COMBUSTION OF SOLID FUELS IN THIN BEDS

By E. P. Carman, E. G. Graf, and R. C. Corey
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COMBUSTION OF SOLID FUELS IN THIN BEDS

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Introduction

OBJECTIVES, SCOPE OF WORK, AND DEFINITION OF TERMS

SINCE ITS INCEPTION the Bureau of Mines has made many studies of the fundamentals affecting the burning of solid fuels on grates, beginning with the early investigations by Randall, Flagg, Kreisinger, and their coworkers (1, 2, 5, 6, 14-18, 22-27, 29, 30, 33, 34, 63) on the principles of overfeed combustion and continuing with the work of Barkley, Sherman, Rice, Nicholls, and others (3, 4, 7-13, 19-21, 28, 31, 32, 35-46, 48-52, 54-99) on underfeed and other burning and gasification processes. The investigations described in this report are a continuation and extension of these commercial and pilot-scale tests to include an investigation of the ignition and burning of solid fuels in thin beds, as on traveling- or chain-grate stokers, and a study of pure crossfeed combustion. The tests were subject to close control and measurement to provide data that would aid in more efficient design and operation of combustion equipment and would help to clarify the effects of various factors on ignition and burning in thin beds of solid fuels.

A number of combustion investigations have been conducted on chain- or traveling-grate stokers, particularly in England (100-106, 109-111, 113-116, 119-124, 128). Developments in this country have resulted in drastic changes in design that have improved operation materially by eliminating many initial ignition difficulties of the front radiant arch (47, 74, 107, 108, 112, 118, 125, 126, 129). Although some of the data developed in the investigation reported herein confirm or were confirmed by data developed in these earlier investigations, it is believed that significant new material and conclusions on the behavior of fuels during ignition and burning in thin fuel beds have resulted from this investigation to warrant publication.

The traveling-grate-stoker tests were conducted in a small pilot-scale furnace with a stationary grate that simulated a traveling-grate stoker-fired furnace except for size and movement of the grate. Test operations and measurements were simplified by the stationary grate, and time observations were substituted for grate movement. The crossfeed tests were run in a modified traveling-grate test furnace adapted to provide a pair of vertical grates so arranged as to give pure crossfeed ignition and burning conditions, after the top of the bed was ignited.

Factors studied included the time required for initial ignition of the surface of the fuel bed by heat transferred by radiation, determination of the absolute radiant heat received by the fuel, travel of ignition through the bed (74), and burning after ignition reached the grate. The resistance of the fuel beds to the flow of air, or bed pressure drop, was measured and its effects analyzed. The temperatures of experimental fuel beds and grates and the factors that

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\(^{1}\) Work on manuscript completed May 1, 1956.

\(^{2}\) Chemical engineer, Branch of Bituminous Coal Research, Division of Bituminous Coal, Bureau of Mines, Washington, D. C.

\(^{3}\) Formerly, chemical engineer, Combustion Section, Division of Solid Fuels Technology, Region V, Bureau of Mines, Pittsburgh, Pa.


\(^{5}\) Italicized numbers in parentheses refer to items in the bibliography at the end of this bulletin.
influence these temperatures were determined. The effects of water tempering and of a limited number of chemical treatments also were studied, and tests of a coal prepared with various ash contents gave data on the effect of ash on initial ignition, rate of ignition travel through the bed, and burning rates. Measurements were made to determine the effects of preheating primary air and of using secondary air.

A total of 391 fuel-burning tests and 30 tests to measure and calibrate the heat output of the radiant hood were made in the traveling-grate-stoker investigation. The data developed are applicable to either traveling- or chain-grate types of stokers; hereafter statements referring to the “traveling-grate stoker” in this report also are generally applicable to the chain-grate stoker. Initial experiments were made on high-temperature coke, as this fuel does not smoke, cake, or contain high moisture. Coke of various closely screened sizes was used in 61 tests, and coke breeze of 3 different size consists was used in 40 tests. Anthracites of various burning characteristics, ash contents, and sizes were used in 146 tests, including 1 series to determine the effects of wide variation of ash content and others to determine the effects of chemical treatment, use of secondary air, and preheating of primary air. These tests revealed unexpected data on bed pressure drop that were later confirmed by theoretical calculations. Coals ranging in rank from low-volatile bituminous to subbituminous and lignite were used in 144 tests to determine the effects of coal rank, size, caking tendencies, emission of volatile matter, and high inherent moisture.

In the crossfeed investigation 27 tests were made on 4 fuels: Coke breeze, anthracite, high-volatile A bituminous coal, and subbituminous B coal. Quantities of these fuels were prepared and stored in sealed steel drums for the traveling-grate tests and were used in both investigations to eliminate variations that might arise from use of fuels from different sources and to permit comparison between the traveling-grate and crossfeed tests.

Four terms or factors are used throughout this report. One relates to the time required to obtain initial ignition of the top surfaces of the particles comprising the bed top. This is defined as initial ignition time and is given in minutes and fractions thereof. The method of determining initial ignition time is described later in the report.

The second factor is rate of travel of the ignition plane through the bed. This factor, designated for brevity in the report as travel of ignition, is determined from the thermocouple records and is expressed in inches per hour.

The third factor, rate of ignition, is derived from the second, plus analyses of the fuels and bed-density data obtained from volume and weight of fuel charged, and is expressed in pounds of combustible ignited per square foot-hour. As may be noted, both the second and third factors are rates; the difference in designation is derived from the difference in units in which these rates are expressed.

The fourth factor is rate of burning of the fuel in the bed, expressed in pounds of combustible per square foot-hour. This factor differs from the third in two respects: (1) It is a burning rather than an ignition rate, and (2) it is derived as a material balance from the gas analyses and air rate rather than from thermocouple records and other data.

More detailed description of the method of calculating rates of ignition and rates of burning are given in the section, Determining Combustible Ignited and Burned and Ignition and Burning Rates (p. 24).

One of these factors, rate of ignition, needs further explanation to avoid possible misunderstanding. This factor, determined as described, may indicate a higher rate of ignition travel in pounds of combustible than has actually taken place, particularly with large-size fuel. Based partly on thermocouple data, this factor shows the rate of travel of an assumed isothermal plane past the surfaces of the pieces of fuel in the bed, thus indicating that the surfaces of the particles are ignited down to the ignition plane. It does not necessarily follow that the entire fuel particle all the way to its center is ignited as the ignition plane passes the particle. Since more time may be required to ignite a large particle to its center than may be required for the plane of ignition to pass
the particle in its downward travel because of the low heat conductivity of coal and since the entire weight of the particle is included in the calculation of rate of ignition, this calculated value may be slightly inaccurate. However, considering that the hottest zone in the fuel bed, where the major volume of the oxygen available for reaction with the fuel is consumed, is only a short distance above the ignition plane, it is also probable that the intense heat of this rapid burning zone rather quickly forces ignition to the center of even moderately large pieces (as used in this investigation, even up to 1½- by 1-inch sizes). The rate of ignition as used herein therefore is believed to be a reasonably accurate representation of the true rate of ignition, especially for the smaller sizes.

Another item that should be considered in this report is the informal allocation of coke to anthracite-rank classification and of steam-dried lignite to a higher rank classification than natural lignite in discussing general effects of various combustion factors as affected by rank classification. Coke, a manufactured fuel, does not actually belong in a rank classification of natural fossil fuels. However, the relatively low volatile-matter and high fixed-carbon contents of coke are in the range that corresponds with the anthracite-rank classification; therefore, in this report the words “effects of rank” are taken to mean “effects of rank and of kind of fuel” as regards both high-temperature coke and steam-dried lignite, which by drying is also removed from the rank position of raw lignite with natural bed moisture.

ACKNOWLEDGMENTS

This study was initiated by the late Percy Nicholls, former supervising engineer of the Fuels Section (now Combustion Section), Bureau of Mines, who originally planned the project, designed the apparatus, and supervised the early phases of the work. W. T. Reid designed the airflow regulating device described and illustrated herein and took the pictures used to illustrate fuel-bed conditions.

The Bureau sincerely appreciates the cooperation of several coal companies, which supplied (without charge) the major portion of the fuels used in this investigation, and of the University of North Dakota, which dried some of the lignite in its steam-drying pilot plant. The Philadelphia & Reading Coal & Iron Co., Philadelphia, Pa., supplied some of the smaller sizes of anthracite from its regular production and specially prepared anthracites containing varying amounts of ash which were used to determine effects of variable ash content on ignition and burning rates. The Bell & Zoller Coal Co., Chicago, Ill., supplied washed coal from its preparation plant at Zeigler No. 2 mine, and Pittsburgh Coke & Iron Co. furnished coke breeze from its coke plant. The Pittsburgh & Midway Coal Co., Pittsburg, Kans., the Clayton Coal Co., Denver, Colo., and the Knife River Coal Mining Co., Beulah, N. Dak., supplied coals from their regular production.
PART I.—TRAVELING- OR CHAIN-GRADE STOKERS

CONCLUSIONS

Observations made during this investigation and analysis of test data have led to the conclusions given here. The principles on which these conclusions are based, with additional significant points and conclusions, are more fully discussed and illustrated later.

STAGES OF IGNITION: INITIAL IGNITION AND IGNITION THROUGH BED

Ignition of the fuel on a traveling-grate stoker takes place in two stages. The first is ignition of the top pieces of coal on the bed or initial ignition. The second is the travel of ignition down through the bed.

STAGES OF INITIAL IGNITION

Initial ignition is considered to be established when the fuel continues to burn after the igniting source is removed. For a given fuel and air rate initial ignition time is a function of the heat received at the top of the bed. When initial ignition of bituminous coals and lignite is affected by radiation (as in most of the tests in this investigation), the exposed fuel surfaces are devolatilized and coked or charred, and these coke or char surfaces begin to glow before the volatile matter ignites. Ignition and flaming of the volatile matter usually follow quickly and result in rapid spread of ignition and burning across the entire bed top. In burning coke and anthracite the glowing spreads across the bed until CO or H₂, or both, are generated in sufficient quantity to ignite; these gases then burn with a blue flame. The stages of initial ignition are hereafter referred to as glowing and flaming ignition.

EFFECT OF COAL SIZE ON INITIAL IGNITION

For fixed rates of heat transfer to the bed top (to obtain initial ignition by radiation) it was found that initial ignition took place most rapidly at low air rates for small sizes of high-rank fuel and for larger sizes of low-rank fuel. Conversely, at high air rates the larger sizes of high-rank fuels and the smaller sizes of low-rank fuels ignited more rapidly. This behavior of the high-rank fuels is believed to be due to the increase in cooling effect with increase of air rate as related to the area of the particles receiving radiant heat and being cooled by convection. The reverse behavior of the low-rank fuels is believed to be due to availability of oxygen aiding ignition of the small sizes; that is, this ignition behavior is believed to be a function of the airflow pattern past different-size particles.

EFFECT OF RANK OF COAL ON INITIAL IGNITION

As compared to beds of bituminous coals and lignite, the tops of the beds of high-temperature cokes and anthracites were relatively difficult to ignite. The time required for initial ignition (glowing) of the cokes and anthracites was 5 to 10 times that for the lower rank coals for comparable radiant-heat and air-rate conditions. Within the rank range from low-volatile coal to lignite there was an overall decrease in initial ignition time of 2½ to 1. Steam-dried lignite required the shortest initial ignition time of all fuels tested.

EFFECT OF SURFACE MOISTURE ON INITIAL IGNITION

A moderate amount of surface moisture (up to 8 percent for the coke breeze tested) appeared to have little or no effect on initial ignition. Increase of moisture content above an optimum amount appeared to retard initial ignition.

TRAVEL OF IGNITION OR "PLANE OF IGNITION"

When the bed top is ignited quickly and evenly, travel of ignition through the bed proceeds in an essentially horizontal plane. The "plane of ignition" is therefore considered as a horizontal, isothermal plane moving down through the fuel bed and touching the individual fuel pieces at points on their surfaces where the heat received by the particles from radiation, conduction, and convection and that generated by the oxidation reaction begin to exceed the heat loss from the points in question. (See discussion and fig. 68 in part II.)

NORMAL AND ABNORMAL RATES OF IGNITION TRAVEL

When initial ignition is reasonably fast (initial ignition time, 3 minutes or less), the plane of ignition for most fuels and air rates, travels through the bed at a definite rate determined only by the characteristics of the fuel and the air rate. When initial ignition is very slow, however, the rates of ignition travel are retarded in at least part of the bed. Also, when the rate of burning is so close to the rate of ignition that there is only a very thin layer of burning fuel above the ignition plane, variations in the temperature of surfaces to which the thin burning layer is exposed can materially alter the heat loss from, and the rate of burning
of this thin layer. Such variations in turn affect the rate of ignition travel. In thin burning beds ash layers above the combustion zone can also affect ignition and burning rates materially.

**PRINCIPLES OF IGNITION AND BURNING: UNDERFEED AND OVERFEED**

While the ignition plane is traveling through the bed, ignition and burning proceed essentially in accordance with unrestricted underfeed principles (74). (See fig. 20.)

After ignition reaches the grate, burning of the residual fuel proceeds by overfeed principles. As shown in part II of this investigation, the crossfeed-ignition component does not affect ignition travel significantly in a traveling-grate stoker, except when banked.

**EFFECT OF COAL SIZE ON IGNITION TRAVEL THROUGH BED**

For all fuels tested rate of ignition travel through the bed increased with decrease of average particle size down to about \( \frac{3}{8} \)-inch average diameter. An optimum particle size for coke and anthracite was found in the range of \( \frac{1}{2} \)- to \( \frac{3}{8} \)-inch average diameter for maximum rate of ignition travel. Decrease in particle size of these fuels below this optimum gave decreasing rates of ignition travel. However, the other fuels studied revealed no optimum minimum size, and rates of ignition travel increased with decrease of size down to the smallest sizes tested.

**EFFECT OF RANK OF COAL ON IGNITION THROUGH BED**

After the top of the bed was ignited, underfeed ignition through the bed was found to vary with rank and air rate as well as with size. At low and moderate air rates (50 to 400 pounds per square foot-hour) ignition rates through the bed were highest in a bed of coke breeze that had been moistened and placed in the furnace damp and then predried before igniting. Of the fuels moistened to give bed stability and ignited while damp, the small sizes of both low-volatile and Pittsburgh-bed high-volatile A bituminous coals gave the highest rates of ignition at air rates of 50 to 400 pounds, followed closely by the small sizes of coke and coke breeze. Ignition rates decreased rapidly with rank below high-volatile A bituminous.

The high ignition rates obtained in testing the low-volatile and Pittsburgh high-volatile A bituminous coals at the lower air rates were exceeded by the ignition rates obtained with these coals as air rates were increased above 400 pounds per square foot-hour, whereas such increases in air rate resulted in decreases in ignition rates for the cokes and anthracites as well as for the lower rank coals below high-volatile A. These results indicate that where underfeed ignition is involved maximum rates of ignition and therefore the highest fuel-burning capacities possible will be obtained with low- and medium-volatile and high-volatile A bituminous coals at air rates of 600 to possibly as high as 1,000 pounds per square foot-hour.

**EFFECT OF SURFACE MOISTURE ON IGNITION THROUGH BED**

Optimum conditions for underfeed ignition in forced-draft stokers prevail when the fuel has the minimum amount of surface moisture that will give reasonable stability of the fuel bed. In natural-draft stokers optimum surface-moisture content of the bed is that which gives maximum agglomeration of fines to reduce bed pressure drop. In both instances, increase of surface moisture above the bare minimum needed to maintain bed stability or to obtain minimum bed pressure drop (through agglomeration) results in decreased ignition rates for given air rates.

**EFFECT OF PREHEATED AIR ON INITIAL IGNITION AND IGNITION THROUGH BED**

Preheating primary air, under normal conditions of furnace operation, has relatively little effect on initial ignition, because the sensible heat in the air is used largely in heating the bottom layers of fuel as they enter the furnace. However, preheated air increases travel of ignition materially. The increase was almost directly proportional to the temperature increase of primary air above ambient at any given air rate and was more pronounced at high air rates.

**EFFECT OF CHEMICAL TREATMENT ON INITIAL IGNITION AND IGNITION THROUGH BED**

Moderate chemical treatment of coals (0.2 to 2.0 percent of sodium carbonate) reduced initial ignition time by about one-third (at one hood temperature from about 2.7 to 1.5 minutes). Records of thermocouples on and in the fuel bed indicated increasingly lower bed temperatures with increase of treatment. Heavier treatments (up to 4 percent) with sodium carbonate were detrimental, and moderate treatment with a sugar-refining byproduct showed negligible effect.

**EFFECT OF ASH CONTENT OF COAL ON INITIAL IGNITION, IGNITION THROUGH BED, AND BURNING IN BED**

Rather surprisingly, change of ash content of a fuel within very wide ranges (5 to 70 percent) showed no appreciable change in initial ignition
time but affected ignition travel rates significantly. High ignition rates may be obtained at a much wider range of air rates with low-ash than with high-ash coal. Burning rates after ignition has reached the grate, however, are not affected materially by moderate variations of ash content, and there is some indication that a nominal amount of ash tends to increase bed stability after ignition reaches the grate.

**EFFECT OF HIGH ASH CONTENT ON SLAG AND CLINKER FORMATION**

High ash content of coal may have another deleterious effect on furnace operation, aside from the limiting effects on ignition rates. Many ashes and slags expand or “bloat” when heated to high temperature in the fuel bed, and in very low grade, high-ash coals such ash and slag may occupy a volume as great or greater than the coal as charged and create a removal problem.

**PRESSURE DROP THROUGH BED**

Bed pressure drop increased with travel of ignition through beds of coke and anthracite, so that maximum pressure drop was recorded at the instant ignition reached the grate. Though unexpected, the reasons for this were determined later by theoretical calculations. For most bituminous coals, however, pressure drop fell off as ignition proceeded through the bed. This trend was most pronounced in the low-rank coals, which tended to burn in very thin layers, and was least pronounced in the high-rank, low-volatile coals. Reasons for both of these behaviors are discussed later in the report.

**PRACTICAL ASPECTS OF TEST DATA AND APPLICATION TO STOKER OPERATION**

The primary purpose of this investigation was to develop data that would aid in the design and operation of traveling-grate stokers, though much of the information obtained is applicable to combustion and gasification of fuels in many types of thin fuel beds. The following deductions, based on test data, are believed to be directly applicable to operation of commercial chain- or traveling-grate stokers.

**OVERCOMING SLOW BED-TOP IGNITION, AS AFTER BANKING OR LOW-RATE OPERATION**

Slow initial ignition results in slow rate of ignition in the top layers of the bed. In some instances the rate was retarded throughout the bed, but the effect was less pronounced with depth. Slow ignition rates reduce overall rates of combustion and furnace capacity. Therefore, after banking or operating at low burning rates, it will be necessary to reestablish high ignition hood temperatures or, in rear-arch furnaces, to reestablish adequate blowback of incandescent burning fuel before grate speed and air rates can be increased to give high ignition and burning rates and high furnace capacity.

**QUICK IGNITION BY FLUIDIZING PART OF BED**

In zoned stokers rapid ignition and burning in some instances can be quickly reestablished after banking, low burning rates, or operating difficulties by blasting the bed and fluidizing it in a zone where some of the fuel has been ignited. Under proper conditions, particularly with preheated undergrate air, this fluidizing or “boiling” of a section of the bed very quickly will spread ignition throughout the bed. However, if too little fuel has been ignited before the “blast,” ignition will be lost entirely in this section. This fluidized ignition is so fast that under most circumstances where rapid pickup is desired it would be worth while to attempt it, even considering the possibilities that under some circumstances it will not work and ignition will be lost in the section being fluidized.

**IMPROVING BED-TOP IGNITION BY LAYERING COALS**

Bituminous coals and lignite ignite initially much more rapidly than high-temperature cookes and anthracite (5 to 10 times as rapidly on the basis of equal heat input to the bed); obviously, therefore, use of a layer of bituminous coal over beds of coke breeze or anthracite would materially reduce initial ignition troubles.

**IMPROVING BED-TOP IGNITION BY PROPER MOISTURE CONTENT**

Excessively wet coal or coke may cause ignition troubles that can be eliminated by draining, partial drying, or mixing with dry coal to give a moisture content such that the fuel will form a stable ball when compressed in the hands.

**IMPROVING BED-TOP IGNITION BY USING MOST FAVORABLE FUEL SIZES**

Anthracites and high-rank bituminous coals of about $\frac{3}{8}$- to $\frac{1}{2}$-inch average particle size (diameter) ignite faster initially at low air rates than larger sizes of these fuels. This statement applies to the overall average size in run-of-mine or slack coals containing mixed sizes. If ignition difficulties are encountered in front-radiant-hood furnaces, ignition can be speeded up by feeding a coal or mixture of coals of the optimum average particle size for quick ignition at low air rates. For high-rank fuels this is in the $\frac{3}{8}$- to $\frac{1}{2}$-inch average size. Initial ignition of low-rank subbituminous coals and lignites is obtained more rapidly at low air rates on larger
size pieces, and these should be used to obtain most rapid initial ignition.

**SPEEDING UP BED-TOp IGNITION BY REDUCING AIR RATE OR USING "DEAD PLATE"**

Although size and moisture content affect ignition in front-radiant-hood furnaces to some extent, the quickest and most effective temporary measure that can be taken to increase initial ignition is to reduce the air rate. The word "temporary" is used because in nonzoned stokers high air rate is necessary to obtain rapid ignition and high burning rates. Therefore, a drop in air rate for this purpose should be only long enough to obtain such ignition. In nonzoned stokers burning fuels that are hard to ignite a "dead plate" at the front of the grate will reduce the air rate at that point enough to permit adequate ignition without impairing ignition and burning rates over the remaining grate area. In zoned stokers the air rate in the first zone should be maintained at a rate that is just low enough to permit adequate ignition of the bed top.

**CHEMICAL TREATMENT NOT RECOMMENDED**

Moderate treatment of coal (up to about 2 percent by weight) with sodium carbonate will speed up initial ignition and ignition through the bed and at the same time reduce overall bed temperatures. In general, however, the benefits from chemical treatment did not compensate for the additional expense and trouble of such treatment.

**PREHEATED PRIMARY AIR TO INCREASE IGNITION RATES AND FURNACE CAPACITY**

Preheated primary air will increase ignition and burning rates and thereby increase furnace capacity. Such increase is approximately proportional to the increase in absolute temperature of the preheated air for given air rates and is relatively more effective at high than at low air rates.

**DIFFICULTIES WITH HIGH-ASH COALS**

High-ash coals, while exhibiting normal behavior as regards ignition of the bed top, have much lower rates of ignition in the bed and a much more limited range of permissible air rates than low-ash coals. Consequently, they will give lower furnace capacities as compared with low-ash coals. Furthermore, since high-ash coals ignite through the bed and burn at lower rates, they also may indirectly cause ignition difficulties in either the front- or rear-arch type of furnace. However, rear-arch furnaces should burn high-ash coals more successfully than front-arch furnaces because it is more difficult to maintain high temperatures in a front arch at lower burning rates and because the rear arch provides ignition from glowing particles thrown forward onto the incoming fuel.

**EFFECTS OF BED PRESSURE DROP WITH SOME FUELS**

In beds of coke and anthracite the increase in pressure drop, or resistance to flow of air through the bed as ignition proceeds into the bed, can materially delay ignition of the fuel bed in nonzoned stokers by reducing the air rate in the ignition zone. Reduced air rate would spread the ignition zone farther back on the grate and result in a substantially reduced overall average air rate, which would reduce ignition and burning rates and furnace capacity. For these fuels, therefore, zoned stokers with forced and induced draft would be preferable to nonzoned, natural-draft stokers. Marked improvement in burning these fuels on the latter-type stoker can be obtained by adding forced- and induced-draft fans to aid in overcoming the higher fuel-bed resistance encountered as ignition proceeds through the bed or by preheating the primary air. In general, this condition does not prevail in beds of bituminous and lower rank coals, since the bed pressure drop is usually highest as the fuel enters the furnace, and some reduction in air rate at this point is desirable to accelerate ignition of the raw fuel.

**USE OF DATA TO CALCULATE STOKER PERFORMANCE**

The data presented in this bulletin can be used to calculate stoker performance, as shown in figure 1. This figure is based entirely on calculations from the test data for an anthracite, but similar data are presented for the other fuels tested. Values for length of grate, rate of grate travel, amount of available draft, and CO₂ content of the flue gas were assumed. Perfect mixing and combustion in the furnace of the gases generated in the bed and constant bed pressure drop, simulating a nonzoned stoker, were also assumed. In this particular example burning of the fuel was essentially completed in 13 feet of grate travel, or 52 minutes elapsed time, and the air rate through the rear 2 feet of grate was excessive. Thorough mixing of this air and the combustible gases generated in the fuel bed (which was assumed in developing this figure) is therefore necessary or the combustible will be lost up the stack and efficiency in burning the fuel will be reduced. By running the stoker just a little faster or carrying a slightly deeper bed, the "burnout" point could be moved back to the bridge wall and the overall burning rate increased, with better distribution of air through the bed; however, to maintain the same (assumed) CO₂
in the stack gases, it would be necessary to introduce secondary air over the bed to replace the relatively large volume now going through the burned-out portion of the bed and to provide oxygen for the higher burning rates obtained in deeper beds. This can be done in such a way as to improve mixing and turbulence over the bed to give more complete combustion of the combustible gases there and so materially improve the efficiency as well as the capacity of the unit.

OTHER SIGNIFICANT POINTS

Other significant points and conclusions from the test work are given in the more detailed discussions that follow and are italicized for emphasis.

TYPES OF FUEL BEDS

The type of ignition and burning in a stable fuel bed is determined by the relative direction of flow of fuel and air, as described for some types of beds by Nicholls (10) and Landry (117) and for traveling-grate stokers by Carman and Reid (74). These are briefly reviewed here, particularly to emphasize the traveling-grate and crossfeed types of beds studied in this investigation. For unstable beds, as encountered in some of the traveling-grate-stoker tests, the physical state of the fuel and the bed temperature will largely control the type of ignition and burning.

In overfeed beds, as shown diagrammatically in figure 2, the fuel and air travel in opposite directions. Usually the fuel is fed at the top, and air enters from the bottom of the bed. As all of the oxygen will be consumed in the lower part of the bed, there will be a high-temperature zone there, and the hot products of combustion will undergo further gasification and preheat the upper part of the bed as they move up through it. At some level in the bed the down-moving fuel will be preheated to ignition temperature, but since all of the oxygen from the primary air will have been utilized in the gasification reactions below this level Landry (117) has referred to this level as the plane of virtual ignition, where ignition temperature is reached in the absence of oxygen. This plane of virtual ignition is indicated in figure 2.

Figure 3 represents an underfeed bed wherein the fuel and air travel in the same direction, while the plane of ignition moves into the green fuel in a direction opposite to that of the fuel.

Figure 1.—Ignition and Burning of Fuel Bed in a Traveling-Grate Stoker.

Fuel is \( \frac{3}{4} \) inch medium-burning anthracite. Bed pressure drop assumed to be 0.4 inch H₂O; CO₂ in flue gas assumed to be 14 percent; all air supplied under grate.
and air travel. Since there will be unreacted oxygen at the level where the green fuel becomes heated to the ignition temperature in this type of bed, there will be a true or real plane of ignition with available oxygen as contrasted to the virtual plane of ignition without available oxygen, as in overfeed beds.

Usually in underfeed beds the fuel and air are fed from the bottom and move upward, as in many types of small domestic screw-feed underfeed stokers. In the traveling-grate stoker, where ignition is also underfeed, the fuel is fed from the side and air from the bottom. Ignition starts at the top of incoming fuel and moves downward into the bed as the fuel is carried through the furnace, giving underfeed ignition although the directions of fuel and air feed are similar to those in crossfeed beds.

Figure 4 shows typical overfeed and underfeed ignition and burning curves; the overfeed ignition curve $AI$ is shown as a dashline since, as far as the authors are aware, actual unrestricted overfeed ignition rates have never been determined experimentally. Theoretically, overfeed ignition, if not restricted by bed depth or by heat losses from the bed, would proceed at a much more rapid rate than overfeed burning, as indicated in the postulated dash curve $AI$. Under these conditions depth of ignited bed would increase indefinitely with time. However, under actual operating conditions gasification reactions and heat losses from very deep beds would reduce the temperature of the rising gases until at some level in the bed this would be below the ignition temperature of the fuel. Then there would be an equilibrium depth of bed in which there would be a plane of virtual ignition where ignition and burning would proceed at a rate determined by the rate of overfeed burning, shown by curve $AO$.

In underfeed beds ignition proceeds according to the underfeed curve $ABC$ in figure 4, while burning proceeds at the rates indicated by the underfeed burning curve $AU$. At low to moderate air rates, that is, at rates corresponding to points lying between $A$ and $E$ on curve $ABC$, ignition proceeds at a faster rate than burning, and depth of ignited bed will increase with time unless restricted by depth of available fuel or by heat losses, as in overfeed beds. Theoretically, if the fuel bed is deep enough, the depth of ignited fuel will increase until heat losses above the real ignition plane exceed the heat in the products of combustion and gasification, whereupon the remaining fuel will drop in temperature below the ignition temperature. There will then be an upper plane of virtual ignition, with fuel above it that had been ignited but that had cooled below the ignition temperature. Burning would then be controlled by the underfeed burning rate (curve $AU$), but ignition would continue at the rate determined by curve $ABC$ if fuel were fed from beneath at this rate. Any excess fuel over this ignition rate that is fed from beneath will be discharged as partly burned fuel from the top of the bed, when operating within the range of air rates cited.

As the air rate in underfeed beds is increased above an optimum for ignition, as represented by point $B$, the difference between ignition and
burning rates declines rapidly, until at point E they become the same. If at point E the minimum thickness of ignited fuel necessary to maintain live burning in the bed has been ignited at a lower air rate, ignition and burning will proceed at identical rates, and the preignited layer becomes the equilibrium bed thickness that remains stationary in the retort (or moves across the traveling grate) as the fuel is moved in at this ignition and burning rate. This is referred to as equilibrium ignition and burning in underfeed beds (10).

Where more than the minimum thickness of ignited fuel necessary to maintain live burning has been preignited at low air rates, as in an air-zoned traveling-grate stoker, and underfeed air rate is then increased beyond point E, figure 4, burning will proceed at a higher rate than ignition, as may be noted by points F and G, respectively, to give overequilibrium burning. Actual test data showing such overequilibrium burning are shown in figure 50 (p. 56) wherein the maximum underfeed burning rates for the subbituminous B coal are higher than the ignition rates at air rates exceeding 250 pounds per square foot-hour. For example, at a 600-pound air rate the maximum underfeed burning rate is 42 pounds C+H₂ per square foot-hour, while the ignition rate is only 35 pounds.

This overequilibrium burning is possible only because of the presence of the preignited layer and will take place only so long as there is an excess of preignited fuel over the minimum required to maintain a live-burning bed. When the burning rate is faster than the ignition rate, as at F, the preignited layer burns off, the burning rate then drops back to the ignition rate, as at G, and ignition and burning proceed through the bed at the same lower rate, limited by the ignition rate.

In a traveling-grate stoker it is thus possible to preignite continuously a layer of fuel, using a low air rate at the front of the grate, and have a zone of overequilibrium burning at a very high air rate immediately following this preignition zone. Proper manipulation of air controls, using data from this investigation, would in this manner give the highest possible rates of ignition and burning; for example, the preliminary ignition would take place at an air rate represented by point B and further ignition and burnout at the air rate represented by point F. Such operation would require close attention, and minor changes in the air rate could result in changes in rate of burning that would affect the area of grate covered by the overequilibrium burning.

To clarify the term "minimum thickness of ignited fuel necessary to maintain live burning in the bed," Nicholls' studies (10), as well as the present investigation, have indicated that there is a minimum bed thickness necessary to utilize the oxygen in the primary air and maintain active, live burning and that this minimum thickness is 3 to 6 average particle diameters; that is, the minimum live-bed thickness for fuel of $\frac{1}{4}$-inch average particle diameter would be about 2 inches.

In a pure crossfeed bed (fig. 5) the fuel would be introduced at virtually right angles to the air stream, and the plane of ignition would move in the opposite direction into the incoming green fuel. Figure 5 shows one possible type of pure crossfeed bed using a fuel-feed arrangement on a traveling-grate stoker. Another type of pure crossfeed bed is that described in part II of this investigation (fig. 6) in which the fuel is restrained between an inlet-air grate and a water-cooled outlet grate. Although this type of bed was used in a batchwise operation for the tests described in part II of this bulletin, with appropriate fuel-feeding and ash-removal facilities it could be adapted to continuous operation. This type restricts the fuel between the two vertical grates so that very high air rates can be used (and were used) without

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**Figure 5.** Diagrammatic Pure Crossfeed Fuel Bed on Traveling Grate.
destroying bed stability. Obviously, the bed shown in figure 6 could be turned 90°, so that the grates shown in vertical position would be horizontal, and air flow would be from bottom to top, or vice versa, while fuel flow would be horizontal along the air-inlet grate. This position would not in any way affect the pure crossfeed aspects of the bed.

Ignition in the traveling-grate stoker (fig. 7) occurs across the top of the incoming fuel, either by radiant heat and convection from hot gases, or in a rear-arch furnace by deposition of ignited fuel blown from the rear. The ignition plane travels down through the bed in a direction nearly opposite to that of the airflow, and therefore during the travel through length U, up to the point where the ignition plane touches the grate, ignition and burning are essentially underfeed. Following a short changeover period after ignition reaches the grate, that is, during travel through length O, the burning is overfeed. The traveling-grate stoker is quite commonly referred to as a type of overfeed stoker, but fundamentally the fuel is igniting and burning underfeed over a large portion of the length of the bed with high-rank coals and over almost the entire length of the bed with low-rank coals.

The spreader stoker has the suspension-type fuel bed, so called because most of the ignition and some of the burning in this furnace occurs while the fuel is in suspension in the gases and flame over the bed. The spreader stoker and the cyclone burner are mentioned here (figs. 8 and 9) to complete the list of different types of fuel beds and because fluidized beds were encountered at high air rates in the traveling-grate-stoker tests. The fluidized, "boiling," or "jiggling" bed is obtained in unrestricted beds when air rates are high enough to destroy bed stability. The main differences between the suspension or spreader-stoker bed and the fluidized bed is that in the former the fuel is thrown forcibly into the flame and combustion products over the residual fuel and ash that falls and remains on the grate, thus giving essentially overfeed ignition and burning, whereas in the fluidized bed the fuel is carried or fluidized by the air and products-of-combustion stream, and ignition may involve a combination of underfeed and overfeed principles. In both types of beds ignition can be extremely rapid under certain conditions.

DESCRIPTION AND ANALYSIS OF FUELS USED

The fuels used in this investigation ranged from high-temperature coke and anthracite to lignite and were chosen to represent reasonable differences in rank, rather than from consideration of their commercial usefulness on traveling-grate stokers. Actually all of the fuels tested are burned in this type of equipment, although strongly coking coals are sometimes less desirable, despite the conclusions from this investiga-
tion that highest ignition and burning rates can be obtained with such coals. The analysis and source of each fuel tested are shown in table 1.

All fuels tested were screened down to very close sizes and then, when required, remixed by weighing out proper quantities of each size and rolling them together on a rubber blanket before laying the bed. For example, Rice-size anthracite originally was separated into plus-$\frac{3}{8}$-inch oversize, $\frac{3}{8}$- by $\frac{1}{2}$-inch size, and minus-$\frac{1}{8}$-inch undersize, and for each test the proper proportions of each size were remixed. The coke breeze and the mixed-size consists of bituminous coals were prepared in the same way.

When moisture or chemicals (in solution) were used, they were added to the individual test batches of "as stored" fuel, and the total moisture was calculated by adding the "as stored" moisture. Any added moisture was sprinkled and mixed on the coal in small increments on a rubber mixing blanket the day before the test, and the moistened (or treated) fuel was then carefully wrapped in the blanket and stored overnight to let the added moisture "soak in" insofar as there was a tendency for it to do so.

Samples of all size fractions of all fuels were taken for analysis when the sizes were originally prepared and separated. The prepared sizes were retained until used in sealed steel drums.
Additional details of specific sizes and size mixtures used for various purposes are given under Discussion of Test Data by Rank and Type of Fuel (p. 26).

**TEST APPARATUS AND METHODS**

**FURNACE, RADIANT HOOD, AIR SUPPLY, AND PREHEATER**

The apparatus used in the traveling-grate-stoker investigation is shown in figure 10. It was designed for the purpose of obtaining carefully controlled, reproducible test conditions in which small variations could be observed and their causes determined. The furnace proper (1, Fig. 10) was constructed of welded steel with insulating refractory lining. The fuel-bed opening was 20 inches square, and fuel-bed depths up to 10 inches could be used without blocking, peephole 16 in the front wall of the furnace. The top of the furnace was open, and two interchangeable covers or hoods were used (2 and 3, Fig. 10). These were supported on corner posts resting on hydraulic jacks so they could be moved alternately to cover the furnace.

Hood 2 had 6 (later changed to 8) Globar heating elements mounted under a carborundum backing plate. These Globars could be heated electrically to 2,800° F., and the current could be controlled very closely by means of variable transformers, giving smooth variation of power input up to 70 kw. During the heating-up period before a test was started, this hood rested on a support at the side of the furnace, and the Globars and heating surfaces were exposed to a water-cooled “cold box” (13, Fig. 10) of virtually the same dimensions as the furnace with the fuel bed laid. The purpose of this arrangement was to duplicate the cold furnace and fuel bed with respect to heat absorption when the Globar hood was first moved over the cold bed and furnace. Thus, no appreciable change in temperature conditions in the radiant hood occurred at the beginning of the test.

Hood 3 was refractory-lined steel, and it rested on a small gas-fired furnace, 17, at the side of the test furnace, where it could be preheated before the tests were started. When the top of the fuel bed (not shown) was thoroughly ignited by the Globar igniting hood, both hoods were raised, the ignition hood was returned to its original position, and the refractory hood was transferred to the test furnace for the remainder of the test. This saved the Globars from excessive heat and contamination by smoke, combustion gases, and fly ash after initial ignition of the bed, while preheat-
<table>
<thead>
<tr>
<th>Types of fuel and classification by rank</th>
<th>Source: State, county, mine, and bed</th>
<th>As received</th>
<th>Proximate analysis, percent</th>
<th>Heating value, B. t. u. per pound</th>
<th>Ultimate analysis, percent</th>
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</thead>
<tbody>
<tr>
<td><strong>High-temperature coke</strong> (sized)</td>
<td>Pennsylvania, Neville Island plant, Pittsburgh Coke &amp; Iron Co.</td>
<td>4.2</td>
<td>1.4</td>
<td>85.0</td>
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<td><strong>High-temperature coke</strong> (breeze)</td>
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<td>10.2</td>
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<td>Anthracite (slow-burning) (Pea and Rice sizes)</td>
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<td>3.4</td>
<td>83.4</td>
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<td>Anthracite (medium-burning) (Pea and Rice sizes)</td>
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<td>2.0</td>
<td>6.1</td>
<td>82.4</td>
<td>9.5</td>
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<td>Anthracite (free-burning) (Pea and Rice sizes)</td>
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<td>1.7</td>
<td>6.8</td>
<td>79.7</td>
<td>11.8</td>
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<td>Anthracite, Barley</td>
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<td>4.9</td>
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<td>7.6</td>
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<td>80.9</td>
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<td>High-volatile B bituminous</td>
<td>6.7</td>
<td>35.7</td>
<td>52.0</td>
<td>5.6</td>
</tr>
<tr>
<td>Anthracite, Barley</td>
<td>Subbituminous B</td>
<td>21.8</td>
<td>30.2</td>
<td>43.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Anthracite, Barley</td>
<td>Lignite</td>
<td>35.5</td>
<td>27.5</td>
<td>30.2</td>
<td>6.8</td>
</tr>
<tr>
<td>Anthracite, Barley</td>
<td>Lignite, steam-dried</td>
<td>11.9</td>
<td>37.0</td>
<td>40.7</td>
<td>10.4</td>
</tr>
<tr>
<td>Anthracite, Barley</td>
<td>Lignite char (for quick ignition)</td>
<td>10.5</td>
<td>14.2</td>
<td>49.9</td>
<td>10.4</td>
</tr>
</tbody>
</table>

In most tests only primary or undergrade air was used; it was supplied by fan 9, which could deliver up to 1,000 pounds of air per hour and square foot of furnace area at a static pressure of 3.7 inches of water or lower air rates at higher back pressure, if desired. Close control of the quantity of air supplied was provided by a regulating valve, 8, which was operated by an electric control mechanism, 10 and 11, actuated by the pressure differential across a measuring orifice, 6, in the air line. (See fig. 11.) By this means a fixed air rate could be maintained automatically throughout a test. In a few tests secondary air was supplied over the bed by blowing it down the side stack with an auxiliary blower.

A tubular heat exchanger (4, fig. 10) in the air line between the orifice and the furnace permitted use of preheated air in some of the tests. (See fig. 12.) Heat was supplied by a gas burner in a refractory combustion chamber beside the heat exchanger. A mixer and air distrubutor in the ashpit insured even distribution of air at the grate.

**Sampling and Analyzing Gases**

The furnace was equipped with a side-outlet stack which was used when the Globar hood was over the furnace, but it was capped off when the refractory hood was in use, as this hood had a center stack. Both stacks had nipples (20, fig. 10) for inserting water-cooled gas samplers which had been modified to take samples across the stack rather than only at one position near the center. Gas samples were collected over mercury and analyzed, usually the next day, in Orsat apparatus, using acidified sodium sulfate solution as the confusing liquid. A photoelectric smoke meter, 19, was installed on the side-outlet stack. When this was in use, the center stack of the refractory hood was capped off, and only the side stack was used.

A Siemens-Halske indicating CO₂ meter was connected with the gas-sampling line in such a manner that the CO₂ content of the combustion gases could be read continuously. This instru-
Figure 10.—Cross Section and Diagrammatic Arrangement of Furnace and Auxiliary Apparatus Used in Traveling-Grate Investigation.
ment was calibrated periodically for time lag in it and in the sampling lines and was used as an aid in determining initial ignition to indicate when to shift hoods and when the effects thereof were over so that gas sampling over mercury could be started. The meter also indicated the rate of burning at the end of the test after the last gas sample had been taken and only CO₂, N₂, and O₂ were present in the stack gases. After the hoods had been shifted and ignition and burning had been stabilized, gas samples were taken approximately for each inch of penetration of ignition into the bed in the slower tests and as fast as possible in the tests at high air rates. After ignition reached the grate, one or more samples were taken to determine overfeed burning rates, depending upon time available.

METHODS OF OBTAINING TEST DATA

Initial ignition of the top of the fuel bed, travel of ignition through the bed, and bed temperatures were determined by thermocouples inserted at vertically spaced intervals in the bed and connected successively to recording potentiometers. Initial ignition of the bed top and of bed conditions during the test were observed through a peep hole in the front wall of the furnace.

Temperature of the radiant hood was determined by a pair of thermocouples inserted through the hood top and projecting down to positions between pairs of Globars to a distance (checked by radiometer and optical-pyrometer readings) that gave a representative reading for the whole radiant hood when the couples were connected in series and the readings halved.

The radiometer (14, fig. 10) used at the center of the cooling box for the Globar hood was a square, water-cooled copper radiometer with external shielding shell. The shell was maintained at the same temperature (approximately) as the center radiometer. The exposed top surfaces of both the radiometer and its shield were blackened with a thin layer of soot from a smoky acetylene flame. The weight and temperature of water from the radiometer were taken at measured, critical times, such as just
before moving the Globar hood over the furnace for initial ignition. Another radiometer (15, fig. 10) was used in many of the tests to aid in determining the instant of initial ignition of the bed. This was similar in operation to the cooling-box radiometer, except for shape. It was inserted through the side wall of the combustion chamber with its lower edge at the exact top of the fuel bed. It was rectangular, rather than square, and the soot-blackened surface was at a 45° angle to the horizontal; this surface therefore received radiation simultaneously from the Globar hood, which was some distance above it, from the opposite side wall of the furnace, and from the igniting fuel surface, which was much closer but at a much more acute angle.

Relative smoke density was determined with a conventional selenium cell and light apparatus mounted in the side stack (19, fig. 10).

In the tests on expanding coking coals and the special high-ash anthracites, the height of the bed above the grate was measured by means of a water-cooled copper-tube plunger, with refractory base, mounted in the refractory hood (18, fig. 10).

Pressure drop across the bed before and during the tests was observed on an inclined U gage and was recorded on the chart of a water-float manometer.

In a few tests on high-volatile A bituminous coal, tar and soot samples were taken to aid in making combustible balances, but they were not considered worth while for most of the other fuels.

**PREPARING FUELS AND LAYING BEDS**

The method of mixing, moistening, or adding chemicals to the fuels for tests has been described. At the time of test the previously mixed batches were weighed, and the fuel was laid in the bed by sprinkling from a small shovel to obtain as nearly uniform bed conditions for all tests as was possible. A special sheet-steel form about 1 inch smaller than the grate in each horizontal dimension was used for closely sized fuels to permit putting in a narrow band of smaller size fuel around the edges to reduce wall effects and to make air flow more evenly through the bed, after preliminary tests had shown some air leakage at the walls. The mixed-size fuels were tamped slightly around the edges to obtain the same effect.
In most of the tests the beds were 6 inches deep. However, in beds of the smaller (No. 4 Buckwheat) anthracite difficulty was experienced in maintaining even air distribution across the bed because of the tendency to develop “blowholes.” A “pinhole” or “Lloyd type” grate with very small airholes, such as is used in the anthracite region of Pennsylvania to burn No. 4 and No. 5 Buckwheat and river-dredged anthracite, was simulated in these tests by laying over the regular bar grate of the test furnace a 2-inch layer of “grog” or refractory brick ground to about 1/4 to 1/2 inch average particle size and screened to remove the under-1/4-inch fines. Over the grog, beds of “steam size” anthracites 3 to 4 inches thick were laid. In a very few tests on various fuels some bed thicknesses were as thin as 2 inches and some as thick as 9 inches.

Thermocouples were carefully arranged and laid so the junction was against the top of a piece of fuel. The exact height of this junction above the grate was measured by a special measuring device operated from the top of the furnace. The lateral spacing within the furnace was also noted. The couples usually were grouped laterally within about a 4-inch-diameter circle at the center of the bed. The top couple was placed on a piece of fuel at the top of the bed, the remainder of the bed top being laid so that the extreme tips of the top pieces were one-half the average particle diameter above the “nominal” bed height. By this method of laying beds, very close checks on “as laid” bed bulk densities were obtained, and these are believed to be fairly representative of beds used in commercial stokers.

TEST METHODS

While the test fuel bed was being laid, the Globar hood was being heated. Under ideal conditions, quite frequently attained after a little experience, the bed was ready just about the time the hood reached the preselected temperature. Then, just before the hood was swung over, a radiometer check was made with the cold-box radiometer to determine the intensity of radiation. Meanwhile, the test clock and all potentiometers were checked and set to zero time, and the current was turned off at a master switch. To start the test, the radiant hood was swung over and dropped into place, and the clock and recording instruments were started by pulling the master switch.

At first 3 (and later 4) means of determining initial ignition were used—observation through the peephole, the temperature record of the top thermocouple, and the indicating CO$_2$ meter. Later, the bed-top radiometer also was used as an indicator. Unless there was definite indication that one of these measurements was “off”, the individual measurements were averaged to obtain the initial ignition time used in the report.

The various steps in ignition of nonsmoking fuels are:

1. Tiny dull red spots appear upon scattered projecting pieces of the fuel, usually near the center of the bed top.

2. The dull red spots increase in number and size, and any volatile matter present shows as hazy wisps rising from the red spots or areas. (See fig. 13.)

3. The dull red spots spread in magnitude to cover all of some projecting pieces and join with those of other pieces to form a glowing area across the center of the bed, as new glowing spots and areas develop across the bed toward the edges. This is about the time of initial ignition, as used in this report, and if volatile matter is present short flames appear over the larger glowing areas. (See fig. 14.) Figure 15 shows the same stage in a bed with incipient fluidizing.

4. After initial ignition has occurred at or near the bed center, the glowing quickly spreads across the bed top, and more short flames appear over these areas as they become established. In this way ignition spreads across the bed top but has not yet started to penetrate the bed appreciably. (See fig. 16.) Figure 17 shows this same stage for a bed actually beginning to fluidize.

These further steps were observed in beds of bituminous coals and lignites:

5. The glowing of the bed top increases in intensity and brightness, and luminous flames flow up from and between the top pieces of fuel, increasing in length and intensity with time.

6. As ignition proceeds down into the bed, the luminous flames completely fill the combustion space with smoke and soot, preventing further view of the bed.

After ignition was well established across the bed top, as determined by observation, the Globar hood was removed, and the previously preheated refractory hood was moved into place. When the effects of this move and of stepping up the air rate (where higher rates were used for part of the test) had stabilized, rate of ignition travel through the bed was determined from thermocouple-potentiometer records. A couple peened into the top of the grate showed when ignition reached the grate. Burning conditions—underfeed before ignition to the grate and overfeed afterward—were noted by visual observations and from gas analyses. Rates of burning were later calculated from the gas analyses. After ignition to the grate overfeed burning was continued until the CO$_2$ meter reading dropped to about 1 percent, when the test was discontinued and the furnace left to cool overnight.

Figure 18 shows a fluidized bed during ignition through the bed. In some tests ignition by fluidization was so rapid that it was extremely difficult to obtain good thermocouple records from succeeding thermocouples.

Figure 19 shows an almost-burned-out bed as preparations are made to discontinue the test. Observations of the kind, location, and
Figure 13.—Second Stage in Bed-Top Ignition.

Figure 14.—Initial Ignition of Stable Bed Top.
Figure 15.—Initial Ignition of Bed Top With Incipient Fluidization.

Figure 16.—Bed Top Almost Completely Ignited.
Figure 17.—Bed Top Almost Completely Ignited and Beginning to Fluidize.

Figure 18.—Fluidized Bed During Ignition Through the Bed.
amount of residue (unburned fuel, if any, ash, slag or clinker) from one test were made before starting preparations for a new test. The total residue was removed and weighed, and, where need was indicated, samples were taken for analysis of combustible residue.

**ANALYZING AND CHECKING DATA**

In the test furnace the grate and bed were stationary, and transfer of the hot igniting hood over the fuel bed was comparable to emergence of the green fuel on a traveling-grate stoker into the furnace. By starting the clocks at the time of this transfer and noting the condition of the bed at any given time thereafter, conditions were obtained that were believed to be quite comparable to those in a thin vertical section across a bed on a traveling-grate stoker. It was possible to relate the progress of ignition through the bed to time, thus simulating bed conditions on an actual moving grate. Bed temperatures were determined by means of thermocouples, bed height was measured by a depth gage, and rate of burning was found from analyses of gas samples and recorded rate of air supply.

Early in the investigation the question arose as to the validity of applying this stationary grate-time fuel-bed data to moving beds on traveling-grate stokers because the plane of ignition on traveling-grate stokers slopes from the horizontal. Observations in this study indicated that the ignition plane was horizontal.
during ignition of the test beds; that is, during the tests the travel of ignition was in a vertical direction normal to the horizontal plane of ignition. The unknown factor as regards applying the data of these tests to traveling-grate-stoker beds was the horizontal component (fig. 20) that might be involved because of the sloping ignition plane. Figure 20 shows a wide enough section through a traveling-grate-stoker bed to illustrate the slight slope at the top of the bed resulting from burning off some of the fuel and the larger slope of the ignition plane.

In figure 20 the direction of travel of ignition (heavy line at right) was assumed to be normal to the ignition plane, as was observed in the tests of this investigation. Figure 20 also illustrates the vertical and horizontal components of this line; the vertical component corresponds to the effect of pure underfeed ignition and the horizontal component, to the effect of pure crossfeed ignition. The lengths of the vectors for these components (fig. 20) are shown proportional to the relative effects of the respective components, assuming equal rates of underfeed and crossfeed ignition.

As a search of the literature revealed no data on pure crossfeed ignition rates, this investigation was extended (part II) to determine the relative magnitude of crossfeed ignition rates as compared to the pure underfeed rates determined in part I. It was found that, within air rates at which traveling-grate-stoker beds are stable, underfeed ignition rates exceed crossfeed ignition rates by ratios up to 3 to 1. The horizontal or crossfeed component, shown in figure 20 on an equal-rate basis, should therefore be only about one-third as long as illustrated. If it is replotted to one-third the length shown in figure 20, the "direction of travel of ignition" will not form a 90° angle with the ignition plane, as illustrated on the basis of assumed equal underfeed and crossfeed ignition rates, but will be more nearly vertical, and the actual rate of travel of ignition, as represented by the heavy arrow of figure 20, will even more closely approach that of the pure underfeed component, as represented by the vertical arrow. This conclusion indicates that the pure underfeed component is definitely a controlling factor during ignition in a traveling-grate stoker operating normally. Therefore, the test data on pure underfeed ignition in a stationary bed can be considered applicable to normal traveling-grate-stoker operations with negligible loss of accuracy resulting from neglect of the very small horizontal component of pure crossfeed ignition.

In analyzing the test data time was used instead of distance traveled on a moving grate. At any given time after the test was started the condition of the bed in the test furnace was considered to be equivalent to the conditions that would prevail in a thin slice of a traveling-grate-stoker bed at a comparable time after emergence of that thin slice into the furnace proper. The actual distance that that slice would have traveled toward the bridge wall would depend on the grate speed. So, where time is shown as the horizontal scale in charts illustrating the test data, distance of travel of a moving grate can be substituted where rate of grate travel per unit of time has been established.

Since in most of the traveling-grate tests initial ignition of the top of the fuel bed was initiated by radiant heat from the Globar hood, determination and computation of the heat received at the bed top gave data that apply generally to radiant-hood stoker operation rather than only to the specific test apparatus. For this purpose, quantitative determination of the radiant heat received at the bed top in the test apparatus was essential. Relatively simple laws fix the amount of heat transferred per unit of area and time by radiant energy, and it was possible to control this energy and also to measure fairly accurately the amount received by the igniting fuel. Thus, if an igniting-hood temperature of $T$ degrees is required to produce a certain igniting effect, then its equivalent of $Q$ B. t. u. per square foot-hour would be transferred to the fuel.

The geometry of the system used was such that, with cold side walls in the combustion space of the pilot furnace at the beginning of the tests, maximum heat energy was received at the center of the bed until the side walls became heated. The cold box used during heating of the Globar hood simulated the cold furnace walls and bed top at the beginning of the tests, and the radiometer in the center of the cold box measured the heat received at the center of the fuel bed when the test was begun. After the test was started, the sidewall radiometer indicated the radiant-heat energy received on the bed during initial ignition, in addition to serving as an indicator of the time of initial ignition.

To determine the most suitable energy-absorbing surface for the radiometers and to compare calculated and experimentally determined rates of transfer of radiant energy to the bed, a radiometer similar to the one in the cold box was inserted in the center of a bed of refractory grog, with the top of the radiometer at the same level as the top of the fuel beds as laid for test purposes. A set of infrared lamps mounted in a fixed position over the simulated bed and radiometer to give a constant heat input to the radiometer was used in the tests with various surface materials. Of the three surfaces tested—polished copper, a thin layer of 40- to 60-mesh anthracite fines
over polished copper, and a thin coating of soot from a small, luminous acetylene flame over polished copper—the soot coating gave the highest heat absorption and was used for all subsequent radiometer tests. According to the data then available, lampblack had a radiation constant of 1.56, compared to 1.73 for a perfect black body in the Stephan-Boltzman radiation equation \( E_\beta = \sigma T^4 \), where \( E_\beta \) is the total black-body radiation, \( \sigma \) is the Stephan-Boltzman constant, and \( T \) is the temperature of the body in degrees Rankine.

Very careful observations were then made with a calibrated optical pyrometer of the igniting hood while it was held at predetermined mean temperatures. At each of these temperatures the hood, after pyrometer scanning, was moved into igniting position on the furnace, and the heat received by the radiometer in the simulated bed was measured. From the pyrometer data and the radiation constant noted, the rather complex calculations necessary to convert these observations to heat received by the radiometer were made.

Table 2 shows the agreement between the heat measured by the radiometer and the computed heat received at the bed center for various mean hood temperatures. As may be noted, the mean hood temperatures as determined by the thermocouples and by optical-pyrometer readings differ considerably, but measured heat and computed heat absorbed are quite close, using the thermocouple-indicated mean hood temperature. Also the optical-pyrometer-measured and calculated mean hood temperatures computed from radiometer-measured heat absorbed are quite close.

In the early work with water radiometers it was found that discrepancies in test results with the first model using straight-across water flow could be corrected by installing baffles to make the water take a circuitous course from inlet to outlet, thus increasing the water-residence time and its velocity against the heated surface and increasing the temperature rise for a given water throughput. This change gave more reproducible, and as indicated by table 2, more accurate data.

After the hood and radiometer calibration tests were completed, a series of tests was run at Globar-hood temperatures averaging 1,660\(^\circ\)F, 1,830\(^\circ\)F, 2,050\(^\circ\)F, 2,200\(^\circ\)F, and 2,400\(^\circ\)F, and at an air rate of 50 pounds per square foot-hour to determine actual heat received at the center of the bed top for various Globar-hood temperatures under actual operating conditions. These tests indicated the increase with time of heat received at the bed top from heating the test-furnace walls. The data are shown graphically in figure 75 in the appendix (p. 87), and in figure 76 (appendix, p. 88), they are replotted to give average heat absorbed for any given elapsed time as a function of the initial heat absorbed, that is, as a function of the heat absorbed at the instant the Globar hood is moved into place on the pilot furnace. This initial value, of course, is virtually the same as that given by the cold-box radiometer, which was measured just before each combustion test was started. Figure 76 was used in calculating the average heat input to the bed center for the period of initial ignition, using the initial heat absorbed by the cold-box radiometer and the time required for initial ignition and reading the average heat input for the required time from the ordinate scale.

**DETERMINING COMBUSTIBLE IGNIITED AND BURNED AND IGNITION AND BURNING RATES**

Definitions of the terms “rate of ignition” and “rate of burning” were given in the introduction of this report, but the methods of determining and calculating these factors are explained in detail here. Rate of ignition was

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Thermocouple-indicated mean hood temperature, (^\circ)F (^1)</th>
<th>Mean hood temperature computed from optical-pyrometer readings, (^\circ)F</th>
<th>Mean hood temperature computed from radiometer heat absorbed, (^\circ)F</th>
<th>Radiometer-measured heat absorbed, B. t. u. per min. (9 sq. in.)</th>
<th>Computed heat absorbed from couple-indicated mean hood temperature, B. t. u. per min. (9 sq. in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>297b</td>
<td>1, 501</td>
<td>1, 660</td>
<td>1, 668</td>
<td>9. 80</td>
<td>9. 66</td>
</tr>
<tr>
<td>295</td>
<td>1, 801</td>
<td>1, 948</td>
<td>1, 972</td>
<td>16. 70</td>
<td>16. 15</td>
</tr>
<tr>
<td>296</td>
<td>2, 066</td>
<td>2, 198</td>
<td>2, 220</td>
<td>24. 93</td>
<td>25. 93</td>
</tr>
</tbody>
</table>

\(^1\) Average during test.
The curvature at the bottom of the curves of figure 21 is due to use of too high a temperature for the grate couple. This couple was peened into a grate bar, and its temperature increase with approach of the ignition plane was much slower than that of the bed couples, owing both to the large heat content of the grate bar itself and to its cooling by the primary air. Use of a lower temperature for this couple to indicate the approach of ignition to the grate would have given essentially straight-line ignition curves for the entire lower half of all of the curves of figure 21. Theoretically there is no reason why ignition should slow up as it approaches the grate except for possible greater heat radiation to and conduction in the grate itself as compared to the fuel. Not over two layers of particles at the most should be so affected. When thermocouples were placed only 1 or 2 particles above the grate, they indicated no slowing up of rate of ignition as the plane of ignition approached the grate.

Combustible ignited or rate of ignition was determined from the thermocouple records, bulk density of the fuel as laid in the bed, and analysis of the fuel. Combustible was taken as the C and net H₂ from the ultimate analysis.
Net \( H_2 \) was considered to be the \( H_2 \) reported in the ultimate analysis less that required to form water with the \( O_2 \) reported in the ultimate analysis. All values were corrected for moisture (or added chemicals) according to conditions of the fuel as laid in the bed.

Combustible burned was calculated from the gas analyses as the amount of \( C \) and \( H_2 \) gasified; the \( S, P, O_2 \), and \( N_2 \) combined as fixed gases soluble in caustic solution; and as higher hydrocarbon fixed gases driven off during ignition and combustion of the fuel. This sum was corrected for unburned carbon (or fuel) in the asphit residue. Moisture (whether surface, natural bed, or formed from \( O_2 \) in the fuel) that was driven off and not converted to fixed gases was condensed in the sampler and lines before the fixed gases were analyzed. The Orsat gas-analyzing apparatus used included the combustible-gas-burning tube. This was used to determine residual combustible gases after successive removal of \( CO_2 \) (plus \( SO_2 \), \( P_2O_5 \), \( NO \), \( NO_2 \), etc., all calculated as \( CO_2 \) where this method did not involve grave errors), \( O_2 \), and \( CO \). The combustion tube gave the amount of any hydrocarbon in the gas, though all were calculated as \( CH_4 \). Since the volume of such hydrocarbons was never large in proportion to the total gases present, the calculation of all hydrocarbons as methane is believed to involve only negligible errors, probably less than those involved in operation of the Orsat itself.

Rates of burning were determined by plotting the calculated combustible burned against time of the gas analyses; they are represented by bars of appropriate thickness according to the time required to take the samples. A smooth curve was drawn through the ends of the bars as shown in figure 22. Near the beginning and end of a test, where samples were not taken, the \( CO_2 \) meter readings were used to calculate the ends of the burning-rate curve. Integration of the area under the curve gave total combustible burned, which was equal to moisture- and ash-free coal charged minus asphit losses, except for errors in measurement or unaccounted loss (as by unburned tar and soot and unburned combustible thrown up the stack). Figure 22 is a typical plot of this type obtained from a test on low-volatile coal, during which about half of the fuel was burned before ignition reached the grate (underfeed) and about half afterward (overfeed).

Material balances between combustible charged and combustible burned and lost with the ash in many tests indicated quite accurate sampling and analysis procedures, the balances in most instances checking to within less than 4 percent.

**DISCUSSION OF TEST DATA BY RANK AND TYPE OF FUEL**

**COKE AND COKE BREEZE**

Sizes and Size Consists

Source, analysis, and heating value of the high-temperature coke and coke breeze used in these investigations are given in table 1 (p. 14). Both the traveling-grate series of tests of part

![Figure 22](image-url)

**Figure 22.**—Combustible Burned in Testing Low-Volatile Coal at a 200-Pound Air Rate.
I and the crossfeed series of part II were begun with coke, as it offered the least test difficulties from such factors as swelling and coking, evolution of large quantities of volatile matter, tar, soot and smoke, or of significant quantities of water vapor encountered in burning the high-volatile and the lower rank coals.

The investigations were begun with rather closely sized cokes, ranging from $\frac{1}{2}$ by 1-inch size, by approximately $\frac{1}{2}$-inch steps, to as small as $\frac{1}{8}$ by $\frac{1}{8}$-inch coke. Except for the minus-1/16-inch fines in coke breeze, these sizes covered the range customarily used in traveling-grate stokers. Two batches of coke breeze obtained for test purposes were screened on square-mesh wire screens to the sizes and weight percentages shown in table 3. All pieces of the second coke, FS-35, over $\frac{3}{8}$ inch were crushed and added to the appropriate smaller sizes. The individual sizes and breeze made by recombining the sizes of coke FS-28 were used in one series of tests, while those made with coke FS-35 were used in another series.

**Table 3.—Size consist of as-received coke breezes**

<table>
<thead>
<tr>
<th>Coke FS-28</th>
<th>Coke FS-35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size, inch</td>
<td>Percent, by weight</td>
</tr>
<tr>
<td>$\frac{1}{4}$ by $\frac{1}{4}$</td>
<td>19.0</td>
</tr>
<tr>
<td>$\frac{3}{8}$ by $\frac{3}{8}$</td>
<td>29.4</td>
</tr>
<tr>
<td>$\frac{3}{8}$ by $\frac{3}{8}$</td>
<td>19.3</td>
</tr>
<tr>
<td>$\frac{1}{8}$ by $\frac{1}{8}$</td>
<td>12.5</td>
</tr>
<tr>
<td>Minus $\frac{1}{8}$</td>
<td>19.8</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
</tr>
</tbody>
</table>

For special tests to determine ignition and burning characteristics of coke breeze, as affected by the size consist of the breeze, three other breeze combinations were made up from the sizes prepared from FS-35. As shown in table 4, these ranged from a breeze with no minus-$\frac{1}{16}$-inch material (breeze B) to one containing 67 percent (breeze C); breeze A contained approximately the proportions of an average commercial breeze.

**Initial Ignition**

A large quantity of coke breeze is burned on traveling-grate stokers, and its initial ignition has always been an operating problem, although not so serious since introduction of the low-rear-arch, air-zoned stoker.

The most important factors affecting initial ignition of coke breeze were the amount of radiant heat received at the bed top and the primary-air rate (fig. 23), although the size of the coke being ignited also had some influence, as shown in figure 24. This figure indicates that at low air rates the optimum particle size of coke to give minimum time of initial ignition is that averaging about $\frac{3}{4}$ by $\frac{1}{8}$ inch by square-mesh wire screens. Evidently, if difficulty is experienced in obtaining initial ignition of coke on traveling-grate stokers, it can be reduced to a minimum by using $\frac{3}{4}$ by $\frac{1}{8}$-inch coke, or a mixture averaging this size, and low initial-ignition-zone air rates.

Another point revealed by figure 24 is the fact that relatively high hood temperatures were required for initial ignition at air rates above 25 pounds per square foot-hour. As coke was the first fuel tested and about the hardest to ignite, it has been used in this report as the basis for comparison with some other fuels.

Initial ignition at the highest air rate used in the tests was more easily obtained with large-size coke (fig. 24), probably because the larger pieces had more top surface shielded from the cooling primary air, which surface slowly ignited and spread—ultimately across the bed under some conditions of heat supply and air rates. At air rates above 150 pounds per square foot-hour it was necessary to ignite without the primary-air blower running, as with a "dead plate" in a traveling-grate stoker, or it was necessary to use a thin layer (approximately $\frac{1}{4}$ inch thick) of some easily ignited fuel, such as lignite char or low-temperature coke. Both methods were used to ignite high-temperature coke and coke breeze at high air rates.

**Ignition to Grate or Underfeed Ignition**

Figure 25 shows rate of ignition travel (A) and ignition rate (B) in 6-inch beds of high-temperature coke. There is a fairly regular increase in rate of ignition travel and combus-
tible ignited with decrease of size in the ranges of sizes studied. There is also an increase in the magnitude of the air rate at which maximum ignition rates occur with decrease of particle size. Consequently, not only will decrease of average size of piece within certain limits give faster rates of ignition for a given air rate but also higher air rates can be used in beds of the smaller size fuel to increase rate of ignition travel still further.

Increasing the air rate above that which gives the maximum rate of ignition causes a rapid decrease of ignition rate in a bed of high-temperature coke, as may be noted from the curves for the 1- by ¾-inch size; after this size had been initially ignited, ignition was extinguished when the air rate was increased to 350 pounds per square foot-hour. Increasing the air rate by only about 120 pounds per square foot-hour above the optimum stopped ignition completely for this particular size of fuel.

In tests where initial ignition was rapid, that is, occurring in less than 3 minutes, ignition traveled through the bed at a constant rate. When initial ignition was slow, however, the rate ranged from very slow to almost that obtained with rapid initial ignition, as shown by the curve for test 19, figure 21. Tests showed that slow initial ignition affected chiefly the top 2 inches of a 6-inch bed but that some slowing of ignition travel was evident even in the lower two-thirds of the bed. The following tabulation shows ignition hood temperature, initial ignition time, and average rate of ignition travel in the entire bed and in the bottom 4 inches of 6-inch beds of high-temperature coke at a 50-pound air rate:

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Mean hood temperature, °F.</th>
<th>Initial ignition time, minutes</th>
<th>Average rate of ignition travel, inches per hour</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>6 inches to grate</td>
</tr>
<tr>
<td>35</td>
<td>2,323</td>
<td>1.8</td>
<td>13.7</td>
</tr>
<tr>
<td>36</td>
<td>2,018</td>
<td>4.5</td>
<td>12.3</td>
</tr>
<tr>
<td>37b</td>
<td>1,898</td>
<td>5.8</td>
<td>11.5</td>
</tr>
</tbody>
</table>
The curves in figure 25 represent moderate to fast initial ignition and consequently show no effects of slow initial ignition on rate of ignition travel; that is they are the maximum that can be expected of fuel having the physical and chemical characteristics of the fuel tested. Points for tests in which initial ignition was slow are marked with an S to indicate that slow initial ignition affected the rate of ignition.

Curves of ignition travel and combustible ignited for the coke breezes listed in table 4 are shown in figure 26 as a function of the size consist (percentage of fines) in the breezes. As the percentage of fines was increased, the bulk density increased, and the rate of ignition travel, in inches per hour, decreased. On the basis of combustible ignited per square foot-hour, however, there was remarkably little change in the rate of ignition travel with change of size consist, indicating that the ignition data for the tests with breeze A (34 percent minus-1/16-inch fines) could be used with reasonable accuracy for other breezes having a wide range of size consist.

This does not mean that all coke breezes can be ignited and burned with equal operating ease, however, as the physical difficulties of maintaining uniform bed conditions and air distribution increased with the percentage of fines in the fuel.

Coke breeze containing enough fine material to render its burning on traveling grates in a dry state quite impracticable can be ignited and burned readily when moistened sufficiently, as shown by the “snowball” test wherein the moisture content is satisfactory if the fine fuel can be made into a stable ball in the hands that
will hold its shape without cracking or falling apart when the hands are opened. Ignition curves for breeze A of varying moisture content are shown in figure 27. The effect of varying moisture content is clear from the curves. The optimum moisture content of the breeze used in these tests was 12 percent added water; this permitted maximum air rates for reasonably stable bed conditions and yet gave the maximum rate of travel of ignition through the bed. With this optimum moisture content, an ignition-travel curve somewhat similar to that for 
\[ \frac{3}{4} \] - by \[ \frac{1}{2} \]-inch coke was obtained, indicating that moisture agglomerates the fines and thus gives a bed with better distributed voids, such as with closely sized coke. However, since the maximum size of coke in these breeze tests was 
\[ \frac{3}{4} \] - by \[ \frac{1}{2} \]-inch particles and the average size was much smaller than this, it is evident that the added moisture contributed to some extent in retarding ignition travel.

Increasing moisture content above the optimum increased the agglomeration of the fines but gave a more sticky material exhibiting a greater tendency to pack in the bed. This effect would be worse in a traveling-grate stoker, where movement of the grate would tend to settle the material in the bed and thus reduce the beneficial effects of agglomeration. Obviously, increase of moisture results in decreased rates of ignition (fig. 27).

When the moisture content was below the optimum and ignition rates were higher, greatly increased fuel-bed pressure differentials indicated incomplete agglomeration of the fines. In natural-draft stokers this would mean a sharp drop in the air rates that could be used with natural draft and reduction in furnace ca-
Figure 26.—Rate of Ignition in Coke Breeze of Varying Proportions of Minus-$\frac{1}{16}$-Inch Fines.

Figure 28 shows ignition and burning rates of 1/2- by $\frac{3}{4}$-inch coke particles in pounds of combustible per pound of primary air as a function of air rate. The curves show that the ignition rate per pound of primary air used varies much more with variation of the primary-air rate than does the burning rate.

Underfeed and Overfeed Burning Rates

As previously pointed out, the type of burning that prevails during travel of the ignition plane to the grate is essentially pure underfeed, whereas after ignition to the grate burning of the residual fuel left on the grate is overfeed. The most intensive overfeed burning, using only primary air, takes place at the bottom of the bed in a thin layer that, according to observations during this and other investigations, is approximately only 3 to 6 particles thick. Above this intensive-burning zone all oxygen is consumed, and the producer-gas reaction takes place in proportion to bed temperature to produce varying amounts of CO until the bed thickness has burned down to a thickness of 3 to 6 particles. During this last thin-bed stage generation of CO$_2$ jumps to a peak and then falls off as the combustible is burned out.
Figure 27.—Rate of Travel of Ignition Plane (A) and Rate of Ignition (B) in High-Temperature Coke Breeze Varying in Moisture Content.

Figure 29 shows gas-analysis curves (A) and burning rates and bed pressure drop (B) for a typical test on $\frac{3}{4}$-inch coke in which the air rate was 264.5 pounds per square foot-hour. As may be noted, CO$_2$ by gas analysis and by the indicating meter are identical or very close when other gases (except air) are absent, but CO, CH$_4$, and H$_2$ affect the CO$_2$ meter. The CO$_2$ peak at the beginning and at the end of the tests is typical of all tests in this investigation. The first peak occurred when approximately $\frac{1}{2}$ inch of the top of the bed (about 2 to 3 particles thick) was ignited and the second when only a very thin layer of residual fuel was left on the grate as the end of the test approached.

The burning-rate curve of figure 29, B, shows the burning rates obtained in the tests; these are underfeed before ignition reaches the grate and overfeed thereafter. The maximum rate of underfeed burning was about 35.4 pounds C+H$_2$ burned per square foot-hour, while the maximum rate of burning for the test (approximately 42.0 pounds per square foot-hour) was reached during the overfeed period. Figure 29, B, also shows bed pressure drop $\Delta P$; this is discussed later (p. 62). The average burning rate for the entire test can be found by dividing the area under the curve in figure 29, B, by the time. This has not been done, but examination of the curves indicates that the average burning rate for this test will be around 30 to 32 pounds of combustible or about 35 to 37 pounds of coke burned per square foot-hour.

Figure 30, A and B, shows the maximum underfeed and the maximum overfeed burning rates as heavy lines and the ignition curves as light lines. There are 2 maximum burning curves in each plot, the lower one for the $\frac{3}{4}$- by $\frac{1}{2}$-inch and larger sizes, shown on the chart as "larger sizes," and the other for the $\frac{3}{4}$- by $\frac{1}{2}$-inch and smaller sizes, designated as "small
sizes." Possibly there should be a separate curve for each size, as for the ignition curves, but in the tests both the 3 smaller sizes and the 3 larger sizes came so close together that 2 curves appear to be sufficient for the ranges covered. These are maximum rates in pounds of combustible; the average coke burning rates can be calculated from the burning-curve plots obtained from the individual tests and converted from pounds of combustible to pounds of coke. Line OC, figure 30, represents the theoretical maximum or complete rate of conversion of carbon to CO for each rate of air supply, that is, the rate and condition of burning where only CO and N₂ would be present in a dry-gas analysis of the combustion products after all H₂ in the fuel had been converted to H₂O and condensed before analysis of the gases. Line OP represents theoretical perfect combustion where all dry combustion products would be
Figure 29.—Gas-Analysis Curves (A) and Burning Rates and Bed Pressure Drop (B) for Test on \(\frac{1}{4}\)-by-\(\frac{1}{4}\)-Inch High-Temperature Coke.
CO₂ and N₂. The analysis sheets and table of calculations used in plotting the OC and OP lines on the charts are included in the appendix.

The actual burning rates, both underfeed and overfeed, cannot exceed the rate represented by line OC, unless the composition of the ignited fuel differs appreciably from that of the raw fuel or unless other reactions yield products other than CO and N₂ in the gas. For underfeed burning, where heat is being extracted from the bed to ignite lower layers of fuel or to heat the grate as ignition reaches the grate,
the burning curves are closer to the \( OP \) (high \( CO_2 \)) line, whereas for overfeed burning, where more of the heat generated in the bed is available for the producer-gas and water-gas reactions, the burning curves lie closer to the high-CO \((OC)\) line.

The curve illustrating the maximum underfeed burning rate for the smaller sizes of coke shows a definite tendency to reach a maximum and then drop off, as do the ignition curves. This behavior is reasonable since, when the ignition-rate curve drops off at high air rates, the ignition and burning rates more closely approach each other in magnitude and the layer of ignited fuel forming the combustion zone does not increase in depth, as at low air rates where the ignition rate is so much higher than the burning rate.

**Ash and Slag Residues**

For the coals tested ash and slag residues were not of particular interest, since they were what would be expected under the conditions of test. In most tests at moderate to high air rates ash on the grate was fused into globules or small, porous sheets of clinker. There was no indication of any factors that would cause operating difficulties, nor was there any reason to believe that the ash and clinker in a commercial furnace would not pass the bridge wall and drop to the ashpit without difficulty, since even the fused clinker was protected underneath by a thin layer of unfused ash directly against the grate that would prevent sticking difficulties as long as air rates were sufficiently high and evenly distributed to prevent overheating of the grate bars. This unfused-ash layer directly on the grate indicated that the grates were not being overheated.

**ANTHRACITE**

**Description of Anthracites**

As shown in Table 1 (p. 14), 4 different anthracites of normal ash content and 5 of specially prepared ash content were used in these investigations. The slow-, medium-, and free-burning sizes, listed in the table as Pea and Rice sizes, were prepared by crushing Chestnut size left from other investigations and stored by the Bureau. The Locust Summit and St. Nicholas breaker coals were received in the sizes shown in the table but were carefully hand-screened on round-hole screens to separate oversize, nominal size, and undersize, and these three sizes were remixed in proper proportions for each test. At the time of such remixing moisture or chemicals, if used, were added, and the mixed coals were stored overnight wrapped in the rubber mixing blanket.

Various mixtures of the St. Nicholas breaker anthracites that had been float-and-sink separated to give fractions containing 4.5, 9.8, 16.7, 24.4, and 81.3 percent ash, as-received basis, were used to give mixed anthracites containing 4.6, 10, 17, 25, 40, 55, and 70 percent ash on the moisture-free basis. These mixtures were used in the tests to determine the effect of ash in coal on initial ignition, ignition travel, and underfeed and overfeed burning rates.

**Initial Ignition**

Figure 31 shows graphically the time required initially to ignite beds of various types and sizes of anthracites at various hood temperatures and air rates. The range of temperatures and air rates that will give rapid (1 to 2 minutes) initial ignition is clearly evident. The amount of heat absorbed at various mean hood temperatures, calculated from the relation between mean hood temperatures and heat received at the bed top in B. t. u. per square foot-hour, assuming an average initial ignition time of 2% minutes, is given below the hood-temperature scale. These data can readily be related to other furnaces where the heat received at the bed top is known or can be determined by observation or calculation.

Figure 32, A, shows for a slow-burning anthracite the variation of time of initial ignition as affected by size of coal. It also shows by two points the effect of packing the bed to increase bulk density. Down to the minimum practicable size, ignition time decreased with size for given hood temperatures and air rates. In the tests on anthracite the time required for initial ignition did not increase with decrease of size below a certain optimum, as noted with coke.

**Underfeed Ignition**

Figure 32, B, shows underfeed ignition rates for several anthracites (and a dotted comparison curve for coke) as a function of size and air rate. At the relatively low air rates shown optimum ignition rates for both the anthracites and the coke occur at an average particle size of about \( \frac{3}{8} \) inch, and reasons for ignition and burning difficulties with very small sizes are obvious because of the much lower ignition rates found for the small sizes. It is interesting to note that when special effort was made to increase bulk density of a bed of small-size anthracite by packing, not only the initial ignition time but also the rate of ignition was more unfavorable than were these factors in normal beds.

Results of tests with Locust Summit Barley and No. 4 Buckwheat anthracite are shown in Figure 33, A and B. The optimum air rate that gave the maximum rate of ignition travel was about the same for anthracite as for coke (350
to 400 pounds per square foot-hour, but the transition from increasing to decreasing rate of ignition was more gradual for anthracite. Ignition rates were lower for the No. 4 Buckwheat than for the Barley, illustrating the decrease in rate of ignition with decrease in size below the optimum of approximately ¾-inch average diameter (fig. 32, B) mentioned earlier.

The curves for the Barley anthracite emphasize the observation made in connection with coke breeze that more difficulty was often experienced in maintaining even bed conditions at moderate than at high air rates. Up to the 100-pound air rate the bed was entirely stable; at the 150- and 250-pound air rates irregular blowing and “boiling” of the coal were noted at scattered areas in the bed, with resulting maldistribution of air. At the 350-pound air rate, however, the boiling (so-called because the bed top resembled a vigorously boiling fluid) or fluidization was evenly distributed across the bed, which burned down very evenly. The broken curve for the Barley anthracite indicates the ignition rates that normally would be expected with this fuel, but the solid line shows rates that were found under the test conditions.

Underfeed and Overfeed Burning Rates

Figure 33, B, shows both underfeed and overfeed burning rates for the Barley anthracite. As with the cokes, the burning rates lie between the OC line (CO + N₂ in gases) and the OP line (CO₂ and N₂ in gases) and in about the same relative positions between these lines.

As may be noted, the maximum overfeed burning curve crosses the ignition curve at air rates above 400 pounds per square foot-hour owing to the fact that at the highest air rate used (450 pounds) the bed was completely ignited at a lower air rate; therefore for the overfeed burning an ignited bed of moderate thickness had already been established. At this high air rate the preignited bed burned at a higher rate than the ignition rate in another test at this high air rate—another example of “overequilibrium” burning or burning at a higher rate than fuel can be ignited underfeed.
Figure 32.—Initial Ignition Time (A) and Rate of Ignition (B) of High-Temperature Coke and Anthracite of Different Particle Sizes.
at the air rate used, as described earlier. This overequilibrium burning was first noted in testing the anthracites but was more pronounced in burning fuels of lower rank.

Anthracite was used in tests to determine the effects of moisture, ash content, and chemical treatments on ignition and burning rates; the results are given later in appropriate sections.

**Ash and Slag Residues**

In tests at air rates where the bed burned out fairly evenly the residue on the grates at the end of the tests was about what would be expected; that is, at low air rates unfused ash remained, much of it retaining the shape of the top pieces of coal on the bed, but the whole dropped down to a thin layer on the grate. Under these conditions the grate did not get excessively hot, and with a moving grate the ash would sift through or readily move off and drop into the ashpit. At high air rates, of course, some clinker formed on the grate as the ash fused, but the slag pieces were not large and were porous. They were coated on the bottom, against the grate, with unfused ash, which indicated that the grate did not get excessively hot and that this slag would readily drop off into the ashpit from a moving grate. In several of the high air-rate tests a nominal amount of unburned fuel was left on the grate, indicating that at high air rates the combustible losses to the ashpit were higher than at low air rates. Interesting effects were obtained with the very high ash anthracite tested, as discussed under Effect of Ash Content on Initial Ignition and on Ignition and Burning Rates.

**LOW-VOLATILE BITUMINOUS COAL**

**Description of Fuel**

When tests on all other fuels were nearly completed, the test data showed that differences in various factors between the anthracites and the high-volatile A bituminous coals were such as to suggest the desirability of running a few tests on a low-volatile coal to fill the gaps.

The source and analysis of the Jerome low-volatile coal from Somerset County, Pa., used for these concluding tests are shown in table 1 (p. 14). Tests were run on this coal crushed and screened to \( \frac{3}{8} \)-by \( \frac{3}{8} \)-inch, \( \frac{3}{8} \)-by \( \frac{3}{8} \)-inch, and \( \frac{3}{8} \)-by \( \frac{3}{8} \)-inch sizes only, without drying, moistening, or other treatment.
Figure 34.—Initial Ignition Time as a Function of Mean Hood Temperature and Air Rate for Various Sizes of Low-Volatile Coal.

**Initial Ignition**

Figure 34 shows initial ignition time as a function of mean hood temperature, heat received at the bed top, and air rate for various sizes of the Jerome coal. For comparison, the light curves show ignition time for 3/6 by 3/6-inch medium-burning anthracite at 2 air rates. Since the main curves (heavy, full lines) represent ignition at a 200-pound air rate for the low-volatile coal, obviously this coal ignites much more easily than the anthracite at 50- and 150-pound air rates. The chart also shows significant differences in ease of ignition as a function of size, the largest size being more easily ignited at the 200-pound air rate. This behavior is similar to that of coke at the 150-pound air rate, as shown in figure 24 (p. 29). Much lower hood temperatures were possible in igniting low-volatile coal at higher air rates than were possible for rapid initial ignition of the anthracite, as would be expected. Heavy dash-lines represent extrapolation or expected behavior based on only one point; they should be considered as only an approximate guide to expected behavior.

**Underfeed Ignition**

Figure 35 gives the underfeed ignition rates and the maximum underfeed and overfeed burning rates obtained with Jerome low-volatile coal. For comparison, the light curve shows the ignition rate for 3/6 by 3/6-inch coke (fig. 35, A). This coke curve is remarkably close to the 3/6 by 3/6-inch low-volatile coal up to the 400-pound air rate, but beyond this rate the low-volatile-coal curve drops much less sharply with increase of air rate. This behavior shows that while the maximum rate of ignition through the bed is not much higher for low-volatile coal than for coke ignition could be held much easier at a high rate, since the range of air rates that gives high ignition rates is much broader for the low-volatile coal. Furnace operation at high rates therefore would be much easier with low-volatile coal than with coke, though there is not much difference in maximum ignition rates under optimum conditions.

Figure 35, A, indicates unusual difference between the ignition rates for the 2 smaller sizes and that of the larger 3/6 by 3/6-inch size. This may be due in part to the difference in
ash content of the different sizes, as the ash in this coal tended to segregate in the larger sizes. For example, the ash in the \( \frac{3}{4} \) by \( \frac{3}{16} \)-inch size, as used, was 10.4 percent; in the \( \frac{3}{8} \) by \( \frac{3}{16} \)-inch size, 14.7 percent; and in the \( \frac{3}{8} \) by \( \frac{3}{8} \)-inch size, 16.4 percent. The ignition and burning rates for the \( \frac{3}{8} \)-inch size are remarkably high, considering the ash distribution as between sizes and the effect of ash on ignition and burning rates, discussed more fully in the section Effect of Ash Content on Initial Ignition and on Ignition and Burning Rates.

**Underfeed and Overfeed Burning Rates**

The long dashline of figure 35, B, represents maximum underfeed burning and the 3 solid lines the maximum overfeed burning for the 3 sizes of this coal. There was enough difference in overfeed burning between the sizes of this coal to show separate overfeed curves for each size, but not for underfeed burning. (Note the quick drop in both types of burning rates as air rates are increased above about 500 to 600 pounds per square foot-hour, that is, where ignition rates begin to affect burning rates.)

Underfeed burning rises to a higher peak (average of rather widely scattered points) than the overfeed rates, but at approximately the 600-pound air rate it reaches the optimum and at higher air rates is affected by the drop in ignition rates above the 600-pound air rate shown in figure 35, A. *Maximum rates of igni-
tion and burning and therefore highest furnace capacity can be attained with this low-volatile coal at air rates ranging from 400 to 600 pounds per square foot-hour (fig. 35). The burning rates at high air rates are substantially higher for the low-volatile coal than for coke, clearly indicating that higher furnace capacities can be attained with the low-volatile coal.

Figure 35, B, shows that maximum rates of conversion of carbon to CO for the low-volatile coal are notably higher as related to the OC line than are those found for the cokes and anthracites. This trend is indicated by the location on the OC line of the maximum underfeed burning rates for air rates up to about 500 pounds and the location above the OC line of the maximum overfeed burning rates for air rates up to 500 pounds. For the cokes and anthracites these maximum burning curves lie between their OC and OP lines, that is, below the OC lines for these fuels.

The fact that the curves of figure 35, B, show higher rates of conversion to CO than those of the OC line indicates either that reactions other than the simple ones assumed for this conversion are taking place in the fuel bed or that the assumptions for calculating the OC line are not applicable to the fuel as burning in the bed. The basic equations assumed for calculating the OC line are:

\[2C + O_2 \rightarrow 2CO\]  
\[2H_2 + O_2 \rightarrow 2H_2O.\]

The water vapor formed in this second reaction condenses and leaves only CO and residual N\(_2\) from the combustion air in the gas analyzed. Examples of other possible reactions that might occur, two of which may account for higher than theoretical gaseous products, follow:

\[CO + H_2O \rightarrow CO_2 + H_2,\]  
\[C_3H_8 \rightarrow 3C + H_2,\]  
\[CaCO_3 \text{ (in ash)} \rightarrow \text{CaO} + \text{CO}_2.\]

Equation (3) results in no change of combustible in the system and thus will not affect the position of burning curves relative to the OC line, even though it produces larger volumes of fixed gases. Equation (4) would affect the position of the burning curve only insofar as high-molecular-weight gases were analyzed and reported as CH\(_4\).

The gas analyses for the several tests in which overfeed burning rates exceeded the rates indicated by the OC line show high percentages of CO along with some CO\(_2\), H\(_2\), and CH\(_4\), indicating that reactions in accordance with equations (3) and (4) were taking place. Although this low-volatile coal was not analyzed for ash to determine the possibilities of equation (5), it came from a region where appreciable proportions of CaO have been found in the coal ash; consequently, there is a possibility that a little of the CO or CO\(_2\) may have come from carbonate in the coal ash.

Calculations indicate, however, that the overfeed burning rates are higher than those that can be accounted for by the reactions given and appear possible only on the basis that when they were found the composition of the ignited fuel was so altered from the fuel as charged as to materially change the position of the OC line, and the rates of conversion indicated a fuel containing a higher proportion of fixed carbon than the coal as charged. This supposition appears plausible since in every instance the high maximum rates were found after ignition reached the grate, when all or most of the volatile matter in the coal had been driven off and the residual fuel was a high-carbon coke. Also, because of the highly expanding properties of low-volatile coal, relatively deep beds of coke were formed during the period of underfeed ignition and burning. Beds 11 to 13½ inches deep were formed from 6-inch beds as charged. As these thick beds of high-carbon coke increased in temperature (as burning changed from underfeed to overfeed after ignition to the grate) the water-gas shift and thermal-cracking reactions (reactions 3 and 4) appear to have increased, and the driving off of the volatile matter from the coal during ignition so altered the chemical structure that the basic assumptions establishing the position of the OC line appear to have been sufficiently altered to make the original position no longer applicable, as may be noted by comparing the crossing of the OC lines with the 70-pound combustible lines in figures 30, B, and 35, B. In coke beds this occurs at about a 410-pound air rate, whereas in low-volatile coal beds it occurs at a 491-pound air rate. Assuming that the residual fuel in the ignited bed of low-volatile coal was coke of the approximate composition of that of figure 30, B, and that the OC line is located as in 30, B, all of the curves of figure 35, B, would fall on or below the adjusted OC line.

Ash and Slag Residues

As would be expected from a coal with ash softening temperature in the 2,700° to 2,800° F. range, the residues from testing low-volatile coal consisted of fine, unfused ash and weak, porous clinker in sheets or in large pieces that broke easily on handling. Even where the layer of clinker was deep (2 to 2½ inches), there was fine ash on the grate between the grate bars and the clinker and on top of the clinker pieces. This shows that the grate did not become excessively hot when this fuel was burned and the ash and clinker structures were so porous and weak that removal on conventional traveling grates should present no difficulties.
HIGH-VOLATILE A BITUMINOUS COALS

Description of Fuels

Two high-volatile A bituminous coals were tested, one of which was from the Pittsburg & Midway Coal Co., Bevier bed, Crawford County, Kans., and the other from the Pittsburg Coal Co. (now Pittsburgh Consolidation Coal Co.), Pittsburgh bed, Allegheny County, Pa. (For sources and analyses, see table 1, p. 14.)

The Bevier coal represented a high-volatile A bituminous coal from the Midwest, while the Pittsburgh coal was typical of the better steam and coking coals of the East. The slag from the Bevier coal behaved peculiarly, and for this reason several tests were run on a mixed-size consist to represent run-of-mine or Nut and slack. This was prepared by crushing 3- by 2-inch size so that all material passed a 1¾-inch round-hole screen. Using all of the crushed coal gave a size consist comprising:

- 41.7 percent of 1¾-inch by 1¾-inch particles,
- 27.6 percent of 1¾-inch by ¾-inch particles,
- 30.7 percent of minus-¾-inch particles.

As with other fuels, these sizes were separated after crushing and were then remixed in proper proportions for each test. A few tests were run on 1½- by 1½-inch, ¾- by ½-inch, and ½- by ¾-inch closely sized fractions of the Bevier coal for comparison with other fuels.

The Pittsburgh coal from Montour No. 10 mine was obtained in the 4- by 3-inch Egg size and was crushed to give 1½- by ¾-inch, ¾- by ½-inch, ½- by ¾-inch, ½- by ¾-inch, ¾- by ¾-inch, and minus-¾-inch sizes.

These were tested in the individual sizes and in two mixtures simulating a stoker and a Nut-and-slag or run-of-size, as given in table 5.

**Table 5.—Size consist of simulated stoker and Nut-and-slag test coals**

<table>
<thead>
<tr>
<th>Size, inch</th>
<th>Mix A, 6 percent added moisture</th>
<th>Mix B, 10 percent added moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1½ by ¾</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>¾ by ½</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>½ by ¾</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>¾ by ½</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>Minus ¾</td>
<td>10</td>
<td>30</td>
</tr>
</tbody>
</table>

Mix B was intended to simulate the mixed sizes of run-of-size containing considerable fines, as frequently used on traveling-grate stokers. The added moisture for both mixtures was just enough to agglomerate fines and give a good "ball" when tested in the hands.

Initial Ignition

Figure 36 shows the initial ignition time (heavy lines) as a function of mean hood temperature and air rate for the mixed-size 1¾-inch by 0 Bevier coal. For comparison, the initial ignition curves for the ¾-inch by ¾-inch medium-burning anthracite at 2 air rates are also shown. Comparison of this figure with figure 34, which shows initial ignition of low-volatile coal, indicates that the mixed-size Bevier coal ignited initially a little more slowly at low mean hood temperatures than the ¾- by ¾-inch size of low-volatile coal (3.0 minutes compared to 2.3 minutes at 1,800°F) but somewhat faster at higher hood temperatures (0.7 minute compared to 1.6 minutes at 2,100°F mean hood temperature). Considering the effect of size, the Bevier coal apparently ignites a little more readily than the low-volatile coal.

Figure 37 shows initial ignition time for the Montour No. 10 Pittsburgh coal, the heavy line for mix A and the light line for the mixed-size Bevier coal shown for comparison. On this and following initial ignition charts the abscissa is given only as initial heat available at the bed center during the actual time for initial ignition, in B. t. u. per square foot-hour, rather than as mean hood temperature. However, curves for converting from one to the other are given in figures 75 and 76 in the appendix, so such conversion can readily be made when initial ignition time is known.

Figure 37 shows that the Pittsburgh coal ignites more easily than the Bevier coal of the same rank classification. As the Bevier coal contained only 54.4 percent fixed carbon (moisture- and ash-free basis) compared to 60.0 percent (same basis) for the Montour coal, the Bevier coal is a little lower in the high-volatile A rank classification; since the reactivity and ignitability of coals tend to increase with decrease in the rank classification scale, the Bevier coal would be expected to ignite more readily, but it does not. An explanation for this deviation from expected behavior is not evident, and study of this anomaly would be of interest in an investigation of initial ignition characteristics and reactivity of fuels as related to rank.

Underfeed Ignition and Underfeed and Overfeed Burning Rates

Figure 38 shows ignition rates and maximum underfeed and overfeed burning rates as a function of air rate for the 1¾-inch by 0 mixed-size Bevier coal. The comparative (light) curve for ¾- by ¾-inch coke shows that the ignition-travel rate for Bevier coal is substan-
tially less than that of the coke up to the air rates where the coke ignition rate begins to fall off sharply. The ignition rates are also substantially below those for mixed sizes of Pittsburgh coal (fig. 39). This difference may be due, at least in part, to the difference in ash content, which was about twice as high in the Bevier coal as in the Pittsburgh coal.

The single curve for both maximum underfeed and overfeed burning rates results from fast burning of the coke formed in the bed above the ignition plane during the underfeed burning period, giving high underfeed burning rates and reducing the thickness of unburned coke so much that the burning rate did not increase as the type of burning changed from underfeed to overfeed when ignition reached the grate. This condition, as contrasted to experience with the higher rank coals and coke, results in the highest burning rates being obtained during the period of ignition through the bed, that is, with underfeed burning. It is typical of all ranks of bituminous coal from high-volatile A to the subbituminous and lignite ranks. At moderate to high air rates so much of the fuel is consumed by underfeed burning during travel of ignition to the grate that the burning rate is dropping so fast when ignition reaches the grate that it is difficult to determine the actual maximum overfeed burning rate with any degree of precision. Consequently, the maximum overfeed burning rates for the lower rank coals are shown as approximations.

Ignition rates for the Montour No. 10 Pittsburgh coal are shown in figure 39. The curves are characterized by high ignition rates over a much wider range of air rates than was found possible for the anthracites and cokes but lower rates at low to moderate air rates. At the lower air rates difficulties were encountered from coking of the coal and bypassing of air around the edges of the bed, giving somewhat unreliable ignition rates at air rates below 400 pounds. At higher air rates definite evidence of a decrease in ignition rate with increase of air rate for the sized coals was noted at a 750-pound air rate or higher, indicating the possibility of using very high air rates to obtain high ignition and burning rates with this coal. The mixed sizes, particularly mix B containing 30 percent fines, lacked bed stability at moderate to high air rates, and rates of ignition were variable, as indicated by the high point for mix B at the 400-pound air rate. With this exception, the ignition rates for the two mixtures were virtually identical when not affected by slow initial ignition.

Slow initial ignition resulted in slow travel of ignition through at least part of the bed, as indicated by the relatively low positions of the curves for the 1½- by ¾-inch and the ¾- by ½-inch sizes and by the lower curve for mix A,
as compared with the higher curves for mixes A and B and the \( \frac{3}{4} \)- by \( \frac{3}{32} \)-inch and \( \frac{1}{16} \)- by \( \frac{3}{32} \)-inch sizes with faster initial ignition.

After ignition had proceeded 2 to 3 inches into the bed at air rates of 200 pounds or less, swelling and caking of this coal so interfered with air distribution that the rate of ignition in the bottom part of the bed was extremely low at the bed center where the thermocouples were located. Ignition rates shown for these tests therefore were taken only from the upper parts of the bed. Because of this swelling and caking when burning highly caking coals, such as from the Pittsburgh bed, more uniform fuel-bed conditions would be expected in thin beds (2 to 3 inches deep) at moderate or low air rates and higher stoker speeds than in deeper beds at slower stoker speeds. Deep beds can be used with high air rates to obtain very high rates of ignition and burning (high furnace capacity).

A bed of dry \( \frac{3}{4} \)- by \( \frac{3}{32} \)-inch coal ignited more slowly than the damp coal containing 12 percent moisture, although initial ignition was reasonably rapid; however, slow ignition may have been due to caking of the bed, which possibly was more rapid with the dry than with the damp coal. This was the only instance noted in this investigation where a dry coal ignited more slowly than a damp coal and suggests that moisture may reduce the caking power of the coal; however, additional tests to confirm this point have not been made.

Two tests on the fine size, \( \frac{3}{8} \)-inch by 0, gave ignition rates notably less than those for the next larger size, confirming the decrease in ignition rate for fuel below some optimum size, which for this coal appears to be particles averaging about \( \frac{3}{4} \) inch in diameter.

Figure 40 shows the variation with size of maximum underfeed burning rates for the Pittsburgh coal. As for the Bevier coal, the maximum overfeed burning rates were approximately equal to or less than the maximum underfeed rates and hence are not significant in establishing maximum burning rates; they therefore have not been plotted. At air rates
Figure 38.—Rate of Ignition and Maximum Underfeed and Overfeed Burning Rates as a Function of Air Rate for 1\% -inch by 0 Pittsburg, Kans., High-Volatile A Bituminous Coal.

up to 400 pounds per square foot-hour the burning curves occupy approximately the upper half of the OC–OP band; the smaller sizes are on or close to the OC line.

A typical log of a test on \% - by \% -inch coal from the Pittsburgh bed is shown in figure 41. The curves show the expansion of the bed during ignition, bed pressure drop, relative smoke density, composition of the gases, and underfeed and overfeed burning rates throughout the test. At the 400-pound air rate used in this test initial ignition was slow, as shown by the horizontal line for the bed height for approximately the first 7 minutes.

Ash and Slag Residues
The Bevier coal yielded the most interesting slag residue and in fact was tested only because
a quantity was made available both for use in these tests and in the Bureau’s investigations of the properties of coal-ash slags being conducted simultaneously with these tests. Particularly in the high air-rate tests some pieces of hard, glassy, brown to black, well-fused slag remained on the grate at the end of the tests, along with the usual unfused or partly fused ash immediately touching the grate, and in spots where it did not have opportunity to agglomerate with the larger slag pieces. When this hard, glassy slag was set aside for a few days it disintegrated into a very fine powder. If left long enough, the entire slag pieces changed completely to a fine, brownish powder. Since several days to weeks are required for this transition to take place, its practical significance is not evident other than that this clinker probably would not be suitable for making cinder blocks.

The usual ash and slag, in relative amounts depending on the air rate used, were residues of the Montour coal. However, the quantities were smaller than for most other coals, since this coal analyzed only 6.0 percent ash as received.

HIGH-VOLATILE B BITUMINOUS COAL

Description of Fuel

Coal from the Illinois No. 6 bed was used as a typical midwestern high-volatile B bituminous steam coal. Its source and analysis are shown in table 1 (p. 14). This coal was mined mechanically, washed at 1.4 specific gravity,
dewatered, and screened to 3- by 2-inch Egg size at the mine. Sizes and size consists used in the tests were the same as those prepared from the high-volatile A (Montour) bituminous coal.

Initial Ignition

Figure 42 shows initial ignition time of the Illinois No. 6 coal as a function of initial heat received at the bed center during the initial ignition period. The solid line represents an approximate average for the various sizes shown as plotted points. Comparison with the broken curve for the Bevier coal shows that the Illinois coal ignites initially more rapidly than the Bevier coal, which accords with the relative rank classifications of the two coals and the observation that ease of ignition generally increases with decrease of rank. In testing this coal variations of initial ignition time with size were not nearly so pronounced as in testing some other fuels. Also the differences due to change in air rate are smaller than for most other fuels.

Rates of ignition in 6-inch beds of the Illinois No. 6 coal are shown in figure 43. Variation of ignition rate with size was much less for this coal than for the higher rank coals and coke. Ignition rates for the two largest sizes of Illinois coal were higher than those for the corresponding sizes of the higher rank Pittsburgh coal in inches per hour, but in pounds of combustible per square foot-hour the rates were lower, since the average combustible in Illinois coal was only 75.3 percent compared to 82.8 percent for the Pittsburgh coal. Considering this difference in combustible, however, the ignition rates for all sizes of the Illinois coal were relatively high and consequently high ignition and burning rates for this coal can be expected over a wide range of air rates.

As would be expected with a less strongly caking coal, less difficulty was experienced with caking
and poor air distribution in the tests on Illinois coal than in those on Pittsburgh coal at the lower air rates, while ignition and burning at air rates of 400 pounds and higher were accompanied by relatively little caking.

The preignited bed of this coal could be burned readily at a higher rate than the remainder of the green fuel was igniting. Over-equilibrium burning occurred only briefly at very high air rates in the tests on the higher rank fuels but was more pronounced with this coal. Owing to heat-output limitations of the igniting hood, it was necessary to obtain initial ignition at moderate air rates in all tests and then to raise the air rate for high-rate tests after the hoods had been shifted, thus simulating a zoned stoker in which a low air rate is used in the first zone. Therefore, when the high air rate was started, there was approximately 1 inch of preignited fuel at the top of the bed. With the Illinois and lower rank coals, the higher air rate burned this preignited layer at a faster rate than the fuel beneath was igniting, thereby rapidly diminishing the thickness of the burning layer. As this layer burned thin, an increase was noted in the ignition rate, giving a rate of travel of ignition having two distinct slopes. The reasons for this appear to be as follows:

In all tests the thermocouple records, gas analyses, and instantaneous CO₂ meter readings definitely have indicated a thin zone of high-temperature burning immediately above the ignition plane. In this primary oxidation zone the oxygen is almost, if not entirely, converted to carbon dioxide, as indicated by the CO₂ meter and gas analyses. Above this relatively thin, high-temperature, high-CO₂ zone CO begins to appear, and the percentage of CO₂ and the temperature of the fuel bed drop; that is, when certain temperatures and burning depth or time of contact are established above the primary oxidation zone, reduction of CO₂ to CO by
reaction with the hot carbon of the fuel at the upper edge of the zone lowers the fuel temperature there to some relatively stable narrow range, which prevails in the remainder of the bed above the hot zone and appears to moderate the temperature of the hot zones (fig. 44). Figure 44 shows the travel of the ignition plane as a function of time (A) and the instantaneous temperatures in the bed at regularly spaced intervals above the grate as a function of location of the ignition plane (B) in the bed. For example, the top curve of figure 44, B, represents temperatures in the bed at the instant when the ignition plane is 5 inches above the grate. At this moment the curve is applicable to bed-temperature conditions after the ignition plane has traveled from the top of the bed to a point 5 inches above the grate, as shown by that part of the ignition-travel curve (fig. 44, A) lying between 6 and 5 inches above the grate. The crossing of the 5-inch line is shown at approximately 7 minutes after the test was started or about 5 minutes after initial ignition (indicated by a in fig. 44, A). Similarly, each successive lower curve in figure 44, B, represents instantaneous bed temperatures at the time the ignition plane reaches, respectively, 4, 3, 2, and 1 inches above the grate and finally the grate itself, as represented by point b in figure 44, A, and the lowest curve in figure 44, B. In all but the bottom curve the assumed ignition temperature of 1,000° F. is about at the midpoint of the rapid temperature rise shown, the lower temperatures dropping off to ambient at the left of the 1,000° line. At the right of this line the bed temperature in the ignited part of the bed rises rapidly to a peak of about 2,250° F. about ½ inch above the ignition plane and then drops off to a relatively stable temperature of approximately 2,100° in the remaining ignited part of the bed.

When the temperatures indicated in figure 44, B, have been established in the zone of peak temperature and the cooler reducing zone above it, ignition into the green fuel will be a function of the temperature of the thin hot zone immediately following the ignition plane, as moderated by the cooler gasification zone above it.

If the reactivity of the fuel is such that the cooler reduction zone is burned off, exposing the zone of peak temperature to hot furnace walls or flame or if a layer of ash rather than hot carbon remains, ignition and burning will proceed in the bed at essentially two rates, one during the overequilibrium burning period and the other when burning-bed thickness becomes stabilized. This effect was first noted in a few tests on the Illinois coal, but it became very pronounced in tests on lower rank coals.

Figure 45 is the log of a test on ¾- by ½-inch Illinois coal in which initial ignition was obtained at a 200-pound air rate and ignition through the lower two-thirds of the bed at a 600-pound rate. In this test the burning rate

![Figure 42](attachment:image-url)
exceeded the ignition rate from approximately 9 to 12½ minutes, giving overequilibrium burning; then the rate of ignition increased as burning rate dropped. As may be noted, the depth of burning bed decreased rapidly from about 9 to 13 minutes, while the rate of ignition increased. From 13 to 20 minutes CO₂ increased, CO decreased, and the higher rate of ignition remained approximately constant.

**Underfeed and Overfeed Burning Rates**

As may be noted in figure 46, which shows maximum underfeed burning rates for high-volatile B bituminous coal, the underfeed burning rates for this coal lie above the OC line at air rates up to 200 pounds for some sizes and up to 400 pounds for others. In one test (¾-inch size; 600-pound air rate) the maximum underfeed burning rate substantially exceeded the maximum ignition rate for this size, a clear indication of overequilibrium burning.

The position of maximum underfeed burning curves above the OC line appears to indicate that this coal tends to give high-CO gas when burned with primary air only. Even though the fuel is in an underfeed bed at the time of maximum burning, where not all of the green fuel has been completely ignited, it has a higher carbon content than when the coal was charged. Thus, the maximum burning rates represented by the curves of figure 46 are, in the main, burning rates for a fuel containing more carbon than when the coal was charged, as would be expected for a coke formed from this coal. Therefore, a true OC line for the fuel actually being burned would lie to the left of the line.
calculated on the basis of coal as charged (fig. 46).

By the conventional concepts of reactivity, coals of low rank are more reactive and would be expected to burn more readily than those of higher rank. This conclusion is borne out by examination of the burning curves of the fuels described, as well as the lower rank coals described later. The highest burning rates were obtained for the low-volatile coal at high air rates, as shown in figure 35, B; these high maximum rates, however, were overfeed burning rates, and the maximum underfeed burning rates for this fuel were lower than the maximum overfeed rates up to 350- to 500-pound air rates. Although the maximum overfeed rates of the cokes and anthracites (figs. 30 and 33) did not quite equal those of the low-volatile coal, probably because of the much deeper beds of coke formed with this coal, these maximum overfeed rates also were substantially higher than the maximum underfeed rates. In fact, the overfeed rates were relatively much higher than the maximum underfeed rates, size for size, than were those for the low-volatile coal.

The maximum underfeed rates of the high-volatile A coals (figs. 38 and 40) were equal to or higher than the maximum overfeed rates, probably because more of the combustible material was removed during the underfeed period, as would be expected from increasing reactivity with decreasing rank. For the still lower rank high-volatile B coal, high underfeed burning rates remove so much of the combustible before ignition to the grate that relatively little material is left to burn out after ignition reaches the grate, and the rate of burning begins to drop so fast (fig. 45) as ignition reaches the grate that it is difficult to determine accurately the maximum overfeed burning rate. This trend continued throughout the range of ranks tested, indicating increasing reactivity, in the conventional sense, with decrease in rank of coal. Because increasing reactivity results in removal of increasing relative amounts of the available combustible in the bed during the ignition period, depth of ignited fuel at moderate to high air rates decreases with rank from low-volatile coal to lignite. Consequently, the layers of burning fuel above the ignition plane become increasingly thinner with decrease of rank, and, beginning with the high-volatile B coal, this depth of burning bed noticeably affects the maximum rates of ignition and burning obtained. This factor, then, is of major importance in considering ignition and burning rates as related to conventional reactivity concepts and indicates the need for a means of more clearly relating reactivity to ignition and burning rates of fuels.

**Ash and Slag Residues**

No unusual ash or slag conditions were encountered with this fuel. As the initial deformation temperature of the ash was 2,370° F. and the fluid temperature 2,710° F., it was a normal medium- to high-temperature fusing
ash, which remained unfused at low air rates but fused and slagged at higher air rates. No difficulty was encountered with maldistribution of air due to slag, and no unusual difficulties would be expected with this fuel under normal traveling-grate-stoker operation, either from air distribution or ash and slag removal from the furnace.

**SUBBITUMINOUS B COAL**

**Description of Fuel**

Source and analysis of the Laramie subbituminous B coal from Weld County, Colo., are given in Table 1 (p. 14). This coal was received from the mine as 3- by 1½-inch Egg or Nut in sealed drums, was crushed and screened to the same sizes as the Pittsburgh coal, and was stored in sealed drums until prepared, day by day, for the next test, as previously described. Each test batch was stored overnight wrapped in a rubber blanket to prevent loss of natural bed moisture.

**Initial Ignition**

As shown in Figure 47, the smaller sizes of the Laramie coal ignited more readily than the larger sizes, while the air rate appeared to have little or no effect, a significant difference from the behavior of the high-volatile coals because it is the reverse of that found for the higher rank coals and coke at moderate to high air...
rates. The explanation advanced earlier in this report for change in initial ignition time with change in size for coke and anthracite obviously does not apply here. However, another unusual factor (not presented in previous tests) offers a suggestion. The dotted curve for ignition of the %- by %-inch size at the 400-pound air rate is below that at the 200-pound air rate. For all other fuels so far described increase of air rate increased initial ignition time; this curve shows a decrease. The explanation appears to lie in the much higher reactivity of this lower rank fuel, the ignition of which seems to depend upon amount of oxygen present. As mentioned in the discussion of higher rank fuels, the air has more chance to sweep the top surfaces of small pieces than the surfaces of the larger pieces, and ignition of this coal appears to depend upon the amount of air (oxygen) sweeping over the heated top surface. The sweeping action does two things: (1) It provides more oxygen at the affected surface, and (2) it sweeps away the moisture being driven off the coal by the radiant heat. This departure in initial ignition characteristics of the low-rank fuels from the previously established factors for initial ignition of the higher rank fuels emphasizes the statement, made later in connection with initial ignition of fuels varying in ash content but having like combustible characteristics, that the character or nature of the fixed carbon and volatile content of coal apparently is the factor that affects initial ignition and not the ash or inert content (unless in unusual circumstances these should happen to catalyze the reaction).

In conclusion, if trouble is experienced with initial ignition of subbituminous coals, operation can be improved by feeding the fuel so that the surface is composed largely of fines and by increasing the air rates, at least up to the 400-pound rate. Even if it is necessary to wet the fines to obtain stable bed conditions, this apparently will have no retarding effect on initial ignition, though too much added water will slow up ignition through the bed.

Underfeed Ignition

Ignition rates for 6-inch beds of Colorado subbituminous B coal are shown in figure 48. Effect of increase in reactivity with decrease in rank, resulting in decreased thickness of burning bed with consequent lower ignition and burning rates, is evident, as virtually all the rates of ignition are below 20 inches per hour and 40 pounds per square foot-hour of combustible ignited. Also, peak ignition rates are obtained with air rates ranging from 400 to 500 pounds per square foot-hour, above which ignition rates drop with increase of air rate.

The curves shown apply only to 6-inch beds, however, as the rate of ignition varies during travel through the bed except at very low air rates. This fuel, being more reactive than higher rank fuels, burns to a very thin bed at moderate as well as high air rates, after which the rate of ignition depends largely upon the temperature of the surfaces to which the fuel bed is exposed. If such surfaces are hot, as from incandescent refractory arches and walls or radiant luminous flames, and radiation from the bed top is not excessive, the rate of ignition will increase when the bed burns thin, giving an ignition curve with two slopes. Under these conditions, ignition in the lower part of a bed will be more rapid than in the top part, and the most rapid average rate of ignition will be obtained in deep beds. Since the burning layer is very thin, there will be little fuel to be burned after ignition reaches the grate, and overfeed
Figure 47.—Initial Ignition of Colorado Subbituminous B Coal.

Figure 48.—Effect of Size on Rate of Ignition Travel (A) and Rate of Ignition (B) in 6-Inch Beds of Subbituminous B Coal.
burning rates will be much lower than underfeed rates. It appears, therefore, that in burning low-rank fuels most satisfactory operation should be obtained in refractory-lined furnaces or with luminous flame deployed close to the bed top, in deep beds, with stoker speeds regulated to give ignition to the grate just ahead of the rear bridge wall.

Figure 49 shows rate of ignition travel as a function of size; in contrast, figure 32 shows an opposite trend for anthracites. This is believed to reemphasize the importance of availability of oxygen at igniting surfaces and the increased reactivity of this fuel compared to the reactivity of the higher rank anthracite.

Underfeed Burning Rates

Figure 50 reveals strikingly different conditions of ignition and burning in beds of \( \frac{3}{8} \)-by \( \frac{3}{16} \)-inch high-volatile A bituminous coal and of subbituminous B coal. Up to a 600-pound air rate the ignition rate exceeds the burning rate for the high-volatile A coal, and therefore the depth of burning fuel tends to increase as ignition proceeds through the bed. The ignition rate of the subbituminous coal, however, is so much lower that equilibrium burning is reached at an air rate of 250 pounds; therefore, at air rates above this, burning can proceed at a higher rate than ignition (over_equilibrium burning) only when preheated fuel is available.

The fact that the maximum underfeed burning curve for the subbituminous coal lies to the left of that for the high-volatile A coal at low air rates indicates that this fuel will burn readily to high-CO gas at these low air rates. As overfed burning was negligible, no analysis of it has been made. This fact reflects the high reactivity of this fuel, which accounts for the thin layers of burning fuel at moderate to high air rates.

Ash and Slag Residues

No difficulties were experienced in beds of this subbituminous coal or would be expected in normal operation. At low air rates the ash residues were powdery or slightly fused, while at high air rates much of the residue was fused to small clinker balls or small, glassy slag pieces, possibly up to 1- by 2-inch size. These
residues should cause no operating difficulty, but owing to the relatively low ash content (4.1 percent in the as-received coal) the grate was exposed over much of the furnace area and could become overheated, with resulting high maintenance expense for replacing burned sections unless the beds were relatively deep so that all of the grate would be covered with fuel or ash. Therefore, if this coal were used with a hot refractory rear arch, either relatively deep fuel beds would have to be used or care would have to be taken to prevent radiant heat from damaging the grate bars, and air should be zoned so as to cool the bars at the rear end where they might become exposed. If ideal operating conditions were maintained, so that the fuel was at the bridge wall or close to it just as ignition reached the grate, there should be no difficulty from burned bars.

RAW AND STEAM-DRIED LIGNITE

Description of Fuel

The raw lignite used in these tests (table 1, p. 14) was shipped to the Bureau as approximately 4- by 2-inch Egg, packed with fines, in sealed drums. It was crushed and screened to the same sizes as the Pittsburgh high-volatile A coal and stored in sealed drums until used. Close sizes were weighed and immediately laid in the bed; mixed sizes were mixed one day, stored overnight in the rubber blanket, and used with minimum possible exposure to evaporating influences.

The steam-dried lignite was prepared from a batch of raw lignite shipped in sealed drums to the University of North Dakota by the Knife River mine at the same time the drums of raw lignite were shipped to the Bureau. Through the courtesy of the late Dean Harrington of the University of North Dakota, the shipment sent there was steam-dried in the university’s steam-drying pilot plant, and the dried lignite was shipped in sealed drums to Pittsburgh, where it was screened and crushed to the usual sizes and stored in sealed drums until it was needed for testing or mixing for test.

Initial Ignition

Figure 51 shows initial ignition data for raw lignite. The only initial ignition curve for close sizes is the heavy line for the 1½- by ¾-inch and the ¾- by ¾-inch sizes, for which the data points lie so close together that a single curve suffices. The curve for mix A, which is much lower than the curve for close sizes, shows increase in speed of initial ignition with decrease in average size, as noted also for the subbituminous coal. Not as many tests were run on the lignite as on the subbituminous coal, since variation with size appeared to be less for lignite than was found for subbituminous coal. However, lignite was the easiest to ignite of all the fuels tested, despite the fact that it contained 35.5 percent moisture as received. This finding is believed to be further confirmation of the principle that initial ignition depends on the nature and character of the fixed carbon and volatile matter in

![Figure 51.—Initial Ignition of Raw Lignite.](image-url)
the coal and not on other constituents, unless unusual ash characteristics should catalyze the initial ignition reaction. This latter phenomenon was not encountered in this study but is mentioned as a possibility.

Underfeed Ignition

Containing only 43.4 percent combustible, raw lignite, the lowest rank fuel used in this investigation, gave ignition rates under 20 inches per hour and 30 pounds per square foot-hour of combustible ignited, as shown in figure 52. Rates of ignition reached a peak at air rates of 200 to 300 pounds. Under the test conditions no gain was indicated by increasing air rates above 250 pounds per square foot-hour for the raw lignite, although no sharp drop in the rate of ignition was indicated at higher air rates. This fuel was still more reactive than the subbituminous coal, and ignition and burning rates differed less for the lignite than for the subbituminous coal, even at air rates under 200 pounds per square foot-hour.

Since ignition and burning proceed at nearly the same rate, even at low air rates, an appreciable layer of preignited fuel was not developed at the initial air rate, as in burning the higher rank fuels. Consequently, when the air rate was increased, there was little or no preignited fuel to burn off at high overequilibrium burning rates, and the rate of ignition therefore was not accelerated by such high burning rates and by the hot furnace walls resulting from them. Instead of an ignition curve having two distinct slopes, as found for subbituminous coal, the lignite gave two general types of ignition curves at moderate to high air rates. In one type enough heat was generated during the test to increase the temperature of the furnace walls gradually, and the hotter the furnace the more rapid the ignition rate. In many tests development of a layer of ash, which became hot, produced this same effect. In the other type ignition and burning were just barely maintained in a thin layer, but too little energy was available to raise the furnace walls to visible red heat. In this type ignition proceeded at a virtually constant slow rate until a layer of ash formed to shield the burning zone. These types of ignition curves indicate that in a continuously operating traveling-grate furnace, where refractories can be brought up to and maintained at a high temperature where luminous flames provide adequate

![Figure 52.—Rate of Ignition Travel (A) and Rate of Ignition (B) in 6-Inch Beds of Raw and Steam-Dried Lignite.](image-url)
radiation, substantially higher ignition rates probably can be obtained than were possible under the test conditions, where the furnace walls initially were relatively cold.

The ignition rate of the steam-dried lignite, in inches per hour, was only slightly higher than for the raw fuel; but the ignition rate of the dried lignite, in pounds of combustible, was roughly double that of the raw lignite. Unfortunately, only a few tests could be made with the limited quantity of dried lignite available. Since burning rates of this highly reactive fuel are limited by the rate of ignition at moderate to high air rates, doubling the ignition rate will permit a proportional increase in burning rates.

In contrast to the behavior of the low-ash subbituminous coal, the lignite tested, which contained more high-fusion ash, soon developed in many tests a layer of partly fused, spongy ash over the thin burning zone. The bottom of this spongy ash layer appeared to become quite hot and to shield the thin burning zone from heat loss to the cold furnace walls. Under these conditions, a bed in which ignition is proceeding at a low rate owing to excessive heat loss from the top of the bed increases in temperature below this ash-clinker layer and begins to burn vigorously as ignition approaches the grate. This effect increases the rate of ignition in the bed as ignition approaches the grate, and pre-drying the lower layers of lignite further accelerates the rate. In all tests except at very low air rates there was noted a definite tendency for ignition to speed up as it approached the grate. The rates shown in figure 52 are averages of the bottom 4 inches of 6-inch beds, where initial ignition effects are the minimum in this depth of bed and where the other influences mentioned reach the maximum.

**Underfeed Burning Rates**

Maximum underfeed burning rates for lignite are shown in figure 53. The curves show (1) that maximum underfeed burning rates are affected, even at relatively low air rates, by ignition-travel-rates; (2) that the smaller the fuel, the higher the maximum burning rates; and (3) that high-CO gas will be produced, at least at low air rates. It would be expected that curves similar in shape to that shown for the ½- by ¾-inch size, but indicating higher burning rates, would be appropriate for the 2 smaller sizes. Such curves should pass through or close to the 2 points shown on the 200-pound air-rate line; however, since no data were available for these sizes, the predicted curves were not shown on the chart. The much higher burning rates for the steam-dried lignite are in accord with what would be expected from the higher ignition rates of the dried fuel.

In 2 tests at a 50-pound air rate very high percentages of free H₂ gas were found in the gas samples, indicating extensive water-gas reaction in the bed, despite the relatively thin active depth of burning fuel. Maximum overfeed burning rates were so much less than underfeed rates that they were not plotted.

**Ash and Slag Residues**

The effect of a top spongy layer of partly fused ash on rate of ignition travel in beds of this lignite has already been mentioned (p. 58). Beds of this lignite appear to be matted after burning has proceeded for a time, as though the fuel were softening and fusing together. Observation of the behavior of this matted material during the tests and examination of the residue after the tests indicated that the apparent agglomeration was due to incomplete fusion of a very spongy ash.

There was nothing unusual in the ash or clinker layers remaining after the tests and nothing to indicate that the residues of this particular lignite would cause any operating difficulties. The ash-softening temperature of the lignite used in the tests was about 2,500°
which is somewhat higher than the 2,000° to 2,300° range of many North Dakota lignites. At low air rates only fine ash, with traces of spongy fused ash, was scattered across the grate. In tests at higher air rates a spongy slag or clinker layer was distributed rather uniformly across the grate, but it was friable and porous and should cause no operating difficulties. With a high-fusion-ash lignite such as this, the main operating factor to watch, particularly with a rear radiant arch, would be that ignition reached the grate at or very close to the rear bridge wall, as the fuel is essentially burned out at the time of ignition to the grate. Any exposed grate beyond this point would be subject to heat damage, while at the same time it would be passing unreacted primary air.

**DISCUSSION OF TEST DATA—COMPARISON BETWEEN RANKS**

**INITIAL IGNITION AS AFFECTED BY SIZE AND RANK**

A number of comparisons have been made between fuels in the discussion of individual ranks, but more direct comparisons, some on the basis of combustible (C + H₂) in the fuels, show some interesting trends. Figure 54 shows initial ignition time as a function of heat input to the bed top for comparable sizes of all the fuels tested. Air rates are as noted. Except for the two high-volatile A coals, which are reversed as regards their ignition characteristics related to their position in the rank classification scale, initial ignition became easier with decrease of rank. Almost as much time was
required to ignite anthracite and high-temperature coke at the 50-pound air rate as to ignite the low-volatile coal at the 200-pound air rate.

An approximate formula relating initial ignition time for 3/4- by 3/4-inch coke has been found to be:

\[ Y = 0.0588X^{0.58} \]

where \( Y \) = initial ignition time at an air rate of 50 pounds per square foot-hour,
\( X \) = air rate, in pounds per square foot-hour.

Although the formula is only approximate (since the log-log curve derived from it is a slightly curved line, indicating a more complex relationship), it is quite adequate for practical purposes for high-temperature coke within the time range for normal initial ignition, that is, 1 1/2 to 3 minutes.

Since all the curves of figure 54 are not of the same relative shape, the formula calculated for coke is not directly applicable to the other fuels. However, it does indicate the initial ignition periods for the high-temperature coke at various air rates. Values computed for the 200-pound air rate are calculated below:

\[ Y = 0.0588 \times (200)^{0.58} = 4.8 \text{ times the rate at 50 pounds} \]

Heat input, B. t. u. per square foot-hour

| 30,000 | 40,000 | 50,000 |

Initial ignition time for 3/4- by 3/4-inch coke at 200-pound air rate, minutes

| 16.6 | 11.3 | 8.65 |

Obviously, these computed time intervals are both off the scale of the chart and too long for practical operation, but they indicate the difficulty of igniting coke and anthracite as compared to the more volatile fuels. They show the advantage of using a layer of bituminous coal over these higher rank types of fuels to obtain rapid initial ignition and ignition through the bed.

Figure 54 appears to offer a good index of the reactivity of various ranks of coal under conditions of radiant heating and exposure to air as in fuel beds. It could be replotted in various ways and augmented by other initial ignition curves and data given in this report to yield data on reactivity versus rank of coal, reactivity versus size of coal, reactivity versus air rate for the different fuels, as was done for high-temperature coke. The data are somewhat similar to, but broader, than the range of results reported for the British critical air-blast method for determining reactivity. The only apparent anomaly relates to the positions of the two high-volatile A coals, which appear to be reversed with reference to their respective positions in the rank classification scale as indicated by their volatile-matter and fixed-carbon contents.

SLOW INITIAL IGNITION

In most tests where more than 3 minutes was required to establish an exothermic combustion reaction in the top layer of fuel, the average rate of ignition in the bed was much lower than in similar tests with rapid initial ignition. The rate of ignition usually increased as the plane of ignition traveled through the bed; even with the slowest initial ignitions, the delaying effect of slow initial ignition apparently would ultimately have disappeared if the beds had been sufficiently deep, as it did in many tests in the 6-inch beds where the initial delay was not too severe. However, in the thin fuel beds used in this type of stoker, slow initial ignition has a definite retarding effect on the average rate of ignition travel calculated for the entire bed depth, as was clearly shown in the curve for test 19, figure 21 (p. 25).

EFFECT OF SURFACE MOISTURE

Figure 55 shows the effect of moisture on initial ignition of coke breeze. The curves are shown as dashlines, since data are available at only two hood temperatures; however, the curves are similar in general shape to the many others included in this report and are believed to represent reasonably well change of ignition time with hood temperature. The curve for the highest moisture breeze tested (16 percent H₂O) shows the slowest initial ignition, while the curve that is close to the points for the dry, predried, and 4- and 8-percent-moisture coals shows significantly more rapid initial ignition. These data indicate that, all other factors being equal, initial ignition is not affected by surface moisture on the fuel up to some optimum moisture content, but as moisture is increased above this optimum percentage initial ignition is retarded, the retardation increasing with increase in surface moisture above the optimum. (The word "optimum" is used here because the best moisture content for ignition through the bed appears to be higher than the best for initial ignition; hence, the highest moisture content that will not retard initial ignition will be "optimum" as regards initial ignition.)

The effects of surface or added moisture (as contrasted to natural or bed moisture) on rate of ignition in the bed were determined in tests on coke breeze and have already been adequately discussed and illustrated (p. 30 and fig. 27, p. 32). With a single exception, one or more tests with each of the other fuels used were run to confirm the data from the coke-breeze tests described, and no significant variations were noted.
EFFECT OF RANK ON RATES OF IGNITION

Some apparently important relationships were developed in this investigation from a comparison of the ignition rates of various fuels as expressed by both rate of ignition travel in inches per hour and ignition rate in pounds of combustible per square foot-hour as a function of air rate. It is proposed further to analyze these data and to present the results, along with other data on bulk density of fuels, in a later bulletin.

EFFECT OF SIZE CONSIST, MOISTURE, AND IGNITION RATE ON BED PRESSURE DROP

Records were kept of bed pressure drop in all tests, and some unexpected data, later confirmed by theoretical calculations, were revealed. These data mainly concerned the very low volatile and noncaking fuels, coke and anthracites. Figure 56 is a plot of the bed pressure drop in a bed of medium-burning (Rice) anthracite at the 100-pound air rate. As ignition proceeded into the bed, the pressure drop in the ignited part of the bed built up to a peak (just before ignition reached the grate) that was nearly six times the cold-bed pressure drop. Calculations based on estimated gas analyses and temperatures in the bed, determined from analyses of gases from the stack and thermocouple records, showed that this increase accorded with theory. It is due to increase in volume and viscosity of the gases with temperature and the fact that at low air rates in beds of high-rank fuels only a relatively small
fraction of the fuel is burned off during ignition to the grate, and the residual ash tends to hold the shape and the relative volume of voids of the cold bed. Figure 57 shows the ratio of maximum hot-bed pressure drop to cold-bed pressure drop in beds of two different sizes of anthracite as a function of primary-air rate.

In beds of coking high-rank coals at low air rates bed pressure drop sometimes rose as ignition proceeded into the bed, as with the non-caking coke and anthracites, and then rapidly fell off. However, the rise was not over 2 to 3 times the cold-bed pressure drop and was obviously due to a certain amount of blocking of the bed by coking ahead of the ignition plane. At moderate to high air rates in beds of the high-volatile coals and at all air rates in beds of the lower rank coals bed pressure drop decreased as ignition proceeded through the beds, as shown in figure 41 (p. 49).

As may be noted in figure 57, the ratios of cold- to hot-bed pressure drops vary with the size of coal used; however, the shapes of the curves are virtually the same, within the range of stable-bed air rates, indicating that the same factors apply in both instances. Naturally, the larger the fuel, the smaller the $\Delta P$ (bed pressure drop).

The effect of moisture on $\Delta P$ was mentioned in the discussion of coke breeze. Moisture in mixed-size-consist fuels is very effective in reducing $\Delta P$ and increasing the air rate at which beds are stable. Even after moistened-coke beds have been dried out, they retain their moist-state low $\Delta P$ unless jarred or disturbed to destroy the agglomeration of fines produced by moistening. It was found that increase of surface moisture up to the amount that any given coke or coal mix would hold without water running off consistently decreased the $\Delta P$, provided the moist coal was not tamped or settled. However, the moister the coal, the easier it is to increase its bulk density by tamping or jarring, and this, of course, would increase the $\Delta P$. The capacity of natural-draft stokers can be materially increased if optimum (not maximum) moisture content is used, since the decreased $\Delta P$ resulting from proper use of surface moisture will permit increased airflow with natural draft. Added moisture tends to retard ignition through the bed, so increased airflow due to moisture must be balanced against decrease of ignition rate; however, the ignition curve for high-rank coals at air rates up to 200–300 pounds per square foot-hour rises so rapidly that an increase of air rate, at least up to these limits, with natural-draft stokers would be expected to more than offset decreased ignition travel in the bed due to increased moisture. The highest rate of ignition and burning probably would be obtained by using the surface moisture of the snowball stage, previously described, which was optimum for the coke breeze tested.

AIR RATES AND STABILITY OF BEDS

Figure 33 (p. 39) shows effects upon ignition through the bed of varying degrees of bed stability, using small sizes of anthracite. At air rates below 100 pounds per square foot-hour the beds were completely or nearly stable throughout the test. Air rates of 100 to 350 pounds caused irregular bubbling and boiling of the bed. In this range the bed tended to
develop scattered blowholes or small fluidized areas. These would sometimes shift around the bed and burn out in one small area, but the net effect was an overall drop in average ignition and burning in the bed, as shown by the solid portions of the curves of figure 33 (p. 39) between the 100- and 350-pound air rates. Air rates above 350 pounds caused uniform boiling or fluidization of the bed and uniform ignition and burning, showing that if air rates above those that give stable beds are to be used they should be high enough to be above the irregular range; that is, in fluidized or boiling beds the air rates should be high enough to fully accomplish fluidization.

Effect of Preheated Primary Air on Initial Ignition and on Ignition and Burning Rates

Preheated primary air caused a substantial decrease in initial ignition time when the bed was fully preheated before testing; but it had relatively little effect on initial ignition when the preheat was applied as in commercial furnaces (started through the bed at the beginning of the test), because the cold fuel in the bed absorbed the heat from the air before it reached the top of the bed where it could affect initial ignition.

Preheated primary air used in beds of St. Nicholas Barley anthracite materially increased rates of ignition through the bed, the increase being almost linearly proportional to the temperature increase above ambient. In the first tests both air and fuel were heated to the desired temperature before initial ignition to eliminate the effects of variable heating of the fuel as the test proceeded. Figure 58 illustrates the effects of preheat to increase ignition rates under these test conditions. Although the increase in the rate of ignition at the 50-pound air rate was substantial, the increase at the 200-pound air rate was much greater proportionally, and at still higher air rates extremely rapid ignition was obtained by mechanical mixing of ignited and unignited fuel in boiling beds. The proportional increase of ignition rate over the rate with air and fuel at ap-

Figure 58.—Effect of Primary-Air Rate and Preheat on Rate of Ignition of Barley Anthracite.

Figure 59.—Percentage Increase of Ignition Rate With Preheated Primary Air.
proximately 80°F, is shown in figure 59. At the 50-pound air rate preheating the fuel and air to 240°F caused an increase of only 11 percent in ignition rate, whereas at the 200-pound air rate the increase in ignition rate at the 240°F preheat over that obtained at 80°F was 35 percent. Increase in rate of ignition with preheated primary air was therefore much more pronounced at high than at low air rates, when the entire bed was brought up to preheat temperature.

In later tests simulating actual traveling-grate stoker operation, where cold fuel is fed into the preheated air stream, the tests were started in a cold bed. In these 4-inch beds the ignition plane traveled downward through the top 2 inches of fuel at an average rate only slightly higher than that obtained without preheat, whereas in the bottom 2 inches the ignition rate approached that obtained when both coal and air were at preheat temperature. The fundamental curves obtained with air and coal at room temperature and with both at preheat temperature therefore give the minimum and maximum limits, respectively, of the rate of ignition travel through fuel beds that would be expected in traveling-grate stokers supplied with preheated air.

EFFECT OF ASH CONTENT ON INITIAL IGNITION AND ON IGNITION AND BURNING RATES

As shown in figure 60, ash content had little if any effect upon the initial ignition or the establishment of ignition in the top layer of fuel beds, the controlling factor apparently being the character of the combustible material in the coal. However, once small glowing ignition areas were established, longer time was required for ignition to spread across a bed of high-ash coal, and this in turn would be expected to affect ignition rates in the bed.

Variation of ash content, on the other hand, has a pronounced effect upon the rate of ignition of anthracite, as shown in figure 61. A special batch of St. Nicholas Rice anthracite was separated by the donor, using the float-and-sink process, into fractions containing 4.5, 9.8, 16.7, 24.4, and 81.3 percent ash on the as-received basis. The moisture-free proximate analyses are given in table 6.

Figure 60.—Initial Ignition Time as a Function of Mean Hood Temperature and Air Rate for Anthracites Varying in Ash Content.
Figure 61.—Rate of Ignition Travel (A) and Rate of Ignition (B) as a Function of Ash Content in 4-Inch Beds of Rice Anthracite.

Table 6.—Proximate analyses of St. Nicholas Rice anthracite varying in ash content

<table>
<thead>
<tr>
<th>Condition</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>As-received basis</td>
<td>4.5</td>
<td>9.8</td>
<td>16.7</td>
<td>24.4</td>
<td>81.3</td>
</tr>
<tr>
<td>Moisture-free basis</td>
<td>4.6</td>
<td>10.0</td>
<td>17.0</td>
<td>25.0</td>
<td>82.2</td>
</tr>
<tr>
<td>Volatile matter, moisture- and ash-free basis</td>
<td>3.7</td>
<td>5.2</td>
<td>5.0</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>Fixed carbon, moisture- and ash-free basis</td>
<td>96.3</td>
<td>94.8</td>
<td>95.0</td>
<td>93.6</td>
<td></td>
</tr>
</tbody>
</table>

Fractions A, B, C, and D were tested first, giving the four upper curves in figure 61. The results were sufficiently interesting to justify preparation of higher ash batches by appropriate mixtures of D and E fractions to give blends containing 40, 55, and 70 percent ash.

Three definite effects were found to result from increase in the ash content of anthracite: (1) Decrease in ignition rate at all air rates; (2) decrease in the range of air rates giving high ignition rates; (3) decrease in the optimum air rate giving maximum ignition rate. At an air rate of 200 pounds per square foot-hour the anthracite containing 25 percent ash ignited at only 43.8 pounds of combustible per square foot-hour compared to 61.8 pounds for the lowest ash coal, a ratio of approximately 0.7 : 1.0. At 200 pounds, however, the ignition curve for the low-ash coal was still rising rapidly, and increase of air rate up to 325 pounds gave increasing ignition rates, whereas for the 25-percent-ash coal the 200-pound air rate was the optimum.

The limitations of air rate with increase of ash content have considerable significance from the operator’s viewpoint. An ignition rate of 40
pounds per square foot-hour or more of combustible can be obtained with the 25-percent-ash coal only at air rates of about 125 to 290 pounds per square foot-hour, but with the 4.6-percent-ash coal a range of about 60 to 600 pounds can be used. Low ash content is therefore a definite aid to stoker operation, insofar as high ignition and burning rates and ability to use a wide range of air rates are concerned.

However, other factors affect stoker operation, and to avoid a misleading picture it is necessary to analyze not only the ignition data but the burning data for these tests on anthracite varying in ash content.

Curves were drawn showing burning rates (combustible gasified) for complete tests at various air rates, similar to those shown in figure 62 for the 200-pound air rate. They were corrected for slight differences in initial ignition conditions and were not extended beyond a 5-pound burning rate at the end of the tests (2 pounds for tests at 50-pound air rates). The areas under the curves were then measured by a planimeter. The beds in all tests were 4 inches thick. The burning was underfeed before ignition reached the grate and overfeed thereafter; all rates reached the maximum during the overfeed burning period.

Average burning rates were calculated from the areas of the curves and are shown in figure 63 as a function of primary-air rate. Up to a 350-pound primary-air rate there was rela-

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**Figure 62.** Rates of Underfeed and Overfeed Burning of Rice Anthracite Varying in Ash Content.

Initial ignition at an air rate of 50 pounds per square foot-hour and burning at an air rate of 200 pounds.
Although the lower ash coals exhibited much higher rates of ignition travel than those of higher ash content (fig. 61), neither maximum nor average rates of burning were substantially affected by variation of ash up to 17 percent at air rates in the ranges normally employed in burning anthracites. As shown in figure 62, the underfeed burning rate of the lowest ash coal was slightly higher than for the other coals tested; the overfeed burning rate was also higher, but as the coal burned down and the pieces became smaller and the bed thinner, with little ash to impart stability, and depth, blowholes and maldistribution of air developed, adversely affecting the burning rates. The same conditions prevailed in burning the 10-percent-ash coal but to a lesser degree. As a result, the overall average burning rates were very close for the three lowest ash coals up to primary-air rates of 350 pounds, despite the rather distinct differences in ignition rates shown in figure 61. There was a substantial decrease in both ignition and maximum and average burning rates with increase of ash above 17 percent.

Figure 64 shows burning rates at different air rates for complete tests on the 4 lower ash anthracites—the 4.6- to 25-percent-ash coals. These data were replotted to show possible maximum effective bed depth with variation of ash content and are presented in figure 65. This figure shows that for low-ash coals bed depths can be effectively increased to increase burning rates at high air rates but that for the higher ash coals little increase of burning rate with increase of bed depth can be expected in beds exceeding 4 to 6 inches in depth.

Figure 66 illustrates graphically the relation between bed depth and combustible removed in burning anthracites varying in ash content. The left side of the chart shows the original bed depth (4 inches). The lines show the depth of bed as the combustible is burned out, and the end points of the lines indicate how much of the total combustible originally present
was removed by burning as well as the depth of residual ash or clinker. For the highest ash material, the bed of residual ash and clinker was actually deeper than the original bed of coal. Special provision to remove this large quantity of residue would be necessary in commercial furnaces if use of such residues were contemplated, as for example, in preparing concrete aggregate.

**EFFECT OF CHEMICAL TREATMENT ON INITIAL IGNITION AND ON IGNITION AND BURNING RATES**

Several tests were made on Locust Summit No. 4 Buckwheat (anthracite) treated as follows by sprinkling the coal with water solutions and mixing thoroughly:

a. No added treatment.

b. 0.2 percent (of the weight of the coal) added as Curbay X (a sugar-refining byproduct).
The effect of ash and sodium carbonate on the bed was negligible. Addition of sodium carbonate to anthracite in small increments ranging from 0.2 to 4.0 percent decreased initial ignition time, while increase of sodium carbonate delayed ignition. Initial ignition was reduced slightly below 790°F. The initial ignition time was approximately 2.3 minutes. The maximum depth of burning bed was approximately 1.75 inches.

**Figure 6:** Burning Rates of Rice Anthracite as a Function of Depth of Burning Bed and Ash Content.
to 0.50 minute with 2 percent added carbonate.

Rate of ignition dropped slightly with a small increment of sodium carbonate, increased with increase of treatment up to 2 percent, and then dropped again with heavy treatment. Apparently, heavy treatment caused a shielding effect that resulted in lower ignition and burning rates.

Only a very light treatment with Curbay X was used; since no beneficial effects could be detected, heavier treatments were not attempted. Any chemical treatment of coal should show definite advantages from such treatment to repay the expense and trouble required.

Thermocouple records of the tests with sodium carbonate treatment indicated that temperatures in the bed were lowered by increasing treatments. Despite this lowering of bed temperatures, rates of ignition increased with increase of treatment from 0.2 to 2.0 percent.

**CONCLUSIONS ON SCOPE OF TESTS AND POSSIBLE FUTURE RESEARCH**

Major conclusions are given at the beginning of this part of the bulletin, and many significant points have been italicized in the detailed discussions for emphasis. A few points that arose during the investigations were not completely investigated because of change in personnel assignments and projects. One of these questions relates to the effect of moisture tempering on the caking characteristics of highly caking coals, such as the high-volatile A Pittsburgh coal used in these tests. In a paper presented before the American Society of Mechanical Engineers in 1944 (92) the senior author stated that a few tests had indicated that water tempering of fine sizes of highly caking coal had reduced their caking tendency in fuel beds. Ralph Sherman, in his discussion of the paper, pointed out that this was an interesting conclusion that deserved more study. However, no further test work on this particular point has been possible as yet, and the statement must stand until confirmed or denied by further study. Striking differences in a limited number of tests indicated that watertempering reduced caking properties and very noticeably improved ignition and burning of the highly caking Pittsburgh coal at low to moderate air rates. This needs further study.

Another notation made during the course of the investigation related to the effect of smoke and soot formation in the combustion space of the test furnace on heat received at
the bed top from the radiant igniting hood. Special radiometer tests were made wherein a radiometer was placed in the center of the bed at bed-top level; in some tests the radiometer was surrounded with a "grog" bed of crushed and sized refractory-brick particles, while in others the bed top comprised a ¾-inch layer of small-size high-volatile A bituminous coal. In the tests on the coal both the temperature of the radiant hood and the heat reception at the bed top increased very rapidly as the furnace became filled with smoke and soot from the coal, before flame became visible, as contrasted to slow steady increases of heat received at the bed top and stable hood temperatures in the grog bed. This condition suggests that the dense smoke at the center of the furnace may have been ignited by the hot hood and ignition quickly transmitted to the bed top, accelerating ignition there, while the cooler regions of smoke around the edges that were visible remained unignited longer than that at the center of the furnace. Under these conditions, observation through the peephole in the side wall of the furnace would not disclose the flaming at the center of the furnace. What could not be determined, because of lack of visibility, and should be carefully checked is whether the temperature and rate of heat reception increased before actual flaming at some part of the bed top. Flaming when first observed usually spread very rapidly through all the volatile matter over the bed top.

As mentioned earlier, effect of moisture tempering on initial ignition was not particularly important up to certain percentages of moisture, above which the effect was adverse. In duplicate tests to determine whether water vapor and moderate to dense smoke had significant effect upon heat received at the bed and initial ignition, a small-size high-volatile A bituminous coal (minus ½ inch) containing 20.1 percent moisture and a larger size of the same coal (½ by ¾ inch) containing only 2.0 percent moisture were ignited under identical radiant-hood conditions. Although the high-moisture fine coal ignited more rapidly than the larger size, this fact can be attributed largely to the size of fuel, considering the low air rate used (50 pounds per square foot-hour). The significant differences and lack of differences are shown by the condition of the combustion-space atmosphere and the heat received by the side-wall radiometer (table 7). This tabulation reveals two interesting points:

1) Despite its high moisture content, the wet, fine coal ignited before the dry, larger size coal, further suggesting that moisture tempering, at least up to some optimum amount, does not retard and may actually accelerate initial ignition;
2) comparison of heat received at the side-wall radiometer in the two tests indicated that the smoke and vapors generated from the dry coal may not have reduced the radiant heat available at the top of the bed. The increased heat received by the radiometer with the bed of relatively dry, large-size fuel may possibly be explained by relatively higher temperatures of the surfaces of the larger coal pieces and relatively higher radiation to the radiometer from these high-temperature surfaces.

The apparatus used in this investigation has proved very satisfactory for determining the effects of some of the numerous variables encountered in studying combustion of fuels in thin beds. The possibility of adapting the radiant-hood igniting technique to a smaller scale unit for further study of the reactivity of fuels as related particularly to ignition and burning in fuel beds has been suggested as another step in the study of fundamentals of fuel combustion.

### Table 7.—Effect of moisture on coal and furnace atmosphere on heat received at bed top

[High-volatile A bituminous coal; air rate, 50 pounds per square foot-hour]

<table>
<thead>
<tr>
<th>Elapsed time, minutes</th>
<th>Fuel size and moisture content</th>
<th>Heat received at side wall, B. t. u. per minute</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minus ½ inch, 20.1 percent H₂O</td>
<td>Furnace atmosphere</td>
</tr>
<tr>
<td>0.0</td>
<td>Clear</td>
<td>0.0</td>
</tr>
<tr>
<td>0.5</td>
<td>do</td>
<td>6.47</td>
</tr>
<tr>
<td>1.0</td>
<td>do</td>
<td>7.52</td>
</tr>
<tr>
<td>1.4</td>
<td>do</td>
<td>8.00</td>
</tr>
<tr>
<td>1.5</td>
<td>Flame</td>
<td>11.00</td>
</tr>
<tr>
<td>2.0</td>
<td>do</td>
<td>(!)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Minus ½ inch, 2.0 percent H₂O</td>
<td>Furnace atmosphere</td>
</tr>
<tr>
<td></td>
<td>Clear</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Slight smoke</td>
<td>6.92</td>
</tr>
<tr>
<td></td>
<td>Dense, light-gray smoke</td>
<td>7.35</td>
</tr>
<tr>
<td></td>
<td>Dense gray smoke</td>
<td>8.63</td>
</tr>
</tbody>
</table>

1 Rising owing to bed flame.
PART II.—CROSSFEED BEDS

CONCLUSIONS

Pure crossfeed ignition does not usually occur in actual operation in fuel beds on traveling grates, where underfeed principles govern ignition under conditions of normal operation. Only under the unusual conditions of very low rates of grate travel and very high air rates can pure crossfeed ignition be significant.

The rates of ignition in pure crossfeed beds are much lower than underfeed travel rates at comparable primary-air rates. However, in confined fuel beds, such as the test bed used in this investigation, and at air rates above the range that gives stable beds on traveling-grate stokers all fuels tested showed increased rates of ignition with increase of air rate, and no maximum ignition rates were obtained up to air rates of 1,200 pounds per square foot-hour. The slopes of the ignition curves definitely suggest that even higher crossfeed ignition rates could be expected at still higher air rates. Two fuels, coke and subbituminous coal, gave measured maximum crossfeed ignition rates that were noticeably higher than those obtained with underfeed ignition within the range of air rates used. When the rates of ignition for high-volatile A bituminous coal were adjusted for maldistribution of air, the adjusted rates for this coal also were higher with crossfeed ignition at higher air rates.

Evolution of tars, vapors, and soot from beds of high-volatile A and subbituminous B coals masked the radiation effect in the ignition zone, and development of a plastic layer in the high-volatile coal accounts at least in part for the low rates of ignition of such highly reactive coal, as compared to high-temperature coke of comparatively low reactivity. Two other possible retarding effects are also discussed.

Chemical reactivity, in its conventional concept, apparently bears no direct relation to rates of ignition; this conclusion applies to both underfeed and pure crossfeed ignition. The behavior of the two fuels with extreme properties—high-temperature coke and subbituminous B coal—indicates that the reactivity as measured by the rates of ignition in the bed is affected significantly by the mode of heat transfer. This, in turn, is affected by such physical characteristics as the masking effect of volatiles and cooling effects of drying.

Up to the present time there have been no known applications of pure crossfeed ignition and burning in fuel beds, recognized and described as such, except for a small anthracite stoker. The present investigation, originally started because of scientific curiosity, has indicated that the pure crossfeed principle could be applied in commercial processes for special purposes. One of these possibilities is the combustion of low-grade fuels, such as washy refuse.

REASONS FOR INVESTIGATION

The pure crossfeed tests reported here supplement previous Bureau work on pure underfeed and overfeed beds and the traveling-grate-stoker data of part I. The immediate interest in the study was occasioned by the preceding traveling-grate-stoker investigation, since it was thought that data on the horizontal ignition component in moving beds would show whether this factor was sufficiently important in traveling-grate stoker operation to affect materially the conclusions based on the data for stationary beds.

No reports of studies on pure crossfeed burning that recognized this principle were found in the literature, and it was believed that in addition to the immediate application in connection with previous investigations such data would be of general interest to combustion engineers. The availability of the test apparatus and of fuel samples remaining from the previous investigation permitted this test work to be carried out with minimum expense and time and permitted direct comparison of results with the same fuels in the two types of beds.

IGNITION PLANE IN TRAVELING-GRATE AND CROSSFEED BEDS

The role of the ignition plane in traveling-grate and crossfeed beds is described in more detail here than in part I and is intended to show the relationship between the two investigations and the importance of various factors influencing the direction and speed of ignition travel. Ignition characteristics on top of a traveling-grate-stoker bed differ from those in crossfeed fuel beds. In the older, unzoned type of traveling-grate stokers with front radiant arches ignition of the bed top is mainly caused by incident radiation (from flames, radiant arches, and hot furnace walls), whereas in the later zoned-air types the front arch is shortened or it is omitted and replaced by a long, low rear arch. In this type an additional important quantity of heat is supplied by incandescent particles blown forward from the rear of the grate. Figure 67 represents diagrammatically a traveling grate in which the ignition plane slopes from the point of ignition of the top layer (A) down to the point where ignition
has reached the grate (C). The rate of travel of the ignition plane at given air rates and grate speeds is affected to some extent by the physical and chemical properties of the fuel, and this in turn affects the slope of the ignition plane. Other factors controlling the slope of the ignition plane are the rate of grate travel and, in instances of slow initial ignition, the rate (or mode) of ignition at the top of the bed. The length of grate covered by green fuel (B–C) is determined by the travel of the grate (r_g, see fig. 67, inches per hour) and the downward travel of the ignition plane (r_h, inches per hour).

Suppose that the fuel is burning under steady-state conditions at a grate speed and air rate that will give an ignition plane such as represented by plane A–C. If the speed of the grate is progressively decreased and the air rate is maintained constant, the plane of ignition would form an increasingly steeper angle with the grate until C has reached B. At this point the entire bed will have been ignited, and the plane of ignition will be perpendicular to the grate surface and parallel to the direction of airflow as at AB, with the fuel moving at right angles to the air stream. Under these conditions of relatively slow rate of fuel feeding (grate travel) ignition would be crossfire, and the fuel, of course, would burn off rapidly so that only a short length of grate would be required. In this state of equilibrium grate speed r_g would be equal to horizontal rate of ignition travel r_h.

The studies discussed in part I relate to the correlation of the upward airflow and the downward travel of the ignition plane, whereas the present studies deal with the relation between the horizontal travel of ignition plane r_g and vertical airflow. Owing to the difficulties of measuring r_h in terms of r_g, experiments were conducted in a stationary bed in a manner that permitted direct measurement of r_h. The pilot apparatus with horizontal grate was modified, as described later, to accomplish this purpose of establishing and measuring pure crossfire ignition in order to compare this mode of ignition with the other two, overfeed and underfeed. This investigation was concerned only with the rate of travel of the ignition plane, no effort being made to determine the weight of combustible consumed during the ignition period.

**MODE OF ILLGITION OF A SOLID FUEL PARTICLE**

A discussion of some of the factors affecting the ignition of fuels may help clarify the test data and the conclusions derived therefrom. The ignition temperature of a small fuel particle or, more precisely, of a small part of a fuel surface has been arbitrarily taken in this investigation to be 1,000°F. This temperature can be reached only when the heat generated chemically equals or exceeds the net heat transfer from the particle, as shown in figure 68. In this figure the quantity of heat developed chemically, Q_a, and the net heat transfer, Q_n, from the particle are plotted schematically. Q_n is the difference between the heat received and lost by the particle during the process of ignition. Thus, the ignition temperature of a small fuel particle, t_ign, is that temperature at which the heat produced by the chemical reactions of combustion is equal to or exceeds the heat loss of the particle to the surrounding colder surfaces and gases under normal fuel-bed conditions.

The small size of the surface under consideration is emphasized because even with small fuel particles no homogeneous temperature can be ascribed to the fuel, since the heat will reach
the particle preferentially from one side and even when this side is ignited the opposite side and the center part may still be below the vaporization temperature of moisture. Thus, in a single particle of fuel combustion may take place at one part of the surface simultaneously with the driving off of moisture and vapors from colder parts of its surface. Although the temperature range of thermal decomposition of bituminous coals overlaps the temperature range of ignition of the coke obtained, immediate ignition of the volatiles at the surface does not necessarily follow even on that part of the surface where ignition of the solid has taken place because the ignition temperatures of the gases and vapors of decomposition, in general, are higher than the ignition temperatures of the very reactive surface of coke. However, the temperature of the coal surface after initial ignition (glowing) will rise rapidly enough to ignite the evolved gases quickly. It was noted that glowing ignition of newly formed coke surfaces occurred before flaming ignition of the vapors being evolved.

The ignition of a fuel particle, then, is governed by its oxidation rate at certain minimum temperatures and by the rate of heat flow by the two basic mechanisms of radiation and convection. Conduction, aside from that within the particles themselves, is not considered a significant factor in heat transfer in fuel beds because of (1) the irregularity of particles, resulting in relatively small contact surfaces, and (2) the relatively low conductivity of coal and the coke formed therefrom.

The travel of ignition through fuels of about the same rank, grade, and size will depend on the supply of oxygen and the rate of heat transferred from one fuel particle to another, as discussed in the following section.

**ROLE OF HEAT TRANSFER IN IGNITION TRAVEL**

Heat transfer in an underfeed fuel bed will be considered first because it is the simplest. Heat is transferred by three modes: (1) Radiation from both the surface of the hotter particles and the surrounding luminous flame and nonluminous gases, (2) convection between the gases and the particles, and (3) conduction within individual particles and between contiguous particles.

Figure 69 illustrates the importance of surface radiation as the primary mode of heat transfer in the ignition zone. It shows the position of the thermocouple (which is assumed to indicate the arbitrary ignition temperature of 1,000° F.) between an ignited particle, A, and an unignited particle, B.

For example, the heat conducted downward through a layer of low-temperature coke of an average particle diameter of 0.25 inch, with an assumed \( k \) value of 0.1 B. t. u. per foot-hour-degree F. and an assumed temperature gradient of 1,500° F., is about 2,000 B. t. u. per square foot-hour. To simplify calculation, the layer of cold particles (B) was assumed to be replaced by a perforated \( \frac{1}{4} \) -inch plate of coke having an open area of 30 percent.

The heat that could be transferred by convection from the layer of \( \frac{1}{4} \)-inch particles to air of ambient temperature passing upward can be estimated by using the conventional formula for heat transfer between air and spheres:

\[
\frac{h_c D_p^2}{k_f} = 0.33 \left( \frac{D_p G}{\mu_f} \right)^{0.8},
\]

where

- \( h_c \) = heat-transfer coefficient,
- \( D_p \) = particle diameter,
- \( G \) = mass velocity of air,
- \( k_f \) = heat conductivity of air film,
- \( \mu_f \) = absolute viscosity of air at film temperature.

Thus, for an average particle diameter of 0.02 foot (0.25 inch), an air-film temperature of about 100° F., and air-mass flow of 200 pounds per square foot-hour an \( h_c \) value of about 4 B. t. u. per square foot-hour (degrees F.) is obtained. For an assumed average temperature gradient between particles B and the air of about 600° F. and a surface area of 3 square feet of particles B per square foot of cross section, the heat transferred by convection from the particles to the air becomes 7,000 B. t. u. per square foot-hour, which corresponds to a temperature increase of 150° F. for the air.

Since the overall heat-transfer rate is controlled by the maximum resistance to heat flow in the system, the air preheat will be limited by

**Figure 68.**—Definition of Ignition Temperature of a Small Coal Particle.
the heat conducted through the particles and absorbed by radiation at their surfaces. The heat transfer by conduction, shown earlier to be about 2,000 B. t. u. per square foot-hour, would give a temperature increase of about 50° rather than the 150° obtained by considering only the convection heat-transfer rate of 7,000 B. t. u. per square foot-hour.

The effective radiant temperatures of the surfaces surrounding the thermocouple junction can now be estimated from the heat balance of the thermocouple. It may be assumed that heat losses by radiation to gases and heat conduction through the copper wires can be neglected. The heat lost by the couple by convection to the air then equals the heat received by radiation from the radiant surfaces:

\[ h_e(t_e - 120) = \epsilon_r h_r(t_R - t_e), \]  
(7)

where

- \( t_e \) = the unknown couple temperature;
- 120 = air temperature at thermocouple, \( ^\circ \) F.;
- \( t_R \) = the effective radiant surface temperature;
- \( h_e \) = heat-transfer coefficient for couple wire and junction;
- \( h_r \) = heat-transfer coefficient for surface radiation;
- \( \epsilon_r \) = emissivity factor for radiation of couple, assumed to be 0.80.

\( h_e \) can be calculated from the formula for forced convection to wires:

\[ \frac{h_e D_e}{k_f} = 0.32 + 0.43 \left( \frac{D_g C}{\mu_f} \right)^{0.59} \]  
(8)

and the following data:

- \( D_e = 0.002 \) foot (22-gage wire),
- \( k_f \) (for 100° F. approx. average air-film temperature) = 0.015 B. t. u. per foot-hour-degree F.,
- \( G = 200 \) pounds per square foot-hour,
- \( \mu_f = 0.045 \) pound per foot-hour.

When the above figures are used in equation (8), \( h_e \) is obtained as 24 B. t. u. per square foot-hour-degree F.

Substituting this value and the original assumed value of 1,000° F. for the thermocouple temperature in the radiant-heat-balance equation (7) gives an equation with two unknowns, \( h_r \) and \( t_R \). The term \( h_r \) can be represented approximately as a function of \( t_R \). Simultaneous solution of the two functions by trial and error gives a value of 42 for \( h_r \) and 1,700 for \( t_R \). This latter figure is the mean temperature of the surfaces surrounding the thermocouple.

The heat flow by radiation between the surfaces depends on the temperature difference. If this difference is successively assumed to be 200°, 400°, and 600° F., with a mean temperature of 1,700° F., the heat flow from particle A to particle B under black-body conditions is 14,000, 28,000 and 42,000 B. t. u. per square foot-hour, respectively. The \( h_r \) value is essentially constant at about 70 B. t. u. per square foot-hour-degree F. for these conditions.

This example indicates that radiant-heat transfer is the major factor in raising the surface
temperature of the colder particles (B) to the ignition temperature. Because of the poor thermal conductivity of coal, the bottom surfaces of the particles probably are heated by multiple reradiation from surfaces below voids receiving radiant heat through the voids. The formula also shows that the influence of air rate on the indicated ignition temperature is roughly the square root of the air rate. However, if clouds of opaque material, such as volatile matter fill the voids, radiant-heat transfer is markedly reduced by absorption. This phenomenon would account for the fact that high-temperature coke, which had a negligible volatile-matter content, was found to respond to ignition travel more readily than subbituminous B coal, which had a high volatile-matter content.

**APPARATUS AND TEST PROCEDURE**

The arrangement of the test furnace is shown in figure 70. The fuel bed was 6.5 inches thick (in the direction of the airflow), 12.75 inches high, and 19.0 inches wide. The airflow from the plenum chamber at the rear was directed horizontally through the air-cooled rear grate and the bed. Any unreacted air, the volatile matter, and combustion products generated in the bed passed through the water-cooled grate and thence upward to the exhaust hood. Part of the fuel bed could be observed at all times through the spaces between tubes of the water-cooled grate. The relative opacity of the products of combustion, condensation on the grate bars, and the progress of combustion thus observed were important in interpreting test data.

A refractory-lined stack hood supported on a corner post resting on a hydraulic jack could be raised and moved aside to give access to the fuel bed.

The desired air rates were maintained automatically by a regulating valve that was operated by a mechanism controlled by the pressure
differential across the measuring orifice, as illustrated and described in part I.

The ignition temperatures in the bed were determined by 28-gage chromel-alumel thermocouples inserted through the firebrick bottom of the furnace. All 10 couples were placed in the vertical middle plane of the bed, perpendicular to the grates, and spaced as shown in figure 70. One set of 4 couples was placed in a line approximately 1 inch from the water-cooled grate and a similar set about 1 inch from the rear grate; 2 other couples were located at the center of the bed. The technique of placing the bed and locating the thermocouples was the same as described in part I.

In exploratory tests with coke the fuel bed was used without the refractory hopper shown in figure 70. Ignition of the top layer was obtained by means of the preheated ignition hood (not shown in fig. 70), as described in part I. After ignition was established to a depth of about 1/4 to 3/4 inch, as indicated by the upper row of couples, the ignition hood was moved aside, the top of the bed was covered with a preheated plate of firebrick, and the edges were sealed with mortar; the exhaust hood was then transferred to the test furnace and the blower started. Thus, no air was blown through the bed until ignition was well established in the top layers of fuel. This procedure, as may be noted, differs from that followed in part I, where initial ignition was determined as a function of air rate.

Temperature rise of the thermocouples at the respective levels was recorded up to 2,000°F., or until the couples were destroyed, depending on operating conditions.

The 1,000°F. isotherm plane in the fuel bed was chosen arbitrarily as the ignition plane for all 4 fuels tested, although their ignition temperatures would vary if determined in accepted and laboratory testing devices for determining the reactivity of fuels. The order of magnitude of the ignition temperatures of fuels similar to those used in these tests, determined in other investigations under well-defined laboratory test conditions in a stream of air, was found to be as follows:

- a. Subbituminous coal, 300°F. to 500°F.
- b. Bituminous coal, 550°F. to 1,100°F.
- c. Anthracite, 900°F. to 1,100°F.
- d. High-temperature coke, 1,100°F. to 1,300°F.

In all the tests made in this study the temperature increase with time was rather steep in the range 600°F. to 1,200°F., which indicates that the rate of ignition travel for other isotherms would be virtually the same as that at the selected temperature.

Measurement of CO₂ and sampling for complete analysis of the stack gases was discontinued after the first few tests because too little information could be obtained owing to the continuous change of the respective positions of the combustion, the ignition, and the green-fuel zones and to the continuous change of the extent or depth of burning, with primary air passing through both unignited and ignited fuel. Gas samples therefore would not represent combustible burned in the bed.

When air rates exceeding 400 pounds per square foot-hour were used, consumption of the fuel in the combustion zone (above the ignition zone) was so rapid that maldistribution of the air was caused by the empty spaces created in the top of the bed, necessitating development of new igniting and bed maintenance techniques. The furnace was provided with a firebrick hopper (fig. 70), the capacity of which was 80 percent of that of the bed proper. Initial ignition was then accomplished by spreading a layer of incandescent coke (about 2,000°F.) on top of the bed. This coke was heated in a small gas-heated furnace. The hopper then was filled quickly with crushed refractory of the same size consistent as the fuel. Finally, the cover plate was sealed quickly in place and the test started. This procedure proved satisfactory with all of the fuels tested.

FUELS TESTED

The 4 fuels used in the study were taken from batches of fuel prepared for the tests described in part I of this investigation to provide direct comparison between the 2 studies as regards fuels used. They also are fairly representative of fuels in commercial use; they included high-temperature coke, anthracite, high-volatile A bituminous coal, and subbituminous B coal. The size and analysis of the fuels tested are given in table 8, and the origin is given in table 1, part I (p. 14). Since, as shown in part I, ash content affects ignition travel rates, it is interesting to note from table 8 that the ratio of ash to fixed carbon, that is, the "ash of coke," does not vary significantly in the four fuels and that therefore consideration of ash content as a parameter may not materially affect analysis of these crossfeed data.

TEST RESULTS

One of the first observations was to determine the slope of the ignition plane at any given time, as indicated by the thermocouples in the bed. In figure 71 the position of the ignition isotherm is shown for coke at two different air rates. The ignition plane in the test bed of coke was found to slope upward in the direction of airflow at the 50-pound air rate. At air rates of 100 pounds per square foot-hour and higher the plane of ignition became horizontal, as shown in figure 71 for the 340-pound air rate.
Table 8.—Fuels tested in pure crossfeed study

<table>
<thead>
<tr>
<th></th>
<th>High-temperature coke</th>
<th>Anthracite</th>
<th>High-volatile A coal</th>
<th>Subbituminous B coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size range, inch</td>
<td>¾ by ¾</td>
<td>¾ε by ¾ε</td>
<td>¾ by ¾ε</td>
<td>¾ by ¾ε</td>
</tr>
<tr>
<td>Bulk density, lb. per cu. ft.</td>
<td>27</td>
<td>50</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Void volume, per cent.</td>
<td>52</td>
<td>49</td>
<td>49</td>
<td>48</td>
</tr>
<tr>
<td>Proximate analyses on as-received basis, per cent:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>2.1</td>
<td>2.0</td>
<td>1.6</td>
<td>21.6</td>
</tr>
<tr>
<td>Volatile matter</td>
<td>1.0</td>
<td>6.1</td>
<td>37.2</td>
<td>30.6</td>
</tr>
<tr>
<td>Fixed carbon</td>
<td>86.2</td>
<td>82.4</td>
<td>55.8</td>
<td>43.4</td>
</tr>
<tr>
<td>Ash</td>
<td>10.7</td>
<td>9.5</td>
<td>5.4</td>
<td>4.4</td>
</tr>
<tr>
<td>Ash-softening temperature, °F (approx.)</td>
<td>2,350</td>
<td>2,700</td>
<td>2,600</td>
<td>2,300</td>
</tr>
<tr>
<td>&quot;Ash of coke&quot; 1</td>
<td>10.7</td>
<td>10.3</td>
<td>8.8</td>
<td>9.2</td>
</tr>
</tbody>
</table>

1 All volatile matter in the original coal was assumed to be driven off in coking. Then, "ash of coke" = \( \frac{\text{ash}}{\text{fixed carbon} + \text{ash}} \)

Figure 71 also shows that propagation of the ignition isotherm for coke from top to bottom of the bed was uniform throughout the depth of the bed even at air rates as low as 50 pounds of air per square foot-hour. This accords with results obtained from previous investigations and indicates that ignition, once having been well established in a fuel bed, proceeds at a uniform rate through the bed, regardless of the type of ignition (overfeed, underfeed, or crossfeed) so long as there is no change in fuel or air rate.

The rates of ignition travel in inches per hour and the rate of ignition in pounds of combustible ignited per square foot-hour for the 4 fuels tested, as determined from the propagation rate of the 1,000° F. isotherms in the bed, are plotted against the air-mass velocity in figure 72. In the crossfeed tests rates of ignition and air-mass velocity were calculated on the basis of total grate area, that is, the area of a vertical plane through the bed parallel to the grate. This figure also shows for comparison the pure underfed travel of ignition and rate of ignition of these fuels as determined in part I.

The travel of ignition in inches per hour (chart A, fig. 72) was determined, as in part I, by the propagation rate of the 1,000° F. isotherm. These data were then used to determine rate of ignition in pounds of combustible ignited per square foot-hour (chart B, fig. 72) by considering the bulk density of the green-fuel bed and its combustible content (table 8).

The total number of crossfeed tests made was 27. Of the 15 coke tests, 10 are represented in figure 72, but 5 tests obtained before the hopper was installed are omitted because of the irregular air distribution. Anthracite was used in 6 tests, and high-volatile A bituminous and subbituminous B coals were used in 3 tests with the hopper. Table 9 compares the travel and rate of ignition in pure underfeed and pure crossfeed beds at air rates corresponding approximately.
Figure 72.—Comparison of Rates of Ignition Travel in Crossfeed and Underfeed Ignition Studies.

Table 9.—Relative rates of ignition and "reactivity"

<table>
<thead>
<tr>
<th></th>
<th>High-temperature coke</th>
<th>Anthracite</th>
<th>High-volatile A bituminous coal</th>
<th>Subbituminous B coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Conventional concept of reactivity:</td>
<td>Lowest</td>
<td>1,200</td>
<td>1,000</td>
<td>700</td>
</tr>
<tr>
<td>Qualitative statement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Approximate ignition temperatures, °F,</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Pure underfeed ignition:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum ignition travel at optimum air rates, in. per hr.</td>
<td>30.5</td>
<td>18.3</td>
<td>28.5</td>
<td>16.6</td>
</tr>
<tr>
<td>Optimum air rates, lb. per sq. ft.-hr.</td>
<td>400</td>
<td>275</td>
<td>900</td>
<td>500</td>
</tr>
<tr>
<td>Ratio of maximum ignition travel of fuels to that of coke.</td>
<td>1.00</td>
<td>0.60</td>
<td>0.94</td>
<td>0.55</td>
</tr>
<tr>
<td>Maximum ignition rates at optimum air rates, lb. combustible per sq. ft.-hr.</td>
<td>71.0</td>
<td>59.5</td>
<td>79.5</td>
<td>36.2</td>
</tr>
<tr>
<td>Ratio of maximum ignition rates of fuels to that of coke</td>
<td>1.00</td>
<td>0.84</td>
<td>1.12</td>
<td>0.51</td>
</tr>
<tr>
<td>3. Pure crossfeed ignition:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ignition travel at highest available air rate (1,200 lb. per sq. ft.-hr.), in. per hr.</td>
<td>32.5</td>
<td>13.4</td>
<td>1&quot;22.5&quot;</td>
<td>20</td>
</tr>
<tr>
<td>Ratio of ignition travel of fuels to that of coke</td>
<td>1.00</td>
<td>0.41</td>
<td>0.69</td>
<td>0.62</td>
</tr>
<tr>
<td>Ignition rates at 1,200 lb. air per sq. ft.-hr., lb. combustibles per sq. ft.-hr.</td>
<td>77.0</td>
<td>59.0</td>
<td>84.0</td>
<td>59.0</td>
</tr>
<tr>
<td>Ratio of ignition rates of fuels to that of coke</td>
<td>1.00</td>
<td>0.77</td>
<td>1.09</td>
<td>0.77</td>
</tr>
</tbody>
</table>

1 Adjusted for air bypassing the bed.
to the upper limits that give stability in an unrestricted bed.

**DISCUSSION OF TEST DATA**

**SLOPE OF IGNITION PLANE**

The upward slope of the ignition plane noted at low air rates (fig. 71) might be explained, in the absence of gas-flow patterns, by the combined effect of decreasing oxygen concentration along the ignition plane and the natural tendency of hot gases to rise rather than to proceed straight across the bed. This explanation suggests that at low air rates the overall effect of gas flow across the bed is more nearly streamline than turbulent. The ignition planes become more nearly in line with the direction of air flow at increasing air rates. Apparently greater velocity of air through the voids results in more turbulent flow, more nearly horizontal flow of the hot gases, and consequently more nearly horizontal preheating of the fuel across the bed.

Horizontal ignition planes were not anticipated. It was expected either (1) that the quick depletion of oxygen at the air-inlet side would give a high-temperature burning zone there, with the remainder of the ignition zone across the bed being at lower temperatures and resulting in an ignition plane sloping upward from the air inlet to the outlet side, as at low air rates, or (2) that the ignition plane would tend to move toward the supply of unreacted oxygen and so would develop a slope downward from the air inlet to the outlet side, since the only source of unreacted air would be below the ignition zone.

Oxygen appears to be supplied to the ignition plane exclusively from below the plane. Except for a very narrow vertical zone along the air-inlet grate, virtually no oxygen can reach the ignition plane from above. Expressed in average particle sizes, the coke bed was about 15 particles thick in the direction of airflow, while the beds of other fuels ranged from 20 to 25 particles. When ash distribution in the bed was studied, after cooling the bed in the apparatus tightly closed, it was evident that oxygen must have been consumed within about 1 inch from the air-inlet grate, corresponding to a width of about 3 to 4 particles.

**IGNITION RATES IN RELATION TO REACTIVITY OF FUELS**

As may be seen in figure 72, the ignition rates in the fuel beds tested decrease as follows: High-temperature coke > subbituminous B coal > anthracite > high-volatile A bituminous coal, as originally determined. The numerical ratios of the ignition rates to the coke rate, which is taken as 1, are shown in table 9.

In comparing the ignition rates obtained in these tests with those obtained in pure underfeed ignition, distinction will be made between the results of the three free-burning fuels—high-temperature coke, anthracite, and subbituminous B coal—and the non-free-burning coal, high-volatile A bituminous coal. The crossfeed ignition rates obtained for the latter coal, as given in figure 72, are believed to be too low owing to bypassing of air; probably about 80 percent higher rates could be obtained if the testing procedure were modified to prevent such bypassing. An adjusted, postulated value for the rate of ignition travel and for the rate of ignition is shown in figure 72 as a light dashline. This line indicates what might be expected in a moving bed if bypassing of air could be avoided.

For primary-air rates up to about 500 pounds per square foot-hour the measured crossfeed ignition rates of the 3 free-burning fuels are about 40 to 60 percent or roughly half those obtained in pure underfeed ignition. The same figure would hold also for the high-volatile A coal if its ignition travel is so adjusted. This phenomenon may be due to the air flowing turbulently along the ignition plane, where products of combustion and of devolatization dilute the air and thus tend to reduce temperatures in the ignition zone. Moreover, these products may also interfere with heat transfer by radiation in this zone. This action is not possible in pure underfeed ignition.

Generally, in a bed restricted between two grates rates of crossfeed ignition equal to or exceeding the maximum obtained under pure underfeed conditions can be reached if the air rates are increased sufficiently. For example, high-temperature coke, which ignites at a maximum rate under underfeed conditions of 71 pounds per square foot-hour at a 400-pound primary-air rate, will ignite at the same rate at a 1,000-pound primary-air rate under crossfeed conditions. Indications are that pure crossfeed ignition rates will further increase as the air rate is increased beyond the maximum air rate available for use in these tests.

The lowest temperature at which a small particle of solid fuel ignites often is used as a relative measure of its reactivity. This ignition temperature is approximately that listed in table 9 for the kinds of coal used in these tests. As may be seen, high-temperature coke had the highest ignition temperature (1,200° F.) and therefore the lowest reactivity, and subbituminous B had the lowest ignition temperature (400° F.) and therefore the highest reactivity. However, the rate of ignition in underfeed or in crossfeed combustion would be a more rational
index of the reactivity of the fuel, if not affected by bed conditions, since the rate of ignition reflects the quantity of fuel consumed. The maximum ignition rates for both modes of combustion also are given in Table 9. Evidently, the rates of ignition of the high-temperature coke and subbituminous B coal are completely reversed as regards order of reactivity. The relation between anthracite and high-volatile A bituminous and the subbituminous B coals shows less discrepancy from the conventional reactivity concept, but the reactivities and ignition rates still deviate rather widely. The discussion in part I (p. 28) of the effect of bed depth on ignition rates and the analysis of the effects of various modes of heat transfer between particles in the ignition zone given in this section of the report (p. 75) may help to explain these discrepancies and differences between conventional reactivity data and observed burning rates in fuel beds. Figure 73 and the following analyses of the test data by type and rank of fuel will further clarify them.

Figure 73 illustrates schematically the temperature gradient and the relative positions of the zones of drying, devolatilization, ignition, and burning in a bed of subbituminous B coal. The clouds of volatile matter evolved below the ignition zone will limit the radiant heat transferred between ignited and unignited fuel particles and therefore retard the rate of travel of the ignition plane, as compared to a fuel with a very low volatile content. Latent heat of vaporization of the moisture in the coal will absorb additional heat. These same phenomena in differing degree may be expected in burning high-volatile A bituminous coal and any other fuel with appreciable volatile content.

HIGH-TEMPERATURE COKE

The most striking fact is that the rate of crossfeed ignition of the high-temperature coke was the highest of all such rates experimentally determined for the fuels tested. This may be ascribed to the following factors: (1) The volatile content of the coke was negligible, and therefore radiant heat transfer between the particles in the ignition zone was not absorbed by opaque vapors in the void spaces; and (2) the temperature in the ignition zone is believed to be higher for high-temperature coke than for bituminous coals for given sizes and air rates, at least up to air rates of 400 to 500 pounds per square foot-hour. This phenomenon has been confirmed by Nicholls (10) at a 350-pound air rate. Of course, additional physical and chemical factors may account for the differences in behavior of high-temperature coke and low-rank bituminous coals; further studies of combustion in fuel beds are therefore needed to obtain a complete picture of the complex heat- and mass-transfer processes in such beds.

ANTHRACITE

The reasons given for high rates of ignition observed in pure crossfeed beds of coke would also appear to apply to beds of anthracite, yet ignition rates for anthracite are about half those for coke in inches per hour and about three-quarters in pounds of combustibles.

The most reasonable explanation for this difference appears to lie in the relatively large difference in thermal diffusivity of the two fuels. Thermal diffusivity is the thermal conductivity divided by the product of the density and the specific heat of a solid. Since the bulk density
of anthracite is roughly twice that of high-temperature coke, the thermal conductivity of the anthracite is roughly one-third that of the coke; and since the specific heat of these materials is about the same, the thermal diffusivity of the coke would be about six times that of the anthracite. Accordingly, the rate of ignition for a given amount of radiation would be less for the anthracite than for the coke in proportion as the ignition rate is affected by the thermal diffusivity of the two fuels. However, since thermal diffusivity relates to conduction of heat within the particles and, as shown earlier, radiation is the major factor in establishing rates of ignition, the effect of differences in thermal diffusivity will be much smaller than the 6:1 ratio mentioned.

The pronounced effect of differences in bulk density is shown by the relative positions of curves for coke and anthracite in figure 72, A and B. The curves are much closer in chart B where compensation has been made for differences in bulk density.

Another difference between coke and anthracite that might appreciably affect the relative rates of ignition is the shape of the pieces. Anthracite pieces tend to be flatter and more rectangular in cross section than the more nearly spherical or cube-shaped pieces of coke, and these pieces may lie in such a way that they reduce radiation through the voids materially. The effect of thermal diffusivity would then be greater. Investigation of the basic reasons for these differences would be interesting, but lack of facilities and time did not permit such a study in connection with these tests.

HIGH-VOLATILE A BITUMINOUS COAL

The rates of ignition travel in this coal under pure crossfeed conditions were the lowest of the four fuels, as experimentally determined. Maldistribution of air was obvious in testing this coal; if the test values are adjusted for this, using the data of part I as a guide, the adjusted rates fall close to those for high-temperature coke. These adjusted values are shown by the light dashlines of figure 72.

If certain retarding factors could be eliminated, it appears probable that the rate of ignition for the high-volatile A coal would exceed that for the high-temperature coke in crossfeed beds, as it did at high air rates in underfeed beds. One of these retarding factors is undoubtedly the large volume of volatile matter and soot driven off from the coal ahead of the ignition plane. This retards the flow of heat by radiation. Another retarding factor is the latent heat of vaporization of the volatile matter that must be supplied from the heat source before the fuel is ignited. A third retarding factor may be the plastic layer itself, which not only reduces the diffusion of air to the ignition zone but, probably more important, substantially reduces the void space, with consequent reduction in radiant surfaces and in passages for travel of heat by radiation.

Overcoming the above retarding factors in a fixed-bed test apparatus as used in this investigation would be difficult, because it would involve the use of a moving shield or plenum to force air through the igniting and burning zones. In a proposed commercial furnace, in which the bed would move downward between the restraining grates, such difficulty need not be encountered, as a plenum could be used on the air-supply side that would provide an air blast just as the ignition-burning zone passed the plenum. As contrasted to the fixed-bed test apparatus, the proposed commercial moving-bed furnace could provide proper air distribution to the ignition and burning zones, and under these conditions rates of ignition of the order of magnitude represented by the adjusted light line in figure 72 are believed possible.

SUBBITUMINOUS B COAL

The reactivity of the subbituminous coal was the highest of the four fuels tested by conventional methods for determining reactivity. However, in both the underfeed and the crossfeed tests this coal gave the lowest rates of ignition of these four fuels at high air rates. This fact may be explained, at least in part, by examining the characteristics of the coal and the respective test conditions. In underfeed ignition the relatively high natural bed moisture of the subbituminous coal must be evaporated before the coal is ignited. This moisture first retards ignition by taking up its latent heat of vaporization; then, when it reaches the hot burning zone of the bed, it is involved to some extent in the heat-consuming water-gas reaction, as indicated by the analysis of combustion gases, referred to in part I. Also, in underfeed ignition and burning of subbituminous coal there is a very thin layer of burning fuel at all practical air rates, and the heat content of the bed, including that available to force the ignition plane down into the green fuel, is materially affected by radiation from the top of the bed.

In pure crossfeed ignition moisture in the coal being heated by the ignition plane is vaporized and travels across the bed under, rather than through, the ignition plane; mixes with primary air, volatile matter, and combustion products; and leaves the bed beneath the ignition plane, as shown in figure 73. The high reactivity of the subbituminous coal promotes a relatively high rate of pure crossfeed ignition.
travel, despite the shielding effects of the vapors and gases and the heat-of-vaporization requirements.

Calculation of the heat necessary to bring coke and subbituminous coal with 20 percent moisture up to 1,000° F. shows that the latter fuel consumes approximately twice the heat required by coke—one reason for the slower crossfeed rate of ignition travel for the subbituminous coal.

PRACTICAL ASPECTS AND POSSIBLE FUTURE RESEARCH

The basic considerations involved in drawing a diagram of a traveling-stoker bed (fig. 67) indicate that pure crossfeed burning will be approached in this type of bed if the ignition rate can be materially increased in relation to the rate of travel of the grate. Although one method of increasing the ignition rate would be to increase air rates, the extent of such increase is limited without exceeding the point of bed stability in the traveling-grate stoker. However, if the bed were restrained, as in these tests, very high rates of crossfeed ignition travel might be attained at air rates higher than the maximum rates possible in pure underfeed beds. The difference in behavior would be expected to be most pronounced in beds of high-temperature coke and the highest rank bituminous coals, that is, low-, medium-, and high-volatile A bituminous coals.

Another method of increasing ignition rate in relation to grate speed on traveling-grate stokers is to reduce the rate of grate travel to the extent that ignition becomes essentially the crossfeed type. This is accomplished when a traveling-grate fire is banked, so there is little or no grate movement. It is also accomplished in a certain type of anthracite stoker such as the Risdon retort shown in figure 74 (127).

Although basically this stoker is like a traveling-grate stoker, except that the fuel moves instead of the grate, ignition is essentially crossfeed because the fuel is fed only as fast as it ignites in a crossfeed bed. The slotted grate area is 0.42 square foot, and the total area, including the spillover plate at the rear, is 0.75 square foot. The feed rates used by Mulcey for medium and high burning rates were 14.3 and 18.4 pounds per hour, respectively, of dry Rice anthracite. Calculation of the air rates from the data given in Mulcey’s report, assuming reasonable ash content and coal density, indicates that air rates were approximately 740 to 800 pounds per square foot-hour of actual slotted grate area of 0.42 square foot.

In figure 72 the pure crossfeed ignition-travel rate is about 50 pounds per square foot-hour at these air rates for anthracite of comparable size consist and chemical composition. This corresponds to an ignition rate in a horizontal direction of 21 pounds per hour for a cross section of 0.42 square foot, which is the area of the mouth of the Risdon retort. Since Mulcey reported feed rates of 14.3 and 18.4 pounds per hour for medium and high rates, respectively, it is obvious that at both the medium and high burning rates ignition was entirely crossfeed and that the rates of ignition and burning found by him do not represent the highest obtainable. This conclusion is compatible with Mulcey’s comment that the fan capacity in his tests was the limiting factor in stoker output and that higher air rates would indeed give higher ignition and burning rates. However, such increased crossfeed rates, within the air rates used in this investigation, would still be below the maximum underfeed ignition rates shown in figure 72. While the maximum ignition rates of pure underfeed burning are not utilized in the type of stoker shown in figure 74, the air rate that can be applied is about twice the air rate that could be used in pure underfeed ignition to obtain maximum rates of ignition.

This fact emphasizes the very interesting finding in this part of the investigation that crossfeed ignition provides a means of igniting and burning fuels at very high air rates, exceeding those possible with underfeed ignition. An investigation to determine whether there is an upper limit or optimum crossfeed ignition and burning rate for each of the fuels tested, similar to that found for underfeed ignition and burning, would provide more fundamental data on combustion of solid fuels. However, it should be noted (fig. 28, p. 33) that burning rates per pound of primary air used, at least in underfeed ignition and burning, tend to decrease with increase of air rate. The high rates of crossfeed ignition require such high primary-air rates that one would expect burning rates per pound of primary air to be even lower than those found for underfeed ignition and burning. By contrast, this would seem to indicate that less secondary air would be required for perfect
combustion or the nearest practical approach to perfect combustion obtainable in commercial fuel-burning equipment. Possible disadvantages to crossfeed burning at high air rates would be high bed pressure drops, with consequent high air-box pressures on the air-supply side and high power requirements for the blowers and fans. These may be offset, particularly where high temperatures and high burning rates are required, as in the combustion of very low grade fuels, such as washery refuse, where ignition limitations for underfeed ignition and burning severely restrict the range of air rates.

A study to determine the effect of shape of fuel pieces on the crossfeed ignition and burning rates, as mentioned under discussion of the anthracite tests, might prove valuable. Another fundamental study could include a study of bed pressure drop, as affected by temperature, increasing volume of combustion gases, and their flow characteristics, and the effect of these variables on crossfeed ignition.

A practical application of the pure crossfeed ignition principle can be visualized if the fuel would be allowed to move downward by gravity. (See fig. 70.) One advantage over the principle of the Risdon retort would be that no power would be necessary to move the fuel. Very high rates of primary air would be expected for this restricted bed. To obtain a clearer insight into the advantages and disadvantages of this principle, a more thorough basic study seems desirable.
APPENDIX

Figures 75 and 76 present a summary of the radiometer test data for 29 tests (271 to 300, inclusive), which involved 66 separate tests and parts of tests covering the quite thorough investigation of the design, testing, and calibration of the radiometers used in this investigation with fixed-heat-output lamps. Based on these tests, the heat output of the Globar hood, as measured in tests following test 300, are believed to represent absolute values that can be compared with absolute heat received in other furnaces and under other conditions, where such other absolute heats can be measured or calculated. These data have been used also to calculate the average heat output of the Globar hood for an assumed average initial ignition time, as shown on the bottom scale of the charts giving initial ignition time as a function of hood temperature for tests preceding test 271.

The method and formulas used to calculate the perfect gasification (OC) and perfect combustion (OP) lines on the charts in part I are also given in table 10.

### Table 10. Calculation of OC and OP lines

Combustion to CO.... (point A) at 70 pounds C+H₂. 1

Perfect combustion to CO₂... (point B) at 800-pound air rate 1 based on carbon and net hydrogen of fuels.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Percent by weight</th>
<th>a = C/(C+H_2)</th>
<th>b (70a)</th>
<th>(A = \frac{4/3b+70(81-a)}{0.232})</th>
<th>B (8/3a+8(1-a))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coke breeze</td>
<td>97.3</td>
<td>0.4</td>
<td>97.7</td>
<td>0.996</td>
<td>69.72</td>
</tr>
<tr>
<td>St. Nicholas anthracite</td>
<td>94.4</td>
<td>2.0</td>
<td>96.4</td>
<td>0.979</td>
<td>68.53</td>
</tr>
<tr>
<td>Jerome low-volatile bituminous</td>
<td>89.2</td>
<td>4.1</td>
<td>93.3</td>
<td>0.956</td>
<td>66.92</td>
</tr>
<tr>
<td>Montour No. 10 Pittsburgh</td>
<td>84.3</td>
<td>4.7</td>
<td>89.0</td>
<td>0.947</td>
<td>66.29</td>
</tr>
<tr>
<td>high-volatile A</td>
<td>80.8</td>
<td>4.3</td>
<td>85.1</td>
<td>0.949</td>
<td>66.43</td>
</tr>
<tr>
<td>Bevier high-volatile A</td>
<td>82.1</td>
<td>4.2</td>
<td>86.3</td>
<td>0.951</td>
<td>66.57</td>
</tr>
<tr>
<td>Illinois high-volatile B</td>
<td>77.3</td>
<td>3.3</td>
<td>80.6</td>
<td>0.959</td>
<td>67.13</td>
</tr>
<tr>
<td>North Dakota lignite, raw...</td>
<td>73.7</td>
<td>2.9</td>
<td>76.6</td>
<td>0.962</td>
<td>67.34</td>
</tr>
<tr>
<td>North Dakota lignite, steam-dried...</td>
<td>72.7</td>
<td>2.4</td>
<td>75.1</td>
<td>0.968</td>
<td>67.76</td>
</tr>
</tbody>
</table>

1 70 pounds C+H₂: and 800-pound air rate selected arbitrarily as representing the limiting values used on most of the charts.

2 \(C = \) percent C in moisture- and ash-free coal.

3 \(H_2 = \) percent H₂ in moisture- and ash-free coal minus H₂ required to form H₂O with O₂ in m. a. f. coal; that is, H₂ = H₂−1/8 O₂.

4 \(C+H_2 = (2)+(3),\) above.

5 \(a = C/\(C+H_2\) = \) ratio of C to total net combustible.

6 \(b = \) pounds O₂ in 70 pounds combustible.

7 \(A = \) Air rate required to gasify completely 70 pounds combustible to CO and H₂O = \(\frac{(4/3b+70(81-a))}{0.232}\).

where 4/3 = pounds O₂ per pound C.

8 \(1-a = \) ratio of net H₂ to total net combustible.

9 \(800\times(0.232) = \) pounds O₂ required to combine with net H₂ to form water, 70(81−a) = O₂ required to combine with net H₂ in 70 pounds combustible, 0.232 = conversion factor from O₂ to air.

10 \(B = \) pounds net combustible burned to CO₂ and H₂O (perfect combustion) at 800 pounds per square foot-hour air rate = \(\frac{8/3a+8(1-a)}{800(0.232)}\).

where 800(0.232) = pounds O₂ in 800 pounds air.

11 \(a\times(8) = \) pounds O₂ required to burn C in 1 pound C+H₂.

12 \(8(1-a) = \) pounds O₂ required to burn net H₂ in 1 pound C+H₂.
Figure 75.—Heat Absorbed by Radiometer as a Function of Time and Mean Radiant-Hood Temperature.
Air rate in all tests, 50 pounds per square foot-hour.
Figure 76.—Heat Absorbed at Center of Bed in Traveling-Grate Pilot Furnace as a Function of Time and of Heat Available From Globar Hood.
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Note.—Publications marked with a dagger (†) are out of print but may be consulted in many libraries. Bulletins, technical papers, miners’ circulars, and handbooks may be obtained from the Superintendent of Documents, Government Printing Office, Washington 25, D. C., at the price indicated (stamps not accepted in payment for such purchases). Reports of investigations and information circulars are distributed free of charge upon request to Publications Distribution Section, U. S. Bureau of Mines, 4800 Forbes Street, Pittsburgh 13, Pa.

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