RESEARCH AND DEVELOPMENT, SYNTHESIS-GAS LABORATORIES AND PILOT PLANTS, MORGANTOWN, W. VA., AND FIELD TESTS, GORGAS, ALA.

Experimental Development of Processes for Producing Synthesis Gas

There is an ever-increasing appreciation of the fact that the new developments in coal gasification are of major importance in determining the cost of synthetic liquid fuels. The cost of synthesis gas is 60 to 70 percent of the total cost of gasoline produced from coal by the gas synthesis process. Intensive work has been conducted on the experimental development of pulverized coal gasification with oxygen and steam at Morgantown, W. Va. Field-scale experimentation in underground gasification of coal has continued at Gorgas, Ala.

During the past year planning of improved facilities for process development work in coal gasification was continued in connection with the new Bureau station at Morgantown that has been approved by Congress.

Pulverized-Coal-Gasification Pilot Plants, Morgantown, W. Va.

During the past year experiments have been carried on in three types of gasification units. The results of work on the smallest unit are contained in a report[1] recently issued. In this unit about 50 pounds of powdered coal is gasified per hour, and its operation has resulted in a better understanding of the conditions under which a given coal can be gasified with maximum efficiency.[2] This apparatus proved to be convenient also for evaluating the ease with which various types of coal can be gasified.

Atmospheric Pressure Gasifier

The large (500 lb. coal/hour) atmospheric pressure generator, previously described[3][4] was remodeled to reduce the interior diameter so that, with the auxiliary equipment available, runs could be made more nearly at capacity. During the year eight more test runs were made in this unit, which then was dismantled to make room for a newly designed atmospheric-pressure gasifier.

1/ Sebastian, J. J. S., Edeburn, P. W., Bonar, F., Bonifield, L. W., and Schmidt, L. D., Laboratory-Scale Work on Synthesis-Gas Production: Bureau of Mines Rept. of Investigations 4748, 1951, 41 pp.

2/ Sebastian, John J. S., Effect of Variables in Powdered Coal Gasification: Presented before the Gas and Fuel Division of the American Chemical Society, Diamond Jubilee Meeting, New York, N. Y., Sept. 7, 1951.

3/ Synthetic Liquid Fuels Annual Report of the Secretary of the Interior for 1950, Part I. - Oil from Coal: Bureau of Mines Rept. of Investigations 4770, 1951, pp. 51-58.

4/ Strimbeck, G. R., Holden, J. H., Rockenbach, L. P., Cordiner, J. B., Jr., and Schmidt, L. D., Pilot-Plant Gasification of Pulverized Coal with Oxygen and Highly Superheated Steam: Bureau of Mines Rept. of Investigations 4733, 1950, 41 pp.

This new unit gasifies about 500 pounds of coal per hour. It was designed in cooperation with the Babcock & Wilcox Co., which also fabricated the unit. This gasifier, shown in figure 44, was designed to determine the physical construction that would be necessary in a larger-scale apparatus; that is, it can be considered the prototype of a large-scale gasifier. Studies will be made of (1) slag tapping and (2) the behavior of slag on water-cooled tubes, which can be installed to simulate a waste-heat boiler. The unit is constructed so that individual sections (that is, the slag pot, primary reaction zone, secondary reaction zone, and gas-cooling zone) may be changed or revised without changing other sections. The reactants, coal and oxygen at atmospheric temperature and steam at 1,000° F., are introduced at the top of the primary reaction zone. The two coal and oxygen nozzles are directed downward in such a way as to impinge on the pool of liquid slag at the bottom of the gasifier and, at the same time, impart a spin to the reactants in the gasifier. Ample provision also has been made for introducing reactants at other locations in the reactor.

A small portion of the make gas is drawn down through the lower throat into the slag pot and thence back to the main gas stream to help in attaining adequate throat temperatures for slag tapping. The larger portion of the make gas goes upward into the secondary zone; the purpose of this zone is to provide cooling, so that the fly ash carried in the gas will not coat the cooling tubes. From the cooling zone the gas goes to the dust-removal train. The latter is substantially as described in Report of Investigations 4733,5/ except that the cyclone dust collectors have been removed. Experience indicates that the residues removed in the dust train are high in ash content and consequently have so little value that dry removal is unnecessary. In figure 45 the lower part of the unit, slag pot, and part of the primary reaction zone are shown. Figure 46 is a view of the upper part of the unit. Test runs on this gasifier were begun in August 1951 and are continuing. Too few data have been obtained to permit drawing final conclusions. However, the unit has functioned well mechanically, and it has been shown that the gases can be handled in the cooling section without serious build-up of fly ash on the tubes. The present work is concentrated on reactant-nozzle design and placement.

Pressure Gasifier

Synthesis gas is almost always used at high pressures. The cost of compressing synthesis gas to the pressure at which it is used is a major cost item. Consequently, it is desirable to develop a gasifier that will operate at pressures somewhat above that of the usage pressure. In the case of Fischer-Tropsch plants for making synthetic liquid fuels, this usage pressure is about 30 atmospheres or approximately 450 p.s.i. The experimental pressure gasifier built at Morgantown is designed for gasifying 500 pounds of powdered coal per hour at an operating pressure of up to 30 atmospheres.6/ Figures 47 and 48 show the design of this pressure gasifier. Early test runs in this high-pressure unit have been made at 100 p.s.i. pressure, using oxygen at atmospheric temperatures and steam at 1,000° F. Because of difficulty in obtaining proper equipment, the oxygen has not been preheated. New equipment now on order will permit work at high oxygen temperatures and higher gasifier pressures.

5/ See footnote 4.
6/ See footnote 3.

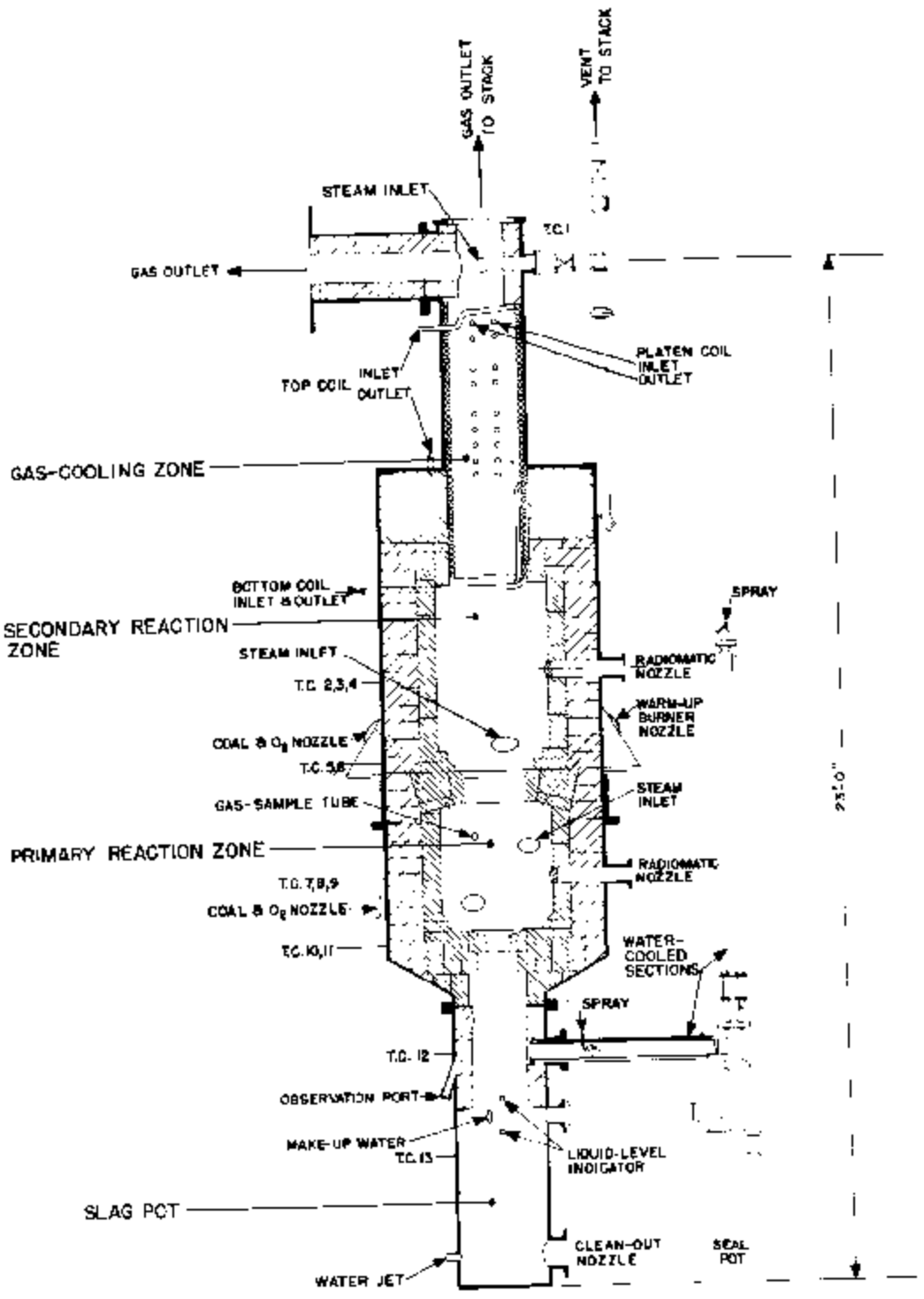


Figure 44. - Atmospheric generctor design 4.

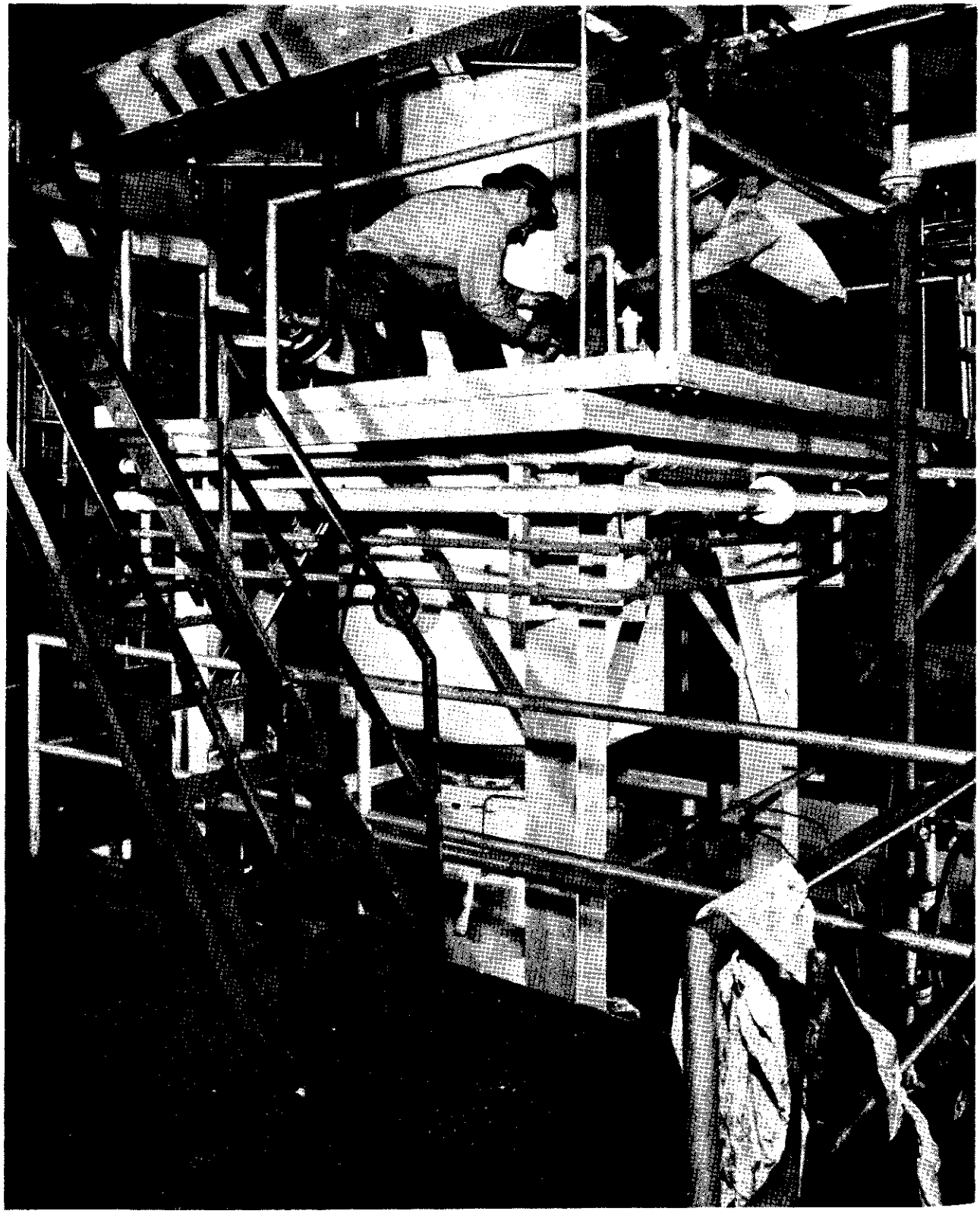


Figure 45. - Atmospheric-pressure gasifier (capacity, 500 pounds of coal per hour), showing slag pot and primary and secondary reaction zones.

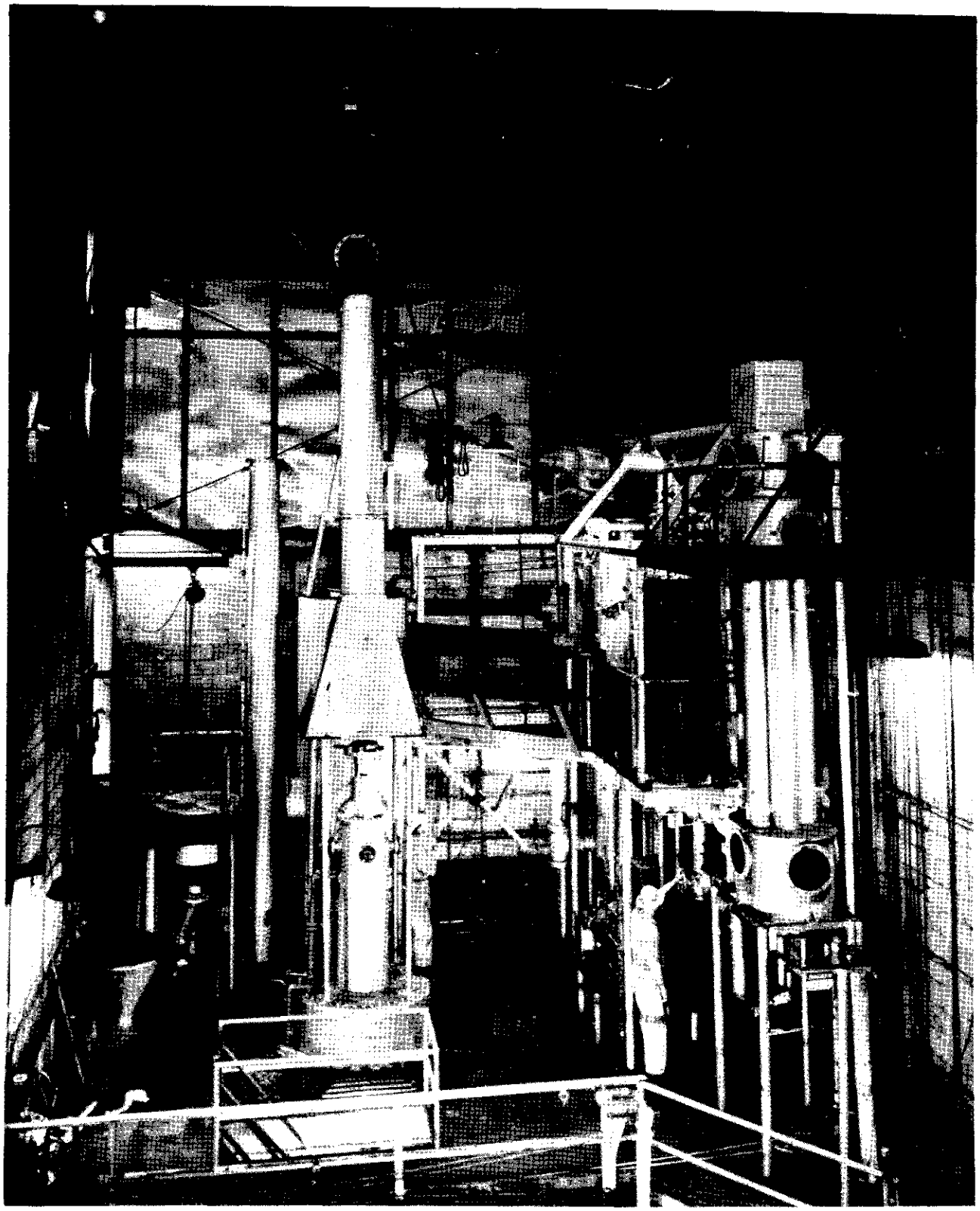


Figure 46. - Atmospheric-pressure gasifier (capacity, 500 pounds of coa per hour), showing upper part of unit and dust-removal equipment.

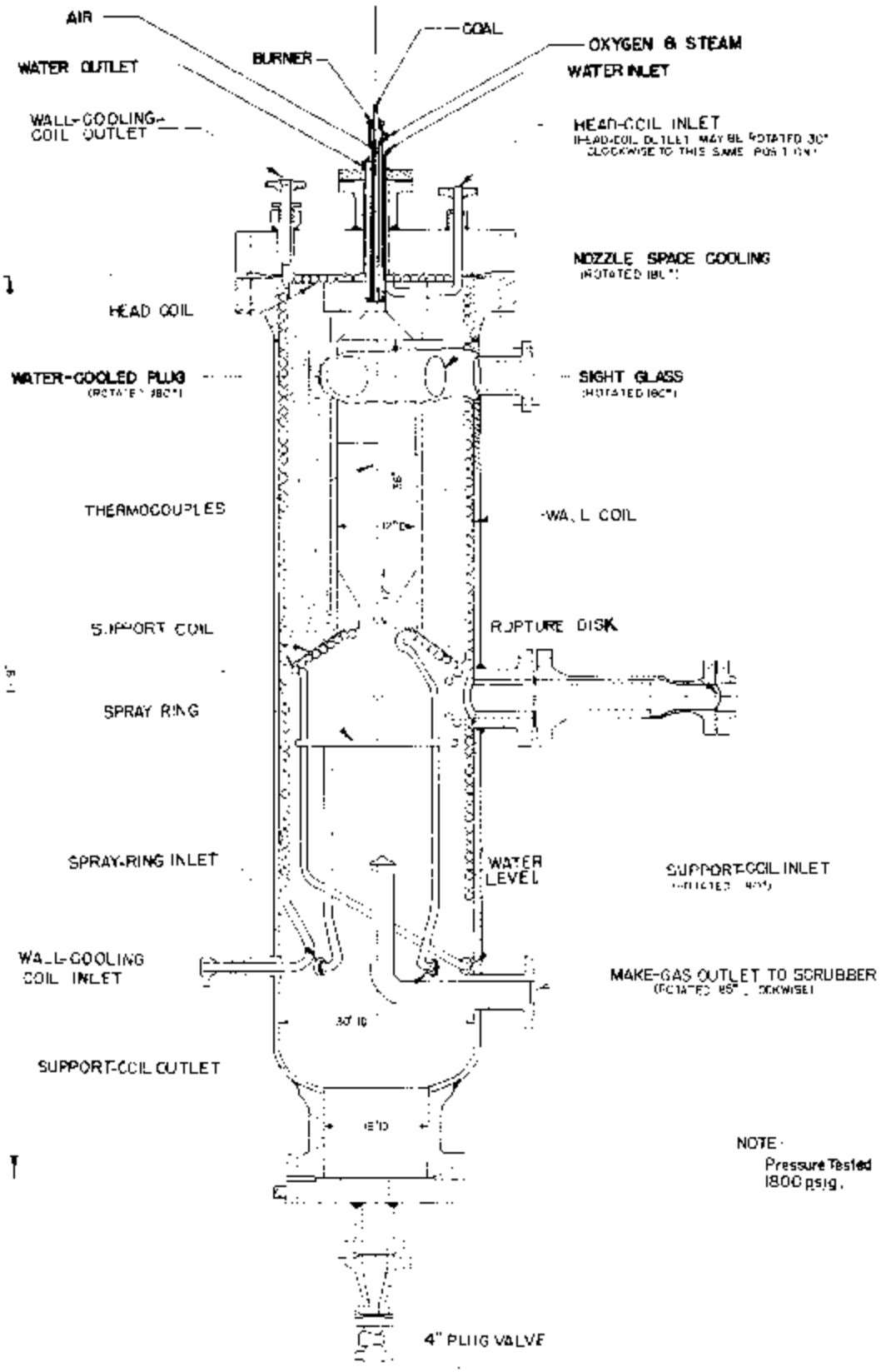


Figure 47. - Reactor for pressure gasification.

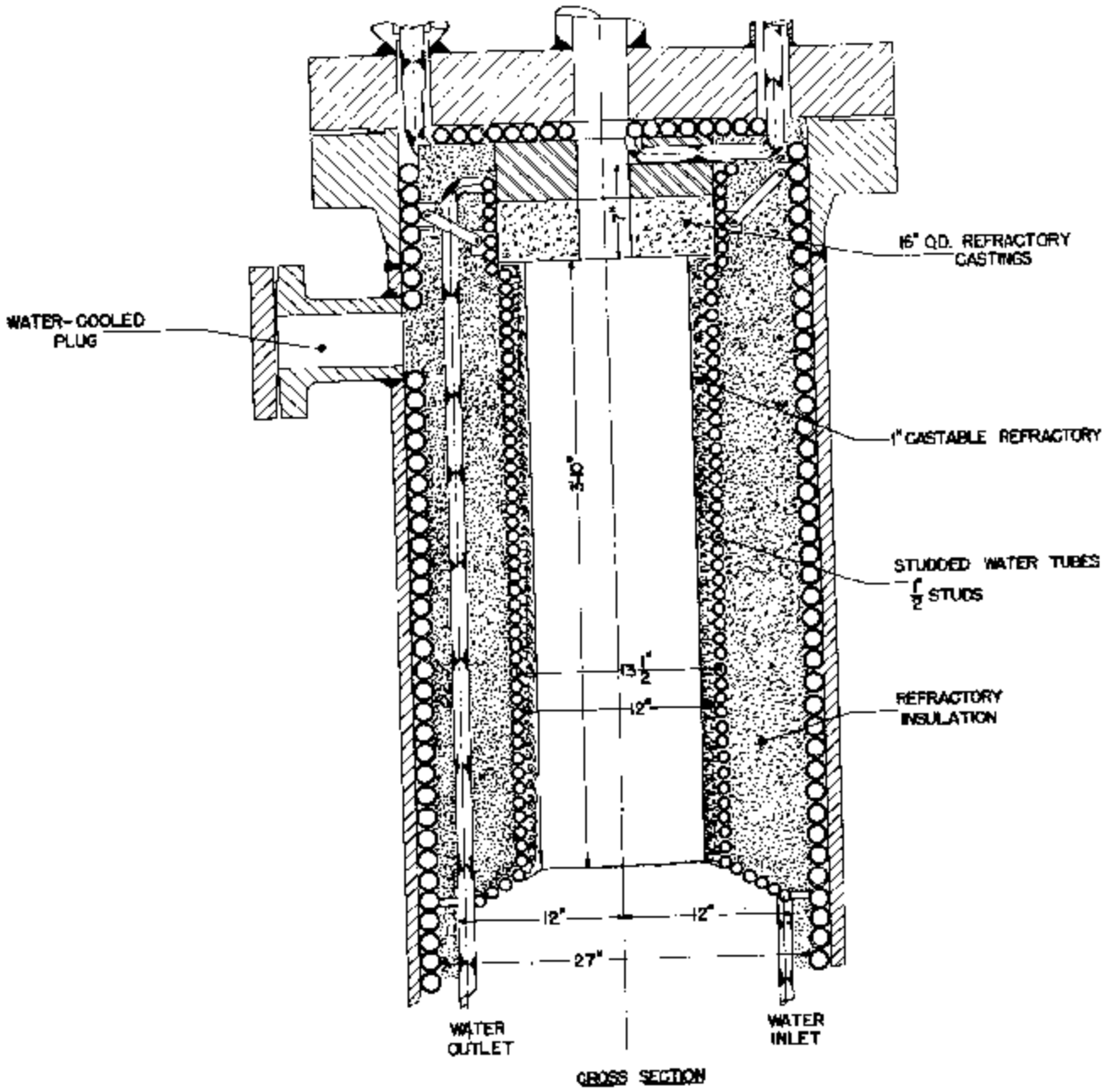


Figure 48. - Pressure gasifier refractory and water walls (upper section).

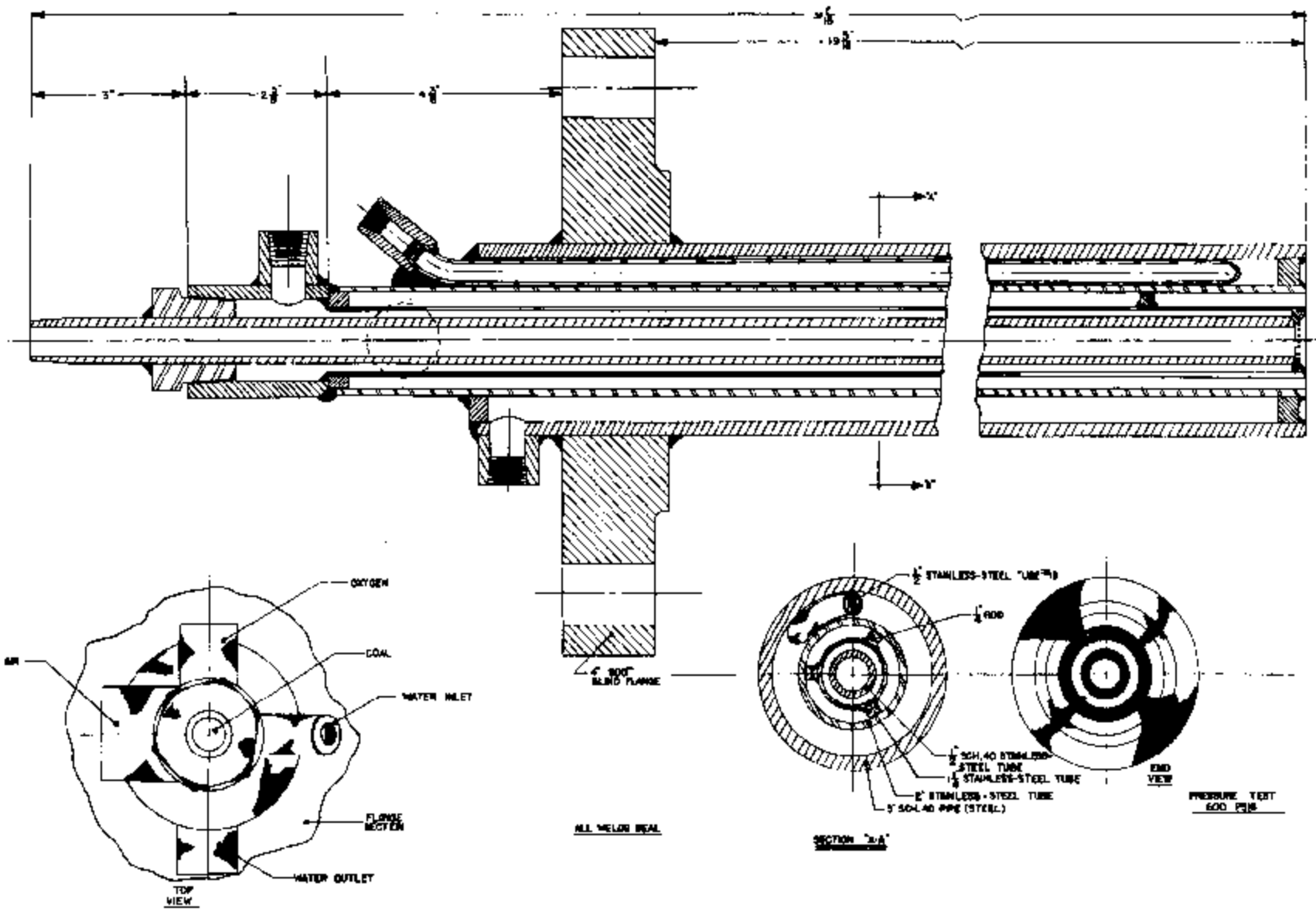


Figure 49. - Combination heat-up and reactant injection nozzle.

In the early runs, the reactants were introduced through separate nozzles. These nozzles were in a horizontal plane and tangent to about a 4-inch-diameter circle. Early tests showed that refractory linings could not be maintained in the upper part of the generator under these conditions. A new nozzle (fig. 49) was designed to introduce all reactants vertically downward through the top. The coal - carried by inert gas - enters through the center tube. Into the space around this tube the oxygen and steam are introduced the mixture is injected into the coal stream through the small holes. This method of entry results in excellent mixing of the reactants and prevents development of excessive heat at the top of the generator. This nozzle is also used as a heat-up burner. For that purpose, natural gas is admitted through the coal tube, oxygen through the next concentric space, and air through the next space. During a run, a small amount of inert gas is admitted to the air space. This provides some insulating effect between the jacket and the oxygen-steam tube. Test runs with this nozzle have shown very high percentages of gasification at low oxygen consumption and with little refractory damage.

The original generator design provided for a support coil to carry the refractory lining. Tests showed that the cooling effect from this coil was excessive at the slag throat. Several turns have been removed from the coil, and the gasifier internal diameter of the refractory lining is now 12 inches along its entire length.

Throughputs of more than 115 pounds of coal per cubic foot of reactor volume per hour have been obtained at 100 p.s.i.g. These high throughputs were even greater than anticipated and promise lower gasification costs than expected. Table 20 shows the performance of the pressure gasifier at this high throughput rate. The high percentage of carbon gasified, together with the rather low requirements of coal, oxygen, and steam per thousand cubic feet of hydrogen and carbon monoxide produced, also promise lower costs. Performance in a large-scale gasifier no doubt would be still better because of decreased heat loss per pound of coal gasified. Severe erosion of the refractory lining occurred during the tests. Additional tests will be made to determine whether operation with a water-cooled coil covered with a "steady-state" thickness of slag is feasible.

The projected program for this unit calls for test runs in the pressure range 100 to 450 p.s.i.g., using superheated steam, preheated oxygen, and preheated coal.

All of the pilot-plant work has demonstrated that pulverized coal can be satisfactorily gasified under ash-slagging conditions, with economical consumption of oxygen. The program as now projected calls for intensive testing and equipment development for both high- and low-pressure gasification.

TABLE 20. - Typical performance of pressure gasifier operating at 100 pounds per square inch pressure on pulverized, Sewickley-bed coal

Duration of run	hours	10
Raw coal rate	lb./hr.	463
Steam inlet temperature	°F.	931
Process oxygen inlet temperature	do.	60
Coal inlet temperature	do.	327
Oxygen input per pound coal	std.cu.ft.	9.2
Steam input per pound coal	lb.	0.3
Synthesis gas analysis (corrected for inert gas introduced with coal) percent:		
CO_2		7.1
Illuminants		.5
H_2		34.4
CO		55.4
CH_4		.4
$H_2 + CO$	std.cu.ft. per hour	12,870
Total carbon gasified	percent	88
Coal required per M.c.f. ($H_2 + CO$)	lb.	36
Oxygen required per M.c.f. ($H_2 + CO$)	std.cu.ft.	333
Process steam input per M.c.f. ($H_2 + CO$)	lb.	10.9

Auxiliary Experiments

Some small-scale experiments have been carried out on a gasifier that uses pulsating flow. The objective of pulsating flow is to increase the rate of transferring both heat and material to the carbon particles by moving the gas surrounding the particle back and forth past the particle so that the carbon continually comes in contact with more gasifying agent. The pulsations are achieved by providing a gasifier with an exit too small to carry off immediately all the products of reaction. The resulting pressure rise causes a momentary stop in the reactant supply, in turn causing the pressure to fall. The resulting pressure fluctuations cause waves to travel down the exit pipe, moving the gas with respect to the carbon particle. Insufficient data are available to draw firm conclusions as to the operating characteristics of this gasifier, but pulsations have been achieved at about 100 cycles per second, and throughput rates of the order of 1,000 pound of coal per cubic foot of gasifier volume per hour have been obtained. No data are available on the percentage gasification of the coal at these high throughput rates. Severe erosion of the refractory lining occurred, and the possibility of operation with a slag-covered, water-cooled reactor wall is to be investigated.

Since the gasification of powdered coal is, in general, a cocurrent process, the exit gas leaves at a high temperature, carrying with it a considerable amount of sensible heat. To utilize this sensible heat, it must be transferred to the entering reactant streams. Hence, studies have been carried out on preheating of the entering coal. Powdered coal in dense phase flow from the feeder (described in the two previous Annual Reports) is passed through a tube in the form of a coil that is heated externally. Coal side-heat transfer coefficients

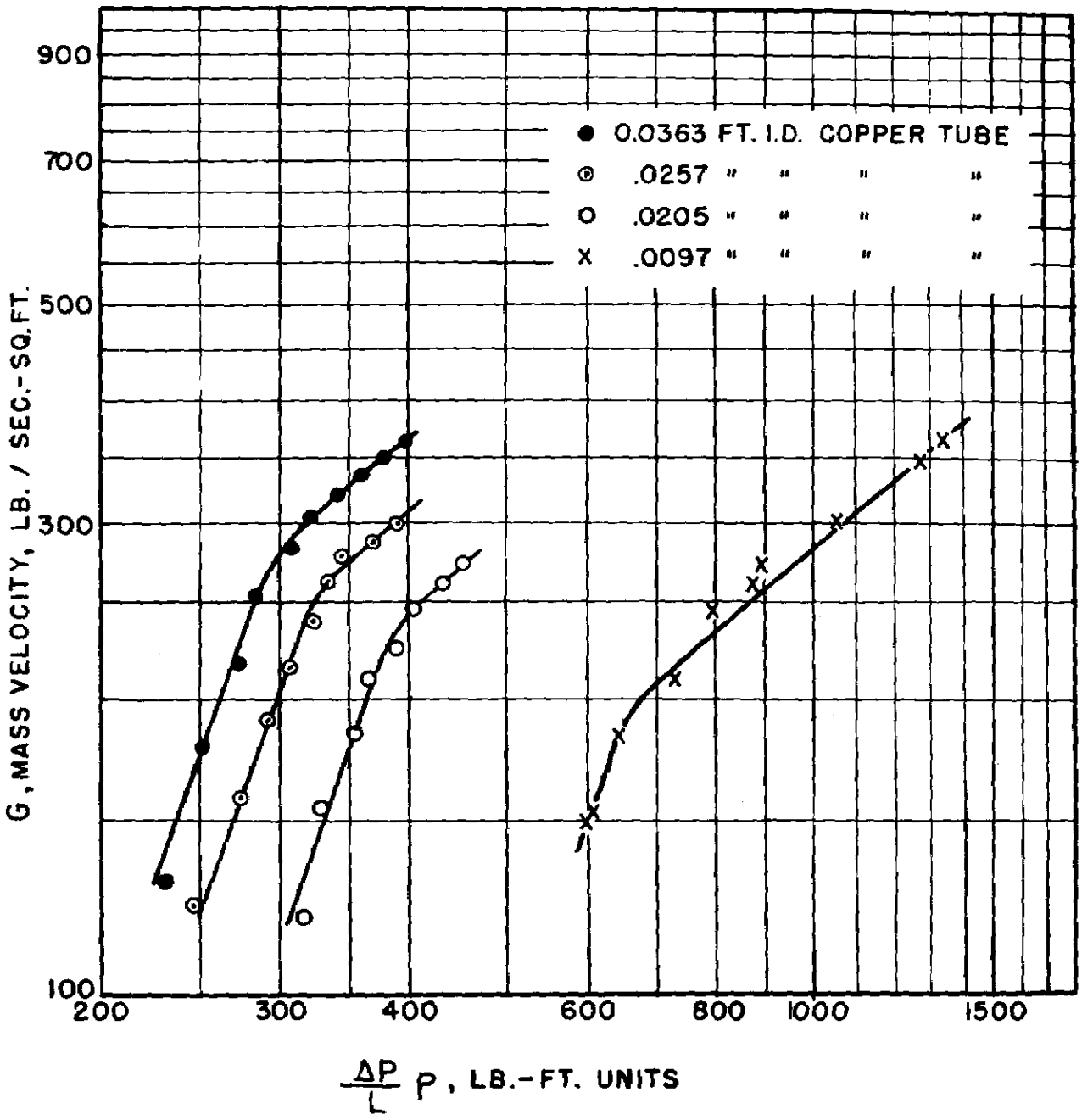


Figure 50. - Effects of $(\Delta p/L)\rho$ on resulting mass velocity in various sizes of tubes.

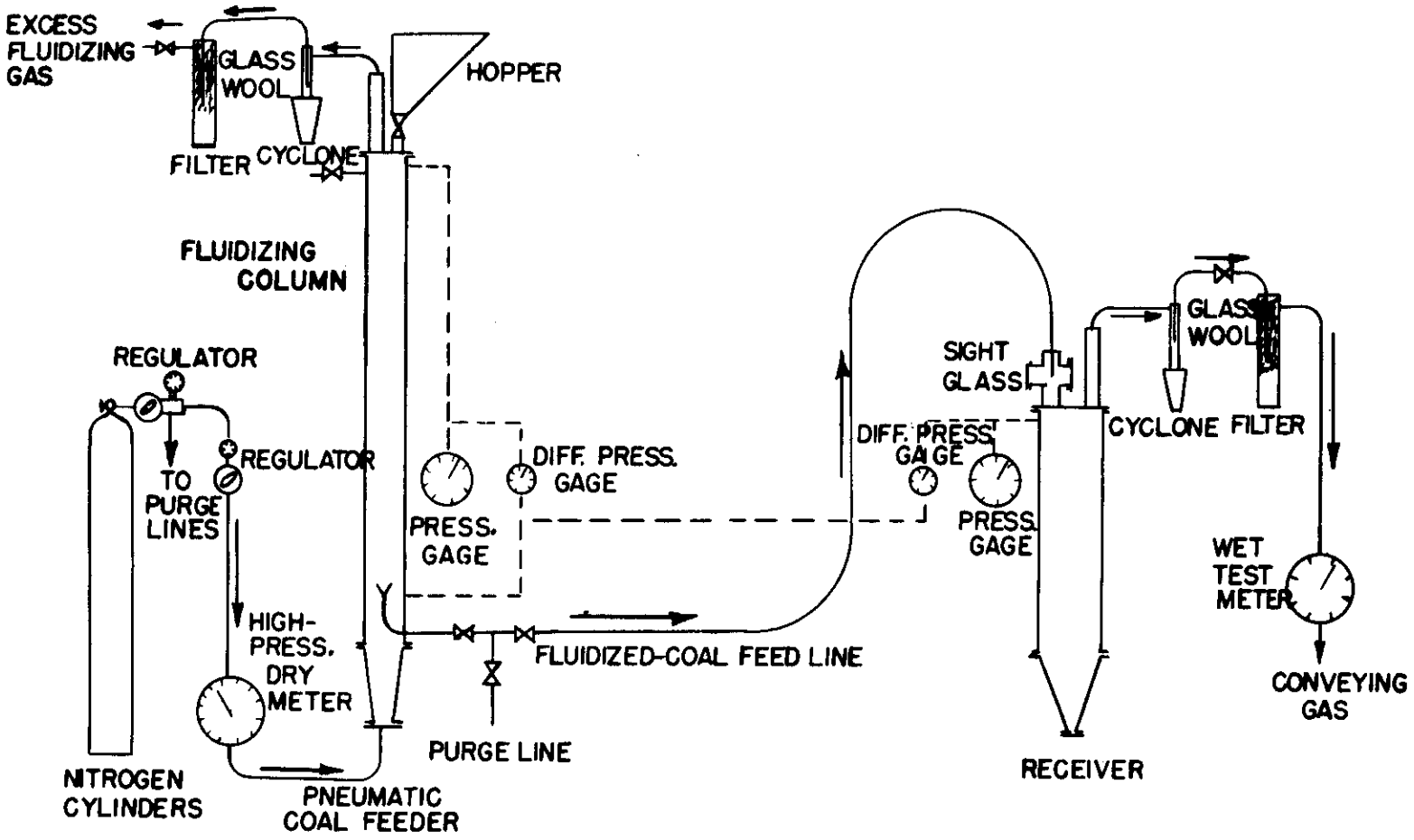


Figure 51. - Apparatus for study of continuously feeding finely powdered coal at superatmospheric pressures.

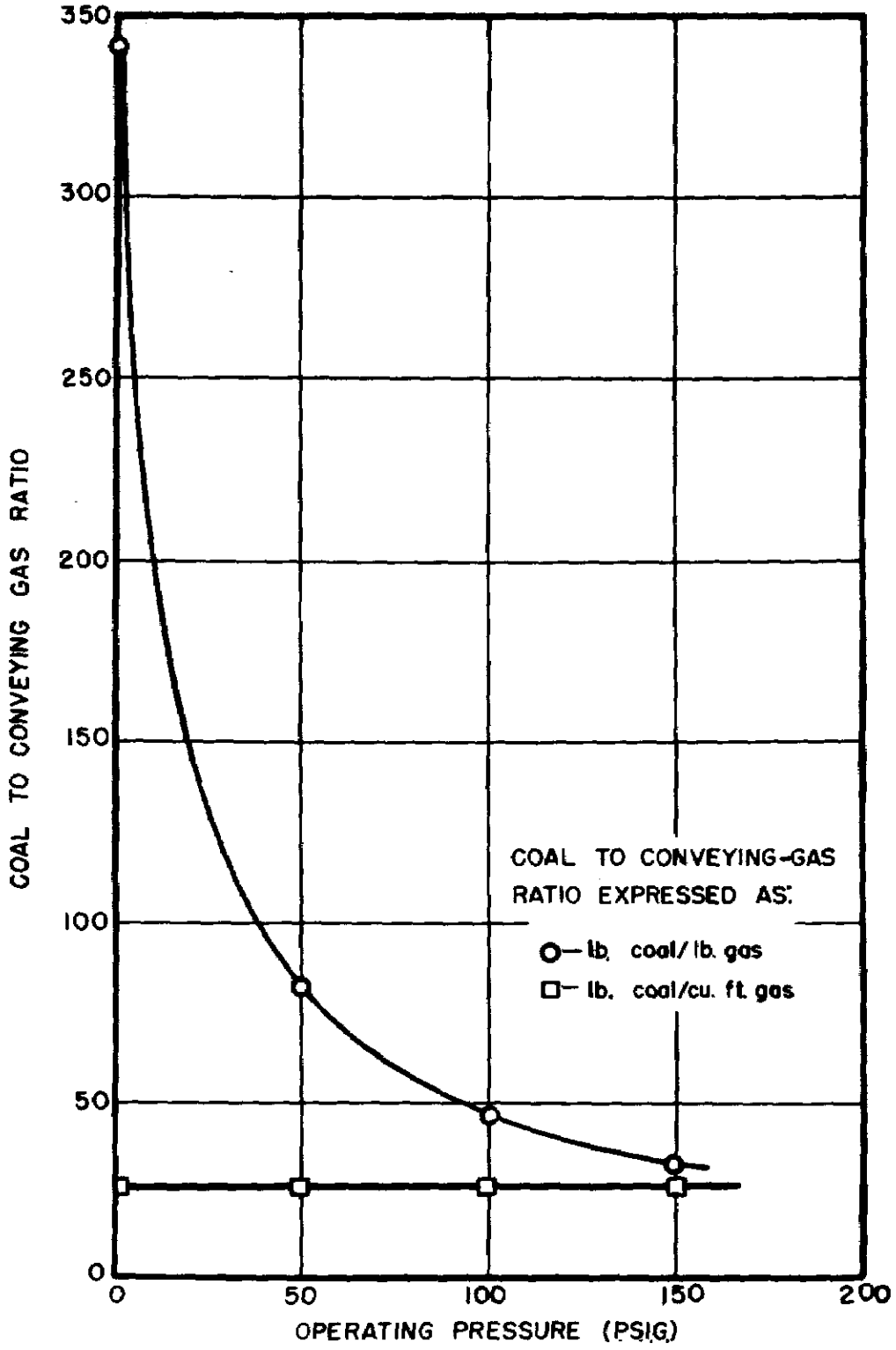


Figure 52. - Effect of operating pressure on coal:conveying-gas ratio.

of the order of 40 B.t.u. per square foot per hour per degree F. have been determined. It has been demonstrated that coking coal can be heated to 700° F. in a small-diameter tube (0.2 inch inside diameter) without build-up of any deposits on the tube wall. The use of preheated coal as feed to a gasification unit will be tested on the small gasifier during the coming year.

Pressure drop measurements on the flow of dense coal-air mixtures through tubes[7] have been correlated on an empirical basis. Figure 50 shows $(\Delta p/L)\rho$ plotted against the mass velocity, where $\Delta p/L$ is the pressure drop in pounds per square foot of length and ρ is the average density of the coal-air mixture in pounds per cubic foot. The curves may be considered to consist of two straight segments. Because the points of inflection lie on a straight line and the lines for the different diameters are parallel, an empirical equation that represents the results with an accuracy of about 5 percent is given below.

For $G(\Delta p \rho/L)^{0.35} > 1950$, $\quad \Delta p \rho/L = 0.022\, G^{1.12}/D^{0.94}$

and for $G(\Delta p \rho/L^{0.35} < 1950$, $\quad \Delta p \rho/L = 3.5\, G^{0.35}/D^{0.73}$.

G is the mass velocity in pounds per second per square foot, and D is the inside diameter of the tube in feet.

Conveying and Feeding Powdered Coal Under Pressure

As the high cost of compressing synthesis gas favors gasifying coal at elevated pressures, it was necessary to develop a method for continuously conveying and charging finely powdered coal into a pressurized gas generator. Experimental work at pressures up to 150 pounds per square inch has been carried out in the apparatus shown in figure 51.

The investigations[8] showed that powdered coal can be conveyed pneumatically, in a dense phase, from a fluidized bed and discharged at a constant rate. With other conditions equal, the discharge rate was found to be solely a function of the pressure differential across a conveying line of given dimensions, irrespective of the magnitude of the operating pressure. As the difference in pressure between the fluidizer and receiver is increased, the coal feed rate increases. The amount of coal conveyed per unit volume of gas, measured at the existing pressure, is virtually constant at all operating pressures, as seen from the diagram in figure 52. For the type (high-volatile West Virginia bituminous) and particle size (83.5 percent through 200-mesh) coal conveyed by nitrogen through copper tubing (12 feet long, 3/16-inch inside diameter), and the type of upright funnel inlet used, this ratio was 25.7 pounds per cubic foot of conveying gas. However, the weight of coal carried per unit weight of conveying gas, represented by the upper curve, is seen to decrease rapidly with increasing operating pressures.

7/ Albright, C. W., Holden, J. H., Simons, H. P., and Schmidt, L. D., Pressure Drop in Flow of Dense Coal-Air Mixtures: Ind. Eng. Chem., vol. 43, 1951, pp. 1837-1840.

8/ Barker, K. R., Sebastian, J. J. S., Schmidt, L. D., and Simons, H. P., Pressure Feeder for Powdered Coal or Other Finely Divided Solids: Ind. Eng. Chem., vol. 43, May 1951, pp. 1204-1209.

Gas Purification

Development of Analytical Methods

During 1951, satisfactory procedures were established for determining nitric oxide, naphthalene, iron carbonyl, and solid and liquid impurities in crude and also in highly purified synthesis gas.

In connection with laboratory experiments on the catalytic removal of oxygen from synthesis gas, an analytical method was studied for determining low concentrations of oxygen in gas. The method adopted was a colorimetric one, which is described in the literature, but this laboratory increased the accuracy of the method by measuring the color intensity with a spectrophotometer rather than by visual comparison using Nessler tubes. The sensitivity of the method can be noted from the calibration curve shown in figure 53.

Bench-Scale Experiments

Bench-scale experiments were conducted to study the performance of a copper-chromium-vanadium catalyst at elevated temperatures and pressures for removing simultaneously the hydrogen sulfide and organic sulfur compounds from synthesis gas. Earlier work with this catalyst at atmospheric pressure has been described in the Annual Report for 1950. The pressure at which the operation is carried out has a considerable effect, both in the efficiency of sulfur removal and in the total amount of sulfur absorbed before regeneration is necessary. Employing two catalyst beds in series, operating at a pressure of 300 p.s.i.g. and temperatures of 450° and 300° C., the total sulfur content of raw synthesis gas containing 540 grains of H_2S and 33 grains of organic sulfur per 100 cu. ft. was reduced to less than 0.1 grain per 100 cu. ft. Indeed, the total sulfur outlet generally ranged from 0.00 to 0.02 grain per 100 cu. ft. Before regeneration was required, the catalyst absorbed about 15 percent of its weight in sulfur - about 40 percent more than at atmospheric pressure.

Figure 54 shows the bench-scale apparatus used in catalytic removal of sulfur at elevated pressures. Construction is underway on three catalyst reactors for use in the purification pilot plant.

At the request of the Demonstration Plant, a limited number of experiments were made to study the catalytic removal of small amounts of oxygen from synthesis gas. The tests were made at 575° F. and 300 p.s.i.g., using copper turnings as the catalyst. Employing space velocities as high as 20,000 standard cubic feet per cubic foot of reactor volume per hour, the oxygen content of the gas was reduced from 0.9 percent to less than 0.1 percent. In view of the fact that in plant practice the copper catalyst would be subjected to traces of sulfur, experiments were performed to study the catalytic activity of heavily sulfided copper. Results indicated that sulfided copper effects the removal of oxygen as efficiently as unsulfided copper. This catalytic activity of copper sulfide is important, as it eliminates the need of regenerating the copper catalyst when it becomes fouled with sulfur.

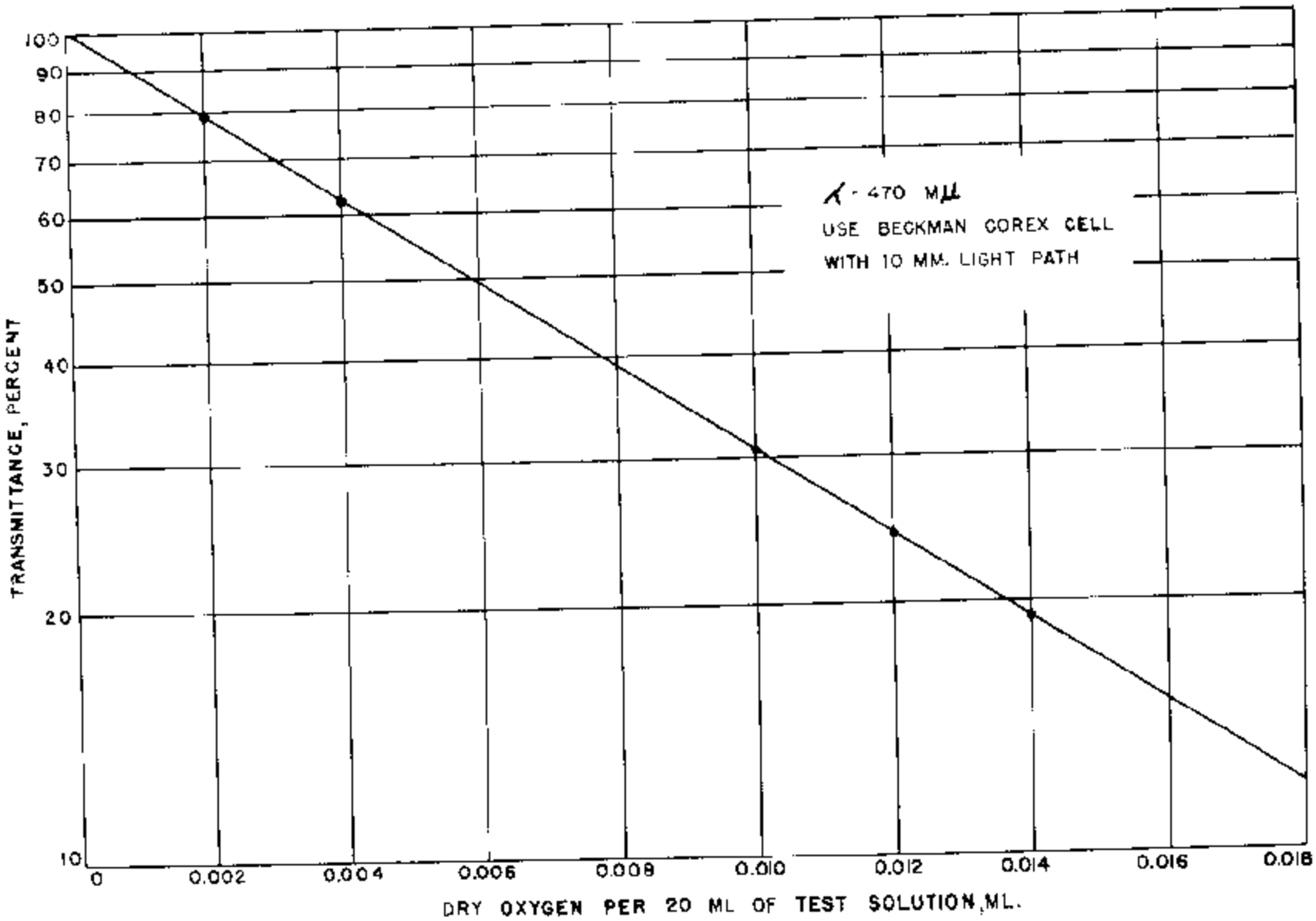


Figure 53. - Calibration curve for determining oxygen in gas.

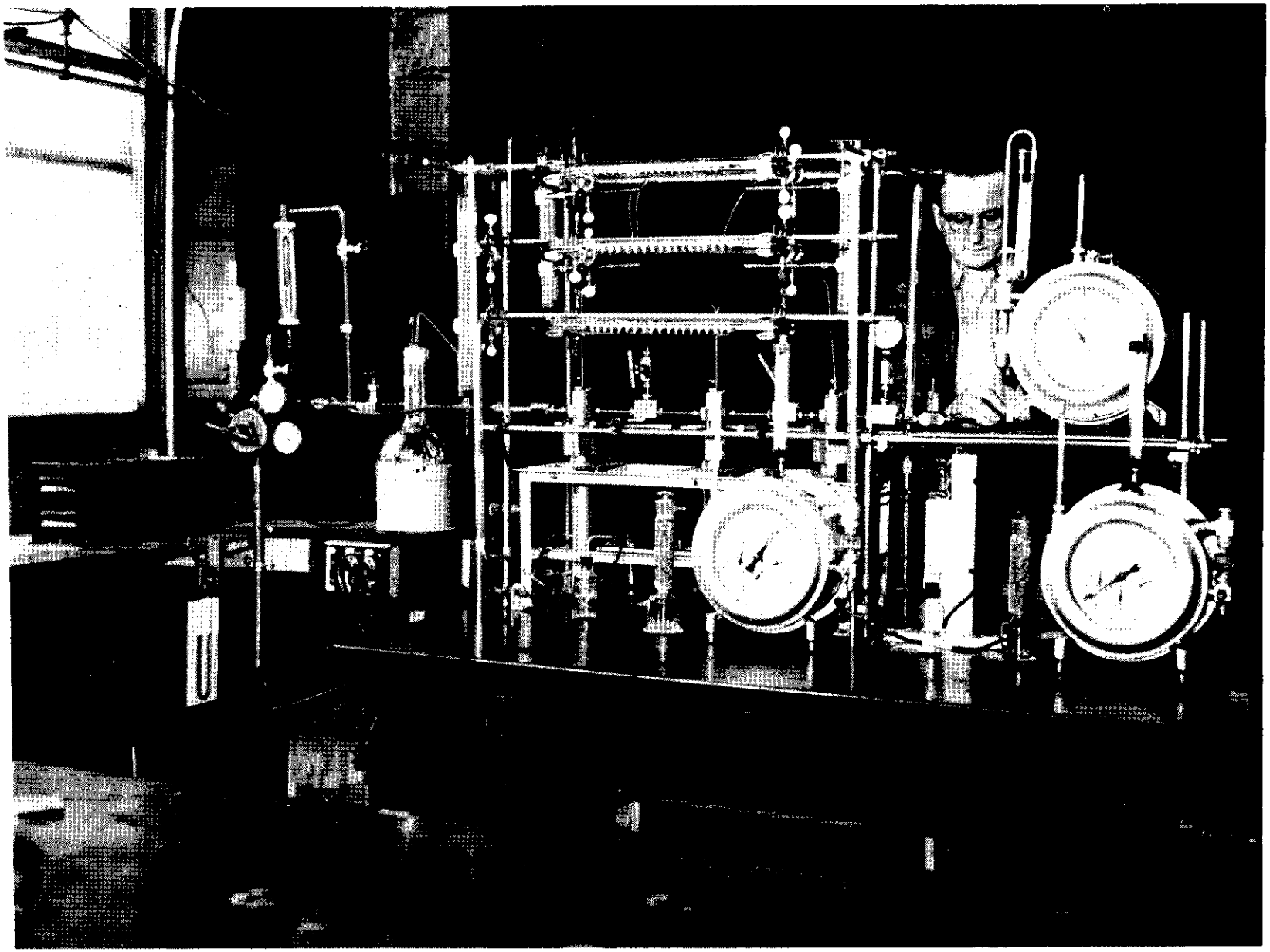
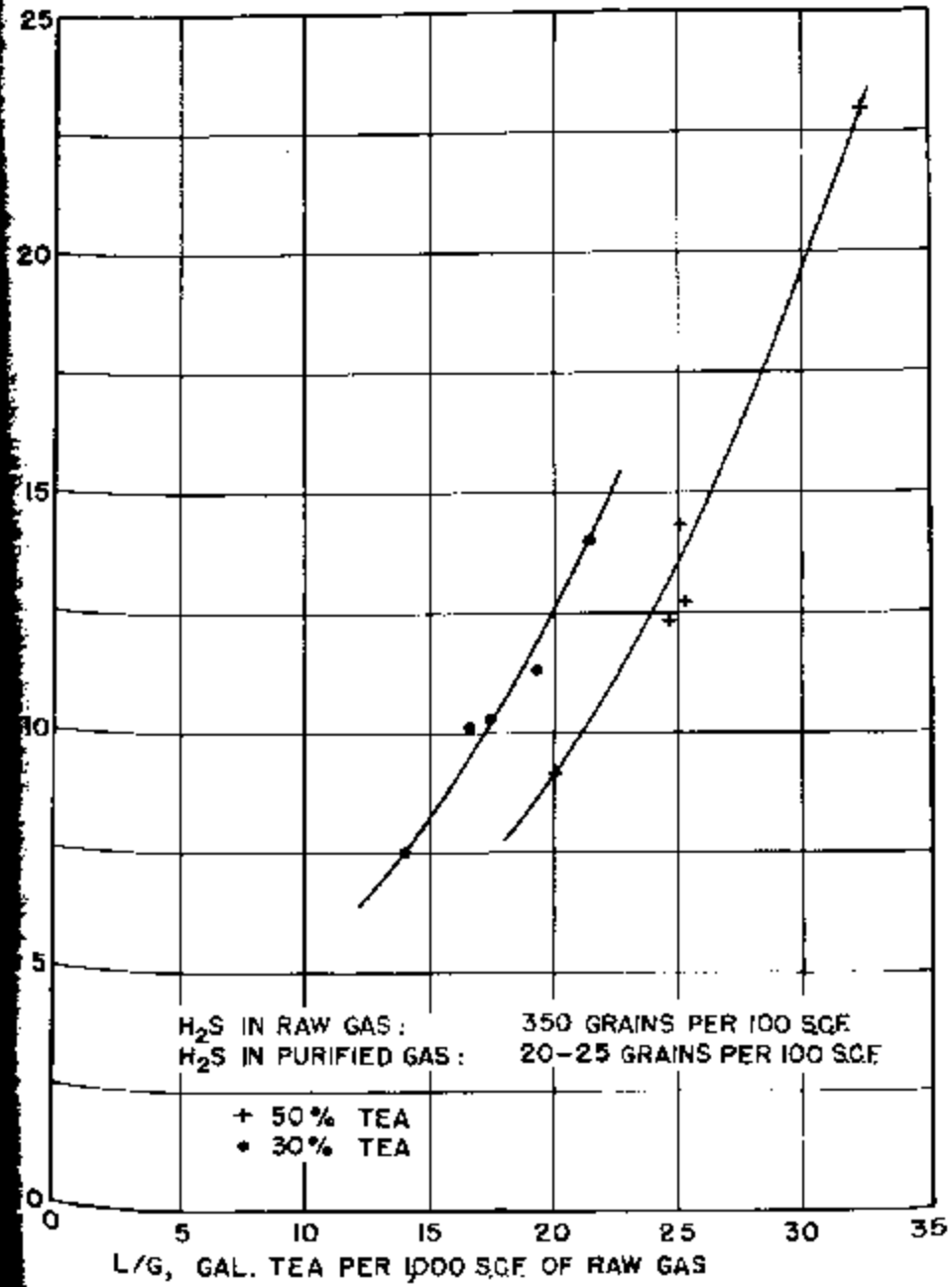


Figure 54. - Apparatus for removing hydrogen sulfide and organic sulfur compounds at elevated temperatures and pressures.



ure 55. - Effect of carbon dioxide content of raw gas on triethanolamine scrubbing rates.

0 - 32 - 11

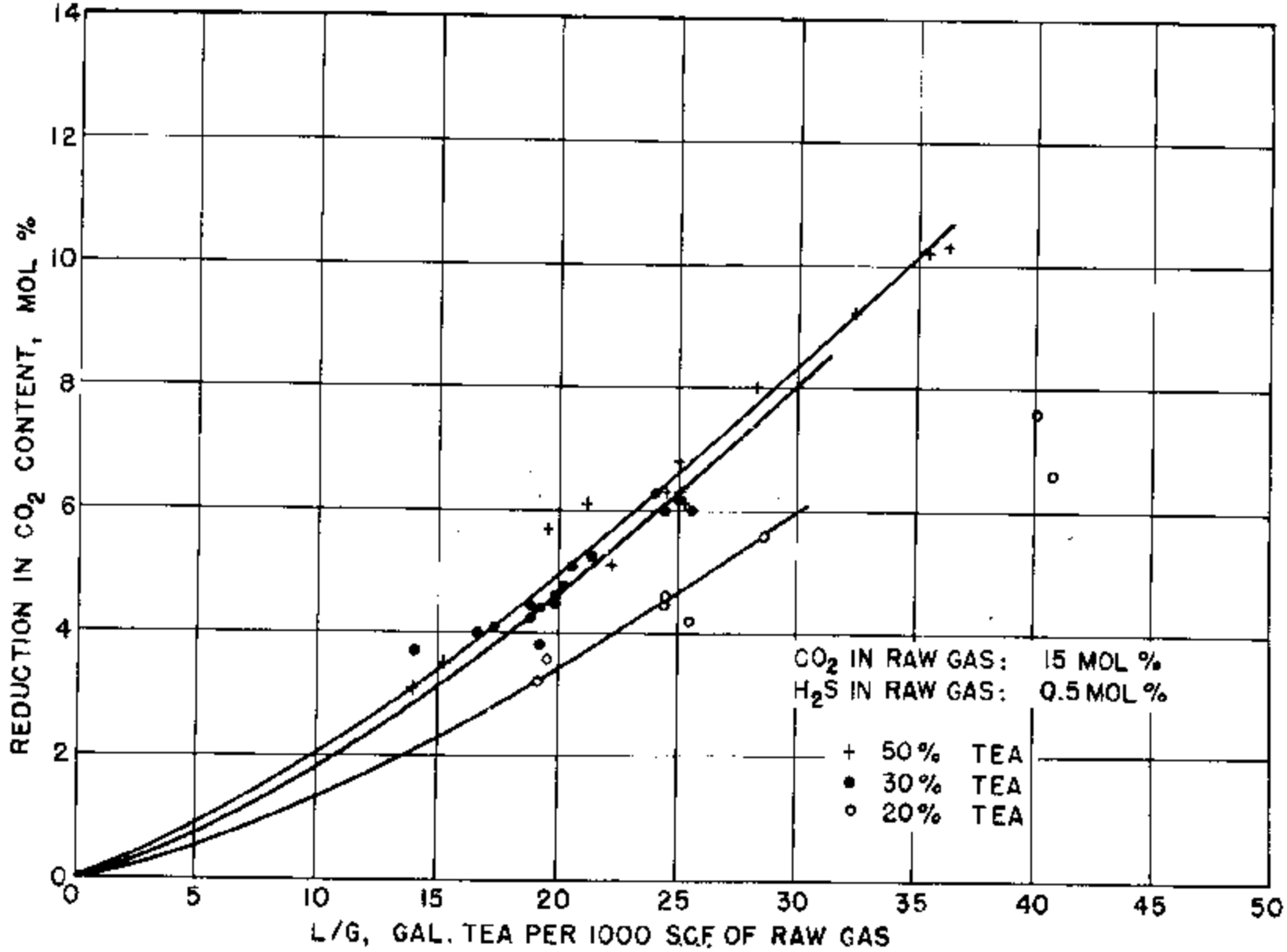


Figure 56. - Effect of triethanolamine scrubbing rates on removal of carbon dioxide.

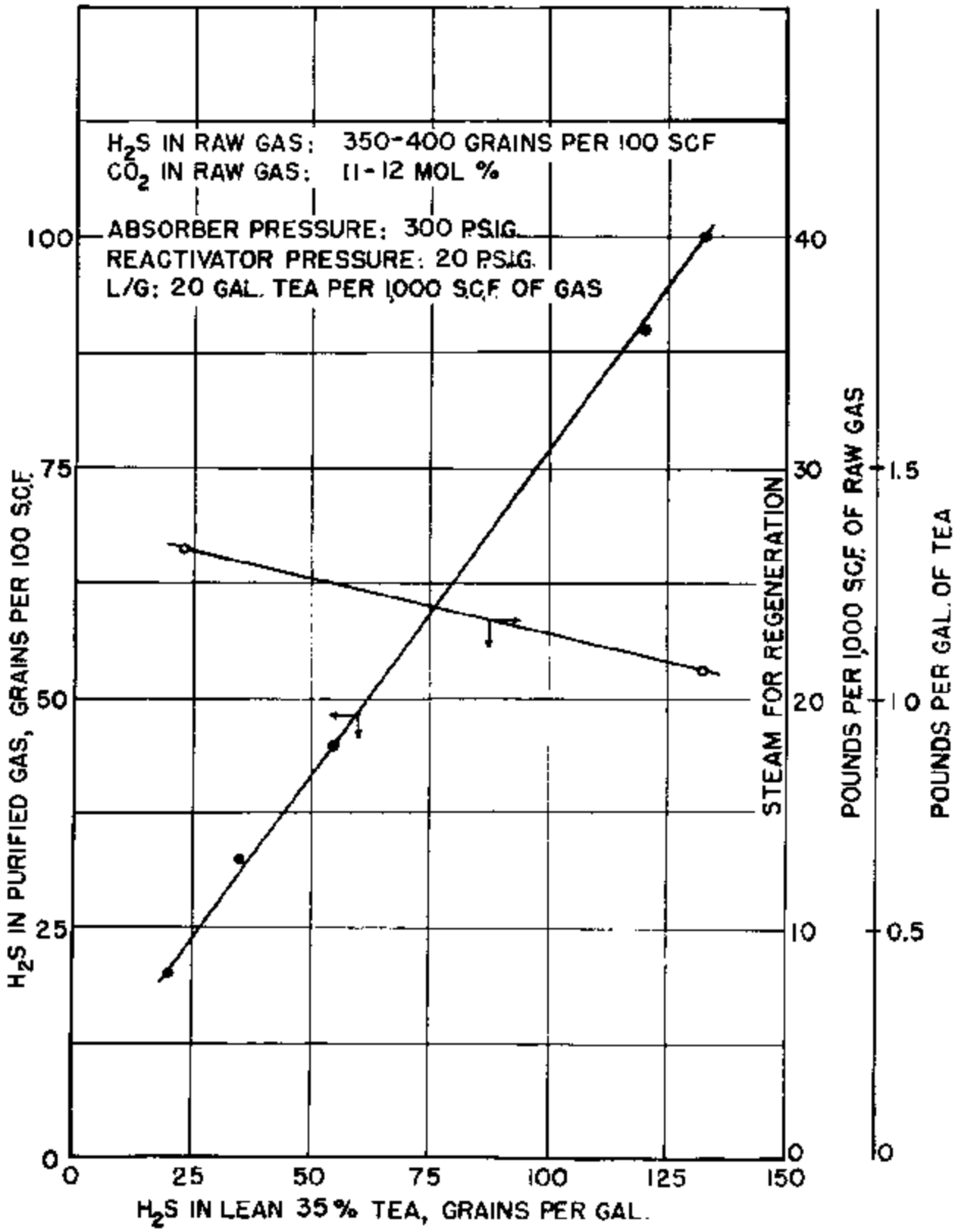


Figure 57. - Effect of steam used for regeneration on hydrogen sulfide concentration in lean triethanolamine solution.

Operation of Pilot Plant

The gas-purification research program at Morgantown always contemplated the necessity of including sulfur recovery as a feature of the gas-purification system in any large commercial plant. This was based not only on the important credits resulting from the sale of byproduct sulfur, but on the assumption that venting appreciable amounts of sulfur in one form or another could not be tolerated. In view of the critical supply situation of sulfur today, the need for sulfur recovery is evident.

Numerous pilot-plant runs have been made, with the primary object of studying the effectiveness of various solutions in selectively removing hydrogen sulfide from a gas containing a relatively large amount of carbon dioxide. Among the absorbents studied have been triethanolamine, sodium carbonate, potassium carbonate, and tripotassium phosphate. It was desirable also to obtain enough data so that cost estimates could be made on the purification of gases having various compositions. A study was made of the effect of various concentrations of solutions, the effect of varying concentrations of carbon dioxide and hydrogen sulfide in the raw gas on the rate of circulation of the solution, the effect of organic sulfur compounds on the purifying solution, the effect of scrubbing rates on residual hydrogen sulfide in the gas, and the foaming characteristics of the scrubbing medium.

Data from 37 runs in which triethanolamine was used have been correlated and the data are presented graphically in figures 55, 56, and 57.

Figure 55 shows the effect of carbon dioxide concentration in the raw gas on triethanolamine scrubbing rates. Figure 56 shows the effect of scrubbing rates of 20, 30, and 50 percent triethanolamine on the removal of carbon dioxide. Although the curves in figure 56 are for a raw gas containing 15 percent carbon dioxide, they have been found to be accurate enough through the range of 5 to 25 percent carbon dioxide if the abscissa (carbon dioxide removed) is increased by 0.1 percent for each additional 1.0 percent carbon dioxide in the raw gas.

As the steam used in regenerating fouled absorbents constitutes the greatest part of hydrogen sulfide removal costs, pilot-plant data were obtained on the amount of steam required to give various concentrations of hydrogen sulfide in a lean 35-percent triethanolamine solution. During these pilot-plant runs, the liquid:gas ratio was held constant, so that a correlation could be obtained between the hydrogen sulfide content of the lean solution and the hydrogen sulfide content of the purified gas leaving the absorber. These data, plotted in figure 57, were obtained during the initial runs with triethanolamine when the reactivator was operated at a pressure of 20 p.s.i.g. Although the steam consumption and hydrogen sulfide content of the lean solution will vary with reactivator pressure, the relationship between hydrogen sulfide in solution and hydrogen sulfide in the purified gas will hold true.

The potassium phosphate process for selective removal of hydrogen sulfide is being studied at present in the pilot plant. When using triethanolamine and a raw gas containing 350 grains of hydrogen sulfide per 100 cu. ft. and 15 percent carbon dioxide, an acid gas containing about 10 percent hydrogen

sulfide was obtained. Data thus far obtained on the phosphate process indicate that, using this same gas, an acid gas having a hydrogen sulfide content of about 20 percent can be obtained.

Under a cooperative agreement with the Southern Natural Gas Co., pilot-plant runs were made to study removal of carbon dioxide from gas using diethanolamine. Data from these runs are plotted in figure 58. These curves show the reduction in the carbon dioxide content of a gas when various solution rates of 20, 30, and 40 percent diethanolamine are used.

In addition to the removal of hydrogen sulfide and carbon dioxide, pilot-plant runs have been made in which the organic sulfur compounds have been removed from raw synthesis gas with "GW" activated carbon. Results from bench-scale experiments using this carbon were reported in the Annual Report for 1950. The results obtained in the pilot plant, as well as those in the Demonstration Plant, corroborated those obtained in the laboratory.

By first removing selectively the bulk of the hydrogen sulfide from raw synthesis gas, removing the residual hydrogen sulfide with iron oxide, and finally removing all the organic sulfur with activated carbon, it has been possible in the pilot plant to reduce the sulfur content of synthesis gas to less than 0.1 grain per 100 cubic feet. In fact, during most of the pilot-plant runs, the sulfur content of the purified gas has been less than 0.05 grain per 100 cubic feet.

Underground Gasification Project, Gorgas, Ala.

The Bureau of Mines and the Alabama Power Co. have jointly conducted field-scale experimentation on the underground gasification of coal at Gorgas, Ala., since 1946. Until February 1951 the program included the construction and operation of two field-scale experiments, the first of 50 days continuous operation and the second of 22 months continuous operation. A third experiment was started in the latter part of June 1951 and is being continued at present.

By underground gasification of coal it may be feasible to produce cheap gas for the production of synthetic liquid fuels or for the generation of power. It may be possible by this means also to exploit coal deposits that are not now mined because of thinness of beds, presence of mineral impurities, or difficult mining conditions.

In the first two experiments, the principles of the "stream method" of underground gasification were utilized wherein air (or oxygen) and steam flow past a 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. Successful operation of the U-shaped and straight-line passages, which were employed, depended upon proper roof action, wherein the roof would fuse and slump in front of the reacting coke face and force contact between it and the gas-making fluids. The objectives were to determine the quantity of coal that can be gasified in a given initial combustion zone; to ascertain the quality and quantity of the product gases generated; to obtain information regarding the effect of heat on the overlying strata; and to develop fundamental

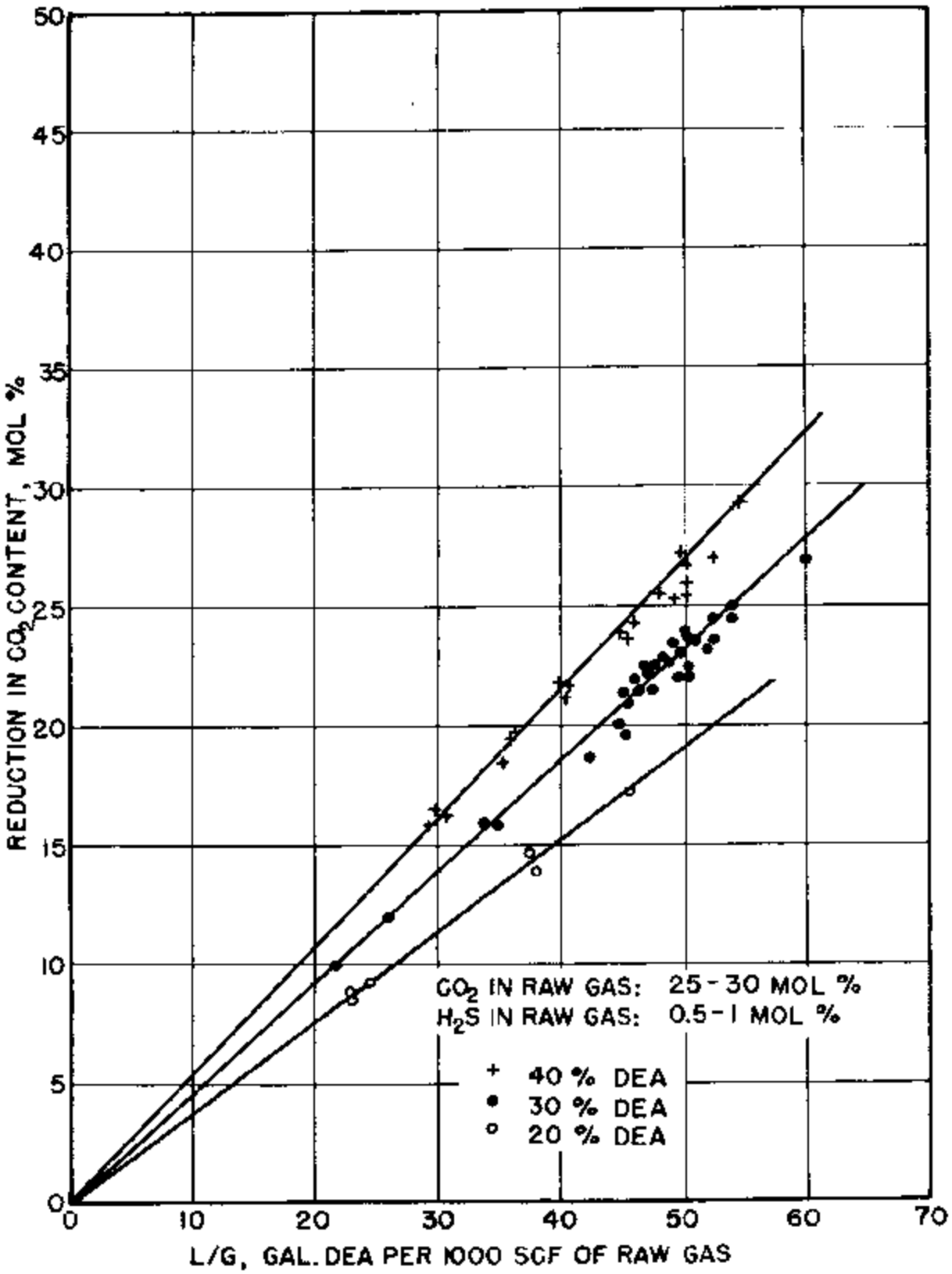


Figure 58. - Effect of diethanolamine scrubbing rates on removal of carbon dioxide from gas.

technical and economic information with regard to the choice of plant sites, installation, and operating procedures.

During the second experiment, 10,500 tons of moisture-and ash-free coal was consumed underlying an area of approximately 2 acres adjacent to the original 1,450 foot entry. Up to the time the project was discontinued, no difficulty had been experienced in maintaining combustion, and no absolute limit had been determined as to the quantity of coal that could be gasified from the original opening. It was part of the original plan of this second experiment to extend gasification to cover a large area of coal bed by providing new inlets and outlets through 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 gasification area could be extended. It appears that there is no definite limit to the area of coal bed that may be exploited in this manner.

During much of the operation, the energy of the coal was brought out of the ground as sensible heat in the product gases. At intervals during the 22 months of operation, a combustible gas was obtained. When boreholes were drilled tangent to the perimeter of the burned-out area, subsequent operation resulted in production of gas ranging from 90 to 150 B.t.u. per cu. ft. Gas of this quality was obtained for short periods, following which free oxygen appeared in the effluent gas, and the heating values diminished to 30 B.t.u. per cu. ft.

Throughout the entire experiment, it was evident that efficient contact between air and the coal faces was required to produce good-quality gas. In consequence, much of the experimental effort was directed toward improving efficiency of contact. Dry sand fluidized with air and injected into voids near the original entries was partly successful. Construction of new boreholes tangent to the coal faces, as noted above, resulted in excellent contact for short periods. Operation with increased area of coal face, achieved by use of double entries or by lengthening of the passage traversed underground, indicated only slight improvement of contact efficiency.

Experiments were conducted to determine optimum rates of air input in the existing system. Little variation in gas quality was observed in the range 4,000 to 7,500 c.f.m.; but, at lower rates, steam generated from ground water appeared in increased concentration. The initial effect of the steam was to increase the calorific value of the gas by production of hydrogen and carbon monoxide. Following this, the generation of steam and its reaction with the incandescent carbon brought about cooling of the underground system and resulted in steady deterioration of gas-making conditions. In view of the moisture effects, therefore, rates of air input for a given system must be maintained at a level at which the moisture concentration is not harmful. The minimum heat loss underground was experienced when blasting was done in the same direction for long periods at high rates of air input.

Leakage from the underground system increased with time and with enlargement of the area of coal consumed. The mechanism of the leakage is not known. No appreciable gas outflows were found at the surface. Tests made toward the end of the experiment showed that leakage was slight from the younger sections

but was very serious from the older, where the coal had been consumed over a wide area.

After the experiments were completed, the fire was extinguished and the underground area cooled by flooding with water. At the end of 7 weeks of flooding, 4.4 million gallons of water had been pumped underground; of this amount, 2.4 million gallons had been discharged as steam. The steam was accompanied by approximately 10 percent of its volume of gas, consisting mostly of products of the reaction between steam and hot carbon. Ten million gallons of water were put underground in 14.5 weeks, and the elevation of water recorded in the boreholes was sufficient to cover the coal bed over the active combustion area. Measurements in various boreholes and test holes indicated that the average temperature near the coal-bed horizon was 200° F.

These first two experiments required underground mining operations in preparing the "U"-shaped and straight-line passages employed. This is both expensive and time consuming. Therefore, the investigation of other methods for preparing the underground system is warranted. For several years the Sinclair Coal Co. and the Missouri School of Mines have been experimenting at Hume, Mo., in connecting pairs of boreholes at the level of a coal bed by inserting electrodes in the coal and passing a current between them. The object was to establish an electrical connection and then carbonize enough coal electrically to permit the flow of air or other gas-making fluids through the system. These experiments have indicated that it is possible to make such a connection.

The major difficulty encountered at Gorgas during the second experiment was inability to enforce contact between gas-making fluids and the coal faces. For these reasons it was decided to develop a new system using electrolinking (see figure 61) as a method of preparing the underground workings and, as the system between two connected boreholes deteriorates during operation, to add more sections, each having a small cross-sectional area, to the original system and thus eliminate underground mining and maintain good contact.

Figure 59 shows a vertical section of the system that was constructed to utilize these principles. The air compressors and piping already at Gorgas were modified for use in the new experiment. The electrical equipment, consisting primarily of a 500 kv.-a. autotransformer fitted with variable voltage taps in 100-volt steps from 200 to 1,800 volts, previously used by the Sinclair Coal Co. at Hume, Mo., was obtained under a cooperative agreement between the Bureau and the company and installed at Gorgas. Additional substation capacity also was provided.

The electrolinking experimentation was performed in the American coal bed rather than the Pratt which had been employed in all previous work at Gorgas. This bed lay under almost 50 feet of additional cover, which included fire clay and sandstone, and it was believed that it would permit the installation of a tighter system. The American bed at this location, as shown in figure 59, appears thicker than the Pratt bed. However, this is due to the presence of fire clay and carbonaceous shale partings. Actually the American coal is slightly thinner than the Pratt.

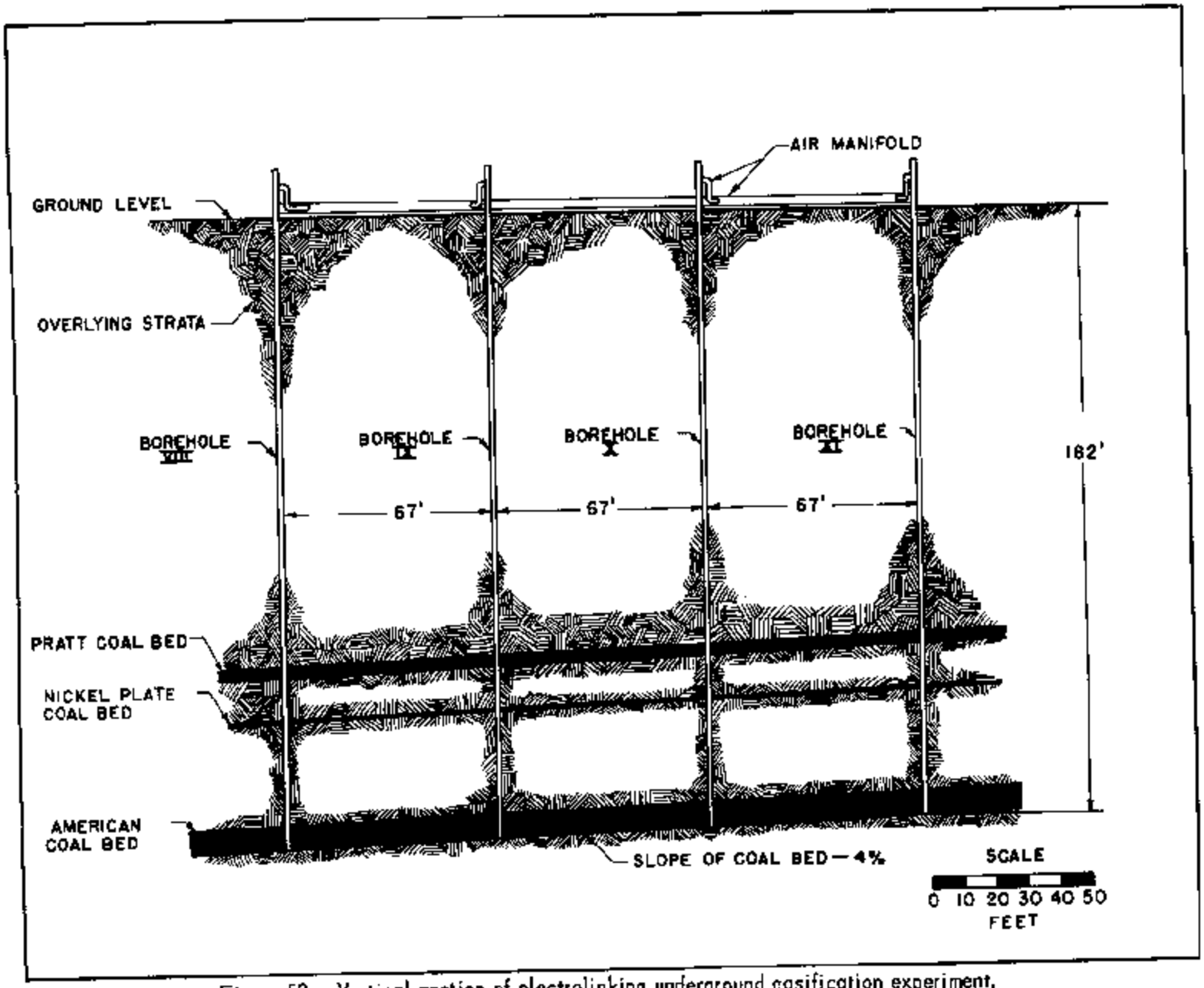


Figure 59. - Vertical section of electrolinking underground gasification experiment.

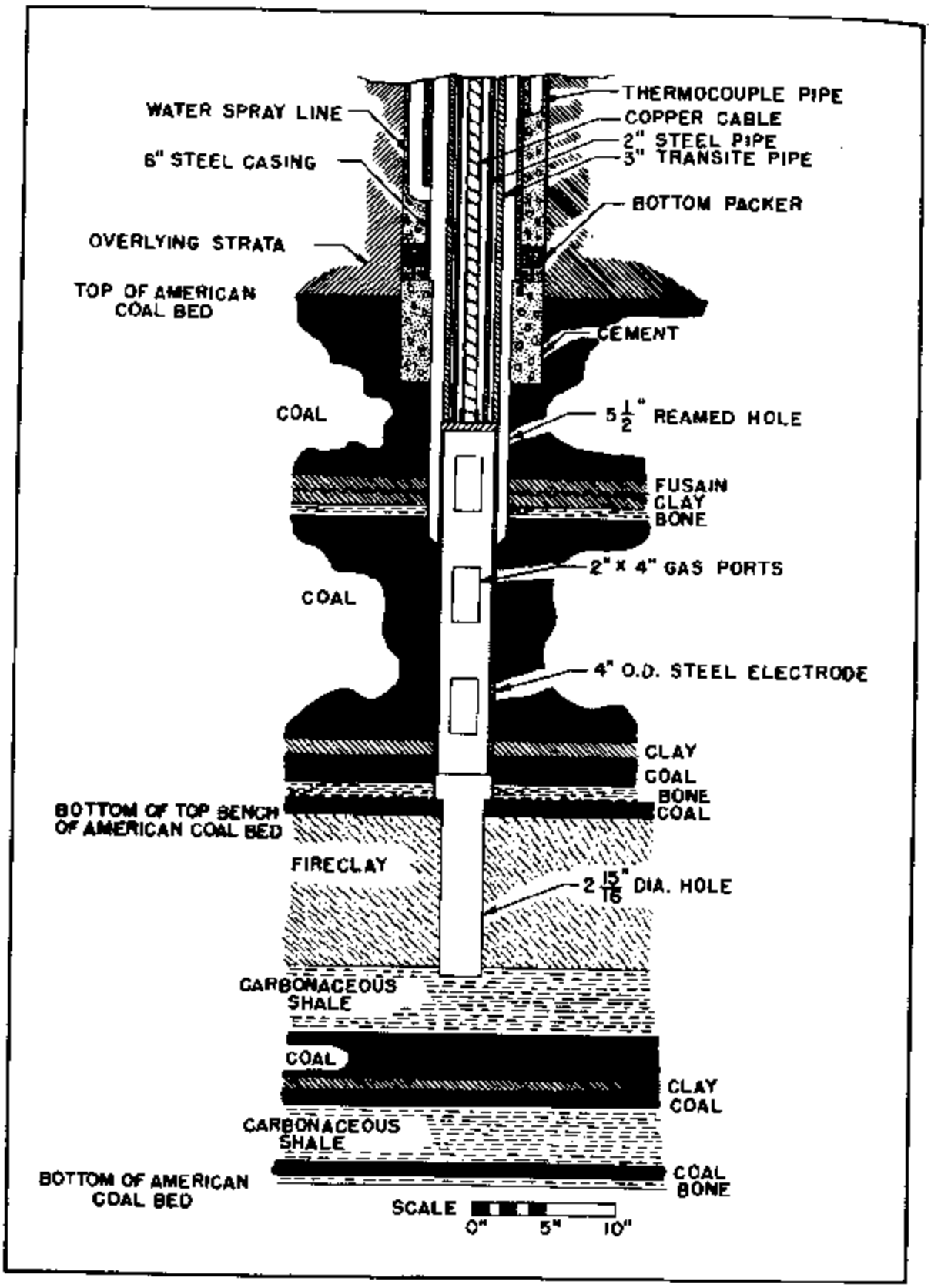


Figure 60. - Installation of electrode in coal bed.

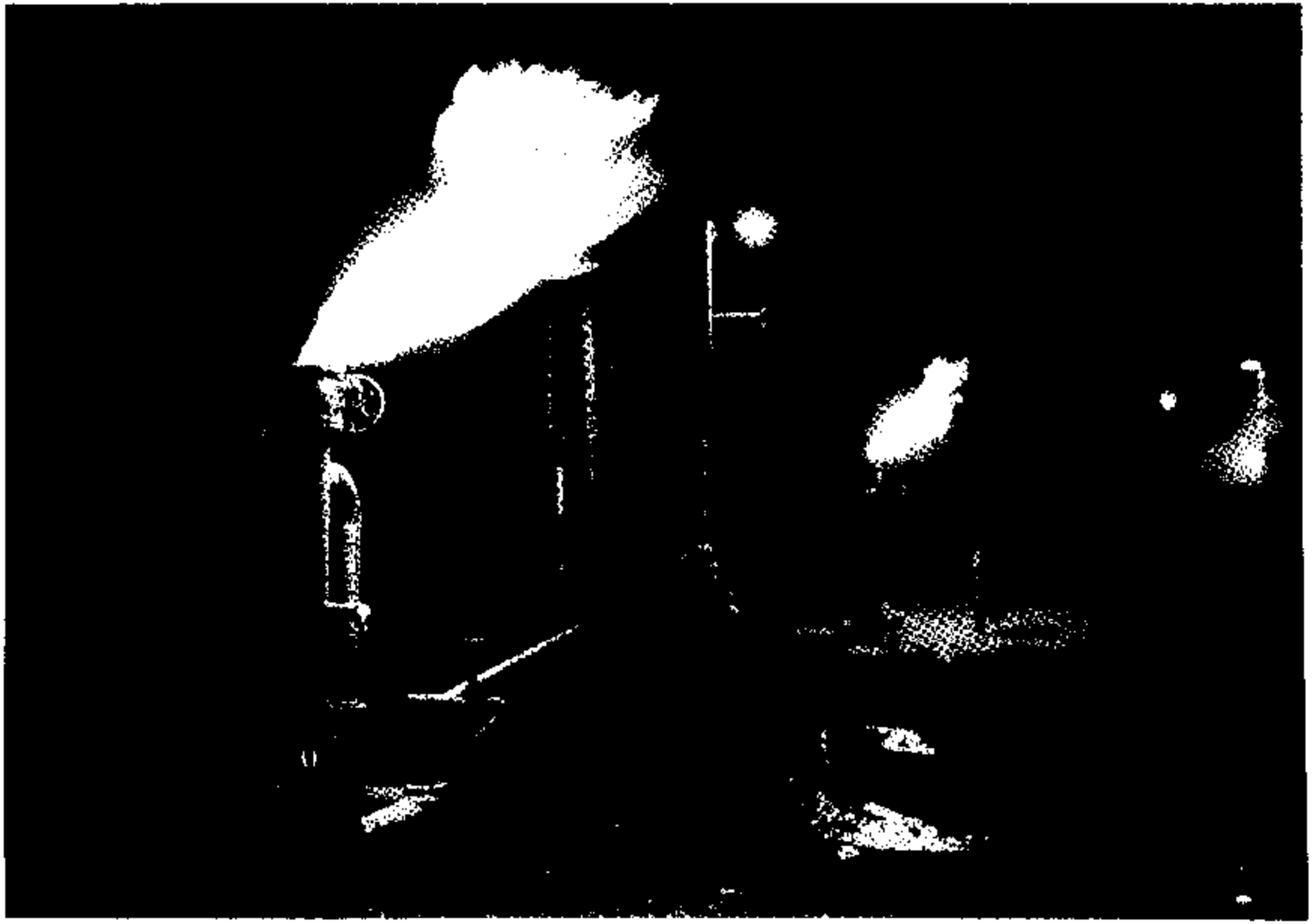


Figure 61. - Burning the gases produced in electrolinking gasification experiment.

Figure 60 shows a typical electrode installation in the coal bed. A 10-inch-diameter borehole was drilled from the surface to the top of the bed. Six-inch steel pipe casing was placed, a water spray line and a thermocouple well were installed, and the annulus between the casing and the strata was filled with cement grout under pressure to seal cracks and crevices in the strata. The coal bed was cored with an NX diamond bit to locate partings and then cored with a 4-inch diamond bit to seat the 4-inch-diameter electrode. At the top of the electrode, the 4-inch hole was reamed to 5-1/2 inches to permit passage of gases formed during the electrolinking. The electrode stem was encased in transite pipe to insulate it from the walls of the hole.

Construction of the installation was completed in June, and electrolinking was begun on the 28th. A potential was applied on the electrodes in boreholes IX and X. On the following day, a potential was applied on electrodes at boreholes VIII and XI. Table 21 gives the results obtained. At the end of the periods given in table 21, arcing occurred between the electrode stems and the casing of the boreholes. Current flow between pairs of electrodes was continued for approximately 2 weeks. Arcing prevented efficient application of current over an interval long enough to carbonize enough coal to reduce the underground resistance to fluid flow to a good operating level. However, electrolinking did increase the permeability of the coal bed, and paths were established between boreholes VIII and IX and boreholes X and XI. Some increase in permeability was obtained between boreholes IX and X, but this was not enough to develop the system in this section further.

TABLE 21. - Electrolinking of boreholes

Time, hours	Potential, volts	Current, amperes	Resistance, ohms
	Electrodes in boreholes IX and X		
0	1,800	0 - 110	-
.5	1,960	120	15.3
1.0	1,960	115	16.6
2.0	2,520	210	12.0
4.0 to 16.0	1,380 - 1,840	290 - 320	4.7 - 5.6
16.5	1,280	460	2.8
17.5	1,280	480	2.7
	Electrodes in boreholes VIII and XI		
0.25	1,960	70	34.7
.75	1,960	90	22.2
1.25	1,960	101	18.6
3.75	2,500	155	16.7
4.75	2,500	190	13.0
5.75	2,500	215	11.7
6.75	2,500	248	9.8
8.75	2,480	263	9.2
9.75	2,480	292	8.1
10.75	1,820	275	6.5

Boreholes IX and X are 67 feet, center to center, while boreholes VIII and XI are 200 feet. Table 21 shows that length has little effect on the difficulty of establishing an electrical path in the coal bed. Distance does increase the electrical requirements of the system, for more power is required to carbonize the increased quantity of coal. Approximately 7,500 kw.-hr. were required to reduce the resistance between IX and X from an initial value of 32 ohms to 2.7 ohms and 5,000 kw.-hr. to reduce the resistance between VIII and XI from 44 ohms to 6.5 ohms. The power factor for the system varied between 0.95 and 1.00 during this phase of the work.

The original plan of operation called for development of the section between boreholes IX and X, followed by gasification with air until deterioration occurred. The section between VIII and IX was to be added to the system, air injected at X and the products removed at VIII. Such operation would permit use of new coal and insure good contact between reactants. Upon deterioration of the section between VIII and IX or when reversal of flow was required, the section between X and XI was to be used in a similar manner.

During and following the application of electric power, air at pressures up to 100 p.s.i.g. was injected at the various boreholes in order to start gasifying the coke formed underground. It was found that the section between VIII and IX was in the best condition for operation, and this section was used for gasification first. Arcing of electrodes had choked the original boreholes with debris, and it was necessary to drill new holes at the same locations.

In the 44-day period ending August 11, air injection using various pairs of boreholes was attempted. The input air varied from 95 to 365 c.f.m. at pressures of 32 to 100 p.s.i.g. The calorific value of the effluent gases averaged 186 B.t.u. per cubic foot and generally varied from 80 to 300 B.t.u. The high heating value was usually due to methane from coal distillation products, but during one 123-hour portion of the period the carbon monoxide content averaged 13.2 percent, indicating that gasification was taking place. During this period, the volume of the effluent gases was small, and a large fraction of the air pumped underground was not accounted for.

In the 24-day period from August 11 to September 4, the section between boreholes VIII and IX was operated with the air injected at VIII and the outlet at IX. During the first 6 days, the air input averaged 199 c.f.m. at 46 p.s.i.g.; the calorific value of the effluent gases averaged 97 B.t.u. per cubic foot; and 24 percent of the entering air was accounted for in the products. During the next 10 days operation, the air input averaged 301 c.f.m. at 75 p.s.i.g.; the calorific value of the effluent gases averaged 110 B.t.u. per cubic foot; and 45 percent of the input air was accounted for in the products. In the final 8 days of the period, the air input averaged 306 c.f.m. at 51 p.s.i.g.; the calorific value of the effluent gases averaged 130 B.t.u. per cubic foot; and 93 percent of the input air was accounted for in the products. The 24-day period was characterized by an opening up of the underground system, increasing temperature level, and good contact between the reactants resulting in the production of a good quality product, especially during the latter part of the period. The high pressure drop was due in part to the resistance to fluid flow at the horizon of the coal bed and in part to the

condition of borehole VIII, which was partly choked with debris from electrolinking. Borehole IX at this time had been redrilled, but borehole VIII was not yet repaired. During the first part of the period, air was lost by leakage from the underground system, and in the latter part the underground system had opened up enough to remedy this effect.

On September 4 the direction of flow was reversed because of the rising temperature at the outlet, and until the 18th the system was operated with the outlet at borehole VIII and the inlet at IX. The calorific value of the product gases averaged 87 B.t.u. per cubic foot, the system leakage was high as a result of the resistance at borehole VIII. From September 18 until October 30, the system was operated by alternating the direction of flow. During a total of 17 days, the air input was at VIII, with the output at IX. The calorific value of the effluent gases averaged 88 B.t.u. per cubic foot, and good contact between the reactants was maintained. The pressure drop over the system increased, and paralleling this effect leakage increased.

In the immediate future it is planned to open up the system between boreholes IX and XI by inserting new electrodes and applying the electrolinking technique. The experiment has shown that the electrolinking technique can be employed and a system set up for underground gasification whereby underground mining can be eliminated. Further, where good reactant contact is maintained good quality gaseous products can be produced. Better electrode installation, it is believed, will materially decrease the time required for development and result in larger throughputs than have been obtained.

APPENDIX. - BIBLIOGRAPHY OF PAPERS AND REPORTS PRESENTED OR PUBLISHED IN 1951

PROCESSING, Coal-to-Oil Demonstration Plants, Louisiana, Mo.

1. BALCERZAK, C. E., and SKILLERN, J. A. Performance of High-Pressure Instruments in the Bureau of Mines' Synthetic Fuels Demonstration Plant. Am. Soc. Mech. Eng. Tech. Paper 51-PET-7, September 1951, 15 pp.
2. BATCHELDER, H. R., and INGOLS, H. A. Performance of a Pebble-Heater-Type Steam Superheater. Bureau of Mines Rept. of Investigations 4781, 1951, 16 pp.
3. DONOVAN, J. T., LEONARD, B. H., and MARKOVITS, J. A. Design and Development of High-Pressure Injection Pumps for Hydrogenation Service. Am. Soc. Mech. Eng. Tech. Paper 51-A-71, November 1951, 22 pp.
4. DOUGHERTY, R. W. A Survey on the Hydraulic Transportation of Coal. Bureau of Mines Rept. of Investigations 4799, 1951, 22 pp.
5. HIRST, L. L., DRESSLER, R. G., and BATCHELDER, HOWARD R. Bureau of Mines Completes Gas-Synthesis Plant. Crane Valve World, vol. 48, No. 1, 1951, pp. 98-103.