To date the material taken from the unit has been small enough to pass readily through a 4-inch plug valve. Data on the nature of the residue obtained are given in tables 2 and 3 in the section on Results.

The product gas, water, and remaining ash-carbon mixture pass to the bottom of the scrubber through a water-jacketed line. The gas is scrubbed with water as it passes upward through the ring-packed section. The water level in the base of the scrubber is kept constant with a float-controlled letdown valve. The water, containing fine ash and carbon, is blown into a letdown tank, and the stream from this tank is measured and sampled for residue content.

The scrubber (fig. 10) is a simple shell designed for pressure operation and contains a section filled with ceramic Raschig rings. The gas and water stream from the gasifier enters the scrubber tangentially. A renewable baffle to protect the shell from abrasion is provided. The gas is washed with cold water; all the water and residue leave through a float-controlled letdown valve (fig. 11). Examination has shown that the Raschig rings remain clean and that no residue is retained in the scrubber. From our present knowledge we can say that the residues produced by this process probably can be handled with adaptations of equipment now available.

The exit gas leaves through an automatic valve that controls the gasifier pressure. Because of its design pressure limitations, the Theisen disintegrator (fig. 12) cannot be used at more than 250 p.s.i.g. Consequently, a second letdown valve is used after it to keep the pressure at that point. Between the scrubber and the disintegrator are pressure-relief valves that will act should the regular gas-letdown valve fail.

A separate line was provided so that the gas could be bypassed around the disintegrator and measured in a positive-displacement rotary meter at 20 p.s.i.g. and an orifice meter at atmospheric pressure.

The various high-pressure water pumps used to supply spray and cooling water are all standard items.

Reactant Nozzle Development

The reactant nozzle has undergone several changes, necessitated because of changes in reactant preheating and operating pressures. Using a low-velocity coal stream carried by a minimum quantity of inert gas, there is an optimum velocity for the jets of combined steam and oxygen if best mixing is to be obtained. Changes in the gasifier pressure affect the actual reactant volumes, as do changes in the reactant ratios, that is, pounds of steam to pounds of oxygen in relation to pounds of coal fed.

The present nozzle (fig. 4) is designed for coal-feed rates of 700 pounds per hour at 325° F., oxygen rates of 7,000 std. c.f. per hour and steam rates of 210 pound per hour when the steam and oxygen are at 600° F. and the reactor pressure 300 p.s.i.g. This sets the maximum velocity for the oxygen-steam mixture, leaving the small nozzle orifices at 500 feet per second. Experimental work has not proceeded far enough to allow more exact statements as to the optimum nozzle discharge conditions or the effect of nozzle design on gasification results. The number of variables affecting nozzle design are such that an extended experimental program will be required. For the present, the problem is complicated, inasmuch as the nozzle is used as a preheat burner also.

Referring to figure 4, coal enters tube D, and the steam-oxygen mixture enters through tube C, mixing taking place at the nozzle orifices. An insulated space surrounds tube C to prevent undue cooling of the steam and is followed by the water jacket. The threaded orifice piece shown in this drawing has been replaced by an all-welded type of construction. When the unit is heated under atmospheric pressure, natural gas is used in tube D and air-oxygen or straight oxygen in tube C.

Steam-Oxygen Superheater

The steam-oxygen superheater is shown in figure 13. Water under pressure is introduced to the lower coil, of type 304 stainless steel. Oxygen enters the unit and is partly preheated before meeting the steam at the point indicated by TC(T2-A) on drawing. The oxygen coil is also type 304 SS. The steam-oxygen mixture coil is made of SA 213 type 316 SS. Using these alloy materials it is possible to preheat the steam-oxygen mixture to 900° F. in the superheater unit.

The unit is equipped with valves on the outlet side so that it may be brought up to approximate test rates on steam with CO_2 in the oxygen coil before the gasifier is pressurized. The mixture is heated with a standard premix-type burner, using air and natural gas.

Coal Preheater

The coal preheater is a simple pipe coil heated externally by 100 p.s.i.g. steam through which the coal flows. Experimental work now in progress indicates that the coal, in the fluidized state, may be heated to about 600° F. or just below the plastic stage. By such preheating about 140 B.t.u. per pound of coal fed may be recovered and returned to the process. It appears that use of the preheated coal is beneficial because, for one thing, it decreases the reaction time, making smaller vessels possible. Such a reduction in reactor size also reduces the overall heat losses from the process. When lignites and certain subbituminous coals are used, the moisture content of the air-dried, pulverized fuel would supply all or most of the steam for the reaction. Consequently, plans are underway to carry out a test program to determine how coal preheating can best be utilized in large-scale units.

Safety and Control System

Operation of any pressure vessel, particularly one handling potentially explosive mixtures at high temperatures, calls for careful examination of protective devices and systems. In designing the safety system, shown schematically in figure 14, it was desired to cover the following possible emergencies:

(1) Failure of coal flow, which could set up an explosive condition owing to excess oxygen.

(2) Steam-generator failure or steam-line failure, which could endanger personnel from steam and/or allow gas to escape into the operating area.

(3) Oxygen-supply failure or line rupture, which could cause fire in several ways.

(4) High-pressure cooling-water failure, which could allow development of excessive shell temperatures.

Since in any plant operating on electric power such power may fail, the emergency system and the normal operating controls were devised so that the plant would be placed in a safe condition automatically if such failure occurred. Also, provision was made for emergency shutdown of the plant from outside the operating area if necessary. In addition to the routine checks on this system made before any run, there have been

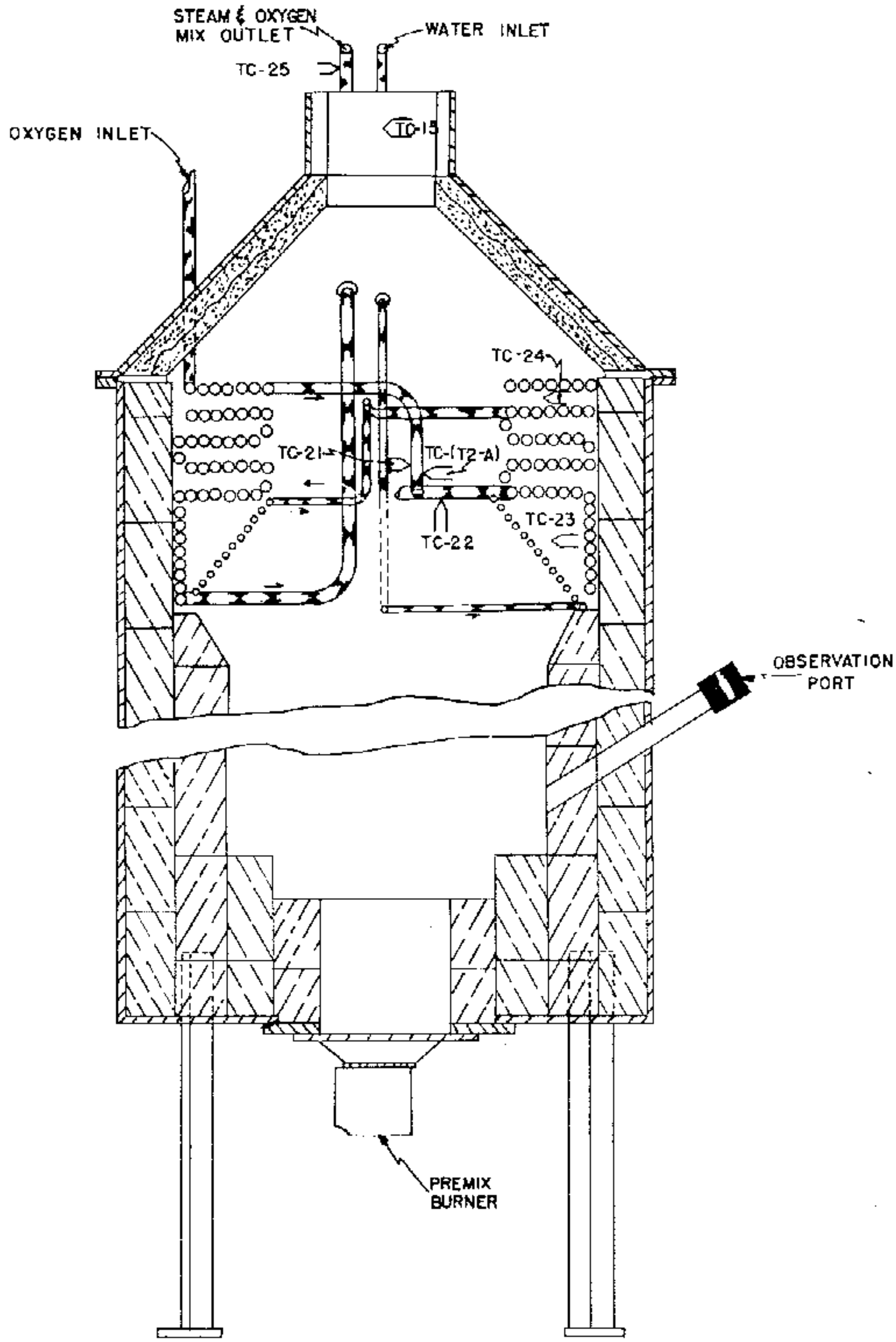

Figure 13. - High-pressure oxygen and steam superheater.

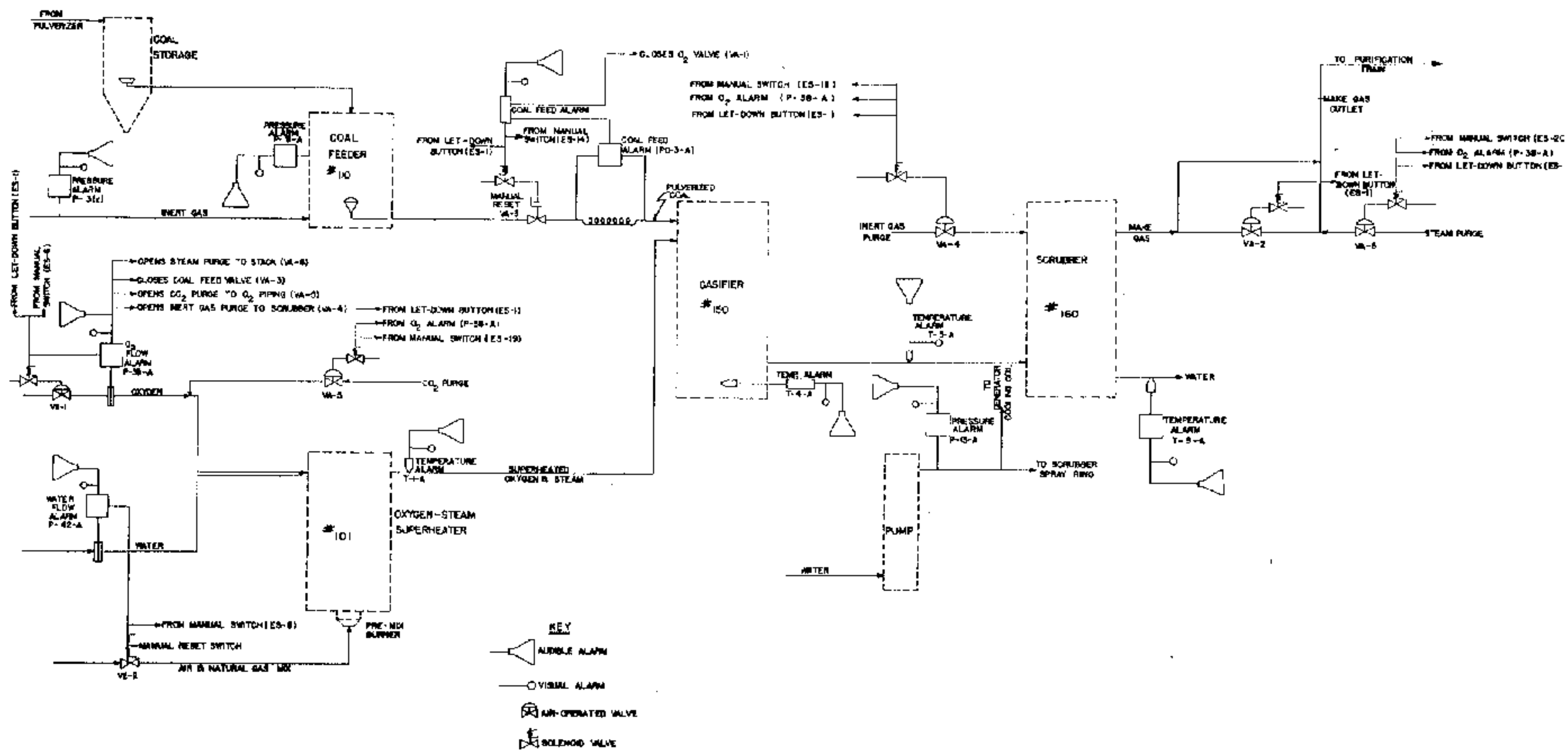

Figure 14. - Safety system for pressure-gasification pilot plant.

several occasions when it was used during a run, for example, steamline leaks, momentary stoppage of coal feet at startup, etc., and it has functioned satisfactorily every time.

Wherever an unsafe condition can build up gradually - for example, line stoppage from sludge or overheating of a piece of equipment - visual and/or audible alarms are used. These permit correction of the condition before a complete shutdown would be needed.

In designing the safety system, the aim has been, in any particular case, to choose a method of control that would fit into any scheme for making remote, automatic control of the process possible. In this early developmental stage of the work, the decision to make an operational change, in most instances, must be made by an individual. But wherever possible, the control mechanism actuated by the individual is of a type that could be activated by some kind of master control unit.

Broadly speaking, all materials being handled in the plant - from the introduction of the pulverized coal into the first pressure hopper to the final product - behave as fluids. Consequently, it appears that, by using equipment now in existence - such as flow controllers, telemeters, continuous gas-analysis apparatus, and even television (to check on ignition and maintenance of same as in boiler practice), etc. - the process can be controlled so that exposure of personnel to hazardous conditions is at a minimum.

The system is dual. Any condition that would create an immediate danger is detected by the safety system, and, through a network of relays and interlocks, the entire system is placed in a standby or "safe" condition. In addition, manual switches may be actuated by the operators to open purges, etc., or place the system in standby. In general, it is impossible for an operator, by throwing the wrong switch or making some other error in operating the unit, to cause an unsafe condition. For example, if the coal flow should be inadvertently cut off, the oxygen flow would also be immediately cut off by the safety system.

The oxygen and water flows to the oxygen-steam superheater are metered by conventional pneumatic differential transmitters employing orifice plates as primary elements. The coal flow is metered by observing the pressure drop across a calibrated section of the coal-feed line.

In either an oxygen- or coal-flow failure, the safety system immediately cuts off the flow of the other reactant and opens valve VA-5, admitting carbon dioxide into the oxygen piping. Steam failure presents no danger to personnel. However, it does cause damage to the superheater coils. For this reason, if the steam fails, heat to the superheater is cut off through alarm P-42-A and solenoid valve VE-2.

Excess-temperature alarms T-1-A, T-3-A, T-4-A, and T-5-A on the superheated oxygen-steam line and in the water in both gasifier and scrubber do not shut down the equipment if actuated. Abnormal temperatures indicated by these alarms give both visual and audible signals, enabling the operator to rectify the condition before damage results.

The letdown or emergency button ES-1 is installed in a prominent place on the control panel. This button, when pushed, cuts off the coal and oxygen flows, admits purges to the vessels, and quickly brings the system to atmospheric pressure. It should be emphasized that in any failure of coal or oxygen, failure of the instrument air, or electrical failure the gasifier and related equipment are placed in a "safe" condition automatically.

Not shown in the drawing is an emergency button, ES-13, which is outside the building housing the equipment. This control is in parallel with ES-1 and can be used in the same way.

This safety system is carefully checked before each trial run. Possible abnormal conditions are simulated, and the actions of the various alarms and interlocks are observed.

Coal-Feeding Equipment

The instrumentation flowsheet for the coal-feeding system from the continuous coal feeder up to the coal preheater is shown as figure 3. For more detailed descriptions of this method of feeding coal, the reader may refer to the following publications:

McGee, J. P., Schmidt, L. D., Danko, J. A., and Pears, C. D., Pressure-Gasification Pilot Plant Designed for Pulverized Coal and Oxygen at 30 Atmospheres: Pres. before Am. Inst. Min. and Met. Eng., New York, N. Y., Feb. 20, 1952. Gasification and Liquefaction of Coal, Am. Inst. Min. and Met. Eng., New York, 1953, pp. 80-108.

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, No. 8, August 1951, pp. 1837-1840.

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, No. 5, May 1951, pp. 1204-1209.

Dotson, J. M., Holden, J. H., Seibert, C. B., Simons, H. P., and Schmidt, L. D., New Method Measures Solid:Gas Ratio in High Solid Flow: Chem. Eng., vol. 56, October 1949, pp. 128-130.

Albright, C. W., Holden, J. H., Simons, H. P., and Schmidt, L. D., Pneumatic Feeder for Finely Divided Solids: Chem. Eng., vol. 56, June 1949, pp. 108-111.

The continuous feeder is supplied from the batch feeder as needed during the test run, the batch feeder being refilled periodically. Inert gas enters through control valves PR-1 and PR-2 in quantities needed to fluidize the coal, bring the units up to operating pressure and, during runs, make up for the conveying gas leaving with the coal. These valves are controlled to maintain constant feeder-gasifier differential pressure.

To fluidize the coal, the inert gas in the feeder is recirculated by the recycle compressor, which is controlled to maintain a superficial upward velocity of 0.1 to 0.2 foot per second through the coal bed. This recycle gas is dedusted by a cyclone-type separator in the feeder and the knock-out chamber in the recycle line. Heat of compression is removed by the heat exchanger.

The fluidized coal is withdrawn from the feeder through an extraction funnel when valve VA-3 is opened. The coal-flow rate is measured by the pressure drop through the calibration coil. The coils are calibrated by feeding into a pressure chamber from which the coal may be withdrawn and weighed. Pressure taps (fig. 15) have been developed that use a micrometallic filter element. These allow transmission of pressure impulses without filling the impulse lines with coal. They can

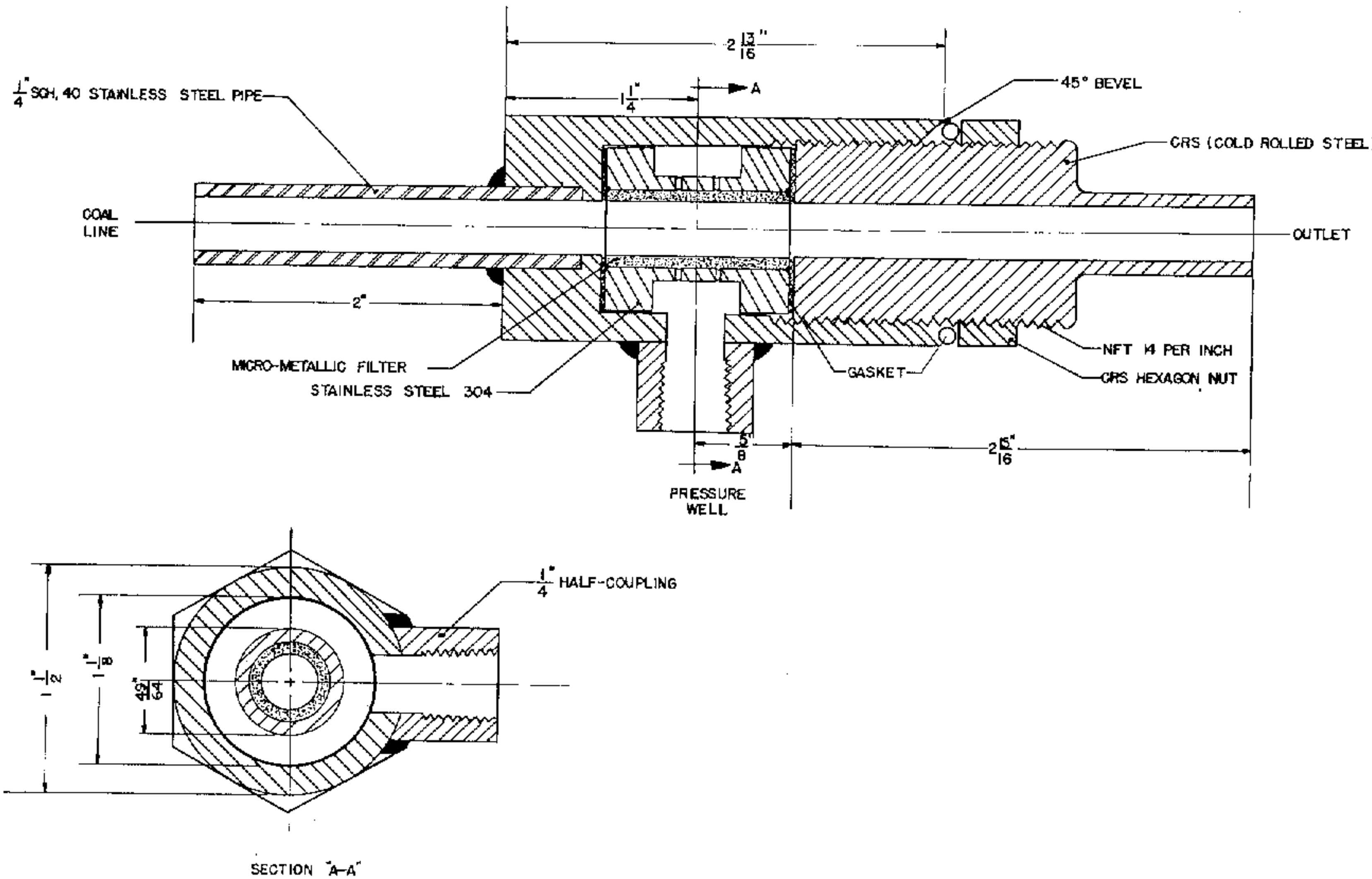

Figure 15. - Feed-line pressure tap.

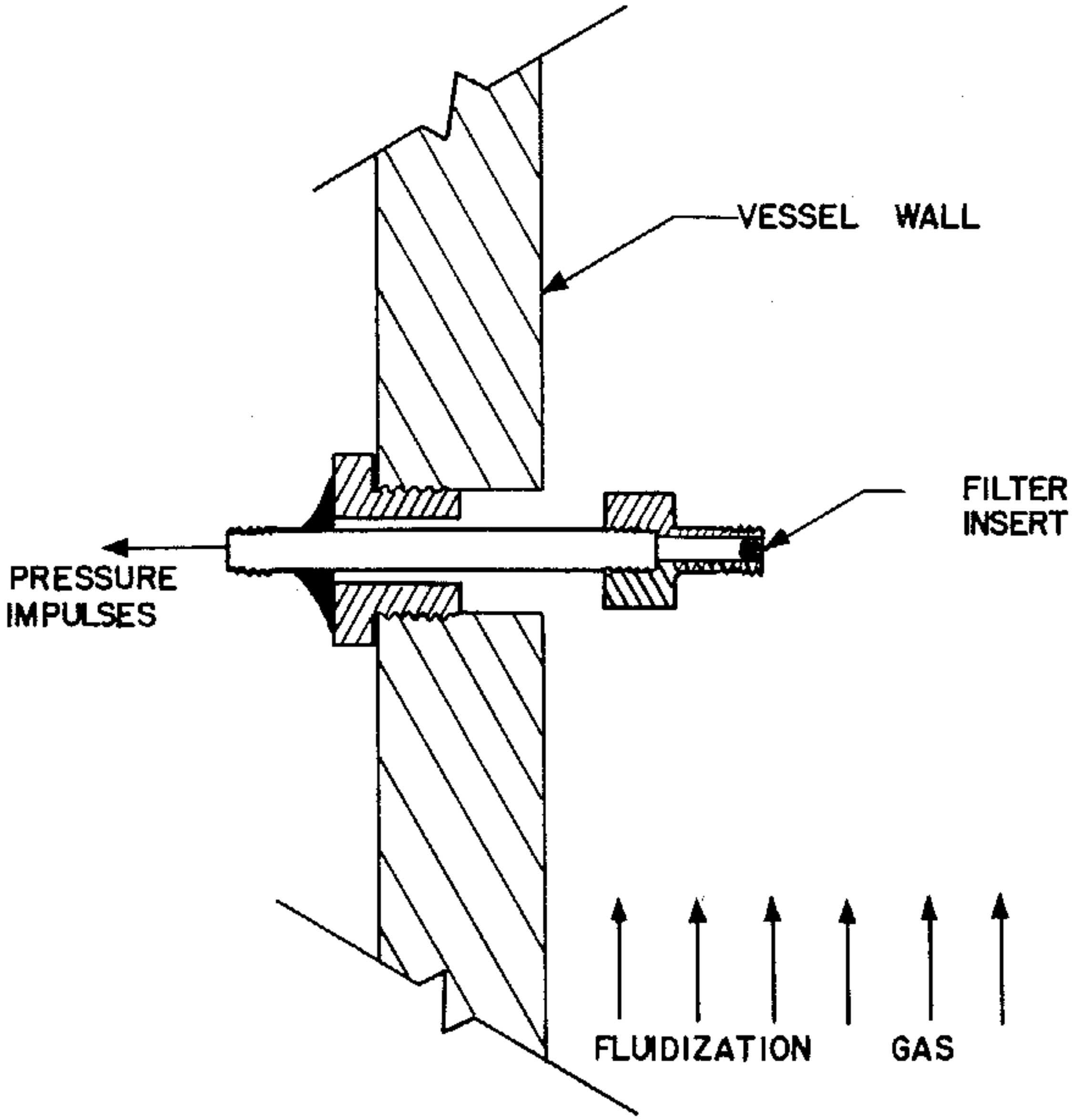

Figure 16. - Vessel pressure tap.

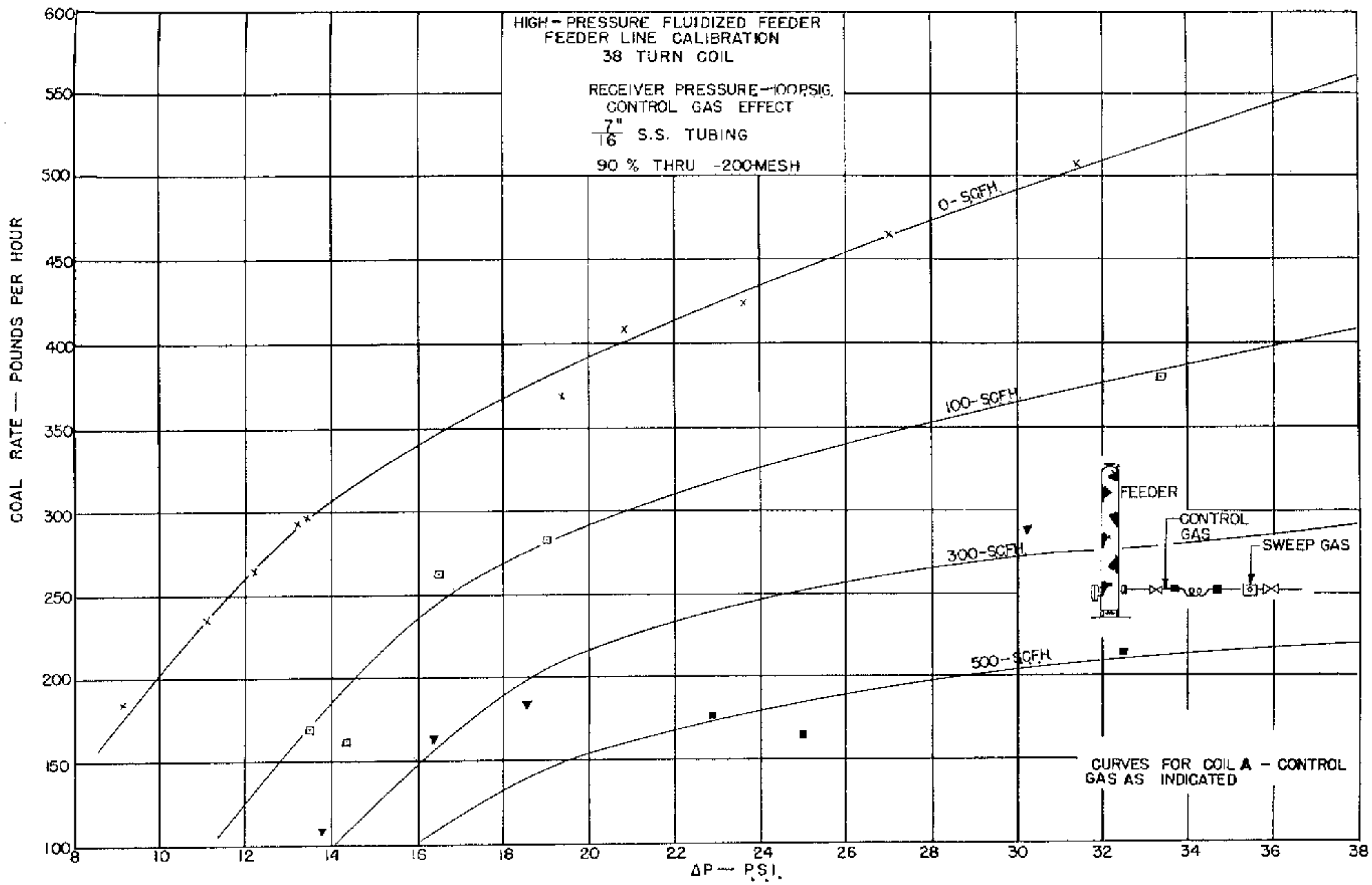

Figure 17. - Typical flow-control curves used for high-pressure pneumatic coal-feeder feed-line calibration.

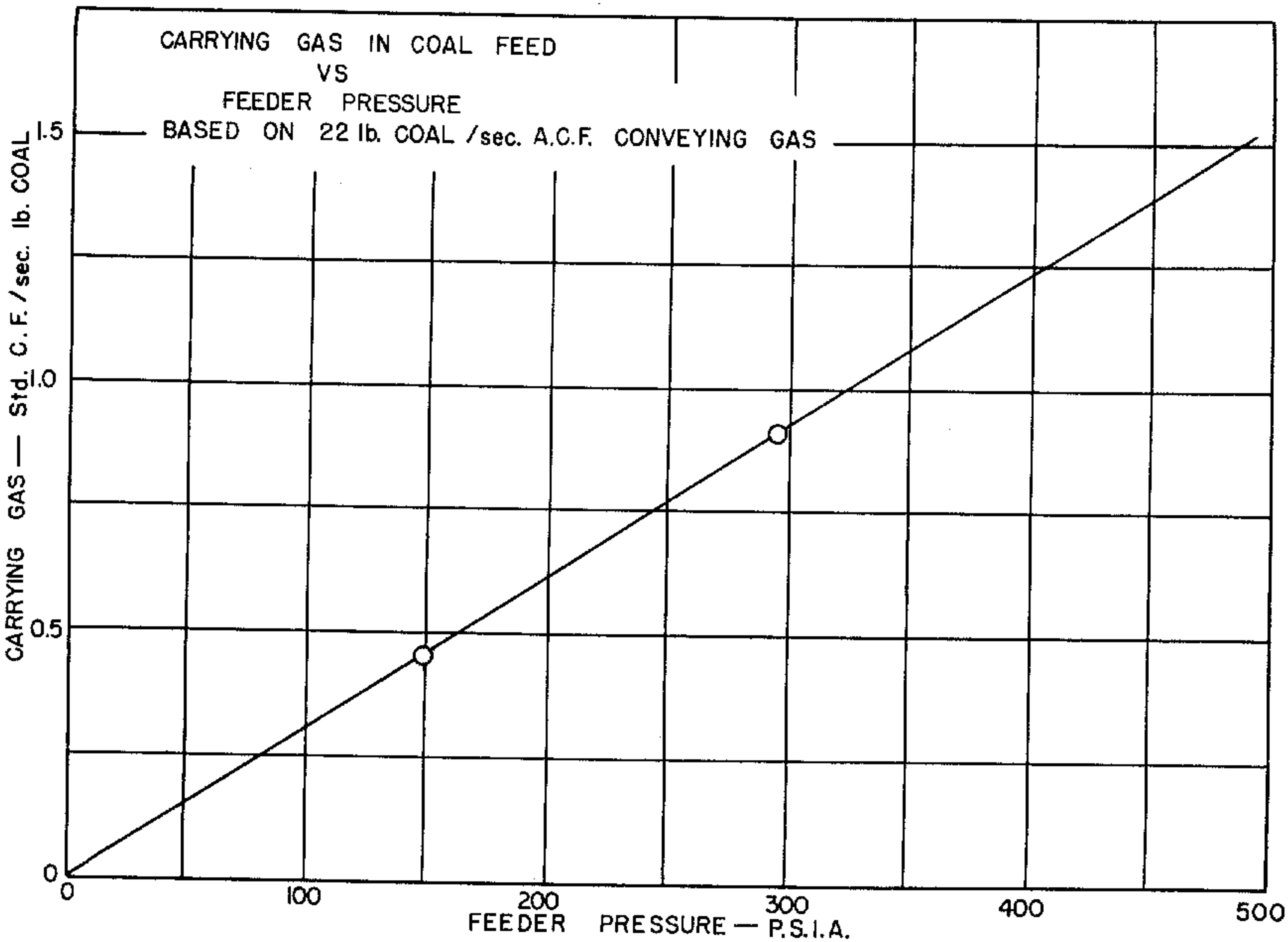

Figure 18. - Effect of coal-feeder operating pressure on amount of conveying gas used per pound of coal.

be kept free by periodic blowback. A similar pressure tap (fig. 16) is used inside the feeder. This is kept free from plugging by the movement of the fluidized gas. From the coil the coal stream goes to a sightglass, which serves as a visual indication of coal flow and also as a pressure tap for the differential pressure alarm PD-2-A and shutdown control PD-3-A. At the sightglass a very small amount - about 120 cu. ft. per hour - of sweep gas is used to keep the glass clean. The action of the alarm and shutdown controls is explained in the description of the safety system.

When runs are made in the gasifier at pressures over 200 p.s.i.g., the procedure has been to bring the coal feeder up to the pressure needed for the test and to begin the test with the gasifier at slightly under the test pressure. To keep the coal flow at the beginning at, or slightly less than, the test rate, it is necessary to add "control" gas through flowmeter FL-10. (See fig. 3) This reduces the amount of coal fed for a given pressure drop across the calibration coil. As the gasifier pressure builds up, the control gas flow is reduced and finally closed off completely.

Figure 17 is a set of typical flow-control curves used during operation of the coal feeder. These show how, by varying the amount of control gas from 0 to 500 std. c.f., the amount of coal fed, pounds per hour, for any given "delta P" across the calibration coil can be changed.

The amount of conveying gas used per pound of coal varies with the operating pressure used (fig. 18).

Further experiments are being carried out with a device that may make the use of the sightglass unnecessary.[11] This unit, which has been designated a Capacitometer, gives a positive indication of coal flow, which is achieved by measuring the change in capacity of a condenser installed in the feed line. The change in capacity is effected by the variance in the coal - conveying-gas ratio of the flow through the condenser. This effect is transmitted to an oscilloscope and can be used as a positive indication of flow. By combining this unit with the pressure-differential controllers, it is believed that fully automatic control of the flow may be achieved.

For any given size consist of coal that can be fluidized, the weight of coal conveyed per unit of time with given line sizes and pressure drops does not vary more than 3 percent.

OPERATING PROCEDURE

On completion of any tests, the gasifier is opened for inspection, the scrubber base is drained and cleaned, and any equipment item that has not functioned properly is removed for checking. Periodically the steam unit is acid cleaned, and the recycle pumps are inspected for accumulation of dust and evidence of wear in rotating parts. To date it has been necessary to remove the reactant nozzle each time, since, as feed rates and operating pressures are changed, the nozzle requires modification to maintain suitable reactant velocities. Consequently, before each test run, the individual units and the plant as a unit are given a complete pressure test and checked after reassembly.

Preheating is carried out at a pressure slightly above atmospheric, about 1 p.s.i.g. at the gasifier. During the early stages, a steam ejector is employed to exhaust the products of combustion from the scrubber. As the preheating proceeds,

11/ Dotson, J. M., Holden, J. H., Seibert, C. B., Simons, H. P., and Schmidt, L. D., New Method Measures the Solid:Gas Ratio in High-Solid Flow: Chem. Eng., vol. 56, Oct. 1949, pp. 128-130.

this ejector is closed off, and the products of combustion are forced out both the gas-outlet line and the water-outlet line from the scrubber by carrying a low water level in the scrubber, which allows the water-outlet line to serve as a stack.

The temperature of refractory surface in the upper part of the gasifier is brought to approximately 2,200° F. before startup. Because of the rapid loss of heat to the cooling coils, the temperature of this surface at the time the coal and oxygen are introduced is about 1,800° F. At present feed rates 30 to 45 minutes is required after reactant flows are started to raise the refractory to equilibrium run temperatures.

Before startup, the coal in the feeder is fluidized and raised to run pressure, and the batch feeder is pressurized. The steam-oxygen preheater has been raised to temperature with steam flow through the coils, the steam exhausting to the atmosphere. When the heatup burner is shut off, the scrubber and gasifier are raised to approximately run pressure by admitting inert gas at the scrubber, the gasifier sightglass, and the coal-feed line. The inert gas admitted through this last line consists of the sweep gas used to keep the sightglass free of dirt and the control gas (fig. 3) used to temporarily reduce the rate of coal flow at startup.

With the gasifier and scrubber pressurized, steam flow is started to the gasifier at the test rate or somewhat less. Coal feed is started at approximately the test rate or less and the oxygen flow at greater than the test rate, generally at the ratio of 11 cu. ft. of oxygen per pound of coal. This is done to assist in quick ignition and to insure rapid heatup of the refractory to run temperatures.

Because of the rapid pressure rise in the gasifier when the oxygen flow is started, the inert-gas flow to the scrubber is shut off automatically when the oxygen is turned on. The inert-gas flow to the sightglass is reduced at this time to the minimum needed to keep the port open or closed off entirely.

The control gas flow is gradually reduced as the gasifier reaches run pressure and finally is shut off. The amount of inert gas used at the sightglass is about 120 std. c.f. per hour, and the amount entering as fluidizing or carrying gas with the coal is approximately 1.0 std. c.f. per pound of coal, at 300 p.s.i.g.

As gasification proceeds the oxygen and steam flows are adjusted to the desired ratios or, in some of these early tests, to the conditions that appear to be satisfactory as judged by two things:

(1) Maintenance of adequate carbon gasification, and

(2) Maintenance of reaction temperatures sufficient to obtain such gasification without excessive fluxing of refractory.

In these tests it has not been possible to set exact rates for all the reactants in advance for the following reasons:

(1) Lack of exact knowledge as to the relationship of the temperatures as indicated by the thermocouples in the refractory and the refractory face temperature.

(2) Variation, generally increase, in interior volume of the gasifier during the early runs.

(3) Variations in nozzle design between runs.

(4) Variations in type of refractory used for lining the gasifier, which existed up to test 15.

To insure flow of slag it is necessary to maintain the exit gas and ash at about 2,400° F. while not overheating the refractory at the top. Until several short tests have been made and temperature data obtained (both from preheat period and test run), along with examination of the refractory, the temperature gradients cannot be exactly known for control purposes. After experience with the initial lining and the second one of B. & W. 80 Firebrick (fig. 7) two thermocouples were placed in each thermocouple opening, and were designated TC 1-5, TC 2-6, TC 3-7 and TC 4-8. If the refractory should flux or erode so that the thermocouple nearest the refractory surface is damaged, the second can be used for control purposes in future tests, since the temperature gradients will be known. Changes in nozzle design, coupled with varying reactant rates, also complicate the problem of determining correct control temperatures, because these changes affect the location, vertically, of the point of maximum heat release.

Until considerably more data are available on capacity-volume (or, more exactly, capacity and diameter-length) relationships, estimates of maximum feed rates for any volume cannot be set in advance with much precision; therefore, it was necessary to make feed-rate adjustments as the test progressed.

As shown in figures 7, 8, and 9, the refractory has tended to develop and ovoid shape, which reflects the vertical temperature gradient in the gasifier. For any lining, at a given gasifier operating pressure, there is a maximum pressure drop through the slag throat that, at least under our present equipment conditions, cannot be exceeded, because above that pressure differential excessive quantities of gas will be bypassing to the wall, with development of hot spots on the shell.

At the present stage of the experimental work, it has been necessary to arrive at a working balance among all these factors by a trial-and-error method during the early part of the run.

It has been found by experience that it is possible to judge quite closely - within 5 to 10 percent - the probable percentage of carbon gasification prevailing at any given time by examining the residues carried out in the scrubber water and from the spot gas samples. A residue that settles quickly and gives no evidence of carbon black floating on the water indicates high ash content and good gasification.

The heavier slag and ash particles settle in the gasifier base and can be removed periodically from the slag pot. There is some settling action in the scrubber base, and this material can be removed periodically by a device (not shown on flowsheets) similar to the gasifier slag pot.

Most of the remaining fine dust is washed out with the scrubber water. Accurate testing of the dust content of the gas leaving the scrubber has not been possible as yet. Simple impingment tests on filter paper and the nonluminous character of the flare-stack flame shows that the dust content is very low, probably under 5 grains per 100 std. c.f. The material collected in the gasifier and scrubber bases is weighed and analyzed. The water from the scrubber base is measured and sampled, so that the amount of ash and unreacted carbon carried out can be determined.

The make gas is sampled continuously, spot tests for CO_2, O_2, and CO are made with an Orsat on the job, additional spot samples are taken for complete analysis, and a composite sample representative of the entire run is obtained for complete analysis. All of these samples are taken at the outlet of the scrubber.

All inert- or purge-gas streams are metered, and this gas is sampled so that corrections can be made for its use.

All coal fed to the unit is weighed; at the end of the test, the coal feeder is emptied and the remaining coal weighed.

Coal Preparation and Nature of Residues Obtained

For all of the test runs shown, Sewickley-bed run-of-mine coal from the Bunker mine, Monongalia County, W. Va., has been used. This coal was chosen, since it is available in large quantities and has an ash-fusion point that is about average, 2,300° F.

In table 2, page 20, analyses of coals of various batches are given. The coal is prepared by being crushed in a hammer mill to 1/4-inch size and then pulverized in a standard Raymond mill. For these early tests coal of the fine size shown (90 percent through 200-mesh) was used, since it was believed fineness would increase the speed of reaction. Other work on the atmospheric pressure gasifiers has shown that a coarser fuel, minus-20-mesh with about 25 percent through 200-mesh, probably will be satisfactory. As the experimental work proceeds and the equipment construction stabilizes, tests will be made with the coarse grind. Use of 20-mesh fuel would reduce grinding costs considerably.

Representative samples of each batch of coal prepared are obtained at the time it is put through the hammer mill. All coal charged to the feeders for these tests was weighed - placed in drums on platform scales. At the end of each run, any coal remaining in the feeder is discharged to drums and weighed. Tests made on the feeder used for both the atmospheric- and high-pressure gasifiers have shown that coal remaining in feeder can be checked by measuring the "equivalent hydrostatic head." On tests that use over 3 tons of coal, any error introduced by using this measurement to determine the amount of coal remaining is negligible.

The residues that settle out in the gasifier base or slag pot and the scrubber base have been collected and weighed at the end of the test. In future tests the slag pot will be emptied periodically and the material weighed. The residues collected are screened, dried, and analyzed. The results are given in tables 2 and 3 (shown later).

The fine material carried out by the water leaving the scrubber is checked as follows:

(1) The flow rate is measured every 10 minutes.

(2) Samples of the residue-bearing water are taken every 20 minutes.

(3) The filtered residue is composited, weighed, dried, and analyzed.

There is one element of error in this method. In some of the tests the action of the water-letdown valve has been erratic because it jams under the higher pressures. This, of course, has caused periodical release of "slugs" of water and residue, which are not truly representative of the average flow condition. The valve action has been improved, and equipment is being prepared for later tests that will make it possible to collect all the residue discharged in the water.

The representative screen analysis of these residues (table 3) shows that the material is of such size that it can be handled through small plug valves. At higher feed rates the residue might be more like that obtained in slag-tap furnaces. However, it now appears that, if the present method is used (that is, withdrawal of all the gas at the slag port and using fine water spray at that point), the slag obtained will not be difficult to remove from the equipment.