The Principles of Underfeed Combustion and the Effect of Preheated Air on Overfeed and Underfeed Fuel Beds[1]

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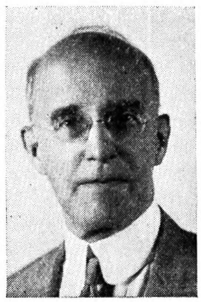
This paper is based on investigations conducted at the Pittsburgh Experiment Station of the U. S. Bureau of Mines. It shows that in underfeed burning the factor of rate of ignition is much more important than it is in overfeed fuel beds and that it fixes limits to the outputs that can be obtained. It uses the principles determined from the experimental results to interpret the much more complex action in fuel beds of commercial underfeed stokers. It also shows what effect preheated air has on overfeed and underfeed fuel beds and how this preheat is utilized. The results from burning a number of fuels on the underfeed principle, both without and with preheat, are given. The variables investigated were kind and size of fuel and rate and temperature of the air supplied.

THE purpose of this paper is to present the results of an investigation conducted at the Pittsburgh Experiment Station of the U. S. Bureau of Mines. It is one of a series of studies which have been made by the bureau on the burning of solid fuels to obtain measures of the actions which occur in fuel beds, in the burning of fuel and the clinkering of its ash. When the investigation was started, it was intended to restrict it to a study of the effect of preheat; however, as preheated air is more commonly used with underfeed stokers, it was necessary to include underfeed burning in the investigation, and this then became its major feature.



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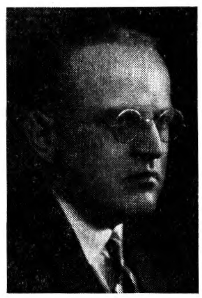

M. G. Eilers

Because the two types of tests were interlocked, it is not convenient to separate them entirely in this report; the study on the effect of preheat on overfeed fuel beds will be treated first, and the effect of preheat on underfeed fuel beds will be included with the report on underfeed combustion.

EFFECT OF PREHEAT ON OVERFEED FUEL BEDS

The objects of the investigations were restricted to studies of the effect of 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 as far 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 there have been numerous papers and reports 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 bed.

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, as a consequence, the rate of burning will be increased for 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, then 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 preheat 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, so that all auxiliary conditions of test would have to be identical, while measurements must be accurate. Even with the closest regulation it is very difficult to get two burnings to give exactly the same result, particularly with fuels

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which cake. Considerable experience had been obtained in the study of fuel beds in connection with the determination of the combustibilities of cokes;[4] also, coke forms the main part of the bed, even when burning coal. It was therefore decided to follow the same method and, as a beginning, to use coke as a fuel, as the principles involved could be more easily determined and better illustrated by a fuel free of volatile matter.

Apparatus Used. Fig. 1 shows the set-up used. The furnace was of welded construction with refractory lining. The inside was 20 in. in diameter and 44 in. high from the grate bars. There were 26 $^1/_2$-in. pipe sampling holes at $1^1/_2$-in. intervals from the grate level, these being scattered round the circumference. The air was supplied by a fan capable of giving 9 in. of water

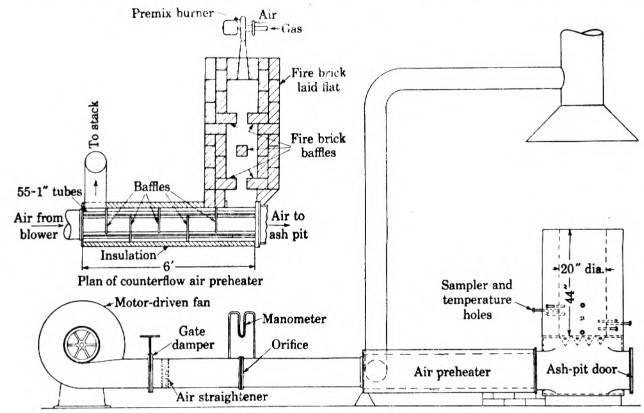

FIG. 1 APPARATUS USED IN THE TESTS

pressure; the air passed through a measuring orifice and the quantity could be closely regulated. The preheater was built specially for these tests, and was designed to give up to 1000 F preheat with the maximum estimated quantity of air. Two sizes of premix gas-burners were used; the gas was burned in a combustion chamber with checker-brick to avoid flame impingement 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 entering the ashpit. Its temperature was measured by a shielded thermocouple at a position of high velocity.

The bureau's standard water-cooled gas samplers were used for inserting into the bed through the various sampling holes. Fuel-bed temperatures were taken by optical pyrometer. All gas samples and temperature observations were taken at 1 in. distance from the vertical axis of the furnace. Other instruments and measurements were of standard type.

Test Procedure. Because the procedure was essentially the same as that used in the combustibility tests already referred to, it will not be described in detail. A very rigid specification was followed to insure duplication of conditions. It consisted in building up a fuel bed to a 24-in. depth, allowing it to come to equilibrium of burning, and then maintaining it at that depth during the period when measurements were taken.

Three complete sets of gas samples and other measurements were taken during one test, and the bed was frequently restored 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 part below the sampling position was not disturbed previous to the taking of the sample.

[4] Nicholls, Brewer, and Taylor, "Properties of Cokes Made From Pittsburgh Coals," Proc. A. G. A., 1926, pp. 1129–1143. Nicholls, P., "Study of Cokes From Various Types of Plants Using Pittsburgh Coal," Proc. A. G. A., 1928, pp. 1127–1136.

The coke used was made by the Philadelphia Coke Company in Koppers ovens, using a mixture of 80 per cent Powellton seam coal and 20 per cent Pocahontas coal. It was crushed and carefully screened to 1 to $1^1/_2$-in. square mesh. Its analyses and properties were:

Proximate analysis, per cent:	
Moisture	0.6
Volatile matter	0.7
Fixed carbon	91.3
Ash	7.4
Ultimate analysis, per cent:	
Hydrogen	0.5
Carbon	89.5
Nitrogen	0.9
Oxygen	1.0
Sulphur	0.7
Ash	7.4
Softening temperature, F	2730
Weight per cu ft of 1 to $1^1/_2$ in. size, lb	31.8

Results of Tests. Four air temperatures were used, 80 (normal), 400, 600, and 800 F. Fig. 2 shows the values of the CO_2, CO, O_2, and N_2 in per cent by volume against the height of the fuel bed, and also 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 the analysis. The water vapor is not plotted; from the analysis of the coke its value would be 0.7 per cent by volume. It is also possible that some producer action of the water vapor in the air and from the coke had occurred; it was not considered worth while to include the extra precision and labor necessary to check these factors. The parts of the curves in the first $1^1/_2$ in. 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 most affected by pieces of clin-

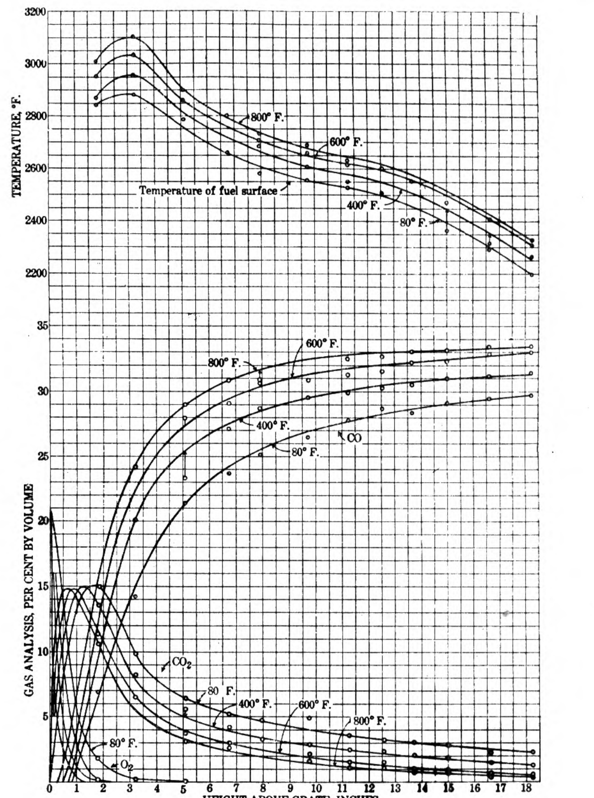

FIG. 2 EFFECT OF PREHEAT ON THE GAS ANALYSES AND FUEL-BED TEMPERATURES OF AN OVERFEED FUEL BED OF HIGH-TEMPERATURE COKE

ker, although the attempt was made to remove the clinker each time the bed was brought back to standard.

The figure shows that the preheat caused larger differences in the reaction in the lower part of the bed and that it increased the rate of reaction.

The temperature observations were, as usual, the weakest part of the measurements. At best, they are the temperature of the coke surface, and the optical pyrometer will show large variations over the small area which is seen through each hole; several readings were taken at each observation and the results averaged. The dip in the temperature curves at 12 in. height shows a drop in temperature which should not occur and is due to conduction to the walls or by convection of cooler gases from the walls.

The figure shows that the preheat is used partly in increasing the CO reaction and partly in raising the temperature. Comparing the values for 80 and 600 F at the 15 in. height, computations show that about 45 per cent of the preheat was used in the conversion of CO_2 to CO and 55 per cent in increasing the sensible heat. The curves of Fig. 2 are based on the test points; computations show that from the heat balances the 600 F curves should be closer to the 400 F curves.

Fig. 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.

The results illustrate the principles of the effect of preheated air in a thick fuel bed. One could deduce the order of the effect on a 10-in.-deep fuel bed; for example, by taking the values at the 10 in. 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 continuously at a rate equal to the rate of burning.

The values given in Figs. 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 for a given depth from Fig. 3; also, ash and clinker would always be present in service and would increase the apparent depth. One can, however, use Fig. 2 to predict with fair accuracy the relative rate of burning that will result from the maintenance of various depths of fuel bed.

Further Work With Preheat. The investigation could have been extended to obtain actual values with normal depths of fuel beds; there would be no object in doing this for cokes, but it could have been done for coals. Preheat is but little used with the overfeed type of fuel bed. Such tests with caking coals would necessitate introducing the factor of breaking up the fuel bed, and this operation is difficult to standardize, so that the accuracy of results is affected. If such tests had been made, it would probably have been of most practical value to have used fuels high in moisture. However, 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 on the underfeed principle.

UNDERFEED BURNING

Previous Work. The principles of overfeed or hand-fired burning are well understood, and there have been many investigations of them. The fundamental ones are those made at the Bureau of Mines by Mr. Kreisinger and his coworkers.[5] Although other investigators have not studied the actions at different heights in the fuel bed, yet 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 investigation made by the bureau 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. Mr. Bert Houghton[7] removed a section of fuel from a retort and by

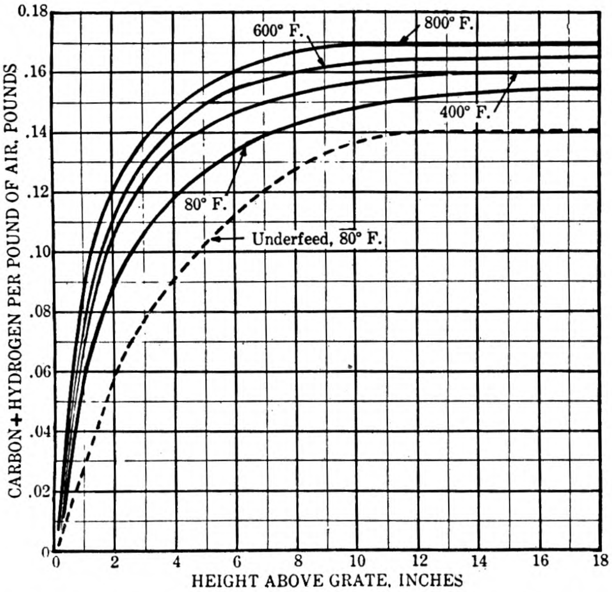

FIG. 3 OVERFEED-BURNING, HIGH-TEMPERATURE COKE. EFFECT OF PREHEAT ON TOTAL COMBUSTIBLE IN GASES

analyses of various sections determined how far the fuel had been consumed. The composition of the gases arising from the fuel bed at various locations has been studied by others. The progress of combustion on a chain-grate stoker was rather ingeniously examined 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. Analyses 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, yet 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 which follows may be considered somewhat elementary, but at least it insures clarity of thought.

The type of a fuel bed is fixed by the absolute direction of flow of the fuel and its relative flow to the air; both fuel and air 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 temperatures of the zones it flows into will influence its motion.

[5] U. S. Bureau of Mines Tech. Papers 137 and 139.

[6] U. S. Bureau of Mines Report of Inv. 2980.

[7] Houghton, "The Burning of Bituminous Coal on Large Underfeed Stokers," Int. Conf. on Bit. Coal, 1931, vol. 2, p. 282.

[8] Grumell, E. S., *Jour. Inst. of Fuel*, vol. 5, Aug., 1932, p. 366.

Fig. 4 shows six of the possible types. Type A, representing hand firing, is of the overfeed principle. Type B shows what we have termed the "unrestricted-ignition underfeed" principle. Type C evidently is the same as B in its combustion principles, but differs in the ash disposal; it is illustrated by the Hawley down-draft heating boiler. Type D, as representing a traveling-grate stoker, is of interest; the length U of the fuel bed is burning on the pure underfeed principle; the length O is burning on the

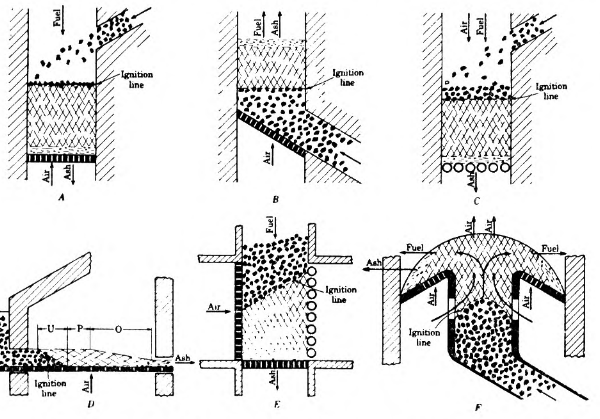

FIG. 4 DIAGRAMMATIC REPRESENTATION OF SIX TYPES OF FUEL BED

overfeed principle; and some unknown length P is in what we have 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 implies that with a fixed rate of air supply there is no imposed restriction which limits the rate at which fresh fuel may be ignited; thus in type B of Fig. 4 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 there is no imposed condition limiting the rate at which the fuel in the 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 only conform to the definition of unrestricted-ignition underfeed burning when the rate of coal feed is equal to or greater than the rate of ignition; in addition, the burning is not completed in the pot. The same arguments would apply presumedly 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 a definition, although the term is self-explanatory. It is used to define 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 is equal to 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 is equal to 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, then the thickness of both beds will increase indefinitely.

Method of Test Discussion. Evidently it was desirable to attempt to determine some of the fundamental principles of underfeed burning—that is, to study a fuel bed as represented by type B of Fig. 4. The use of a bed such as type F would correspond more nearly to practise, 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 type B in which both the fuel and air would be fed from the bottom and a number of schemes were considered. 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 of construction. Finally, the same method was adopted as was used in a previous investigation on clinkering.[9]

The method consisted in starting with a deep bed of fuel and igniting it at the top. This gives a true underfeed burning and restricts the factors affecting the combustion to the fuel and the rate of air supply; for fundamental studies it has the further

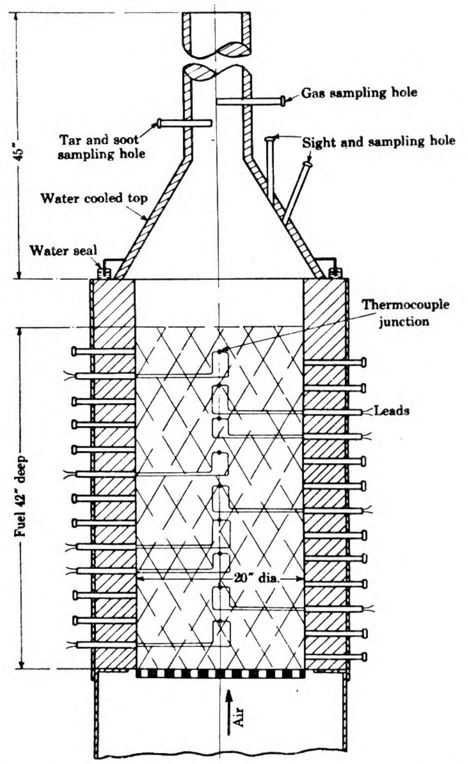

FIG. 5 DIAGRAM OF FUEL BED FOR UNDERFEED-BURNING TESTS

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.

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

Apparatus. The set-up was essentially the same as shown in Fig. 1 except that a water-cooled cone with chimney was used as a top cover to collect the gases so that average samples could

[9] Nicholls and Selvig, "Clinker Formation as Related to the Fusibility of Coal Ash," U. S. Bur. of Mines Bull. 364, p. 50.

be obtained; this cover had a water seal for prevention of inleakage and for ease of removal.

Fuel Bed and Observations. Fig. 5 shows how the fuel bed was arranged. The diameter of the pot was 20 in. and the depth of the fuel 42 in. All fuels were carefully screened 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 in. 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 thence 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-sized 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 there was even ignition all over the area.

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 started after the cover was put on; the samples were taken continuously over periods of 10 to 20 min, depending on the rate of burning.

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 30 mv (1340 F), the couple was switched to the portable potentiometer, and the next lower couple was connected to the recorder.

The progress of combustion was also 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 very closely fixed.

No samples were taken or temperatures measured in the bed itself during the regular tests, except that 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 bringing the whole of the fuel bed up to the temperature to be used. During this period the couple giving the temperature of the entering air and the couples placed at mid-height and at the top of the bed were put on the recorder to assist in avoiding excess heating of any part of the fuel.

The test was continued until the fuel was consumed, except for some tests of bituminous coals in which the caking caused very uneven burning. The furnace was allowed to cool, and then the residue was examined and measures were taken of the ash, the clinker, and their combustible content.

Data Obtained. All the main data were plotted against time as abscissa. Against height above the grate as ordinate were plotted the 30 mv position of the thermocouples in the bed and the level of ignition by observation; 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. The plot of the observed level of the top of the fuel bed on the same diagram gave the thickness of the ignited portion at any time.

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

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; also it has been burned on chain grates, and, as shown in Fig. 4, 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 when investigating principles of burning, because it eliminates the uncertainty of size of pieces that is present 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 very much reduced in that the gas analyses can be made in a much shorter time and in a water Orsat.

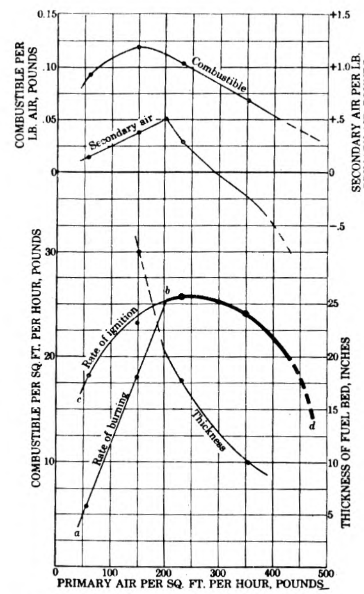

FIG. 6 UNDERFEED-BURNING, HIGH-TEMPERATURE COKE

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 of fairly complete plots being made; the first were made with normal air temperature.

The high-temperature coke used in these tests was made from No. 8 Pittsburgh seam by the Lowell Gas Light Company in horizontal through retorts; its properties have previously been reported.[10] Those of interest are:

Ultimate analysis, per cent:	
Hydrogen	0.6
Carbon	88.8
Nitrogen	1.1
Oxygen	0.6
Sulphur	0.6
Ash	8.3
Ash softening temperature, F	2730
Weight per cu ft of 1 to 1½ in. size, lb	26.8
Pounds of fuel per pound of combustible, ratio	1.12

The rates of combustion will be expressed in terms of the available combustible in the fuel, as this eliminates the variations in the non-combustible.

Variables of Rate of Primary Air and Size of Coke Pieces.

[10] Nicholls, Brewer, and Taylor, "Properties of Cokes Made From Pittsburgh Coal in Various Plants," Proc. A. G. A., 1926, pp. 1129–1143.

The sizes of coke adopted as standard were those between the square-mesh screen sizes of $^1/_2$ to 1, 1 to $1^1/_2$, $1^1/_2$ to 2, and 2 to $2^1/_2$, 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. Fig. 6 shows plots of the data for coke of the $1^1/_2$ to 2 in. size. It will require a detailed explanation and some study 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-hand 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 part *cb* of the ignition curve means that it is for ignition only; the heavy-line part *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-lb air rate the rate of ignition is about 21.5 lb per sq ft per hr, but that the rate of burning is only 12 lb; 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); consequently, the thickness of the burning zone is increasing continually. At an air rate of about 200 lb, the rate of burning is the same as the rate of ignition, so that the live-fuel bed will maintain a constant thickness. At air rates greater than 200 lb, the rate of burning could increase along a continuation of the line *ab*, but it cannot be greater than the rate at which the fuel is ignited, and consequently it does the best it can and follows the rate of ignition curve *bd*, which for this fuel increases a little at first, reaches a maximum at 250 lb of air, and then decreases with further increase of rate of air supply.

The ignition curve indicates that at high air rates 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 any one of the other fuels tested. The causes for this action are two: First, the fuel is ignited by the 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 surfaces of the fuel are being cooled by the air passing over them and this 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 reached, the temperatures through the bed will decrease, and consequently the radiation will be less.

One curve in Fig. 6 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 which follow, were selected in the same manner from the plots of the observed values during the whole test. The full-line part of the curve covers the range in which the thickness is constant. One would expect that the observed thickness would increase with time because of the accumulation of clinker, but the increase was usually small compared with variation caused by 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 Fig. 6 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 lb.

The foregoing results and the interpretations of them 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 Fig. 6 can be applied to restricted burning. The following deductions refer to continuous operation with ability to restrict the rate of feed of the fuel.

(1) To obtain the maximum rate of burning possible with each rate of air supply, the rate of feed must follow the curve *abd;*

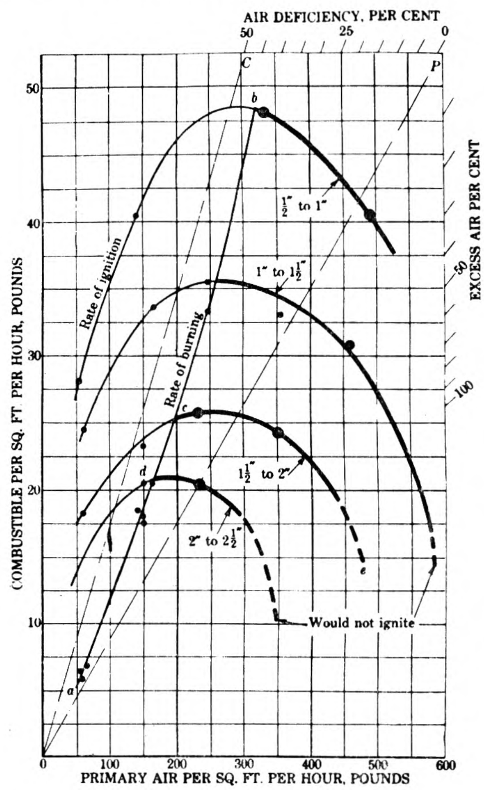

FIG. 7 UNDERFEED-BURNING, HIGH-TEMPERATURE COKE; RATE OF IGNITION AND RATE OF BURNING, WITH RATE OF PRIMARY AIR AND SIZE OF COKE AS VARIABLES

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 lb of combustible (or 29 lb of coke) per sq ft per hr, and no manipulation can increase it.

(3) The equilibrium thickness of the live-fuel bed for rates of air supply above 200 lb and for the corresponding rate of fuel feed fixed by the line *bd* will be those shown by the thickness curve of Fig. 6. The equilibrium thickness for air rates below 200 lb and for the corresponding rates of fuel feed fixed by the 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 the 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 any increase in rate of feed crosses the curve *abd*, the rate of burning will not increase beyond that fixed by the curve *abd;* if it crosses the portion *ab*, the thickness of the live-fuel bed will increase continuously; if it crosses the 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.

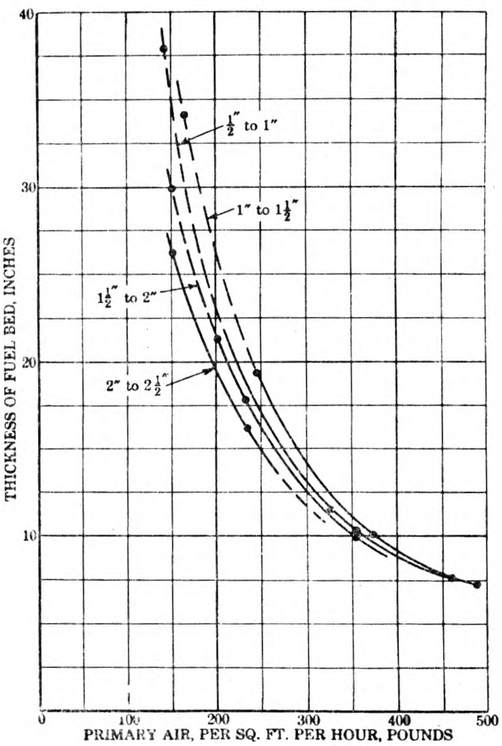

FIG. 8 UNDERFEED-BURNING, HIGH-TEMPERATURE COKE; THICKNESS OF FUEL BEDS, WITH RATE OF PRIMARY AIR AND SIZE OF COKE AS VARIABLES

Fig. 7 shows the rate-of-ignition and rate-of-burning curves for the four sizes of coke when using air at 80 F; to avoid crowding, the thickness of fuel-bed curves are shown in a separate plot, Fig. 8. The test points are shown, and it will be noted that fairly symmetrical curves can be drawn to fit the points.

It is of interest that the rate-of-burning curves previous to 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 on the effect of size.

The figure shows that the rates of ignition increase rapidly with decrease in size, which is in agreement with common experience when starting a fire 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 Fig. 9.

If the air rates were carried high enough, the ignition curves may be expected to have a shape like that of the 2 to 2$^1/_2$ in. size. An attempt was made to burn this size at an air rate of 345 lb. 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 345 lb, the burning gradually decreased and finally the fire was extinguished. This showed 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 2$^1/_2$ in. size, the maximum rate of burning possible was 21 lb, whereas with the $^1/_2$ to 1 in. size it was 48 lb. This shows a fundamental difference between overfeed and underfeed burning principles; in a hand-fired furnace any size of coke can be burned continuously at any rate by keeping the fuel bed deep enough.

It must be remembered that the curves of Fig. 7 are for the conditions used in these tests and that the cooling by the side walls affects the results. It is not probable that it influences the rate of ignition materially, but it does lower the average rate of burning because of the poorer combustion at the sides. For an absolute value—that is, for a fuel bed of very large area—the rate-of-burning line *ab* would be swung somewhat to the left. However, it could never cross the line *OC*, which corresponds for this fuel to a dry-gas analysis containing only CO and N_2—that is, one with the maximum carbon content.

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. All points on the line *OP* have perfect combustion; 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 of reading off the secondary-air requirement at any rate of burning.

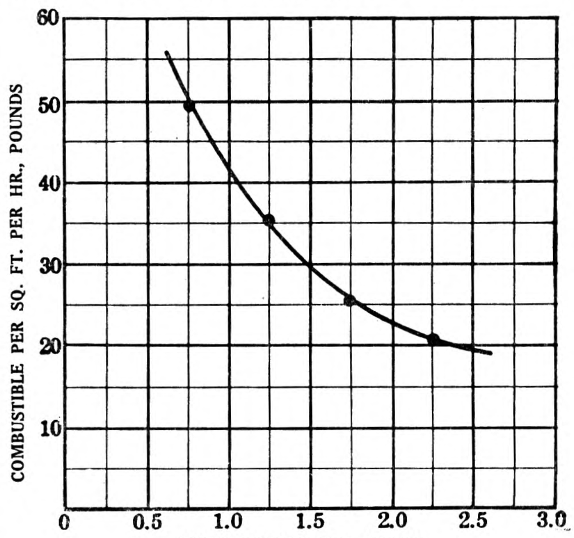

FIG. 9 UNDERFEED-BURNING, HIGH-TEMPERATURE COKE; RATE OF IGNITION AGAINST SIZE OF COKE

It is worth while to grasp fully the meaning of the type of chart represented by Fig. 7 because it is used for all results and because it is interesting and informative. Considering the curves for one size of coke—the 1$^1/_2$ to 2 in., for example—it has been shown that one can operate continuously anywhere within the area *adc*. Selecting, then, any point of operation—17.5 lb of combustible per hour and 200 lb of air, for example—this point fixes the rate of combustion and the deficiency or excess of air. This 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 20.9 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 a 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; also, the same type of diagram could 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 the air supplied below the bed. In the method of test employed, all the air passed through the plane of ignition and also through the whole 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, then 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" only to that which is purposely supplied over the fuel bed and to that 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 per cent excess air in the flue gases, then one is limited to operating along the 20-per cent excess-air line of Fig. 7. If all this air passes through the plane of ignition, the maximum rates of burning possible with each size is reduced to the value given by the intersection of each curve with the 20-per cent excess-air line. A higher maximum rate 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.

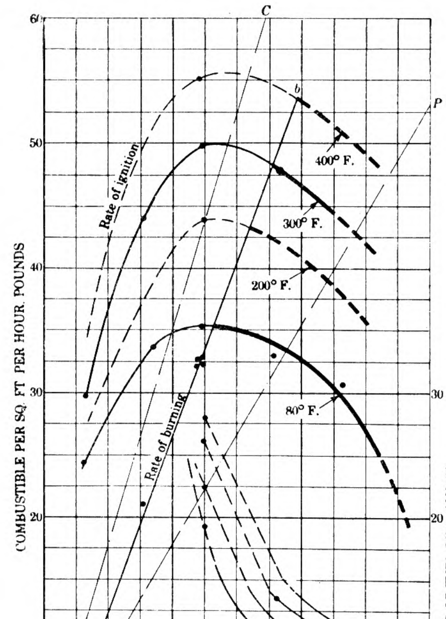

FIG. 10 UNDERFEED-BURNING HIGH-TEMPERATURE COKE, 1 TO $1^1/_2$ IN. SIZE, WITH RATE OF PRIMARY AIR AND ITS TEMPERATURE AS VARIABLES

Fig. 8 shows the thickness of the fuel beds. It will be noticed that the curve for the $^1/_2$ to 1 in. coke falls out of order. There are two factors which influence the thickness; one, the rate of ignition which tends to increase it, and the other, the rate of reaction which tends to decrease it with decrease in size. A previous investigation[6] shows that the second factor increases very rapidly for decrease in size below 1 in.

Effect of Preheating the Air on the Underfeed Burning of High-Temperature Coke. The air temperatures used were 80, 200, 300, and 400 F. There was no necessity to test all sizes, because the characteristics will be similar; therefore only the 1 to $1^1/_2$ in. coke was used.

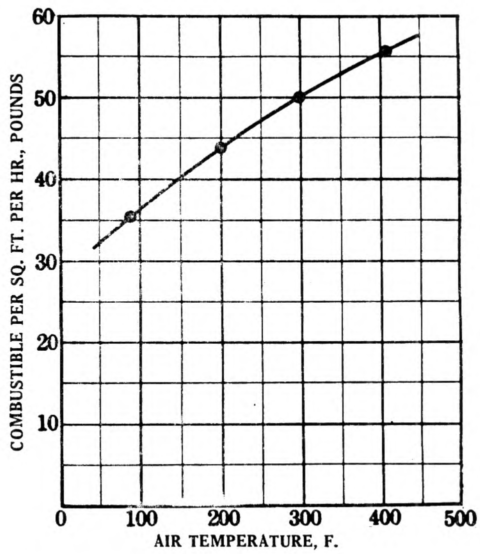

FIG. 11 UNDERFEED-BURNING, HIGH-TEMPERATURE COKE; RATE OF IGNITION AGAINST TEMPERATURE OF AIR

Fig. 10 shows the results; the lines *OC* and *OP* have the same meaning as in Fig. 7. The parts of the rate of combustion curves falling on the line *ab* are not materially affected by the preheat; because the same size of coke is used, *ab* has not an upward bend and is nearly a straight line to the origin.

The rates of ignition increase rapidly with increase of air temperature. Fig. 11 shows the maximum values plotted against air temperature; at some higher temperature the curve would turn upward very rapidly because at a certain temperature, probably between 1100 and 1200 F, the coke would ignite spontaneously.

Fig. 10 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. Above the rate of air supply where the ignition curve for normal air temperature (80 F) meets the burning curve (265 lb of air), preheat permits of 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.

The lower set of curves of Fig. 10 show the thicknesses 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 at first sight may seem an anomaly. The explanation is that the increase in the rate of burning that occurs 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. Fig. 2 illustrates this, but to a different scale.

Underfeed Burning Tests of Low-Temperature Coke. Low-temperature coke is a good example of a truly non-caking fuel with relatively high volatile content. The coke used was a fairly dense and non-fragile type; its properties were as follows:

Proximate analysis, per cent:	
Moisture	3.4
Volatile matter	13.7
Fixed carbon	72.0
Ash	10.9
Ultimate analysis, per cent:	
Hydrogen	3.5
Carbon	73.4
Nitrogen	1.5
Oxygen	9.8
Sulphur	0.9
Ash	10.9
Softening temperature, F	2721
Weight per cu ft of 1 to $1^1/_2$ in. screen size, lb	28.3
Pounds of coke per pound of combustible	1.25

The tests made were confined to the 1 to $1^1/_2$ in. 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.

Fig. 12 shows the results plotted in the same manner as were those of the high-temperature coke. The line *OP*, as before, is that of perfect combustion for a fuel with the foregoing analysis. The line *OC* shows the maximum rate of combustion. The rate of ignition curves for 210 and 300 F air temperature are each based on one test point, but their general shapes will be somewhat as shown.

The plots do not differ in their general relationships from those of Fig. 10 for high-temperature coke, and the principles that would be deduced are the same. The slope of the rate-of-burning line *ab* is a little steeper than of Fig. 10; that is, the gases 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 lb to see whether the ignition would not 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 as it could with the 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 F 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 easily ignited, yet the principle still holds that its rate of burning on the underfeed method did not exceed a certain maximum, which for this 1 to $1^1/_2$ in. size, without preheat, is 49 lb of combustible per square foot per hour; for the high-temperature coke of the same size it was 35 lb.

Underfeed Burning With Anthracite. A complete set of tests have not as yet been made with anthracite, but three different kinds of anthracite were tested at one rate and without preheat to see if they would give their relative ignitibilities for use on another investigation. The size used was 1 to $1^1/_2$ in. square-mesh screen and the rate of air supply 240 lb of primary air per square foot per hour. A few of the results are given in Table 1.

TABLE 1 UNDERFEED BURNING, ANTHRACITES

Item	No. 1	No. 2	No. 3
Volatile matter, per cent	3.2	3.8	8.3
Fixed carbon, per cent	82.5	79.4	78.3
Ash, per cent	11.0	13.2	12.2
Weight per cubic foot, lb	53.0	51.2	46.3
Primary air, sq ft per hr, lb	240	240	245
Rate of ignition, sq ft per hr, lb	27.4	27.8	39.2
Rate of burning, sq ft per hr, lb	27.4	27.8	37.0
Thickness of fuel bed, in	15.0	15.7	10.5

Anthracites 1 and 2 both burned with equilibrium fuel beds because in each test the rate of burning is equal to the rate of ignition. The rate of burning of anthracite 3 was less than its rate of ignition, and therefore the air rate was too low to give equilibrium. Fig. 6 shows that the same size of high-temperature coke also burned in equilibrium at the air rate of 240 lb and that the ignition and burning rates were 26 lb, which is a little below that of anthracite 1.

This measure of ignitibility shows that No. 3 was 43 per cent more easily ignited than No. 1 or No. 2. These comparisons are

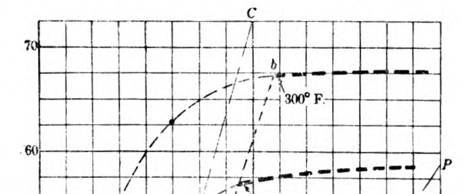

FIG. 12 UNDERFEED-BURNING, LOW-TEMPERATURE COKE; RESULTS FOR 1 TO $1^1/_2$ IN. SIZE, WITHOUT AND WITH PREHEAT

on the weight of combustible basis; to the eye the coke would appear to ignite 1.6 times as fast as anthracite No. 1; that is, the plane of ignition of the coke travels faster because of the relative densities and ash contents of the two fuels.

Underfeed Burning With Bituminous Coals. It was realized that more difficulty would be experienced in obtaining reliable data with coals which fuse and cake, but earlier tests[9] 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.

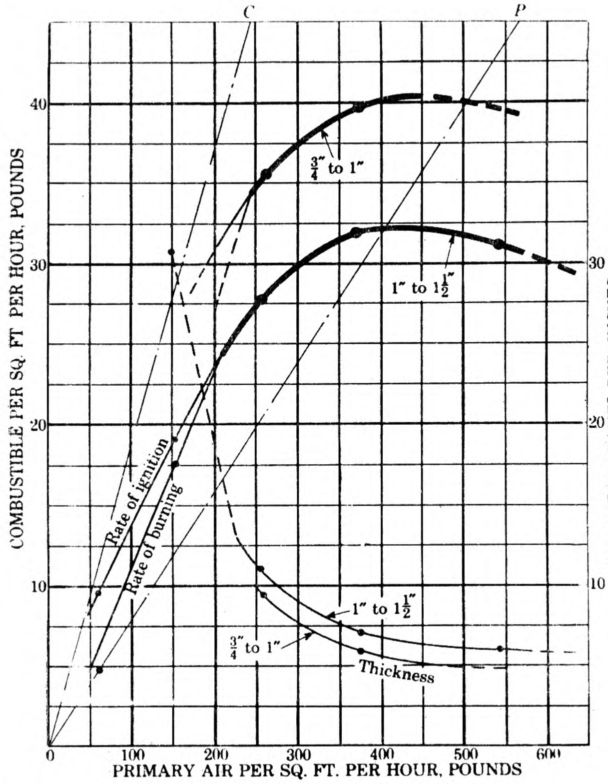

Fig. 13 Underfeed-Burning Illinois Coal, With Rate of Primary Air and Size as Variables

The troubles caused by uneven burning that were encountered in the individual tests will not be described, but they can be summarized as follows. When burning at low rates of air supply, the plane of ignition advanced downward at such a rate that the tar exuding from the coal was not consumed, and thus it would tend to close up the air spaces, or the surface of the coal pieces would not be burned away fast enough to make up for the swelling, and consequently the spaces were closed. Either of these actions is cumulative, because, as the spaces started closing, the air would divert from the center, and thus the quantity of air passing through the center would be reduced; this further reduced the rate of burning and allowed more closing of the 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 had a somewhat spiral form.

At some rate of air supply the bed burned uniformly and acted 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 referred to. A uniform burning can be interpreted to be such a rate of air supply over the surfaces 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.

Good data could be obtained in the tests in which the rate of air supply gave equilibrium burning, but in the tests below this

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, per cent:				
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, per cent:				
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	0.5	1.0
Ash..........	8.0	7.8	4.6	7.9
Calorific value, Btu....	12,340	13,780	13,800	13,850
Softening temperature, F..........	2203	2780	2510	....
Weight per cubic foot, 1 to $1^1/_2$ in. size, lb..	44	44	42	43
Pounds of fuel per pound of combustible	1.37	1.22	1.22	1.22

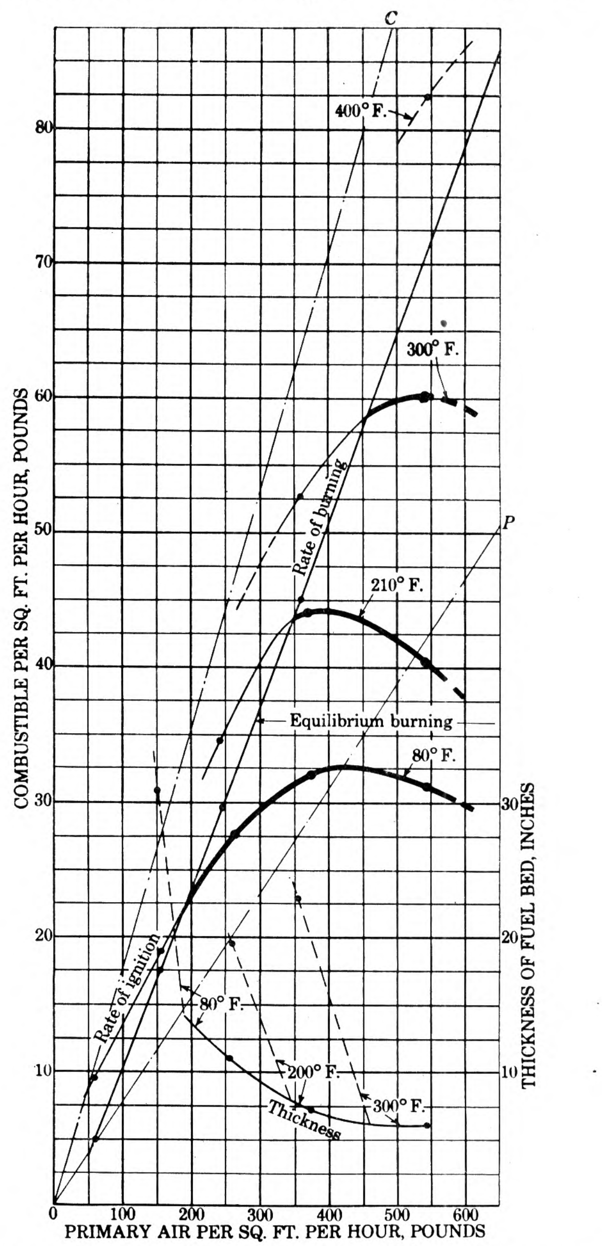

Fig. 14 Underfeed-Burning Illinois Coal, 1 to $1^1/_2$ In. Size, With Rate of Primary Air and Temperature of Air as Variables

rate there was no certainty as to the air rate to use for the ignition except that it should be lower than that of the known air supplied; also, the rate of burning obtained from the gas analysis was not that of the whole fuel bed.

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

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.

Underfeed Burning, 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.

Fig. 13 shows the results with two sizes of coal without preheat. The heavy lines indicate the rates with 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 Fig. 7 for high-temperature coke, and the same deductions as 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, which was 32 lb for the 1 to $1^1/_2$ in. size, as compared with 35.5 lb 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 lesser degree.

Fig. 14 shows the results for the 1 to $1^1/_2$ in. Illinois coal with various preheat temperatures. Again, the general plot is similar to Figs. 10 and 12, 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 non-equilibrium and equilibrium burning, as fixed by there being no clogging of the bed by caking. This means that the tar that is exuded from the pieces of coal is consumed as fast as 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 which is designated as equilibrium burning could be called the free-burning area.

A test was attempted with 400 F air temperature; it will be seen that the point for the test falls to the left of the equilibrium line. The test started out well, but when the ignition line had fallen 20 in., almost suddenly the bed clogged up tight 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 curves would have been swung to the left and the shapes of the curves would have been more similar to those for the cokes.

The dotted parts of curves for the thickness of the live-fuel bed indicate non-equilibrium burning; the thicknesses for equilibrium burning fall approximately on a common curve

Underfeed Burning, Pittsburgh Coal. This being the first bituminous coal tested, attempts were made to improve the method and procedure. To obtain accurate data on the non-equilibrium burning, it was necessary that the air supplied should pass uniformly through the area of the bed instead of being diverted to the sides by the caking. Attempts were made to insure this by increasing the resistance of the bed at the sides by packing it with small-sized coal, so that the coal being tested formed a core 16 in. in diameter with a ring of fine coal around it 2 in. thick; it was accomplished by using a sheet-iron cylinder 16-in. in diameter and 12 in. long, and gradually building up the bed.

This kept the center of the bed more open, but it did not entirely 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-

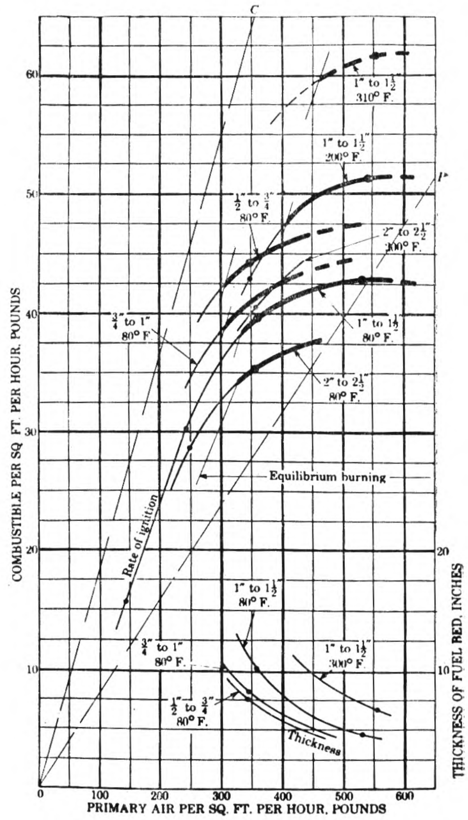

FIG. 15 UNDERFEED-BURNING PITTSBURGH COAL

rate, non-equilibrium area as much as 100 per cent. As would be expected, it made little difference in the equilibrium area but increased the ignition rate a little, both because of the effect of the small-sized coal and because, even with a non-caking fuel, there is always less resistance to air flow at the sides.

Numerous tests were made with the Pittsburgh coal, the majority with small fuel at the sides. Fig. 15 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-sized coal, 1 to $1^1/_2$ in., the maximum rate of burning possible without preheat was higher, 43 to 32 lb; with 300 F air temperature, the maximum rate of burning was about the same, 61 lb. As before, the rate of ignition decreased with increase in size; the sizes were carried to the 2 to $2^1/_2$ in. screen.

There is no common line fixing the area of equilibrium burning; those drawn in the plot can be considered only approximate. It is certain, however, that the line is further to the left for the smaller coals; this can be interpreted to mean that the openings between coal pieces can be kept clear more easily as the size of the coal decreases. Knowing that it occurs, an explanation can be given, but one's first guess would probably be the reverse.

There is no necessity to discuss the results of Fig. 15 in detail.

Underfeed Burning, Splint Coal. Splint coals differ from other bituminous coals in that they do not fuse when heated. On the other hand, they exude their volatile matter as a tarry substance, which will tend to fill the air spaces. It is not known whether splint coal is used on large underfeed stokers, but it has been used in domestic stokers. The coal was not specially obtained, but was tested because it was available and because it had distinctive properties.

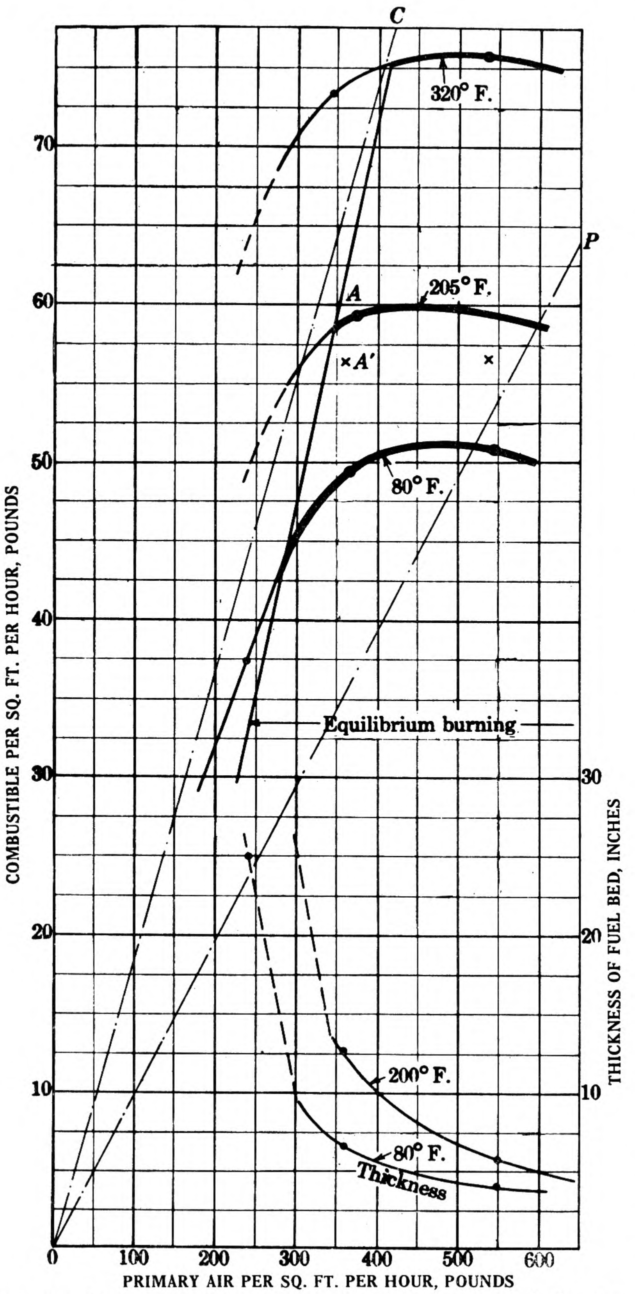

Fig. 16 Underfeed-Burning Splint Coal, 1 to $1^1/_2$ In. Size

All tests were with 1 to $1^1/_2$ in. size, the temperature of the air being varied. Fig. 16 shows the result. All tests are for beds packed with small coal at the sides, except the two tests indicated by crosses. Thus tests *A* and *A'* are duplicates, except that the latter had no packing; their positions indicate the order of the difference obtained by the two methods.

The results show the same relationships as for the other fuels, but the line fixing the equilibrium area is further to the left, thus giving a larger equilibrium area. The maximum rate of burning possible without preheat is decidedly greater than the rates for the other bituminous coals, being 51 lb as against 42.5 lb for the Pittsburgh. However, the increase in the rate of burning by the same preheat is about the same as for the Illinois and Pittsburgh coals.

At non-equilibrium rates this coal burned around the sides, leaving a solid pillar of coke in the center. It would seem that the tarry matter filled up the spaces and coked, but the whole coked mass did not tend to open up cracks as much as in the other two coals, and thus little if any air passed through the center mass.

A test on this coal was also tried at 412 F air temperature and a rate of 535 lb of air. It burned for a time and indicated a rate of ignition of about 100 lb; it then clogged up very rapidly, but not so quickly as did the Pittsburgh coal at 400 F. This clogging would be expected, because Fig. 16 shows that the point of operation used lies outside the equilibrium area.

Summary of Underfeed Tests. There is no necessity to make a detailed summary, nor at this time will this method of test as a means of determining the burning characteristics and of comparing fuels be discussed in full. There is one characteristic important in the operation of stokers which the method does not measure—namely, the ease of breaking up the caked or coked masses. It can be imagined that this quality is compounded of tensile strength and brittleness as measured by elasticity.

The results justify the method of attack used of thoroughly testing high-temperature coke first, as the clear view-point this gave of the relations between quantities, set a standard for interpreting results with fuels which were more difficult to test.

Because the fuels had been in dry storage, their moisture content was low. Some study of the effect of moisture on the rate of ignition is of interest.

REACTIONS IN AN UNDERFEED FUEL BED

It was desirable to have records of the reactions in fuel beds burning on the underfeed principle that would show the same data as does Fig. 2 for overfeed. These tests involved some difficulties because the zone of burning is moving, but complete data were obtained for the high-temperature coke and for the Illinois coal, the latter including tar and soot determinations.

The complete results are not given in this report; they present a good picture of what occurs in the bed and how the ignition progresses. The following are some of the conclusions one can deduce:

(1) In an underfeed bed heat is abstracted from the lower part of the burning zone to heat up 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, yet 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, or, in other words, lengthens the time required for the same total reaction more so than for the overfeed bed, where the rate of reaction is very slow, as is shown by Fig. 2.

(4) Consequently, 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 an overfeed.

To give an idea of the burning of the underfeed bed when using high-temperature coke, the dotted curve was added to Fig. 3; the rate of air supply in the underfeed tests was the same as that in the overfeed. The relative positions of the 80 F, curves illustrate the foregoing conclusions.

That the process of ignition hampers the burning in an underfeed bed was shown in a number of tests made at air rates for which the rate of burning was less than the rate of ignition, and the thickness of the live bed was continually increasing; 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 per cent; with the bituminous coals there was sometimes 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, then the boiler output may be expected to rise temporarily.

APPLICATION OF RESULTS TO UNDERFEED STOKERS

Some deductions on how the experimental burnings are related to the actions which 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 burning which results is the maximum which 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.

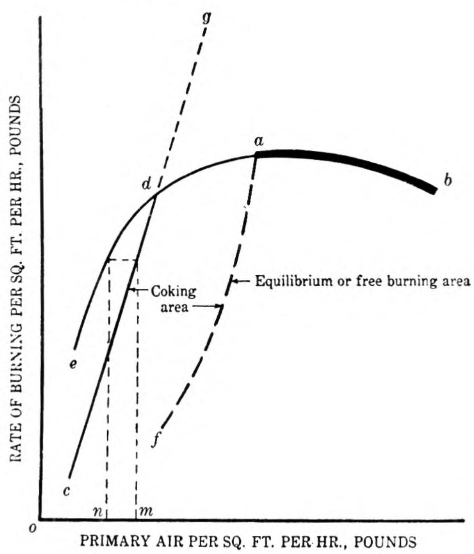

FIG. 17 DIAGRAM OF OPERATION

It also was 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. Presumedly 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, the 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 Fig. 17, the 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, presumedly the burning would not be changed much 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 to maintain the non-caking or free-

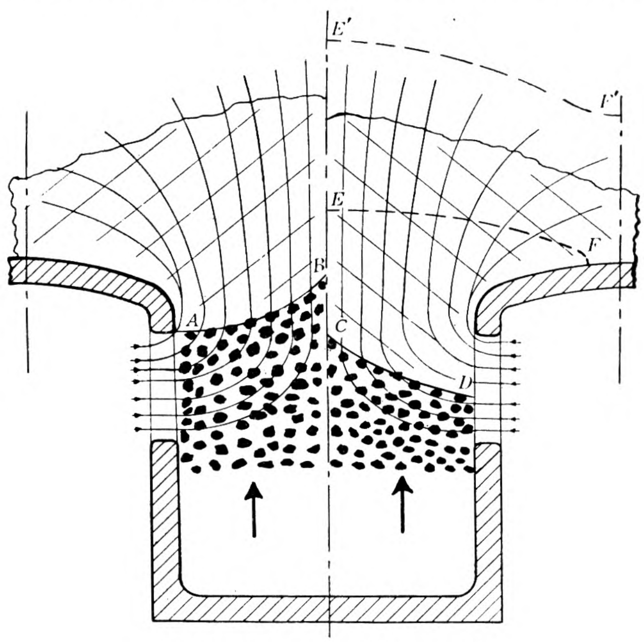

FIG. 18 AT HIGH-BURNING RATE

burning condition, then probably one would move along some curve *af*, although this suggestion is not based on experimental data. Therefore, with a non-agitated bed, operation anywhere in the area *fab* would be free burning.

Assuming that the bed were agitated enough to keep the fuel pieces free from each other, then the curves for unrestricted ignition would be similar to those for non-caking fuel, such as *cdb* and *edb;* it follows that with a restricted feed, operation with an equilibrium bed would be possible anywhere within the 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 one is on safer ground if the stoker is operating at the limit of its ignition rate—that is, on the line *db* of Fig. 17 for an agitated bed. Fig. 18 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 the position *AB* shown in the left-hand 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 the surface *AB*, and the rate of ignition by the ordinate of the point on *db* of Fig. 17 which corresponds to the air rate. If the coal feed were reduced for a time so that the ignition line fell to what would probably be the line *CD* of the right-hand half of Fig. 18, then 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 the line *bd* of Fig. 17; 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, it is probable that the plane of ignition would find some position along the height of the air slot which would produce equilibrium.

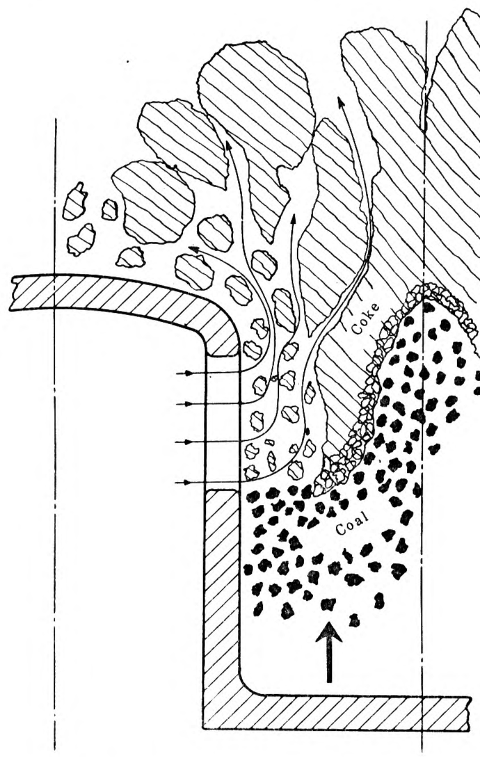

FIG. 19 PROBABLE NORMAL ACTION

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 the line *db*, the rate of burning for any rate of air supply could and would be limited only by the line *dg* if it were not that it is limited by the 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 Fig. 18; with continuous operation the height and shape will adjust themselves to give a rate of burning equal to the rate of ignition.

Although non-caking fuels are not burned in underfeed stokers, yet it is of interest to extend the argument of the last paragraph to what would occur at low ratings. If a non-caking fuel were being burned under conditions represented by Fig. 18, and if the rate of air supply were less than that of point *d* of Fig. 17, under continuous operation the ignition plane would find some level like *CD* of Fig. 18 which would make the rate of ignition equal to the rate of burning. If in Fig. 17 the total quantity of air supplied is *om*, the quantity passing through the ignition plane would be *on* and that above the ignition plane *nm*.

In the foregoing discussion of the ignition in an agitated bed it was assumed that the caked or coked coal is well broken up 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 that most of the actual ignition will occur at the surfaces of the large coke pieces. Fig. 19 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.

At low rates of coal feed for which the point of operation would fall well below the line *cd* of Fig. 17, the rate of ignition would be large compared with the rate of burning. The ignition line would sink as low as it could, but it could not go below the air-stream line; however, the coal below the ignition line would be heated by radiation and conduction and would not be cooled by the air stream, and consequently it would coke and its volatile would rise into the air stream. Although the volatile would be ignited and burned, yet 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 the conditions are as conceived in Fig. 19, there is no definite plane of ignition, but at low rates the actions will undoubtedly be somewhat as depicted. It would be under such conditions that the coking qualities of the coal and the agitation it gets would be of the most importance in determining the fuel bed that would result.

The following generalization on large stokers is probably warranted. The more usual mode of operation as represented by a humped fuel bed implies that the type of bed is an enlargement of that represented by Fig. 19, with possibly a small part as represented by Fig. 18. This will mean that a deep bed will be required to present a large enough surface area of coke for the ignition and burning actions. A type of bed as advocated by Mr. Houghton[7] is premised on a design and on a method of operation which will distribute the plane of ignition over a larger area of the bed, so that more of the action will correspond to that represented by Fig. 18. This mode of operation should permit of more even distribution of the air, result in a thinner fuel bed, and the composition of the gases arising from the fuel bed should be more uniform; one would also expect that the bed can be better controlled to make the analyses of these gases conform more nearly to the average desired, and to require less mixing of the gases in the combustion space.

EFFECT OF FUEL SIZE 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 Fig. 18, a decrease in size will permit of an increase of the maximum rating possible, of course neglecting limitations to 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 then it can be presumed that the effect of size will be that larger sizes will give a better chance for the air to penetrate into a mass when it is only partially 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 considering only 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. The 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 per cent goes to each action.

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

(3) Presumedly 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 is required; moreover, the available higher temperature of the top of the fuel bed and the gases will be lowered because of the increased radiation to the water surfaces. Such questions could only be settled by tests, but the variations to be determined would usually be less than those of operation.

(4) It would thus 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 normal air temperature of 80 F, preheating the Illinois coal increased the maximum rate of ignition 35 per cent for 200 deg and 85 per cent for 300 deg. For Pittsburgh coal the increases were 19 per cent for 200 deg and 43 per cent for 300 deg.

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

(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 Fig. 18, it would seem that the quantity of preheat will influence the position of the plane of ignition and might to some extent be used 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, then it will in general tend to bring the burning nearer to the metal work of the stoker. Consequently, the burning of stoker parts with preheat may be directly due, not to the increase in temperature because of the added heat, but because the burning of the fuel is nearer to the metal. It would therefore appear that troubles might be lessened 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 not possible to make a successful test with 400 F preheat, whereas higher temperatures have been used in service. This is no anomaly, because the method of test necessitated heating up the whole of the coal used and maintaining it at the full temperature for one 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 resulting from the use of preheat at low rates of burning as represented by Fig. 19. The coal will be more thoroughly coked, 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 be in agreement 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. The pictures may, however, help those who operate such stokers better to analyze what actually happens.

One could use the experimental data of this paper to deduce approximations of the thickness of fuel bed that would occur and the secondary air that would be required for various assumed conditions. However, such data can be reliably obtained 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 Fig. 4, the length U (the ignition part) of the bed of a chain-grate stoker is burning on the underfeed principle; the ignition is by radiation. In the tests of this report the top of the bed was ignited by a layer consisting of $1^1/_2$ lb of charcoal and 2 lb of petroleum coke, both wetted with kerosene; the fan was started as soon as the kerosene was alight and was at once brought up to the air rate to be used in the test. There may be a question as to whether this type of ignition is the same as that by radiation, but there can be little difference except in the rate at which the temperature of the top surface will rise; this will also vary in furnaces, both with type and with rate of operation.

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

The test data on this phase have not been analyzed completely; in general, they show that the rates of ignition for the upper part of the bed are of the same order as those given by the curves; the rate of air supply, the size of fuel, and the preheat affected the rates of ignition in the same manner, but not to the same degree. The effect of the caking of the coal at low rates of air supply is of interest; caking does not affect the rate of ignition for about the first 4 in. of depth, but below that the bed apparently cakes enough to lower materially the rate of travel of the plane of ignition. This phase may be investigated further by using shallower beds, corresponding to those used on chain-grate stokers.

Personnel and Acknowledgments

This investigation was conducted under the authorization of Mr. O. P. Hood, chief engineer, Mechanical Division, U. S. Bureau of Mines. Mr. D. T. Rosenthal, junior fuel engineer, assisted in the investigation from its beginning. Acknowledgments are given to the Philadelphia Coke Company, which supplied the coke used for the overfeed tests, and to Eavenson, Alford & Hicks, Pittsburgh, Pa., which supplied the splint coal.

Discussion

Bert Houghton.[11] This paper is worthy of careful consideration because it presents a study of the fundamental re-

[11] Operating Superintendent, Brooklyn Edison Company, Brooklyn, N. Y. Mem. A.S.M.E.

actions which take place within the fuel bed, and while the investigations were made on a small experimental furnace, the authors have been able to set up certain basic principles and to apply them in their conclusions to large underfeed-stoker operation.

The processes that take place within the fuel bed of a large underfeed stoker are of considerable importance to the stoker operator, and while again the authors had made a majority of their runs using high-temperature and low-temperature coke in graded sizes (and in this respect the results are not comparable with stoker operation), the principles of combustion which they were able to investigate in their small closely controlled furnace have no doubt a certain relation to plant practise.

In the underfeed tests the curves showing the variation of the rates of ignition and burning with air flow are significant. The fact that the rate of ignition reaches a definite maximum with any given fuel and primary air temperature indicates that there are definite limitations on the coal-burning capacity of any underfeed stoker which depend on the individual design. The marked increase in ignition rate with increased preheat temperature would, at first glance, appear to offer a very valuable method of increasing the burning capacity of a stoker, but, as the authors point out, other factors work to limit the usefulness of preheated air. Our experience with stokers using preheated air has been that the plane of ignition of the coal is much closer to the metal parts of the stoker, which explains the excessive burning of stoker castings found with stokers using preheated air. Furthermore, we have experienced excessive secondary combustion resulting from the high CO content of the gases leaving the fuel bed.

In discussing the principles of operation of large underfeed stokers, it cannot be too strongly emphasized that an ideal fuel bed is one which is relatively thin, homogeneous, and porous. In such a case the air distribution is even and combustion practically complete in the furnace itself. As the authors point out, a greater effective plane of ignition is obtained. It is of course obvious that the ideal fuel bed is one in which the burning rate is uniform over the entire area. This condition, we have found, is most nearly attained by the use of a thin fuel bed and a high furnace draft. High draft improves air distribution through the fuel bed, and also assists in the dissipation of heat, with a consequent elimination of excessive temperatures. Lower fuel-bed temperatures will reduce volatilization of the ash, slagging, and furnace-wall maintenance.

Our experiments on underfeed stokers burning bituminous coal have not been as detailed as those that the authors were able to carry out on their small stoker, but it is indeed interesting that some of the principles that we have made use of in stoker operation are confirmed by the authors in their work. They are to be commended for their contribution.

E. G. Bailey.[12] This paper lies closer to the fundamental principles of burning fuel in solid form on grates than any that has yet been published, to the writer's knowledge. Had such work been done earlier in the history of fuel burning, there is no question that a great deal would have been gained toward more efficient and more nearly smokeless combustion years ago than has been the case.

Even though this paper comes rather late in the experience of some of us in burning fuel on grates and stokers, it is still very opportune for those who have this problem in hand in assisting to define the limitations, especially with respect to rates of combustion that can be expected from different methods of feeding solid fuels to grates.

This is the kind of research work which I think the U. S. Bureau of Mines should do, and I understand from Mr. Nicholls that much more data have been collected than are presented in this paper. It is to be hoped that all of this research can be made available.

Authors' Closure

Although the subject matter of the paper is relatively simple, yet it requires rather close study to follow the arguments; consequently much detailed discussion was not expected because of the short time the paper has been available. It is hoped that this attempt to formulate principles will be supplemented by those who are associated with stoker design and operation; no data are available at present on the motion of the streams of coal in the fuel bed, or their dependence on the properties of the coal.

There is, however, room for considerable more work of the type reported in the paper; in particular, studies are required to determine whether this method of testing could be used to measure the relative burning characteristics of coals closely alike, and whether these measures could be used to predict their characteristics or peculiarities when used in stokers.

[12] Vice-President, Babcock & Wilcox Co., New York, N. Y. Mem. A.S.M.E.