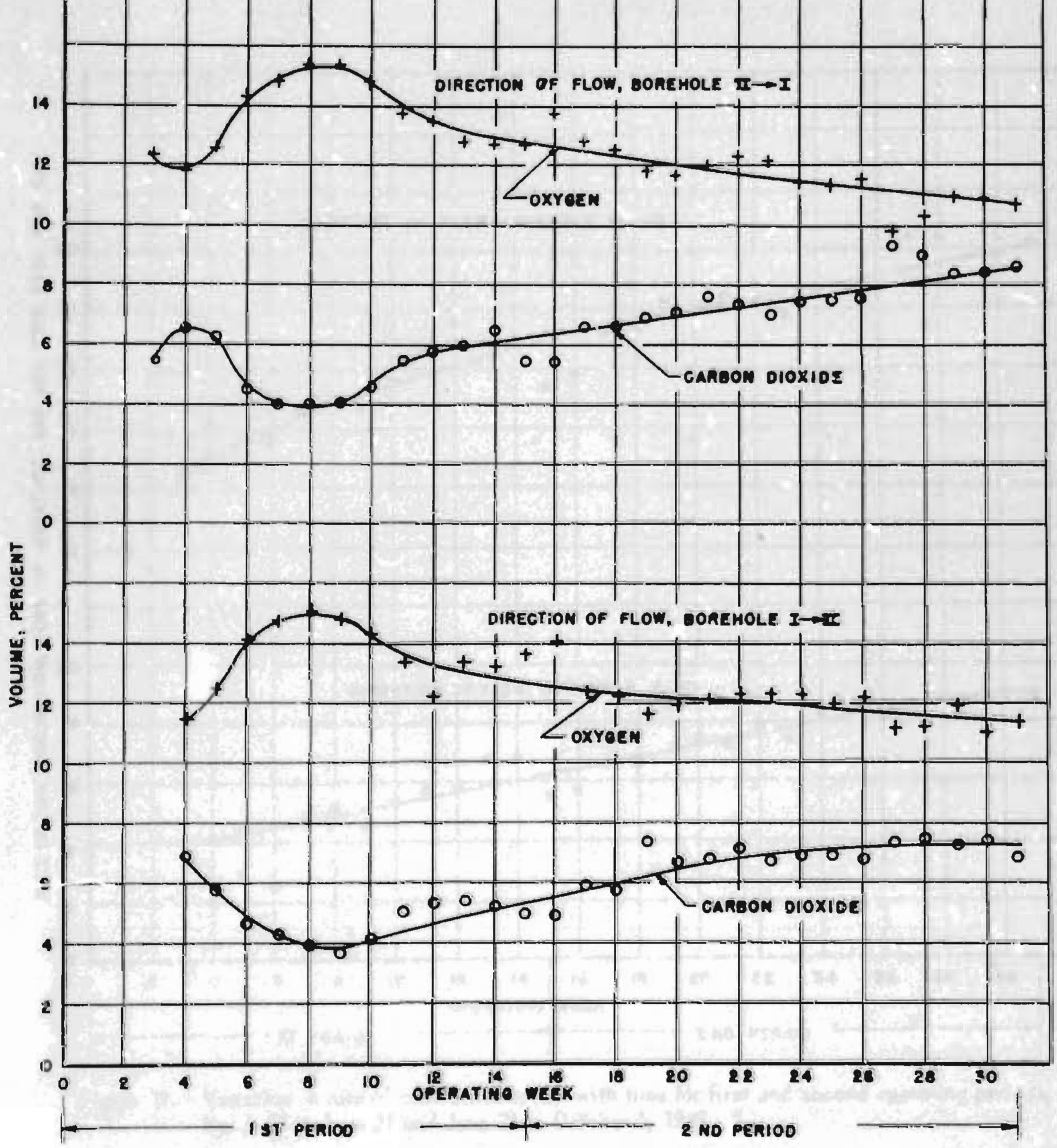


Figure 18. - Variation in effluent-gas composition with time for first and second operating periods, March 18 to June 21 and June 21 to October 5, 1949.

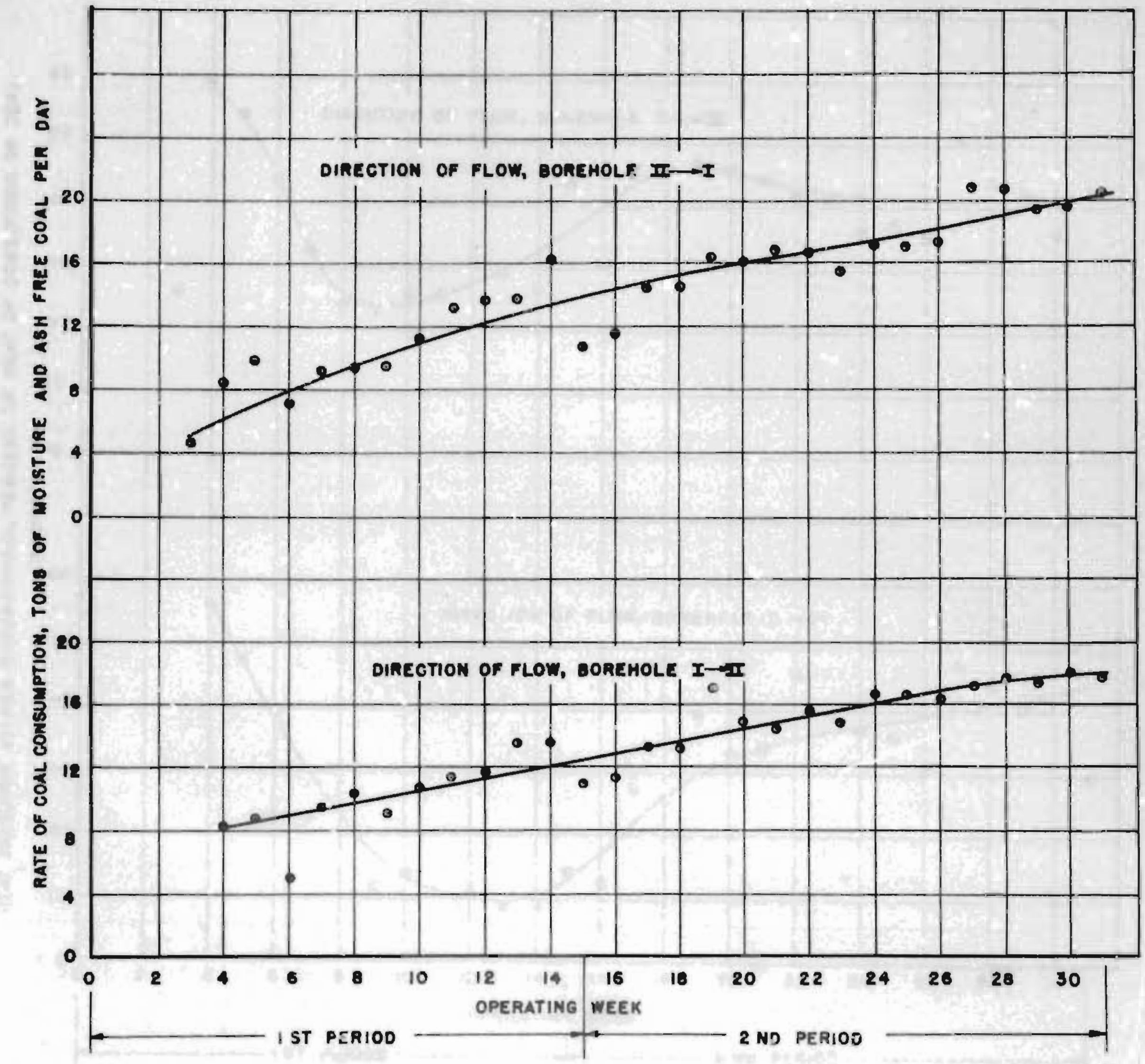


Figure 19. - Variation in rate of coal consumption with time for first and second operating periods, March 18 to June 21 and June 21 to October 5, 1949.

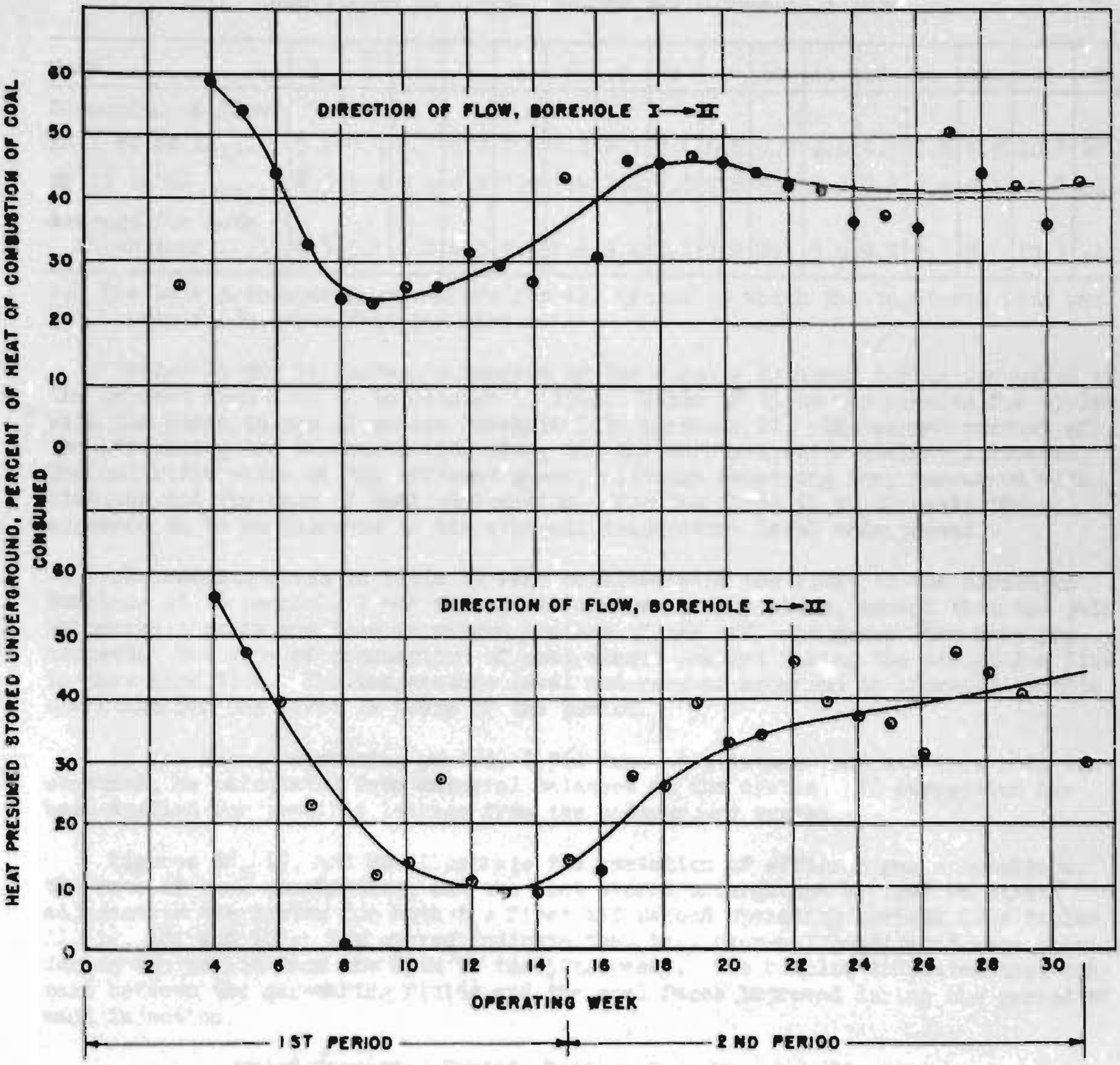


Figure 20. - Variation in heat stored underground with time for first and second operating periods, March 18 to June 21 and June 21 to October 5, 1949.

TABLE 17. - Back-pressure development during the second operating period, June 21 to October 5, 1949

Resistance to flow 1/, pounds per square-inch gage

Week.............	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Direction of flow:																
BH I to BH II.....	5.2	5.8	6.5	6.7	7.5	8.1	8.7	8.4	8.6	8.7	9.0	9.3	9.7	9.9	10.8	12.0
BH II to BH I.....	4.9	5.5	5.9	6.3	7.0	7.4	7.6	7.8	7.8	8.0	8.2	8.8	9.3	9.3	9.8	11.0
Average for both directions......	5.1	5.7	6.2	6.5	7.3	7.8	8.2	8.1	8.2	8.4	8.6	9.1	9.5	9.6	10.3	11.5

1/ The back pressures reported are for all cycles in which the input-air rate was over 7,000 cubic feet per minute.

Tables 18 and 19 contain summaries of the results obtained during operation of the project from June 21 to October 5, 1949. Table 18 lists the results for cycles with the blast in the direction borehole I to borehole II. The oxygen content of the effluent gases decreased with time, and the carbon dioxide content increased. The calorific value of the effluent gases, although remaining low, increased with time, as did the rate of coal consumption. For the first 11 or 12 weeks there appeared to be an increase in the over-all temperature level underground.

The results given in table 19 were obtained with the blast in the direction borehole II to borehole I and were quite similar to the above, except that the gain in carbon dioxide and loss in oxygen content of the effluent gases were more pronounced. The rate of consumption of coal almost doubled during the period for flow in this direction. The temperature level underground appeared to increase in this operation for the first 14 weeks of the period.

In the second operating period, 1,564 tons of moisture- and ash-free coal was consumed, as calculated from material balances on the system. No correction has been applied for possible leakage from the underground system.

Figures 18, 19, and 20 illustrate the variation of effluent gas composition, the rate of coal consumption, and the heat stored underground or lost to strata adjacent to the system for both the first and second operating periods (see tables 11, 12, 18, and 19). The curves indicate that best over-all conditions were obtained during the period from the 25th to the 30th weeks. The results indicated that contact between the gas-making fluids and the coal faces improved during the period of sand injection.

Third Operating Period, October 5, to December 22, 1949

Results of the second operating period showed that improved contact between the gas-making fluids and the coal faces was obtained by injecting fluidized sand. It was noted that during the last 7 or 10 days of this operating period the time required for the effluent gases to reach a predetermined temperature increased. This indicated a general deterioration in operating characteristics. Further, the difficulty in injecting fluidized sand became excessive, and it appeared that complete control of contact between reactants would not be achieved solely by injecting sand.

TABLE 18. - Operating results, June 21 to October 5, 1949. Direction of flow, borehole I to borehole II

Week and cycles averaged 1/	Length of cycle, hours	Average air flow, c.f.m. 2/	Average analysis of effluent gas, Percent: CO_2	Ill.	O_2	H_2	CO	CH_4	N_2	Heating value, B.t.u. per cu. ft. 2/	Mol water per mol dry gas	Temperature of effluent gas: Av. temp., °F.	Max. temp., °F.	Average rate of coal consumption, tons per day 3/	Heat balance 4/, percent of heat of combustion of coal consumed: Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor	Unaccounted for and presumed stored underground, by difference
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1 - 4	11.6	7,112	5.0	0.2	14.2	0.8	0.2	0.4	79.2	11	5/0.1	718	1,126	11.5	36.9	32.2	18.1	12.8
2 - 10	8.7	7,064	6.0	.3	12.5	.3	.3	.2	80.4	10	5/ .1	740	1,095	13.3	32.3	24.7	15.5	27.5
3 - 8	8.1	6,979	5.9	.3	12.3	.9	.6	.1	79.9	13	5/ .1	693	788	13.4	29.7	31.7	15.0	23.6
4 - 8	7.3	7,102	7.5	.2	11.7	1.1	.7	.2	78.6	12	5/ .1	697	1,048	17.0	24.0	23.9	12.2	39.9
5 - 10	7.9	7,159	6.8	.2	12.0	.3	.2	.5	80.0	11	5/ .1	726	1,173	15.1	28.4	24.4	13.8	33.4
6 - 10	9.0	7,139	6.9	.1	12.2	.3	.1	.4	80.0	7.4	5/ .1	729	1,208	14.5	30.3	17.0	14.3	38.4
7 - 8	8.3	7,129	7.2	.1	12.4	.4	.3	.4	79.2	8.4	5/ .1	635	1,145	15.6	23.8	18.1	12.9	45.2
8 - 9	8.6	7,103	6.8	.1	12.4	.4	.1	.6	79.6	9.7	5/ .1	621	1,174	14.7	24.5	22.1	13.6	39.8
9 - 10	7.8	7,142	7.0	.3	12.4	.4	.2	.7	79.0	15	.089	583	1,206	16.4	20.7	31.0	16.8	37.5
10- 7	8.3	7,188	7.0	.2	12.0	.6	.1	.9	79.2	15	.088	599	1,210	16.3	21.6	31.3	10.9	36.2
11- 4	9.6	7,175	6.9	.2	12.3	.6	.2	.8	79.0	15	.085	722	1,275	16.1	26.9	31.7	11.1	30.3
12- 6	11.7	7,107	7.6	.1	11.3	.5	.3	.8	79.4	13	.079	522	1,222	17.0	17.5	25.6	9.4	47.5
13- 5	12.3	7,092	7.7	.2	11.3	.5	.3	.9	79.1	16	.084	512	1,257	17.8	16.4	30.2	9.1	44.3
14- 6	13.4	7,066	7.3	.2	12.0	.7	.5	.8	78.5	16	.093	532	1,181	17.3	17.6	31.2	10.4	40.8
15- 1	18.8	7,340	7.5	.1	11.1	.6	.3	1.1	79.3	16	.052	597	1,098	18.0	20.0	30.8	5.9	43.3
16- 2	28.0	7,075	7.0	.1	11.6	.6	.3	1.7	78.7	22	.080	591	844	17.8	19.3	41.6	9.1	30.0

1/ The first figure is the operating week (1 = the week ended June 25, 1949); the second figure is the number of operating cycles in this direction during the week, the results of which are averaged. 2/ At 60° F., 30 inches Hg. dry. 3/ Basis of moisture- and ash-free coal. 4/ Heat balance is based on 60° F.
5/ Assumed during this period.

TABLE 19. - Operating results, June 21 to October 5, 1949. Direction of flow, borehole II to borehole I

Week and cycles averaged 1/	Length of cycle, hours	Average air flow, c.f.m. 2/	Average analysis of effluent gas, Percent: CO_2	Ill.	O_2	H_2	CO	CH_4	N_2	Heating value, B.t.u. per cu. ft. 2/	Mol water per mol dry gas	Temperature of effluent gas: Av. temp., °F.	Max. temp., °F.	Average rate of coal consumption, tons per day 3/	Heat balance 4/, percent of heat of combustion of coal consumed: Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor	Unaccounted for and presumed stored underground, by difference
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1 - 5	10.8	7,014	5.4	0.1	13.7	0.5	0.2	0.4	79.7	8.3	5/0.1	581	917	11.6	28.2	23.5	17.4	39.9
2 - 9	7.5	7,082	6.7	.1	12.9	.4	.3	.3	79.3	7.3	5/ .1	569	927	14.3	23.0	16.8	14.3	45.9
3 - 8	7.2	7,042	6.6	.2	12.6	.7	.5	.1	79.3	8.9	5/ .1	524	978	14.4	20.6	20.6	13.3	45.5
4 - 7	7.1	7,141	7.0	.1	11.8	.8	.9	.3	79.1	11	5/ .1	497	1,023	16.2	17.5	22.9	11.8	47.8
5 - 10	8.0	7,193	7.1	.1	11.7	.3	.4	.6	79.8	10	5/ .1	559	1,127	16.0	20.3	21.1	12.3	46.3
6 - 10	8.7	7,226	7.7	.1	12.0	.4	.1	.6	79.1	9.7	5/ .1	660	1,211	16.8	23.6	19.8	12.3	44.3
7 - 6	9.1	7,130	7.3	.2	12.3	.4	.3	.5	79.0	11	5/ .1	634	1,201	16.4	22.8	22.7	12.3	42.2
8 - 10	8.3	7,186	7.0	.1	12.1	.4	.2	.6	79.6	10	5/ .1	616	1,197	15.4	23.5	21.9	13.1	41.5
9 - 9	7.8	7,192	7.4	.3	11.4	.4	.2	.7	79.6	15	5/ .1	676	1,208	17.2	23.3	29.5	12.0	35.2
10- 9	7.6	7,285	7.4	.2	11.3	.6	.1	.8	79.6	14	5/ .1	645	1,028	17.0	22.6	28.2	12.1	37.1
11- 5	9.0	7,252	7.6	.1	11.6	.6	.2	.8	79.1	13	5/ .1	747	973	17.2	26.4	26.0	12.5	35.1
12- 7	11.7	7,280	9.4	.1	9.8	.5	.3	.7	79.2	12	5/ .1	656	1,316	20.8	19.3	19.9	10.0	50.8
13- 6	11.4	7,190	9.0	.2	10.2	.6	.3	.9	78.8	16	5/ .1	641	1,355	23.6	18.6	26.5	10.0	44.9
14- 6	12.0	7,136	8.4	.2	11.0	.6	.5	.8	78.5	16	.116	601	1,356	19.6	18.0	27.8	11.9	42.3
15- 1	18.4	7,180	8.4	.1	11.0	.6	.3	1.1	78.5	16	.177	565	1,320	19.5	17.1	28.1	19.0	35.8
16- 2	16.5	7,190	8.6	.1	10.8	.5	.3	1.3	78.4	18	.129	494	1,323	20.4	14.0	30.2	12.3	43.5

1/ The first figure is the operating week (the week ending June 25, 1949 = 1); the second figure is the number of operating cycles in this direction during week, the results of which are averaged. 2/ At 60° F., 30 inches Hg., dry. 3/ Basis of moisture- and ash-free coal. 4/ Heat balance is based on 60° F.
5/ Assumed during this period.

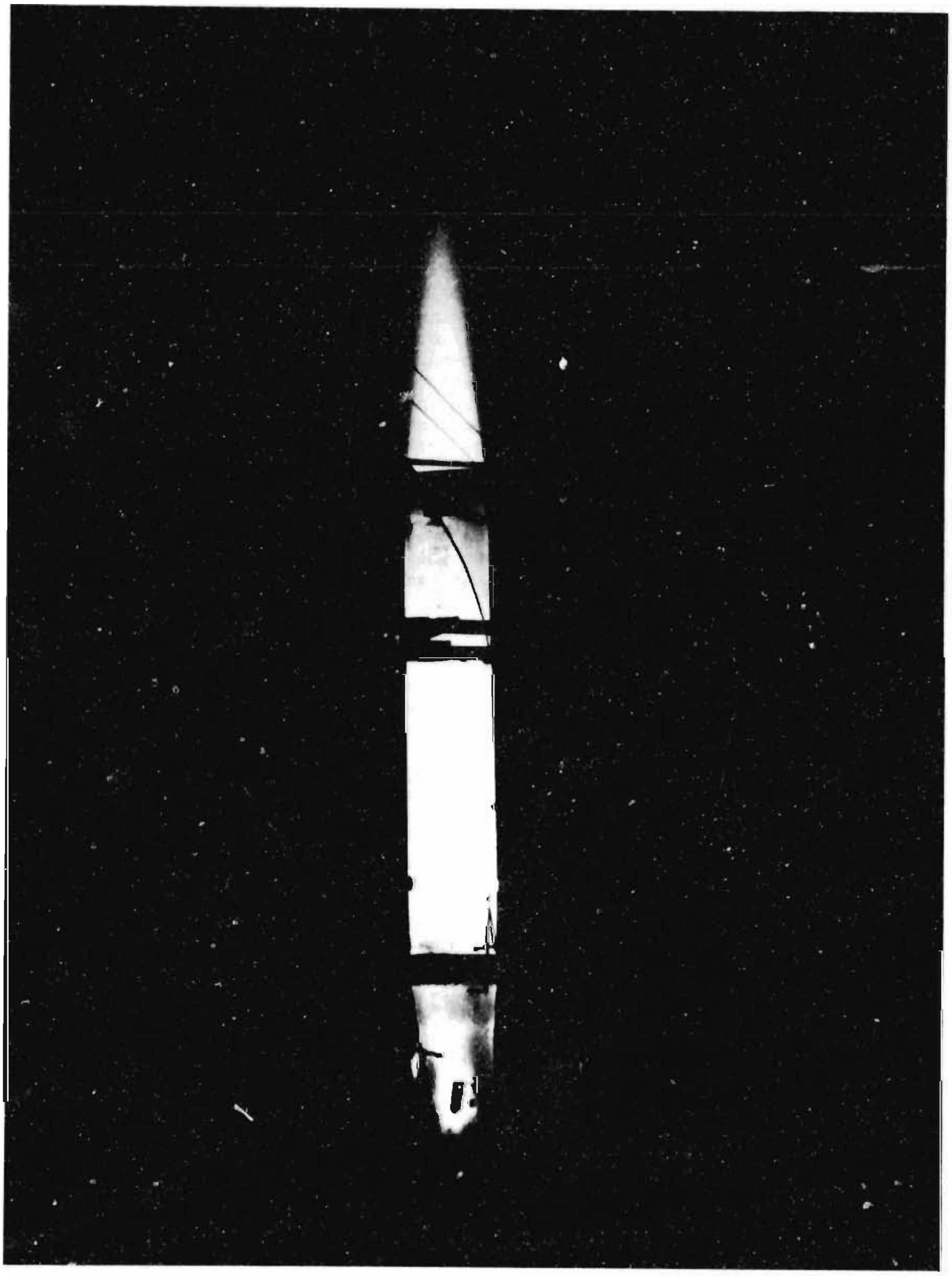


Figure 21. - Burning gas at borehole II.

Operations had never been carried on over an extended period after the temperature of the effluent gases had reached predetermined values, and it was decided to lengthen the cycle time and to determine the maximum effluent gas temperature that could be handled and the general operating characteristics of long cycles with relatively high effluent-gas temperatures.

The results of these long-cycle operations are summarized in tables 20 and 21. When the effluent gases reached a temperature of approximately 800° F. in the outlet borehole it was noted that a sudden and very rapid increase in temperature occurred. This temperature rise was accompanied by an increase in carbon dioxide content and a substantial decrease in oxygen content. Just prior to this temperature change, the effluent gases averaged 24 B.t.u. per cubic foot, and indications were that the temperature increase was caused by combustion of the make gases with excess air, which occurred only when the temperature level of the reactants had reached a high enough value. During this period a flame cone was apparent at the top of the 20-inch diameter outlet stack, as shown in figure 21. The appearance of this flame cone could be modified by changing the input air rates. This extensive secondary combustion must have originated at the level of the coal bed and probably at some distance from the bottom of the outlet borehole, because the indications were that the rate of coal consumption increased greatly after the temperature rose. It was also noted that the time lapse before secondary combustion of the make-gases started increased as the operating age of the system increased, indicating further deterioration in operating characteristics. The operation of the long cycles at the high effluent-gas temperatures resulted in utilization of relatively large quantities of coal near the outlets.

After the extensive secondary combustion started, the installation was operated for periods of 1 to 34 hours. The input-air rates were varied as indicated in tables 20 and 21, with but little effect upon the effluent-gas composition. It was not possible to take advantage of the high temperature level existing near the outlet and to establish a zone where the reduction of carbon dioxide to carbon monoxide would take place.

The effluent gases produced during operations at elevated outlet temperatures contained 63 to 86 percent of the heat of combustion of the coal largely as sensible and latent heat. The gases could be utilized either directly for raising steam or, after tempering with air, for operating gas-turbine units. The rate of coal consumption averaged 24 to 27.4 tons per day when operating with an input air rate of 7,300 cubic feet per minute, the highest coal consumption rate yet attained at the project. During the period October 5 to December 22, 1949, 1,347 tons of moisture- and ash-free coal was consumed.

Boreholes I and II operated satisfactorily at the high temperatures, and no difficulty was experienced with slagging of the walls at either location. Borehole I was an unlined hole, and borehole II was cased with 20-inch steel pipe backed with 4 inches of refractory cement.

TABLE 20. - Operating results, October 5 to December 22, 1949. Direction of flow, borehole I to borehole II

Cycle No.	Length of cycle, hours	Average air flow, c.f.m.1/	Average analysis of effluent gas: Percent							Heating value, B.t.u. per cu. ft.1/	Mol water per mol dry gas	Temperature of effluent gas		Average rate of coal consumption, tons per day2/	Heat balance3/, percent of heat of combustion of coal consumed			
			CO_2	Ill.	O_2	H_2	CO	CH_4	N_2			Av. temp., °F.	Max. temp., °F.		Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor	Unaccounted for and presumed stored underground, by difference
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
										Before combustion started at outlet								
431	38.5	6,720	6.8	0.1	11.0	1.1	0.4	2.1	78.5	28	0.102	488	760	17.4	13.6	51.6	10.5	24.3
433	67.4	6,820	6.9	.0	11.2	2.4	.8	1.5	77.2	26	.151	553	772	17.3	18.0	49.6	16.9	15.5
435	90.2	7,020	6.9	.2	11.2	1.7	.9	1.5	77.6	28	.104	635	819	18.7	19.9	50.8	11.4	17.9
437	49.4	7,010	6.6	.3	11.6	2.0	1.4	.8	77.3	25	-	537	783	18.2	17.0	46.6	4/10.6	25.8
445	56.3	7,380	8.6	.2	10.0	1.6	1.5	.5	77.6	19	-	497	782	22.3	13.4	30.3	5/ 8.8	47.5
448	97.1	7,720	7.0	.3	11.2	2.3	1.4	1.1	76.7	29	.066	512	859	21.7	15.0	50.4	6.6	28.0
451	77.0	8,040	7.6	.1	10.6	1.8	1.0	.5	78.4	16	-	538	813	20.3	17.3	30.3	4/10.6	41.8
454	101.4	8,080	7.4	.1	11.7	1.9	1.5	.6	76.8	19	.063	510	849	21.8	15.6	34.3	6.5	43.6
Av.		7,350	7.2	.2	11.1	1.9	1.1	1.1	77.4	24	.097	533	805	19.9	16.2	42.9	10.0	30.9
										After combustion started near outlet								
Av.		7,350	11.8	.1	6.6	.9	.1	.2	80.3	7.2	5/.184	1,814	1,917	24.0	51.4	10.3	23.6	14.7
Av.		4,780	14.4	.1	4.6	.3	.0	.2	80.4	5.0	5/.184	2,035	2,126	18.8	49.2	5.9	20.8	24.1
Av.		1,825	21.6	.1	2.0	.9	.3	2.2	72.9	28	5/.184	1,987	2,160	13.0	30.2	20.2	12.6	37.0

1/ At 60° F., 30 inches Hg., dry.
2/ Basis of moisture- and ash-free coal.
3/ Heat balance is based on 60° F.
4/ Average moisture content value applied.
5/ After secondary combustion in the stack started, the moisture content of the effluent gas averaged 1.9 times the previous value.

TABLE 21. - Operating results, October 5 to December 22, 1949. Direction of flow, borehole II to borehole I

Cycle No.	Length of cycle, hours	Average air flow, c.f.m.1/	Average analysis of effluent gas: Percent							Heating value, B.t.u. per cu. ft.1/	Mol water per mol dry gas	Temperature of effluent gas		Average rate of coal consumption, tons per day2/	Heat balance3/, percent of heat of combustion of coal consumed			
			CO_2	Ill.	O_2	H_2	CO	CH_4	N_2			Av. temp., °F.	Max. temp., °F.		Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor	Unaccounted for and presumed stored underground, by difference
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
										Before combustion started at outlet								
430	19.5	7,090	8.0	0.1	10.4	0.7	0.5	1.9	78.4	25	-	500	720	18.5	15.5	45.8	4/13.3	25.4
432	27.5	7,140	8.9	.1	10.0	1.1	.3	2.4	77.2	31	-	480	815	23.3	12.0	46.1	4/10.7	31.2
434	42.1	6,800	8.8	.3	10.0	2.6	2.0	.8	75.5	29	0.171	490	807	23.5	11.9	41.7	13.9	32.5
436	42.0	7,210	7.4	.4	11.3	2.6	1.5	.5	76.3	26	.134	431	705	20.6	12.2	44.6	14.2	29.0
442	43.4	7,230	7.1	.1	11.3	1.8	1.1	.8	77.8	20	-	574	819	18.3	18.9	38.1	4/15.7	27.3
444	42.0	7,410	8.8	.2	10.1	.7	.4	.8	79.1	16	-	480	918	20.8	13.6	27.0	4/14.4	45.0
446	54.7	7,430	8.5	.3	9.9	1.5	1.3	.6	77.9	21	.077	520	859	22.4	14.2	33.5	7.0	45.3
450	59.5	7,860	7.8	.3	9.9	1.4	1.4	.6	78.6	21	-	532	829	22.2	15.3	35.4	4/12.4	36.9
453	66.0	8,080	8.8	.2	10.3	1.9	1.6	1.1	76.1	27	.128	523	840	27.0	13.2	39.7	10.8	36.3
Av.	-	7,360	8.2	.2	10.4	1.6	1.1	1.1	77.4	24	.128	503	812	21.9	13.9	39.0	11.9	35.2
										After combustion started near outlet								
Av.	-	7,320	13.5	.1	5.3	.4	.1	.3	80.3	6.6	5/.243	1,658	1,793	27.4	41.0	8.2	25.9	24.9
Av.	-	4,230	16.0	.1	2.7	.3	.0	.3	80.6	6.0	5/.243	1,915	2,015	18.5	41.7	6.4	23.9	28.0
Av.	-	1,880	22.6	.1	1.4	.9	1.3	3.2	70.5	42	5/.243	1,795	1,864	15.5	24.2	27.0	14.0	34.8

1/ At 60° F., 30 inches Hg. dry. 2/ Basis of moisture- and ash-free coal. 3/ Heat balance is based on 60° F. 4/ Average moisture content value applies.
5/ After secondary combustion in the stack started, the moisture content of the effluent gas averaged 1.9 times the previous value.

Use of Test Hole 10 as an Inlet/Outlet and Installation and Operation of Borehole VI

A primary objective of the operation at Gorgas was to advance the reacting coal faces over an area of coal land by drilling boreholes off the line of the original underground passages and providing new inlets/outlets to the coal bed at the perimeter of the burned-out area underground. The first two operating periods indicated that in the area between boreholes I and II a low effective-temperature level underground and inadequate contact efficiency were obtained. It was believed that the use of a short path underground would tend to decrease over-all heat losses to the surrounding strata and result in a relatively high effective-temperature level underground. Gas samples obtained from test holes near burning coal ribs had indicated that a combustible gas was being produced where the contact efficiency was high. Consequently, during the third operating period test hole TH 10 was tried as a possible gas inlet/outlet. (See fig. 6.)

This test hole was midway between BH I and BH II and 35 feet east of the original entry line. The combustion zone was near this point, and TH 10 was connected to the air manifold, and attempts were made to inject air into the hole or by reversing the flow to remove gas from it. At each successive attempt to force air in or take gas out, a greater flow was attained. However, the effluent gas had not made good contact with the coal face, as shown by the following typical effluent-gas analysis:

	Percent
CO	4.0
Ill.	0.4
O_2	17.5
H_2	0.0
CO	0.2
CH_4	0.8
H_2	77.1

Subsequent inspection of the hole revealed that it was plugged for the first 2 feet above the top of the coal bed, and it contained 2.5 feet of water above that point. Apparently the gas was entering through crevices some distance above the coal bed, for temperature surveys indicated that a stream of cool air entered 33 feet above the coal bed. The hole was left open for several weeks during normal operation of the project. A strong flow of gas was maintained, and a bottom-hole temperature in excess of 1,300° F. was reached eventually, but good contact with the combustion face was never established.

Despite the failure to utilize TH 10 as a gas inlet/outlet, it was decided to drill a new borehole off the line of the original entry and to continue this phase of the investigation.

Borehole VI was drilled at the location shown in figure 6. It was 14 inches in diameter and was cased with 10-inch-diameter steel pipe to within 4 feet 6 inches of the top of the coal bed. (See table 5.) Cuttings obtained 4 feet above the coal bed contained red particles. The rock (shale) was very weak at this point, and the sides of the hole caved badly. Thermal effects had resulted in weakening the strata, as shown by comparison of these cuttings with the cuttings from holes drilled in areas unaffected by heat. When the coal bed was drilled through, and after the casing was set, particles of what appeared to be low-temperature coke were blown from the hole. Gas issued freely from the hole when the drill pierced the coal bed.

BH VI was completed and put into operation on January 30, 1950. Air at full capacity of the reciprocating compressor was introduced at BH VI, with the gas outlet at BH II. The initial resistance to air flow was high, but it soon decreased, perhaps as a result of burning passageways through the coke near the bottom of the hole. The gas analyses for this cycle (No. 572) is shown in table 22 and indicates complete utilization of the oxygen but production of very little combustible gas.

TABLE 22. - Operating results, borehole VI-borehole II

Cycle No.	Length of cycle, hours	Average air flow, c.f.m.1/	Average analysis of effluent gas: Percent CO_2	Ill.	O_2	H_2	CO	CH_4	N_2	Heating value, B.t.u. per cu ft.1/	Mol water per mol dry gas	Temperature of effluent gas: Av. temp., °F.	Max. temp., °F.
1	2	3	4	5	6	7	8	9	10	11	12	13	14
			Direction of flow, BH VI to II										
572	8.0	7,720	25.2	0.1	0.9	0.6	0.8	0.2	72.2	8.6	0.159	327	414
			Direction of flow, BH II to VI										
573	8.0	5,790	3.3	.0	.4	11.0	13.8	1.0	70.5	90	4/0.200	1,138	1,482
			Direction of flow, BH VI to II										
574	7.75	6,360	18.1	.0	6.9	.9	.9	.5	72.7	11	0.244	316	455
			Direction of flow, BH II to VI										
575	2.5	6,980	-	-	-	-	-	-	-	-	-	1,600	-

Cycle No.	Rate of coal consumption, tons per day2/	Heat balance3/, percent of heat of combustion of coal consumed: Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor	Unaccounted for and presumed stored underground, by difference
1	15	16	17	18	19
		Direction of flow, BH VI to II			
572	60.7	3.6	5.7	5.6	85.1
		Direction of flow, BH II to VI			
573	31.7	20.1	87.0	14.0	-
		Direction of flow, BH VI to II			
574	36.4	4.6	9.9	9.9	75.6
		Direction of flow, BH II to VI			
575	-	-	-	-	-

1/ At 60° F., 30 inches Hg., dry.
2/ Basis of moisture- and ash-free coal.
3/ Heat balance is based on 60° F.
4/ Assumed to be the same as the average of cycles 572 and 574.
5/ During this cycle borehole VI slagged and plugged.

The direction of blast was reversed after 8 hours, air being introduced at BH II, and gaseous products were removed at BH VI. A sustained production of combustible gas, averaging 9.4 million cubic feet per day at 90 B.t.u. per std. cu. ft., was achieved during this cycle. (See cycle 573, table 22). The combustible constituents of the gas were predominantly carbon monoxide and hydrogen. The oxygen-nitrogen ratio in the gas was less than that of air and indicates that some of the hydrogen being distilled from the coal was probably being burned. The gas was produced at a relatively high temperature, reaching a maximum of 1,480° F. in the borehole. Air input during this cycle was reduced from the normal value of about 7,500 c.f.m. to 5,790 c.f.m. because of the high resistance to flow imposed by the underground system (the back pressure averaged 21.3 p.s.i.g.) as well as the relatively high exit-gas temperatures. The heat balance (table 22) shows more heat being extracted from the system than was furnished by the coal consumed. An equilibrium was not reached during this cycle, and this unbalance was a function of the past history of the system. (i.e. heat stored underground during previous operation).

The direction of blast was again reversed after 8 hours. During cycle 574 (table 22) the input air averaged 6,360 c.f.m., and the resistance to flow 21.4 p.s.i.g. The gas, as during cycle 572, contained little combustible matter, and, in addition, unreacted oxygen appeared in the gas.

The direction of blast was reversed for the third time after 7.75 hours. As before, a high resistance to air-gas flow was found; the back pressure was 20.6 p.s.i.g. Shortly after the start of the cycle, the effluent gas caught fire and burned at the outlet for approximately 15 minutes. The flame was extinguished, and gas of unknown composition was produced at approximately 1,200° F. for about 1 hour. At this time, the recorded outlet temperature increased sharply to about 1,800° F., and flames and molten material issued from the borehole. The air supply was cut off, and the flames were allowed to subside. Upon attempting to introduce air into BH VI, it was found that the hole was completely stopped. The following day, the underground system was placed under a pressure of 23 p.s.i.g. in order to investigate the obstruction. Only a slight flow was observed at BH VI. Inspection of the hole indicated a stoppage 60 feet below the surface and 90 feet above the coal bed. Attempts were made to open the hole by blasting and by churn drilling through the obstruction, but very little progress was made. Numerous pieces of iron-bearing slag somewhat harder than tool steel were thrown from the hole during blasting. In view of the difficulty and probable high cost of opening the hole, it was abandoned and sealed.

The operation of BH VI, although brief, showed that under certain conditions it was possible to produce combustible gas in appreciable volume on a sustained basis. During cycle 573, good contact was obtained between air and carbon in a high-temperature environment. Physical conditions - location, shape, and area of openings available for passage of air and gas near the junction of the borehole with the coal bed - provided contact that improved the quality of the gas. It was evident that choking of the air passageways, perhaps by the slagging or bloating of the roof rock, began during cycle 573. Chilling the heated rock upon reversal during cycle 574 opened passages for air and gas, which permitted them to escape contact with carbon. During the final cycle (575), previously unreacted oxygen mixed with combustible gas in or near the borehole and the mixture ignited, causing the walls of the hole to slag.

Later, a slight flow of gas was observed from BH VI. Inspection of the hole revealed water standing above the stoppage. This gas, therefore, entered the hole through the walls, probably from TH 10.

Sampling of Gases at Various Test Holes and Construction of Borehole VII

The progress of combustion in the coal bed was determined by a temperature-time record at each of the several test holes whose locations are shown in figure 6. During the operation, many of these test holes were burned into; and during the fall of 1949 and the winter of 1950 gas samples were taken at several of these places in an effort to obtain a better understanding of the reactions taking place underground.

Table 23 contains a summary of the gas analyses obtained at test holes 6 and 13, which were burned into during September 1949. All of the average analyses given were obtained with the air-gas flow in the indicated direction, and the test holes were close to the outlet from the system. When samples were taken with flow in the opposite direction, the analyses showed that the gas at these points was unreacted air containing some products of combustion.

TABLE 23. - Average analyses of gas samples taken at test holes 6 and 13

Period averaged	Analysis, percent							Heating value, B.t.u. per cubic foot, dry
	CO_2	Ill.	O_2	H_2	CO	CH_4	N_2	
	TH 6, direction of flow, BH II to BH I							
Oct. 19 to Dec. 22, 1949	10.0	0.2	1.8	8.6	7.8	2.2	69.4	79
Dec. 22 to Dec. 31, 1949	12.4	.2	1.2	3.8	5.6	1.2	75.6	47
January 1950.......	10.9	.2	.2	4.2	8.2	1.4	74.9	58
February 1950......	12.1	.2	.3	4.4	5.1	.8	77.1	43
March 1950.........	13.2	.1	.2	4.0	4.6	.8	77.1	38
April 1950.........	17.4	.1	.2	2.2	2.3	.7	77.1	24
	TH 13, direction of flow, BH I to BH II							
Oct. 19 to Dec. 22, 1949	8.8	0.2	0.2	8.3	10.4	2.2	69.9	87
Dec. 22 to Dec. 31, 1949	11.2	.2	.3	2.8	6.7	1.1	77.7	46
January 1950.......	12.2	.2	.2	3.8	6.8	1.0	75.8	48
February 1950......	14.6	.2	.3	2.4	4.7	.6	77.2	33
March 1950.........	17.8	.0	.6	.6	.7	.3	80.0	7.3
April 1950.........	18.0	.0	1.1	.2	.0	.1	80.6	1.7

The analyses indicate that a combustible gas was being made on the reacting coal faces. All of the analyses given in table 23 are average and cover considerable lengths of time. Individual samples taken during October often were of much better quality than the average for the period, and carbon monoxide and hydrogen at times each exceeded 20 percent by volume. As the age of the system increased, the distance from the reacting face to the sampling point increased, and a steady deterioration in quality of the samples was noted. In April 1950, substantial amounts of oxygen began to appear in samples from TH 13 and TH 6, and the heating value of the gas was reduced materially.

During the period covered in table 23, many samples of gas were obtained from test holes 7, 8, and 12. All of these samples showed that the fluids flowing at the point of sampling were largely unreacted air containing some products of combustion and coal distillation. These streams of high oxygen-content gases were indicative of poor contact efficiency and were responsible for secondary combustion of the gases produced at the coal faces.

The brief operation of borehole VI and the analyses of gas samples taken near a reacting face showed that when the contact efficiency was improved, a product of better quality resulted. This led to the decision to construct another borehole, VII, off the line of the original entry and to set up and operate a new reaction zone between BH VII and BH III. Further, it was decided to block off the entry and the air course between BH III and BH II with fluidized sand, and to attempt to set up a single-face high-temperature reaction zone.

In preparation for the new borehole, test hole 15 was drilled at the location shown in figure 6, and it was bottomed on February 7, 1950, in a region where the coal had been burned out. In order to locate the perimeter of the burned-out area, test hole 16 was drilled and completed on February 14, 1950. This hole, 65 feet east of BH II, was bottomed in a region where the coal had been carbonized, and the carbon was present as low-temperature coke. Steam and gas flowed from the hole when the drill reached the horizon of the coal bed, but the flow of gas was small. It was decided to drill borehole VII 10 feet east of TH 16.

Borehole VII was completed on March 28, 1950, and the specifications are given in tables 5 and 9. It was fitted with a water jacket and surface seal similar to that shown in figure 7. As the drill approached the horizon of the coal bed, warm rock was penetrated about 8 feet above the top of the coal. No voids were found, and water was retained in the hole throughout. No flow of gas was found, and the particles of coal appearing in the drill cuttings were hard and bright, with shiny faces and sharp edges. No physical changes due to heat were noted, either in the coal or in the overlying strata.

Upon completion of borehole VII, various attempts were made to burn into it as quickly as possible. During April and May, samples of gas were taken at this borehole, of which the following analysis is typical.

	Percent
CO_2	17.0
Ill.	1.4
O_2	2.1
H_2	6.2
CO	1.8
CH_4	12.5
N_2	59
Heating value, B.t.u. per cu. ft. dry.	181

Gas samples were also obtained at test holes 15 and 16, and the following analyses are typical of these:

	Percent TH 15	Percent TH 16
CO_2	8.0	5.9
Ill.	.3	.2
O_2	4.1	8.3
H_2	3.2	3.8
CO	3.7	4.6
CH_4	.8	.9
N_2	79.9	76.3
Heating value, B.t.u. per cu. ft. dry	36	40

1113 ELDER JL

THE SECOND UNDERGROUND GASIFICATION EXPERIMENT AT GORGAS, ALABAMA

Despite the many attempts made to burn into borehole VII quickly, it was not until May 30, 1950, that the combustion zone finally reached this point. The borehole was then sealed off, and final preparations were made to put the section between boreholes III and VII into operation.

During the period January to March 1950, sand holes 7 to 13, inclusive, were drilled along the center lines of the entry and air course between boreholes II and III at the locations shown in figure 6. When sand hole 9 was drilled, it was found that the coal had been burned out along the entry beyond this point, although it was possible to drill into the bottom rock below the original coal bed. Sand holes 10 and 13 showed that heat effects had caused some roof falls in this region, and that the perimeter of the combustion zone was very near. Sand holes 7, 8, 11, and 12 were drilled into the original entry and air course, and although some roof fall was noted, the physical changes due to heat effects were found to be slight.

Fourth Operating Period, December 22, 1949, to June 5, 1950

It was decided to discontinue the long cycles used during the third operating period because of the high rates of coal consumption in areas adjacent to the outlet boreholes and the inability to set up a high-temperature zone where efficient reduction of carbon dioxide to carbon monoxide would be obtained. During the construction and testing of borehole VI and the construction and burning into of borehole VII, it was planned to operate the project on regularily scheduled and frequent reversal times. The purpose was to try to concentrate the active combustion zone at the midpoint of the path between boreholes I and II and to consume coal at the highest attainable rate in this region.

The results obtained during this period of operation have been summarized in tables 24 and 25. The cycle lengths were maintained at approximately 8 hours during the first 22 weeks of the period and at approximately 12 hours during the last weeks. The effluent-gas analyses indicated a steady deterioration in operating characteristics with time, the carbon-dioxide content decreasing and the oxygen content increasing. The rate of coal consumption decreased with time. The heat unaccounted for and presumed stored underground, as shown in figure 22, decreased with time when the direction of flow was BH I to BH II and varied irregularly when the direction of flow was BH II to BH I.

During the fifth week of operation, the air-input rate was decreased from 7,600 cubic feet per minute to 2,000 cubic feet per minute in order to determine the effect of reduced air-input rates on the effluent-gas composition. This change in rate of air input had no effect on the quality of the product gases.

Table 26 gives the resistance to flow that was obtained during the period. This resistance increased slightly during the first half of the operating period, possibly due to the injection of some fluidized solids underground. During the last half of the period, the resistance to flow decreased, indicating an opening of strata in the region between boreholes I and II.

During this fourth operating period 2,088 tons of moisture- and ash-free coal was consumed in the region between boreholes I and II. The total coal consumption in this area for the first four periods was 5,876 tons, as calculated from the material balances, with no correction for possible leakage.

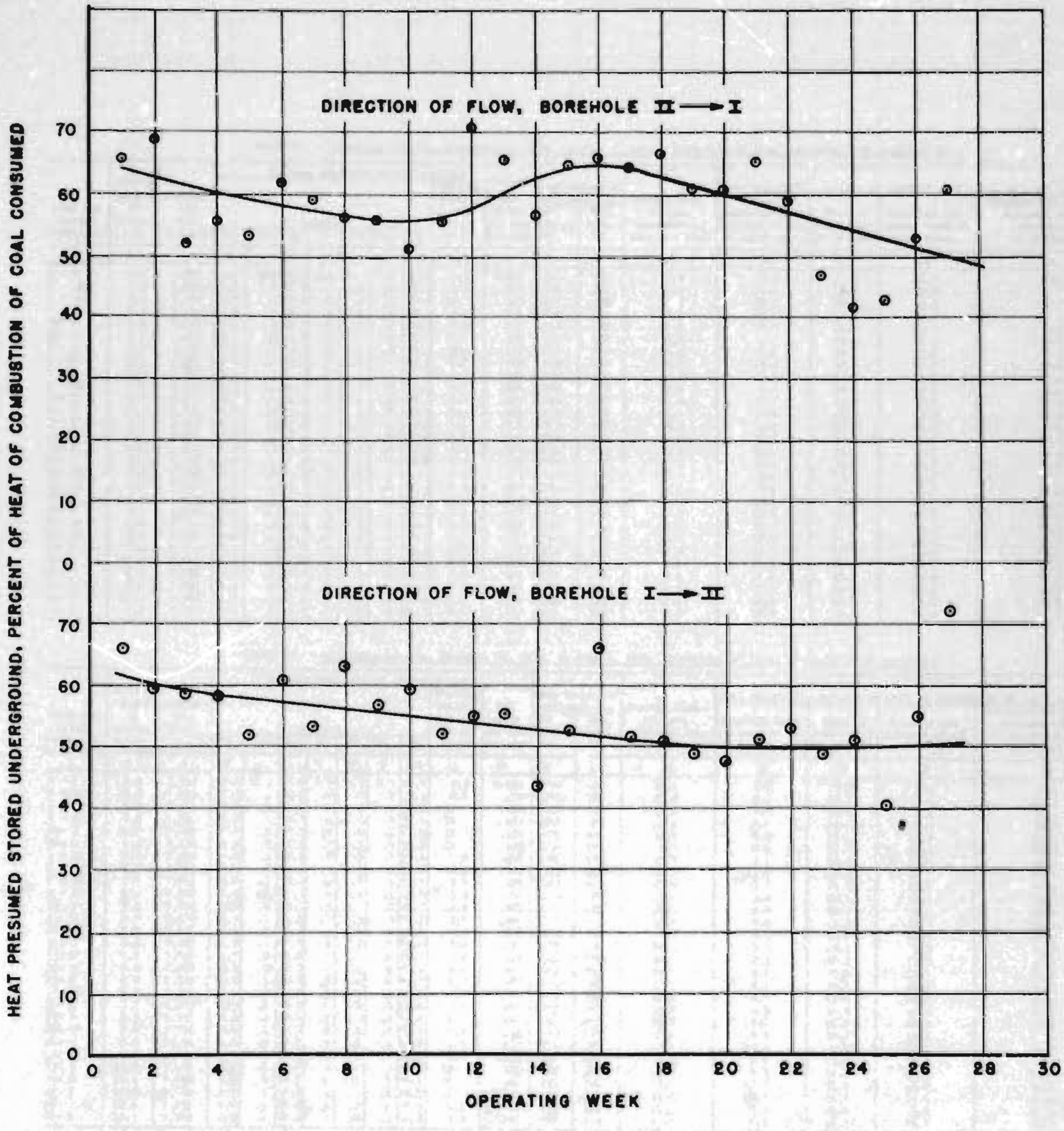


Figure 22. - Variation in heat stored underground with time for fourth operating period, December 22, 1949 to June 5, 1950.

TABLE 24. - Operating results, December 22, 1949, to June 5, 1950. Direction of flow, borehole I to borehole II

Week and cycles averaged[1]	Average length of cycle, hours	Average air flow, c.f.m.[2]	Average analysis of effluent gas: Percent CO_2	Ill.	O_2	H_2	CO	CH_4	N_2	Heating value, B.t.u. per cu. ft.[2]	Mol water per mol dry gas	Temperature of effluent gas: Av. temp., °F.	Max. temp., °F.	Average rate of coal consumption, tons per day[3]	Heat balance[4], percent of heat of combustion of coal consumed: Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor	Unaccounted for and presumed stored underground, by difference
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1 - 4	7.7	7,852	7.0	0.2	12.2	0.4	0.2	0.2	79.8	5.9	0.097	271	365	16.4	9.0	13.3	11.3	66.4
2 - 10	7.9	7,810	7.3	.2	12.4	.3	.2	.2	79.4	7.6	.138	261	381	17.0	8.4	16.5	15.4	59.7
3 - 10	8.1	7,586	7.5	.3	12.2	.2	.1	.3	79.4	10	.125	257	370	17.3	7.7	20.7	13.3	58.3
4 - 11	8.0	7,553	7.4	.2	12.3	.5	.2	.3	79.1	9.2	.154	245	354	16.9	7.4	19.1	16.4	57.1
5A- 4	7.9	7,655	6.3	.2	12.7	.4	.2	.2	80.0	7.9	.155	251	360	14.5	8.8	19.5	19.7	52.0
5B- 5	7.6	2,089	10.1	.1	12.4	.6	.2	.4	76.2	8.7	.553	163	198	6.4	3.2	14.0	44.0	38.8
6 - 9	7.4	7,548	6.6	.1	12.5	.6	.2	.1	79.9	5.6	.137	247	349	14.3	8.6	13.7	17.2	60.5
7 - 8	7.3	7,846	6.4	.1	11.4	.8	.2	.2	80.9	7.2	.144	269	382	14.5	9.9	18.0	18.7	53.4
8 - 9	8.0	7,898	6.6	.1	13.6	.4	.3	.2	78.8	6.3	.093	263	373	15.6	9.3	15.8	11.5	63.4
9 - 11	7.7	7,950	5.9	.1	13.8	.3	.1	.2	79.6	5.3	.134	249	358	13.6	9.7	14.6	18.9	56.8
10- 9	8.0	7,951	5.7	.1	14.0	.2	.2	.2	79.6	5.3	.129	215	357	13.4	8.1	14.8	18.2	58.9
11- 6	8.0	8,128	4.8	.1	13.8	.3	.1	.2	80.7	5.3	.103	269	370	11.4	12.9	17.5	17.6	52.0
12- 9	7.9	7,994	6.1	.1	13.6	.2	.2	.2	79.6	5.3	.091	260	378	14.4	9.9	13.8	12.2	55.1
13- 5	7.2	8,038	5.5	.1	13.9	.3	.2	.2	79.8	5.6	.126	234	334	13.1	9.6	16.3	18.7	55.4
14- 8	7.4	7,848	4.8	.1	13.2	.3	.1	.2	81.3	5.3	.160	255	359	10.9	12.1	17.6	27.3	43.0
15- 7	7.7	7,918	6.0	.1	13.2	.3	.1	.1	80.2	4.3	.170	283	394	13.5	11.4	11.8	24.2	52.6
16- 11	8.0	7,890	6.2	.0	13.2	.3	.2	.1	80.0	2.6	.121	249	351	13.7	9.6	7.0	16.7	66.7
17- 10	7.7	7,848	5.7	.1	14.0	.5	.4	.4	79.2	7.9	.130	232	320	13.5	8.9	21.7	18.2	51.2
18- 8	7.7	7,859	5.2	.1	14.3	.3	.1	.3	79.7	6.3	.127	247	345	12.2	10.6	19.1	19.7	50.6
19- 7	7.7	7,736	5.0	.1	14.1	.3	.1	.3	80.1	6.3	.133	243	340	11.5	10.8	19.8	21.4	48.0
20- 10	7.8	7,721	4.5	.1	14.5	.2	.1	.3	80.3	6.0	.161	260	352	12.5	10.7	17.3	23.9	48.1
21- 10	8.0	7,687	4.6	.1	14.3	.2	.0	.1	80.7	3.7	.127	244	330	10.0	12.3	13.2	23.2	51.3
22- 6	8.0	7,670	4.9	.1	14.6	.2	.0	.2	80.0	4.7	.121	240	323	10.9	11.1	15.5	20.4	53.0
23- 2	11.0	7,620	4.1	.2	14.8	.3	.0	.1	80.5	4.0	.125	255	351	9.5	12.6	14.9	24.0	48.5
24- 5	11.1	7,638	4.4	.0	14.0	.4	.0	.2	81.0	3.3	.123	255	348	9.3	12.9	12.5	24.0	50.6
25- 3	8.6	7,593	4.9	.2	13.9	.2	.1	.3	79.5	8.0	.146	268	400	11.6	12.1	24.6	23.3	40.0
26- 4	11.6	7,620	5.3	.1	13.4	.2	.0	.1	80.9	3.7	.134	266	375	11.3	12.1	11.5	21.6	54.8
27- 2	7.8	7,650	4.9	.0	13.8	.2	.0	.0	81.1	0.7	.079	233	303	9.9	11.4	2.5	14.4	71.7

TABLE 25. - Operating results, December 22, 1949, to June 5, 1950. Direction of flow, borehole II to borehole I

Week and cycles averaged[1]	Average length of cycle, hours	Average air flow, c.f.m.[2]	Average analysis of effluent gas: Percent CO_2	Ill.	O_2	H_2	CO	CH_4	N_2	Heating value, B.t.u. per cu. ft.[2]	Mol water per mol dry gas	Temperature of effluent gas: Av. temp., °F.	Max. temp., °F.	Average rate of coal consumption, tons per day[3]	Heat balance[4], percent of heat of combustion of coal consumed: Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor	Unaccounted for and presumed stored underground, by difference
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1 - 4	8.0	7,910	7.2	0.1	12.2	0.7	0.8	0.3	78.7	9	0.062	230	321	18.2	6.6	20.5	6.5	66.4
2 - 10	8.0	7,735	7.3	.1	12.0	.6	.8	.2	79.0	8.6	.070	217	322	17.8	6.1	17.7	7.3	68.9
3 - 10	8.0	7,644	7.4	.3	12.0	.4	.2	.9	78.8	17	.092	226	357	18.8	6.1	32.8	9.0	52.1
4 - 11	8.0	7,560	7.4	.3	12.1	.9	.6	.3	78.4	14	.091	244	384	18.3	6.9	27.6	9.2	56.3
5A- 3	7.9	7,603	6.6	.3	12.5	.5	.4	.3	79.4	12	.105	253	461	16.2	8.0	26.5	11.9	53.6
5B- 5	6.6	2,120	9.9	.2	12.7	.6	.3	.4	75.9	11	.490	144	197	6.6	2.5	17.4	38.1	42.0
6 - 11	7.5	7,590	6.9	.1	12.5	.6	.3	.2	79.4	7.0	.098	286	442	15.5	9.9	16.2	11.8	62.1
7 - 7	7.7	7,583	6.5	.2	12.6	.5	.4	.2	79.6	6.9	.100	319	502	14.9	11.8	16.5	12.7	59.0
8 - 10	7.8	7,931	6.7	.1	13.0	.9	.5	.3	78.5	9.5	.100	284	435	[illegible]	9.7	21.6	11.8	56.9
9 - 9	7.9	7,948	6.5	.2	13.5	.4	.5	.3	78.6	9.9	.096	274	427	16.6	9.2	22.6	11.3	56.9
10- 9	7.9	8,016	5.8	.4	14.3	.3	.3	.2	78.7	12.0	.074	262	400	15.4	9.4	29.7	9.5	51.4
11- 6	8.0	8,170	6.1	.1	13.9	.4	.3	.5	78.7	9.4	.090	274	411	15.7	10.0	23.3	11.6	55.1
12- 10	7.9	8,059	6.8	.0	13.5	.3	.4	.2	78.8	4.3	.088	239	366	16.2	8.0	10.2	10.6	71.2
13- 3	8.0	8,107	6.6	.1	13.4	.4	.3	.2	79.0	6.3	.076	255	390	16.1	9.0	15.3	9.5	66.2
14- 9	7.7	7,854	6.5	.0	13.0	.5	.1	.2	79.7	3.9	.151	312	460	14.3	12.3	10.1	20.5	57.1
15- 5	8.0	7,968	6.1	.0	12.5	.8	.2	.2	80.4	4.6	.096	251	383	13.7	9.7	12.5	13.4	64.4
16- 8	8.0	7,939	6.6	.1	12.9	.5	.2	.2	79.5	6.2	.087	238	362	15.3	8.2	15.1	10.9	65.8
17- 10	8.0	7,952	6.4	.1	13.5	.5	.2	.2	79.1	6.2	.085	249	369	15.0	8.9	15.6	10.9	64.6
18- 8	7.7	7,885	5.5	.1	14.1	.5	.2	.2	79.4	6.2	.085	201	287	15.0	6.6	15.4	10.6	67.4
19- 8	7.5	7,756	6.0	.1	14.1	.3	.1	.3	79.1	6.3	.124	193	275	13.8	6.6	16.7	16.5	60.2
20- 10	7.8	7,716	5.4	.1	14.3	.2	.1	.2	79.7	5.0	.103	210	297	12.2	8.4	15.8	15.4	60.4
21- 9	7.6	7,701	4.8	.0	14.5	.3	.1	.1	80.2	2.3	.105	214	301	10.2	10.3	8.1	18.7	65.2
22- 6	7.8	7,700	5.0	.0	14.0	.2	.1	.2	80.4	4.0	.113	207	295	11.0	8.8	13.0	18.5	59.7
23- 3	11.8	7,781	6.3	.3	13.8	.9	.1	.4	78.2	13	.110	239	349	15.5	8.1	31.2	13.5	47.2
24- 6	10.3	7,795	5.5	.4	14.2	.2	.1	.3	79.3	12	.106	253	348	13.6	10.6	32.5	14.7	42.2
25- 2	12.0	7,740	5.7	.5	14.6	.1	.0	.4	78.7	14	[5]/.107	239	332	14.9	8.3	34.6	13.5	43.6
26- 4	11.9	7,752	5.9	.3	14.2	.3	.2	.2	78.9	9.6	[5]/.107	239	341	14.5	8.5	24.4	13.9	53.2
27- 2	11.5	7,710	6.0	.2	14.5	.3	.0	.1	78.9	6.0	[5]/.107	222	349	13.5	8.2	16.3	14.7	60.8

1/ The first figure is the operating week (the week ended December 24, 1949 = 1); the second figure is the number of operating cycles in this direction during the week, the results of which are averaged. 2/ At 60° F., 30 inches Hg. dry. 3/ Basis of moisture-and ash-free coal. 4/ Heat balance is based on 60° F.
5/ Assumed by using the average of the five weeks preceding the 25th week.

TABLE 26. - Back-pressure development during the fourth operating period, December 22, 1949, to June 5, 1950

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Resistance to flow 1/, pounds per square-inch gage													
Direction of flow:														
BH I to BH II.....	9.5	9.2	9.0	9.2	9.4	9.5	10.4	10.2	10.3	9.9	10.3	9.7	9.9	10.5
BH II to BH I.....	9.7	8.9	8.7	8.9	9.1	9.3	9.8	9.7	9.6	9.5	9.8	9.3	9.5	10.2
Average for both directions......	9.6	9.1	8.9	9.1	9.3	9.4	10.1	10.0	10.0	9.7	10.1	9.5	9.7	10.[illegible]

Week	15	16	17	18	19	20	21	22	23	24	25	26	27
	Resistance to flow 1/, pounds per square-inch gage												
Direction of flow:													
BH I to BH II.....	10.2	9.5	9.2	8.9	8.6	9.0	9.0	8.9	8.7	8.7	8.6	8.8	8.4
BH II to BH I.....	9.6	9.1	8.8	8.4	8.1	8.4	8.4	8.2	8.2	8.1	7.9	8.4	8.3
Average for both directions......	9.9	9.3	9.0	8.7	8.4	8.7	8.7	8.6	8.5	8.4	8.3	8.6	8.4

1/ The back pressures reported were for all cycles in which the input air rate was over 7,000 cubic feet per minute.

Fifth Operating Period, June 5, 1950, to October 7, 1950

As discussed previously, sand holes 7 to 13 were drilled into the entry and the air course between boreholes II and III, and it was decided to block the entry or west passage as completely as possible before operations were started along the path between boreholes VII and III. Each of the sand holes in this area was cased by grouting 2-inch pipe to a distance 7 to 15 feet above the top of the coal bed. This was done to prevent applying air pressures of about 100 pounds per square inch on the strata through which the hole was drilled. It seemed likely that the overburden cracked somewhat as a result of applied air pressure during sand injection in the region between boreholes I and II. This cracking adversely influenced contact efficiency as well as leakage from the system, and it was desired to eliminate this possibility.

Fluidized sand was injected at sand holes 7, 9, and 13. Also, a small amount of sand was injected at sand holes 8, 10, and 11 in the air course or east passage. Operation of the passage between boreholes VII and III was started on June 5, and immediately after starting, sand was injected as rapidly as possible at sandholes 8, 10, and 11. After the air course or east passage became partly plugged, more sand was injected along the line of the entry. This procedure was carried on for several weeks. Table 27 is a summary of the sand injection.

TABLE 27. - Sand injection during fifth operating period, June 5, 1950, to October 7, 1950

Hole	Location	Sand injection, pounds. Cumulative total through								
		Prior to June 5	June 10, 1st week	June 17, 2nd week	June 24, 3rd week	July 8, 4th and 5th weeks	July 15, 6th week	July 22, 7th week	July 29, 8th week	Aug. 12, 9th and 10th weeks
SH 9	Entry side, 50 feet north of BH II...	Hole plugged, would not take sand.								
SH 13	Entry side, 100 feet north of BH II..	600	600	600	600	600	600	600	600	600
SH 7	Entry side, 150 feet north of BH II..	58,600	58,600	91,410	92,770	92,910	92,910	92,910	92,910	92,910
SH 12	Entry side, 210 feet north of BH II..	93,860	119,900	129,560	129,560	144,490	144,490	144,490	144,490	144,490
	Total, entry side, lb.	153,060	179,100	221,570	222,930	238,000	238,000	238,000	238,000	238,000
	Percent of entry volume filled 1/.....	16.0	18.7	23.2	23.3	24.9	24.9	24.9	24.9	24.9
SH 10	Air course, 100 feet north of BH II..	-	-	-	9,530	9,530	9,530	9,530	9,530	9.530
SH 8	Air course, 150 feet north of BH II..	7,720	24,010	24,760	25,760	25,760	25,760	25,760	25,760	25,760
SH 11	Air course, 200 feet north of BH II..	3,860	112,900	212,330	214,480	214,480	214,480	214,480	214,480	214,480
	Total, air course side, lb.	11,580	136,910	236,340	249,770	249,770	249,770	249,770	249,770	249,770
	Percent of air course volume filled 1/	1.2	14.3	24.7	26.1	26.1	26.1	26.1	26.1	26.1
BH II		-	-	-	2,480	2,480	2,480	2,480	2,480	2,790
TH 13	30 feet west of BH II...............	-	-	-	-	16,130	16,130	16,130	16,130	16,130
TH 15	20 feet north and 35 feet east BH II.	-	-	-	-	180	180	180	180	180
TH 16	65 feet east BH II..................	-	-	-	-	2,580	10,300	10,300	10,300	10,300
BH I		-	-	-	-	-	-	59,180	82,090	109,920
	Total sand injected.................	164,640	316,010	457,910	475,180	509,180	516,860	567,040	598,910	627,090

1/ Measured bulk density of dry sand, 91 pounds per cubic foot. Original entry volume: 10,500 cubic feet; air-course volume 10,500 cubic feet.

The first cycle in the region between boreholes VII and III was operated with the air input at borehole VII and the effluent gases discharged at III. Full capacity of the reciprocating compressor, 7,670 cubic feet per minute, was used for 7-1/2 hours, and the effluent gases showed virtually complete oxygen utilization and a resultant high-carbon dioxide content. The rate of coal consumption was high, and the average temperature of the effluent gases was comparatively low. After 7-1/2 hours of operation in this direction, the flow was reversed. The temperature of the effluent gases rose very rapidly, and after only a few minutes of operation with full air rate the input air was reduced to 2,000 cubic feet per minute in order to maintain control of the system. After 45 minutes, analysis of the effluent gas at borehole VII showed complete oxygen utilization, and the gas had a heating value of 113 B.t.u. per cubic foot, owing primarily to the presence of hydrogen and carbon monoxide. The effluent-gas temperatures were relatively high even at the 2,000 cubic feet per minute flow. In view of the experience obtained during operation of borehole VI, the cycle was discontinued and the flow reversed. The second cycle in the direction VII to III was again carried on for 7-1/2 hours, the effluent gas showed complete oxygen utilization, a lower carbon dioxide content than during the first cycle, and a heating value of 49 B.t.u. per cubic foot. The rate of coal consumption increased to 52 tons per day. After this cycle, the flow was reversed and again reduced to approximately 2,000 cubic feet per minute, the effluent gases being removed at borehole VII. This cycle showed complete oxygen utilization and a heating value of the effluent gases of 151 B.t.u. per cubic foot. The effluent gas temperatures were high.

During the first week, the air in the direction borehole VII to III was maintained at 7,500 cubic feet per minute, and both the time and rate of air input in the direction borehole III to VII was increased gradually. Throughout the first week, oxygen utilization was high but decreased slightly. The heating value of the effluent gases at borehole III ranged from 21 to 49 B.t.u. per cubic foot, and at borehole VII from 56 to 151 B.t.u. per cubic foot. Operation in the direction borehole III to VII was maintained for 51 hours. The gas production averaged 6.7 million cubic feet per day with an average heating value of 72 B.t.u. per cubic foot. In the direction borehole VII to III, operation was maintained for 102 hours. The gas production averaged 11.5 million cubic feet per day, and the heating value 33 B.t.u. per cubic foot.

During the second week of operation, the full capacity of the reciprocating compressor was used in each direction, and the cycle times were varied from 8 to 4 to 6 hours. Some oxygen appeared in the effluent gases, especially when borehole VII was used as an outlet. Contact efficiency between the gas-making fluids and the carbon faces was higher when the direction of flow was from VII to III than when the flow was from III to VII.

Operation in the direction borehole III to borehole VII was maintained for 64 hours. Gas production averaged 9.8 million cubic feet per day, and the heating value averaged 50 B.t.u. per cubic foot. In the direction borehole VII to borehole III operation was maintained for 77 hours. Gas production averaged 11.5 million cubic feet per day, and the heating value averaged 26 B.t.u. per cubic foot.

This operation was continued for the entire period, June 5 to October 7. Table 28 gives operating results for each cycle with the flow direction from borehole VII to borehole III for the first 5 weeks of the period. Table 29 gives operating results for the same period when the direction of flow was from III to VII. Examination of these two tables indicates that the efficiency of contact was greater when the direction of flow was from VII to III than when the direction was from III to VII, and also the rate of deterioration was lower. On several occasions during this 5-week period, the input-air rate was reduced from the usual flow of 7,500 cubic feet per minute, and, regardless of the flow direction, in nearly all instances the heating value of the effluent gases increased with lower air inputs. Where a reduction in the input air rate resulted in the production of a gas of higher heating value, the oxygen content of the effluent gas decreased. In each case the increased heating value was largely due to an increased hydrogen and methane content of the effluent gases. The apparent improvement in quality of the products was due to an unbalance in the equilibrium conditions resulting from the change in flow rate. Relative to the total volume of fluids flowing, the volume of coal-distillation gases increased, the moisture concentration and the resultant dissociation of moisture increased, and the total heat liberated underground by the combustion of carbon decreased. The net result of these changes was an increase in heating value of the products obtained. This increase was a function of the heat storage and high temperatures obtained during past operations.

Tables 30 and 31 give the operating results obtained during the last 13 weeks of the operation. In these tables the data are averaged by weeks. The oxygen content of the effluent gas was greater when the flow direction was III to VII than when the direction was VII to III.

The rate of coal consumption from June 5 to October 7, at flows exceeding 7,000 cubic feet per minute, ranged from 23 to 54 tons per day. This rate of coal consumption was higher than was previously achieved. The rate of coal consumption and the contact efficiency decreased as the operating age of the section increased. The heat lost to the surrounding strata was greater when the flow direction was borehole III to borehole VII. When the flow direction was VII to III, 60 to 75 percent of the heat of combustion of the coal consumed was brought aboveground in the effluent gas.

Material balances, uncorrected for possible leakage from the system, indicated that 2,875 tons of coal, calculated on a moisture- and ash-free basis, was consumed during this period. A total of 8,751 tons of coal was consumed from March 18, 1949, to October 7, 1950.

Table 32 shows the variation in pressure required to force 7,000 or more cubic feet per minute of air underground in this section. The increasing resistance to flow during the first 7 weeks coincides with the period when the major portion of the sand was injected underground.

Operation of the Gas-Turbine Installation

During operations concentrated in the region between boreholes VII and III it was decided to set up a small gas turbine at borehole III. The primary purpose of this installation was to increase the air input at borehole VII and to obtain operating characteristics of the system, using flow rates exceeding the maximum previously employed. It was also desired to learn something of the operating characteristics of the system at a higher average pressure, and a further objective was to determine whether the effluent gases could be used in a gas turbine without requiring excessive cleaning of the gases to prevent solids accumulation and corrosion and erosion of the turbine blades and auxiliary equipment.

TABLE 28. - Operating results, first 5 weeks of period June 5 to October 7, 1950. Direction of flow, borehole VII to III.

Cycle No.	Length of cycle, hours	Average air flow, c.f.m.1/	Average analysis of effluent gas, Percent: CO_2	Ill.	O_2	H_2	CO	CH_4	N_2	Heating value, B.t.u. per cu. ft.1/	Mol water per mol dry gas	Temperature of effluent gas: Av. temp., °F.	Max. temp., °F.	Average rate of coal consumption, tons per day2/	Heat balance3/, percent of heat of combustion of coal consumed: Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor	Unaccounted for and presumed stored underground, by difference
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
917	7.5	7,670	18.1	0.2	0.4	1.7	2.1	0.5	77.0	21	-	315	400	45.3	4.4	17.7	-	-
919	7.58	7,860	17.6	.1	1.1	3.9	1.8	2.8	72.7	49	-	364	564	52.2	4.9	38.8	-	-
921	7.67	7,690	17.2	.4	.2	3.1	4.8	1.1	73.1	45	-	503	516	54.0	6.6	33.3	-	-
923	8.0	7,760	17.4	.1	.5	2.8	2.6	1.4	75.2	34	-	450	510	48.2	6.4	27.9	-	-
925	8.17	7,680	16.3	.2	.9	3.0	2.8	2.2	74.6	45	-	448	502	48.3	6.7	36.7	-	-
927	8.0	7,720	15.4	.3	.5	1.9	2.8	1.1	78.0	32	-	625	-	42.6	10.0	28.4	-	-
929	8.0	7,750	15.6	.1	.5	4.1	3.3	1.6	74.8	42	-	373	444	46.3	9.2	35.9	-	-
931	8.0	7,720	16.0	.2	.5	1.7	2.2	.9	78.3	26	-	513	607	41.5	8.3	23.7	-	-
933	8.0	7,660	16.1	.1	.6	3.8	3.7	1.1	74.6	37	-	694	885	46.8	10.0	31.0	-	-
935	8.0	7,690	16.3	.2	1.2	2.7	2.4	1.0	76.2	31	-	444	582	43.8	6.8	27.3	-	-
937	8.0	7,630	16.3	.1	1.2	1.9	2.7	.4	77.4	21	-	509	678	41.7	8.1	19.0	-	-
939	7.0	7,540	16.4	.0	1.8	1.5	1.5	.9	78.0	18	-	459	605	39.1	8.1	17.1	-	-
941	8.0	7,610	14.9	.2	3.6	1.4	1.5	.6	77.8	20	-	715	1,008	36.7	13.2	20.1	-	-
943	8.0	7,500	17.4	.5	1.4	1.7	2.3	.5	76.2	28	-	878	1,137	45.5	14.0	23.4	-	-
945	8.0	1,750	24.4	.5	.2	3.2	3.1	2.6	63.4	65	-	243	459	18.7	2.2	36.9	-	-
947	6.0	7,640	16.5	.1	2.7	1.6	2.4	1.0	75.7	25	-	546	847	47.7	8.5	22.0	-	-
949	6.0	7,490	17.6	.3	1.9	2.5	1.9	1.1	74.7	31	-	562	823	46.1	8.4	25.9	-	-
951	8.0	7,650	16.9	.1	2.4	1.8	2.1	.7	76.0	22	-	691	968	43.3	11.3	19.5	-	-
953	5.0	7,810	16.7	.1	2.2	1.9	1.3	1.1	76.7	24	-	630	894	42.4	10.5	22.0	-	-
955	7.08	7,570	15.2	.1	1.1	2.6	1.3	1.1	78.6	26	-	1,033	1,066	37.0	19.4	25.9	-	-
957	7.0	7,600	14.8	.3	3.0	1.5	1.9	0.5	78.0	22	-	768	1,140	37.4	14.0	21.9	-	-
959	5.75	7,470	14.4	.3	2.8	1.8	1.1	.8	78.7	24	-	576	884	34.8	9.9	23.2	-	-
961	5.33	7,540	14.6	.1	2.9	1.1	.9	.9	79.5	18	-	960	1,200	34.0	19.3	19.2	-	-
963	4.92	7,520	13.0	.1	2.8	2.9	1.3	1.2	78.8	28	-	719	890	34.4	14.8	31.6	-	-
965	6.0	7,730	13.5	.5	4.2	1.4	1.3	.7	78.4	26	-	596	824	35.1	11.3	27.9	-	-
967	5.5	7,450	12.6	.1	3.6	2.7	1.0	1.4	78.6	28	-	998	1,490	31.4	21.8	32.6	-	-
969	6.0	7,580	13.3	.5	3.1	2.2	1.3	1.1	78.5	33	-	1,446	2,270	34.4	30.0	35.1	-	-
971	6.0	7,610	12.8	.4	2.6	2.7	1.1	1.0	79.4	30	-	1,428	1,920	32.7	31.3	33.9	-	-
973	7.0	7,420	12.8	.3	4.0	1.9	1.2	.8	79.0	24	-	1,448	1,600	31.6	32.4	27.7	-	-
975	6.0	7,650	12.6	.2	4.1	2.3	1.8	.7	78.3	24	0.386	694	1,080	33.1	14.4	21.6	27.2	36.8
977	6.0	7,620	13.4	.1	3.7	2.7	2.1	.9	77.1	27	-	730	-	35.4	14.3	28.7	-	-
979	6.0	7,560	13.1	.4	3.2	4.0	3.0	.9	75.4	40	.297	767	1,070	38.6	14.0	39.8	18.7	27.5
981	6.0	7,620	13.1	.2	3.6	2.6	2.1	.8	77.6	27	.173	715	1,135	34.8	14.0	29.2	11.5	45.3
983	6.0	7,560	11.8	.2	3.8	2.6	1.1	.9	79.6	25	-	686	1,110	29.2	15.4	31.1	-	-
985	6.0	7,580	12.9	.3	3.8	2.0	1.7	.7	78.6	25	-	604	820	33.1	12.0	27.9	-	-
987	5.92	7,590	11.9	.2	3.5	3.0	1.8	1.0	78.8	30	-	785	1,200	31.5	16.5	34.7	-	-
989	6.0	7,320	11.7	.2	4.0	2.7	1.6	1.1	78.7	29	-	792	890	29.8	17.3	34.7	-	-
991	6.0	7,560	11.8	.3	4.2	2.9	1.8	.9	78.1	30	.357	758	1,110	31.6	16.2	34.8	26.1	22.9
993	6.0	5,420	12.7	.3	3.3	4.6	1.2	2.2	75.7	47	-	690	900	25.8	12.4	49.9	-	-
995	6.0	5,220	13.3	.3	3.9	2.9	1.2	1.6	76.8	36	-	898	930	24.5	17.0	38.3	-	-
997	6.0	7,420	12.9	.2	3.5	2.8	1.9	0.6	78.1	25	.408	807	1,435	32.5	16.3	35.5	29.2	18.8
999	6.0	7,550	13.6	.2	3.3	2.3	2.0	.7	77.9	25	.346	860	1,730	35.0	17.0	26.5	24.9	31.6
1,001	6.0	7,490	12.7	.7	3.8	3.2	2.2	.5	76.9	37	.152	795	1,640	35.3	15.4	39.0	10.2	35.4
1,003	5.0	7,560	11.5	.1	4.1	3.4	2.2	.9	77.8	29	.419	632	920	31.1	13.6	34.7	30.0	21.7
1,005	5.0	7,460	11.8	.3	4.2	3.6	2.6	.7	76.8	33	.360	622	980	33.0	12.5	37.2	24.3	26.0
1,007	5.0	7,360	11.2	.1	4.1	3.5	2.4	1.2	77.5	33	.244	572	990	30.8	11.8	38.9	21.5	27.8
1,009	6.0	7,510	11.4	.1	4.3	3.0	2.1	.9	78.2	28	.355	580	760	30.3	12.3	34.0	25.1	28.4
1,011	6.0	7,640	11.6	.1	4.3	2.8	2.1	1.0	78.1	28	.268	684	960	31.5	14.9	33.3	19.5	32.3
1,013	6.0	7,410	9.6	.3	7.3	2.5	1.7	.9	77.7	29	.308	575	680	26.4	13.9	40.0	25.0	21.1
1,015	6.0	7,650	10.0	.2	5.0	3.1	2.2	1.0	78.5	31	.199	466	830	28.6	9.8	40.3	14.6	35.3
1,017	7.0	7,440	11.3	.2	4.6	4.7	2.2	1.1	75.9	38	.295	547	970	31.8	11.3	44.9	20.2	23.6
1,019	7.0	7,540	11.0	.2	3.8	4.1	2.3	.9	77.7	34	.246	497	722	30.7	10.4	41.1	17.0	31.5
1,021	7.0	7,560	10.1	.0	5.0	3.3	2.1	.9	78.6	27	.171	526	780	27.2	12.2	36.6	13.4	37.8
1,023	5.0	7,410	9.1	.2	6.7	2.9	2.3	.7	78.1	28	.345	374	560	25.5	8.6	39.7	26.5	25.2
1,025	5.0	7,560	10.4	.0	5.2	3.0	1.8	1.1	78.5	27	.165	546	970	27.6	12.5	36.0	12.7	38.8
1,027	5.0	7,530	10.2	.0	4.0	3.1	1.5	1.5	79.7	30	.353	497	730	26.9	11.4	40.2	26.9	21.5
1,029	5.0	7,510	10.5	.2	5.0	2.5	1.4	1.1	79.3	28	.164	410	620	27.4	8.8	36.1	11.6	47.5
1,031	5.0	7,550	10.3	.0	5.3	2.9	1.8	.9	78.8	24	.158	674	790	26.9	16.2	32.7	13.2	37.9
1,033	5.0	7,510	10.7	.1	5.0	3.4	2.0	.8	78.0	28	.415	512	640	28.5	11.3	36.2	30.6	21.9
1,036	5.0	7,620	10.5	.0	5.2	2.1	1.4	1.2	79.6	24	.163	466	690	27.1	10.6	32.5	13.4	43.5
1,039	3.75	7,560	9.9	.0	5.1	2.6	1.3	0.7	80.4	20	.370	395	530	24.2	9.6	29.7	30.0	30.7

1/ At 60° F., 30 inches Hg. dry. 2/ Basis of moisture-and ash-free coal. 3/ Heat balance is based on 60° F.

TABLE 29. - Operating results, first 5 weeks of period June 5 to October 7, 1950. Direction of flow, borehole III to borehole VII

Cycle No.	Length of cycle, hours	Average air flow, c.f.m.1/	Average analysis of effluent gas: Percent CO$_2$	Ill	O$_2$	H$_2$	CO	CH$_4$	N$_2$	Heating value, B.t.u. per cu. ft.1/	Mol water per mol dry gas	Temperature of effluent gas: Av. temp., °F.	Max. temp., °F.	Average rate of coal consumption, tons per day2/	Heat balance3/, percent of heat of combustion of coal consumed: Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor	Unaccounted for and presumed stored underground, by difference
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
918	0.75	2,000	11.3	0.0	0.2	15.6	14.4	1.6	56.9	113	-	510	741	20.7	5.7	73.5	-	-
920	1.0	1,975	9.6	.2	.5	19.8	16.9	2.8	50.2	151	-	590	1,040	25.2	6.2	90.2	-	-
922	1.25	2,030	11.9	.4	.4	20.0	18.9	0.7	47.7	141	-	457	727	29.7	4.3	77.4	-	-
924	1.0	1,960	15.8	.0	.4	18.7	15.4	1.5	48.2	126	-	382	610	28.7	3.6	68.4	-	-
926	3.0	2,240	14.4	.2	.9	16.1	12.0	2.5	53.9	120	-	850	1,350	26.3	9.6	72.9	-	-
928	1.0	1,940	14.9	.2	.4	23.3	10.5	1.6	49.1	130	-	650	662	23.3	7.7	84.1	-	-
930	7.5	2,020	16.4	.4	.7	14.7	11.6	1.4	54.8	97	-	600	763	24.0	6.4	57.0	-	-
932	3.0	1,840	15.7	.1	.2	16.2	12.6	1.2	53.0	108	-	1,225	1,532	22.6	14.1	64.1	-	-
934	8.0	3,670	13.8	.2	.7	9.0	8.9	.9	65.5	71	-	1,008	1,152	29.0	14.3	52.6	-	-
936	8.0	3,990	13.6	.2	1.0	6.9	6.5	1.3	70.5	60	-	709	1,013	26.6	10.5	48.9	-	-
938	5.08	4,540	12.5	.2	1.0	6.9	6.2	0.9	72.3	56	-	688	918	27.1	10.9	49.5	-	-
938	2.92	1,735	16.2	.2	2.4	12.4	7.0	1.9	59.9	86	-	464	-	16.0	5.7	59.6	-	-
940	8.0	5,600	12.7	.2	1.7	6.4	6.2	.9	71.9	54	-	763	1,095	33.9	12.2	48.5	-	-
942	8.0	5,660	13.5	.4	2.3	4.9	5.3	.7	72.9	48	-	505	672	34.0	7.8	42.0	-	-
944	8.0	7,070	12.8	.4	3.1	5.7	6.3	.5	71.2	52	-	447	639	42.7	6.6	45.3	-	-
946	6.0	7,760	13.0	.3	2.5	4.8	5.2	.8	73.4	46	-	980	1,225	44.7	16.7	41.7	-	-
948	6.0	7,960	10.5	.3	4.2	6.7	3.8	1.0	73.5	50	-	700	848	37.2	14.1	55.6	-	-
950	4.83	7,450	9.1	.4	4.0	6.0	5.2	.8	74.5	52	-	843	1,180	34.3	17.2	58.0	-	-
952	5.0	7,280	11.5	.3	3.0	4.5	4.3	0.7	75.7	42	-	1,054	1,810	35.5	20.8	43.6	-	-
954	4.25	7,560	8.5	.5	4.0	5.3	5.6	0.6	75.5	51	-	1,020	1,860	34.0	21.3	57.7	-	-
956	3.25	7,580	6.1	.0	4.3	7.0	5.5	2.2	74.9	63	-	310	950	30.1	5.4	81.0	-	-
956	1.50	3,000	7.5	.2	2.0	16.2	4.6	3.9	65.6	111	-	773	-	16.2	15.2	119.4	-	-
958	4.75	7,520	11.4	.2	3.7	3.7	3.9	.5	76.6	34	-	738	1,490	34.3	14.6	37.3	-	-
960	4.0	1,705	14.2	.6	2.5	12.3	9.7	2.3	58.4	106	-	888	1,230	37.3	10.6	68.5	-	-
962	4.0	7,510	8.9	.2	5.8	4.9	4.7	.9	74.6	44	-	1,308	1,640	32.4	29.3	52.4	-	-
964	4.0	7,620	8.3	.4	5.7	5.6	4.3	1.0	74.7	50	-	843	730	31.7	18.8	51.7	-	-
966	4.0	2,490	9.7	.4	5.6	5.6	4.2	.8	73.7	48	-	686	1,005	11.3	13.9	54.8	-	-
968	4.0	7,490	9.5	.1	4.8	4.9	3.1	.6	77.0	34	0.236	855	1,230	29.1	19.9	43.5	19.6	17.0
970	4.0	7,400	11.3	.4	5.0	5.4	4.1	.9	72.9	48	-	802	1,110	37.4	15.2	49.7	-	-
972	4.0	7,660	10.6	.3	4.7	5.6	4.5	.7	73.6	46	-	616	880	36.8	11.8	49.7	-	-
974	4.0	7,460	12.1	.3	4.2	3.7	3.4	.7	75.6	36	-	870	1,090	35.7	17.1	38.1	-	-
976	4.0	7,550	13.2	.5	4.1	2.7	3.4	.6	75.5	36	0.203	744	1,080	39.3	13.2	35.1	12.4	39.3
978	4.17	7,510	13.2	.3	3.9	2.9	3.8	.5	75.4	33	-	694	940	39.0	12.3	32.4	-	-
980	4.0	7,500	10.5	.2	4.7	3.0	4.1	.4	77.1	31	0.150	609	1,020	32.4	12.3	35.7	10.2	41.8
982	4.0	7,460	11.5	.1	3.9	3.2	1.8	1.3	78.2	31	-	672	940	30.6	14.4	37.1	-	-
984	4.0	7,520	12.0	.4	5.3	3.2	1.9	.6	76.6	31	-	564	820	32.4	11.5	36.0	-	-
986	4.0	7,500	11.9	.1	5.4	3.1	2.1	.5	76.9	24	-	608	960	31.0	13.0	28.9	-	-
988	4.0	7,310	11.7	.3	4.8	2.4	1.5	1.0	78.3	29	-	391	-	29.7	12.4	34.8	-	-
990	4.0	7,430	11.5	.5	5.5	2.2	1.5	1.2	77.6	34	.090	574	760	31.4	11.8	39.7	6.2	42.3
992	4.0	7,520	11.5	.4	5.6	2.9	1.4	1.2	77.0	34	.155	486	720	31.4	9.9	40.5	10.4	39.2
994	4.0	5,180	11.1	.2	5.5	4.1	1.6	1.2	76.3	35	-	424	660	20.9	8.8	43.4	-	-
996	4.0	5,130	11.0	.2	5.7	4.0	1.8	1.0	76.3	33	.145	568	780	20.8	12.3	40.3	10.5	36.9
998	4.0	7,380	9.8	.5	6.1	2.7	2.3	.5	78.1	31	.111	591	960	27.4	13.4	40.0	8.6	38.0
1,000	4.0	7,510	10.5	.3	6.4	3.1	2.4	.6	76.7	30	.107	581	790	29.9	12.6	37.3	7.9	42.2
1,002	5.0	7,140	11.2	.2	6.3	3.4	2.3	.6	76.0	29	.276	657	890	29.4	14.2	35.1	20.4	30.3
1,004	5.0	7,540	11.5	.2	6.1	3.2	2.7	.6	75.7	29	.114	688	1,070	32.7	14.4	33.5	8.1	44.0
1,006	5.0	7,320	11.2	.2	5.6	4.0	2.3	.6	76.1	31	.231	823	1,990	30.2	18.3	37.5	18.5	25.7
1,008	6.0	7,510	11.8	.5	5.4	2.6	2.2	.5	77.0	31	.130	942	1,550	30.6	21.4	37.5	27.1	14.0
1,010	5.0	7,400	9.3	.6	6.8	4.8	3.0	.5	74.9	42	4/.225	846	2,000	29.9	19.5	52.6	18.5	9.4
1,012	5.83	7,590	9.2	.1	7.0	3.4	3.0	.6	76.7	29	.216	953	2,000	28.1	23.7	38.8	19.7	17.8
1,014	6.0	7,520	9.5	.1	6.7	3.3	2.3	1.1	77.0	31	4/.259	714	940	27.6	17.2	41.5	21.7	19.6
1,016	6.0	7,400	9.7	.4	7.1	2.7	2.7	.8	76.6	34	4/.259	772	1,180	29.1	17.5	42.5	20.3	19.7
1,018	6.92	7,470	10.2	.1	6.9	3.7	2.3	.8	76.0	30	.221	818	1,490	28.6	19.6	39.0	18.7	22.7
1,020	7.0	7,430	9.6	.6	7.4	3.3	2.9	.4	75.8	36	.266	750	1,470	29.9	16.9	44.7	21.0	17.4
1,022	7.0	7,490	10.3	.0	7.6	2.7	1.9	.9	76.6	24	.287	786	1,290	27.6	19.2	32.2	24.8	23.8
1,024	4.92	7,380	10.1	.3	7.5	2.8	2.1	.8	76.4	30	4/.258	665	1,710	28.3	15.5	38.7	20.4	25.4
1,026	5.0	7,480	9.8	.1	7.7	3.2	2.4	.9	76.0	29	4/.258	724	1,110	28.2	17.3	38.3	21.4	23.0
1,028	5.0	7,480	9.7	.0	6.8	2.9	1.4	1.2	78.0	26	.210	930	1,580	25.5	26.2	38.6	30.2	5.0
1,030	5.0	7,360	9.8	.5	7.1	3.3	1.8	.8	76.7	35	4/.254	920	1,170	27.7	22.9	46.5	22.7	7.9
1,032	5.0	7,480	9.9	.1	7.8	2.4	1.7	.9	77.2	24	.266	614	1,290	25.3	15.8	34.8	23.3	26.1
1,035	5.17	7,420	9.8	.0	6.3	3.0	1.2	.6	79.1	20	4/.254	666	1,105	23.5	18.0	30.2	23.6	28.2
1,038	4.5	7,380	8.7	.2	6.2	2.8	1.4	.5	80.2	23	4/.254	623	680	21.9	17.5	36.7	24.4	21.4

1/ At 60° F., 30 inches Hg., dry. 2/ Basis of moisture- and ash-free coal. 3/ Heat balance is based on 60° F. 4/ Average of the preceding three determined moistures.

TABLE 31. - Operating results, last 13 weeks of period June 5 to October 7, 1950. Direction of flow, borehole III to borehole VII.

Week and cycles averaged 1/	Average length of cycle, hours	Average air flow, c.f.m. 2/	Average analysis of effluent gas: Percent CO_2	Ill.	O_2	H_2	CO	CH_4	N_2	Heating value, B.t.u. per cu. ft. 2/	Mol water per mol dry gas	Temperature of effluent gas: Av. temp., °F.	Max. temp., °F.	Average rate of coal consumption, tons per day 3/	Heat balance 4/, percent of heat of combustion of coal consumed: Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor	Unaccounted for and presumed stored underground, by difference
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
6 - 11	4.3	7,490	9.1	0.2	7.0	2.8	1.8	0.9	78.2	28	0.452	520	777	25.3	12.8	40.5	37.8	8.8
7 - 12	4.0	7,350	10.0	.2	6.3	2.1	1.1	1.2	79.1	27	.302	738	1,109	25.5	18.5	37.7	26.3	17.5
8 - 13	4.7	7,350	10.6	.2	6.7	2.3	1.7	.7	77.8	24	.107	761	1,262	27.3	18.2	31.7	8.9	41.2
9 - 9	5.0	7,490	10.4	.2	7.4	2.4	1.6	.6	77.4	23	.070	518	861	27.2	12.3	31.5	5.5	50.8
10- 9	5.7	3,870	10.0	.2	7.2	2.8	.9	.7	77.2	23	.086	501	728	14.1	11.7	31.3	6.7	50.3
10- 4	5.0	7,500	10.0	.2	7.8	2.8	1.7	.8	76.7	27	.160	5/473	844	27.2	11.0	37.2	12.3	40.5
11- 12	5.7	3,970	10.9	.2	7.5	1.9	1.1	.6	77.8	20	.231	530	850	14.4	12.4	27.2	18.1	42.3
12- 13	5.3	7,430	9.8	.1	8.5	1.5	1.2	.6	78.3	17	.191	455	731	24.2	11.4	25.6	16.1	46.9
13- 3	5.6	7,470	9.9	.1	9.0	1.4	1.0	.4	78.2	14	.235	404	604	23.7	10.3	21.6	19.8	48.3
14- 4	8.0	7,600	9.7	.2	8.8	1.3	.7	.4	78.9	15	.192	496	784	23.3	13.3	23.8	17.3	45.6
15- 11	7.9	7,600	10.8	.1	8.8	1.3	.5	.7	77.8	15	.155	444	731	23.7	11.8	23.7	13.6	50.9
16- 7	8.0	7,420	11.0	.1	8.2	1.5	.6	1.0	77.6	19	.137	334	518	26.3	7.5	26.3	10.1	56.1
17- 9	7.5	7,570	11.6	.2	7.9	1.0	.8	.8	77.7	18	.173	262	397	28.6	5.2	23.5	11.6	59.7
18- 7	7.7	7,610	11.8	.2	7.3	1.0	.4	.7	78.6	16	.165	220	319	27.9	4.3	21.3	11.1	63.3

TABLE 30. - Operating results, last 13 weeks of period June 5 to October 7, 1950. Direction of flow, borehole VII to borehole III.

Week and cycles averaged 1/	Average length of cycle, hours	Average air flow, c.f.m. 2/	Average analysis of effluent gas: Percent CO_2	Ill.	O_2	H_2	CO	CH_4	N_2	Heating value, B.t.u. per cu. ft. 2/	Mol water per mol dry gas	Temperature of effluent gas: Av. temp., °F.	Max. temp., °F.	Average rate of coal consumption, tons per day 3/	Heat balance 4/, percent of heat of combustion of coal consumed: Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor	Unaccounted for and presumed stored underground, by difference
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
6 - 10	4.5	7,520	11.0	0.2	5.0	2.8	1.6	0.9	78.7	27	0.378	558	802	28.6	12.4	34.8	28.1	24.7
7 - 12	5.0	7,440	11.8	.1	5.0	2.1	1.5	1.2	78.3	26	.461	586	801	30.2	12.4	31.3	32.8	23.5
8 - 14	4.2	7,410	10.8	.2	5.4	2.6	1.8	1.0	78.2	28	.315	502	598	28.6	10.8	35.5	22.9	30.8
9 - 14	4.5	7,550	10.0	.4	5.7	2.3	1.3	.7	79.6	27	.326	642	1,397	26.2	15.8	37.4	27.1	19.7
10- 4	5.0	7,510	10.0	.3	5.9	2.5	1.5	.9	78.9	28	.364	578	678	26.7	13.8	38.2	29.0	19.0
10- 9	5.3	4,020	11.9	.1	5.2	2.4	1.0	1.1	78.3	24	.423	570	794	15.8	12.5	29.8	30.7	27.0
11- 12	5.5	4,060	11.7	.2	6.2	2.0	1.1	.6	78.2	20	.339	508	738	15.5	10.3	25.7	26.0	38.0
12- 14	5.3	7,520	9.9	.1	6.9	2.1	1.5	.7	78.8	21	.231	519	755	25.4	13.0	30.2	19.0	37.8
13- 2	5.8	7,560	10.0	.2	7.1	2.0	1.6	.5	78.6	21	.252	552	765	25.1	14.0	30.8	21.4	33.8
13- 3	21.3	1,540	18.1	.4	3.5	8.2	2.7	1.7	65.4	61	.872	651	942	11.8	9.1	46.4	40.1	4.5
14- 2	27.9	1,620	13.9	.2	5.1	2.5	1.1	1.2	76.0	28	.678	839	1,186	7.7	16.4	29.7	46.6	7.3
14- 4	8.0	7,690	9.8	.2	7.1	2.1	1.0	.8	79.0	22	.199	552	896	25.2	14.1	32.6	17.1	36.2
15- 10	7.9	7,700	10.3	.1	7.3	2.4	1.1	.8	78.0	21	.241	465	728	26.4	11.3	30.2	19.3	39.2
16- 8	8.7	7,560	10.6	.1	6.7	1.9	1.1	1.0	78.6	22	.240	437	780	26.7	11.4	30.3	18.7	39.6
17- 6	7.9	7,560	10.4	.1	6.6	2.3	1.2	1.0	78.4	24	.181	420	694	26.6	9.7	33.1	13.8	43.4
18- 7	7.7	7,720	10.2	.1	6.0	1.8	.8	1.1	80.0	22	.188	650	815	25.6	16.7	31.7	16.4	35.2

1/ The first figure is the operating week (the week ending June 10, 1950 = 1); the second figure is the number of operating cycles in this direction during the week, the results of which are averaged. 2/ At 60° F., 30 inches Hg. dry. 3/ Basis of moisture-and ash-free coal. 4/ Heat balance is based on 60° F.
5/ Average of the preceding 3 values of determined moisture contents, in the 7,000 c.f.m. range.

4380

TABLE 32. - Back-pressure development during the fifth operating period, June 5 to October 7, 1950

Resistance to flow[1/], pounds per square-inch gage

Week	1	2	3	4	5	6	7	8	9
Direction of flow:									
BH VII to BH III.............	8.5	10.8	11.2	11.7	11.8	12.6	12.6	11.9	11.8
BH III to BH VII.............	-	12.5	13.4	14.9	15.1	15.2	15.3	15.4	15.7
Average for both directions...	-	11.7	12.3	13.3	13.4	13.9	14.0	13.7	13.8
Week	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Direction of flow:									
BH VII to BH III.............	11.7	-	11.4	11.3	11.4	11.2	10.5	10.4	10.3
BH III to BH VII.............	15.6	-	15.4	15.3	15.5	15.1	13.7	14.0	14.1
Average for both directions...	13.7	-	13.4	13.3	13.4	13.2	12.1	12.2	12.2

1/ The back pressures reported are for all cycles in which the input-air rate was over 7,000 cubic feet per minute.

A single turbo-supercharger unit was installed at borehole III and tested during several cycles at a temperature range of 400° to 600° F. It was found that the maximum pressure obtainable at borehole III was 10 pounds per square-inch gage, and under these temperature and pressure conditions, one turbo-supercharger unit would not operate at an adequate efficiency level to pump air into the manifold against the discharge pressure of the reciprocating compressor. Further, the low temperature of the effluent gases favored the deposition of tarry material on the turbine blades, and after a few hours' operation this deposit caused a serious drop in the turbine efficiency. With an input pressure of 10 pounds per square-inch gage, it was found that the single turbine unit would operate at a speed of 14,000 to 16,000 r.p.m.

Because these tests showed that a single turbine unit was inadequate to pump air at the required pressure, a second turbine was installed. The two turbo-supercharger units were connected as shown in figure 16. The turbine ends of each machine were connected in parallel, and the compressor ends were connected in series. This installation permitted a greater mass flow through the turbines and gave two stages of air compression. Preliminary tests on the units connected in this manner indicated that the compressors could be used to increase the air input to the mine. A series of tests were carried out during five cycles, and the results of the last test, given in tables 33 and 34, are representative of what could be accomplished with these units under the existing conditions.

TABLE 33. - Operation of the project during the turbo-supercharger test. Direction of flow, borehole VII to III.

Period	Length of period, hr.	Air input, average flow, c.f.m.1/	Average analysis of effluent gas, Percent: CO_2	Ill.	O_2	H_2	CO	CH_4	N_2	Heating value, B.t.u. per cu. ft.1/	Average rate of coal consumption, tons per day2/	Heat balance3/, percent of heat of combustion of coal consumed: Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor4/	Unaccounted for and presumed stored underground, by difference
1.....	0.7	7,460	18.5	0.0	0.3	0.3	0.1	0.4	80.4	5	38.1	24.2	4.6	7.1	64.1
2.....	3.6	5/9,110	17.8	.2	.4	.3	.1	.2	81.0	7	44.9	30.7	6.6	8.0	54.7
3.....	2.4	5/9,300	18.8	.1	.0	1.0	.4	.6	79.1	13	50.8	31.2	11.4	7.5	49.1
4.....	3.0	5/9,480	18.3	.1	.1	1.1	1.4	.4	78.6	14	52.8	28.9	12.1	7.4	51.6
5.....	3.8	5/9,550	17.8	.0	.3	1.4	2.0	.6	77.9	17	54.0	26.1	14.6	7.0	52.3
6.....	4.5	5/9,620	17.8	.0	.2	1.5	1.9	.6	78.0	17	54.1	25.9	14.7	7.0	52.4
7.....	3.8	5/9,460	17.[illegible]	.0	.0	1.9	.5	.5	79.5	13	48.2	26.1	12.2	7.7	54.0
8.....	5.2	5/9,170	17.3	.0	.0	2.3	1.6	.7	78.1	20	49.7	27.3	17.9	7.3	47.5

1/ At 60° F., 30 inches Hg., dry.
2/ Basis of moisture- and ash-free coal.
3/ Heat balance is based on 60° F.
4/ Assuming 0.1 mol of water per mol dry gas.
5/ Total output of reciprocating and centrifugal compressors.

TABLE 34. - Operation of the turbo-supercharger units

Period	Gas pressure turbine inlet, pounds per square-inch gage	Gas temperatures, °F.: Entering cleaning train	Entering turbines	Turbine discharge: First turbine	Second turbine	Adiabatic efficiency: First turbine	Second turbine	Compressor operation: Discharge volume, cu. ft. per minute1/	Discharge pressure, pounds per square-inch gage	Over-all adiabatic efficiency of two stages, percent	Ratio of air compressed to gas expanded through turbines: Mol of air per mol of gas	Pound of air per pound of gas2/
1.....	5.4	1,051	840	-	-	-	-	995	7.5	44.5	-	-
2.....	8.3	1,311	1,130	-	-	-	-	1,665	16.6	52.8	-	-
3.....	9.2	1,377	1,190	1,127	1,074	-	59.4	1,850	17.2	45.8	-	-
4.....	9.3	1,356	1,190	1,111	1,088	47.4	48.4	1,935	17.5	44.3	0.448	0.444
5.....	9.5	1,217	1,110	1,024	1,010	46.7	49.5	1,940	17.7	35.4	.445	.443
6.....	9.7	1,194	1,090	987	970	54.7	54.9	1,970	17.7	39.8	.540	.537
7.....	9.6	1,214	1,090	1,004	985	51.4	50.3	1,905	17.6	37.8	.504	.504
8.....	9.3	1,220	1,120	1,028	1,017	47.0	58.2	1,800	17.2	40.5	.472	.474

1/ At 60° F., 30 inches Hg., dry.
2/ Corrected for moisture content.

During the testing of the turbo-superchargers, the project was operated with an average pressure of 17.5 p.s.i.g. on the input air and 9.4 p.s.i.g. on the effluent gas. The average pressure on the underground system was thus 13.5 p.s.i.g. Table 33 shows that throughout the test the oxygen content of the effluent gas was negligible, the rate of coal consumption was high, and the heating value of the gases discharged from the turbines increased steadily with time. The heating value increased slowly, as shown in table 33, but from a visual standpoint it was very marked. From the third period through the eighth period the gas discharging from the turbines burned steadily. At first the flame was visible only around the perimeter of the turbines, where the gases entered the discharge stacks; but from the fourth through the eighth periods the gas discharged from the two 20-inch stacks was burning, and the height of the flame cone increased with time. The increased total pressure and the resultant increase in partial pressure of the oxygen underground resulted in a general improvement in gas quality and in operating characteristics.

Results of the turbo-supercharger operation are summarized in table 34. Under test conditions, the speed of each unit ranged from 14,000 to 16,000 r.p.m. The cyclone-type knock-out chambers installed ahead of the turbines removed a small quantity of fine dust, and occasionally quantities of dust went through the turbines. Examination of the turbine blades following this test and including some 30 hours of prior operation did not reveal any serious damage or build-up on the blades. This was qualitative only as effect of the dust on the blading would have to be determined over long operating periods.

Throughout the test, water was sprayed into the effluent gases at the base of borehole III to prevent the temperature from rising above 1,400° F. The temperature level was held at the desired value, but at the end of the eighth period, the refractory lining slumped and blocked borehole III at two points. This slumping took place at points 42 and 52 feet below the surface of the ground. At each elevation the blocked portion was not extensive, for it was later possible to reopen the borehole by punching a hole through the obstructed regions. A length of steel rail having one end forged into a bit, and the whole weighing approximately 600 pounds, was allowed to fall freely a distance of 15 feet. A few blows sufficed to punch through each obstruction. Further tests with the turbo-supercharger units were not made.

The turbo-supercharger test showed qualitatively that it was possible to use the effluent gas produced by underground gasification. Although the operating efficiency of the aeroplane-type turbo-supercharger units was not high, the test showed that if the outlet pressure was increased to a more satisfactory level and more efficient units were installed, the recoverable energy would be increased at least three or four times. Further, the heating value of the gas was wasted in this test and could be utilized in a more efficient installation. By making these changes, it should be possible to supply an underground gasification system with air and make available a considerable portion of the energy of the coal available as a product.

At the time the turbo-supercharger test was made, the system had been operating continuously for 18 months, and a large area of coal had been consumed. During the test it was not possible to raise the discharge pressure of the effluent gases above 10 p.s.i.g., which indicated that there was leakage from the system. Earlier tests had shown it should have been possible to operate at at least 30 p.s.i.g. An analysis of the test results indicated that the average leakage from the system during the turbo-supercharger test was 62 percent of the input air. As it was not practical to isolate the portion of the installation from borehole III to the entry seal from the section including boreholes I, II, and VII and the path to borehole III, it was decided to discontinue any further tests at elevated pressure and continue operation of the project in the section from boreholes III to V.

Operation in the Section Between Boreholes III and V

Following the turbo-supercharger tests and blocking of borehole III with fallen refractory, the operations were continued between boreholes VII and III at reduced flows. The average air input was 1,650 c.f.m., and the results obtained have been shown in table 35, item 1.

It was desired to establish a high-temperature zone in the region between boreholes III and IV before operation between III and V was started. Air was admitted at borehole VII, and the product gases were removed at IV. Periodically, the flow was reversed. The operating results obtained are given as items 2 and 3 of table 35:

At the conclusion of operations between VII and IV, air was admitted at borehole III, and the product gases were removed at IV. Periodic reversals were accomplished, and the operating results have been shown as items 4 and 5 of table 35. Table 35 shows that there was bypassing of the combustion faces underground, as evidenced by the high oxygen content and the low carbon dioxide content of the effluent gases.

In final preparation for operations in the section between boreholes III and V, a long cycle was run between boreholes III and IV. Air was admitted at III and the gases were discharged at IV. The time was prolonged until the temperature of the effluent gases was 950° F. when 14 gallons per minute of spray cooling water was being admitted at the base of borehole IV. The calculated temperature of the gases was 2,000° F. Immediately after attaining this condition, borehole IV closed, borehole V was opened, and the flow was from borehole III to borehole V.

The product gases were removed at borehole V until their temperature had risen appreciably. Flow was then reversed, and the effluent gases were removed at borehole III. The objective was to blow in at borehole V, remove the gases at III, and to continue the cycle in this direction as long as it was possible to do so. Gas flow in this direction was decided upon because it was believed that there would be minimum leakage, as the inlet borehole was located in an area where combustion had not yet taken place, and the outlet or low-pressure borehole was adjacent to a region that was known to be subject to leakage. A water spray was used in borehole III to maintain the temperature of the effluent gases at a value not exceeding 800° F. in the borehole. Flow was reversed when repairs were needed at the outlet stack and during the initial part of the operation when it was desired to obtain a high temperature level in the section between boreholes IV and V.

The results of the operation between boreholes III and V are summarized in table 36.

It was desired to show what effect the 600-foot length of section between boreholes V and III had on the operating characteristics, as well as to test the system and equipment under prolonged operation in one direction with high effluent gas temperatures. A comparison of the results of the operation in the section between boreholes III and IV with those obtained from III to V indicates that the longer path of travel resulted in better contact between the gas-making fluids and the reacting coal faces. Also, it was possible to operate the system in one direction for a long period, and although the effluent-gas temperatures near the base of the outlet borehole were at a temperature level above 1,900° F., it was quite practical to use a water spray and cool them to any desired level and handle them in the existing borehole.

TABLE 35. - Operating results for the section, boreholes VII to III to IV

Item	Cumulative total time, hours	Average air flow, c.f.m.1/	Average analysis of effluent gas: Percent CO_2	Ill.	O_2	H_2	CO	CH_4	N_2	Heating value, B.t.u. per cu. ft.1/	Mol water per mol dry gas	Average temperature of effluent gas, °F.	Average rate of coal consumption, tons per day2/	Heat balance3/, percent of heat of combustion of coal consumed: Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor	Unaccounted for and presumed stored underground, by difference
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
									Direction of flow, borehole VII to borehole III								
1 4/...	218	1,650	21.5	0.1	1.6	10.3	2.4	2.5	61.6	69	0.09	374	13.8	4.2	45.6	1.8	48.4
									Direction of flow, borehole VII to borehole IV								
2 5/...	271	7,510	13.2	.1	2.7	1.4	.5	1.4	80.7	22	.187	276	30.7	4.9	25.2	11.1	58.8
									Direction of flow, borehole IV to borehole VII								
3 6/...	240	7,490	13.9	.1	5.2	.5	.3	.6	79.4	11	.179	205	30.5	3.4	12.9	10.5	73.2
									Direction of flow, borehole III to borehole IV								
4 7/...	20	7,900	8.4	.0	9.4	.3	.1	.1	81.7	2	-	580	18.0	20.5	4.1	-	-
									Direction of flow, borehole IV to borehole III								
5 8/...	12	7,930	8.0	.0	10.4	.3	.1	.2	81.0	3	-	582	17.5	21.4	6.3	-	-

1/ At 60° F., 30 inches Hg., dry.
2/ Basis of moisture- and ash-free coal.
3/ Heat balance is based on 60° F.
4/ Average results of cycles 1,357, 1,359, 1,360, 1,361, and 1,362. Input-air pressure ranged from 6.5 to 8.2 inches of Hg. The flow of product gas out of borehole III was small; leakage from the system was large.
5/ Average of even-numbered cycles 1,364 to 1,410, inclusive.
6/ Average of odd-numbered cycles 1,363 to 1,409 inclusive.
7/ Average of cycles 1,420, 1,422, and 1,424.
8/ Average of cycles 1,421 and 1,423.

TABLE 36. - Operation of section between borehole III and borehole V

Time for period, total hours	Cumulative time, hours	Average air flow, c.f.m.1/	Average analysis of effluent gas: Percent CO_2	Ill.	O_2	H_2	CO	CH_4	N_2	Heating value, B.t.u. per cu. ft.1/	Mol water per mol dry gas2/	Average temperature of effluent gas, °F.	Average rate of coal consumption tons per day3/	Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor	Unaccounted for and presumed stored underground, by difference
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
									Direction of flow, borehole III to borehole V								
5/	228	7,850	11.2	0.1	5.4	0.5	0.2	0.7	81.9	11	0.25	632	24.3	16.5	16.5	22.5	44.5
									Direction of flow, borehole V to borehole III								
23	23	7,800	13.4	.1	3.6	1.0	.3	1.0	80.6	16	.25	481	30.9	9.9	18.9	17.0	54.2
19	42	8,050	11.1	.0	5.7	.5	.3	.5	81.9	8	.25	559	25.1	13.6	11.8	21.5	53.1
14	56	7,170	10.8	.0	6.2	.4	.2	.4	82.0	6	.25	580	21.4	15.6	9.2	22.6	52.6
12	68	7,900	10.5	.2	7.2	.2	.1	.3	81.5	8	.25	509	23.5	13.6	12.4	22.6	51.4
18	86	7,640	10.1	.2	7.2	.2	.0	.2	82.2	5	.25	620	21.5	18.3	8.4	24.9	48.4
22	108	7,780	10.0	.1	7.2	.1	.4	.4	81.8	7	.25	550	22.4	15.3	11.2	23.3	50.2
19	127	7,770	10.4	.2	7.4	.3	.0	.4	81.3	9	.25	666	23.0	18.5	14.1	23.8	43.6
17	144	8,050	10.1	.1	6.8	.2	.1	.3	80.4	6	.25	6/750	23.0	22.2	9.8	25.7	42.3
38	182	8,070	10.7	.1	7.4	.1	.0	.1	81.6	3	.25	6/1,150	23.3	35.4	4.8	29.2	30.6
121	303	7,690	11.3	.1	6.8	.2	.0	.2	81.4	5	.25	6/1,630	23.7	49.3	7.5	31.9	11.3
574	877	7,670	11.3	.0	7.3	.1	.1	.2	81.0	3	.25	6/1,940	23.6	57.8	4.5	35.5	2.2

1/ At 60° F., 30 inches Hg., dry.
2/ Average of all determinations of water content of effluent gas made during period.
3/ Basis of moisture- and ash-free coal.
4/ Heat balance is based on 60° F.
5/ Average of odd numbered cycles 1,425 to 1,447, inclusive, with exception of 1,429.
6/ Spray water was used: calculated temperature.

The heat balances given in table 36 indicate that the quantity of heat stored underground or lost to the surrounding strata was greatly diminished during the extended operation in one direction. The rate of coal combustion was approximately 2.5 times that for the operation in the single entry between boreholes I and II during the period of March 18 to June 21, 1949 (see tables 11 and 12). This latter fact was indicative of increased contact efficiency due to the increased length of passage and surface area exposed.

In the period of operation from October 7, 1950, to February 7, 1951, a total of 2,094 tons of moisture-and ash-free coal was consumed, making the cumulative total coal used 10,845 tons.

Borehole IV was located at the midpoint of the path between boreholes V and III, and a thermocouple was installed in borehole IV at a point five feet above the top of the coal bed. A temperature-time record of this thermocouple was made during the operation of the long cycles in the flow direction borehole V to III (see fig. 23). This figure indicates that the region adjacent to the base of borehole IV did not cool during extended periods of operation but, rather, showed a tendency to climb. This temperature indicates the stabilization of the combustion zone and a gradual increase in its temperature level rather than a movement of the combustion zone in the direction of flow of the gas-making fluids.

While operating on long cycles, the actual leakage from the system between boreholes V and III was determined to be about 10 to 15 percent. That is, of the total quantity of air admitted at borehole V, 85 to 90 percent was removed as effluent gases at borehole III. The actual leakage between III and V could very easily be less than the indicated value, as it was known that the region beyond borehole III was prone to leakage, and some of the gases could very easily have been leaving the system in this section as well as at borehole III.

After 877 hours on stream, it was believed that operations could be continued in this manner for an indefinite time before serious failure of the installation occurred. However, it appeared that very little additional information could be obtained, and it was decided to make one additional test at a decreased air-input rate and then discontinue operation of the project.

Operation of the Project at Various Input-Air Rates

Following operations in the section boreholes III to V and during the period January 20 to February 7, 1951, a test at low input air rate was made. Air was admitted at borehole VII, and the product gases were removed at borehole IV. The air rate ranged between 830 and 1,270 cubic feet per minute. It was assumed that the combustion zone would be concentrated in the section between boreholes VII and III. and that the products of combustion would be reduced in the section between boreholes III and IV. This latter section was at a high temperature level as a result of previous long-cycle operations, the product gases being removed at III. Thus, a combustion and preheating zone followed by a reduction zone would be available.

During the first 10 days of this test period the heating value of the effluent gas decreased, as shown in table 37, which summarizes results of the test. At the expiration of this period, and for an interval of approximately 48 hours, several variations in the air-input rate were tried, as follows: Using borehole III as an inlet, the same equivalent flow was taken out borehole IV and the residual capacity of the 2,000 c.f.m. blower was removed from borehole VII in an effort to decrease the water content of the effluent gas.

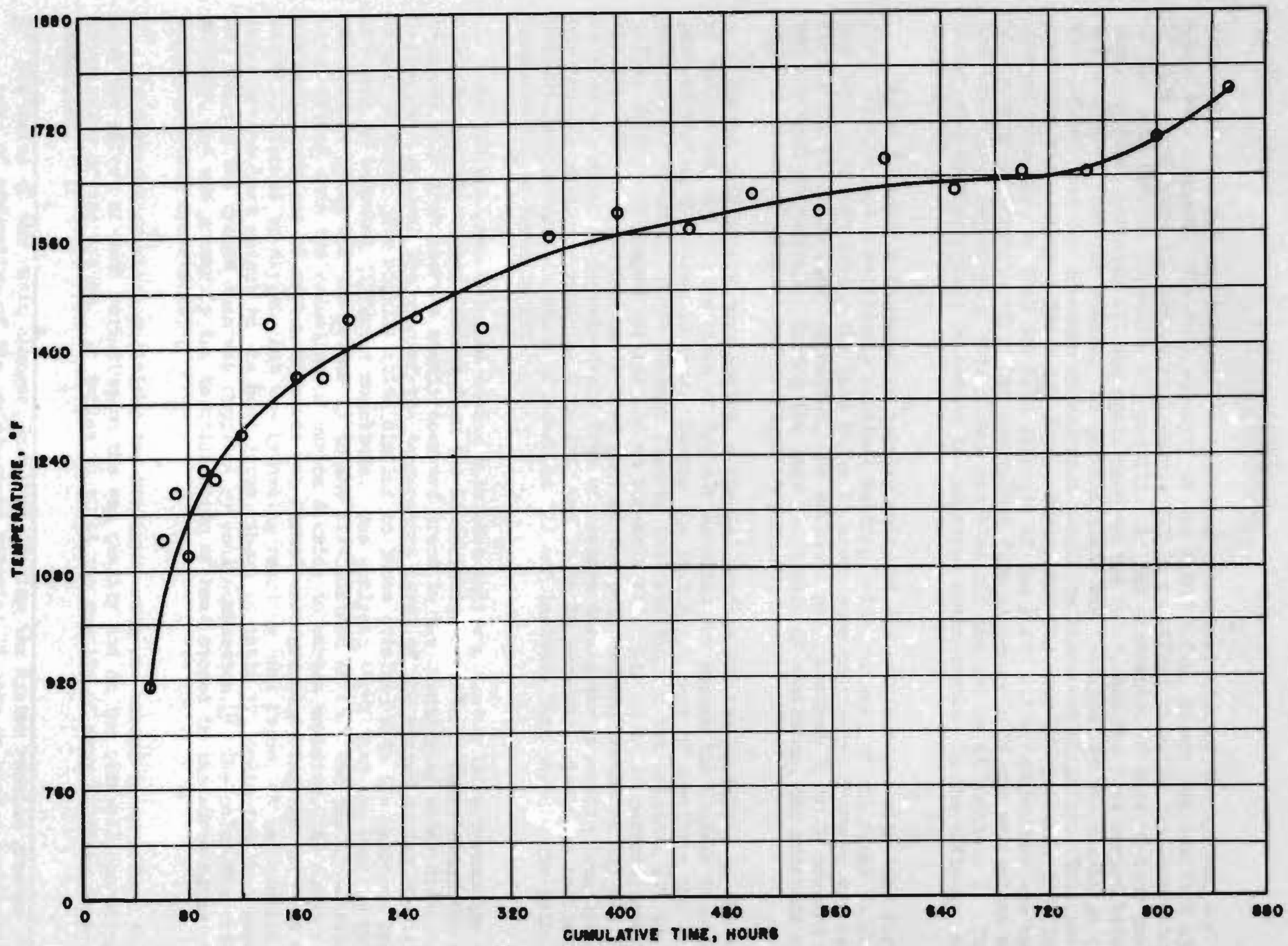


Figure 23. - Temperature at borehole IV, 5 feet above top of coal bed.

This split flow did not improve the operating characteristics of the system, and the flows again were changed. The full capacity of the 2,000 c.f.m. blower was admitted at borehole IV, and gases were discharged at borehole VII in an effort to raise the temperature level of the path between boreholes VII and III. At the expiration of this 48-hour period of changing flow, borehole VII was again used as the inlet, and the flow ranged between 830 and 970 cubic feet per minute. An orifice plate was installed at the discharge at borehole IV, so that the pressure underground would be increased slightly. This period of operation was continued for 7-1/2 days. During the last day of operation the flow was changed slightly, so that the full capacity of the 2,000 c.f.m. compressor was again put underground at borehole VII. The equivalent flow at borehole IV was maintained as before, and the excess capacity of this blower was bled off the system at borehole I. This last change was another effort to reduce the moisture concentration in the effluent gas at borehole IV.

Table 37 shows a decrease in heating value of the effluent gas with time for the first 10 days and a relatively constant heating value for most of the final 7-1/2 days of the test, although during the last 24 to 36 hours some additional decrease was noted. During the first 10 days' operation, the effluent gas contained 57 to 74 percent moisture and averaged 68 percent. During the last 7-1/2 days of operation, the moisture ranged between 69 and 78 percent and averaged 75 percent.

During this entire test period, a special orifice run was installed on the outlet of the system, and on the basis of dry air entering the system the leakage averaged 71 percent during the first 10 days. During the last 7-1/2 days of operation the leakage averaged 82 percent. These leakage figures indicate that of the original 839 to 1,270 c.f.m. of dry air pumped underground at borehole VII, only 29 to 18 percent, respectively, was available for gas making in that part of the path between boreholes III and IV. This section was shown to be relatively free of leakage during the preceding long cycle (leakage for the section, boreholes V to III, was 10 to 15 percent). The data indicate the maximum leakage area is south of borehole III and includes that part of the path from borehole VII to borehole III.

The gas analyses obtained during this test indicate that a large percentage of the hydrogen must have been derived from the dissociation of water. Correlating the hydrogen balances with time shows a steady downward trend in the quantity of water dissociated and indicates a general lowering of the temperature level of the system during the test. Oxygen balances give results quite similar to those obtained with the hydrogen balances, but were of somewhat different magnitude. Gas analysis shows that the heating value of the product gases was due primarily to the distillation of coal and the dissociation of water rather than the reduction of carbon dioxide to carbon monoxide. No doubt a considerable quantity of carbon monoxide was formed underground during the test and was subsequently burned by oxygen that was bypassing reacting coal faces. A calculation of the ratio of the heat output to the heat input, shown in table 37, indicates that more heat was leaving the system than was supplied by coal combustion.9/ The calorific value of the effluent gas was primarily due to utilization of heat stored in the surrounding strata during previous operations.

On numerous previous occasions the air-input rate was varied in an effort to determine the effect of such variation on the gas quality and on the over-all operating characteristics of the system. In tables 38 to 41 the results of many of these tests are summarized.

9/ The value of the ratio changes, but heat leaving the system remains greater than the heat of combustion of the carbonaceous material if coke or partly devolatilized coal was considered as the basis.

TABLE 37. - Operation at low input-air rates, January 20 to February 7, 1951

Period, hours	Air flow, c.f.m.1/	Effluent gas flow, c.f.m.2/	Water content of effluent gas, percent1/	Leakage from system3/, percent	Analysis of dry effluent gas								Average temperature of effluent gas, F.	Ratio of heat output to heat input4/
					Percent							Heating value, B.t.u. per cu. ft.1/		
					CO_2	Ill.	O_2	H_2	CO	CH_4	N_2			
50......	917	1,572	68.8	74.0	28.3	0.3	0.1	21.6	6.3	4.9	38.5	147	1,110	1.44
9......	928	1,408	69.0	72.8	25.9	.3	.2	20.3	4.3	3.3	45.7	119	1,055	1.52
6......	928	1,400	71.4	74.4	25.4	.4	.3	19.6	4.1	3.1	47.1	116	1,045	1.63
15......	985	1,361	70.3	73.5	24.3	.2	.2	18.0	3.3	3.0	51.0	104	1,040	1.64
9......	1,172	1,347	73.9	77.4	20.6	.3	.5	14.7	2.2	2.2	59.5	83	1,025	2.04
12......	1,270	1,300	67.1	73.0	19.9	.1	.1	12.8	1.9	1.9	63.3	69	1,015	1.68
12......	1,115	1,172	66.6	73.2	21.8	.1	.2	13.8	1.8	2.0	60.3	73	1,000	1.47
18......	1,064	1,109	66.7	73.5	21.8	.3	.3	13.0	2.2	2.1	60.3	77	995	1.53
12......	957	1,085	71.7	75.0	21.6	.1	.2	12.7	1.6	2.0	61.8	69	985	1.94
21......	918	1,059	64.2	66.5	20.9	.0	.2	11.9	1.2	2.1	63.7	64	985	1.49
39......	890	981	64.0	66.6	20.0	.0	.1	10.4	1.0	2.1	66.4	58	975	1.50
10......	904	963	56.5	59.8	19.1	.1	.0	9.5	1.0	1.8	68.5	54	970	1.27
48......	Interval during which direction and quantity of input air was varied													
14......	909	-	-	-	16.7	.1	.2	6.8	4.5	.9	70.8	48	375	-
12......	892	-	-	-	22.0	.1	.1	10.0	2.0	1.2	64.6	53	665	-
36......	888	-	-	-	22.4	.1	.1	8.4	1.0	1.9	66.1	52	805	-
36......	887	762	78.0	86.0	25.5	.2	.3	12.2	.7	2.4	58.7	70	895	1.94
20......	839	774	75.8	81.4	22.4	.2	.3	9.9	.7	1.9	64.6	58	930	1.99
12......	841	792	77.7	83.0	23.2	.3	.2	9.4	.6	2.3	64.0	63	925	2.07
12......	920	782	74.9	81.3	20.6	.1	.2	7.7	.5	1.4	69.5	43	940	2.02
20......	970	753	68.5	78.1	19.4	.1	.2	7.3	.4	1.4	71.2	42	935	1.69

1/ At 60° F., 30 inches Hg., dry.
2/ Calculated to 60° F., 30 inches Hg., containing all water as vapor.
3/ Based on nitrogen balance and gas flowing calculated in terms of equivalent air.
4/ The heat output includes the sensible heat, the latent heat, and the heat of combustion of the constituents of the effluent gas above 60° F; the heat input is the heat of combustion of the moisture- and ash-free coal consumed.

TABLE 38. - Variation in operating results with varying input-air rates; operating period December 21, 1949 to June 5, 1950; direction of flow, borehole I to borehole II

Cycle No.	Length of cycle, hours	Average air flow, c.f.m.1/	Average analysis of effluent gas, Percent: CO_2	Ill.	O_2	H_2	CO	CH_4	N_2	Heating value, B.t.u. per cu. ft.1/	Mol water per mol dry gas	Temperature of effluent gas: Av. temp., °F.	Max. temp., °F.	Average rate of coal consumption, tons per day2/	Heat balance3/, percent of heat of combustion of coal consumed: Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor	Unaccounted for and presumed stored underground, by difference
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
4/	6.0	7,590	6.7	0.1	12.6	0.7	0.1	0.1	79.7	5.6	0.173	235	353	14.3	8.2	13.8	22.0	56.0
534 B	3.8	1,840	16.7	.2	12.2	.4	.4	.0	70.1	6.6	-	-	-	6.6	-	9.8	-	-
536	8.0	2,085	12.9	.2	12.1	.9	.0	.4	73.5	11	-	141	160	8.2	2.0	14.2	-	-
538	7.0	1,980	11.2	.0	12.3	.8	.2	.2	75.3	5.2	-	210	337	6.5	4.4	7.9	-	-
540	8.0	2,060	10.1	.2	11.8	.6	.4	.7	76.4	14	0.348	170	172	6.7	3.2	21.1	26.1	49.6
542	8.0	2,140	8.5	.0	12.9	.2	.0	.4	78.0	4.8	.223	150	162	5.2	3.3	9.5	21.7	65.5
544	8.0	2,180	7.8	.0	13.0	.5	.2	.3	78.2	5.2	.440	144	160	4.9	3.3	11.1	48.5	37.1
546	8.0	7,800	4.9	.4	12.4	.2	.2	.2	81.7	11	.146	262	378	12.4	16.9	28.8	21.7	38.6
548	8.0	7,530	6.2	.0	12.5	.7	.2	.0	80.4	2.9	.120	254	370	12.8	10.1	7.9	16.9	65.1
550	8.0	7,530	6.8	.0	12.7	.5	.3	.3	79.4	5.5	.138	252	364	15.0	8.6	13.0	16.8	61.6
552	8.0	7,530	6.8	.4	12.2	.0	.2	.2	80.2	11	.119	251	358	16.0	8.0	24.2	13.4	54.4
554	8.0	7,460	7.3	.0	12.0	.4	.2	.2	79.9	3.9	.142	261	374	15.3	8.7	8.9	15.7	66.7
5/	7.1	8,080	5.4	.1	13.9	.3	.2	.2	79.9	5.6	.128	233	332	12.2	10.1	17.4	20.2	52.3
707	8.0	2,080	10.0	0.2	7.8	.6	.4	.6	80.4	13	6/.104	192	239	4.1	5.9	30.7	12.3	51.1
709	8.0	2,070	9.0	.2	11.8	.9	.7	.6	76.8	15	.093	172	360	6.2	3.4	24.4	7.5	64.7
711	8.0	2,070	8.8	.4	12.2	.8	.2	.6	77.0	17	.115	159	203	6.0	3.2	28.5	9.5	58.8
713	8.0	2,080	7.9	.0	13.2	.8	.3	.5	77.3	8.7	6/.104	155	171	5.0	3.6	17.7	10.3	68.4
715	8.0	7,990	3.3	.0	12.7	.2	.0	.2	83.6	2.7	.353	297	422	7.1	22.4	13.6	9.3	54.7
717	6.8	7,680	3.4	.2	14.2	.0	.0	.2	82.0	6.0	.433	271	375	8.0	17.4	26.3	9.8	46.5
719	7.0	7,960	5.1	.0	13.2	.0	.0	.2	81.5	2.0	.312	234	329	11.0	11.0	6.6	5.3	77.1
721	8.0	8,050	5.0	.0	14.1	.9	.7	.2	80.1	7.2	-	260	382	12.6	11.2	21.5	-	-
723	7.1	7,960	5.8	.2	13.2	.4	.0	.0	80.4	5.3	-	249	358	13.1	10.1	15.0	-	-

1/ At 60° F., 30 inches Hg., dry. 2/ Basis of moisture- and ash-free coal. 3/ Heat balance is based on 60° F. 4/ Average of cycles 524, 526, 528, 530, 532 and 534 A. 5/ Average of cycles 700, 702, 704 and 706. 6/ Average of values for cycles 709 and 711.

TABLE 39. - Variation in operating results with varying input-air rates; operating period December 21, 1949 to June 5, 1950; direction of flow, borehole II to borehole I

Cycle No.	Length of cycle, hours	Average air flow, c.f.m.1/	Average analysis of effluent gas, Percent: CO_2	Ill.	O_2	H_2	CO	CH_4	N_2	Heating value, B.t.u. per cu. ft.1/	Mol water per mol dry gas	Temperature of effluent gas: Av. temp., °F.	Max. temp., °F.	Average rate of coal consumption, tons per day2/	Heat balance3/, percent of heat of combustion of coal consumed: Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor	Unaccounted for and presumed stored underground, by difference
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
4/	7.7	7,570	7.5	0.2	12.2	0.7	0.3	0.3	78.8	10	0.090	247	393	17.4	7.2	20.7	9.5	62.6
533 B	1.0	2,055	12.7	.0	12.6	.7	.2	.4	73.4	7.0	-	-	-	8.0	-	9.2	-	-
535	8.0	2,060	7.6	.2	13.3	.5	.4	.4	77.6	11	-	174	247	5.0	4.3	21.9	-	-
537	3.3	2,030	13.7	.0	12.6	.5	.2	.4	72.6	6.3	0.233	114	158	8.5	1.3	7.8	13.9	77.0
539	5.5	2,170	11.8	.4	12.7	.9	.2	.5	73.5	17	.151	137	159	8.4	2.0	22.4	9.8	65.8
541	8.0	2,170	8.1	.4	11.7	.9	.4	.2	78.3	14	-	152	200	5.6	3.2	26.0	-	-
543	8.0	2,170	8.4	.0	13.1	.4	.4	.4	77.3	6.7	0.156	143	223	5.5	3.0	12.8	14.6	69.6
545	8.0	7,740	4.7	.2	12.7	.0	.2	.2	82.0	6.6	.153	262	574	11.1	12.1	21.0	25.1	41.8
547	8.0	7,760	6.2	.0	12.3	.8	.4	.2	80.2	5.9	.092	306	481	13.8	12.2	15.5	12.7	59.6
549	8.0	7,570	6.7	.1	12.4	.6	.1	.3	79.8	7.3	.100	284	442	14.8	10.8	18.5	13.2	57.5
551	8.0	7,570	7.5	.0	11.9	.8	.2	.0	79.6	3.2	.109	268	429	15.6	9.1	7.3	12.9	70.7
553	7.3	7,590	6.8	.4	12.6	.4	.2	.2	79.4	12.0	.095	253	400	16.3	8.1	26.3	10.7	54.9
5/	8.0	8,040	6.7	.1	13.2	.4	.4	.2	79.0	6.6	.069	249	380	16.3	8.4	15.4	8.3	67.9
708	8.0	1,980	11.9	.2	9.7	.8	.4	.6	76.4	14	.305	300	458	7.4	6.1	18.4	26.5	49.0
710	8.0	2,100	9.1	.2	11.5	.6	.2	1.0	77.4	17	.269	307	437	6.2	7.8	27.9	23.2	41.1
712	8.0	2,055	9.1	.2	12.4	.2	.0	.6	77.5	11	-	342	490	5.6	9.6	19.5	-	-
714	8.0	7,850	2.7	.2	13.1	.0	.0	.4	83.6	8.1	0.151	437	568	7.0	35.5	40.7	42.6	-
716	6.5	8,090	5.5	.2	12.8	.6	.0	.2	80.7	8.0	0.307	366	490	13.0	16.9	23.1	47.8	12.2
718	8.0	7,910	5.8	.0	13.1	.2	.0	.2	80.7	2.7	0.102	317	490	12.5	14.3	7.9	15.7	62.1
720	7.1	7,910	5.8	.0	13.3	.6	.2	.0	80.1	2.6	-	297	458	12.6	13.3	7.6	-	-
722	8.0	8,010	7.2	.0	12.9	.0	.0	.0	79.9	0	-	279	430	15.4	10.5	0	-	-
724	8.0	7,840	6.4	.0	12.9	.9	.0	.2	79.6	4.9	-	296	445	13.9	11.9	13.0	-	-

1/ At 60° F., 30 inches Hg., dry. 2/ Basis of moisture- and ash-free coal. 3/ Heat balance is based on 60° F. 4/ Average of cycles 525, 527, 529, 531 and 533 A. 5/ Average of cycles 703 and 705.

TABLE 40. - Variation in operating results with varying input-air rates; operating period June 5 to October 7, 1950; direction of flow, borehole III to borehole VII

Cycle No.	Length of cycle, hours	Average air flow, c.f.m.1/	Average analysis of effluent gas, Percent: CO_2	Ill.	O_2	H_2	CO	CH_4	N_2	Heating value, B.t.u. per cu. ft.1/	Mol water per mol dry gas	Temperature of effluent gas: Av. temp., °F.	Max. temp., °F.	Average rate of coal consumption, tons per day2/	Heat balance3/, percent of heat of combustion of coal consumed: Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor	Unaccounted for and presumed stored underground, by difference
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
4/	4.0	7,460	11.7	0.3	5.3	2.8	1.7	0.9	77.3	30	0.123	565	815	31.0	11.6	35.3	8.5	44.6
5/	4.0	5,155	11.1	.2	5.6	4.1	1.7	1.1	76.2	34	.145	496	720	29.9	10.4	41.6	10.1	37.9
6/	4.5	7,390	10.8	.3	6.2	3.1	2.4	.6	76.6	30	.152	629	928	30.0	12.2	32.8	10.0	45.0
7/	5.0	7,300	9.9	.2	7.7	2.8	1.7	.8	76.9	27	8/.07	472	844	26.9	10.9	37.0	5.4	46.7
9/	5.7	3,930	11.0	.2	7.4	2.1	1.1	.6	77.6	20	.166	534	867	14.3	12.4	26.7	12.8	48.1
10/	5.6	7,420	10.0	.1	8.5	1.5	1.2	.6	78.1	17	.194	478	767	24.6	11.9	24.8	16.0	47.3
1,269	6.0	1,740	16.3	.2	6.7	3.3	1.3	.9	71.3	28	.602	469	686	10.0	7.7	25.9	31.3	35.1
1,271	30.8	1,715	14.3	.2	6.6	4.3	1.3	.9	72.4	31	11/.536	477	757	8.6	8.6	32.4	31.6	27.4
1,273	29.7	1,595	13.2	.2	6.7	2.1	0.8	0.8	76.2	22	11/.536	793	1,350	6.9	7.6	25.2	39.2	28.0
1,275	29.8	1,625	12.5	.2	7.1	2.0	.5	1.0	76.7	22	11/.536	842	1,350	6.6	6.0	26.7	42.3	25.0
1,277	9.3	1,705	11.1	.2	7.3	1.9	.3	.8	78.4	19	.470	479	725	5.9	11.4	26.5	37.1	25.0
1,279	8.0	7,490	9.1	.3	8.8	.7	.4	.3	80.4	13	.133	582	956	20.8	17.0	21.9	13.2	47.9
1,281	8.0	7,680	9.6	.1	8.4	1.8	.6	.4	79.1	14	.277	499	813	22.6	13.8	22.8	25.7	37.7
1,283	8.0	7,540	10.0	.2	9.0	1.6	.7	.4	78.1	16	-	458	764	24.0	10.5	24.4	-	-
1,285	8.0	7,710	10.1	.0	9.0	1.2	1.0	.6	78.1	13	.308	444	738	27.1	10.3	17.9	23.6	48.2
1,287	8.0	7,570	10.7	.1	9.0	.8	.2	.8	78.4	13	.175	436	743	24.8	10.8	19.1	14.3	55.8

1/ At 60° F., 30 inches Hg., dry. 2/ Basis of moisture- and ash-free coal. 3/ Heat balance is based on 60° F. 4/ Average of cycles 984, 986, 988, 990, and 992. 5/ Average of cycles 994 and 996. 6/ Average of cycles 998, 1,000, 1,002 and 1,004. 7/ Average of cycles 1,176, 1,178, 1,180, and 1,185. 8/ Average value for preceding week. 9/ Average of even-numbered cycles 1,190 through 1,230. 10/ Average of 17 cycles preceding No. 1,269; direction borehole III to VII. 11/ Average for cycles 1,269 and 1,277.

TABLE 41. - Variation in operating results with varying input-air rates; operating period June 5 to October 7, 1950; direction of flow, borehole VII to borehole III

Cycle No.	Length of cycle, hours	Average air flow, c.f.m.1/	Average analysis of effluent gas, Percent: CO_2	Ill.	O_2	H_2	CO	CH_4	N_2	Heating value, B.t.u. per cu. ft.1/	Mol water per mol dry gas	Temperature of effluent gas: Av. temp., °F.	Max. temp., °F.	Average rate of coal consumption, tons per day2/	Heat balance3/, percent of heat of combustion of coal consumed: Sensible heat content of dry effluent gas	Heat of combustion of dry gas	Sensible and latent heat of water vapor	Unaccounted for and presumed stored underground, by difference
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
4/	6.0	7,440	11.8	0.2	4.1	2.8	1.7	1.0	78.4	29	0.351	775	1,000	30.5	16.5	34.1	[illegible]	[illegible]
5/	6.0	5,320	13.0	.3	3.6	3.8	1.2	1.9	76.2	42	-	754	925	25.2	14.4	44.0	-	-
6/	5.8	7,510	12.7	.3	3.8	2.9	2.1	.7	77.5	29	0.331	774	1,431	33.7	15.3	31.5	22.8	30.4
7/	5.0	7,450	10.4	.1	5.5	2.2	1.4	1.0	79.4	24	.344	720	903	28.3	17.4	32.4	28.8	21.4
8/	5.4	4,040	11.8	.2	5.8	2.1	1.0	.8	78.3	22	.379	535	762	15.8	11.5	27.7	26.7	34.2
9/	5.4	7,530	10.0	.1	6.9	2.1	1.5	.7	78.7	21	.233	529	765	25.6	12.9	29.7	19.0	38.4
1,268	6.0	1,280	19.5	.6	3.5	9.5	4.0	1.2	61.6	66	.727	364	546	11.6	4.1	45.3	26.1	24.5
1,270	27.0	1,715	17.3	.4	3.5	7.3	2.1	2.1	67.3	60	.725	816	1,292	12.3	12.0	47.0	36.5	4.5
1,272	31.0	1,640	17.4	.1	3.6	7.7	1.9	1.9	67.4	52	10/.706	772	1,359	11.1	11.9	43.1	36.8	8.2
1,274	28.3	1,640	14.7	.1	4.9	2.6	1.2	1.3	75.2	28	.745	862	1,379	8.8	16.2	28.2	49.0	6.6
1,276	27.5	1,610	14.5	.2	3.9	3.4	1.1	.6	77.3	21	.611	816	1,330	7.5	16.0	21.1	41.3	24.6
1,278	4.2	7,600	8.4	.5	7.6	.5	.2	.3	82.5	15	.069	954	1,104	19.7	31.1	26.7	8.3	33.9
1,280	8.0	7,610	9.0	.1	7.2	1.4	1.0	.5	79.6	16	.212	611	986	22.3	17.4	26.0	20.5	36.1
1,282	8.0	7,680	9.6	.1	7.2	1.9	1.2	.7	79.3	19	.195	546	892	24.5	14.1	28.4	16.9	40.6
1,284	8.0	7,760	9.2	.1	7.0	1.6	1.0	.9	80.0	20	.145	541	875	23.7	18.4	31.0	13.0	37.4
1,286	8.0	7,710	11.3	.1	6.9	2.2	.8	1.1	77.5	25	.242	441	831	28.4	9.8	32.7	17.5	39.9

1/ At 60° F., 30 inches Hg., dry. 2/ Basis of moisture- and ash-free coal. 3/ Heat balance is based on 60° F. 4/ Average of cycles 989 and 991. 5/ Average of cycles 993 and 995. 6/ Average of cycles 997, 999, 1,001 and 1,003. 7/ Average of cycles 1,179 and 1,184. 8/ Average of odd-numbered cycles 1,189 through 1,231. 9/ Average of 17 cycles preceding cycle 1,268; direction borehole VII to III. 10/ Average of two preceding and two following cycles.

Tables 38 and 39 give results of a group of tests made in the section between boreholes I and II during the period December 21, 1949, to June 5, 1950. The operational history before and after the test has been included to show the effect on over-all characteristics of the system. In this period a decrease in the input-air rate from approximately 7,500 to 2,000 c.f.m. had little effect on the quality of the effluent gases. At the start of the reduced-flow period an increase in carbon dioxide content was noted, but very little change in the oxygen content was found, and there was a slight increase in heating value, which, during the course of the operation, tended to decrease. At reduced air flow there was a marked reduction in the rate of coal consumption and usually a decrease in the sensible heat content of the product gases. Upon returning to an input-air rate of approximately 7,500 cubic feet per minute, one or more cycles were required to bring the operating level back to that which had existed before the input-air flow rate was changed. The operating characteristics seemed to indicate a general decrease in the temperature level underground as a result of the decreased input-air rates.

In tables 40 and 41, the results of a series of tests made in the section from borehole III to borehole VII during the operating period of June 5 to October 7, 1950, have been summarized. The input-air rates were varied from approximately 7,500 c.f.m. to 5,200 c.f.m. to 4,000 c.f.m. to 1,800 c.f.m., and the operational history of the project before and after these lower air-input rates are included. A decrease in input-air rate from 7,500 to 5,300 and 4,000 c.f.m. had little effect on the quality of the effluent gases and resulted in reducing the rate of coal consumption.

In every instance when the input-air rate was reduced to approximately 1,800 c.f.m., the heating value of the effluent gases first increased and then decreased steadily with time until, after several cycles, it reached a value approximating that which had been obtained before the change was put into effect. In each instance several cycles were required at 7,500 cubic feet per minute to bring the over-all operating level of the project back to that which had existed prior to the change. A general decrease in temperature level underground was indicated when the input air rates were reduced to the 1,800 c.f.m. figure. The effluent gases contained an increased percentage of moisture during these flows, which resulted in a higher percentage of the heat of combustion of the coal being present as sensible and latent heat of the moisture in the product gases.

Leakage from the Underground System

Before firing the underground installation on March 18, 1949, a test was made to determine leakage from the system. With all outlet valves closed, air was pumped underground until a pressure of approximately 5 p.s.i.g. was attained. The pumping was stopped, and the pressure loss with time was determined. This preliminary test indicated that the leakage from the system would be approximately 5 percent of the input air with an average pressure of about 2 p.s.i.g. underground. It was known that there was some leakage from the air manifold and at the entry seal, and after firing the project each of these leaks was stopped.

To measure gas flow, orifices were installed at the surface in the outlet stacks at boreholes I and II. Piping requirements at these points rendered compliance with orifice-meter installation specifications impossible, and, for this reason, the orifice constant could not be calculated accurately, and the following discussion is based on the assumption that leakage at the start of operations was negligible. The data, therefore, may be regarded as qualitative, and their chief value lies in establishing variation in leakage with time.

Effluent-gas flow data were collected at regular intervals during operations. These data consisted of differential pressure across the orifice, pressure upstream of the orifice, and gas temperature. Moisture content of the gas was determined in most instances. The final leakage figure was based on dry gas outflow at 60° F. and 30 inches Hg. pressure, referred to air input at the same base conditions.

During the first operating period, with flow in the direction borehole I to borehole II, the data of table 42 indicates leakage ranging from zero to approximately 3 percent. The average back pressure or pressure required to force the normal air flow of approximately 7,500 std. c.f.m. through the system, increased during the same period from 3.7 to 5 p.s.i.g.

In the second operating period, June 21 to October 5, 1949, leakage when operating borehole I to borehole II increased from 3 to 6 percent. This accompanied an increase in the back pressure from 5.2 to 12 p.s.i.g. The leakage and back pressure are plotted against time in figure 24. It was observed that somewhat similar trends were followed by both sets of values. During most of the first and second operating periods, the calculated leakage given in table 43 remained at zero, based on gas flow out borehole I. From these observations it can be reasoned that the crevices where leakage occurred were in an area where the increased pressure at borehole I was operative, but similar pressure applied at borehole II was not operative. Little evidence was obtained that the crevices through which leakage occurred increased in size or number during the two periods.

The operating period from October 5 to December 22, 1949 was characterized by long cycles and high effluent gas temperatures. The effluent gas volumes were not measured. The area of coal consumed increased rapidly near boreholes I and II, and high resistance to the flow of hot gases developed at coal-bed level near these boreholes.

Following operations with high effluent gas temperatures and long cycles, and at the start of the operating period December 22, 1949, to June 5, 1950, leakage increased to approximately 16 percent, and by June 5, 1950 it had increased to approximately 18 percent (see table 42 and fig. 25). In both cases the gas flow was from borehole I to borehole II, as repairs to borehole I water jacket had rendered that orifice inoperative. Figure 25 shows that an increase in back pressure early in the period was accompanied by an increase in leakage. Thereafter, a gradual decline in back pressure was noted; whereas leakage remained nearly the same. It was evident that the rise in back pressure, caused perhaps by gradual subsidence of the strata overlying the burned-out area, had changed the pattern of air-gas flow underground and diverted more gas to leakage. It appeared likely that during this period and the preceding period, October 5 to December 22, the cross-sectional area of crevices available for leakage increased.

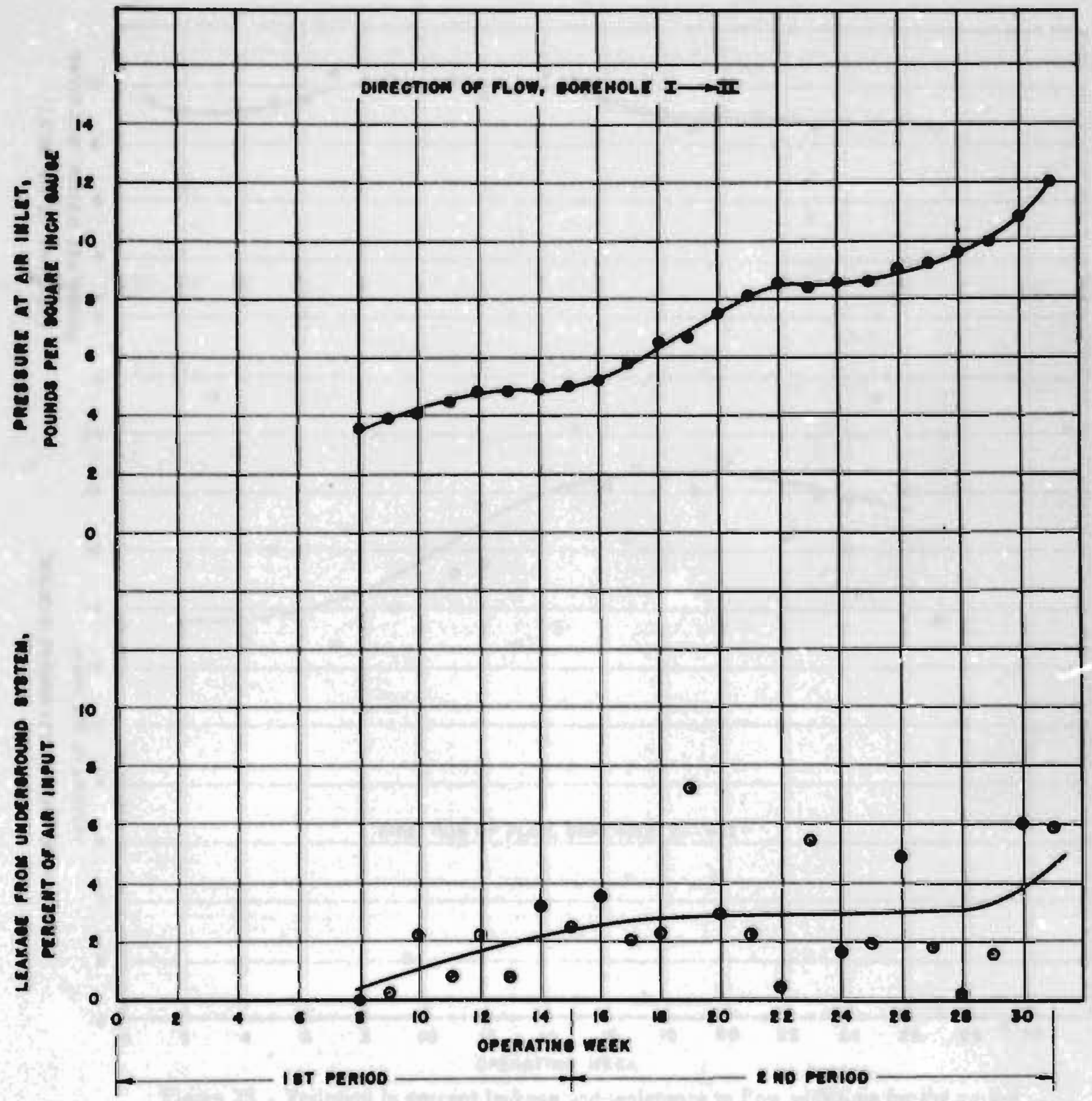


Figure 24. - Variation in percent leakage and resistance to flow with time for the periods March 18 to June 21 and June 21 to October 5, 1949.

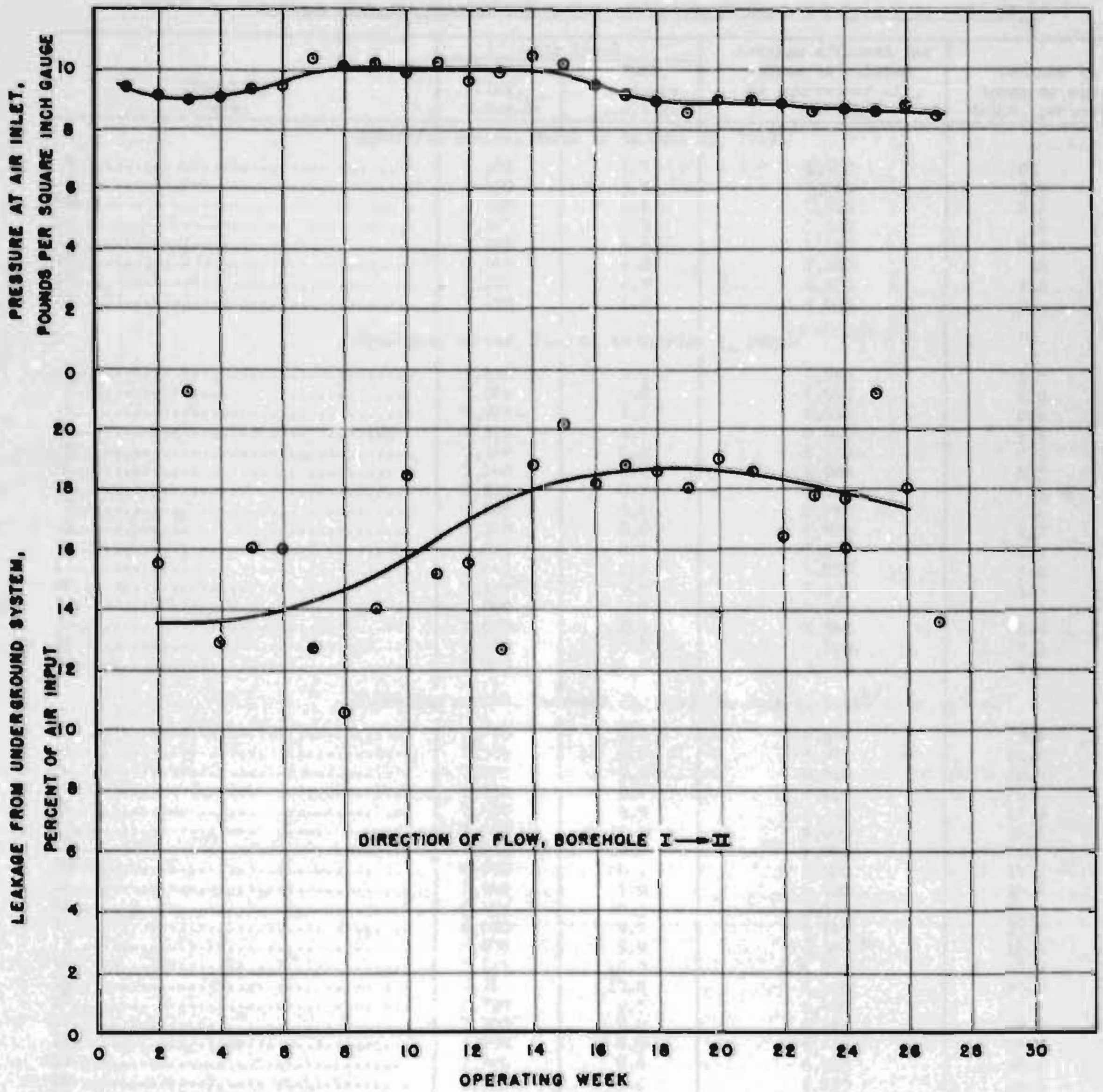


Figure 25. - Variation in percent leakage and resistance to flow with time for the period December 22, 1949 to June 5, 1950.

TABLE 42. - Leakage from the underground system; direction of flow, borehole I to borehole II

Operating week	Air input: Average flow, c.f.m.1/	Air input: Back pressure, p.s.i.g.	Average effluent gas volume calculated as equivalent air, c.f.m.1/	Leakage in terms of air input, percent
Operating period, March 18 to June 21, 1949 2/				
8	7,380	3.7	7,460	0
9	7,490	3.9	7,460	0.4
10	7,680	4.1	7,510	2.2
11	7,560	4.5	7,500	.8
12	7,320	4.8	7,160	2.2
13	7,240	4.8	7,180	.8
14	7,200	4.9	6,970	3.2
15	7,200	5.0	7,020	2.5
Operating period, June 21 to October 5, 1949 3/				
1	7,110	5.2	6,860	3.5
2	7,080	5.8	6,940	2.0
3	6,975	6.5	6,810	2.4
4	7,135	6.7	6,610	7.4
5	7,160	7.5	6,950	2.9
6	7,140	8.1	6,980	2.2
7	7,130	8.7	7,100	.4
8	7,105	8.4	6,720	5.4
9	7,140	8.6	7,020	1.7
10	7,220	8.7	7,080	1.9
11	7,245	9.0	6,880	5.0
12	7,135	9.3	7,000	1.9
13	7,090	9.7	7,080	.1
14	7,050	9.9	6,940	1.6
15	7,245	10.8	6,820	5.9
16	7,075	12.0	6,760	4.5
Operating period, December 22, 1949 to June 5, 1950 4/				
2	7,770	9.2	6,560	15.6
3	7,585	9.0	5,975	21.2
4	7,555	9.2	6,610	12.5
5	7,650	9.4	6,425	16.0
6	7,570	9.5	6,360	16.0
7	7,565	10.4	6,605	12.7
8	7,880	10.2	7,040	10.7
9	7,950	10.3	6,820	14.0
10	7,940	9.9	6,460	18.6
11	8,130	10.3	6,895	15.2
12	8,000	9.7	6,745	15.7
13	8,005	9.9	6,995	12.6
14	7,835	10.5	6,355	18.9
15	7,915	10.2	6,320	20.2
16	7,890	9.5	6,460	18.1
17	7,900	9.2	6,415	18.8
18	7,860	8.9	6,400	18.6
19	7,720	8.6	6,325	18.1
20	7,720	9.0	6,250	19.0
21	7,690	9.0	6,250	18.7
22	7,670	8.9	6,415	16.4
23	7,640	8.7	6,280	17.8
24	7,600	8.7	6,380	16.1
25	7,595	8.6	5,980	21.3
26	7,620	8.8	6,250	18.0
27	7,630	8.4	6,595	13.6

1/ At 60° F., 30 inches Hg., dry. 2/ The week ended Mar. 19, 1949 = 1. 3/ The week ended June 25, 1949 = 1. 4/ The week ended Dec. 24, 1949 = 1.

TABLE 43. - Leakage from the underground system; direction of flow borehole II to borehole I

Operating week	Air input: Average flow, c.f.m.[1]	Air input: Back pressure, p.s.i.g.	Average effluent gas volume calculated as equivalent air, c.f.m.[1]	Leakage in terms of air input, percent
	Operating period, March 18 to June 21, 1949[2]			
7	7,400	-	7,400	0
8	7,450	3.6	7,380	0.9
9	7,525	3.8	7,540	0
10	7,695	3.8	7,380	0
11	7,460	4.4	7,320	1.9
12	7,280	4.6	7,400	0
13	7,300	4.7	7,410	0
14	7,280	4.7	7,280	0
15	7,220	4.7	7,250	0
	Operating period, June 21 to October 5, 1949[3]			
1	7,020	4.9	7,275	0
2	7,090	5.5	7,280	0
3	7,030	5.9	7,180	0
4	7,120	6.3	6,910	2.9
5	7,210	7.0	7,200	0.1
6	7,230	7.4	7,310	0
7	7,180	7.6	7,375	0
8	7,190	7.8	-	-
9	7,190	7.8	-	-
10	7,300	8.0	7,460	0

1/ At 60° F., 30 inches Hg., dry. 2/ The week ended Mar. 19, 1949 = 1.
3/ The week ended June 25, 1949 = 1.

In the succeeding period, June 5, 1950, to October 7, 1950, with operation between boreholes III and VII, effluent-gas flow data were available only when borehole III was the gas outlet. During the first 6 weeks of this period, effluent-gas volumes were not obtained, because the use of spray water in the outlet borehole made it impossible to calculate accurately the volume of gas flowing. Consequently, the first leakage figures obtained were for the seventh week, when the back pressure for the period reached the maximum of 12.7 p.s.i.g. Table 44 and figure 26 show that the leakage increased for the next 7 weeks, despite a constant decline in the back pressure. Thereafter, the percent leakage and the back pressure continued to decrease with time. Several extended periods of operation with reduced flow rendered possible the evaluation of leakage at reduced pressures. At an air input of 4,075 std. c.f.m. and back pressure of 5.7 p.s.i.g., leakage was 42.0 percent, as compared to 46.0 percent at normal air input. With the air input further decreased to 1,620 std. c.f.m. and back pressure at 2.3 p.s.i.g., the leakage was 39.5 percent, compared to 44.0 percent at normal air input. The fraction of entering air diverted to leakage was nearly constant for all air-input rates.

In the early weeks of this period, large amounts of sand was injected into the original entries between boreholes II and III. The increasing back pressure shows that the sand was effective to some degree in plugging the entries against gas flow. The gas flowing from borehole VII to borehole III was therefore compelled to pass through a relatively small burned-out area near the sand plugs. At the same time, the gas had ready access to the large burned-out area bounded by boreholes I, II, and VII, where, it has been concluded, the leakage occurred. The increasing leakage with decreasing back pressure indicates that the cross-sectional area of the crevices available for leakage was increasing with time.

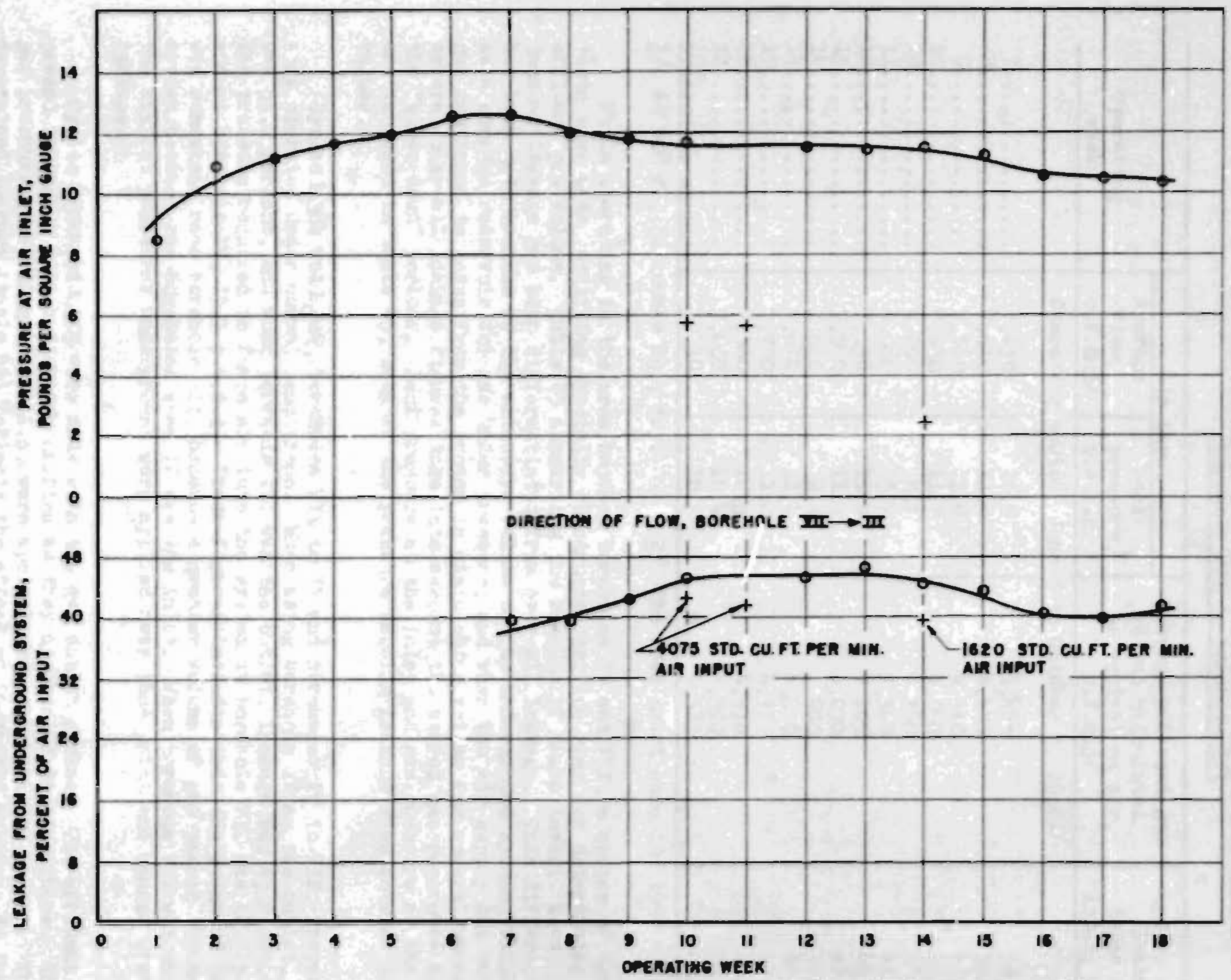


Figure 26. - Variation in percent leakage and resistance to flow with time for the period June 5 to October 7, 1950.

TABLE 44. - Leakage from the underground system; direction of flow, borehole VII to borehole III

Operating week	Air input		Average effluent gas volume calculated as equivalent air, c.f.m.1/	Leakage in terms of air input, percent
	Average flow, c.f.m.1/	Back pressure, p.s.i.g.		
	Operating period, June 5 to October 7, 1950 2/			
7	7,430	12.6	4,485	39.6
8	7,410	11.9	4,485	39.5
9	7,560	11.8	4,340	42.6
10	7,450	11.7	4,050	45.6
10	4,090	5.7	2,360	42.3
11	4,060	5.7	2,360	41.8
12	7,530	11.4	4,105	45.5
13	7,560	11.3	4,050	46.4
14	1,620	2.3	980	39.5
14	7,670	11.4	4,270	44.3
15	7,700	11.2	4,375	43.2
16	7,560	10.5	4,530	40.1
17	7,600	10.4	4,590	39.6
18	7,730	10.3	4,585	40.7

1/ At 60° F., 30 inches Hg., dry. 2/ The week ended June 10, 1950 = 1.

While operating in the area between boreholes IV and VII, a series of leakage tests were made, utilizing specially constructed orifice runs for determining the effluent gas volume. Table 45 summarizes the results of these tests. Here, instantaneous leakage has been differentiated from over-all leakage. This differentiation has been made because of the extensive volume of the underground system, which acted as a storage reservoir for gas under pressure; and when the air supply was cut off, gas continued to issue from the system in diminishing volume for several hours. The several over-all leakage figures take into account the stored gas recovered during the "blown-down" periods. Back pressure at the inlet and gas pressure at the orifice are included in table 45, because the pressure causing leakage lies between the two values.

Cycles 1,384 and 1,387, boreholes VII to IV and boreholes IV to VII, respectively, were operated under normal conditions. When using borehole IV as the outlet, leakage was 53.2 percent, and when borehole VII was the outlet, leakage was 43.2 percent. The pressure required to force air into the system at borehole VII was 10.7 p.s.i.g., and at borehole IV, 15.5 p.s.i.g. These figures indicate that the point of leakage was somewhere near borehole VII, because a greater volume of gas passed through the system between the boreholes when IV was the inlet. When borehole VII was the inlet, the highest pressures underground were applied near that point and caused greater leakage.

Cycles 1,390 and 1,393 were made with the gas outlet choked. The effluent gases passed through a 3-inch-diameter orifice as they discharged to atmosphere. Thus, gas pressures exceeding 10 p.s.i.g. were applied everywhere in the system. The determined leakage (table 45) reflects the effect of increased pressure at the point of leakage. It was noted that again the back pressure at borehole IV was substantially greater than at borehole VII.

TABLE 45. - Tests for leakage from the underground system using various flows and pressures

Cycle	Air input: Average flow, c.f.m.1/	Air input: Back pressure, p.s.i.g.	Effluent gas: Average volume c.f.m.1/	Effluent gas: Discharge pressure, p.s.i.g.	Instantaneous leakage in terms of air input, percent2/
	Direction of flow, borehole VII to borehole IV				
1,384....	7,425	10.7	3,285	1.7	(54.8 3/(53.2
1,390....	7,400	14.1	1,730	9.8	(76.6 3/(75.2
1,412A...	7,425	12.0	3,920	2.1	45.3
1,412B...	6,190	9.8	3,400	1.7	45.2
1,412C...	5,045	7.3	2,820	1.3	46.5
1,412D...	3,365	4.5	2,080	.7	45.9
1,412E...	1,910	2.4	1,320	.3	44.0
1,417A...	1,850	2.7	1,195	.3	43.9
1,417B...	1,850	2.6	1,215	.3	40.8
1,417C...	1,810	2.5	1,195	.3	39.3
1,417D...	1,910	2.5	1,305	.3	39.4
1,417E...	1,985	2.5	1,330	.3	38.6
1,417F...	1,890	2.5	1,290	.3	37.1
1,417G...	1,920	2.5	1,340	.5	37.2
	Direction of flow, borehole IV to borehole VII				
1,387....	7,640	15.5	4,010	3.0	(47.4 3/(43.2
1,393.....	7,225	17.9	1,800	10.5	(75.2 3/(73.1
1,415A...	7,340	16.1	4,015	2.9	45.1
1,415B...	6,870	15.6	2,650	2.8	61.6
1,415C...	5,630	12.9	3,460	2.2	39.8
1,415D...	4,025	9.1	2,750	1.2	34.2
1,415E...	1,840	4.3	1,085	0.4	46.4
	Direction of flow, borehole III to borehole IV				
1,418....	1,850	1.6	1,730	0.5	0

1/ At 60° F., 30 inches Hg., dry.
2/ The gas volume was recalculated to equivalent air through the use of a nitrogen balance and correcting for moisture.
3/ Includes gas stored underground measured during "blowdown."

Cycles 1,412 and 1,415 were made with the air input progressively decreased. Instantaneous leakage only was calculated. In cycle 1,412, borehole IV was the outlet, and the percent leakage remained constant at all air-input rates. In cycle 1,415, the percent leakage varied irregularly with diminished air-flow rates. In subcycles 1,415 B and 1,415 E, the percent leakage was influenced by an increased proportion of water vapor in the gas. The volume of material (including water vapor that is not included in table 45), actually issuing from the system reflected closely the changes in back pressure, due to reduced air input.

Cycle 1,417 represented approximately 1 week's operation with constant air input at borehole VII, with borehole IV the outlet. The determined values of leakage indicate a slight reduction in leakage with time.

Cycle 1,418 again tested the hypothesis that leakage mainly occurred south of borehole III. It will be noted that the air pressure was very low, and that the calculated leakage was zero. Thus, the hypothesis was confirmed, and it was also established that the area of greatest resistance to gas flow at that time was located south of borehole III, probably in the neighborhood of the sand plugs in the entries.

At no time during the entire operation of the project was it possible to discover substantial gas outflow at the surface. Several points of small leakage were found. The first point of gas escape found was approximately 500 feet west of borehole II, where a small stream crossed the coal outcrop. Gas was observed bubbling out below the coal bed, in the coal bed, and above the coal bed. The amount of gas was initially very small but increased with time until bubbles were observed over approximately 50 feet of stream bed. The gas was accompanied by an outflow of water. The volume of gas remained too small to have been detected in the gas-flow data. The gas at this point initidlly contained some carbon dioxide and nitrogen, but after combustion was established between boreholes III and VII, hydrogen with smaller amounts of methane and carbon monoxide also was present.

A slight inflow of gas was detected in a mine in the Pratt bed approximately 600 feet west of the entry portal. The gas entered at a single point through a crack in the roof rock. The gas was flammable, hydrogen being the main combustible constituent.

During heavy rains, bubbles have been observed on the surface between boreholes I and II, west of the entry, and inside the limits of the burned out area. Subsequently, cracks have been observed in the same area, which indicate widespread subsidence with cracking from the coal bed to the surface.

When drilling boreholes VI and VII and sand holes 7 to 13, gas inflow in small quantities was noted at numerous horizons. However, inasmuch as test holes 1 to 13 and borehole I were unlined from the coal bed to within 30 feet of the surface, gas under pressure in the underground system had access to the strata at all horizons. Some gas flow was therefore to be expected in permeable beds.

In the absence of definite evidence as to where and how gas leakage occurred, the mechanics of the process may be explained in several ways. Assuming the presence of pore spaces or crevices filled with water and of near capillary size in the coal bed or adjacent strata, gas pressure could force the water to flow to the outcrop, leaving the space available for gas outflow. Similarly, if small vertical cracks were present and filled with water, drainage of the water into the underground system would free the cracks for gas leakage. A permeable bed lying some distance above or below the coal bed could be exposed to leakage by caving or thermal cracking of the intervening strata. The hypothesis best supported by the available evidence has been that a gradual subsidence of the strata occurred above the burned-out area, producing cracks that extended from the coal bed to permeable strata. The gas flows through the permeable strata and eventually reaches the surface either on the sides of the hill or by means of intersecting vertical fissures. Leakage from this source probably would increase markedly with time and would fluctuate with rainfall and minor rock movements. It has been assumed that the widespread diffusion of the gas outflow through the surface soil accounts for the absence of noticeable gas leakage.

Quantity of Coal Consumed and the Area of the Burned-Out Region

Three methods have been combined and used to determine the quantity of coal consumed and the location of the perimeter of the burned-out area. Material balances were made during all phases of the operation, and the quantity of moisture- and ash-free coal consumed has been calculated from them. Thermocouples were installed at each of the test holes, and a temperature-time record was kept at each of these locations. These temperature data are plotted in figure 27, and from these curves the rate of advance of the coal faces was calculated. The bursting of the mercury capsules and the time when mercury appeared in the effluent gases has also been used in determining the rate of advance of the coal face. Also, as sand holes were drilled in the area, the condition of the coal bed and the drilling conditions have been incorporated as additional evidence.

Table 46 summarizes the above data and shows that 10,845 tons of moisture- and ash-free coal was consumed during operation of the project. This coal would occupy 83,690 square feet of bed, and thus the coal underlying 1.92 acres of land was gasified. Figure 28 shows the perimeter of the burned-out area at the end of each of the major phases of the operation as it has been deduced from the data available.

TABLE 46. - The coal consumed and the area of the burned-out region

Operating period	Length of period, weeks	Coal consumed[1/] During period, tons	Coal consumed[1/] Cumulative total, tons	Area burned out During period, square feet	Area burned out Cumulative total, square feet
Mar. 18 to June 21, 1949	14	877	877	6,950	6,950
June 21, 1949 to Oct. 5, 1949..................	15	1,564	2,441	12,400	19,350
Oct. 5, 1949 to Dec. 22, 1949..................	7	1,347	3,788	10,680	20,030
Dec. 22, 1949 to June 5, 1950..................	28	2,088	5,876	16,560	46,590
June 5, 1950 to Oct. 7, 1950..................	18	2,875	8,751	22,660	69,250
Oct. 7, 1950 to Feb. 7, 1951..................	18	2,094	10,845	14,440	83,690

1/ Basis of moisture- and ash-free coal.

At this time diamond-drill core holes are being drilled into the burned-out area in order to determine the condition of the strata overlying the coal bed in the area where the coal has been consumed. These holes will also be used to determine the perimeter of this burned-out area more exactly.

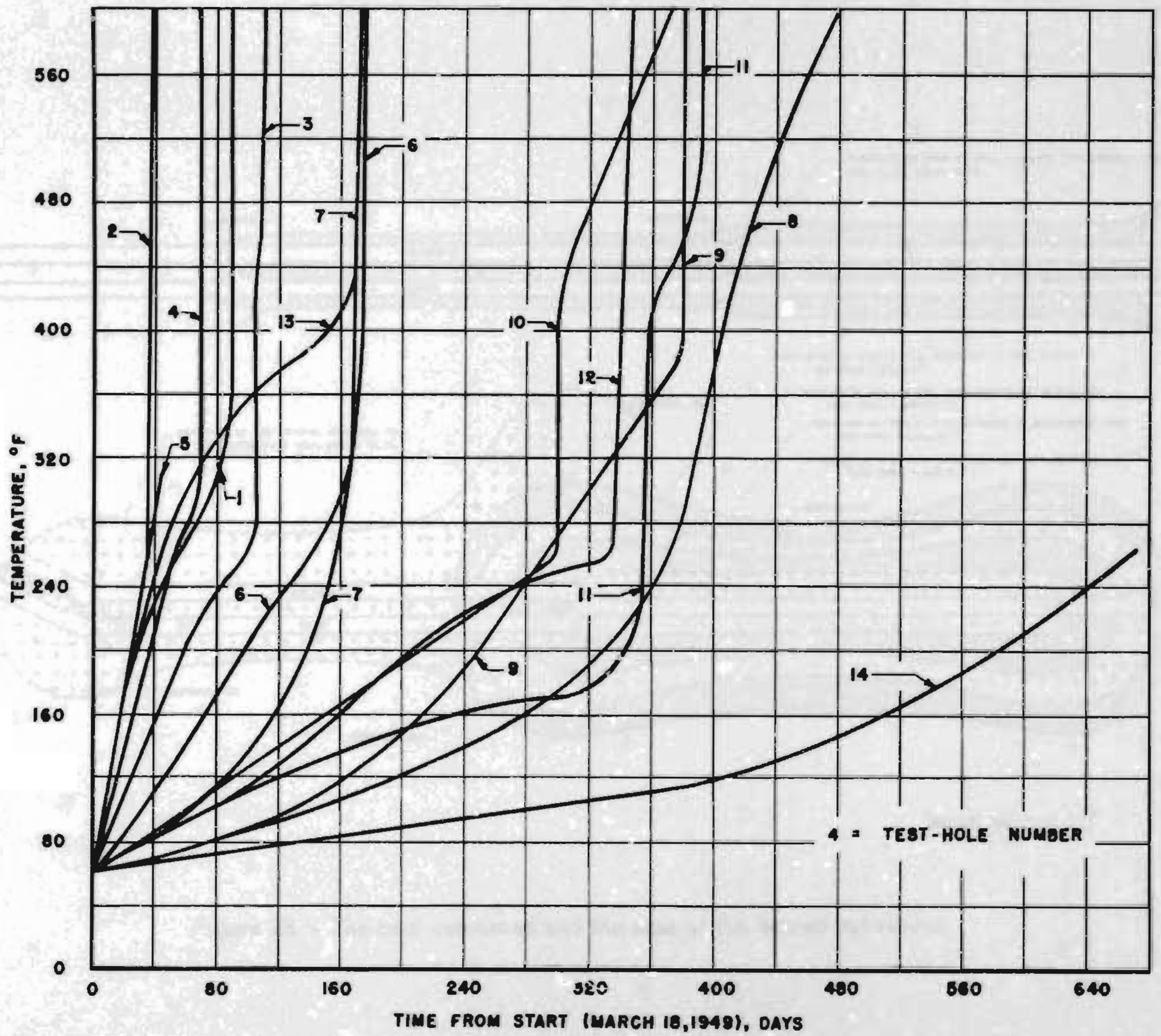


Figure 27. - Temperature variation with time at coal-bed level in test holes.

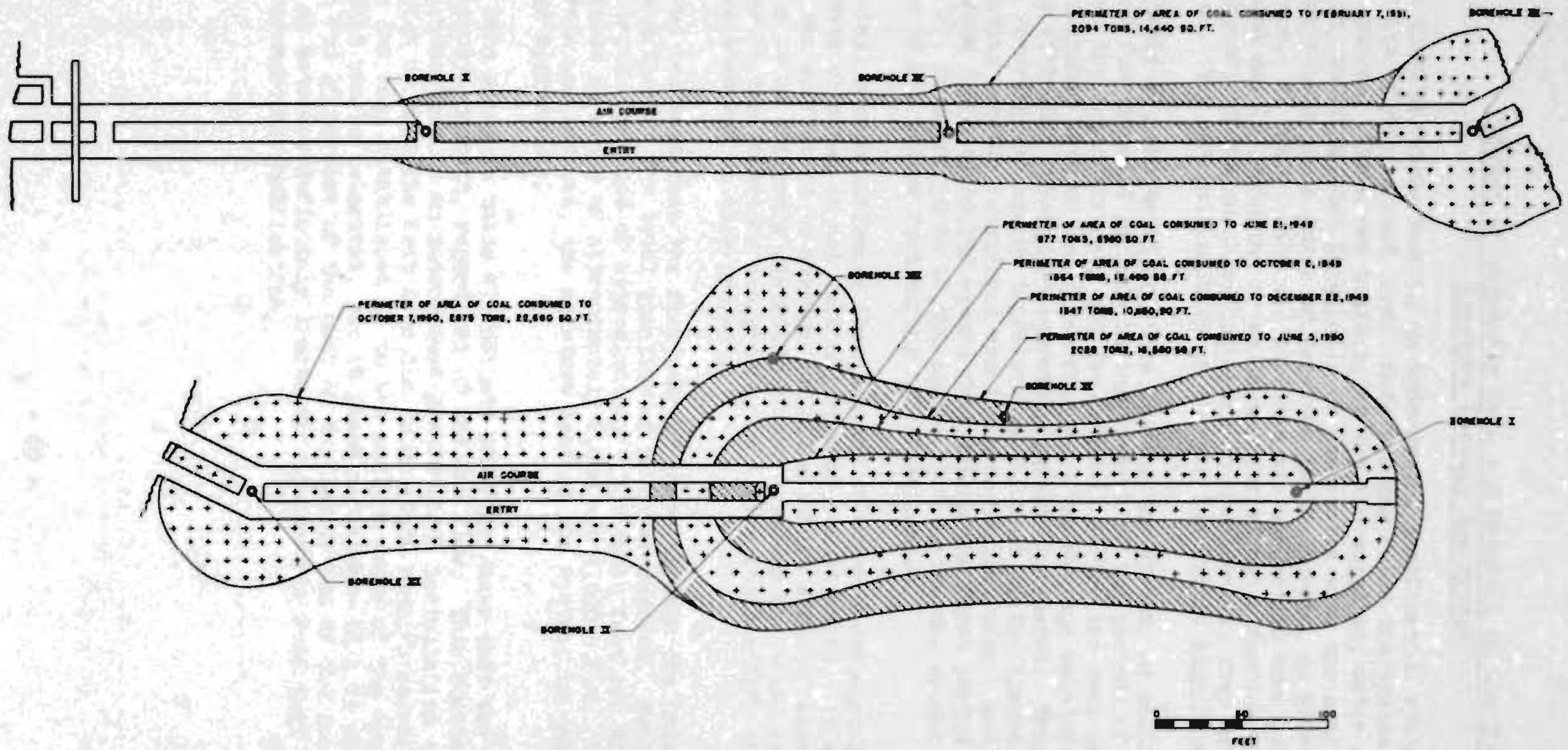


Figure 28. - The coal consumed and the area of the burned-out region.

Effect of Input-Air Rate and Rainfall on the Total Moisture Leaving the System

The total moisture leaving an underground gasification system is important because of its effect on heat loss. Moisture may enter the system from any one of several sources. These are humidity of the air supplied, water as a product of combustion, water related physically or chemically with the coal and adjacent rocks, free water occurring in pores or crevices in the strata, or water percolating from the surface. Of these, only the last two are subject to some control. Free water underground may be collected in wells and pumped out. Surface water may be similarly collected; or, if the crevices supplying it are located, they may be grouted to stop the inflow. The natural humidity of the air has little significance in this connection.

In table 47, the total moisture leaving the system, as gallons per day, has been calculated for extended periods during several of the periods of operation. This table also shows the input air rate and the rainfall during the same periods in order to show the relationship between the three factors. The average moisture leaving the system increased with each subsequent operating period considered. This may indicate that the moisture entering the system increases as the area of the burned-out area increases. The operating periods considered are in chronological order, and the total area increases from 6,950 to 19,350 square feet during the first period of operation given in table 47, from 30,030 to 46,590 square feet during the second period, and from 46,590 to 69,250 square feet during the third period.

Rainfall should influence the quantity of water accompanying the effluent gases, but the data obtained do not show any regular relationship. It was probable that the time lag was sufficient to average out all rainfall effects, especially when the precipitation is as uniformly distributed over the year as it was in this instance. Variations in the geography and geology of a site could modify the effects of rainfall from those observed at this project.

It was believed that the flow rate of gases through the underground system would have some effect on the total quantity of moisture removed. Most of the data given refer to input-air rates of approximately 7,500 cubic feet per minute, but some data are available at rates of approximately 2,000 and 4,000 c.f.m. In each instance where the air rate was reduced, the moisture leaving the system, in gallons per minute, does not change appreciably.

The data given in table 47 indicate that the water that was evaporated underground was relatively constant, regardless of the gas flow. This constancy of water evaporation indicates that in an underground gasification installation the gas flows must be large enough so that the heat loss due to moisture remains relatively low. No definite criterion has been established as to the maximum value of the heat loss due to moisture effects that can be tolerated, but it seems reasonable that it should lie in the range between 5 and 15 percent of the heat of the combustion of the coal gasified. The presence of moisture definitely limits the minimum air rate that can be used to advantage in underground gasification.

TABLE 47. - Input-air rate, rainfall, and total moisture leaving the system

Week	Direction of flow	Input-air rate, c.f.m.1/	Moisture leaving the system, gal. per min.	Rainfall, in.
	Operating period, June 21 to Oct. 5, 1949 2/			
9	BH I to BH II	7,140	3.6	2.25
10	BH I to BH II	7,190	3.5	.03
11	BH I to BH II	7,180	3.3	1.43
12	BH I to BH II	7,110	3.2	2.80
13	BH I to BH II	7,090	3.3	.26
14	BH I to BH II	7,070	3.7	2.35
14	BH II to BH I	7,140	4.7	-
15	BH I to BH II	7,340	2.1	.50
15	BH II to BH I	7,180	7.2	-
16	BH I to BH II	7,080	3.0	.06
16	BH II to BH I	7,190	5.5	-
Average			3.9	
	Operating period, Dec. 22, 1949 to June 5, 1950 3/			
2	BH I to BH II	7,810	5.2	.05
3	do.	7,585	4.3	4.92
4	do.	7,555	5.8	1.26
5	do.	7,655	5.7	.20
5	do.	2,090	5.5	.49
6	do.	7,550	5.0	.72
7	do.	7,845	5.7	1.82
8	do.	7,890	3.7	1.41
9	do.	7,950	5.2	.73
10	do.	7,950	4.8	.29
11	do.	8,130	4.1	1.55
12	do.	7,995	3.5	.29
13	do.	8,040	5.0	5.76
14	do.	7,850	5.9	.28
15	do.	7,920	6.1	1.36
16	do.	7,890	4.5	.49
17	do.	7,850	4.7	.18
18	do.	7,860	4.6	.57
19	do.	7,735	4.8	2.45
20	do.	7,720	5.7	1.16
21	do.	7,690	4.5	.12
22	do.	7,670	4.4	.41
23	do.	7,620	4.5	1.13
24	do.	7,640	4.5	.10
25	do.	7,595	5.0	.00
26	do.	7,620	4.8	.26
27	do.	7,650	3.1	.70
Average			4.8	
	Operating period of June 5, 1950 to Oct. 7, 1950 4/			
8	BH VII to BH III	7,410	8.1	1.0
9	do.	7,550	8.1	2.31
10	do.	7,510	8.5	.0
10	do.	4,020	5.6	.74
11	do.	4,060	4.6	.02
12	do.	7,520	5.4	.0
13	do.	7,560	5.8	6.94
14	do.	1,620	3.8	1.22
14	do.	7,690	4.9	.47
15	do.	7,700	6.0	.33
16	do.	7,560	6.2	.41
17	do.	7,560	4.7	.00
18	do.	7,720	4.8	.00
Average			5.9	

1/ At 60° F., 30 inches Hg. dry. 2/ The week ended June 25, 1949 = 1.
3/ The week ended Dec. 24, 1949 = 1. 4/ The week ended June 10, 1950 = 1.

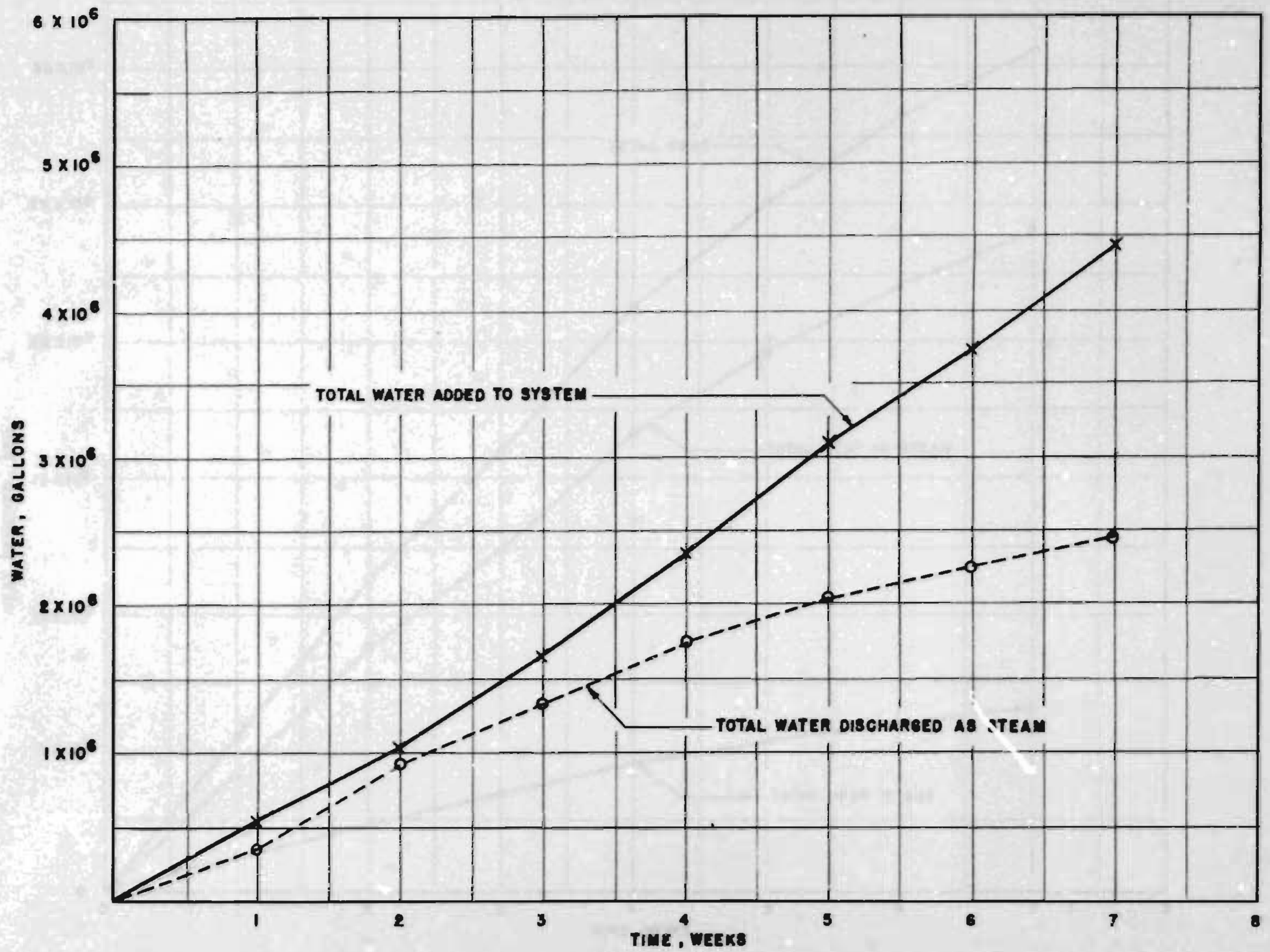


Figure 29. - Distribution of water added to system since start of cooling.

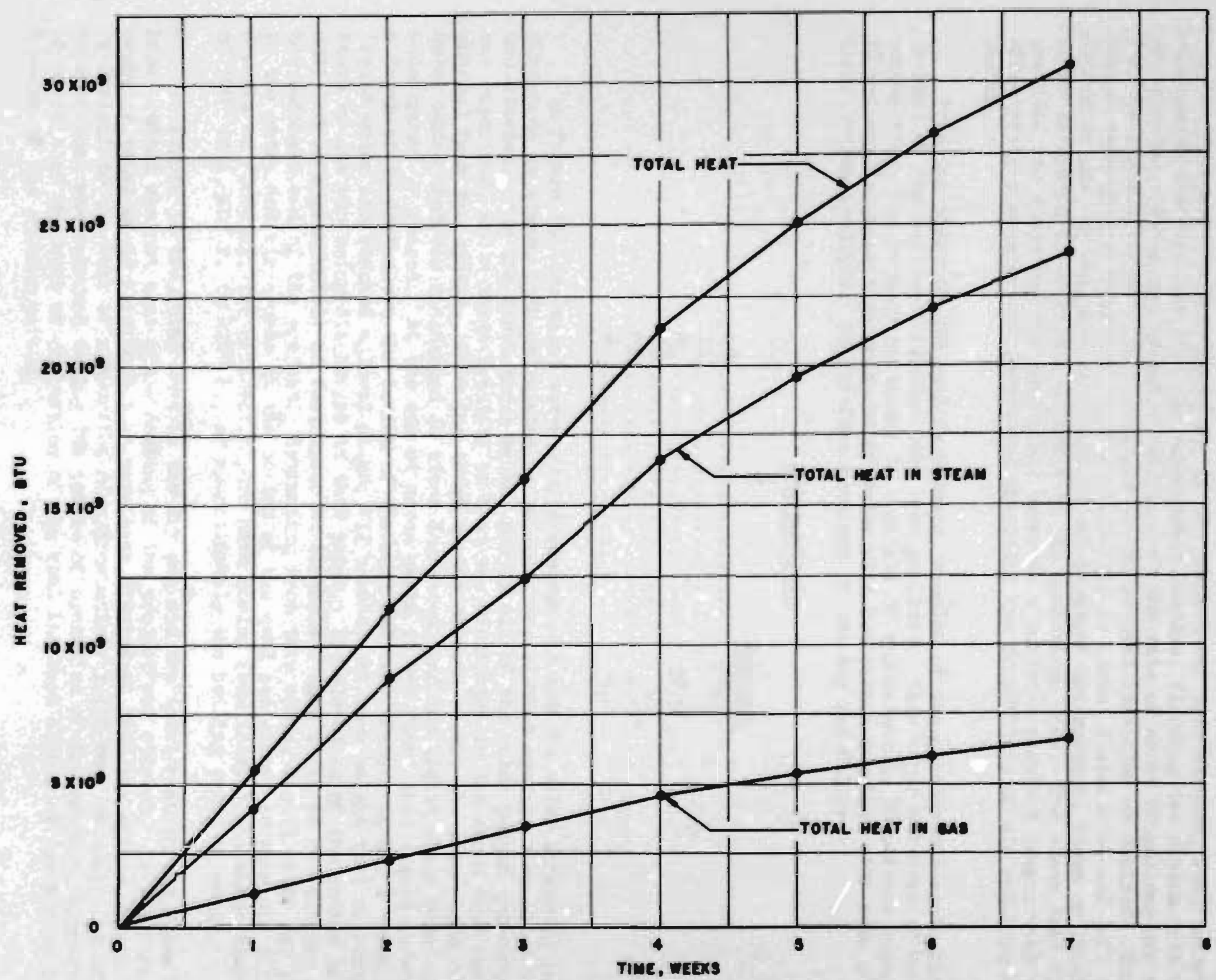


Figure 30. - Total heat removed from system since start of cooling.

Cooling the Underground System

On February 7, 1951, operation of the project was discontinued, and, in order to extinguish the fire and cool the underground residue, flooding the system with water was started. Water was pumped underground at the rate of about 60 gallons per minute, and the steam liberated was discharged at the several boreholes as desired. The water pumped underground vaporized and was discharged as steam, dissociated and left the system as gas, or remained as liquid in the passages underground. Steam or liquid water saturated dried strata adjacent to the combustion zone. The steam that formed, provided its discharge was throttled, asserted a positive pressure underground and effectively blanketed the system and precluded the possibility of air reaching hot carbon.

From the start of the cooling process, samples of the gaseous materials discharged at the various boreholes have been analyzed. This vapor has been of changing composition, but in many instances it consists of approximately 90 percent steam and 10 percent decomposition products of water with hot carbon together with some coal-distillation products. An air-free analysis of the dry gas follows:

Gas analysis

	Percent
CO_2	50.1
Ill.	.7
H_2	38.9
CO	.5
CH_4	4.0
N_2	5.8

In figure 29, the total water pumped underground and the water appearing in the discharge as steam, both calculated in gallons, are plotted against time since cooling was started. For the first three weeks, nearly all of the water pumped underground was vaporized, and a large quantity of heat was dissipated in the steam that was discharged from the system. From the third to the seventh weeks, the proportion of the water added that was discharged as steam decreased, and the liquid water remaining underground increased. At the end of seven weeks it was found that liquid water, to a depth of 18 feet above the bottom of the coal bed, was present at No. I borehole. Liquid water had reached a level at No. VII borehole of such height that no further steam or gas was being discharged at this point. The elevation of the bottom of the coal bed is approximately 60 feet lower at borehole I than it is at the outcrop at the northern end of the project. Estimating from this slope, liquid water was present in the entry and air course at the bottom of the coal bed almost to borehole III. In 8 weeks of flooding, the effluent vapors have cooled from initial discharge temperatures of 700° to 1,000° F. to 220° F., or approximately the boiling point of water.

In figure 30 the total heat in the dry gas and the total heat in the steam have been plotted against time since cooling of the project was started. In the first 7 weeks, a total of 30 billion B.t.u. have been dissipated from the system, which is equivalent to the heat of combustion of approximately 1,150 tons of coal. As 10,845 tons of coal was consumed during the course of operation of the project, approximately 10 percent of the heat of combustion of the coal has been accounted for during these 8 weeks of the cooling period.

Flooding of the underground system is being continued, and liquid water is present at boreholes I to V, as shown in table 48. Approximately 10 million gallons of water was pumped underground in the period February 7 to May 17, 1951. Temperature measurements in the various test holes and boreholes indicate that the average temperature level underground is now approximately 200° F.

TABLE 48. - Depth of water above the bottom of the Pratt coal bed

Date	Depth of water, feet				
	BH I	BH II	BH III	BH IV	BH V
4-18-51	41	28	16	2	-
4-30-51	54	41	28	13	5.7
5-10-51	55	42	28	13	5.8
5-17-51	55	42	28	13	5.8

END OF

PAPER