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UNDERFEED COMBUSTION, EFFECT OF PREHEAT, AND DISTRIBUTION OF ASH IN FUEL BEDS

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ILLUSTRATIONS

UNDERFEED COMBUSTION, EFFECT OF PREHEAT, AND DISTRIBUTION OF ASH IN FUEL BEDS[1]

By P. Nicholls[2]

INTRODUCTION

The investigation herein reported is one of a series by the United States Bureau of Mines on the burning of solid fuels to measure reactions in the fuel beds in the burning of the fuel and in the clinkering of its ash. Throughout these studies the object has been to ascertain the burning characteristics while eliminating or standardizing the factors of furnace, chimney, and attendance; thus they have not been concerned with the absorption or utilization of the heat developed by burning of the fuel, but rather with the action of burning.

Research previously reported has been on the "overfeed" type fuel bed—a general designation that includes hand-firing; moreover, the air used for combustion has been at normal temperatures of about 80°.[3] This report covers studies of the underfeed-type fuel bed—exemplified by underfeed stokers—and of the effect of preheated air on what transpires in both overfeed and underfeed fuel beds. Because preheated air is used more commonly with underfeed stokers it was advisable to combine these two objectives in the same investigation; thus underfeed burning became the major feature.

Because the two types of tests were interlocked it is inconvenient to separate them entirely in this report. The method used will be to treat the effect of preheat on overfeed fuel beds by itself and to include the effect of preheat on underfeed fuel beds with the report on underfeed combustion.

PERSONNEL FOR TESTS

This investigation was conducted at the Pittsburgh Experiment Station of the United States Bureau of Mines, under authorization by O. P. Hood, chief engineer, Mechanical Division. The tests were made by M. G. Eilers, associate fuel engineer, assisted by D. T. Rosenthal, junior fuel engineer. The chemical analyses were made in the Bureau's general analytical laboratory at Pittsburgh under the direction of W. A. Selvig and the coal analyses in the coal-analysis laboratory under the direction of H. M. Cooper.

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[1] Work on manuscript completed June 1933.

[2] Supervising engineer, fuels section, Pittsburgh Experiment Station, U.S. Bureau of Mines.

[3] Degrees Fahrenheit used throughout this report.

ACKNOWLEDGMENTS

Acknowledgments are given to the Philadelphia Coke Co., which supplied the coke used for the overfeed tests; and to Eavenson, Alford & Hicks, Pittsburgh, Pa., which supplied the splint coal.

GENERAL SUMMARY

All the arguments and conclusions cannot be summarized briefly, but the following paragraphs outline the main features of the report; other conclusions are scattered through the text, particularly in the section, Application of Results to Underfeed Stokers (p. 62).

The tests of the effect of preheat on an overfeed fuel bed were limited to high-temperature coke because, with the size of coal used in large furnaces, the volatile matter is driven off quickly and the coal converted into coke. The primary conclusions from these tests were:

(1) The preheat increases the rates of reaction so that the oxygen disappears earlier and the percentage of CO in the gases is higher for the same depth of bed; that is, more carbon is gasified per pound of air.

(2) Part of the preheat is used up in this increase of the rate of combustion in the endothermic reaction of converting CO_2 to CO.

(3) Part of the preheat appears in a higher temperature of the gases.

(4) At the rate of primary air used in these tests about 50 percent of the additional sensible heat of the air due to the preheat was used for each of the actions covered by items 2 and 3.

(5) The same relationships held for each of the air temperatures of 400°, 600°, and 800° employed in these tests.

The tests of underfeed burning were made in a 20-inch-diameter refractory-lined firepot. The underfeed burning was obtained by filling the firepot and igniting at the top, giving unrestricted ignition; that is, the plane of ignition could advance downward as fast as it was able with the constant rate of air supply used in each test. The quantity of fuel burned was also free to be whatever the fuel could do with the rate of air supply. It is evident that if the rate of ignition, expressed in pounds per square foot per hour, was greater than the rate of burning in the same units, the thickness of the live fuel bed would increase gradually. If with some thickness of live fuel bed the rate of burning became equal to the rate of ignition, the burning would be in equilibrium, and a fuel bed of constant thickness would travel down until the plane of ignition reached the grates.

The variables investigated were: Kind and size of fuel, rate of air supply, and temperature of air supply—that is, preheat. The fuels used were high-temperature coke, low-temperature coke, petroleum coke, three anthracites, Illinois coal, Pittsburgh coal, and splint coal. The first four represent noncaking fuels, the Illinois is moderately caking, the Pittsburgh heavy-caking, and the splint a tar-exuding coal.

The summary of the results with underfeed burning and unrestricted ignition follows:

1. All fuels showed the same general characteristics, the only distinction being that up to a certain air rate the bituminous coals

closed the openings so that the distribution of air and rate of burning were not uniform over the area of the bed.

2. At low rates of air supply the rate of ignition was greater than the rate of burning; thus the fuel bed did not reach an equilibrium thickness. Under this condition the rate of ignition did not limit the rate of burning.

3. Each fuel reached equilibrium at a certain air rate; and for all higher rates the fuel bed would be in equilibrium, its thickness decreasing with increase in air rate.

4. The rate of ignition did not increase indefinitely with increase of air rate. For the high-temperature coke and anthracite it reached a maximum and then decreased rapidly; for the other fuels it reached a maximum and tended to decrease more slowly. Thus each fuel had a maximum rate of ignition and hence a maximum possible rate of burning that could not be exceeded.

5. The rate of ignition, and consequently the maximum rate of burning attained, increased with decrease in the size of fuel.

6. Preheating increased the rate of ignition of all fuels very materially at all air rates; thus with the Illinois coal an increase from 80° to 300° increased the rate of ignition and the possible maximum rate of burning 97 percent.

7. Caking prevented uniformity of burning up to the air rate which gave equilibrium; for higher rates the fuel acted as free burning.

8. These results bring out the essential difference in the principles of overfeed and underfeed burning. In the overfeed the only limit to the rate of burning is that the fuel shall not be blown out of the bed, and—except for the limitations imposed by loss of heat from the fuel bed by radiation—by increasing the depth of the bed the combustible gasified per pound of air can be made the maximum the air will carry. In the underfeed the maximum rate of burning for each rate of air supply is fixed by the rate of ignition, and these two factors automatically fix the thickness of the fuel bed and the combustible carried per pound of air.

Studies were also made of the process of ignition and of burning in underfeed beds, both with high-temperature coke and bituminous coal. They show that ignition is rapid when it once begins and that at high rates all the volatile matter is driven off in the first 3 inches of the live fuel bed.

An analytical study of the distribution of the ash and clinker in fuel beds shows the difference between the two methods of burning. The time it takes a piece of fuel to pass through the live bed is 4 to 5 times longer in an underfeed than in an overfeed bed of the same depth and rate of burning. Moreover, the quantity of ash and clinker which accumulates in an underfeed fuel bed is several times as great as in an overfeed bed operating under the same conditions.

These results are applied to deduce what happens in stokers. No attempt is made to analyze the series of complex reactions in large stokers because there are no data from which the paths of the various streams of coal can be predicted; therefore only the bed of a simple-type stoker is used for illustration. The factor of restricted ignition—that is, restricted rate of fuel feed—is introduced, and it is shown how the diagrams obtained from the test data can be used to picture what probably happens in a stoker. Especial emphasis is given to the deductions that can be made from the data obtained with preheat.

PART I. EFFECT OF PREHEAT ON OVERFEED FUEL BEDS

OBJECTS OF TESTS

The investigations were restricted to studies of the effect of the preheated air on the combustion in the fuel bed and did not include the economy or desirability of preheat or even its effect on combustion above the fuel bed, except insofar as the latter can be deduced from the composition and temperature of the gases leaving the fuel bed without and with the use of preheated air.

Although numerous papers and reports have been published on the effect of preheat on the over-all operation of furnaces and on economy, no record was found of any detailed studies of its effect on combustion. Reports have referred to the increased clinker formation caused by preheat and the limiting of preheat temperature because of clinker troubles or increase in the cost of upkeep of the stoker parts, but it can be understood that there would be little opportunity to measure the effect of preheat on combustion in the fuel beds of the furnaces of boilers or other service applications.

The over-all effect of the preheat on a fuel bed is given by the change in the composition and temperature of the gases leaving the bed. It can be predicted that the rate of reaction in the bed will be increased and that, in consequence, the rate of burning will be increased for the same depth of bed and the same rate of air supply. If a fuel bed is deep enough the endothermic reaction of the conversion of CO_2 to CO occurs. If the formation of CO is increased by the preheat, some of the sensible heat of the preheated air will be absorbed, and the increase in temperature of the gases leaving the fuel bed will be less than that which would be computed from the preheat added; of course, even supposing there were no increase in CO, the increase in temperature of the hot gases would be less than that of the air supplied because of the increase in the specific heat of gases with temperature.

A further cause for the loss of some of the preheat will exist if the clinkers or ashes leave the system at a higher temperature than they would without preheat.

It was evident that the differences in the quantities to be measured would be small and therefore all auxiliary conditions of test would have to be identical and measurements accurate. Even with closest regulation it is very difficult to get two burnings to give exactly the same result, particularly with fuels that cake. Considerable experience had been acquired in the study of fuel beds in connection with determination of the combustibility of cokes;[4] moreover, coke forms the main part of the bed, even when coal is burned. It was therefore decided to follow the same method and, as a begining, to use coke as a fuel, as the principles involved could be determined more easily and illustrated better by a fuel free of volatile matter.

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[4] Nicholls, P., Brewer, G. S., and Taylor, Edmund, Properties of Cokes Made from Pittsburgh Coals: Proc. Am. Gas Assoc., 1926, pp. 1129–1143. Nicholls, P., Study of Cokes from various types of plants Using Pittsburgh Coal: Proc. Am. Gas Assoc., 1928, pp. 1127–1136.

APPARATUS USED

Figure 1 shows the set-up used. The furnace was of welded construction, with refractory lining. The inside was 20 inches in diameter and 44 inches high from the grate bars. Twenty-six half-inch-pipe sampling holes were scattered around the circumference at 1½-inch intervals from the grate level. The air was supplied by a fan capable of giving 9-inch pressure; the air passed through a measuring orifice, and the quantity could be regulated closely. The preheater was built especially for these tests and designed to give up to 1,000° preheat with the maximum estimated quantity of air. To cover the large range in the quantity of preheat required it was necessary to use two sizes of premix gas burners. The gas was burned in a combustion chamber with checker brick to avoid impingement of flame on the preheater tubes. The temperature of the hot gases was controlled by the addition of air so that it would be the minimum above the preheat temperature. The air leaving the preheater passed through a mixer before it entered the ashpit. Its temperature was measured by a shielded thermocouple at a position of high velocity.

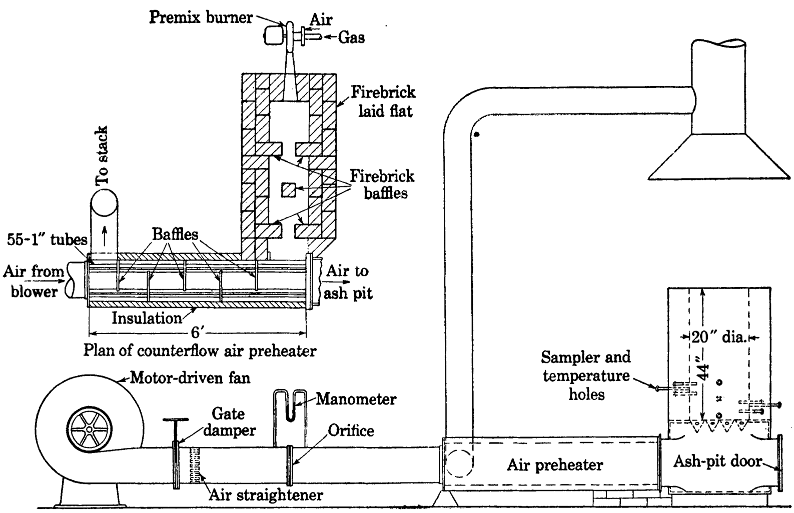

FIGURE 1.—Diagram of furnace assembly.

The Bureau's standard water-cooled gas samplers were used for insertion into the bed through the various sampling holes. Fuel-bed temperatures were taken by an optical pyrometer. All gas samples and temperature observations were taken 1 inch from the vertical axis of the furnace. Other instruments and measurements were of standard type. The samples of gases taken from the fuel bed were stored over mercury and analyzed later.

TEST PROCEDURE

The procedure was essentially the same as that used in the combustibility tests, cited previously; a very rigid specification was followed to insure duplication of conditions, and the specification is given in full in appendix I. It consisted in building up a fuel bed to 24-inch depth, allowing it to come to equilibrium of burning, and then maintaining it at that depth during the periods when measurements were taken.

Three complete sets of gas samples and other measurements were taken during one test, and the bed was restored frequently to its standard condition at fixed times. The samples were taken one at a time, starting at the top of the bed so that the portion below the sampling position was not disturbed beforehand.

The coke used was made by the Philadelphia Coke Co. in Koppers ovens, using a mixture of 80 percent Powellton seam coal and 20 percent Pocahontas coal. It was crushed and carefully screened to 1- to 1½-inch square mesh. Its analyses and properties were:

Proximate analysis:	*Percent*
Moisture	0.6
Volatile matter	.7
Fixed carbon	91.3
Ash	7.4
	100.0

Ultimate analysis:	*Percent*
Hydrogen	0.5
Carbon	89.5
Nitrogen	.9
Sulphur	.7
Ash	7.4
	100.0

Softening temperature ° F. 2,730
Weight per cubic foot of 1- to 1½-inch size pounds 31.8

RESULTS OF TESTS

Four air temperatures were used, 80° (normal), 400°, 600°, and 800°.

Figure 2 shows the values of the CO_2, CO, O_2, and N_2 in percent by volume against the height of the fuel bed, as well as the temperatures by optical pyrometer. Each point is the average of the nine sets of readings. A few gas-analysis values were rejected because they showed internal evidence of errors in the sampling or analysis. The water vapor is not plotted; from the analysis of the coke its value would be 0.7 percent by volume. Some producer action of the water vapor in the air and from the coke also may have occurred; it was not considered worth while to include the extra precision and labor necessary to check these factors. The portions of the curves in the first 1½ inches of the bed below the first sampling position are drawn arbitrarily The largest variations between individual observations occurred with the first two sampling positions because these are affected most by pieces of clinker, although the attempt was made to remove all the clinker each time the bed was brought back to standard.

The curves are drawn to the test points, and their relative shapes could be improved by deductions from computations. In spite of the care taken to have conditions uniform throughout the tests individual values for any one position sometimes differed materially and unduly influenced the average value for that point; yet the positions of the curves are logical, and the plots give a definite idea of the effect of the preheat and what becomes of it.

Because the fuel bed was kept compact and clear of ash the curves are more foreshortened than they would be if the same fuel were burned without the attendance it received in these tests; that is, the curves would be spread out more, and a deeper fuel bed would be required to reach the same final values. If the coke were smaller the curves would be shorter than shown in figure 2 and lengthened as the size of the coke increased.

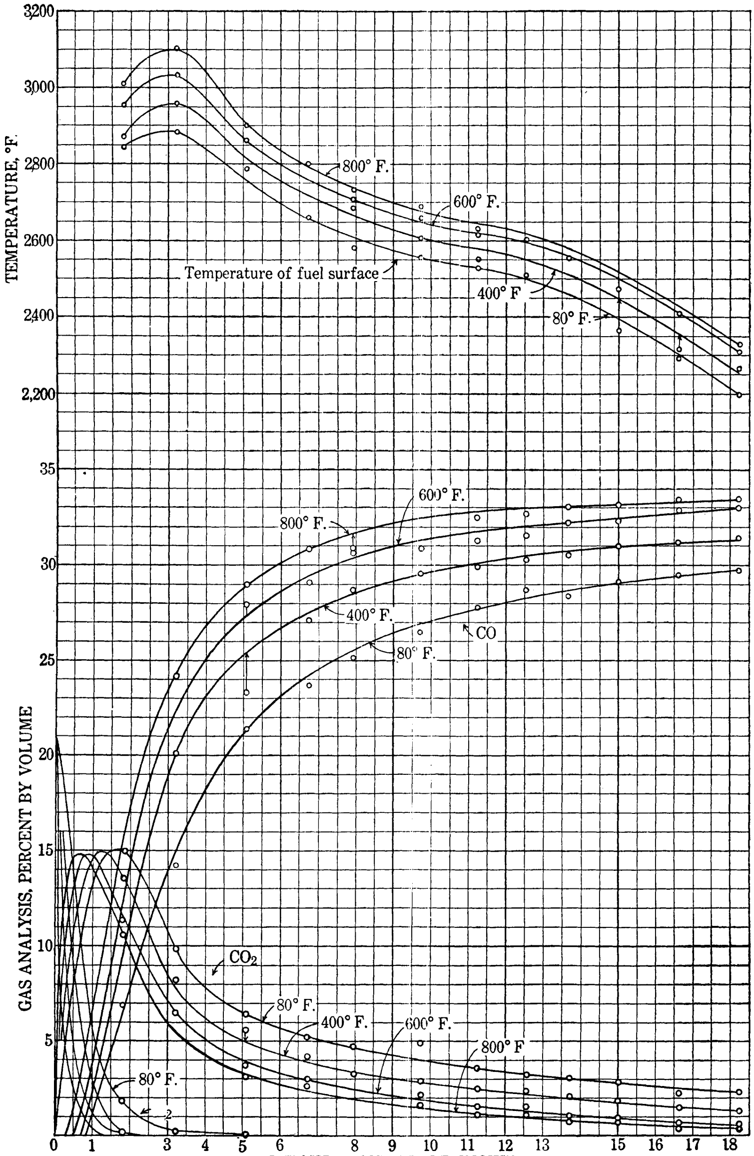

FIGURE 2.—Effect of preheat on gas analyses and fuel-bed temperatures of overfeed fuel bed of high-temperature coke.

Inspection of figure 2 shows that the preheat increased the rapidity of the actions at the lower part of the bed so that they occurred earlier, and the oxygen disappeared in a shorter distance as the preheat increased; there was no oxygen at the 1¾-inch height in any samples with 600° and 800° air temperature. The increase of the reactions caused by the preheat, as indicated by the distance between similar curves, decreases with height and tends to become constant.

Preheat, therefore, in addition to adding a definite amount of heat also acts as an accelerator in causing more rapid combustion and the burning of a greater weight of fuel per pound of air. The increase in fuel gasified will depend on the depth of the fuel bed and will decrease as the depth of the bed is greater; this subject is discussed more fully under Heat Balances.

Figure 3 shows the total carbon and hydrogen content of the gases per pound of air. The rate of burning is proportional to the carbon content; the dotted line will be referred to later.

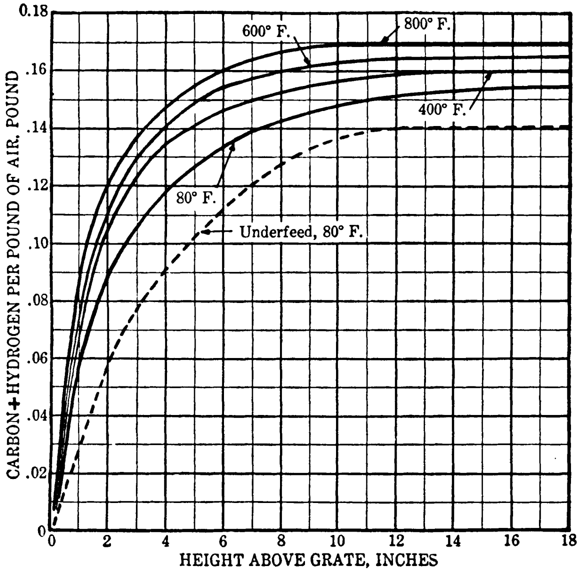

FIGURE 3.—Overfeed burning, high-temperature coke; effect of preheat on total combustible in gases.

The results illustrate the principles of the effect of preheated air in a very thick fuel bed. The order of the effect on a 10-inch-deep fuel bed, for example, could be deduced by taking the values at the 10-inch height. The actual values by gas analysis and by temperatures would be somewhat lower, however, because of the loss of heat by radiation from the top of the bed and by the quantity of heat required to raise the temperature of the incoming coke, assuming that it is fed in continually at a rate equal to the rate of burning.

The values in figures 2 and 3 are based on samples and temperatures taken at the center of the bed and therefore depict the actions in a uniform bed free from holes or cracks or the effect of side walls. In service these factors are always present and reduce the average combustible in the gases below that which would be predicted from figure 3 for a given depth. Moreover, ash and clinker would always be present in service and would increase the apparent depth. One can, however, use figure 2 to predict with fair accuracy the relative rate of burning that will result from maintaining fuel beds of various depths.

HEAT BALANCES

A more detailed explanation of the action of preheat necessitates considering each reaction. The initial reaction of the oxygen of the air combining with the carbon, as expressed by $C+O_2=CO_2$, is exothermic; consequently, any additional sensible heat in the air because of preheat will remain as such. During this reaction an increase in the temperature of the air accelerates the rate of reaction, so that more CO_2 is produced for the same depth of fuel traveled over. If this were the only reaction, all the sensible heat of the preheat would remain as sensible heat. However, fuel beds are usually so deep that all the oxygen is used up and CO is present, and for this argument it can be considered that the CO is formed by the reaction $CO_2+C=2CO$. This is an endothermic reaction—that is, one that absorbs heat—and if it occurs to a greater extent with an increase of the temperature of the air, then some of the additional sensible heat of the air will disappear.

Hydrogen in the fuel can be neglected because there will be very little, if any, at the lower part of an overfeed fuel bed. Water vapor in the air may play some part; if the higher temperature, because of preheat, causes more dissociation through $2H_2O=2H_2+O_2$, the O_2 released will combine with the carbon and there will be a net loss of sensible heat.

Figure 2 shows that the effect of the accelerating action gradually disappears along the height of the bed, and the difference between the CO contents for a given difference in air temperature tends to become constant.

In planning these tests it was not the original intention to make a heat balance by computation, because exactness would have required complete gas analyses which would have increased the time required over 50 percent. However, such computations were made, using the latest values for the specific heats of the gases and allowing for the heat contents for the coke and ash. The total sensible heat of the gases, corrected for the solid fuel and ash, at any plane of the bed should equal the heat released, computed from the composition given by the gas analysis at the plane. Actually the results showed a large deficiency in the measured heat for which no complete explanation can be offered. Because all these measurements were made within 1 inch of the center of the bed the outer fuel should act as a guard ring and supply all the heat lost through the walls. That the gases would tend to be mixed as their height increased was expected; the break in the temperature curves at about 12 inches showed that this occurred, but it would appear that conditions were nearly ideal for obtaining a balance in the first 8 or 10 inches of height.

If all the error is in the temperature measurements, those shown by the 80° curve are about 600° too low and those for the other curves still more in error. The temperatures of the gases may be higher than those of the surfaces of the coke, but not to that extent. Certainly the action of the temperature of fuel beds on the ash of the coal does not indicate that it can be as high as 3,600°.

Other suggestions can be offered, but no one of them would account for the large discrepancy. It was not within the scope of this investigation to try to solve this difficulty, because it was planned only to obtain such a general idea of the action of preheat as is required in service. This problem has therefore been left for the future and will require more concentration on this one phase.

Further computations were made to compare the difference between the heat content of the gases at different temperatures of the primary air. This might be expected to eliminate at least partly the factors that affected the computations of the true heat content. The differences between the heat content with 80° and 600° air temperature were compared with the difference between the sensible heat of the entering air. Figure 4 shows this comparison. The difference between the sensible heat of 1 pound of dry air plus the moisture conditions of test is 904.6 B.t.u. Taking this value as unity the " sen-

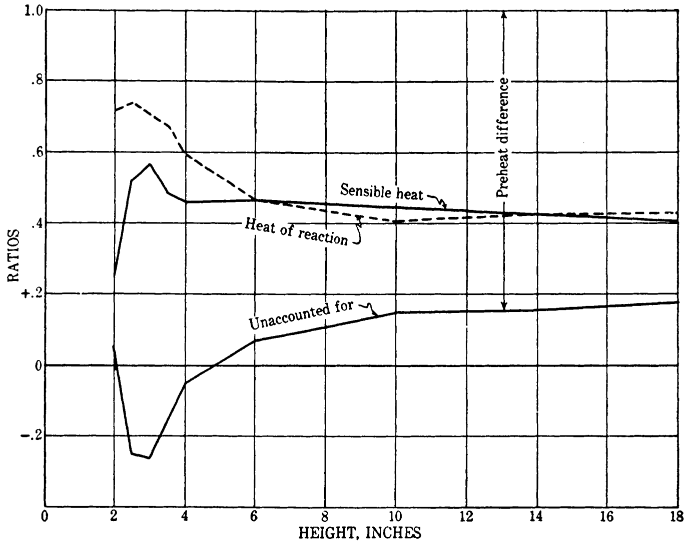

FIGURE 4.—Difference in heat content with 600° and 80° air as ratios of difference in sensible heat in air.

sible heat " curve is the difference between the sensible heat of the gases of the compositions and temperatures given by figure 2, also computed on the 1 pound of air basis. The " heat-of-reaction " curve is the corresponding difference in the quantities of heat liberated in producing the compositions of the gases. The sum of these two curves subtracted from 1.0 is shown by the " unaccounted-for " curve, which is negative below 5 inches and positive above, indicating that some of the sensible heat of the preheat is not accounted for, even when the computations are restricted to comparisons.

Assuming that the unaccounted-for is distributed equally between the two curves, it can be said that 50 percent of the preheat appears as sensible heat and 50 percent in the formation of CO from CO_2, that is, as an increase in the weight of carbon gasified.

FURTHER WORK WITH PREHEAT

The investigation could have been extended to obtain actual values with fuel beds of normal depth; there would be no object in doing this for cokes, but it could have been done for coals. Preheat is used but little with the overfeed-type fuel bed. Such tests with caking coals would necessitate introducing the factor of breaking up the fuel bed; as this operation is difficult to standardize, the accuracy of results would be affected. If such tests had been made it probably would have been of most practical value to have used high-moisture fuels. It was not considered worth while to extend this phase of the investigation but rather to study the effect of preheat on the burning of bituminous coals in connection with the investigation to study the burning of fuels on the underfeed principle.

PART II. UNDERFEED BURNING

PREVIOUS WORK

The principles of overfeed or hand-fired burning are well understood, and there have been many investigations thereon. The fundamental studies were made at the Bureau of Mines by Kreisinger and his coworkers.[5] Although other investigators have not studied the actions at different heights in the fuel bed, all tests of domestic and other small types of furnaces yield over-all data on the principles of the burning of different fuels; but relatively rarely has the effect of secondary air, supplied purposely or by leakage, been eliminated. The Bureau's investigation on the burning of coke [6] extended the study of overfeed fuel beds to the effect of the size of free-burning fuels on characteristics of combustion. A similar investigation has been completed for anthracites.

No corresponding studies have been published of the principles of underfeed burning. There have been investigations of some details of the combustion with underfeed stokers but these give little information on the action in the bed. Houghton [7] removed a section of fuel from a retort and by analyses of various portions determined how far the fuel had been consumed. Others had studied the composition of the gases arising from the fuel bed at various locations. The progress of combustion on a chain-grate stoker was examined rather ingeniously recently by J. D. Maughan,[8] who fed in a wire screen with the coal and when it completely covered the grate quickly withdrew it and quenched the fuel. Analysis of various sections through the bed showed the distribution of the fixed carbon and volatile remaining.

TYPES OF FUEL BEDS

Although the term "underfeed fuel bed" is used in this report, the same principle of combustion occurs in beds to which that term would not apply. The term "up-burning" is sometimes used, but that also is not comprehensive enough. It is therefore worth while to review various types of fuel beds and to connect them with the principles they include. The discussion that follows may be considered somewhat elementary, but at least it insures clarity of thought.

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[5] Kreisinger, Henry, Ovitz, F. K., and Augustine, C. E., Combustion in the Fuel Bed of Hand-Fired Furnaces: Tech. Paper 137, Bureau of Mines, 1916, 76 pp. Kreisinger, Henry, Augustine, C. E., and Katz, S. H., Low-Rate Combustion in Fuel Beds of Hand-Fired Furnaces: Tech. Paper 139, Bureau of Mines, 1918, 54 pp.

[6] Nicholls, P., and Landry, B. A., Coke as a Domestic Heating Fuel: Rept. of Investigations 2980, Bureau of Mines, 1929, 18 pp.

[7] Houghton, Bert, The Burning of Bituminous Coal on Large Underfeed Stokers: Internat. Conf. on Bituminous Coal, vol. 2, 1931, p. 282.

[8] Grumell, E. S., The Evaluation of Fuels from the Consumer's Viewpoint: Jour. Inst. Fuel, vol. 5, August 1932, p. 366.

The type of fuel bed is fixed by the absolute direction of flow of the fuel and its direction relative to the flow of the air; both these can be constrained to move in any direction desired. The ash will flow in the same direction as the fuel independent of gravity unless it becomes fluid, when gravity and the temperature of the zones into which it flows will influence its motion.

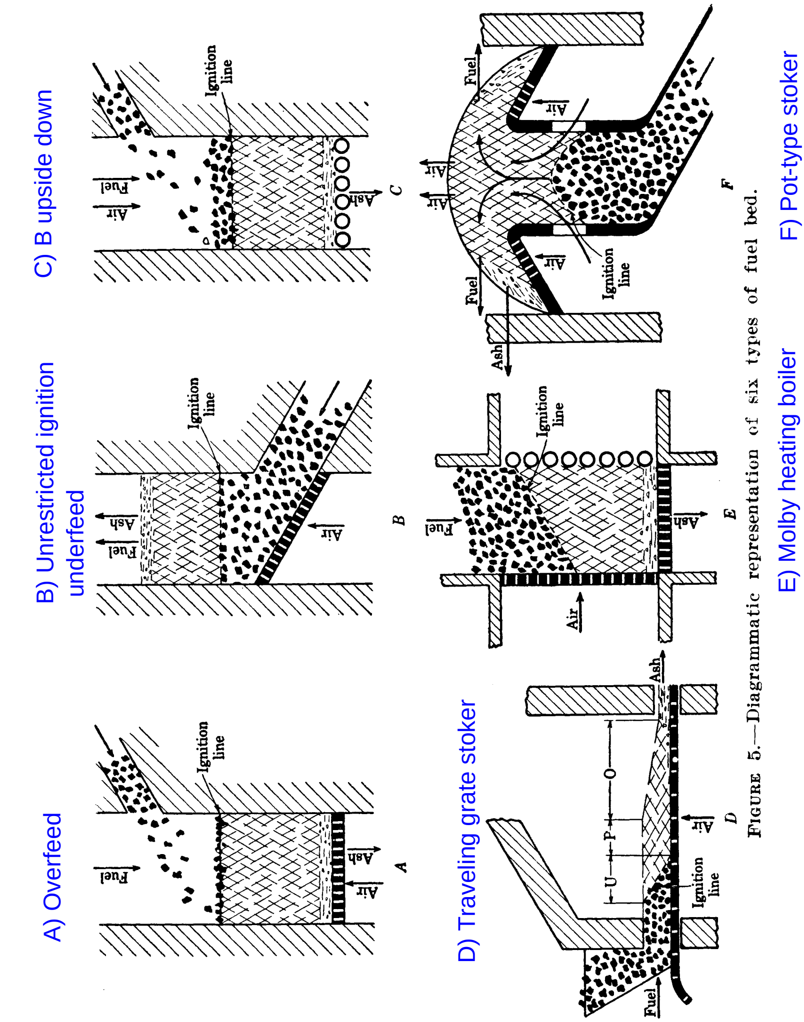

FIGURE 5.—Diagrammatic representation of six types of fuel bed.

Figure 5 shows six possible types of fuel beds. Type *A*, representing hand-firing, is of the overfeed principle. Type *B* shows what the author has termed "the unrestricted-ignition underfeed principle"; both the fuel and air move upward, and the rate of ignition is free to be that fixed by the fuel and the rate of air supply. Type *C* evidently is the same as *B* in its combustion principles but differs in ash disposal; it is illustrated by the Hawley down-draft heating boiler. Type *D*, as representing a traveling-grate stoker, is of interest—length U of the fuel bed is burning on the unrestricted-ignition underfeed principle, length O is burning on the overfeed principle, and some unknown length P is in what the author has termed the change-over state; that is, the burning is adjusting itself because of the cessation of the ignition action. Type E, as represented by the burning in a Molby heating boiler, has some of the underfeed principle at the upper part. Type F represents the pot-type stoker; the burning will be of the underfeed type with restricted ignition.

PURE UNDERFEED BURNING

The term "unrestricted-ignition underfeed" burning used above implies that with a fixed rate of air supply no restriction is imposed which limits the rate at which fresh fuel may be ignited. Thus in figure 5, type B, the fuel is free to ignite, and the level of the line of ignition will rise or fall as the rate at which the coal is pushed in is greater or less than the rate of ignition. In type D no imposed condition limits the rate at which the fuel in length U can ignite, and unrestricted-ignition underfeed burning results; but as soon as the line of ignition reaches the grate bars, the type of combustion changes.

The rate of ignition in type F is controlled, and it can conform only to the definition of unrestricted-ignition underfeed burning when the rate of coal feed equals or is greater than the rate of ignition; in addition, the burning is not completed in the pot. The same arguments presumably would apply to all larger underfeed stokers, with the addition that the motion of the fuel may be much more complex.

EQUILIBRIUM FUEL BEDS

The term "equilibrium fuel bed" is used in connection with the experimental work and requires definition, although the term is self-explanatory. It is used to mean a fuel bed which, for a constant rate of primary air, maintains the same character of combustion and thickness.

In the overfeed, type A, the bed will be in equilibrium when such a thickness is reached that the rate of burning equals the rate of fuel feed. In the underfeed, type B, the bed is in equilibrium when such a thickness is reached that the rate of burning equals the rate of ignition; if the rate of fuel feed in type A—or the rate of ignition in type B—is greater than the rate of burning the thickness of both beds will increase indefinitely.

DISCUSSION OF METHODS OF TEST

Evidently it was desirable to attempt to determine the fundamental principles of underfeed burning—that is, to study a fuel bed as represented by figure 5, type B. The use of a bed such as type F would correspond more nearly to practice; but it would be difficult, if not impossible, to separate the fuel characteristics from the conditions imposed by the particular design of pot used. It was preferable to have a furnace, such as B, in which both the fuel and air would be fed from the bottom, and a number of schemes were con-

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sidered. One of the requirements was that the fuel should be fed uniformly over the area of the bed, which would be difficult to insure without considerable expense for construction. Finally, the same method was adopted as was used in a previous investigation on clinkering.[9]

TLUD The method consisted in starting with a deep bed of fuel and igniting it at the top giving a true underfeed burning and restricting the factors affecting combustion to the fuel and the rate of air supply; for fundamental studies it has the further advantage that the fuel is stationary. It has the disadvantage, compared with forcing the coal in and keeping the burning zone at one position, that the cooling effect of the refractories is greater and the burning cannot be continued indefinitely.

Successful operation, when caking coals are burned in underfeed stokers, depends on breaking up the caked or coked fuel. This is a necessity in practice, yet it introduces a variable difficult to control. Although it was recognized that the caking would affect the burning seriously it was thought advisable to make the first series of tests without disturbing the fuel bed in any way; doing so gave truer measures of the fuel characteristics. When these were known, the breaking-up factor could be superimposed in other tests.

APPARATUS

The set-up was essentially the same as that shown in figure 1, except that a water-cooled cone with a short chimney was used as a top cover to collect the gases so that average samples could be obtained; this cover had a water seal for prevention of inleakage and for ease of removal.

FUEL BED AND OBSERVATIONS

Figure 6 shows how the fuel bed was arranged. The diameter of the pot was 20 inches and the depth of the fuel 42 inches. All fuels were screened carefully to definite size limits, and the furnace was loaded by small increments. Nine thermocouples of no. 28 B. & S. chromel-alumel bare wire were laid in as shown; the junctions were on the center line and were placed in a 1-inch length of small porcelain tubing. The exact height of each junction was recorded by measuring from a crossbar over the top of the furnace. The wires from the junction were run down so that the heat would strike the junction first. The couple leads went to a cold junction and to a switching arrangement by which each could be connected to a portable potentiometer, or one or more connected to a recording potentiometer; usually only one at a time was connected to the recorder.

The fuel was ignited by means of a fixed weight of small charcoal and petroleum coke wetted with kerosene, which was spread over the top of the fuel. The cover was not put on until it was seen that ignition was even over the entire area. In most of the tests the fuel ignited at the first attempt. In a few tests using large fuel the standard quantity of charcoal and petroleum coke was not sufficient, and a second attempt was necessary.

[9] Nicholls, P., and Selvig, W. A., Clinker Formation as Related to the Fusibility of Coal Ash: Bull. 364, Bureau of Mines, 1932, p. 50.

The air rate was maintained constant at a fixed weight of dry air, the pressure drop through the orifice being changed during the test for any material change in the air temperature or barometric pressure. Gas sampling was begun after the cover was put on; the samples were taken continuously over 10- to 20-minute periods, depending on the rate of burning.

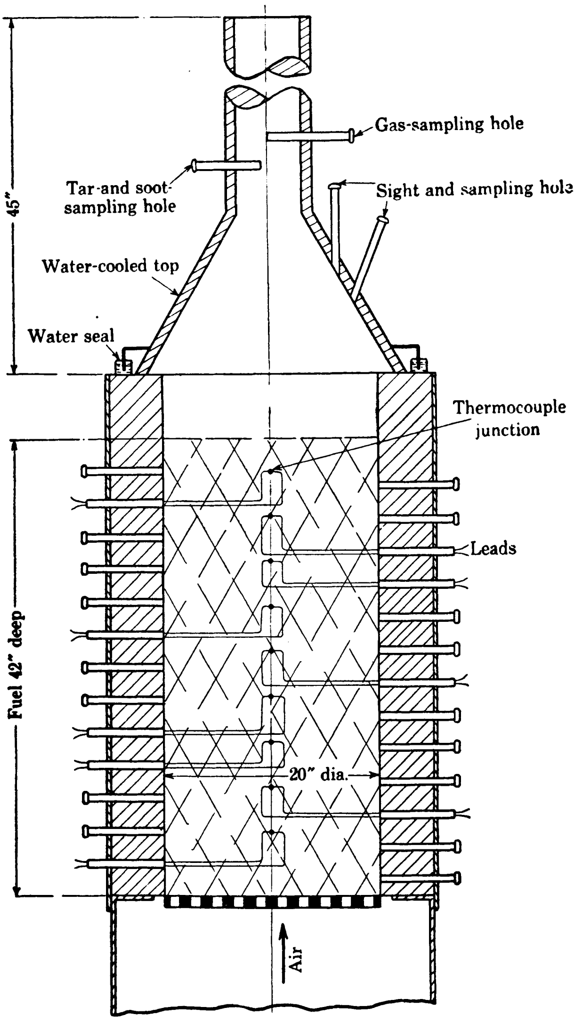

FIGURE 6.—Diagram of fuel bed for underfeed burning tests.

The top couple was connected to the recorder first. When the ignition line reached the couple its temperature would begin to rise, and the record obtained gave a good measure of the progress of the ignition. When the temperature reached 1,378° (the limit of the recorder) the couple was switched to the portable potentiometer and the next lower couple connected to the recorder.

The progress of combustion also was recorded by observations through the 26 sampling holes in the furnace, and the time when the top of the bed or the ignition reached each hole could be fixed very closely.

No gas samples were taken or temperatures measured through the height of the bed of burning fuel during the regular tests, although some special observations were made of the top of the bed through the sampling holes in the cone cover.

The tests with preheat were conducted in the same manner, except for the preliminary period of raising all the fuel bed to the temperature to be used. During this period the couple giving the temperature of entering air and the couples placed at midheight and at the top of the bed were put on the recorder to assist in avoiding excess heating of any part of the fuel.

Each test was continued until the fuel was consumed, except for some tests of bituminous coals in which the caking caused very uneven burning, which made it not worth while to continue. The furnace was allowed to cool, then the residue was examined and measurements taken of the ash and clinker and their combustible content. In a few tests with bituminous coal at low rates the bed was quenched at some stage and the residue carefully pulled apart to determine the progress of caking and coking.

PLOTTING OF TEST DATA

All the main data of each test were plotted as a log, using time as the abscissa. Against height above the grate as the ordinate was plotted the times when each of the thermocouples in the bed reached 30 millivolts (1,378°). In all tests these plots departed very little from a straight line; the slope of these lines gave the rate of ignition in inches per hour, and from the known weight per cubic foot of the fuel as placed in the furnace the rate of ignition in pounds per square foot per hour could be computed.

In the same manner the time when burning was first observed through each of the 26 sampling holes was plotted against height above the grate. These also averaged to a straight line but not so well as did the thermocouples, as would be expected, because the points of observation were distributed around the furnace; the burning observed was that close to the wall, and the travel at the outside edge of the fuel bed was not as uniform as at the center. However, except for tests with bituminous coals at low air rates, not only were the lines straight but closely paralleled the thermocouple lines. Their position relative to the thermocouple line varied and showed whether the ignition surface was convex or concave to the grates; if the lines were not quite parallel it indicated whether ignition tended to travel faster or slower at the sides than at the center.

The position of the top of the fuel bed by observation through the 26 sampling holes was also plotted on the same log. The distance between the top of the bed and one of the ignition lines gave the thickness of the live fuel bed at that time; the thickness of live fuel bed as recorded represents the height between the top of the bed and the thermocouple line, that is, the thickness at the center of the bed.

The flue-gas analyses were plotted against time; from these and the known rate of air supply the rate of burning was computed and plotted. The integral of the rate of burning gave a computed value of total fuel burned which was checked against the known weight of fuel fired, corrected for the combustible in the residue, and the fuel was used for igniting the bed.

The pressure drop between the ash pit and the top of the furnace (that is, the total pressure drop through the live fuel bed and the unignited fuel) was also plotted. Before the test was begun careful measurements of the pressure drop were made both for a standard air rate of 150 pounds per square foot per hour and for that to be used in the test. From the latter and the known position of the plane of ignition at any time the pressure drops through the unignited fuel between the grates and the plane of ignition were computed and plotted. The difference between the two pressure curves gave the pressure drop through the live fuel. A small correction could be made for the height of hot gases between the top of the fuel and the top of the furnace but it is not included in the results as reported.

All these data were plotted on the same sheet and gave a complete log of the test which was very convenient for study and interpretation.

UNDERFEED BURNING OF HIGH-TEMPERATURE COKE

Coke is not burned in underfeed stokers, although it is reported to have been tried in small, domestic, pot-type stokers; in addition, it has been burned on chain grates, and, as shown in figure 5, underfeed burning occurs in a portion of the bed. In spite of this lack of application in service, high-temperature coke was used for the first, and also the most complete, set of tests of underfeed burning. Coke is the most convenient fuel to use in investigating principles of burning because it eliminates the uncertainty of size of pieces when one has to break up a caked or coked fuel, because the bed does not have to be disturbed by poking, and because the cost of the tests is reduced very much in that the gas analyses can be made much more quickly and in a water Orsat.

The primary factors to be investigated were: (1) Rate of air supply; (2) size of coke pieces; (3) temperature of primary air—that is, preheat. A series of tests was therefore planned that would give enough data to permit fairly complete plots being made; the first set was conducted at normal air temperature.

The high-temperature coke used in these tests was made from no. 8 Pittsburgh seam by the Lowell Gas Light Co. in horizontal through retorts; its properties have previously been reported.[10]

Ultimate analysis:		*Percent*
Hydrogen		0.6
Carbon		88.8
Nitrogen		1.1
Oxygen		.6
Sulphur		.6
Ash		8.3
		100.0
Ash-softening temperature	°F	2,730
Weight per cu. ft. of the 1 to 1½-inch size	pounds	26.8
Pounds of fuel per pound of combustible	ratio	1.12

[10] Nicholls, P., Brewer, G. S., and Taylor, Edmund, Properties of Cokes Made from Pittsburgh Coal in Various Plants: Proc. Am. Gas Assoc., 1926, pp. 1129–1143.

The rates of combustion throughout this report are expressed in terms of the available combustible in the fuel, as this eliminates the variations in the incombustible and permits more direct comparison of results.

METHOD OF PLOTTING RESULTS AND THEIR MEANING

The sizes of coke adopted as standard were those between the square-mesh screen sizes of ½ to 1, 1 to 1½, 1½ to 2, and 2 to 2½, all in inches. The air rates were kept constant during each test.

To understand the meaning of the results it is better to consider first those for one size of coke. Figure 7 shows plots of the data for 1½- to 2-inch coke. A detailed explanation and some study will be required to interpret their meaning; because the same method of presenting data is used for other results, they will be discussed at some length.

The abscissa is pounds of dry air per hour per square foot of grate surface. The left ordinate scale is pounds of combustible (carbon+hydrogen) per hour per square foot of grate surface. The test points are shown, and the curves beyond the range of the points are dotted. The two main plots are the rate of ignition and the rate of burning of combustible. The light-line portion—*cb*—of the ignition curve means that it is for ignition only; the heavy-line portion—*bd*—means that it is part of both the ignition and the rate-of-burning curves. The rate-of-burning curve is thus *abd*.

Considering these two curves, they show that at 100 pounds air rate the rate of ignition is about 21.5 pounds per square foot per hour, but that the rate of burning is only 12 pounds; therefore the coke at the bottom of the burning zone is being ignited at a faster rate than the coke above it is burning (being gasified), and consequently the thickness of the burning zone is increasing continually. At an air rate of about 200 pounds the rate of burning is the same as the rate of ignition, so that the live fuel bed will maintain constant thickness. At air rates greater than 200 pounds the rate of burning could increase along a continuation of line *ab*, but it cannot be greater than the rate at which the fuel is ignited, consequently it does the best it can and follows rate-of-ignition curve *bd* which—for this fuel—increases a little at first, reaches a maximum at 250 pounds of air, and then decreases with further increase of rate of air supply.

The ignition curve indicates that at high rates of air the rate of ignition tends to approach zero; results given later will show that this occurred in some tests, and it was impossible to maintain burning; such occurrences are a common experience and are usually spoken of as blowing the fire out. This falling off of the ignition curve was, as might be expected, more in evidence with the high-temperature coke than with any one of the other fuels tested. The causes for this action are two: First, the fuel is ignited by heat radiated from the hot fuel above; very little of the heating of the fresh fuel will be by conduction; at the same time, the surface of the fuel is being cooled by the air passing over it, which will tend to counteract the heating by radiation; and, after some unknown rate which will vary with the fuel and its size, the counteracting effect will increase more rapidly than the increase in the radiation due to a higher rate of combustion. The second cause is that the fuel bed gets thinner as the air rate increases; after some undefined thickness is attained the temperatures through the bed will decrease, and consequently the radiation will be less.

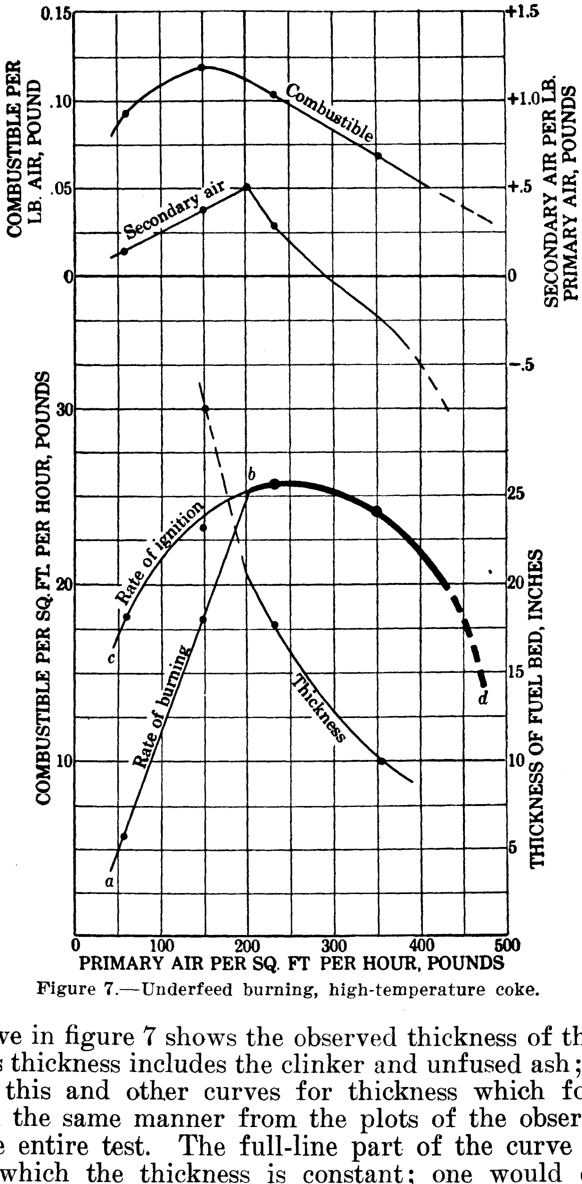

Figure 7.—Underfeed burning, high-temperature coke.

One curve in figure 7 shows the observed thickness of the live fuel bed. This thickness includes the clinker and unfused ash; the values given for this and other curves for thickness which follow were selected in the same manner from the plots of the observed values during the entire test. The full-line part of the curve covers the range in which the thickness is constant; one would expect the observed thickness to increase with time because of the accumulation of clinker, but the increase was usually small compared with individual variations due to the method of observation. For these equilibrium beds of constant thickness a mean value was selected.

The dotted part of the curve covers the range in which the thickness is increasing; the height of the bed when the ignition plane reached the grates is used for the thickness in this range.

The two upper curves of figure 7 show the pounds of combustible in the flue gas per pound of air supplied and the pounds of secondary air required for perfect combustion per pound of primary air. The secondary air curve shows that secondary air would be required up to a primary air rate of 280 pounds.

APPLICATION TO RESTRICTED IGNITION

The foregoing results and the interpretations thereof relate to the condition of unrestricted ignition. Commercial underfeed stokers have restricted ignition in the sense that the rate at which the stream of fresh fuel passes into the primary air stream can be controlled. It is worth while at this stage to consider how the data of figure 7 can be applied to *restricted* burning. The following deductions refer to continuous operation, with ability to restrict the rate of feed of the fuel. To understand clearly what follows it should be recognized that in a plot such as figure 7, the vertical scale of pounds of combustible per square foot per hour can be used for rate of coal feed as well as rate of burning and that the rates of feed and burning need not be the same.

(1) To obtain the maximum rate of burning possible with each rate of air supply the rate of feed must follow curve *abd*; no manipulation other than changing the area of the plane of ignition can make the rate of burning continuously exceed the values fixed by this curve.

(2) The maximum rate of burning possible with this coke and this particular size is about 26 pounds of combustible (or 29 pounds of coke) per square foot per hour, and no manipulation can increase it.

(3) The equilibrium thickness of the live fuel bed for rates of air supply above 200 pounds and for the corresponding rate of fuel feed fixed by line *bd* will be those shown by the thickness curve of figure 7. The equilibrium thickness for air rates below 200 pounds and for the corresponding rates of fuel feed fixed by line *ba* cannot be predicted from these tests; they will not be as large as the values indicated by the dotted part of the thickness line, but they will continue to increase with decrease of the rate of air supply.

(4) An equilibrium fuel bed will result when operating at any point within the area enclosed by curve *abd*. An increase or decrease of the rate of feed—provided it does not cross curve *abd*—will result in a gradual change to a new rate of burning and thickness of fuel bed corresponding to the new rate of feed.

(5) If an increase in rate of feed crosses curve *abd* the rate of burning will not increase beyond that fixed by curve *abd*; if the rate of feed crosses portion *ab*, the thickness of the live fuel bed will increase continuously; if it crosses portion *bd*, the thickness of the live fuel bed will not increase beyond that for *bd*, but the plane of ignition will gradually be raised by the unignited fuel below it.

EFFECT OF SIZE OF COKE

Figure 8 shows the rate-of-ignition and rate-of-burning curves for the four sizes of coke when air is used at 80°; the test points are shown, and it will be noted that fairly symmetrical curves can be drawn to fit the points. To avoid crowding, the thickness of fuel-bed curves is shown in a separate plot, figure 9.

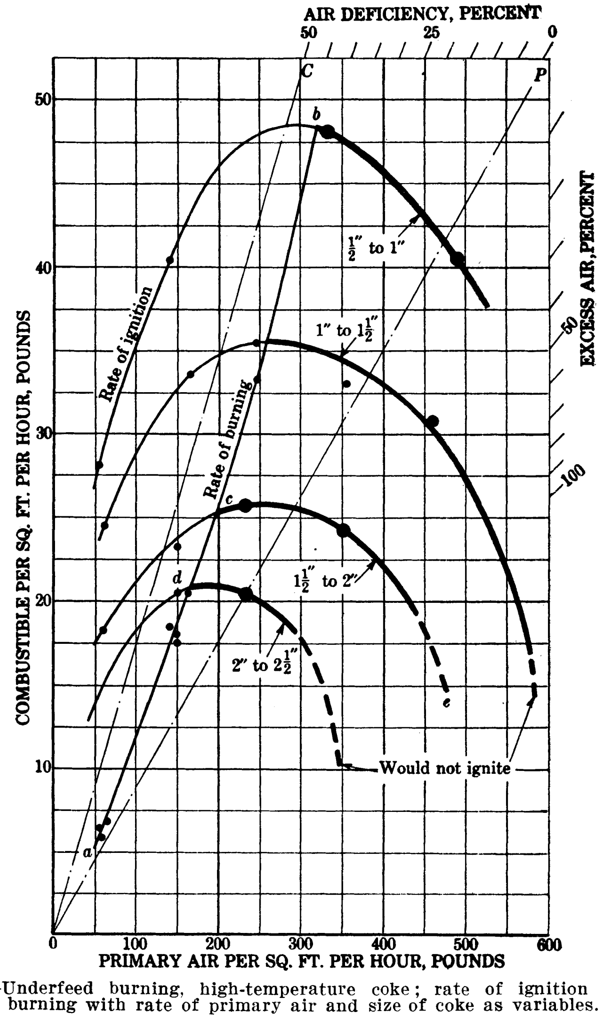

FIGURE 8.—Underfeed burning, high-temperature coke; rate of ignition and rate of burning with rate of primary air and size of coke as variables.

It is of interest that the rate-of-burning curves, before their intersection with their individual rate-of-ignition curves, all fall on a common curve which bends upward slightly for the smaller sizes, as would be expected from previous investigations of the effect of size in overfeed burning.

The figure shows that the rate of ignition increases rapidly with decrease in size, which agrees with common experience when a fire is started in one's home furnace. The relationship, based on the points of intersection of the ignition and burning curves, is of the order shown by figure 10, *A;* the dotted curve will be referred to later.

If the air rates were carried high enough all the ignition curves may be expected to have a shape like that of the 2- to 2½-inch size. An attempt was made to burn this size at an air rate of 345 pounds.

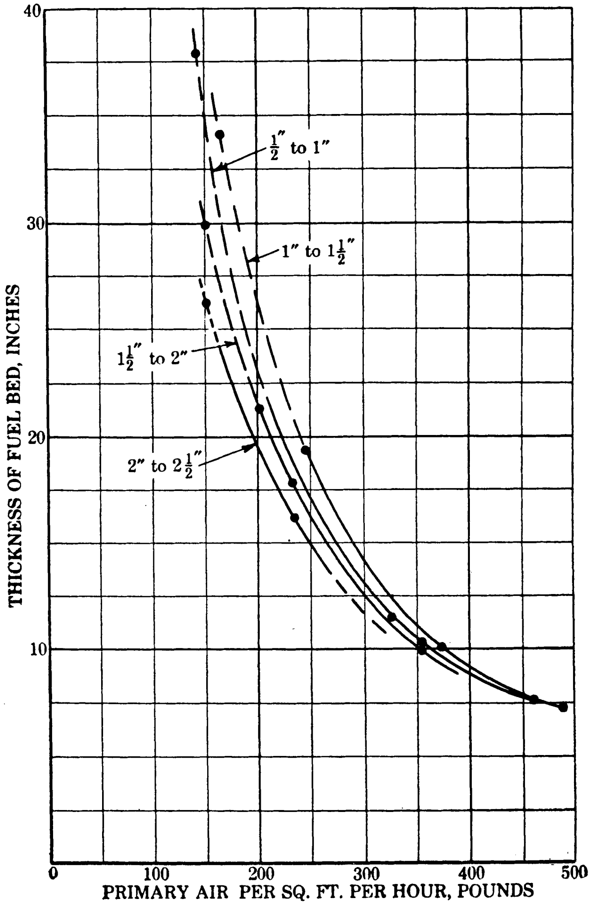

FIGURE 9.—Underfeeed burning, high-temperature coke; thickness of fuel beds, with rate of primary air and size of coke as variables (see fig. 7).

There was difficulty in getting the fuel to start burning; by using larger quantities of igniting fuel and reducing the air rate it was ignited, but when the air rate was increased to the 345 pounds the burning gradually decreased, and finally the fire was extinguished, showing that ignition could not be maintained.

With this fuel, the rates of burning that can be attained are very much affected by the size of the pieces. With the 2- to 2½-inch size the maximum rate of burning possible was 21 pounds, whereas with the ½- to 1-inch size it was 48 pounds, showing a fundamental differance between overfeed and underfeed burning principles; in a hand-fired furnace any size of coke can be burned continuously at any rate by adjusting the air rate and the depth of the fuel bed.

It must be remembered that the curves of figure 8 are for the conditions used in these tests and that the cooling by the side walls affects the results. It is improbable that such cooling influences the rate of ignition materially, but it does lower the average rate of burning because of poorer combustion at the sides. For an absolute value—that is, for a fuel bed of very large area—rate-of-burning line *ab* would be swung somewhat to the left. However it could never cross line *OC*, which corresponds to a dry-gas analysis for this fuel containing only CO and N_2—that is, one with the maximum carbon content.

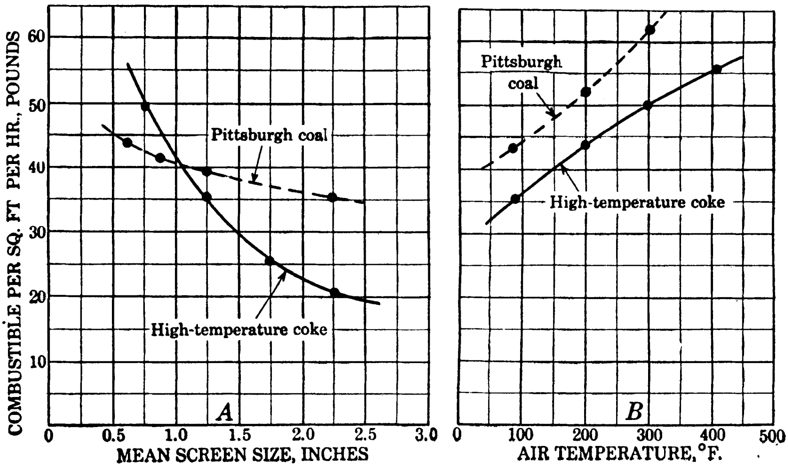

FIGURE 10.—*A*, Underfeed burning, high-temperature coke; rate of ignition against size of coke. *B*, Underfeed burning, high-temperature coke; rate of ignition against temperature of air for 1- to 1½-inch size.

The curves for the pounds of secondary air required per pound of primary air are not shown because this is fixed by the position of each rate-of-burning point on the plot. Line *OC* fixes the theoretical maximum rate of combustion for each rate of air supply—that is, only CO and N_2 in a dry-gas analysis. All points on line *OP* have perfect combustion, that is, all CO_2 and N_2; those to the left of the line require secondary air, and those to the right have excess air. The scales on the top and sides permit the secondary air requirement at any rate of burning to be read.

The scale for excess air is useful in interpreting further the meaning of the plot. Considering the curves for one size of coke—the 1½- to 2-inch, for example—it has .been shown that one can operate continuously anywhere within the area *ace*. Selecting, then, any point of operation—17.5 pounds of combustible per hour and 200 pounds of air, for example—this point fixes the rate of combustion and the fact that there is no deficiency or excess of air because the point falls on line *OP*. Such a deduction is true independently of whether the fuel bed is in a good or bad condition, but it does not show how complete the combustion was; for instance, the dry-gas analysis for this example might be 20.0 CO_2, 0.8 CO, 0.0 O_2, 79.2 N_2, or it might be 12.3 CO_2, 7.8 CO, 3.5 O_2, 76.4 N_2. In the latter the oxygen is available, and whether the CO is burned will depend on the action in the combustion space. A fuel bed which gives the first of the two analyses would be classed as being in good condition because the loss of heat due to free combustible in the gases is reduced to a minimum; the second shows that there were holes in the bed or leakage at the sides. This is elementary and not novel; the same type of diagram could also be used for overfeed burning.

It is also necessary to define the terms "primary air" and "secondary air." Primary air as used in this report means that supplied below the bed. In the method of test employed all the air passed through the plane of ignition and also through all of the live fuel, although even in these tests its distribution over the area of the bed was not uniform. In stokers the distribution of the air is more complex and at moderate ratings the plane of ignition not as definite; however, if a stoker operates continuously with the same shape of bed, the rate of ignition—however we may define or explain that action—must be equal to the rate of burning.

The secondary air in these tests is that which might be supplied and mixed with the gases over the fuel bed. In a stoker some of the air supplied below the fuel bed may not pass through any fuel, so that, correctly speaking, it is secondary air. It seems to be the usual custom to apply the term "secondary air" to that which is purposely supplied over the fuel bed or which leaks through the setting.

If one assumes that in a stoker no air is supplied over the fuel and that it is desired to have 20 percent excess air in the flue gases, one is limited to operating along the 20-percent excess air line of figure 8. If all this air passes through the plane of ignition the maximum rate of burning possible with each size is reduced to the value given by the intersection of each curve with the 20-percent excess air line. Higher rates of burning could be obtained with each size by passing a smaller weight of air through the plane of ignition and supplying some more as secondary air in its meaning as defined above.

Figure 9 shows the thickness of the fuel beds. To interpret the meaning of the relative thickness they must be associated with the corresponding rates of burning as given by figure 7. For equilibrium burning the thickness for a given air rate was approximately the same for all sizes of coke. Two factors influence the thickness—the rate of ignition, which tends to thicken the bed as the rate increases, and the rate of reaction, which tends to decrease it with decrease in size. These two factors approximately balance each other; for lower rates of air supply, the influence of the rate of ignition is somewhat greater than that of the rate of reaction.

It should be remembered that the thickness of fuel bed is that on the center line of the bed but that the burning rate and air rate are averages for the whole bed. The air rate through the center of the bed is less than at the sides, but the pounds of combustible per pound of air are greater than the average; this is discussed more fully in the section, Distribution of Air in Underfeed Burning Tests (p. 37).

The thicknesses given therefore correspond to an equilibrium burning as given by the gases arising from over the center of the fuel bed; because these gases contain more combustible than that given by the analysis of the average of the gases, the thickness given is greater than it would be if the composition of the gases were the same over the area.

This explanation shows why, in figure 8, the 1½- to 2-inch coke with 350 pounds of air has 30 percent excess air; and yet figure 9 shows that the thickness was 10 inches, with which thickness one might expect a deficiency of air.

The same explanation applies to the data that will be given for other fuels, but because high-temperature coke is less reactive at lower temperatures the cooling effect of the side walls dampens the burning there more than with other fuels.

The thicknesses as given are logical because they include the cooling effect of the sides, which is always present with stokers. The thickness at the side wall, or the difference in thickness between that at the center and the side, could be given.

EFFECT OF PREHEATING AIR

The air temperatures used were 80°, 200°, 300°, and 400°. There was no necessity to test all sizes because the characteristics will be similar; therefore only the 1- to 1½-inch coke was used.

Figure 11 shows the results; lines *OC* and *OP* have the same meaning as in figure 8. The parts of the rate-of-combustion curves falling on line *ab* are not affected materially by the preheat; because the same size of coke is used, *ab* has not an upward bend and is closely a straight line to the origin.

The rates of ignition increase rapidly with increase of air temperature. Figure 10, *B*, shows the maximum values plotted against air temperature; at some higher temperature the curve would turn upward very rapidly because at some temperature—probably between 1,100° and 1,200°—the coke would ignite instantaneously.

Figure 11 shows that preheat will have little effect on operation at rates of air supply below that at which the ignition curve meets the burning curve; it increases the rate of ignition but does not affect materially the rate of burning, which is the limiting factor. Above the rate of air supply where the ignition curve for normal air temperature (80°) meets the burning curve (265 pounds of air), preheat permits large increase in the rate of burning with a given rate of air supply but, of course, with the necessity of increasing the secondary air. Thus, with an air temperature of 80°, the maximum rate of equilibrium burning was 35.5 pounds with 265 pounds of air; and, as pointed out previously, no manipulation of the fuel bed, other than increasing the area of the ignition surface, could increase this rate. With an air temperature of 400° the maximum rate of burning would be about 53.5 pounds with 390 pounds of air.

The lower set of curves of figure 11 shows the thickness of the live fuel beds, for which, however, there were not many test points. The full-line portion indicates that the burning is in equilibrium. The fact that for the same rate of air supply the thickness increases with increase in temperature of the air may seem an anomaly at first sight. The explanation is that the increase in the rate of burning occurring with the preheat requires a thicker fuel bed for equilibrium burning; the increase thus required is more than can be offset by the increase in the rate of reaction resulting from the preheat. Figure 2 illustrates this, but to a different scale.

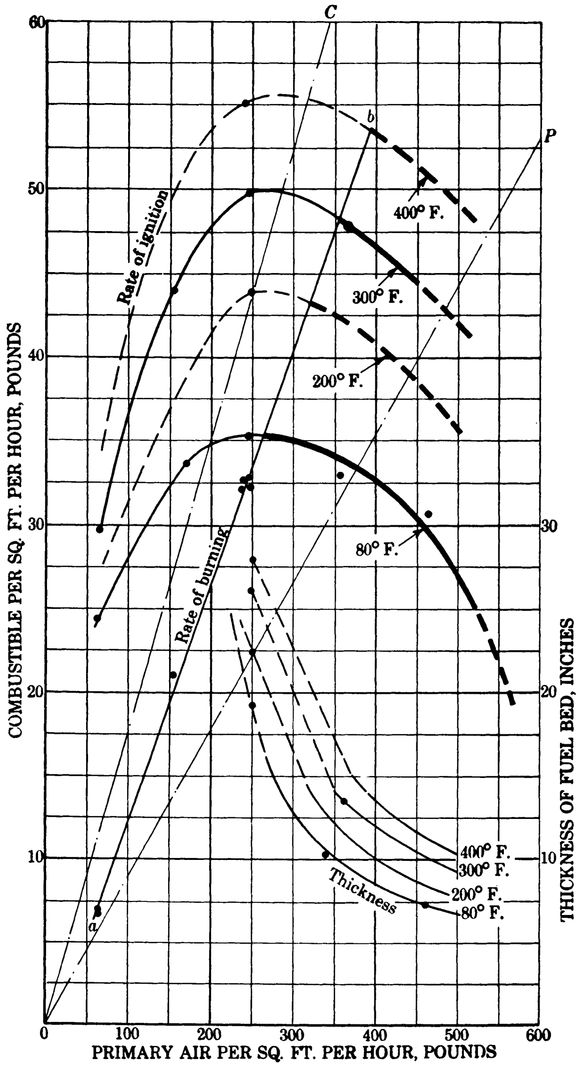

FIGURE 11.—Underfeed burning, high-temperature coke, 1- to 1½-inch size, with rate of primary air and its temperature as variables.

UNDERFEED BURNING OF LOW-TEMPERATURE COKE

Low-temperature coke is a good example of a truly noncaking fuel with relatively high volatile. The coke used was a fairly dense and nonfragile type; its main properties follow:

Proximate analysis:	Percent
Moisture	3.4
Volatile matter	13.7
Fixed carbon	72.0
Ash	10.9
	100.0

Ultimate analysis:	Percent
Hydrogen	3.5
Carbon	73.4
Nitrogen	1.5
Oxygen	9.8
Sulphur	.9
Ash	10.9
	100.0

Softening temperature	degrees	2,721
Weight per cubic foot of 1- to 1½-inch screen size	pounds	28.3
Pounds of coke per pound of combustible	ratio	1.25

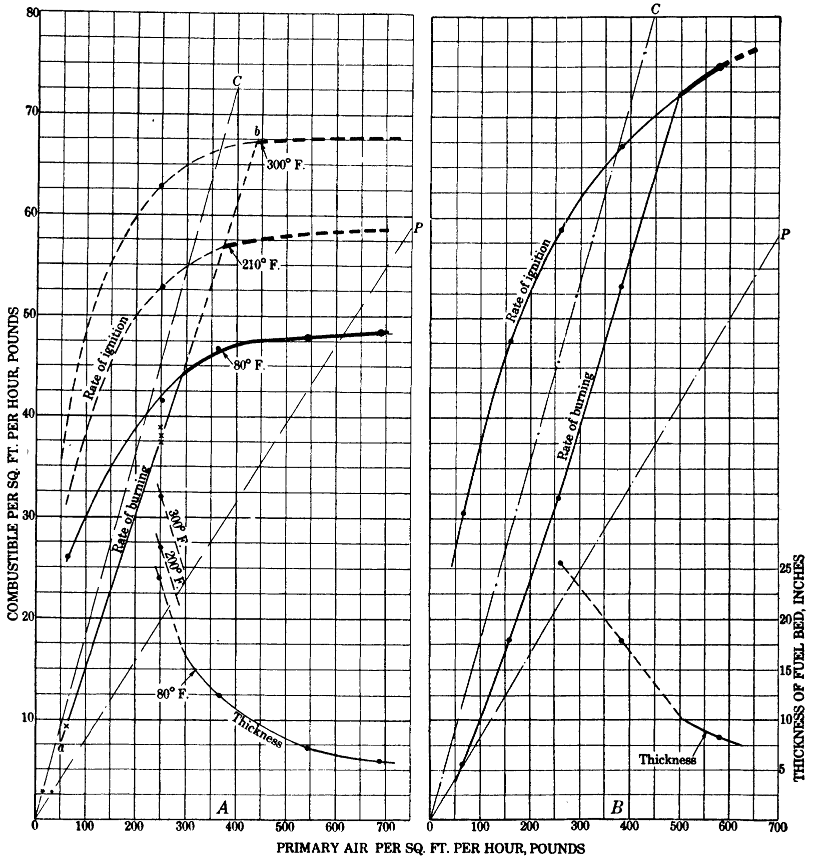

FIGURE 12.—*A*, Underfeed burning, low-temperature coke, giving results for 1- to 1½-inch size, without and with preheat. *B*, Underfeed burning, petroleum coke, 1- to 1½-inch size, 80° air temperature.

The tests made were confined to the 1- to 1½-inch size. The main series were at increasing rates of air supply without preheat; these were followed by single tests at the same air rate but increasing preheat.

Figure 12, *A*, shows the results plotted in the same manner as those of the high-temperature coke. As before, line *OP* is that of perfect combustion for a fuel with the foregoing analysis. Line *OC* shows the maximum rate of combustion, but with fuels containing volatile it does not have the definite position it has with coke because the gases may contain hydrogen, hydrocarbons, and tar and soot, the quantities of which do not depend on the available oxygen. The rate-of-ignition curves for 210° and 300° air are each based on one test point, but their general shapes will be somewhat as shown.

The plots do not differ in general relationship from those of figure 11 for high-temperature coke, and the principles that would be deduced are the same. The slope of rate-of-burning line *ab* is a little steeper than that of figure 11; that is, the gases from the fuel bed contain more combustible per pound of air; the main difference is that the rate-of-ignition curves are higher and do not fall off after they reach a maximum. The air rate was carried to 680 pounds to see whether or not ignition would fall off, but it did not; to have gone higher would have meant blowing fuel out of the bed. The interpretation of this is that the fire with this low-temperature coke cannot be extinguished by a high air rate, as it could with a high-temperature coke.

The increase of the rate of ignition by the same preheat was greater than that with the high-temperature coke. A test with an air temperature of 400° was included, but the coke ignited spontaneously in the center of the bed. This does not mean that the average coke would ignite at this temperature but that exothermic reactions occurred in some individual pieces.

For the same air rate the thickness of the fuel bed was increased by the preheat, as it was with the high-temperature coke.

Although this coke is ignited easily, the principle still holds that its rate of burning by the underfeed method did not exceed a certain maximum, which for the 1- to 1½-inch size, without preheat, was 49 pounds of combustible per square foot per hour; for high-temperature coke of the same size it was 35 pounds.

UNDERFEED BURNING OF PETROLEUM COKE

Petroleum coke was tested because it represents an ashless fuel. The tests made were limited to a series using the 1- to 1½-inch size and air at 80°.

The properties of coke were as follows:

Proximate analysis:	*Percent*	Ultimate analysis:	*Percent*
Moisture	2.0	Hydrogen	3.5
Volatile matter	6.7	Carbon	90.3
Fixed carbon	90.8	Nitrogen	1.1
Ash	.5	Oxygen	3.4
		Sulphur	1.2
	100.0	Ash	.5
			100.0

Softening temperature	degrees	1,792
Weight per cubic foot of 1- to 1½-inch screen size	pounds	22.6

Figure 12, *B*, shows the results of tests at five air rates. The plot shows that not only did the rate of ignition exceed that of any other fuel tested but that it was still increasing at the maximum air rate used—560 pounds. With 560 pounds of air per square foot per hour, the rate of ignition was 75 pounds of combustible; the next highest, low-temperature coke, had 48 pounds for the same size and air temperature (see fig. 12, *A*).

The absence of ash would not be expected to increase materially the rate of ignition, because at the time and in the location of ignition no ash is released. However, the nature of the ash may cause it to be an accelerator because it lowers the ignition temperature of soot.[11]

UNDERFEED BURNING OF ANTHRACITE

For industrial purposes anthracite is not burned on large underfeed but on traveling-grate stokers. On the other hand, stokers for burning anthracite in heating boilers and domestic warm-air furnaces are more commonly of the underfeed type.

Because small sizes of anthracite are used for both industrial and domestic stokers, it would have been useful if the effect of size could have been determined. However, the immediate purpose of this investigation was to study principles, and therefore the tests were confined to the 1- to 1½-inch size, so that the results would be comparable with those for the other fuels.

Pennsylvania anthracite from three different mines was used, but only limited amounts of these were available from another investigation. The first objective was to determine what relative values for ignitibility this method of test would give so that these data could be used in the other investigation.

One test was made with each of the three anthracites; they were burned under the same conditions of using the 1- to 1½-inch square-mesh screen size, 240 pounds of primary air per square foot per hour, and normal air temperature of 80°. The main data and results are given in table 1.

TABLE 1.—*Underfeed burning, anthracites*

Item	1	2	3
Volatile matter .... percent	3.2	3.8	8.3
Fixed carbon .... do	82.5	79.4	78.3
Ash .... do	11.0	13.2	12.2
Weight per cubic foot, 1- to 1½-inch size .... pounds	53.0	51.2	46.3
Primary air, per square foot per hour .... do	240	240	245
Rate of ignition, per square foot per hour .... do	27.4	27.8	39.2
Rate of burning, per square foot per hour .... do	27.4	27.8	37.0
Thickness of fuel bed .... inches	15.0	15.7	10.5

Anthracites 1 and 2 both burned with equilibrium beds, because in each test the rate of burning equals the rate of ignition. The rate of burning of anthracite 3 was less than its rate of ignition; therefore the air rate was too low to give equilibrium. This measure of ignitibility shows that anthracite 3 was 43 percent more easily ignited than anthracites 1 and 2, the ignitibility of which did not differ materially, although the small difference between them was in the direction that would be expected because of the higher volatile content of anthracite 2.

[11] Nicholls, P., and Staples, C. W., Removal of Soot from Furnaces and Flues by the Use of Salts or Compounds: Bull. 360, Bureau of Mines, 1932, p. 28.

35093°—34——3

Figure 7 shows that the same size of high-temperature coke at the same air rate of 240 pounds had an ignition rate of 35.5 pounds and a burning rate of 33 pounds—4 pounds less than the values for anthracite 3. These comparisons are on the weight-of-combustible basis; to the eye the coke would appear to ignite 1.5 times faster than anthracite 3; that is, the plane of ignition of the coke travels faster because of the relative density and ash content of the two fuels.

A series of tests was also made with several rates of air supply. The previous tests had shown that anthracites 1 and 2 were very

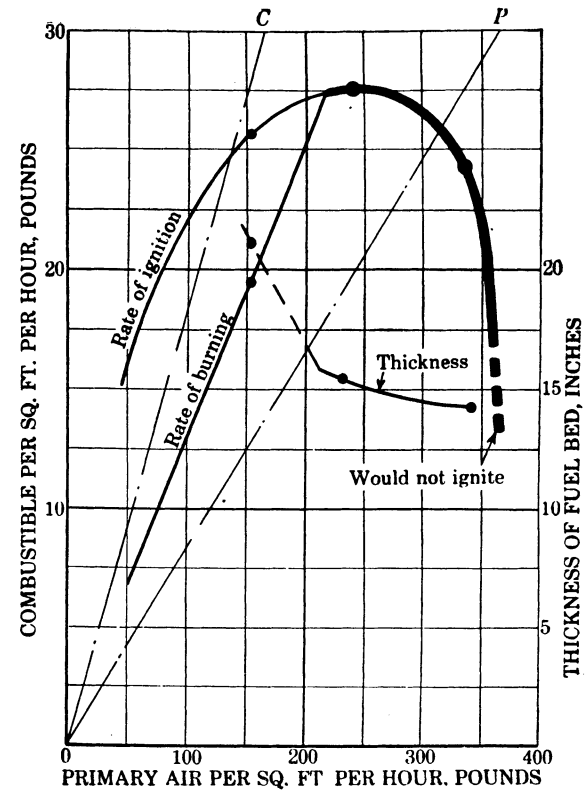

FIGURE 13.—Underfeed burning of anthracite containing 3.5 percent volatile matter, 1- to 1½-inch size, 80° air temperature.

similar and were representative of Pennsylvania anthracite as commonly sold. As there was not enough of either for the series they were mixed in the proportion of 40 of anthracite 1 to 60 of anthracite 2. The tests were made with the 1- to 1½-inch size and air at normal temperature.

Figure 13 shows the results. The curve for the rate of ignition is of the same shape as those of figure 8 for high-temperature coke but shows lower values than did the same size of coke. A test was run at 370 pounds of air, but combustion could not be maintained; one with 330 pounds was successful. This is a narrow range, and therefore the rate-of-ignition curve falls off very rapidly, as is shown in the plot of figure 13. Comparison of the curves for the rate of ignition of anthracite and coke is given later on the same plot in figure 18, *A*.

UNDERFEED BURNING OF BITUMINOUS COALS

It was realized that more difficulty would be experienced in obtaining reliable data with coals which fuse and cake, but earlier tests [12] had shown that they could be burned with equilibrium fuel beds by igniting the bed at the top, provided the air rate was high enough and the coal of uniform size.

The troubles, caused by uneven burning, that were experienced in the individual tests will not be described, but they can be summarized as follows: In tests at low rates of air supply the plane of ignition advanced downward at such a rate that the tar exuded from the coal was not consumed and thus would tend to close up the air spaces; or the surface of the coal pieces would not be burned away rapidly enough to make up for the swelling, consequently the spaces were closed. Either of these actions is cumulative because, as the spaces began closing, the air would divert from the center, and thus the quantity passing through the center would be reduced, further reducing the rate of burning and allowing more closing of spaces. As the air rate was maintained constant, that passing up the sides would be increased; or sometimes a hole or channel would develop along the sides, which might be straight but usually was somewhat spiral.

At some rate of air supply the bed would burn uniformly and act in the same manner as the cokes. Tests could not be made with the rates close enough together to determine the exact rate at which this change occurred; but it appeared to be comparatively sudden, as would be expected from the cumulative action mentioned. Uniform and free burning can be interpreted to be such a rate of air supply over the surfaces of the fuel that all volatile matter is burned as soon as it is evolved, or in which the rate of burning is greater than the rate of swelling. Although the bed as a whole acted as if the fuel were free burning, yet it would be expected that some of the pieces would fuse together, so that the average size of the pieces would be larger than that of the original coal.

Good data could be obtained in the tests in which the rate of air supply gave equilibrium burning, but in the tests below this rate there was no certainty as to the air rate to use as corresponding to the ignition given by the test, except that it should be lower than that of the known air supplied; moreover, the rate of burning computed from the gas analysis was not representative of the whole fuel bed.

All the coals were crushed and screened over square mesh to definite sizes; some sizes used were larger than would ever be employed in underfeed stokers, but to facilitate generalization it was desired to obtain data that could be compared with those of the cokes.

Table 2 lists the properties of the bituminous coals tested. When different sizes were used the analyses differed somewhat but not enough to affect comparisons of the results.

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[12] Nicholls, P., and Selvig, W. A., Clinker Formation as Related to the Fusibility of Coal Ash: Bull. 364, Bureau of Mines, 1932, p. 50.

TABLE 2.—*Bituminous coals used in underfeed tests*

Name, designation	Illinois	Pittsburgh	Splint	Westmoreland
State	Illinois	Pennsylvania	Kentucky	Pennsylvania
County	Franklin	Allegheny	Harlan	Westmoreland
Bed	No. 6	Pittsburgh	----------	Pittsburgh
Proximate analysis (percent):				
Moisture	6.5	1.7	3.1	1.3
Volatile matter	35.1	34.7	37.0	32.3
Fixed carbon	50.4	55.8	55.3	58.5
Ultimate analysis (percent):				
Hydrogen	5.5	5.2	5.8	5.2
Carbon	68.8	77.2	77.5	77.5
Nitrogen	1.5	1.5	1.5	1.5
Oxygen	14.1	7.2	10.1	6.9
Sulphur	2.1	1.1	.5	1.0
Ash	8.0	7.8	4.6	7.9
Calorific value ... B.t.u.	12,340	13,780	13,800	13,850
Softening temperature	2,203	2,780	2,510	2,600
Weight per cubic foot, 1- to 1½-inch size ... pounds	44	44	42	43
Coal per pound of combustible ... do	1.37	1.22	1.22	1.22

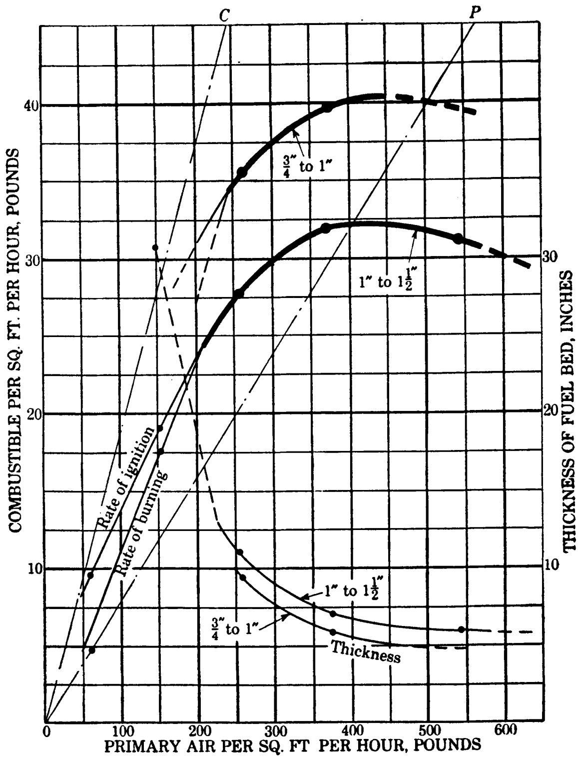

FIGURE 14.—Underfeed burning, Illinois coal, with rate of primary air and size as variables.

UNDERFEED BURNING OF ILLINOIS COAL

The Illinois coal was tested last; but it is discussed first, because its caking properties are lower than those of the Pittsburgh coal and the tests were more complete.

Figure 14 shows the results with two sizes of coal without preheat. The heavy lines indicate the rates at which equilibrium burning occurred. The actual data for rates below equilibrium burning are given; but, as explained, these values are associated with the test furnace used and include the factor of the clogging of the bed by the caking.

The plot is exactly similar to figure 8 for high-temperature coke, and the same deductions as were made for coke apply, namely: (1) Decrease in size increases the rate of ignition; (2) decrease in size decreases the thickness of the fuel bed; (3) there is a maximum rate of burning which cannot be exceeded—32 pounds for the 1- to 1½-inch size compared with 35.5 pounds for the high-temperature coke.

It would seem that the rate of ignition tends to decrease with very high air rates, similar to that which occurred with high-temperature coke but to a smaller degree.

Figure 15, *A*, shows the results for the 1- to 1½-inch Illinois coal with various preheat temperatures. Again, the general plot is similar to figures 11 and 12, *A*, and the increases in the rate of ignition by the preheat are of the same order. The light line designated as rate of burning has not exactly the same meaning as it had in the plots of the coke tests; rather, it is the dividing line between nonequilibrium and equilibrium burning, as fixed by there being no clogging of the bed by caking. This means that the tar exuded from the pieces of coal is consumed as fast as it exuded, or that the rate of burning at the surface counteracts the swelling. Thus the coal acts as a free-burning fuel, and the area of the figure designated as equilibrium burning could be called the free-burning area.

A test was attempted with 400° air temperature; it will be seen that the point for the test falls to the left of the equilibrium line. The test began well; but when the ignition line had fallen about 20 inches, the bed clogged up tight almost instantaneously, and no air could be forced through it with the pressure available. The rate of ignition given is approximate.

It is obvious that if the caked fuel had been broken up as quickly as it was formed, the light-line portion of the curves would have been swung to the left, and the shape of the curves would have been more similar to those for the cokes.

The dotted parts of the curves for the thickness of the live fuel bed indicate nonequilibrium burning; the thicknesses for equilibrium burning were approximately the same for the same air rate and thus fall on a common curve.

UNDERFEED BURNING OF PITTSBURGH (PA.) COAL

As the Pittsburgh coal was the first bituminous coal tested attempts were made to improve the method and procedure. To obtain accurate data on the nonequilibrium burning it was necessary for the air supplied to pass uniformly through the area of the bed instead of being diverted to the sides by the caking. Attempts were made to insure a uniform air distribution by increasing the resistance of the bed at the sides by packing a 2-inch ring of small coal around a 16-inch-diameter sheet-iron cylinder 12 inches long and gradually building up the bed. The coal to be tested thus formed a 16-inch core with a ring of fine coal around it.

This kept the center of the bed more open but did not eliminate the clogging, and the small coal at the sides also burned out more rapidly, or channels were formed. However, this method did increase the rate of ignition in the low-air-rate, nonequilibrium area as much as 100 percent. As would be expected, it made little difference in the equilibrium area but increased the ignition rate a little, both

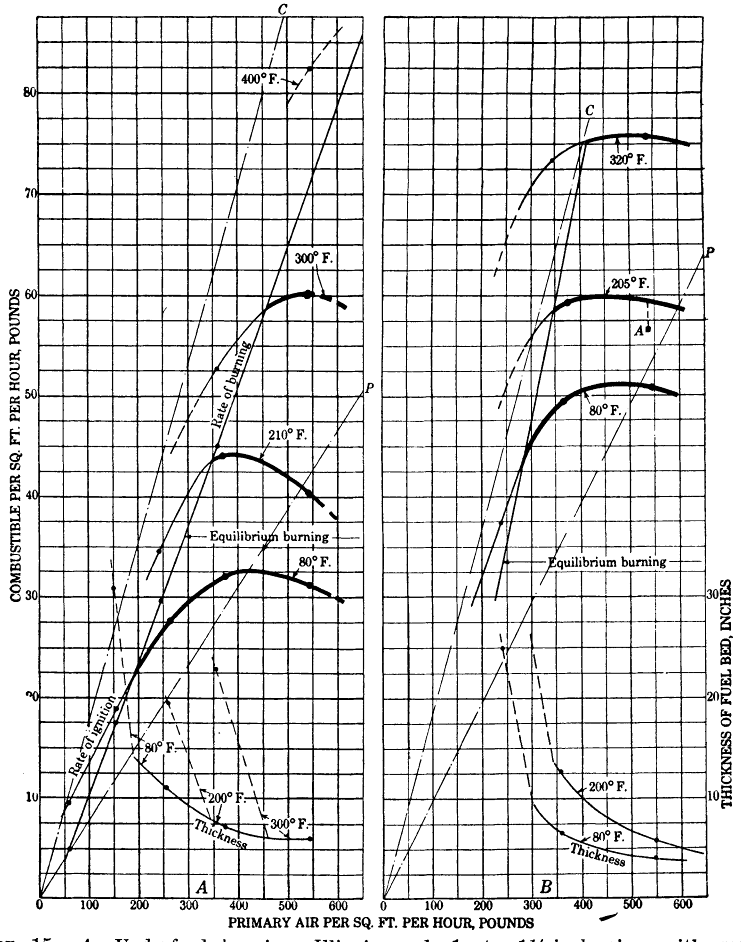

FIGURE 15.—*A*, Underfeed burning, Illinois coal, 1- to 1½-inch size, with rate of primary air and its temperature as variables. *B*, Underfeed burning, splint coal, 1- to 1½-inch size.

because of the effect of the small coal and because—even with a uniform fuel—there is always less resistance to air flow at the sides.

A variety of tests were made with the Pittsburgh coal, the majority with small fuel at the sides. Figure 16 shows plots of most of the tests, both for different sizes of fuel and for different air temperatures. The order of the results is the same as for the Illinois coal; with the same size coal, 1 to 1½ inches, the maximum rate of burning possible without preheat was higher, 43 against 32 pounds; with 300°

air temperature the maximum rate of burning was about the same, 61 pounds.

As before, the rate of ignition decreased with increase in size but not nearly as much as it did with high-temperature coke; the sizes

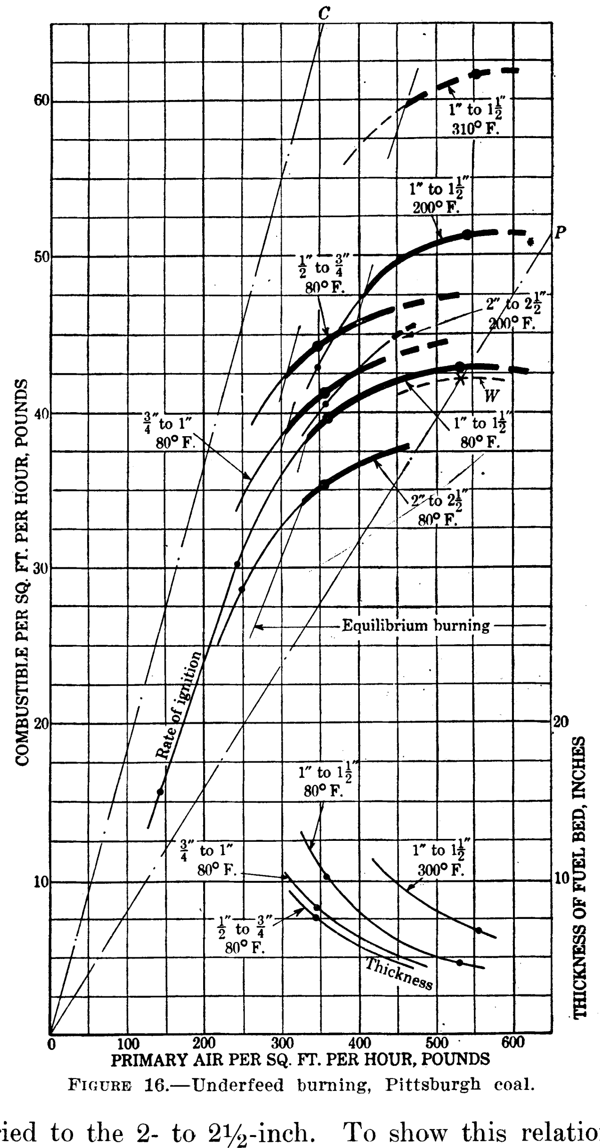

FIGURE 16.—Underfeed burning, Pittsburgh coal.

were carried to the 2- to 2½-inch. To show this relationship, the values for the Pittsburgh coal have been added as a dotted curve to figure 10, *A*, (p. 23). The points for the coke are the maximum rates; those for the coal are the test points, which are probably about 4 pounds less than the maximum, but the object of the plot is to show comparison of the rate of change with size.

The effect of preheat is of the same order as it was with high-temperature coke; this is shown by the dotted curve which has been added to figure 10, *B* (p. 23). The points for these two curves are approximately on the same basis.

There is no common line fixing the division into equilibrium and nonequilibrium areas; not enough tests were made to fix the lines closely, but the lines in figure 16 are approximate. It is certain, however, that the line is farther to the left for the smaller coals. It might be suspected that this was caused by the small coal used at the sides in these tests; but figure 14 shows that the same relation held for the Illinois coal, in testing which no small coal was used. The meaning of this must be that the spaces between the small pieces of coal are kept open more easily than those between larger pieces. At first thought this does not seem logical, but it becomes more so when considered on the basis that the small pieces present a larger area and that burning will occur at a higher rate.

UNDERFEED BURNING OF WESTMORELAND (PA.) COAL

Westmoreland (Pa.) coal was used because there was a small stock on hand and because it had been burned in the same manner previously in connection with an investigation on clinkering.[13]

Two tests were made, both with 1- to 1½-inch size. The first test was with an air rate of 364 pounds and without any small coal at the sides, which was below the equilibrium rate and did not give a satisfactory test. The second was with 540 pounds of air and with small coal around the sides. As would be expected, the results were very similar to those for the same size of Pittsburgh coal. The main values are given below; also, the test point for the 540 pounds is shown on figure 16 by a cross and by curve *W*.

Primary air, per square foot per hour	pounds	364	540
Air temperature	degrees	80	80
Rate of ignition, per square foot per hour	pounds	32.5	41.5
Rate of burning, per square foot per hour	do	26.7	41.7
Thickness of fuel bed	inches	--	7.5

Although the Pittsburgh and Westmoreland coals had approximately the same rate of ignition with an air rate of 540 pounds, a difference in the coals is indicated by the fact that the thickness of the live fuel bed averaged about 5½ inches for the Pittsburgh and 7½ inches for the Westmoreland. The simplest explanation would be that the pieces of Westmoreland coal tended to stick together more and thus the equivalent sizes were larger than those of the Pittsburgh, requiring a deeper bed for the same rate of burning; additional tests would be required to obtain an assured explanation. This difference has been pointed out, as it suggests the possibility of those smaller differences in the burning characteristics of coals otherwise very much alike which may prove rather important factors in operation.

UNDERFEED BURNING OF SPLINT COAL

Splint coal has the peculiarity that it does not deform when heated; on the other hand it, at least in large part, exudes its volatile matter as a tarry substance which will tend to fill the spaces between

[13] Nicholls, P., and Selvig, W. A., work cited, p. 50.

the pieces of coal. It is not known whether splint coal is used on large underfeed stokers, but it is with domestic stokers. The coal used in these tests was not specially obtained but was tested because it was available and because it represented another type of bituminous coal.

All tests were with the 1- to 1½-inch size. Experiments were made both with and without the device used with the Pittsburgh coal of packing the sides with the small (¾- to 1-inch) size to prevent most of the air from passing up the sides of the bed and to keep the distribution more uniform. At low rates below equilibrium burning there was very uneven burning, more so than with the Pittsburgh coal. Without the small coal at the sides the outer edge would burn away, leaving a solid column of fuel in the center, which shows that the center was packed solidly and the air could not pass through it. The same type of action occurred with the Pittsburgh coal, but the sealing did not seem to be as complete. Beds of both fuels were quenched after being partly burned and then examined, but because the quenching may have affected the coke definite conclusions are not warranted. Two suggestions are offered: First, that tar exuding from the splint coal may fill the spaces more suddenly than does the swelling of the pieces of the Pittsburgh coal and thus does not give the air as much time to burn the matter and keep the spaces open; second, that the mass of splint coal in its caking and coking is not as likely to open cracks which will again permit the air to pass through it.

Tests with small coal around the sides gave better burning, but even then 240 pounds of air was the lowest rate at 80° that permitted the completion of a test. Figure 15, *B* (p. 34), gives the results of the tests from which values were obtained and includes burnings without and with preheat of 205° and 320°. A test was also tried with a temperature of 415° and 535 pounds of air. It burned for a time and indicated an ignition rate of about 100 pounds; then it clogged very suddenly, and the air rate could not be maintained. The plot shows that the air rate was not high enough to give equilibrium burning.

Small coal was used around the sides in all the tests shown in figure 15, *B*, except in that marked *A*; because this point lies in the area of equilibrium and free burning there was no necessity to use small coal at the sides. If small coal had been used in this test the point would have fallen on the 205° F. curve; its departure therefrom shows the order of the effect of the small coal on the values in the equilibrium area.

DISTRIBUTION OF AIR IN UNDERFEED-BURNING TESTS

Coal burned in underfeed stokers is bounded more or less by the sides of the trough or pot, and there will be a cooling effect on the fuel in contact with the sides. It was therefore logical that this same factor should be included in the tests, although it was known that the air would not be uniformly distributed and that a larger proportion of it would pass through the area of lower resistance at the sides of the pot. With a free-burning fuel the lower resistance at the sides is solely mechanical because of large air spaces. With a caking fuel there is the additional factor that the fuel next to the sides is kept cooler and therefore does not cake as much; in addition, the results of this investigation show that the higher air velocity resulting from the more open space will tend to prevent caking.

As stated previously, small coal at the sides was first used in the attempt to force the air through the center of the bed when the Pittsburgh coal was burned at low rates; the size of the small coal was varied and was larger as the size being tested was larger. The small coal tended to accomplish the result expected, but at rates below equilibrium burning the sides still burned out.

There was naturally some doubt as to whether small coal should be used in all further tests, and there was not a complete enough conception of the meaning of the results to make an assured decision. The practice was continued with the Pittsburgh and the splint coals, but not with the Illinois coal or cokes tested later, because it was thought that it would be better to have the results comparable with those of the high-temperature coke, with which no small coke was used.

The regular analysis of the stack gases was by water Orsat. In the tests of fuels containing volatile matter and at air rates that gave equilibrium burning, 15-minute samples were taken simultaneously of the gases in the stack—that is, an average of the gases from the whole bed—and of the gases arising from the center of the bed. These samples were taken after equilibrium had been reached and when the top of the bed was a certain distance from the grate. They were stored over mercury and analyzed in a mercury Orsat. From these analyses the weight of combustible (C+H) per pound of air was computed. Because the bed burned down uniformly all over its area the weight of fuel gasified was the same for each part of the area. As the fuel gasified is equal to the weight per pound of air multiplied by the pounds of air, it follows that the air rates are inversely proportional to the pounds of combustible per pound of air; thus these data show the order of the distribution of the air.

Table 3 summarizes these data. All the tests included are within equilibrium rates, but others at equilibrium rates are not included because gas samples were not taken or were unsuccessful. The first four columns identify the tests and permit locating the test points in the figures. The last column but one gives the amount of air passing through the center of the bed, expressed as a percent of the average air rate. The conclusions that can be drawn are:

1. Comparison of low-temperature coke, anthracite, and Illinois coal shows that for the same size of fuel, air rate, and temperature the Illinois coal had a greater resistance at the center; hence, its simulation of a free-burning fuel was not perfect.

2. The small coal at the sides materially improved the distribution; the splint and Pittsburgh coals had a more uniform distribution than the Illinois in spite of their higher caking characteristics.

3. For the same conditions the distribution was more uniform as the size of the fuel was smaller; in one instance—the Pittsburgh ½- to ¾-inch size—it was 100 percent. This is to be expected because in many other tests it has been found that side leakage increases materially with increase in the size of fuel.

4. The distribution of air was less uniform as its rate increased; this is shown by all the fuels. It is believed that the direct cause

was that the thickness of the live fuel bed decreased with increase in air rate. With thin beds the effect of the clinker in the bed would be more important; the ash near the wall does not clinker because of the cooling effect of the wall, and thus a great part is blown out as fly ash.

TABLE 3.—*Distribution of air over bed*

Fuel		Primary air		Carbon + hydrogen per pound of air, pound		Air rate at center as per-cent of average	Small coal at sides
Name	Size, inches	Rate, pounds	° F.	Average	Center of bed		
Low-temperature coke	1 to 1½	255	80	0.152	0.183	83	No.
	1 to 1½	360	80	.132	.160	82	No.
	1 to 1½	545	80	.087	.139	63	No.
	1 to 1½	350	210	.138	.168	82	No.
Anthracite:							
No. 1	1 to 1½	240	80	.116	.144	81	No.
No. 2	1 to 1½	240	80	.127	.148	85	No.
No. 3	1 to 1½	245	80	.152	.167	90	No.
Nos. 1 and 2	1 to 1½	335	80	.772	.133	58	No.
Illinois coal	¾ to 1	260	80	.131	.181	73	No.
	¾ to 1	370	80	.109	.154	71	No.
	1 to 1½	255	80	.098	.145	67	No.
	1 to 1½	543	80	.062	.137	45	No.
	1 to 1½	365	210	.115	.156	74	No.
	1 to 1½	540	210	.079	.152	52	No.
	1 to 1½	540	300	.115	.160	72	No.
Splint coal	1 to 1½	364	80	.131	.145	90	Yes.
	1 to 1½	365	205	.147	.165	89	Yes.
	1 to 1½	545	210	.107	.136	79	No.
	1 to 1½	540	320	.126	.144	88	Yes.
Pittsburgh coal	½ to ¾	350	80	.129	.128	100	Yes.
	¾ to 1	360	80	.112	.133	84	Yes.
	1 to 1½	360	80	.103	.131	79	Yes.
	1 to 1½	530	80	.086	.120	72	Yes.
	1 to 1½	540	200	.091	.138	66	No.
	1 to 1½	550	310	.118	.145	81	Yes.

5. For the same air rate, preheat did not appear to harm distribution but rather tended to improve it.

Whether or not small coal should be used at the sides would depend on the results desired. If one wishes the results to represent burning in which the effects of the sides are eliminated as much as possible, small coal should be used; this would be desirable in the study of actions on a chain-grate stoker. However, the tests showed that the average result is not much different, even if distribution is not uniform.

Finally, actions will be affected materially by the design of the stoker, and close comparisons could be made only by tests in the appliance used.

SUMMARY OF UNDERFEED-BURNING TESTS

The similarity of the relationships in all the fuels tested justifies the method of thoroughly testing high-temperature coke first, as the clear viewpoint that this gave of the relations between quantities set a standard for interpreting results with fuels that were more difficult to test.

A general summary of the conclusions was presented in the introduction to this report, and the section "Application of Results to Underfeed Stokers" extends these conclusions further.

The various plots of results can be said to represent the burning characteristics of the fuels tested when these are burned on the principle of unrestricted ignition. They illustrate the fact that such characteristics cannot be stated as 1-figure values for each fuel, but that they depend on the other variables of—at least—size, rate, and temperature.

The values obtained and the curves for the bituminous coal at rates of air supply below those of equilibrium burning are tied up with the method of test; the numerical values are therefore less important, except that they show that equilibrium—that is, free burning—did not occur at those rates. The device of using small coal at the sides to prevent side leakage of air gave values for nonequilibrium rates which correspond more nearly to the true values for the nominal air rate.

The factors not covered by this method of test are: (1) Restricted ignition; (2) precoking of the fuel; and (3) breaking up of the coked fuel by motion of the incoming fuel or by other means.

OTHER DATA FROM UNDERFEED-BURNING TESTS

The three subjects treated in this section are based on data that were not used in the preceding. These discussions will have less interest to those concerned only with general conclusions.

RATE OF IGNITION

The rate of ignition involves a number of factors which come under the two headings of the rate at which the temperature of the piece being ignited rises and of the ignitibility of the fuel. The latter is an indefinite quality because it necessitates distinguishing between the ignition of the piece itself and of the gases it may give off when heated.

When a piece of fuel is below the plane of ignition there will come a time when it will begin to receive heat by radiation from the burning fuel above; its chance of receiving this heat will depend mainly on its position. Heat also will be conducted from piece to piece, and the depth below the plane of ignition to which the conducted heat will reach will depend mainly on time and will decrease as the plane of ignition travels more rapidly toward the piece considered. On the other hand, the incoming air will cool the piece and carry the heat back into the bed. The actual rate of rise of temperature is compounded from these actions and consequently is complex. It is evident, however, that a fuel which has high ignitibility will tend to put a brake on itself, because, as the rate of advance of the plane of ignition is more rapid, the time for the transmission of heat is less, and thus the heat will not penetrate to as great a distance relative to the plane of ignition.

The thermocouples in the bed gave plots of temperature against time; from the known rate of travel of the plane of ignition the temperature could be plotted against distance from that plane. Naturally the curves of the recorder were not exactly the same for all thermocouples of one test, because the rate of heating would depend on the arrangement of the pieces of fuel around the couple, but an average value could be selected for each. These were plotted against rate of air supply, preheat, and other factors but did not give simple relationships.

Figure 17 shows a plot of temperature against distance below the plane of 1,378° for some of the fuels of 1- to 1½-inch size at an air rate of 350 pounds and air temperature of 80°. The rise of temperature extended farther into the bed with the cokes than with the coals, probably owing to the larger and more definite spaces between the irregular pieces of coke; this relationship held at other rates. On the other hand, the penetration was smallest with the Pittsburgh coal; a reasonable explanation is that the smoke evolved partly blanketed the radiation.

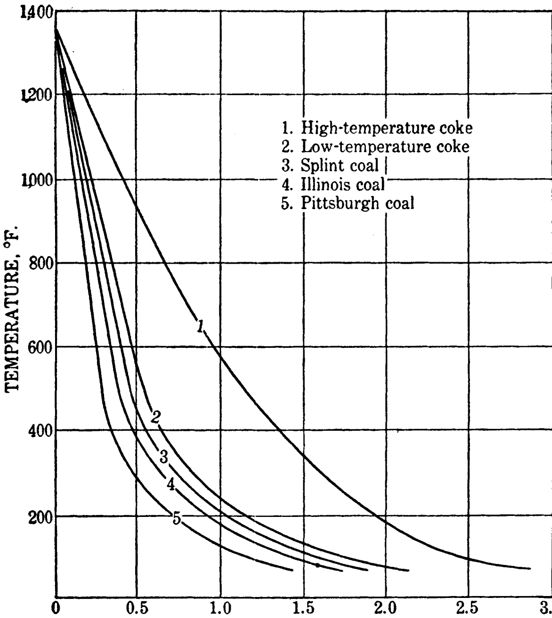

FIGURE 17.—Temperature below plane of ignition.

In general, the depth of penetration of the temperature rise decreased with increase of air rate, but there were enough variations in all bases of comparisons to show that the results were compounded of many factors. The size of the pieces appeared to have no marked effect, but then again size materially affects the rate of travel of the plane of ignition.

Figure 10, *A* and *B*, showed the relationships for high-temperature coke of the rate of ignition to the size of the coke and the air temperature. Figure 18, *A*, compares the rates of ignition of all fuels for the 1- to 1½-inch size, 80° air temperature, and varying air rates; the rates of ignition are again expressed as pounds of combustible per square foot per hour. The portions of the curves of the bituminous coals shown dotted are below the equilibrium rate of burning. They have been swung to the left from the values obtained in the tests on the assumption that they would have the shapes shown if the bed were kept open by agitation; this makes them more comparable with the other fuels.

All the fuels except the petroleum and low-temperature cokes reached a maximum rate of ignition, which then fell off; it can also be assumed that, having once started to fall, the decline would have continued if the air rate had been carried higher and that there would have been a limiting rate above which it would have been

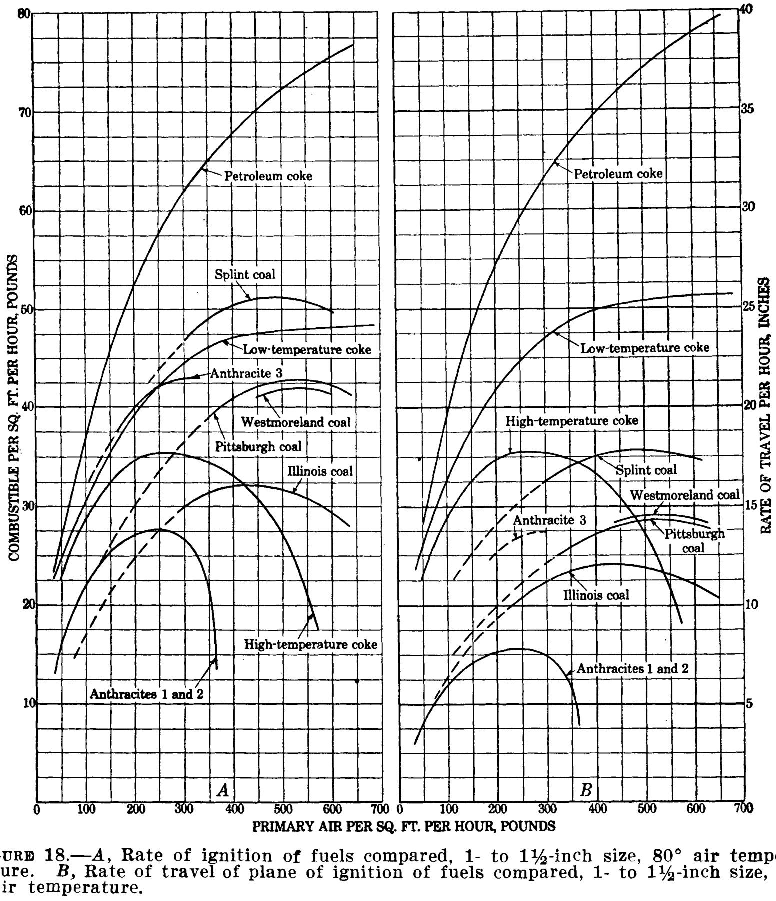

FIGURE 18.—*A*, Rate of ignition of fuels compared, 1- to 1½-inch size, 80° air temperature. *B*, Rate of travel of plane of ignition of fuels compared, 1- to 1½-inch size, 80° air temperature.

impossible to maintain the burning. The curves for both petroleum and low-temperature coke appear to be still rising; whether they would have fallen off if the air rate could have been increased indefinitely is of some interest. An assured answer cannot be given, but because the factors of size, spaces between pieces, and thermal conductivity could not have differed much from those of the other fuels one would expect that these two cokes had greater inherent ignitibility.

The rate of ignition of the petroleum coke much exceeded that of the others. On the weight basis of measurement, that for the low-temperature coke is less than that for the splint coal. The curve for the low-volatile anthracites 1 and 2 falls completely within the high-temperature coke, but the curve for the high-volatile anthracite probably would be entirely outside it.

The minimum values for the Pittsburgh and splint coals are probably about 2 pounds higher than they should be relative to those of the Illinois coal, because in the tests of the two former small coal used at the sides of the furnace, but even with this allowance the Illinois coal had the lowest ignition rate of the three.

Figure 18, *B*, shows the rate of travel of the plane of ignition, in inches per hour, for the same fuels shown in figure 18, *A*. The scale of pounds per hour is more useful for the combustion engineer, but inches per hour is probably more logical when ignitibilities are compared because the direct effect of density on rates of ignition cannot be great; the indirect effect of density as defining the type of exposed surface is very important. The rate in inches per hour will sometimes be the more pertinent scale, even in service—for example, in the tendency of fuels to ignite down through pot-type stokers.

Figure 18, *B*, materially changes the relative position of the fuels. The curve for low-temperature coke now lies considerably above that for splint coal and that of high-temperature coke is over twice as high as that for low-volatile anthracite. The relative positions of the coals are not changed materially.

Not enough tests were made with different sizes of all the fuels to determine whether the same relative values shown in figure 18, *A* and *B*, would hold for other sizes than the 1 to 1½ inches. They may hold when cokes are compared, but figure 16 shows that size had less effect with Pittsburgh coal than with high-temperature coke (fig. 8). This would be expected because, although a caking coal may burn, as a whole, like a free-burning coal, there must be some agglomeration of the pieces, and this should be more pronounced as the sizes of the pieces decreases.

The curves of figure 18, *A* and *B*, can be considered direct measures of the ignitibility of the fuels under the conditions of test used—that is, for underfeed burning. Such measures of ignitibility can be expressed only as curves and not as single values. A more complete set of tests might reveal some common basis for connecting the values as expressed by the curves; the first step would be to extend the tests of all the noncaking fuels to include the variables of size and air temperature.

PRESSURE DROP THROUGH LIVE FUEL BED

Complete records of pressure were taken during each test; these include the pressures in the ashpit and at the top of the furnace. After the furnace had been loaded with the fuel and before the test was started careful measurements were made of the pressure drop across the fuel at the air rate to be used in the test; this gave the pressure drop per inch of height of fuel. During the tests, the only record of pressure drop was that through the live fuel bed plus that through the unignited fuel below the plane of ignition, but as the position of the plane of ignition was known, the pressure drop through the unignited fuel could be computed; this, subtracted from the total pressure drop, gave the pressure drop through the live fuel bed. These pressure drops through the live fuel bed were plotted for each test against the position of the plane of ignition as fixed by the 30-millivolt line of the thermocouples; all tests for each fuel were plotted on the same sheet.

As would be expected, these plots make a rather confused mass of data because the pressure drop results from a number of factors, including size of fuel, rate of air supply, thickness of fuel bed, amount and nature of clinker, effect of caking, temperature of preheat, and temperature head of the column of hot gas. Again, some factors are interdependent, particularly the thickness of the bed and the rate of air supply. It is not worth while including all the data, especially because the conditions obtaining in these tests do not correspond to those in service.

The pressure drop through a bed of given thickness of broken solids increases rapidly with air rate; at high temperatures the increase will be of the order of the 2.5 power of the air rate. Naturally, the cokes gave the most regular curves and more concordant values; and they illustrate that because the thickness of the bed decreased with increase in air rate the pressure drop reached a maximum and then decreased, as the following table shows.

Total pressure drop, inches of water

Air rate, pounds	60	150	250	350	450
½- to 1-inch coke	0.12	0.50	--------	1.13	0.80
1- to 1½-inch coke	.015	.21	0.475	.34	.33

In the attempt to reduce values to a comparative basis the pressure drop for sizes of cokes for which a series of tests was made was computed to per inch of thickness of the live fuel bed at the time when the ignition reached the grates. Figure 19 shows the values plotted on a log-log basis. Although the points do not make good curves because of uncertainty as to the thickness of the fuel bed or because of chance conditions in single tests, yet they illustrate several general principles. The air rates at which equilibrium burning began are indicated by a cross on each curve. The following deductions result:

(1) Below the equilibrium rate the relationship between air rate and pressure drop is approximately the same for all the series and can be expressed by pressure drop$=Kx$ (air rate) $^{2.5}$, where K is a constant for each size. This general agreement results because the fuel is not completely consumed and because there is not much clinker to upset the normal arrangement of the pieces. If the gases were cold the index for these sizes of fuels would be 1.7 to 1.8; the higher value of 2.5 is due to the gases being at a high temperature.

(2) The pressure drop per inch—that is, the value of K—decreased with increase in size of the coke pieces in the order that would be expected, as shown by curves *1*, *2*, *3*, and *4*, for the ½- to 1-, 1- to 1½-, 1½- to 2-, and 2- to 2½-inch sizes, respectively, of high-temperature coke.

(3) Curve 5 is for 1- to 1½-inch coke with 300° preheat. Its position with respect to curve *1* for the same coke without preheat shows that the preheat materially increases the pressure drop. This same increase occurred with other cokes.

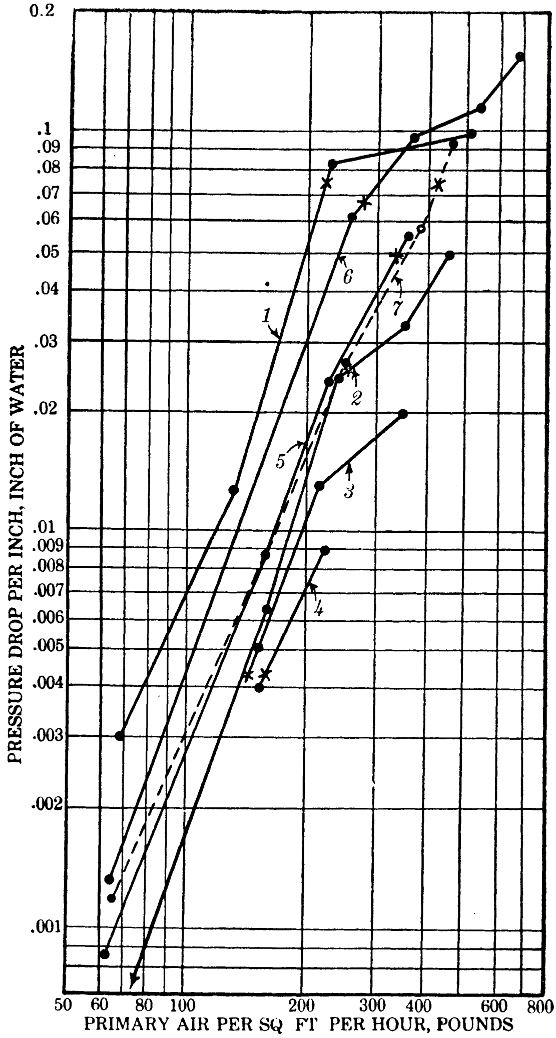

FIGURE 19.—Pressure drop per inch thickness of fuel bed: *1*, High-temperature coke, ½- to 1-inch size, 80° air temperature; *2*, high-temperature coke, 1- to 1½-inch size, 80° air temperature; *3*, high-temperature coke, 1½- to 2-inch size, 80° air temperature; *4*, high-temperature coke, 2- to 2½-inch size, 80° air temperature; *5*, high-temperature coke, 1- to 1½-inch size, 300° air temperature; *6*, low-temperature coke, 1- to 1½-inch size, 80° air temperature; *7*, 1- to 1½-inch petroleum coke, 80° air temperature.

(4) For the same size and air temperature the pressure drop of the high-temperature and petroleum cokes—curves *2* and *7*—was nearly the same up to the equilibrium rate, but that for the low-temperature coke—curve *6*—is smaller; the reason for this is not clear.

(5) After equilibrium burning is reached—as indicated by the crosses—the pressure drop per inch does not increase as rapidly with increase in air rate, and the index averages to 1. The most probable explanation is that the fuel beds are much thinner, and a considerable portion of their volume consisted of clinker which kept the spaces more open; this suggestion is supported by the fact that this change did not occur with the petroleum coke, which had no ash.

The pressure drop through the bed when coals that cake are burned has no meaning for rates of burning below those of equilibrium, because resistance of the bed to the flow of air may be increased enormously by the sealing up of the spaces and most of the air flows along the walls.

The most striking difference between the sets of curves for the Illinois, Pittsburgh, and splint coals was that the pressure drop for Illinois coal continued to increase uniformly, even after equilibrium was reached, whereas that for the other two reached a maximum value and remained approximately constant. This was probably caused by the greater fusibility of the ash of the Illinois coal and by the slag closing the openings.

Out of the several ways in which the results for the coals might be shown, the one selected was to divide the pressure drop through the live fuel bed by the pounds of combustible burned per square foot per hour; this is the nearest approach to a serviceable value; but, with the many factors, its meaning is limited. The values were all taken when the plane of ignition was 16 inches above the grate.

TABLE 4.—*Pressure drop through fuel bed per pound of combustible burned per square foot per hour, inch of water*

Air rate, per square foot per hour, pounds		255	350		550		
Air temperature, degrees		80	80	200	80	200	300
	Size of coal, inches						
Illinois coal	¾ to 1	0.028	0.014	-------	-------	-------	-------
	1 to 1½	.033	.014	0.013	0.020	0.020	0.016
Pittsburgh coal	½ to ¾	-------	.012	-------	-------	-------	-------
	¾ to 1	-------	.011	-------	-------	-------	-------
	1 to 1½	-------	.010	.017	.008	.015	.014
Splint coal	1 to 1½	-------	.0075	.02	.007	.009	.007

Table 4 gives the results. They show fair regularity, and the only value much out of line is that of the splint coal, at the 350 rate and 200°; figure 15, *B*, shows that this point fell just beyond the equilibrium rate. The original size of the fuel did not make much difference in the pressure drop; but, on the other hand, size affects the rate of burning and the thickness of the fuel bed, and the pressure drop is the resultant of all these factors.

COMPOSITION OF GASES FROM FUEL BEDS

It has already been shown that the position of the point of operation on charts, such as figure 8, fixes the percent deficiency or excess of the primary air. The position thus gives a general idea of the average composition of the gases arising from the fuel bed or—in the method of test used—the composition of the gases in the stack of the hood. It is of some interest to compare the exact compositions, and if there were enough data these comparisons would compound some of the burning characteristics of the fuels; however, complete sets of tests were not made of all the fuels nor were there complete analyses of all the samples of the gases. As a compromise, some special gas samples were taken in the tests of fuels containing volatile matter and complete analyses were made. These consisted of at least two samples taken simultaneously and covering 15 minutes. One was from the gases arising from the center of the fuel bed; the other was from the stack, which gave an average of the whole bed.

Utilization of these data is limited to showing the effect of air rate and of air temperature on the composition of the gases; in addition, such data as were obtained on soot are included.

EFFECT OF AIR RATE

Figure 20, *A*, shows the composition against the pounds of primary air supplied in the test of 1- to 1½-inch low-temperature coke an air temperature of 80°. The tests with which these samples are

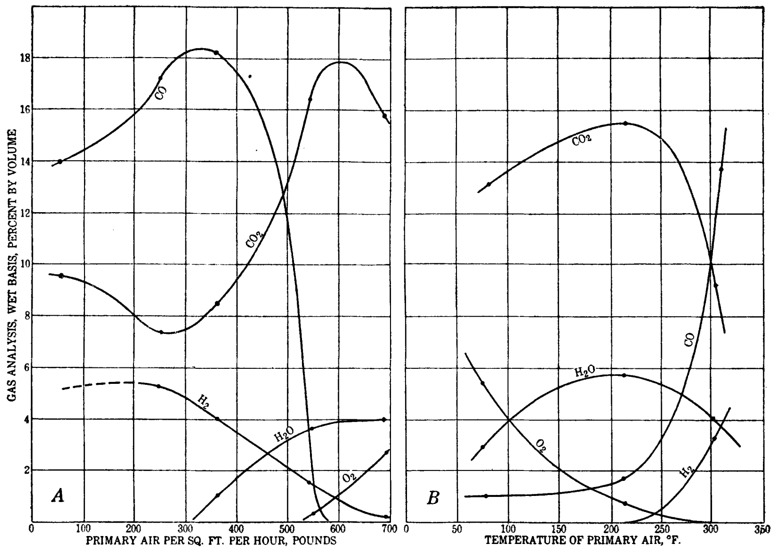

FIGURE 20.—*A*, Composition of flue gases as related to primary air rate, 1- to 1½-inch low-temperature coke, 80° air temperature. *B*, Composition of flue gases as related to temperature of primary air, 1- to 1½-inch Illinois coal, with air rate of 540 pounds per square foot per hour.

associated are shown on the 80° curve of figure 12, *A*. The rate of burning at the lowest air rate of 65 pounds was so far below the ignition rate that no special sample was taken; however, the rate of burning became constant with the CO and CO_2 values shown, but that for hydrogen is assumed.

The relationships in figure 20, *A*, are regular and consistent. They are tied up with the thickness of fuel bed formed by balancing the rate of burning against the rate of ignition. Both the 65- and the 260-pound rates lie below equilibrium burning; in consequence, the thickness of the fuel bed would increase indefinitely. In spite of this—as just stated—the composition of the gases became constant. This means that the temperatures in the upper part of the bed fell below that necessary to continue the reduction of the CO_2 to CO. At about 300 pounds of air the CO_2 reached a minimum; figure 12, *A*, shows that this is the rate at which equilibrium burning started. At about 600 pounds of air the CO_2 reached a maximum; in figure 12, *A*, this is the rate at which the curve crosses line *OP*—zero excess air.

It is interesting to note that at low rates the oxygen in the air combines with the carbon of the fuel in preference to the hydrogen; water vapor does not appear until the air rate reaches about 300 pounds.

EFFECT OF AIR TEMPERATURE

The number of tests with low-temperature coke were not enough to permit it being used to illustrate the effect of preheat on the gas analysis, but figure 20, *B*, shows the effect of temperature for Illinois coal, 1- to 1¼-inch size and with a primary-air rate of 540 pounds; the test points are shown in figure 15, *A*. Gas samples were not taken in the test at 400° because caking of the coal clogged the bed.

The important point this plot illustrates is the much greater effect preheat has on the composition of the gases than in overfeed burning, as illustrated by figure 2.

Figures 15, *A*, and 15, *B*, are not comparable in the relationships they show except that the values at 540 pounds of *A* are comparable with those of 80° of *B*.

TAR AND SOOT

It would be expected that there might be tar and soot in the gases from the center of the bed when operating below the equilibrium rate, but probably not with rates giving equilibrium burning. Sampling for tar and soot was only done during one test of the Pittsburgh coal; as no soot appeared in the collector no further attempts were made.

A trial sampling was made with the Illinois coal and showed soot, so samples were collected in all other tests, as well as with the splint coal. Unfortunately most of these samples were lost in a small fire in the analytical laboratory, and results can be given only for a few of the tests of Illinois coal. No tar was found; but there was appreciable soot in all, as is shown in table 5.

TABLE 5.—*Soot in gases from Illinois coal*

Nominal air rate per square foot per hour, pounds	Air temperature,°	Soot per pound of air, pound	Nominal air rate per square foot per hour, pounds	Air temperature,°	Soot per pound of air, pound
260 (*a*)	80	0.0045	575	200	0.0045
260 (*b*)	80	.0120	575	300	.0075
380	80	.0056	575	400	.0071
575	80	.0030			

All the tests are single values and for 1- to 1½-inch coal, except that for 260 (*b*), which is for ¾- to 1-inch coal and is taken from figure 22, which is based on three tests. The value for 260 (*a*) probably is low, and it is also logical that the soot should be higher at the low air rate.

The conclusions from table 5 are that with Illinois coal burned on the underfeed principle, with unrestricted ignition:

(1) The gases arising from the fuel bed contained soot at all rates of burning and with all preheats.

(2) With constant air temperature the quantity of soot decreased with increase of air rate.

(3) With constant air rate the quantity of soot increased with increase of the preheat.

If the test points corresponding to the rates and temperatures of table 5 are located in figure 7, it will be seen that the quantity of soot was greater as the ratio of fuel to air was greater; thus the results can be considered logical.

The samples were taken at about 2 inches above the top of the bed; however, there was no possibility of the quantity of soot decreasing at greater distances, unless secondary air were added.

The absence of soot in the one trial when Pittsburgh coal was burned should not be taken as conclusive. If it is true that soot escapes from a bed of Illinois coal and not from one of Pittsburgh coal, it would be of decided interest to find out why, and how the actions in the bed differ.

REACTIONS THROUGH UNDERFEED FUEL BED

It was desirable to have records similar to those of figure 2 of the reactions through fuel beds burning on the underfeed principle. The tests could not be made in the same manner as those for figure 2, because the live bed is traveling downward continually. All data must be referred to the plane of ignition, and it was therefore necessary to time and record each gas sample and temperature observation so that it could be referred to the position of the plane of ignition and to the positions and records of the thermocouples in the center of the bed.

A further requirement was that the time taken to collect all the samples should be the shortest possible, so that conditions through the fuel bed would not be altered materially and the positions of the sampling points relative to the plane of ignition would be known with the greatest certainty, but it was not desirable to insert all samplers at the same instant because they would cool the bed. Not more than four samplers were in the bed at any one time, and the schedule was so arranged that their positions would be distributed around the furnace. In addition, they were inserted so that their ends were 3 inches from the vertical axis of the bed; thus the gas passing the end of any one sampler was not affected by any other sampler. To offset this advantage it follows that the same gas stream was not sampled, and lack of uniformity in the results would be expected unless the burning over the 6-inch diameter areas was absolutely uniform.

HIGH-TEMPERATURE COKE

High-temperature 1- to 1½-inch coke was investigated first. A deep fuel bed could be used and thus give a greater length to examine, because it was not necessary that it be an equilibrium bed. Therefore the rate of air supply was fixed at 160 pounds per square foot per hour, which, during the period of the observations, gave a bed about 20 inches deep; this same air rate was used in the overfeed tests for figure 2. Figure 21 shows a plot of the results on the same plan as was used for figure 2. Two tests were necessary to obtain a complete set of readings, and this plot is a composite of the two. One pair of gas values is wild, and probably there was some error in the timing; but, considering the difficulties involved, the values for the single determinations fit the curves fairly well. The plane of ignition is used as the zero position for height; this plane was moving downward at a rate of 14 inches per hour.

The plots of the gas analyses are of the same form as those for the overfeed bed but are spread out more at the start, and the CO did not reach as high a value. The temperature curve, as showing the rise before ignition, is of interest; it would indicate that ignition

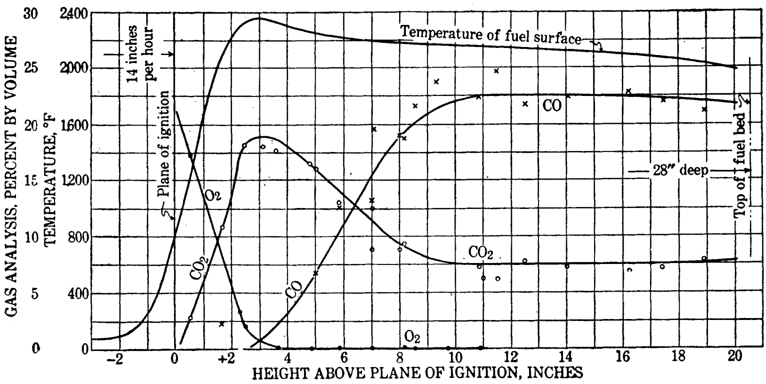

FIGURE 21.—Combustion process in underfeed fuel bed, high-temperature coke, 1- to 1½-inch size, primary air 160 pounds per square foot per hour.

occurred at 500°, which is low for high-temperature coke and probably is due to a lag in the heating of the thermocouples. Readings from 1,500° up were by optical pyrometer; these also appear low, but this would be expected because the observations were on the surfaces of pieces of coke, the body of which would still be cool.

The coke used in these tests was not from the same stock as that of figure 2, but their properties were near enough alike so that the results of the overfeed and underfeed burning can be compared by comparing figures 2 and 21; but they are shown better by the dotted line on figure 3 which falls below that of the 80° curve for overfeed burning. The conditions of test were more favorable to the overfeed burning because the refractory walls were heated by the continued location of the bed at one position; but apart from that, it can be deduced that for the same depth of bed, underfeed burning will give a lower rate of burning.

ILLINOIS COAL

The same type of test was made with the Illinois bituminous coal; the ¾- to 1-inch size was used, as this would approach nearer the average size used with stokers. In this test it was necessary to have an equilibrium bed, so an average air rate of 260 pounds per square foot per hour was used, giving rates of ignition and of burning of 35 pounds of combustible per square foot per hour. The same procedure was followed; but, in addition, a tar and soot sample was taken to correspond to each gas sample.

The tar and soot were collected by passing the gases at a constant rate through alundum thimbles filled with asbestos;[14] a glass tube was inserted in the water-cooled sampler and reached to within one half inch of its end in the fire. The time for taking a tar and soot sample must be long enough to collect sufficient for analysis; the upper limit of the time taken is fixed by the drop in pressure through the thimble becoming too great to permit the rate of flow to be maintained at the value being used. In these tests the period of sampling was 7 to 10 minutes. The gas sample was taken in the middle of this period, and the exact time of all operations was recorded; the gas sample was collected quickly and covered a period of not longer than 1 minute.

It was necessary to design a special, compact, water-cooled sampler for these tests, and two tests failed because of leakage of water and lack of practice in the rather complicated technique required. The third test was successful.

The results can be depicted in several ways. The first operation was to plot the gas analyses by volume against height above the plane of ignition. These plots are not given because interpretation of their meaning requires experience in assigning weight to their values. The most informative basis is to compute the weight of the various components in the gases at each point per pound of dry air supplied.

Figure 22 shows the weight of the carbon and hydrogen in their various forms per pound of dry air supplied; the four top curves have been plotted as separate diagrams to avoid the confusion that would be caused by the curves crossing. The curves were drawn to give relatively consistent values; that is, they were started from the values of each constituent in the sample taken at the highest point—3 inches above the top of the fuel bed. That all the values do not fall on the curves is unimportant, nor would it be expected that they would be the same over the area 6 inches in diameter; moreover, values at any one position of the fuel bed will vary from time to time. Two sets of points at the bottom of the bed—indicated by small arrows—are particularly out of place; this is very likely to occur because of spurts of evolution of gas from the coal during the period when it is being coked.

All the values are experimental except those for the H_2O as water vapor, which were computed from the oxygen balance; in doing this the oxygen and nitrogen in the coal were included on the assumption that the coal lost these constituents uniformly between 0- and 5-inch height, when all of these constituents were assumed to have been evolved. The sulphur in the coal was low and was allowed for by distributing it to the ash, to that absorbed by the water during collection, and as equivalent CO_2.

Oxygen was found in only one sample, and all had disappeared in the first 3 inches. Samples were also taken at positions below

[14] Kreisinger, Henry, Augustine, C. E., and Katz, S. H., Low-Rate Combustion in Fuel Beds of Hand-Fired Furnaces: Tech. Paper 139, Bureau of Mines, 1918, pp. 15–18.

the plane of ignition, and they analyzed as air; these samples helped to confirm the position of the plane of ignition.

The shapes of the curves for carbon in CO_2 and carbon in CO are, of course, the same as they would be in the ordinary plots of the dry-gas analysis, because the weight of carbon per unit volume is the same in CO and CO_2. It will be noted that their shapes are the same as in an overfeed bed.

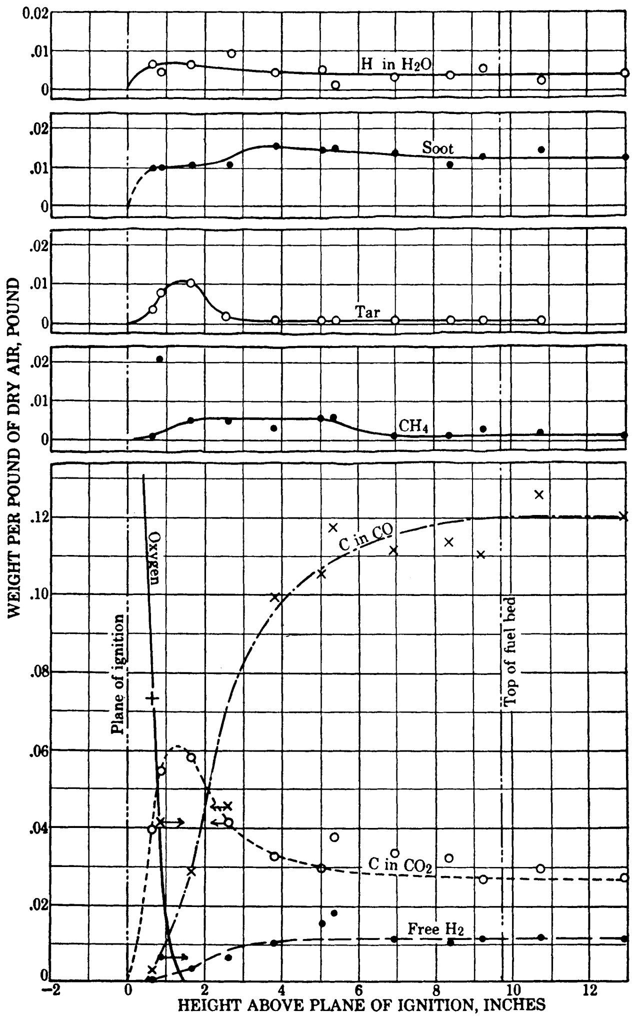

FIGURE 22.—Underfeed burning, action through fuel bed expressed as weight of fuel products carried per pound of dry air supplied, ¾- to 1-inch Illinois coal.

The curve of hydrogen in H_2O is of interest. The weight of the H_2O (water vapor) would be 9 times those shown. The oxygen of the air, once it has been combined, must all appear in the CO_2, CO, and H_2O; but it can interchange during the passage of the gases through the fuel bed or, as is more probable with these samples from different gas streams, it may not originally combine in the same way. Thus, in the sample at 5.4 inches height nearly all the oxygen was combined with the carbon, and there was more free hydrogen. The computed H_2O may come negative, and some of the values would have done so if the oxygen in the coal had not been included. If they had come negative in spite of allowing for the oxygen in the coal it would have implied that there had been a producer action of the carbon with the water vapor in the air, which is not included in the curve for H_2 in H_2O. The points of the H_2O curve are scattered, but the curve as drawn indicates that, on the average, as the gases pass upward through the bed some of the O_2 in the H_2O is lost to the carbon by the action $C+H_2O=CO+H_2$.

The curve for free H_2 shows that hydrogen is released gradually, reaches a maximum, and remains constant. Plotted on a volume basis the hydrogen would appear to be relatively much greater.

Although the curve for methane (CH_4) shows a gradual increase over the first 2 inches of the bed, it should have been drawn through the second point at 0.9 inch, thus making a hump in the curve. When Illinois coal is coked at a low temperature, the weight of the methane evolved is several times that of the hydrogen, which it was in this instance; as the total C+H per pounds of air was 0.175 pound, the 0.021 pound of methane in that particular sample represents 12 percent of the total combustible. The curve shows that the methane combined with the oxygen very quickly, although its incomplete combustion may be responsible for some of the soot. Part of the methane was not burned but reached a height of 6 inches, beyond which it was very small; as there was no free oxygen beyond 2 inches, it was evidently broken down by the heat into simpler components.

A relatively large amount of tar was released at the lower part of the bed but was broken up and probably appears partly as soot, which increases as the tar decreases. The analyses show a very small quantity of tar as leaving the fuel bed; although it is designated as tar, more correctly it should be called material soluble in benzol, which is used to separate the tar from the soot. There may be doubt whether this small residue is actually a soluble, carbonaceous material from the gases, but in any event from an operating standpoint it can be said that there was no tar in the flue gases.

The test points of the curve for soot indicate that it reached a maximum and then fell off slightly, which would mean that some of the soot was used in converting CO_2 to CO. There was 0.012 pound of soot per pound of air in the gases leaving the fuel bed. This is 7.5 percent of the total carbon, or 0.051 pound of soot per pound of coal as fired.

.Figure 23 is a parτ of figure 22 but has been plotted separately to avoid confusion. It shows the total hydrogen per pound of dry air and the total carbon plus hydrogen; their difference gives the total carbon. The ratio of carbon to hydrogen at the top of the fuel bed is 11.7 to 1; the coal analysis of table 2 gives a ratio of 12.5 to 1. The analysis was that of an average sample of the lot of coal as received; the portion used in this test may have differed somewhat, but on the other hand the curves, as representing the average of the test points, could have been drawn to maintain the ratio given by the coal.

Figure 23 also shows the temperatures through the fuel bed; the values are variable enough so that the exact position of the curve is in doubt. The points up to 1,378° are from the thermocouples; the higher ones are optical pyrometer readings. The absence of the hump that occurs in overfeed burning is noticeable, and the highest temperature recorded was 2,600°, whereas in the overfeed burning shown by figure 2 it was 2,880° without the preheat; the existence even of the small hump shown is questionable. The causes for these differences will be discussed later.

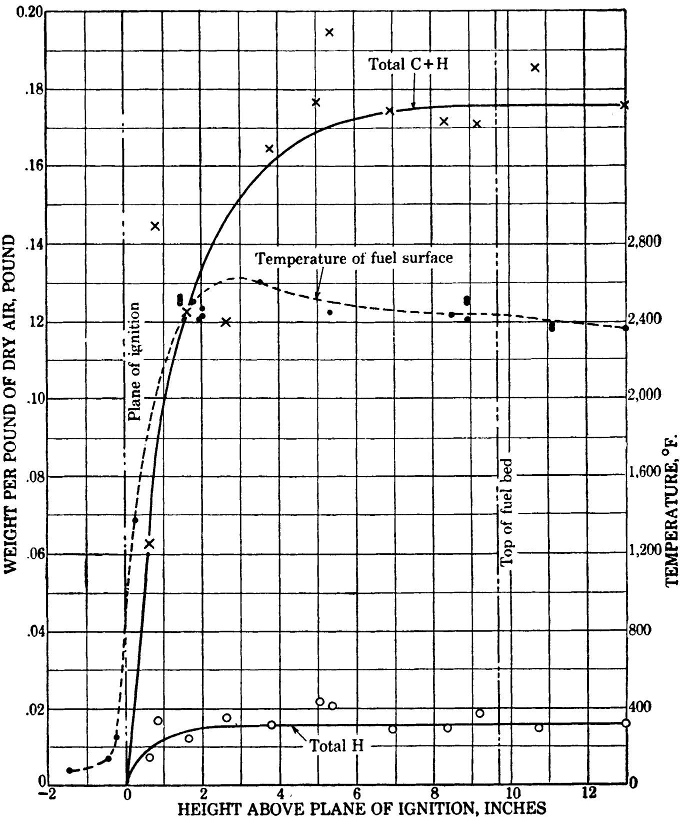

FIGURE 23.—Underfeed burning, action through fuel bed expressed as weight of fuel products carried per pound of dry air supplied as temperature, ¾- to 1-inch Illinois coal (see also fig. 22).

Figure 24 shows the distribution of heat in the products of combustion through the fuel bed per pound of primary air; the heat values for the hydrogen of the H_2, H_2O, and CH_4 are on the gross and not the net basis. The " heat released " comes from the reactions forming CO_2, CO, and H_2O, and the total of these heats at each height fixes the temperatures through the bed. The full-line curves show the " heat not released " but as available to be released in the combustion space. Comparison of the amounts for the various constituents at each height is of interest but need not be discussed. It will be noted that the H_2O value becomes zero at 6 inches, whereas the top curve of figure 22 shows that water vapor was part of the constituents all through the bed. The reason for this is that the final weight of H_2O, as expressed by its equivalent of 0.004 pound of H_2, happens to correspond to the weight of H_2O corresponding to the O_2 in the coal; this O_2 in the coal has been assumed—as is customary—to be combined with hydrogen, and thus its heat equivalent is not available to be released during combustion. The following gives some summary values for the gases leaving the fuel bed:

	Percent of total available heat
Heat released in bed	36.6
Heat not released	63.4
Heat available in soot	5.2

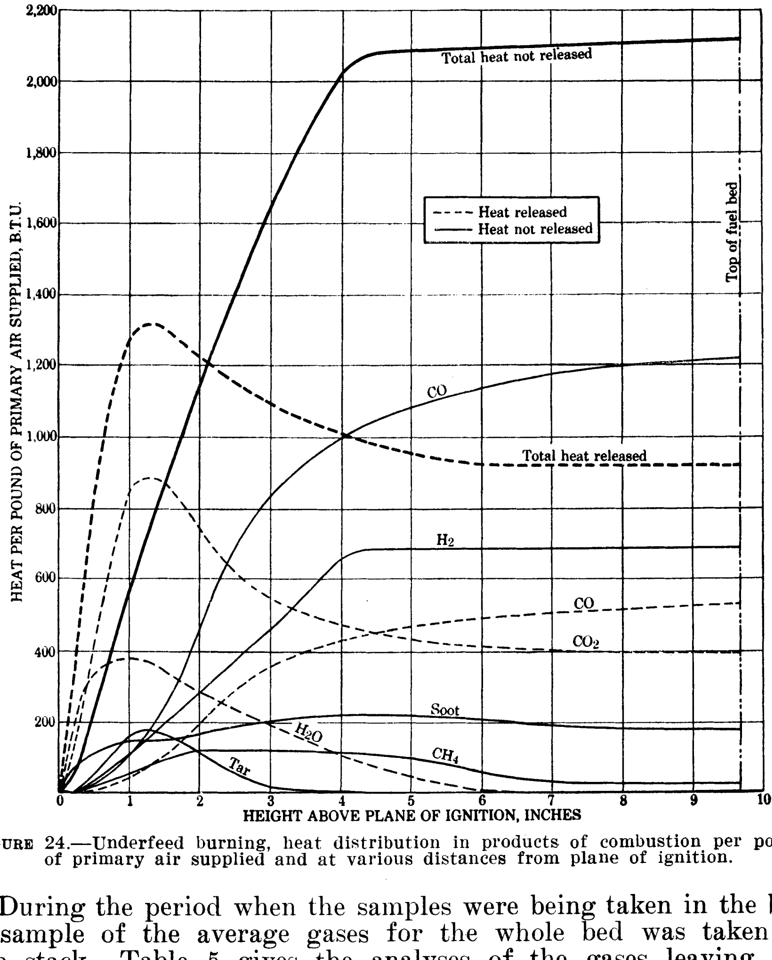

FIGURE 24.—Underfeed burning, heat distribution in products of combustion per pound of primary air supplied and at various distances from plane of ignition.

During the period when the samples were being taken in the bed a sample of the average gases for the whole bed was taken at the stack. Table 5 gives the analyses of the gases leaving the central 6-inch area studied and the average for the whole bed.

Table 6 shows that the air was not distributed uniformly over the bed but that a greater proportion passed around the sides. Because the average air rate in pounds per square foot per hour was 260, that at the center would be 190. Leakage around the sides always occurs, and that it was not more than these values show indicates there was relatively little caking of the fuel.

TABLE 6.—*Gas analysis at center and for whole bed*

Constituent	Percent by volume, wet basis		Constituent	Percent by volume, wet basis	
	At center	Average		At center	Average
CO_2	4.79	8.17	CH_4	0.09	0.19
O_2	0	0	N_2	58.07	64.29
CO	21.08	14.13	H_2O	4.22	7.97
H_2	11.75	5.25	C+H per pound of air ....pound..	.175	.130

DISCUSSION AND CONCLUSIONS

The results of these two studies of the process of ignition and of burning present a fairly complete picture of what occurs. The particular numerical values found should not be stressed, as they will vary with the fuel, its size, and the air rate. One might have expected that the process of ignition would be more drawn out—that is, would have extended over a longer length of the bed; but although the heating up of the fuel extended 3 to 5 inches below what has been designated as the plane of ignition, when the fuel is once ignited the rate of combustion increases very quickly, so that the curves rise almost as rapidly as they do in overfeed burning.

The volatile matter also evolves very quickly. Most of it had been evolved in the first inch above the plane of ignition, equivalent in this test to about 4½ minutes, during which time the piece of coal ¾ to 1 inch in diameter had to pass from initial ignition to complete coking.

Some general conclusions follow:

(1) In an underfeed fuel bed, heat is abstracted from the lower part of the burning zone to heat the incoming fuel so that reactions all through the bed lag because of this abstraction of heat.

(2) In an overfeed bed, the heat required by the incoming fuel is not abstracted until the reactions through the bed are completed; although the same quantity of heat is required as with the underfeed and the temperature of the outgoing gases is lowered, this does not affect the reactions in the bed below.

(3) The fact that the fuel is being heated up and is of a larger size at the ignition end of an underfeed bed reduces the rate of reaction there; in other words, it lengthens the time required for the same total reaction more so than does the fresh fuel at its ignition end of an overfeed bed, where the rate of reaction is very slow, as figure 2 shows.

(4) Consequently, for the same size of fuel, for the same rate of air supply, and the same weight of combustible per pound of air carried by the exit gases—that is, the same rate of burning—the equilibrium depth of an underfeed bed will be greater than that of the overfeed.

That the process of ignition hampers the burning in an underfeed bed was shown in a number of tests at air rates for which the rate of burning was less than the rate of ignition, and the thickness of the live bed was increasing continually; in these tests the rate of burning was approximately constant when the plane of ignition reached the grate. When it reached the grate, and there was no more fuel to ignite, the rate of burning increased very rapidly, although the air rate was not changed. This increase with the cokes was sometimes more than 50 percent; with the bituminous coals sometimes there was no increase, because at low rates the burning was not uniform over the area of the bed.

Evidences of this action should occur in stokers; when at low rates the coal feed has been too rapid, and it is stopped, one would expect the boiler output to rise temporarily.

It should be remembered that the actions depicted are for fuel beds with unrestricted ignition. With high-temperature coke and restricted ignition the forms of the curves could not differ much from those of figure 21; the maximum value that would be attained by the CO could be predicted fairly accurately from the point of operation, as given by figure 8 or 10, *A*. Prediction for a coking coal is less certain, and probably the actions will depend materially on the particular conditions—that is, the size and design of the stoker.

DISTRIBUTION OF ASH THROUGH FUEL BEDS

The release of ash from a fuel can occur only as the pieces of fuel decrease in size by the burning of the combustible, which thus exposes the ash. When the high-temperature coke is burned it is not far wrong to assume that the quantity of ash released is proportional to the carbon gasified, although this will not be entirely true because the gases may penetrate the pieces of coke, and some gasification of carbon may occur in the interior; thus the proportion of ash released will increase as the piece of fuel grows smaller.

When coal or other fuel containing volatile matter is being burned the fixed carbon will not burn until the piece of fuel is coked, although the truth of this statement is limited by the size of the pieces of fuel and the rate of burning, because the fixed carbon at the surface of a large piece may burn before enough heat has penetrated to the center and completed the coking; however, the statement is correct for fuels as used on stokers.

Ordinates of curves such as those of figure 3, when multiplied by the pounds of air per hour, give the sum of the rates of burning of the combustible up to each height; therefore the rate of burning at any height is proportional to the slope of the tangent—or the difference between successive ordinates; assuming coke is being burned, this derived curve is also that for the rate of release of the ash to a scale fixed by the pounds of combustible per hour multiplied by $\frac{\text{percent of ash}}{\text{percent of combustible}}$ in the coke.

Figure 25, *A*, illustrates the rate of ash release. The depth of the live fuel bed is 10 inches. Curve *C* is for the total pounds of combustible (C+H) carried in the gas per hour per square foot and is assumed to be the same for an overfeed or underfeed bed; this assumption is justified because the same shape of curve can be obtained by adjusting the size of the fuel and the rates of air supply; a somewhat smaller size would be required for the underfeed. Curve *A*

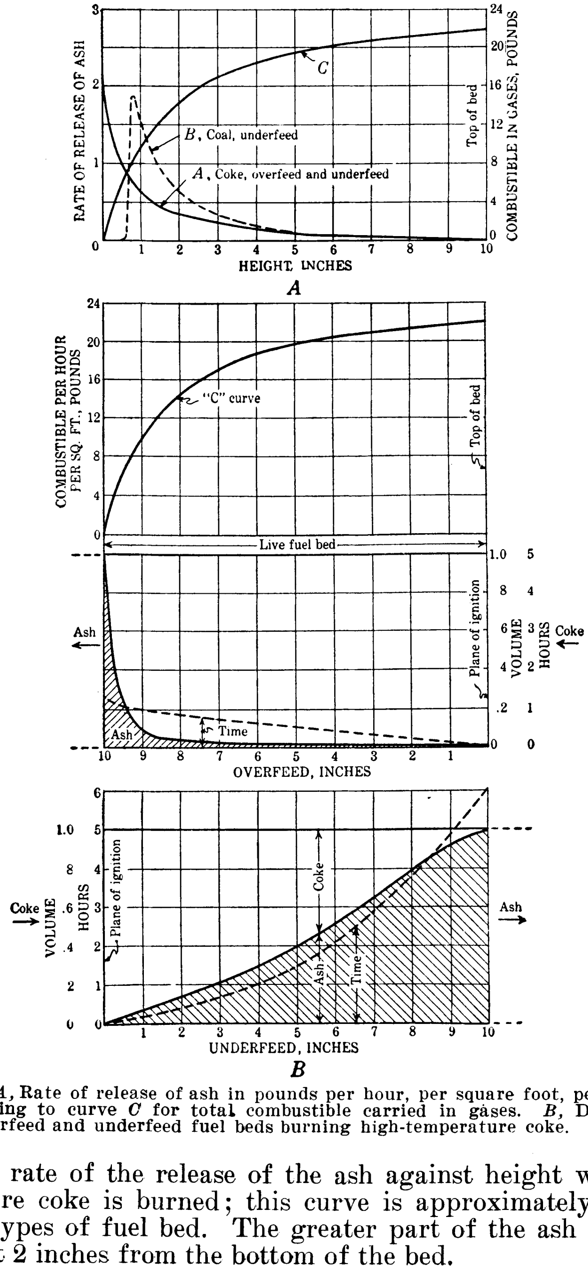

FIGURE 25.—*A*, Rate of release of ash in pounds per hour, per square foot, per inch height, corresponding to curve *C* for total combustible carried in gases. *B*, Distribution of ash on overfeed and underfeed fuel beds burning high-temperature coke.

shows the rate of the release of the ash against height when high-temperature coke is burned; this curve is approximately the same for both types of fuel bed. The greater part of the ash is released in the first 2 inches from the bottom of the bed.

For bituminous coal with the same ash content as the coke the curves for the rate of release of the ash would not be the same for the two types of fuel bed. For an overfeed bed the curve would be the same as *A*, except that it would start at about the 9- instead of 10-inch height, the volatile being released in the first inch. For bituminous coal and underfeed burning, there would be a material difference as shown by curve *B*, but even then curve *B* differs little from curve *A*, except that it is shifted about three fourths of an inch higher in the bed.

The ash released at a given height does not remain there but is carried along with the fuel; therefore the distribution of the ash through the bed is the resultant of the rate of release and the movement of the fuel. The rate of travel varies through the bed; at the plane of ignition the velocity is that of the entering fuel, and at the other end of the bed it is that of the ash and clinker. Some of the ash which is released may be carried out of the bed as fly ash. If the relation between the weight of the ash which remains in the bed and the volume it takes is known, it is possible to compute the movement of a piece of fuel through the bed, as well as the distribution of the ash; in fact, a complete picture of the bed may be obtained. Appendix II is a mathematical treatment of ash distribution; it gives formulas for the various quantities and shows how the corresponding curves can be obtained.

The distribution of the ash can be pictured best by the proportional part of the volume that it occupies; thus, in a plane through the fuel bed at a given height the ash can be said to occupy three tenths of the volume, and the fuel the remaining seven tenths; these are apparent volumes—that is, they include the spaces, or voids, between the pieces. In distributing the total voids it has been assumed in the numerical examples that the unburned coke has the same apparent weight as the coke had before it was fired and that the volume of the bed occupied by the ash and clinker includes the voids which always exist in fuel beds unless they are continually poked or shaken down.

Figure 25, *B*, is an application of the mathematics to show a comparison between overfeed and underfeed fuel beds when high-temperature coke is burned. Both beds are assumed to be burning in equilibrium and to have the same rate of burning, the same height of live fuel bed, and the same *C* curve. The numerical values taken for the constants required by the equations in appendix II are:

F, rate of feed of coke = 25 pounds per square foot per hour.
W, apparent density of coke = 30 pounds per cubic foot.
w, apparent density of ash = 30 pounds per cubic foot.
m, proportion of combustible in coke by weight = 0.88.
n, proportion of ash in coke by weight = 0.10.
r, proportion of ash retained in bed = 0.80.
H, height of live fuel bed = 10 inches.

The top plot shows the *C* curve—the pounds of combustible carried by the gases; at the top of the bed the weight of combustible equals 25 times 0.88, or 22 pounds per square foot per hour. The middle plot shows the curves for the overfeed and the bottom plot those for the underfeed bed; each of these contains a time and an ash-distribution curve. The zeros for the time curves are at the planes of ignition; their ordinates give the time that it takes an imaginary plane of the fuel to travel the corresponding distance or, what is the same thing, the time taken by any piece of coke. The ash curves show the distribution of the released ash that remains in the bed; thus the shaded areas show the quantity of ash in the bed.

These curves bring out the great differences between underfeed and overfeed beds. The time required for an average piece of coke to travel through the live fuel bed is 6.1 hours for the underfeed and 1.35 hours for the overfeed bed, or 4.5 times as long. The percentage of the whole volume of the live fuel bed occupied by the ash (given by equation 7 in appendix II) is 44.3 for the underfeed and 3.1 for the overfeed, or 14 times as great for the underfeed.

These relationships may appear to be large, but they are relatively correct. The only constant the numerical value for which may be questioned is w—the apparent density of the ash and clinker; its value will vary with the type of clinker formed and probably would be larger for the underfeed than for the overfeed because the ash will be more fused. An increase in the numerical value of w will increase the time it takes any piece of coke to pass through the bed; this can be deduced from the form of equation (2). Common sense dictates that a greater *weight* of clinker will accumulate in the bed as the time for a piece of coke to pass through it is longer; the form of equation (7) shows that the *volume* of the ash in the fuel bed may or may not increase, depending on the values of the other constants. These relationships apply both to the underfeed and the overfeed bed, but the numerical changes in the time or in the volume occupied would not be the same.

The exact numerical values have no particular interest at this time; it is more important that the principles disclosed by these computations and curves should be understood.

The analysis assumes that the released ash travels along with the piece of coke from which it came; actually some of the ash will melt and will tend to fall to a lower level, which will decrease the quantity of ash stored in the bed in the overfeed and increase it in the underfeed.

The question might be raised that if the underfeed bed contains so much more ash, the assumption is not justified that it can have the same C curve for the same depth of bed. However, figure 25, *B*, shows that the ash with underfeed burning is not dense at the lower part of the bed where the greater part of the burning reactions occur, although the combustion reaction of converting CO_2 to CO probably could not be carried as far in the underfeed and it would not be possible to have as much CO in the exit gases; this is indicated by the two curves for 80° air in figure 3. By using a smaller size of coke with the underfeed the rate of reactions could be made the same as for overfeed burning of a larger coke, and the assumption that the C curves could be approximately the same was justified.

In an overfeed bed distribution of ash when coal is burned would be the same as that for coke because all coal is coked at the top of the bed. Figure 26, *A*, shows curves for the underfeed burning of coal. For this illustration the Illinois coal listed in table 2 was used; the rate of burning corresponds to the tests that gave figures 22 and 23. From the analysis the volatile matter of the coal formed 30 percent of the total combustible; the resulting values for the constants for the coke formed in the bed (see p. 76) are: $F'=28.25$; $m'=0.863$; $w'=25.7$; $n'=1.37$; r was assumed as 0.7 and w as 30. The curve for total combustible was derived from figure 23 and that for the burning of the coke as fixed carbon from figure 22.

Figure 26, *A*, shows that even at this high rate of burning of 48 pounds of coal per hour a piece of coal requires 5 hours to pass

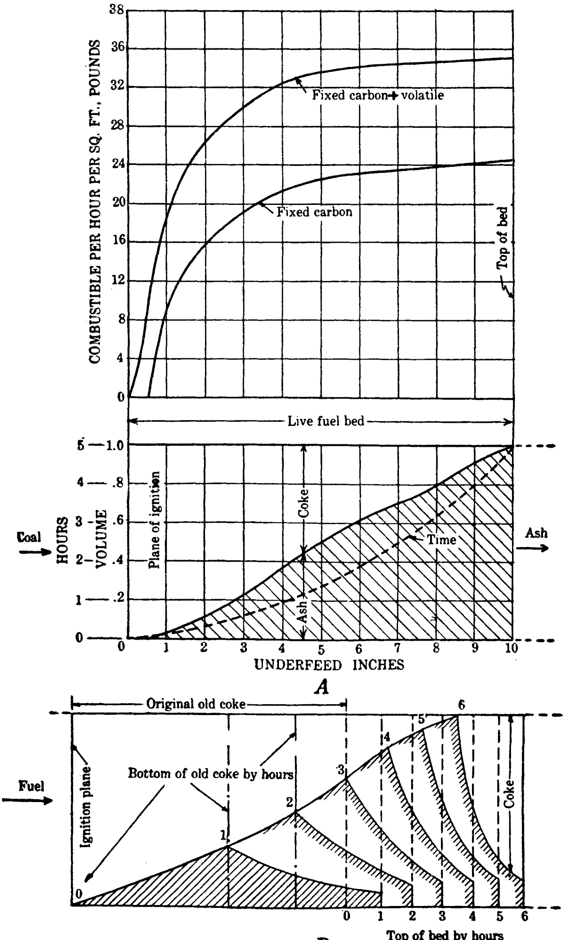

FIGURE 26.—*A*, Distribution of ash in underfeed fuel bed when burning Illinois coal. *B*, Progress of accumulation of ash.

through the live underfeed fuel bed and that there would be a large accumulation of ash in the bed.

In the foregoing examples, it was assumed that the ash was uniformly distributed through the coal. If some of the ash were lumps of slate, the curves for the distribution of the ash would have to be modified. A close approximation to the modified curve could be obtained by assuming that the slate passes through the bed without change in volume.

The following is an illustration of how understanding these principles may assist in explaining peculiar occurrences in fuel beds: Assume that a stoker of the pot or single-retort type has been burning and has become full of clinker, as indicated by the plot for underfeed in figure 25, *B*. Then—as is customary—let the attendant clean the fire, and, assuming that the clinker is such that he can do a good job, let him remove it all and leave a good bed of coke; then let burning proceed while the same rate of feed is maintained. The distribution of ash in the part of the bed which will be formed by the fresh coke will still apply, but the accumulation of ash in the old coke must be traced through. Assuming that the constants are the same as those for figure 25, *B*, the tendency for ash to accumulate is shown in figure 26, *B*, in which the curves are for distribution of the ash at successive hours indicated by their numbers. The point brought out is that, finally, the top of the bed will be covered with a layer of good coke, while actually below the coke the bed is completely covered with ash and clinker; moreover, the possibility is that the upper layer of coke never will have a chance to burn.

This same isolation of coke at the top of the bed would occur in the method of underfeed burning used in this investigation, in which a live fuel bed is formed quickly by down-ignition, but it would require a deeper original bed than that used. It also will occur in large stokers, although the successive steps will be more complex. Actually, stokers are so operated that the coke has some opportunity to burn at the end of the travel, but it is one of the factors that may cause loss of combustible.

APPLICATION OF RESULTS TO UNDERFEED STOKERS

Some deductions on how the experimental burnings are related to the actions that occur in the fuel beds of underfeed stokers have been suggested in the previous part of this report. All the tests were made with unrestricted ignition, and it was shown that the resultant burning is the maximum that can occur with each rate of air supply and that, with a given rate of air supply, a restriction of the rate of feed below its corresponding rate of ignition will result in a thinner fuel bed and a rate of burning equal to the rate of feed, together with a reduced requirement for secondary air.

It was also shown that the main difference between overfeed and underfeed burning is that with the former the rate of burning can be increased indefinitely, provided the fuel is not blown out of the bed, but with the underfeed there is a limitation to the rate fixed by the rate of ignition.

No attempt will be made to picture completely what goes on through the length of the fuel bed of a large underfeed stoker because that would necessitate defining the paths of the various streams of incoming coal and the distribution of the air. Presumably some coal may have a superimposed vertical motion; and undoubtedly, even in the same stoker, the actual paths will not be the same at all rates and with different coals. In addition, distribution of the air flow through the coal will depend on the caking and on how the caked coal is broken up by the motion. However, one can draw some conclusions as to possibilities, especially for rates of burning near the limit of the ignition rate, because this is the range covered by these tests.

Considering figure 27, line *ab* corresponds to the heavy lines of one of the figures for bituminous coal, and it gives the rate of burning with unrestricted ignition in a quiet (that is, unagitated) fuel bed; because a caking coal burns as a free-burning fuel along this line, presumably the burning would be changed little, even if the bed were agitated. Considering still the unagitated bed and assuming that one is operating at the feed and air rates of point *a*: If one began to restrict the rate of feed and to reduce it below the ordinate of point *a* and at the same time to reduce the air rate just enough

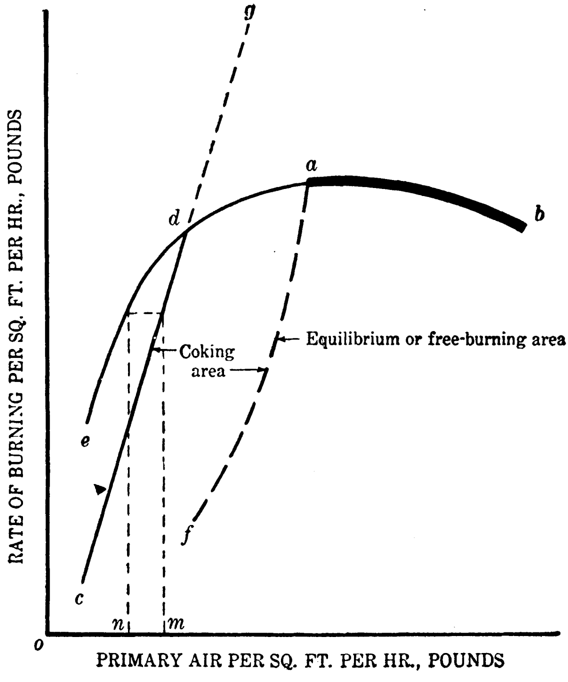

FIGURE 27.—Diagram of operation.

to maintain the noncaking, or free-burning condition, probably one would move along some curve *af*, although the position and shape of this line are not based on experimental data. Therefore, with a nonagitated bed, operation anywhere in area *fab* would be free burning.

Assuming that the bed were agitated enough to keep the fuel pieces free from each other, the curves for unrestricted ignition would be similar to those for a noncaking fuel such as *cd* and *edb*; it follows that with agitation and with a restricted feed, operation with an equilibrium bed would be possible anywhere within area *cdb*.

These deductions are based on the assumption that the air passes through the incoming coal and keeps it cool; if it did not, and if the coal were heated up and coked before it reached the air stream, then—unless this coke were broken up—the deductions for the non-agitated bed would not hold.

One has to use more imagination when trying to picture a cross-section of the fuel bed of an actual stoker but is on safer ground if the stoker is operating at the limit of its ignition rate, that is, on line *db* of figure 27 for an agitated bed. Figure 28, *A*, represents a section of a stoker operating at maximum rate, but on the assumption that the fuel is moving vertically.

Assume that the coal feed has brought the ignition plane to position *AB*, shown in the left half; then the conditions of ignition are the same as those of these tests, and the same values should apply. The rate of air supply per square foot would be fixed by the area of surface *AB*, and the rate of ignition by the ordinate of the point on *db* of figure 27 which corresponds to the air rate. If the coal feed were reduced for a time, so that the ignition line fell

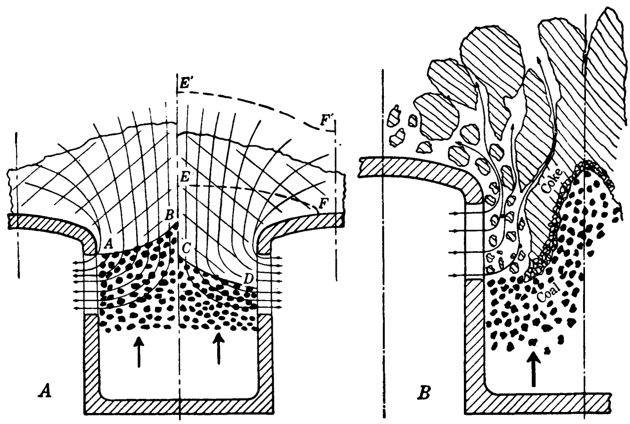

FIGURE 28.—*A*, At maximum burning rate. *B*, Probable normal action.

to what probably would be line *CD* of the right half of figure 28, *A*, the average air flow through the ignition plane would be reduced—although the total air was not changed—and the measure of the ignition rate would move along line *bd* of figure 27; as it approached *d* the rate of ignition, and consequently the rate of burning, would decrease. With a fixed rate of coal feed and air supply the plane of ignition would find some position along the height of the air slot which would produce equilibrium.

As one tried to push the output by increasing the coal feed it can be conceived that the line of ignition might be raised to *EF* with the top of the bed as shown dotted; because this increases the area of ignition, a corresponding increase in the maximum rate of burning would be possible.

It must be recognized that in all these illustrations there is no question about the ability to burn the coal; as long as one is operating—for an agitated bed—along line *db*, the rate of burning for any rate of air supply could and would be limited only by line *dg* if it were not that it is limited by rate-of-ignition line *db*. It does not matter whether the stoker is a simple pot, which was the type used in these tests, or whether the fuel flows over the side, as is represented in figure 28, *A*. With continuous operation the height and shape will adjust themselves to give a rate of burning equal to the rate of ignition.

Although noncaking fuels are not burned in large underfeed stokers it is of interest to extend the argument of the last paragraph to what would occur at low ratings. If a noncaking fuel were being burned under conditions represented by figure 28, *A*, and if the rate of air supply were less than that of point *d* of figure 27, under continuous operation the ignition plane would find some level like *CD* of figure 28, *A*, which would make the rate of ignition equal to the rate of burning. If in figure 27 the total quantity of air supplied is *om*, the quantity passing through the ignition plane would be *on* and that above ignition plane *nm*.

In the foregoing discussion of the ignition in an agitated bed it was assumed that the caked coal is well broken by its movement. This will not occur with a good caking coal, and the motion will split the mass into relatively large pieces. The result will be that most of the coal will not come in contact with air until it has been coked and most of the actual ignition will occur at the surfaces of the large coke pieces. Figure 28, *B*, presents such a conception. Because of the large size of the pieces of coke the equilibrium depth of the bed must be greater to allow enough area of the surface of the fuel for the reactions to occur. The fuel around the air slot will be consumed more rapidly, thus undermining the coke mass so that it may fall over, or the coal rising in the center may act as a wedge and push the coked fuel toward the sides.

At low rates of coal feed for which the point of operation would fall well below line *cd* of figure 27, the rate of ignition would be large compared with the rate of burning. The ignition plane would sink as low as it could, but it could not go below the plane of the air stream; however, the coal below the ignition plane would be heated by radiation and conduction and would not be cooled by the air stream. Consequently, it would coke, and its volatile would rise into the air stream. Although the volatile would be ignited and burned, the remainder of the coal or the coke cannot be said to be ignited until it rises and its surface meets the air stream. If conditions are as conceived in figure 28, *B*, there is no definite plane of ignition, but at low rates the reactions undoubtedly will be somewhat as depicted. It would be under such conditions that the coking qualities of the coal and the agitation it gets would have the greatest importance in determining the fuel bed that would result.

Continuous operation of power-plant type underfeed stokers probably is based on the coking of the most of the coal before it met the air stream. The heat to produce this coking is supplied by burning of the volatile matter driven off from the coal. The thoroughness of the coking will depend on the depth to which the heat will penetrate—that is, the temperature gradient through the coal; again, the gradient will depend on the rate of movement of the coal. There have been a number of investigations on the rate of coking,[15] and

[15] Burke, S. P., Schumann, T. E. W., and Parry, V. F., The Physics of Coal Carbonization: Proc. Am. Gas Assoc., 1930, p. 820.

these data could be used as a guide if the travel of the coal were known.

The size of the lumps of coke will depend on the thoroughness of the coking, but the action of the motion of the bed in breaking up the masses is so important that an attempt to separate these effects would be mere speculation. However, it is not necessarily true that the most thorough coking will give the largest lumps, because in complete coking shrinkage of the coke develops cracks; moreover, a caked mass which is not coked thoroughly is tougher and will deform without breaking. The period during which the coal is heated probably will be increased because it does not move directly into the air stream but enters it at an angle or even moves parallel to it; this action is illustrated by figure 28, *B*, in which the lump in the center is represented by a coking zone. It is certain, however, that as the output and rate of feed are increased the time of the coking will be reduced and that at least some of the bed will approach the state illustrated by figure 28, *A*.

The suggestion has been made that as the size of the lumps of coke increases the depth of the bed must be increased if the CO_2 content of the gases from the bed is to be maintained. This will be more necessary if the coke is moved longitudinally, so that it is no longer over the part of the bed where the volatile matter is being evolved—that is, if the oxygen of the air has not been used up by the volatile matter. Thus one would expect that the depth of the "hump"—usually recommended for moderate-size stokers—should be greater, as the coal gives large lumps of coke.

Figure 28, *B*, depicts a column of uncoked coal in the center of the bed, and it is common knowledge that this sometimes occurs in small stokers. Presumably it is usually caused by poor adjustment of the rate of feed, but the tendency to form such columns will be a function of the coking characteristics of the coal. It is not known whether similar formations occur in larger stokers; but there is no reason why they should not, although they may be checked by the longitudinal movement of the bed.

The foregoing discussion shows that in underfeed stokers, coals which cake will not burn on the pure underfeed principle but partly as underfeed and partly as overfeed. The relative amounts of the two types of burning will depend on the degree of caking, the rate of burning, the size of the pot in small stokers, the width of the trough in large stokers, and how far the air is forced into the coal rising into the fuel bed. Some of the coal will be ignited on the pure underfeed principle, but over this more or less coked coal will be fed from the center of the pot or trough. The quantity of coal ignited by underfeed ignition will increase with rate of burning; but on the other hand, the rate of burning will not necessarily be limited by the rate of ignition as long as the other combined actions result in the feeding of coked coal into the path of the stream of air and gases. The principles fixing the final limitation to rate of burning will be, first, the time and conditions necessary to coke this coal at least enough that it will be so bound together that it will not be blown out of the bed, or will not create too much smoke; and, second, that this overfed coke will so smother the coal below it which is being ignited that it also will not be blown out of the bed. In large stokers there will be the additional limitation of the ability to maintain uniformity over the whole area of the bed and to prevent the formation of blowholes.

EFFECT OF SIZE OF FUEL IN UNDERFEED STOKERS

The effect of the size of the coal pieces on the burning in a stoker will depend on the rate of burning. When working at high ratings, as illustrated by figure 28, *A*, a decrease in size will permit an increase of the maximum rating possible, neglecting, of course, limitations by the quantity of air that can be forced through the bed because of increase in resistance with decrease in size. When working at low ratings in which masses of coke are formed, the first effect will not come into play, and it can be presumed that the effect of size will be that larger sizes will give a better chance for the air to penetrate a mass when it is only partly fused together and is not fully coked; this will mean that the mass will be partly burned and therefore more open and fragile.

EFFECT OF PREHEAT IN UNDERFEED STOKERS

The results of the use of preheat with underfeed stokers have been described in a number of papers by operators, and the subject has also been debated extensively. It is therefore worth while to attempt to interpret the results of these tests. The argument will be itemized.

(1) Neglecting the effect of ignition and only considering the effect of preheat on a fuel bed of a given depth the tests show that the additional heat contained in the preheated air is utilized partly in increasing the rates of reaction in the fuel bed—that is, in increasing the rate of combustion for the same air rate—and partly in increasing the temperature of the gases leaving the fuel bed. Partition of the total heat into these two portions will depend on the depth of the bed, but approximately it can be said that 50 percent goes to each action.

(2) As a result of item 1, with preheat usually there will be more CO in the gases, and more secondary air will be required.

(3) Presumably the higher temperature of the gases leaving the fuel bed will tend to cause better combustion in the combustion space, but as this increase is added to an already high temperature it is questionable whether the benefits gained because of the increased temperature of the gases from the preheat will offset the disadvantage that there is more CO in the gases and thus more secondary combustion action will be required; moreover, the available higher temperature of the top of the fuel bed and in the gases will be lowered because of the increased radiation to the water surfaces. Such questions could be settled only by tests, but the variations to be determined usually would be less than those of operation.

(4) Thus it would appear that preheat will give only limited assistance to the combustion. This does not, of course, affect its value as a means of producing an increased over-all economy of the system.

(5) The tests showed that the outstanding effect of preheat on all fuels was that it increased the rate of ignition; for example,

based on a normal air temperature of 80°, preheating the Illinois coal increased the maximum rate of ignition 35 percent for 200° and 85 percent for 300°. For Pittsburgh coal the increases were 19 percent for 200° and 43 percent for 300°.

(6) It would therefore appear that the most useful function of preheat is that it permits higher rating to be obtained and that a moderate preheat will increase the range of output materially.

(7) No attempt has been made to suggest the position or shape of the ignition plane in the complex fuel beds of large stokers. Still confining our argument to high ratings, for which the ignition would correspond in principle to figure 28, *A*, the quantity of preheat would influence the position of the plane of ignition and might be used to some extent to control it.

(8) Because preheat increases the rate of ignition, if the preheat used produces a rate of ignition greater than that required for the rate of burning, it will in general tend to bring the burning nearer the metalwork of the stoker. Consequently, burning of stoker parts with preheat may be directly due, not to the increase in temperature because of the added heat but because it causes the fuel to burn nearer the metal. It would therefore appear that troubles might be decreased by reducing the preheat temperature if it is higher than that required to give the rate of ignition necessary for the rate of burning.

(9) In this investigation it was impossible to make a successful test with 400° preheat, whereas higher temperatures have been used in service. This is no anomaly, because the method of test necessitated heating all the coal and maintaining it at the full temperature for 1 hour or more. In service the coal will not be heated materially until it meets the air stream.

(10) It is difficult to suggest any advantages because of improvements in burning characteristics that will result from the use of preheat at low rates of burning, as represented by figure 28, *B*. The coal will be coked more thoroughly, and the improvements must be found in the actions covered in items 1, 2, and 3.

It is recognized that the pictures suggested in the foregoing may not agree with what occurs in a large stoker; a much larger proportion of the coal may be heated, lose its volatile, and be coked before it meets an air stream. They may, however, help those who operate such stokers better to analyze what actually happens.

The speculations in this section on what may happen in the fuel beds of underfeed stokers are not based on experiments but are given as suggestions. Such data can be obtained reliably only by experimentation with each type of stoker and of coal; and the usefulness of the data presented in this report is limited to presenting a picture which may help in explaining what has been found to happen, or in suggesting the causes of troubles and possible methods for alleviating them.

IGNITION ON CHAIN-GRATE STOKERS

As pointed out in connection with figure 5, length *U* (the portion in which ignition is taking place) of the bed of a chain-grate stoker is burning on the underfeed principle with unrestricted ignition; the ignition is by radiation. In the tests covered by this report the top of the bed was ignited by a layer consisting of $1\frac{1}{2}$ pounds of charcoal and 2 pounds of petroleum coke, both wetted with kerosene; the fan was started as soon as the kerosene was alight, and in most tests the rate of air supply was at once brought up to that to be used in the test, There may be question as to whether this type of ignition is comparable to that by radiation; but at least it was consistent, and the results are comparable after initial ignition of the top layer—that is, for the rate of travel of the plane of ignition.

The time required for the plane of ignition to travel down the first 4 or more inches would correspond to the similar action on a chain-grate stoker; compounding this rate with the speed of the grate gives the slope of the plane of ignition.

The two top thermocouples were about 3 and 7 inches, respectively, below the original surface of the bed and thus gave the elapsed time between the lighting of the fire and the plane of ignition reaching these known depths. These values were plotted and showed fairly consistent results.

There is no necessity to give all the results, so some of those for Pittsburgh coal are selected for illustration.

TABLE 7.—*Rate of ignition of top portion of fuel bed; Pittsburgh coal, 1- to $1\frac{1}{2}$-inch size*

Air rate per square foot per hour, pounds	Air tempera-ture,°	Time to travel, minutes		Air rate per square foot per hour, pounds	Air tempera-ture,°	Time to travel, minutes	
		0 to 3 inches	0 to 6 inches			0 to 3 inches	0 to 6 inches
142	80	28	100	350	200	15	26
240	80	21	66	540	300	13	25
350	80	16	27	540	400	9	19
540	80	19	32				

Table 7 lists these results and shows the time taken by the plane of ignition to travel the first 3 and the first 6 inches; these depths do not include the charcoal and petroleum coke used to start the ignition. Figure 16 gives the average rate of ignition, and comparison of these two sets of values shows that they are of the same order and are influenced by the same factors of rate of air supply, size, and temperature. The same conclusion applies to the other fuels.

There is, however, one important distinction. Table 7 shows that at the 142- and the 240-pound air rates the time to travel 3 to 6 inches is much longer than that from 0 to 3, whereas for the 300-pound and higher rates the times are about the same. From figure 16 it is seen that equilibrium burning of the 1- to $1\frac{1}{2}$-inch size started at 330 pounds and that the curve for the rate of ignition decreases very quickly for lower rates. This slowing of the rate of ignition is caused by the caking; the same action occurred with the Illinois coal. On the other hand, high- and low-temperature coke and splint coal did not show this difference. That the latter did not cake in the first 6 inches is not surprising, as its caking is less definite and takes more time; also, figure 15, *B*, and these analyses show that its rate of ignition is high, and thus the time is shorter.

These results on the effect of the thickness of the fuel bed on the time it takes coal to ignite clear through may have some importance in the operation of chain-grate stokers burning a caking coal. The deductions would be as follows:

(1) When burning proceeds at a rate below that of equilibrium burning there will be a certain thickness of fuel bed above which it is not desirable to go because thicker beds will allow the coal to cake, with the result that:

(*a*) The time for the ignition to reach the grates will be increased materially.

(*b*) The slope of the plane of ignition will be lengthened materially.

(*c*) The resistance of the fuel bed—or rather, at least that portion of the bed which is being ignited—will be increased.

(2) If burning is at high rates above that of equilibrium the coal will not cake, and the thickness of the bed may be increased to any degree that will facilitate obtaining the high rate.

It is granted that actions 1 (*a*) and (*b*) may not—within moderation—be a disadvantage, as they may make the burning more uniform over the length of the grate, provided the draft is available.

The rate of burning for equilibrium is high and will be beyond that usually required in operation; from figure 14 it is 35 pounds per square foot per hour for ¾- to 1-inch Illinois coal and from figure 16, 42 pounds for ½- to ¾-inch Pittsburgh coal.

Table 7 shows that preheat increases the rate of travel of the ignition, and its effect also can be judged from figure 16. At low rates it may be a disadvantage, because it will increase the caking and thus the resistance of the bed. After the ignition has reached the grates the type of burning will go through the change-over period, then the actions through the fuel bed will correspond to those of overfeed burning. Because the fuel beds of chain-grate stokers are not thick the preheat can exercise its accelerating effect, which was discussed in part I of this report under Effect of Preheat on Overfeed Fuel Beds; thus it should produce a material increase in the rate of burning for a given rate of primary air.

There is one weak link in the data on which the deduction is based that caking will decrease as the fuel bed is thinner. It is assumed that the clogging that was found in the 6 inches was due to the caking in the thicker bed. It has not been proved that caking does not occur in a 3-inch-thick bed after ignition has reached the grate, even though it does not occur during the time of travel. However, it has been shown that the rate of burning increases as soon as the travel of the ignition plane is stopped by the grates, and this should tend to keep the spaces open. More experimental work is needed on this phase.

This discussion of ignition on chain-grate stokers refers only to the rate of travel. These tests do not give any information on or comparison of what may be termed the initial ignition of fuels by radiation.

APPENDIX I.—SPECIFICATION FOR PROCEDURE IN OVERFEED TESTS

The apparatus and the procedure followed in the tests to determine the effect of preheated air on overfeed burning were essentially the same as those used in the investigations of the combustibility of cokes,[16] except that in the former the diameter of the furnace interior was 20 inches and in the latter, 13.5 inches. The apparatus is described briefly in the text. There are many details in the assembling of the apparatus and in the precautions necessary that are not touched on but are important. The following gives additional data on the apparatus and full instructions for the test procedure; quantities apply to the 20-inch-diameter furnace.

FURNACE

The shaking grates should be such that they will crush the clinker and should be in several sections so that little coke will fall through. There should be at least two openings at the grate level through which a poker can be inserted and the clinker broken up; these must be sealed when not being used.

The position of the end of the water-cooled sampler when inserted through each sampling hole must be known accurately. These positions should be measured when the furnace is cold and checked occasionally.

AIR SUPPLY

The air should enter the ashpit at a low velocity so that it will be distributed uniformly over the area of the bed.

GAS CONTAINERS

The gas samples are collected over mercury in glass sample containers of 125-cm^3 capacity. The type used and the method of mounting are described in Bureau of Mines Bulletin 214, page 63; but in these tests they were mounted 12 in a frame, which had trunnions at the ends for mounting on a special table. The assembly of the gas-collecting apparatus is important and should be such that the rubber tubing is kept free from leaks, that it can be swept out by the gas, and that a sample can be taken in the shortest time. The gases should pass through a glass-wool filter to take out the dust.

STANDARD CONDITIONS

The standard depth used for the bed is 24 inches. The standard rate of burning 25 pounds of coke per square foot per hour, for which the air rate for the 20-inch-diameter furnace is 325 pounds per hour. For this rate a thin-plate orifice 2 inches in diameter is convenient.

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[16] Nicholls, P., Brewer, G. S., and Taylor, Edmund, Properties of Cokes Made from Pittsburgh Coal: Proc. Am. Gas Assoc., 1926, pp. 1129–1143.

BUILDING FIRE

The fire is kindled with paper and wood of uniform size; 20 pounds of coke are thrown on as soon as the wood is ignited, and the fan is started. When the coke is ignited more coke is added to increase the depth of the bed to 24 inches, and the air is increased to the standard rate.

TIME FOR HEATING UP FURNACE

The fire is allowed to burn 2 hours before sampling to heat up the refractory.

PREPARATION OF FUEL BED

The objective in handling the fuel bed is to have the same conditions throughout its depth during sampling. The bed must therefore be kept free of clinker; as this cannot be done continuously the sampling must be divided into periods, which comprise: (1) Removing clinker; (2) letting the bed burn to recover its equilibrium; (3) taking one or more gas samples; (4) shaking grates slightly and again poking; (5) taking more samples and repeating this process till a sample had been taken from each hole; (6) taking a temperature reading at each hole; (7) adding more coke. This whole process from 1 to 7 was repeated three times during a day's test.

The poking is done from the top and standardized to five thrusts through the fuel bed. The number of samples taken between each poking should depend on the time taken in the sampling; that used in these tests was after sampling at holes 11, 7, 6, 5, 4, 3, 2, and 1, but the number of pokings may be decreased.

COLLECTING GAS SAMPLES

The gas sampling is started at the top hole. A hole is punched in the fuel bed with a rod which reaches to the center, and the sampler is inserted. The time required to clear the train of old gas should be computed or determined by trial and a time interval fixed when the cocks of the container should be opened. When the sampler is full the gas should be put under pressure by the mercury to prevent leakage.

TEMPERATURE READINGS

Readings are taken by optical pyrometer. A hole similar to that for the gas sampler is punched in the fuel bed; if coke falls into the hole so that the center of the bed is not seen, it should be repoked. It is necessary to have a device with a glass window in it to screw onto the sampling pipes. A special device which has a metal shutter for the glass is used because the pressure in the bed will blow hot gases and flames out of the hole when its cap is removed, and these will dirty the glass of the window. The glass should be kept perfectly clean, and the optical pyrometer should be calibrated with this window as part of the set-up. In these tests a quartz window was used, but good flint glass is equally satisfactory. Three independent readings should be taken at each hole.

APPENDIX II.—MATHEMATICAL TREATMENT FOR DISTRIBUTION OF ASH

The following section gives the simple mathematics to find, in particular, the distribution of the ash through the bed. A complete treatment would include the progress of the burning, as deduced from the rate of the combustion reactions; there are, however, a number of complex conditions which influence the rate of reaction that will require more experimental data before over-all results, such as those given in this report, can be predicted from first principles. It is therefore necessary to depend on curves, such as those shown in figure 3.

When coke is burned the rate of release of the ash is assumed to be proportional to the rate of burning of the combustible; when fuels containing volatile matter are burned, no ash will be released until all the volatile is driven off, unless the pieces of fuel are large. The same mathematical treatment applies to both kinds of fuel, except that for fuels containing volatile matter the curve used for combustible carried in the gases must represent the burning of the coke alone; for simplicity it will be assumed first that coke is being burned.

Burning of fuel means a reduction in its volume, and the volume lost will equal the volume burned minus the volume occupied by the ash that is released by the quantity of fuel burned. The underfeed fuel bed will be considered first.

The following symbols are used in the units of feet-pounds-hours; the area of the portion of the bed considered is 1 square foot.

h=height in fuel bed from plane of ignition, feet.
H=height from plane of ignition to top of bed, feet.
C=combustible carried by gases at height h, pounds per square foot per hour.
t=time from zero time as fixed, hours.
F=rate of feed of fuel, pounds per square foot per hour.
W=apparent density of fuel, pounds per cubic foot.
w=apparent density of clinker in bed, pounds per cubic foot.
m=combustible in fuel, pounds per pound of fuel.
n=ash in fuel, pounds per pound of fuel.
r=ash remaining in fuel bed, pounds per pound of ash in fuel.
y=proportion of volume occupied by ash in bed at height h.

UNDERFEED FUEL BED

It will be assumed that the air rate is constant, that the area of the bed is 1 square foot, and that the fuel is fed uniformly at F pounds per square foot per hour. The only other assumption necessary is that the rate of feed is not greater than the rate of ignition.

In figure 29, A, OI is the plane of ignition and is taken as the zero ordinate. It is required to trace the progress of an imaginary plane of the fuel through the bed, that plane being assumed to be on the plane of ignition at zero time, which can be taken to be at any time after the rate of ignition has become constant.

Curve OT is the total weight of combustible carried by the gases and is therefore the product of the pounds of combustible per pound of air and the pounds of air per hour.

If at a time, t, the plane being considered is at h and advances dh in time dt, then

$1 \times dh$=(volume of fuel fed—volume lost between O and h) in time dt.

But, volume lost=volume of fuel burned—volume of ash retained in the bed.

Therefore, $$dh=\frac{F}{W}\cdot dt-\left(\frac{C}{mW}-\frac{C}{m}\cdot\frac{nr}{w}\right)dt,$$

$$=\frac{F}{W}dt-\frac{C}{m}\left(\frac{1}{W}-\frac{nr}{w}\right)dt,$$

and $$\frac{dt}{dh}=\frac{1}{\frac{F}{W}-\frac{C}{m}\left(\frac{1}{W}-\frac{nr}{W}\right)}. \tag{1}$$

Values for C depend only on h, therefore

$$t=\int_0^h\frac{dh}{\frac{F}{W}-\frac{C}{m}\left(\frac{1}{W}-\frac{nr}{w}\right)}. \tag{2}$$

Because C is only known as a curve, values for t against h must be found by tabulation or graphically.

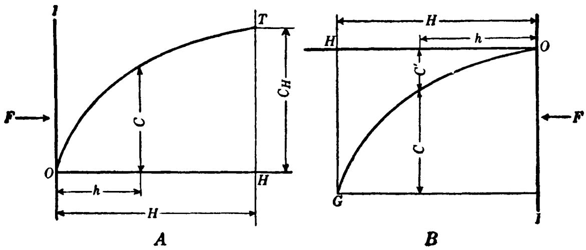

FIGURE 29.—*A*, Underfeed bed. *B*, Overfeed bed.

Up to time t, when the plane under consideration has reached height h, the total loss of volume=(volume of fuel burned—volume of ash released), and this must=(volume of fuel fired—volume it occupies).

Therefore, (weight of fuel burned) $\times\left(\frac{1}{W}-\frac{nr}{w}\right)=\frac{F}{w}t-h\times 1,$

or (weight of fuel burned) $$=\frac{\frac{F}{w}t-h}{\frac{1}{W}-\frac{nr}{w}}=\frac{wW}{w-nrW}\left(\frac{F}{W}t-h\right). \tag{3}$$

Therefore, up to h,

Weight of ash in bed=(weight of fuel burned) $\times nr$,

$$=\frac{nrwW}{w-nrW}\left(\frac{F}{W}t-h\right), \tag{4}$$

and, volume of ash in bed $$=\frac{nrW}{w-nrW}\left(\frac{F}{W}t-h\right). \tag{5}$$

Let y=proportion of volume occupied by the ash at height h. Then volume of ash in a length dh is $1\times ydh=ydh$, and volume between 0 and h is $\int_0^h ydh$. Therefore, from (5)

$$\int_0^h ydh=\frac{nrW}{w-nrW}\left(\frac{F}{W}t-h\right).$$

Differentiating both sides with respect to h,

$$y=\frac{nrW}{w-nrW}\left(\frac{F}{W}\frac{dt}{dh}-1\right). \tag{6}$$

From (6) and (1) values of y against h can be found and a plot made for distribution of the ash in the bed.

The top of the live fuel bed will be at H, where $C=mF$.

The time for any one piece of coke to pass through the bed will be t_H, which is obtained in the plotting of equation (2).

From (5) the volume of ash in the whole bed will be

$$\frac{nrW}{w-nrW}\left(\frac{F}{W}t_H-H\right).$$

As the volume of the whole bed is $1\times H$, the fraction of the whole volume that the ash occupies is

$$\frac{nrW}{w-nrW}\left(\frac{F}{WH}t_H-1\right). \tag{7}$$

The foregoing assumes that the released ash or clinker formed from it moves with the coke and does not melt and run through the bed. Fairly accurate numerical values can be assigned to the various quantities, except for w, the apparent weight of the clinker in the bed; the value taken should be low, as this will allow for the tendency of a fuel bed to develop hollow spaces. The values for F and W should be on the moisture-free basis.

The device used of assuming that the apparent density of the coke in the bed is the same as that of the coke as fired and of associating any increase in voids in the fuel bed with the clinker is not necessarily in agreement with what will happen in a fuel bed. It would probably be more correct to use a variable apparent density for the coke which would decrease with distance from the plane of ignition; it might be of the form $Wf=W(1-kh)$. Moreover, the value of w will vary with the fusibility of the ash and the rate of burning. However, the simple device used is satisfactory for illustrating the principles involved.

OVERFEED FUEL BED

Figure 29, *B*, shows the diagram for an overfeed bed burning in equilibrium with constant rate of air supply, in which OI is the top of the bed, which is also the plane of ignition. Heights h are now measured from the top. Curve GO is, as before, the pounds of combustible carried by the gases per square foot per hour; the values of C are measured from GI.

Following the progress of any imaginary plane of fuel which starts from OI at zero time the pounds of fuel burned between O and h in time t will now be $\frac{G_H-C}{m}$, which is the C' of figure 29, *B*.

It follows that the equations developed for the underfeed bed can be used for the overfeed by taking h from the top of the bed and by using values of C' for C.

FUELS WITH VOLATILE MATTER

The procedure must be modified for a coal or fuel containing volatile matter. The curve for total combustible carried in the gases could not be used, and a new curve would have to be derived which would represent the burning of the fixed carbon only. This could be done very accurately if one had a set of curves, such as figures 22 and 23; it would be more difficult to separate out the combustion of the fixed carbon as the thickness of the bed decreased or the size of the pieces of coal increased. Moreover, the values used in the equations would have to be for the fuel free of volatile matter; this would present no difficulty, unless the size of the pieces changed during the coking period.

If the volume of the coke formed in the bed is assumed to be the same as that of the coal and if the proximate analysis of the coal is known, then

$$F' = \text{pounds of coal per square foot per hour} \times \frac{\text{fixed carbon} + \text{ash}}{100},$$

$$W' = \text{weight per cubic foot of coal} \times \frac{\text{fixed carbon} + \text{ash}}{100},$$

$$m' = \frac{\text{fixed carbon}}{\text{fixed carbon} + \text{ash}},$$

$$n' = \frac{\text{ash}}{\text{fixed carbon} + \text{ash}}.$$

O