

The Pennsylvania State College Bulletin

MINERAL INDUSTRIES EXPERIMENTAL STATION

BULLETIN 22

DETERMINATION OF THE MINIMUM TEMPERATURE OF SUSTAINED COMBUSTION OF SOLID FUELS

By

H. W. Nelson, O. P. Brysch and J. H. Lum



Price 50 cents

THE PENNSYLVANIA STATE COLLEGE
SCHOOL OF MINERAL INDUSTRIES
STATE COLLEGE, PENNSYLVANIA

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DETERMINATION OF THE MINIMUM TEMPERATURE OF SUSTAINED COMBUSTION OF SOLID FUELS

H. W. NELSON, O. P. BRYSCHE AND J. H. LUM

I. INTRODUCTORY

THE initial stages of combustion of a solid fuel, familiarly known as ignition, are primarily reactions between the fuel substance and oxygen and proceed according to the physico-chemical laws which govern such reactions. The complex nature of the compounds constituting the coal substance has made it extremely difficult to obtain information concerning the mechanism by which these compounds react with atmospheric oxygen to produce the common phenomenon known as combustion. In practice we know that under proper conditions coal will unite with oxygen with the liberation of heat and that temperature profoundly influences the rapidity with which these oxidation reactions occur. From a fundamental viewpoint we know but little of the actual mechanism by which these reactions take place. In this investigation we were not concerned with determining the nature of these oxidation reactions but have attempted to devise a practical method by means of which the ignition temperature or minimum temperature of sustained combustion may be determined.

When a combustible material such as coal is gradually heated in the presence of air or oxygen, a series of reactions takes place as the temperature is increased, the speed of these reactions being very slow at room temperature but increasing as the higher temperatures are reached. These reactions are exothermic and liberate heat which serves to raise the temperature of the coal substance and further increase the speed of the reaction. All the heat evolved is not retained by the coal, as under most conditions heat is lost to the surroundings, the amount dissipated being dependent upon the conditions to which the coal is being subjected. Conditions being favorable, however, the oxidation reactions proceed at a rate sufficiently rapid so that gradually, as the temperature increases, the rate at which heat is produced is greater than the rate at which heat is lost to the surroundings, the reactions are accelerated and the coal is heated rapidly. Conditions still being favorable, these reactions continue at rapidly increasing rates until visible evidences of combustion occur.

From a consideration of the processes involved in the ignition of a solid combustible it is obvious that there is no sharply defined temperature which may be called the true ignition temperature of that combustible. Ignition is a phenomenon which requires time rather than being a definite event in time (19) and there is no sharp transition from

slow to rapid heating (?). When dealing with the ignition of any solid fuel, therefore, it is necessary to define unmistakably the objective sought and to take into account all external conditions, slight variations in which might seriously affect the observed results. Hence, in determining the ignition temperature or the minimum temperature of sustained combustion of any fuel, it is necessary that all conditions or factors external to the sample be rigidly defined and controlled in order that the results may be accurate and reproducible and that they may be properly interpreted. In addition, the physical state of the fuel and the amounts of reactants (fuel and oxygen) must be accurately defined and regulated since these factors greatly influence the experimental results obtained.

It is evident, then, that a test for an ignition temperature is essentially empirical and that the temperature at which sustained combustion will occur is not a definite physical property of a coal. However, by keeping the variables affecting the test at definite but arbitrary values there remains only the chemical reactivity of the fuel which may affect the observed results and these results will have a relative significance when comparing the coals tested. It was the purpose of this investigation to adjust these variables so that it might fairly be said that the minimum temperature of sustained combustion had been determined.

In developing a method for determining the minimum temperature of sustained combustion, sensitivity, accuracy and ease of manipulation must be considered. The method to be described was developed primarily as a test for anthracites. Other coals, such as lignites and some bituminous coals, may be more sensitive to slight changes in temperature in the presence of oxygen than are anthracites. This may require a modification of the test procedure to distinguish the specific change in the fuel that is being brought about by the increasing temperature.

It is believed that the method described accomplishes the desired results in a highly satisfactory manner.

ACKNOWLEDGMENT

The authors gratefully acknowledge a grant from the Anthracite Institute, whose financial assistance at the outset made possible the initiation of the work described in this publication. They also wish to express their sincere thanks to Dr. A. W. Gauger, Director of Mineral Industries Research, The Pennsylvania State College, under whose direction this investigation was made, for invaluable assistance and advice.

II. LITERATURE SURVEY

A large number of experimental methods for the determination of the "ignition temperature" of solid fuels have been reported in the scientific literature of the last 20 or 30 years. The results and conclusions reached in these investigations are difficult to compare because of the extremely wide variations in definitions of the desired objectives, experimental conditions, design of apparatus and operative

technique. A number of the published papers have presented certain data concerning the application of the methods described but have omitted from consideration certain factors inherent in a test for ignition temperatures which make it difficult to correlate any one set of experimental results with those obtained by other workers.

Classes of methods.—Since we are primarily concerned with temperature relationships in a study of this kind, we may well place the methods used by the various investigators in three general classes: (1) constant-temperature methods, (2) rising-temperature methods, and (3) compensated or adiabatic methods. Each class may, of course, be further subdivided into groups in which certain experimental conditions are considered to be essentially similar.

Illustrative of the methods used in the first class are those described by Moore (15) during which he observed the inflammation of small known weights of finely ground coal in an excess of oxygen, the temperature conditions being known and maintained constant. By progressively raising the furnace temperature and holding other factors constant, a point was reached where the coal dust flashed. This point was then considered to be the ignition temperature of the coal being tested. From the time-temperature effects Moore calculated values for the "tendency to spontaneous combustion" and the "relative combustible capacity" for a given fuel. Considerable data were presented on the effect of variations in volatile matter, ash, banded constituents in the coal and degree of fineness of the sample. The constant-temperature type of method, with various modifications, has been used by other workers in similar investigations (10, 13, 14, 21).

The rising-temperature method has been used by Wheeler (26), Parr and Coons (17), Arms (1), Gauger *et al.* (9), and others (2, 3, 5, 12, 18). Wheeler modified the temperature-rise method by recording the temperatures of the coal sample and the space between the sample container and the furnace wall as a vertical tube containing a sample of coal was heated at a constant rate in an electric furnace. During the heating process a controlled flow of oxygen was passed through the sample. The temperatures of the coal sample and the furnace were then plotted against time and the ignition temperature was arbitrarily taken as that of the crossing point of the coal and furnace temperature curves. This served as a relative measure of the temperature at which ignition occurred and the method has been used by several later workers.

The method used by Davis and Byrne (6) is an example of the methods included in the third class of ignition temperature methods. The essential feature of this method is that the heat produced during the oxidation process was prevented from leaking from the system and was used to raise the temperature of the reactants, thus producing a cumulative heating of the sample over a measured time interval. From the time-temperature curves a theoretical critical temperature was calculated for several coals below which heating would not occur in the presence of oxygen. Compensated temperature rise methods have

also been used by Dennstadt and Schaper (8), Schaper (20), and Winmill (27).

Criteria of ignition.—A survey of the literature shows that a number of criteria have been proposed for the selection of the temperature at which ignition begins. Arms (1) has used the appearance of a definite glow through the mass of the coal sample as an index of ignition. This method, depending almost entirely upon the visual judgment of the observer as to the color and uniformity of the glow, would undoubtedly lack the accuracy of certain other tests. The appearance of a uniform glow would mark the end of a series of rapidly accelerated reactions, whereas the critical temperature below which such combustion could not be sustained must certainly lie below this point. In addition, the temperature of the coal sample was that of some point in the interior of the sample, while it is logical to believe that the glow would first manifest itself on the surface of the coal pile where there is greater accessibility to a supply of oxygen.

The sudden increase in the rate of evolution of carbon dioxide in the exit gases from a reaction chamber containing coal and oxygen has been used as a criterion of ignition (17). Carbon dioxide is given off at fairly low temperatures, however, and although the appearance of carbon dioxide is a relative phenomenon its initial appearance could not be within the temperature range at which active combustion would be sustained. It would, therefore, be necessary to decide arbitrarily as to the rate of increase of carbon dioxide evolution above which rate the observer could be confident that combustion had been initiated. The use of the sudden rise in temperature of the coal specimen as an index of the ignition point is based on the selection of a point on the temperature-time curve where the temperature of the coal sample exhibits an abrupt increase in temperature. As has been shown, there is no definite point at which ignition occurs, the heating effect of the oxidation reactions being continuous and cumulative; hence the selection of this point with any degree of accuracy is very often difficult. Myer (16) has proposed, upon the basis of measurements of the electrical resistance of various anthracites, that the sudden change in this property observed during the gradual heating of the sample could be used to indicate the point at which ignition occurred. An investigation of this method was included as a part of the study described in this paper.

The use of an external reference temperature reported in conjunction with the temperature of the coal sample has been reported by a number of investigators. Wheeler (26) was first to use the crossing point of the furnace and coal temperature curves when plotted against time as a criterion of the ignition temperature. The use of this criterion is open to the objection that a more or less rapid oxidation (combustion) has occurred previous to the crossing temperature in order for the coal temperature to rise sufficiently to reach and go above that of the furnace. It has the advantage that the observer is not required to make a decision as to the point on the curve where the temperature of the coal sample begins to exhibit the sudden heating effect.

Brown (4) has selected a criterion for the ignition temperature based on the inflection in the curve showing the difference between the furnace and coal temperatures when plotted against time. While a plot of this kind may possess an advantage over the ordinary methods for selecting the temperature at which the coal sample begins to show a tendency toward self-heating, it is difficult to regulate the furnace current so that a specifically gradual increase in furnace temperature with time may be secured. Swietoslawski, Roga and Chorazy (24) have used the intersection of projections of the coal temperature curve before and after the rapid temperature rise. Using this method as an index, the ignition temperature may be either considerably above or below the crossing temperature depending on the heating characteristics of the type of coal being tested. In the case of anthracites the projected temperature would be considerably higher than the crossing temperature and with lignites the opposite would be true.

Factors influencing determination.—In addition to the type of method and the criterion selected to denote the ignition temperature, the chief factors inherent in the experimental procedure itself which may affect the determination of ignition temperatures are: (1) rate of heating, (2) composition of ignition atmosphere, (3) rate of air or oxygen flow, and (4) time of exposure. To these may be added certain factors inherent in the material being tested, such as (5) fineness of division, (6) mineral matter, (7) quantity and quality of the constituents in the coal, and (8) other factors.

(1) **RATE OF HEATING.**—The heat conductivity of coal is comparatively low. Hence, the heat supplied to the coal sample from the furnace must be supplied at a rate such as will insure a uniform distribution of heat within the sample. This, in effect, would tend to limit the size of the sample being tested and the temperature of ignition recorded would also depend to some extent on the position of the thermometer or thermocouple within the coal sample. It is generally believed that lower ignition temperatures are obtained with the slower rates of heating. No detailed studies have been made, however, and according to Brown (4) for a given coal there is likely to be a certain rate of heating which will give minimum results. Using a number of samples of combustible solid materials (not, however, including coal), Brown found a minimum ignition temperature for each of a number of different substances with a definite rate of heating. There was a considerable range, however, over which the ignition temperatures did not vary greatly from the minimum.

(2) **COMPOSITION OF IGNITION ATMOSPHERE.**—As would be expected, the ignition temperatures of coals are lower in oxygen than in air (5,9). Moreover, more reproducible results are obtained when using oxygen (23). Davis and Byrne (6) have found that lower values for the ignition temperature were obtained when oxygen saturated with moisture was used than when the oxygen was dried. The reverse was found to be true by Gauger *et al.* (9) during their investigations. Many investigators have used an inert gas such as carbon dioxide or nitrogen while the test sample was being gradually heated and then passed

oxygen or air through the sample after the temperature range where ignition was expected had been reached. While this was done to prevent oxidation reactions taking place previous to ignition, there are few data presented to show the effect this may have on the ignition temperatures obtained.

(3) **RATE OF AIR OR OXYGEN FLOW.**—The rate of flow of oxygen or air affects the determination of the ignition temperature in that the speed of the oxygen reactions taking place is affected, as is also the rate at which heat is lost from the test sample. It has been found that there is a gradual decrease in ignition temperature as the rate of flow of the air or oxygen is increased (9,24) or that after a given point an increase in the rate of oxygen flow produced little or no effect (13). Brown (4) has concluded that "for each material, or possibly class of material, there is a certain rate of air or oxygen flow that should give minimum results."

(4) **TIME OF EXPOSURE.**—This factor is of great importance only when using constant-temperature or adiabatic methods. For rising-temperature methods this factor would be included as a part of the effect of the rate of heating, the rate of air flow and the degree of fineness of the sample.

(5) **DEGREE OF FINENESS OF SAMPLE.**—The effect of variations in particle size of the test sample is that as the fineness of the sample is increased the ignition temperature is decreased. For example, Davis and Byrne obtained the following results using a coal from the Freeport seam:

SIZE, SCREEN MESH	IGNITION TEMPERATURE, °C
Through 10 on 20.....	231
Through 20 on 35.....	228
Through 35 on 60.....	198
Through 60 on 100.....	184
Through 100 on 200.....	181
Through 200.....	171

Since the various investigators have used many different mesh sizes as a standard when reporting the results of their work, it can be seen that this fact is one of the reasons for the difficulties encountered in attempting to compare the results obtained by the various workers. In addition, the results of investigations wherein the test sample was selected as being a given mesh size are liable to error since a single mesh size is not indicative of the ignition characteristics of the coal sample as a whole. It is well known that the different sizes of a given coal will vary in analysis and composition.

(6) **MINERAL MATTER OR ASH CONTENT.**—Little can be found in the literature regarding the specific effect of mineral matter upon the ignition temperature because of the difficulties involved in arbitrarily increasing or decreasing the mineral content of a given coal without altering the characteristics of the coal substance. Kreulen (12) determined the ignition temperature of a series of coals within a narrow range of volatile matter content but containing varying amounts of

ash and found a slight increase in ignition temperature with increasing ash content. The amount of ash does not seem to be an important factor when it is present in small amounts. When inert mineral substances are added to a given coal the ignition temperature rises gradually until the proportion of added material becomes large and the ignition temperatures obtained are very high and meaningless.

(7) QUANTITY AND QUALITY OF CONSTITUENTS IN THE COAL SUBSTANCE.—Moore (15) has shown that in general the ignition temperature is decreased as the per cent of volatile matter in the coal is increased and other investigators have found this to be true for both coal and coke. The results of Wheeler's (26) investigations show that the ignition point decreases as the oxygen content of the coal increases. Davis and Byrne (6), Swietoslowski (24), Moore (15) and others have studied the ignition temperature of the banded constituents in coal. Davis and Byrne found that while anthraxylon has a lower ignition temperature than attritus, yet coals in which anthraxylon is predominant do not necessarily have lower ignition temperatures.

(8) OTHER FACTORS.—The moisture in the coal apparently has little effect on the value of the ignition temperature if present in amounts from 5 to 30 per cent, but below this range the ignition temperature tends to be increased as the moisture content is decreased (4). Gauger and his co-workers (9), however, found that as a sample of lignite was dried in air from a moisture content of 34 per cent to 8 per cent the ignition temperature also decreased from a value of 228° C to one of 193° C. Considerable work has been done with respect to the relation between the ignition temperature of coals and their tendency toward spontaneous combustion in storage. Attempted correlations have also been made of variations in the physical and chemical properties of coal (specific gravity, calorific values, friability, etc.) as related to the ignition temperature.

III. EXPERIMENTAL METHOD

The experimental method used in the present investigation is based upon that proposed by Wheeler (26) in which the crossing point of the coal and furnace temperatures when plotted against time is used as the criterion for ignition. Certain tests which will be described later served to show that the method gave crossing point data occurring at a temperature which was very significant in the critical range of the ignition reactions.

During the early part of the investigation attempts were made to develop a practical method of obtaining ignition temperature data by means of an adiabatic apparatus. This part of the work was discontinued when it became apparent that an accurate and simple procedure capable of being used in different laboratories with comparable results could not be developed. The apparatus finally developed may be used for ignition tests under constant-temperature conditions, but in such cases a number of tests must be made at varying temperatures in order to obtain a result by the method herein described in a comparatively short length of time.

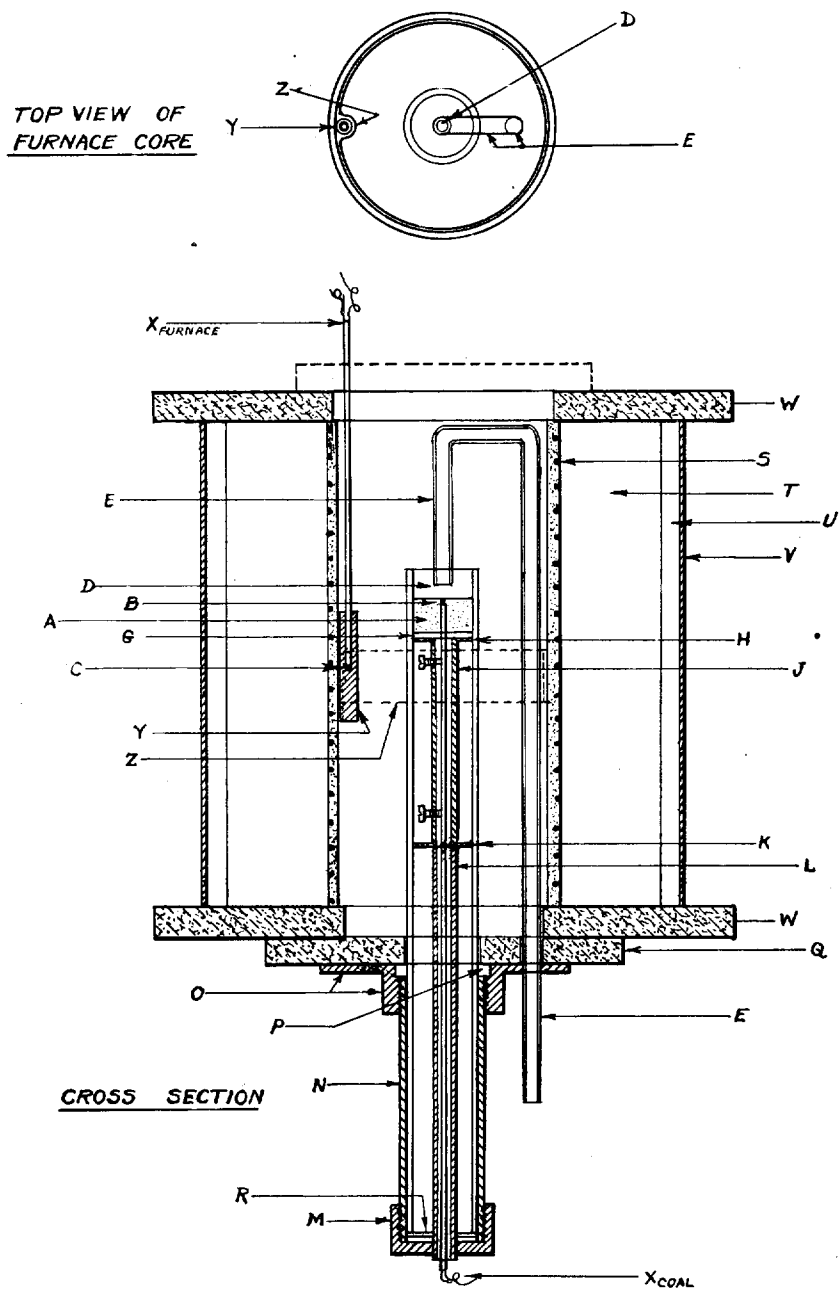
Results of an investigation to determine the value of the temperature-resistance method of obtaining the ignition temperature of anthracites as proposed by Myer (16) are also presented.

Apparatus.—The apparatus consisted of a small vertical electric furnace having a reference thermocouple fixed upon the inner wall for determining the furnace temperature. The construction was such as to permit ready insertion of the sample container holding a charge of fuel in the exact center of which was a thermocouple with the junction head just at the surface of the fuel and a short distance below the nozzle of the oxygen supply tube. The zone of combustion was thereby confined to the surface layer of the charge, in a restricted area of which the couple formed the center and across which oxygen moved at a high velocity.

A cross-sectional diagram of the assembled furnace and fuel container is shown in figure 1. In this figure, *A* is the 5-gram layer of fuel contained in a *Pyrex* tube 1 inch in diameter, at the center of which was placed the coal thermocouple *B* (chromel-alumel). The fuel is supported from below by the centering spool *J*, which also serves to hold the thermocouple bead *B* in a fixed position. The spool is held in place within the tube by the flanges *H* and *K* and is supported by the tube *L* which is threaded into the metal cap *M*. The socket tube *N*, which supports the *Pyrex* coal container, is also threaded into *M*, so that the couple, spool and socket are fixed in concentric relation but can be adjusted in a vertical direction. The socket *N* also supports the bottom closure plate *Q*, as well as the oxygen inlet tube *E* and nozzle *D*, by means of screw fastenings. The furnace consists of a spiral winding of *Nichrome* wire upon an alundum refractory core *S*, surrounded by a space packed with *Silocel* powder and asbestos and closed by the transite end plates *W*. The furnace reference thermocouple *C*, is fitted into a steel well *Y* which is forced into contact with the inner furnace wall by the sheet metal band *Z*.

The oxygen nozzle *D* had an inside diameter of .071 inches (1.80 mm.). Purified, dry oxygen at a rate of flow of 200 cc. per minute was measured by an oil-gauge flow-meter and passed through the nozzle against the fuel surface .2 inches (5 mm.) below at a linear velocity of 4.25 feet or 130 cm. per second. This rate had been found by trial to be necessary in testing anthracite coals. *Pyrex* glass was used for the nozzle during the experiments to be discussed later but this has been replaced by a heat-resistant alloy steel for tests at higher temperatures. It was essential that the diameter of the nozzle remain constant for all tests and constant checking showed no changes to have occurred.

The assembled coal container tube, with the coal thermocouple, test sample and oxygen nozzle rigidly fixed with relation to each other, was supported by a large laboratory clamp gripping the socket *N* which could be moved vertically into the furnace until the plate *Q* made contact with *W* and thereby closed the bottom of the furnace. Plates *Q* and *W* carried alignment marks so that when these were in the proper position, the coal container was always centrally located in the furnace space at a fixed distance from the furnace thermocouple *C*.



Obviously this was essential if reproducible and comparable results were to be obtained. The relative location of the various parts was determined by numerous experiments in which anthracites of the highest and lowest ignition temperatures were used in order to find the best positions for the whole range of anthracite coals.

The experimental runs were made by inserting the assembly with its fuel charge into the cold furnace, connecting the oxygen supply at the proper rate of flow, then turning on the furnace current and regu-

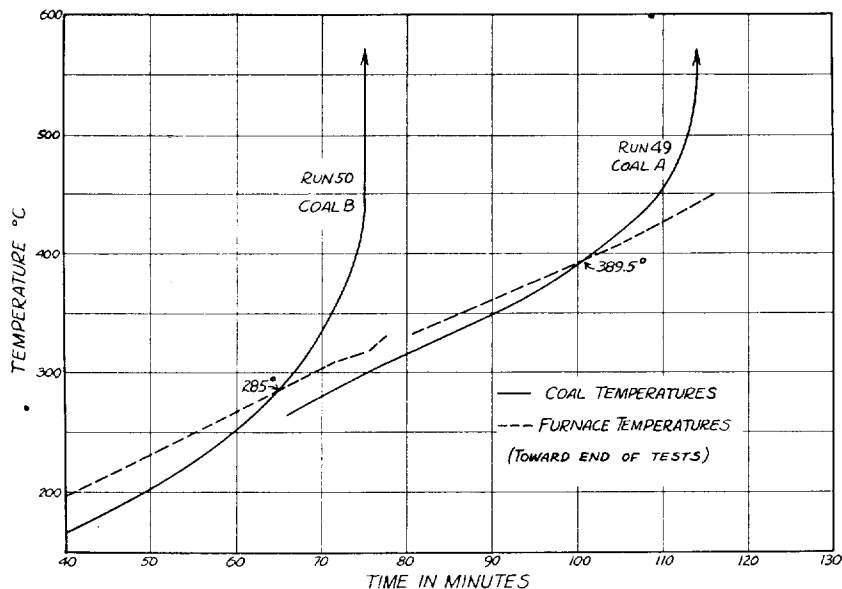


Figure 2.—Time-temperature curves showing crossing temperatures.

lating the amperage in accordance with a fixed heating schedule. The heating schedule was arranged to raise the furnace temperature at a uniform rate of 3.8°C per minute. The temperatures indicated by the coal and furnace thermocouples were recorded at five-minute intervals at the start of each experiment and at half-minute intervals as the two temperatures approached each other. Curves plotted from the data obtained from typical runs are shown in figure 2. Once the temperatures had crossed, the coal temperature rose rapidly until it suddenly increased at a rate of 600 to 1000°C per minute. If in a position to observe the test sample at the beginning of this rise, the observer saw a brilliant white scintillating crater around the coal thermocouple bead, but no flame. This died to a cherry red color after 4 to 5 seconds.

Anthracite samples.—Representative samples of a wide variety of anthracites were obtained through the cooperation of the Anthracite Institute, the Philadelphia and Reading Coal and Iron Company, and the Glen Alden Coal Company.

Preparation of samples for testing.—A critical examination of data presented in scientific literature and tests made in these laboratories served to indicate the importance of obtaining a uniform and representative sample of any coal to be tested for its ignition characteristics. Many previous investigators have used a given screen fraction of a ground coal for their test sample and have used the results of these tests to indicate the ignition temperature of the original coal. In view of the fact that different mesh sizes of a given coal are certain to have different ignition temperatures not only because of variations in reactive surface areas but also because of differences in chemical constituents, a method was sought whereby a uniform sample with respect to the above could always be obtained. After a number of grinding experiments on anthracites of varying composition and toughness, a simple procedure was established which yielded a pulverized product containing approximately uniform amounts of different-sized particles with a minimum of fine material below 200-mesh (.0029-inch screen opening) in size. In this procedure, no material of any size of a given sample subjected to the grinding process was discarded; hence the integrity and the representative nature of the sample used in the ignition test were not impaired. The size of the samples tested for the temperature of sustained combustion, expressed in terms of Tyler standard screen mesh, was as follows:

Through 20-mesh on 28-mesh 2%	Through 28-mesh on 35-mesh 11%	Through 35-mesh on 48-mesh 22%	Through 48-mesh on 65-mesh 21%
Through 65-mesh on 100-mesh 15%	Through 100-mesh on 200-mesh 16%	Through 200-mesh	

This size composition is designated as the standard size in later work. The ground samples were used in the condition as received. They were in equilibrium with the laboratory air with respect to moisture content.

Another method of obtaining uniform test samples was investigated in which lump pieces were sawed and ground to form a cylinder which fitted into the coal container tube. These cylinders were cut to a uniform length, leaving one of the ends as a naturally fractured surface, after which a one-eighth inch hole was drilled through the center to allow the thermocouple.

The coal thermocouple was adjusted so that, after lightly tapping the sample container, the 5 grams of the pulverized sample filled the coal container tube to a level just covering the thermocouple bead. The lumps were cut to a length just equaling this level, each piece weighing about 8 grams.

Experimental results and discussion. RELATION OF CROSSING TEMPERATURE TO THE THRESHOLD OF COMBUSTION.—In order to establish the relationship of the arbitrarily chosen crossing temperature to the temperature at which self-sustained combustion would

begin, the following experiments were made. The coal container was charged with the fuel and the flow of oxygen started. The cold charge was then inserted into the furnace which had been heated previously to a definite temperature near the range of occurrence of the critical reactions. Readings of the furnace and coal temperatures were taken at close intervals. If the initial furnace temperature was too low for sustained combustion to begin, the coal heated up to this temperature

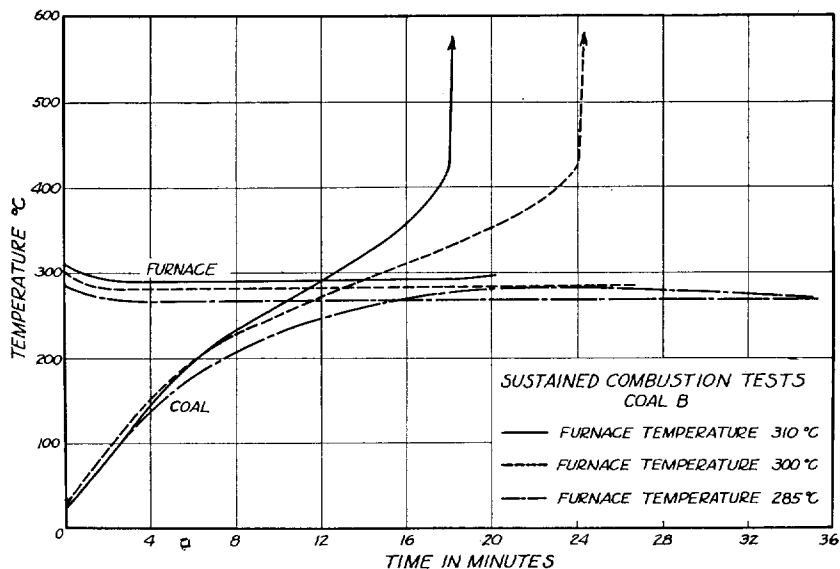


Figure 3.—Tests made by constant-temperature method.

and then remained at a constant value, or after a period of several minutes it dropped off very slightly. The experiment was repeated with the furnace temperature raised a few degrees and with a fresh cold charge, the coal heated to the temperature of the furnace, remained fairly steady for a short interval, and then began to heat again. The rate of heating of the coal then became steeper until it suddenly rose at a very rapid rate and the coal burst into a glow. In this case the initial furnace temperature was somewhat above that required to bring the coal to a temperature of self-sustained combustion. Trials were then made at intermediate temperatures until one was found at which the coal reactions just furnished the impetus to start the combustion process. This point then represented the minimum temperature of sustained combustion.

Curves illustrating the results obtained by means of these constant-temperature tests are shown in figure 3. The initial furnace wall temperature is read at the zero time ordinate, the temperatures of both the coal and the furnace wall being plotted against time. At 300° C the coal had passed the critical temperature above which combustion was self-sustaining and continued to rise until an active glow

was initiated, whereas at a furnace temperature of 285° C this did not take place. Hence, the temperature of sustained combustion must be at some temperature between 285° and 300° C. The temperature of sustained combustion for this coal as determined by the proposed crossing-temperature method was found to be 285° C.

Table 1.—Comparison of results of crossing-temperature and constant-temperature methods.

COAL	CROSSING TEMPERATURE °C	TEMPERATURE OF SUSTAINED COMBUSTION, °C
Composite	316	327 to 350
A	390	400
B	285	285
Anthracite No. 1 (Lump)	482	480
Anthracite No. 2 (Lump)	553	563

Table 2.—Reproducibility in duplicate tests, standard size.

TEST NO.	COAL	CROSSING TEMPERATURE, °C
41	Composite	316
46	Composite	316
84	K	295
84'	K	296
95	L	281
95'	L	279
96	F	298
96'	F	303
111	E	295
111'	E	293
138	J	351
139	J	344

A number of these constant-temperature tests were made with various samples of pulverized and lump-size anthracite and a consistently close agreement was found to exist between the minimum temperatures of sustained combustion determined in this way and the results obtained by the proposed crossing-temperature method. Some comparative temperatures are given in table 1. Although the constant-temperature tests are also arbitrary because of the fixed oxygen rate

Table 3.—Tests on commercial sizes of anthracites, single lump sizes.

COMMERCIAL SIZE	CROSSING TEMPERATURE, °C	DEVIATION FROM AVERAGE, °C	CROSSING TEMPERATURE STANDARD MESH SAMPLES, °C
<i>Results on Anthracite No. 1</i>			
Pea	482	-4	268
Furnace	489	+3	275
<i>Results on Anthracite No. 2</i>			
Pea	552	+2	379
Pea	553	+3	379
Pea	559	+9	379
Nut	545	-5	379
Nut	542	-8	379
<i>Results on Anthracite No. 5</i>			
Pea	489	0	268
Nut	497	+8	268
Stove	488	-1	268
Furnace	482	-7	268
<i>Results on Anthracite No. 6</i>			
Pea	530	+5	384
Nut	518	-7	384
Stove	530	+5	384
Furnace	521	-4	384

of flow, particle size and surrounding conditions, these results served to indicate that the crossing temperature as determined by the proposed method was a very significant one for the oxidation reactions occurring during the process of ignition of a particular anthracite and was within a few degrees at least of the critical point above which the oxidation of the fuel was accelerated to active combustion.

REPRODUCIBILITY AND ACCURACY OF THE PROPOSED CROSSING-TEMPERATURE METHOD.—The crossing-temperature method for obtaining the minimum temperature of sustained combustion, determined according to the procedure described previously, better satisfied the requirement of ease of manipulation than the constant-temperature method and also required less time. As to reproducibility and accuracy of test results, the duplicate runs on both standard pulverized and single lump samples were found to check each other very closely as is shown in tables 2 and 3.

EFFECT OF SIZE OF COAL PARTICLES.—Since a greater amount of surface area per unit volume of coal was available when finely ground coal was tested, such samples gave lower crossing temperatures than the more coarsely ground samples. The data presented in table 4 show the effect of particle size on the crossing temperature as obtained by the present method. The difference in crossing temperature between samples ground to the standard proportion of mesh sizes and test pieces in lump form is also shown. It will be observed that the crossing temperatures of the solid test samples are 150 to 200 degrees higher than those of the standard mesh sizes of the same sample.

Table 4.—Effect of particle size on crossing temperature.

SAMPLE	SIZE	CROSSING TEMP., °C
Composite	Standard	357
Composite	-20 +28	390
Composite	-28 +35	377
Composite	-65 +100	240
Composite	-200	220
No. 1	Standard	276
No. 1	Lump	486
No. 2	Standard	379
No. 2	Lump	550
No. 5	Standard	268
No. 5	Lump	489
No. 6	Standard	384
No. 6	Lump	525

Shown in table 3 are the results of tests using solid pieces of several anthracites. The test pieces were cut from commercial sizes of pea, nut, stove and egg coals. A comparison with the average crossing temperature of standard proportion sizes is given for each of the commercial sizes of coal. No great difference in crossing temperature is shown by solid samples from the several commercial sizes. It is likely that the ignition characteristics of a commercial size anthracite in a fuel bed are more closely indicated by the crossing temperatures of the lump samples, but more reproducible results for comparison of the relative ignition characteristics are given by the samples pulverized to standard proportions. For the same reason, pure oxygen was used in the test procedure rather than air. The crossing temperatures were, of course, higher when air was used. A comparison of the crossing temperatures of several anthracite coals using air and oxygen is given in table 5.

APPLICATION OF THE CROSSING-TEMPERATURE METHOD TO A STUDY OF REPRESENTATIVE ANTHRACITES.—After determining the effect of the variables mentioned above upon the crossing temperature or minimum temperature of sustained combustion, the standardized procedure was applied to a study of a number of representative anthracites. An effort was then made to correlate the crossing temperatures found with certain properties commonly determined by means of the usual methods of fuel analysis.

Since it seemed logical that the volatile-matter content might furnish a basis for the comparison of anthracitic coals in connection with the minimum temperature of sustained combustion, the results were first classified in the order of increasing amounts of this constituent. The coals tested, their identity, certain analytical

Table 5.—Effect of oxygen concentration upon the crossing temperature.

COAL No.	CROSSING TEMPERATURE		DIFFERENCE, °C
	Pure Oxygen	Air (20.9 Per Cent Oxygen)	
1	276	340	64
2	379	538	159
5	268	361	93
6	384	546	162

information and the crossing temperatures obtained using the method herein described are given in table 6. The analyses given have been calculated to the "dry, 1.1 × ash-free basis" in order to eliminate the variations in per cent composition due to the mineral matter content. It is evident that the crossing temperature tended to become lower as the volatile-matter content increased, yet no fixed rule could be formulated since many of the results deviated widely from any curve which could be drawn on a plot of volatile-matter content against the crossing temperature. It appeared that the other properties of the anthracites exerted an important and undetermined influence on the oxidation reactions leading to ignition. These deviations existed even when anthracites from the same seam were compared and the results plotted as shown in figures 4 and 5. This was of interest from the standpoint of paleobotanic examination, since the Primrose seam was known to be composed chiefly of attritus or macerated plant tissue debris mixed with spores, leaf-cuticles, and other decay-resistant material, whereas the Mammoth seam was primarily of anthraxylon or bright coalified wood tissue. Descriptions of anthracite coals in terms of these constituents have been given by Turner (25).

An attempt was made to determine more exactly the role of the volatile matter in the initial combustion reactions by testing several samples which had been devolatilized. This devolatilization was accomplished by heating the standard pulverized coal placed in a silica tube to a temperature of 950° C for 75 minutes while a current of nitrogen was swept through the tube. These samples, essentially free of volatile matter, then gave very much higher crossing temperatures, just as was expected. These still bore some relationship to the volatile content of the raw coal, as the treated low-volatile coals gave higher crossing temperatures than the treated coals of higher volatile-matter content. The porosity of the residue after such treatment was directly related to the volatile-matter content. Therefore, the more porous

Table 6.—Comparison of crossing temperature and volatile-matter content. Special samples from survey of seams.

DESCRIPTION OF COAL			DRY, 1.1 × ASH-FREE			SPECIAL GRAVITY AS REC'D	CROSSING TEMPERATURE, °C
Field	District	Seam	Per Cent Volatile Matter	Per Cent Hydrogen	B.t.u. per Lb.		
E. Middle	Black Creek	Mam. Btm.	3.2	2.0	15,020	1.61	390
E. Middle	Black Creek	Wharton Btm.	3.2	2.1	15,060	1.64	354
E. Middle	Black Creek	Buck Mt. Top	3.3	1.9	14,800	1.63	397
South	Panther Creek	Primrose	3.4	1.9	15,000	1.71	391
E. Middle	Black Creek	Wharton Btm.	3.5	2.0	15,000	1.64	371
South	Panther Creek	Primrose	3.5	1.8	15,000	1.62	413
E. Middle	Black Creek	Primrose	3.7	2.2	15,030	1.65	384
South	Panther Creek	Primrose	3.7	2.2	15,050	1.61	375
E. Middle	Black Creek	Buck Mt. Btm.	3.8	2.0	14,950	1.62	372
E. Middle	Black Creek	Primrose	3.9	2.2	15,090	1.64	360
W. Middle	W. Mahanoy	Primrose	4.2	2.4	15,170	1.61	294
W. Middle	W. Mahanoy	Primrose	4.3	2.4	15,190	1.61	315
W. Middle	W. Mahanoy	Mam. Btm.	4.5	2.2	15,000	1.63	333
South	Panther Creek	Primrose	4.6	2.2	15,050	1.64	380
W. Middle	W. Mahanoy	Holmes Top	4.8	2.4	15,080	1.66	342
North	Plymouth	Ross	4.9	2.6	15,050	1.59	312
South	Panther Creek	Mam.	5.3	2.2	15,000	1.67	375
South	W. Schuylkill	Mam. Top	5.5	2.6	15,110	1.60	318
North	Plymouth	Red Ash	5.6	2.5	15,080	1.61	308
North	Carbondale	#4 Dunmore	5.8	2.9	15,150	1.53	276
North	Plymouth	Btm. Ross	5.9	2.6	15,080	1.59	304
South	W. Schuylkill	Primrose	6.0	2.5	15,100	1.64	309
North	Carbondale	Clark	6.0	2.8	15,140	1.57	276
North	Carbondale	New County	6.1	3.3	15,290	1.54	272
North	Wilkes Barre	Top Red Ash	6.5	2.6	15,200	1.67	317
North	Plymouth	Btm. Red Ash	6.5	2.6	15,100	1.60	300
North	Carbondale	14 foot	6.6	3.3	15,300	1.52	281
North	Carbondale	14 Foot Btm.	6.6	3.2	15,290	1.54	286
North	Carbondale	Upper 4 Foot	6.8	3.4	15,330	1.46	255
North	Plymouth	Top Ross	7.1	2.6	15,050	1.62	296
North	Carbondale	Rock Top	7.2	3.2	15,360	1.50	269
North	Carbondale	Rider	7.3	3.2	15,290	1.51	273
W. Middle	Shamokin	Buck Mt.	7.6	3.5	15,450	1.46	293
South	Lykens Val.	Mam. Mid.	7.8	3.4	15,430	1.51	283
North	Carbondale	No. 2	7.9	3.3	15,200	1.56	256
W. Middle	Shamokin	Primrose	8.5	3.6	15,520	1.44	264
South	Lykens Val.	Big Lykens	8.6	3.5	15,300	1.48	279
W. Middle	Shamokin	Holmes	9.0	3.5	15,060	1.56	276
W. Middle	Shamokin	Little Prim.	9.0	3.6	15,320	1.49	246
W. Middle	Shamokin	Diamond	9.1	3.4	15,400	1.51	264
W. Middle	Shamokin	Mam. Btm.	9.4	3.8	15,480	1.49	264
South	Lykens Val.	Big Lykens	9.5	3.8	15,460	1.50	283
W. Middle	Shamokin	Primrose	9.7	3.7	15,520	1.45	286
W. Middle	Shamokin	Mam. Top	9.8	3.8	15,520	1.47	270
W. Middle	Shamokin	Mam. Top	10.0	3.8	15,520	1.49	281
South	Lykens Val.	No. 5	10.0	3.2	15,440	1.55	300

Table 7.—Effect of devolatilization of anthracites upon crossing temperature (standard pulverization).

SAMPLE	SEAM	ORIGINAL VOL.-MATTER CONTENT		CROSSING TEMPERATURE, °C	
		1.1 × ASH-FREE		Original Fuel	Fuel Devolatilized at 950° in N ₂
C	Primrose	3.5		413	435
D	Primrose	3.9		360	417
E	Primrose	4.2		294	412
F	No. 5	10.0		300	395
G	Big Lykens	9.5		283	382
H	Diamond	9.1		264	395
No. 1		4.0		273	416
No. 2		9.2		349	448

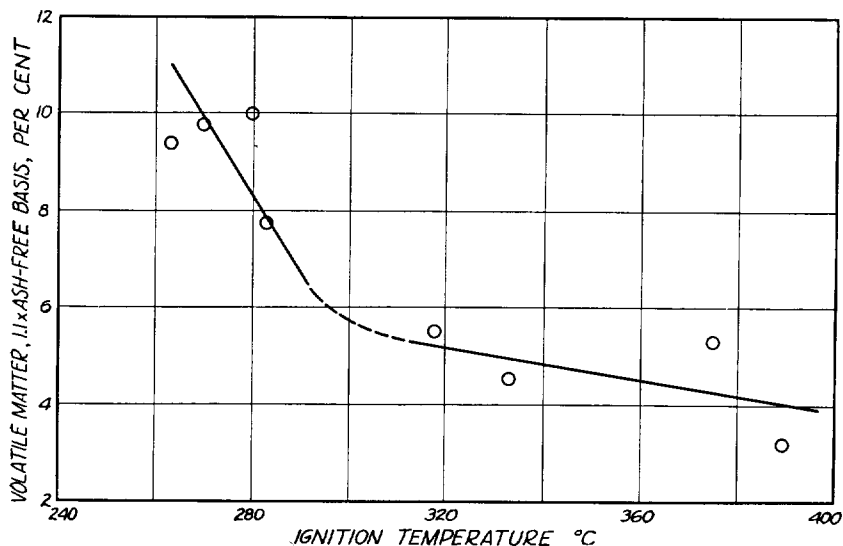


Figure 4.—Ignition temperature *vs.* volatile-matter content of Mammoth seam coals.

residues from the coals of higher volatile-matter content probably had lower crossing temperatures because they presented a larger reaction surface to the oxygen. The results of these tests are shown in table 7.

The effects of devolatilization during combustion in oxygen, however, were found to be complicated by other unknown factors. Table 8 gives a summary of the results of these tests, which were not studied

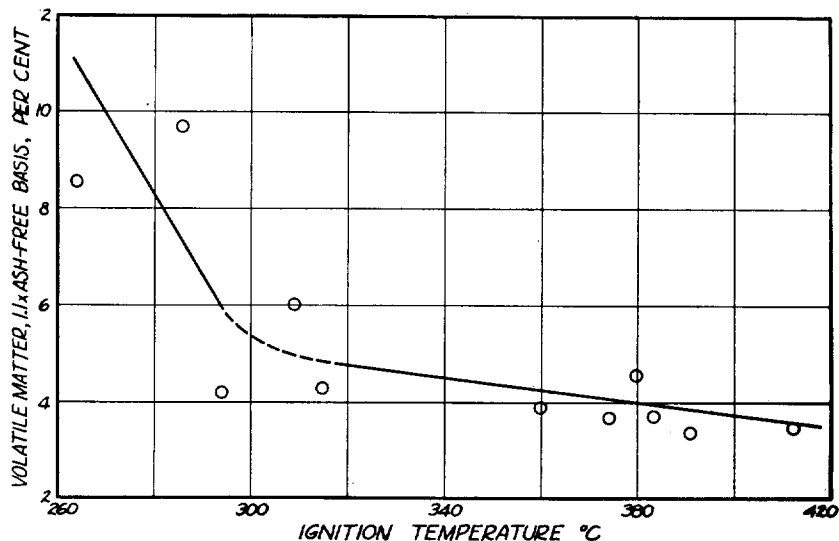


Figure 5.—Ignition temperature *vs.* volatile-matter content of Primrose seam coals.

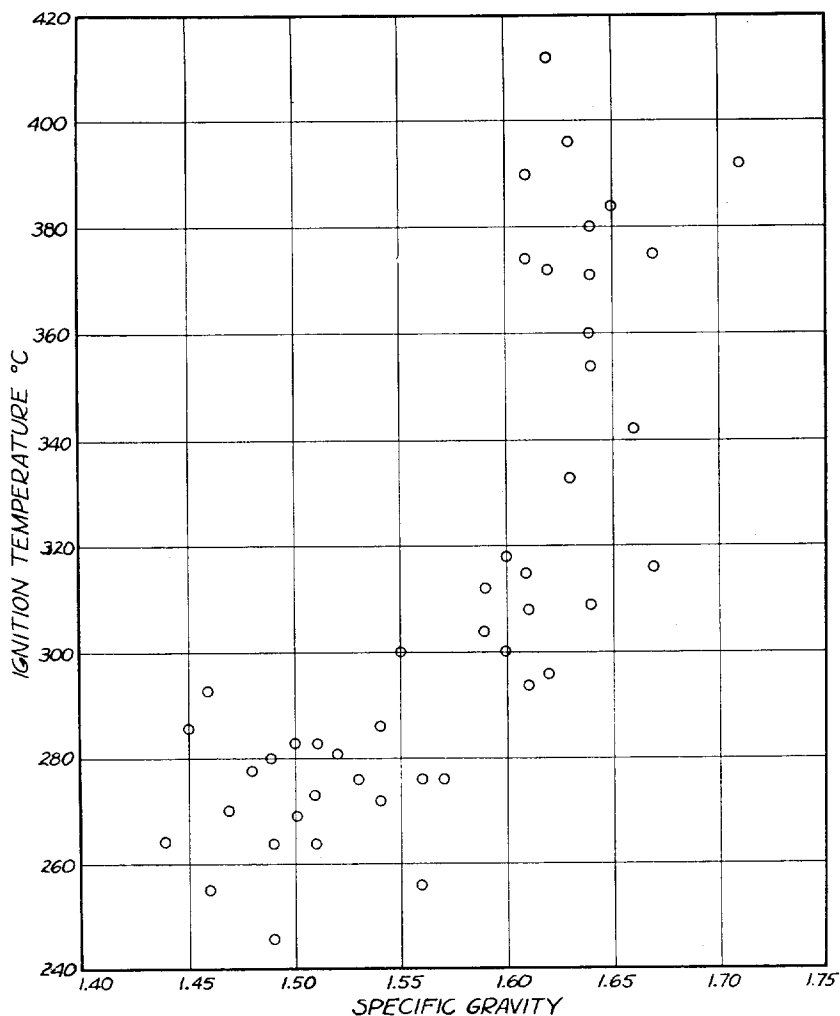
Figure 6.—Ignition temperature *vs.* specific gravity.

Table 8.—Effect of previous ignition of same lump upon crossing temperature, lump samples.

	ANTHRACITE No. 1		ANTHRACITE No. 2	
	Crossing Temp., °C	Difference, °C	Crossing Temp., °C	Difference, °C
First Ignition	458		542	
Second Ignition	430	-28	526	-16
Third Ignition	421	- 9	506	-30
Fourth Ignition	425	4		

further at the time. The tests were made upon solid samples of two anthracites, each of which, after it had passed the crossing temperature and had glowed actively for 4 to 5 seconds, was cooled to room temperature and again subjected to the ignition test. A noticeably lower crossing temperature was found with successive ignitions up to the

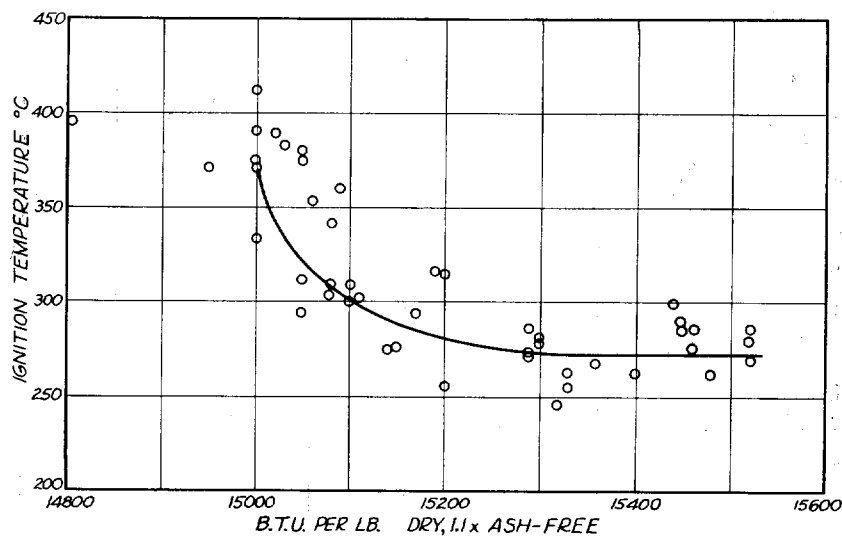


Figure 7.—Ignition temperature vs. calorific value.

third, indicating that previous oxidation rendered these lump anthracites more sensitive to the oxidation reactions.

A general classification of anthracites on the basis of specific gravity and calorific value yielded no definite relation between these properties and the crossing temperature, as will be seen in figures 6 and 7. A general trend was noted, however, for anthracites of higher specific gravity required a higher temperature for the initiation of combustion. Also the anthracites in the order of increasing calorific value showed decreasing crossing temperatures. This was to be expected since the dense, lower calorific value fuels contain less volatile matter and hydrogen, constituents which are known to influence the ignition reactions.

The hydrogen content of the various test samples when plotted against the corresponding crossing temperatures, figure 8, showed only a general trend in the relations between these two variables, much the same type of result being obtained as was found for the volatile-matter content-crossing-temperature plot referred to above. Similar conclusions as to these general relationships have been presented by Hack (11).

CORRELATION OF VOLATILE MATTER AND HYDROGEN CONTENT WITH CROSSING TEMPERATURE.—Because of the predominant effect

of volatile-matter content upon the minimum temperature of sustained combustion, a further attempt was made to correlate these results with the hydrogen content. Since most of the hydrogen of a solid fuel is known to be associated with the volatile matter, this correlation was essentially a comparison of volatile matter composition and crossing temperature for the different anthracites. The results are shown graphically in figure 9, where the per cent volatile matter of each

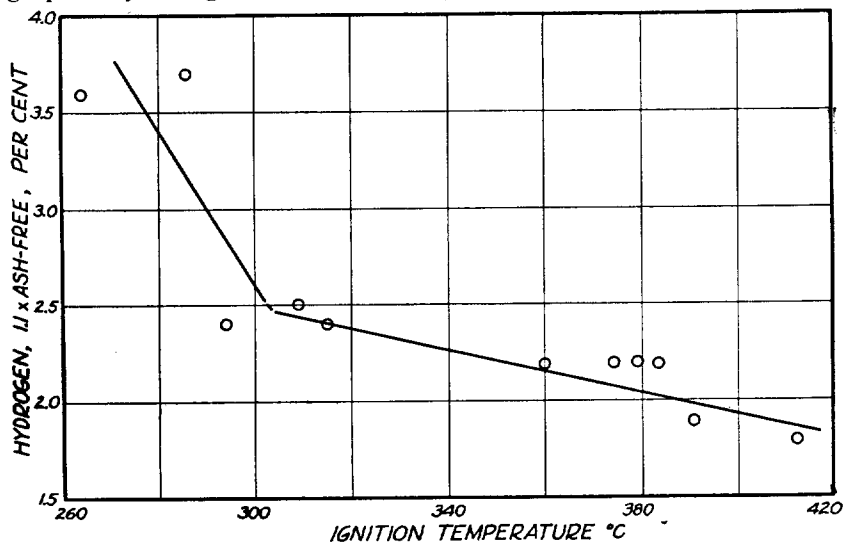


Figure 8.—Ignition temperature vs. hydrogen content of Primrose seam coals.

anthracite tested was plotted against the per cent hydrogen (both corrected to dry, $1.1 \times$ ash-free basis), and the minimum temperature of sustained combustion of each sample was marked beside this point. Lines were drawn between points of equal crossing temperatures, thus permitting coals having the same crossing temperature to be placed in iso-ignition bands. The diagonal lines extending from certain irregular points give consideration to possible errors of analysis. These iso-ignition bands possessed a peculiar curvature and trend over the range of volatile matter and hydrogen content so that the anthracites could be roughly separated into two groups, namely those above 2.6 per cent hydrogen and those below this value. These groups were found to correspond approximately with the free- and hard-burning classes of anthracites which had been differentiated previously by practical combustion experience. Hence, the diagram of bands of iso-ignition temperatures formed a basis for the more definite rule that anthracites with equal amounts of volatile complex compounds of carbon, hydrogen and oxygen, were more sensitive to oxidation and ignition when the proportion of hydrogen was higher.

Deviations of certain samples from this rule might be explained by difference in a third property or constituent such as ash, density, nature of the fuel surface, etc. This effect of a third variable or set of

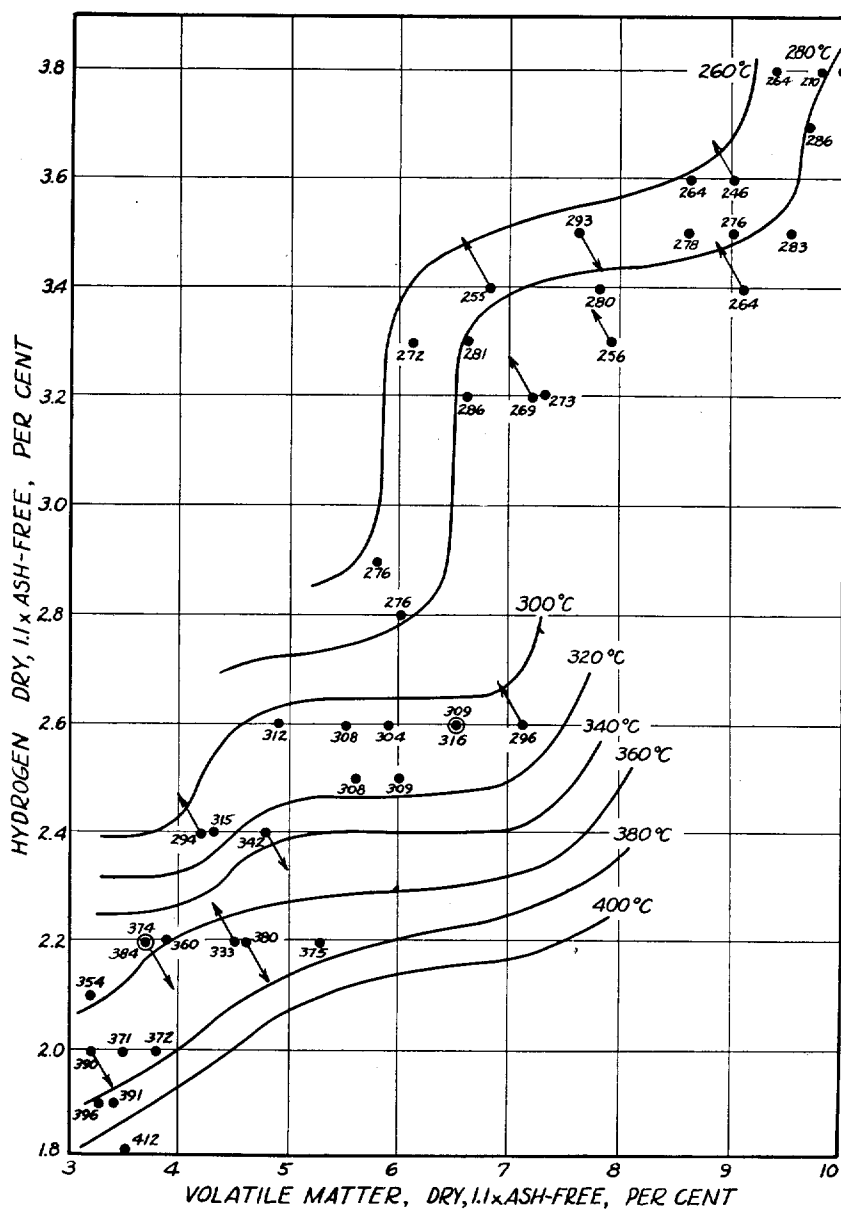


Figure 9.—Iso-ignition bands on a plot of volatile-matter vs. hydrogen content of various anthracites.

variables was not investigated further. Definite conclusions upon this point would require the analysis and testing of a very large number of representative anthracites.

IV. INVESTIGATION OF THE PROPOSED ELECTRICAL-RESISTIVITY METHOD FOR DETERMINING IGNITION TEMPERATURES

In connection with the present study it was decided to investigate the possibilities of the electrical-resistivity method of determining ignition temperatures of anthracite coals proposed by Myer (16). If found feasible, the method would be dependent upon most of the variable factors inherent in the common test methods but would not be dependent upon a criterion of ignition, since, according to Myer, the ignition temperature was clearly indicated by a sharp break in a curve plotted from temperature and resistance readings at definite time intervals.

The method proposed by Myer consisted of placing a 2-gram sample of 20-40 mesh anthracite between two porous metal electrodes fitting closely in a *Pyrex* glass tube. The coal was subjected to a constant pressure between these two electrodes and oxygen was passed up through the bottom electrode, through the coal sample and out of the top electrode. Wires from the two electrodes led to a Wheatstone bridge circuit by means of which resistance measurements were made. The *Pyrex* tube was mounted vertically in an electric furnace equipped with a rheostat which could be manually adjusted for the purpose of controlling the temperature.

When making a test, dried oxygen was passed through the coal sample for five minutes, after which the furnace temperature was raised at a constant rate of 8° C per minute. The resistance bridge was kept balanced, and resistance readings were recorded at minute intervals. A curve plotted between the temperature and resistance readings obtained in this way was found to be a smooth curve with slowly increasing temperature and rapidly decreasing resistance until a sharp break in the curve was obtained where the rate of change of resistance with the temperature suddenly changed to a low value. Myer suggested that the temperature corresponding to this break in the resistance curve might be considered as a basic criterion of the temperature at which ignition occurred in the coal sample being tested. No comparison was made with data obtained by other methods for determining the ignition temperature.

Spicer (22) in an attempt to verify Myer's conclusions and compare the results obtained with those given by other ignition temperature methods, found no break nor discontinuity in the temperature-resistance curve plotted from his data even when the data were plotted on a greatly enlarged scale with the resistance and temperature readings taken every minute during the test. He made runs using an apparatus similar to Myer's, using both solid pieces and standard mesh samples of anthracite. In all cases, the curves plotted from the data were smooth with no sign of a break or discontinuity at any point. A more detailed study of the temperature-resistance method was carried on from this point.

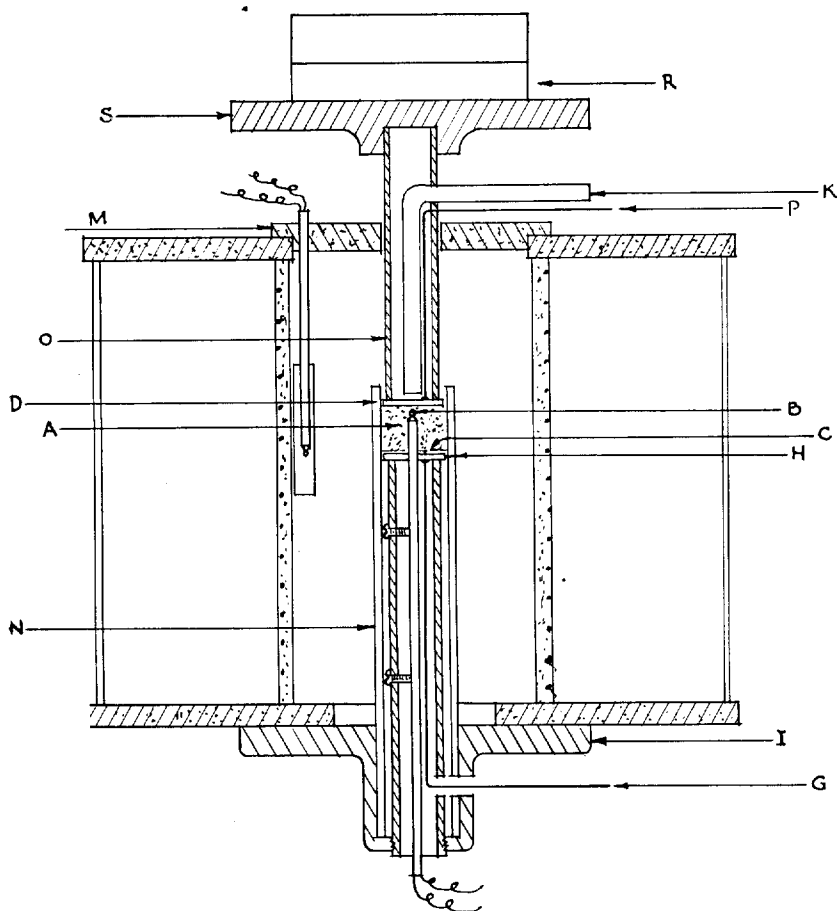


Figure 10.—Apparatus for test of ignition temperature by temperature-resistivity method.

Apparatus and procedure.—A cross-sectional view of the apparatus used is shown in figure 10. It was basically similar to the apparatus used in the study of the minimum temperature of sustained combustion with a few changes as shown. *D* and *H* are perforated metal electrodes between which the coal sample is placed. The top electrode is pressed onto the surface of the coal sample by a metal tube *O*, which is free to move vertically in the top closure sleeve *M*, as the load *R* is placed on the load platform *S*. *K* is the oxygen entry tube which directs the stream of gas onto the perforated electrode and through the holes to the top surface of the coal sample. In several of the experiments the oxygen was passed up through the bottom electrode, through the test sample and out of the top electrode. (In this case, the thermocouple *B* was fixed so as to be at the center of the bottom of the coal charge with the bead close to the bottom surface of the coal.)

The electrode wires *P* and *G* are connected to a Leeds and Northrup Type S testing set for resistance measurements. The bottom support plate *I* bears the weight of the load platform, weights and container, and is rigidly held in the exact center of the furnace by support clamps.

The oxygen was dried and passed through an oil-gauge flow meter at a rate of 200 cc. per minute before being directed onto the top surface of the coal charge. This rate was found to be correct for determining the ignition temperature in the first part of this investigation, although it was considerably less than the flow of oxygen reported by Myer, who used a rate of flow of 180 cc. per second. The position of the coal thermocouple was adjusted so that when the coal was subjected to the pressure of the weights on the platform, the bead of the thermocouple was just covered by the coal particles.

When making a run, a 3-gram sample of anthracite was placed upon the bottom electrode in the alundum tube *N*. The top slide tube was then placed upon the charge and the load platform and weights put in place. The slide tube and top electrode were rotated slightly in order to secure a firm contact with and between the coal particles. Oxygen was then admitted at the prescribed rate, and after a few minutes the electric furnace was turned on. The current was regulated by means of a rheostat so that the temperature of the coal sample was raised uniformly at a rate of 5.5° C per minute, and temperature and resistance measurements were made every five minutes for 30 to 45 minutes and at one-minute intervals thereafter. The run was discontinued when the temperature of the coal sample reached 650° C or more. If a furnace-crossing curve was to be obtained, the run was discontinued following the abrupt and rapid rise in temperature following ignition.

When several of the experiments were made, the sample container was changed so that the oxygen was admitted from the bottom, passing up through the coal charge and out the top electrode. With this modification, the apparatus was essentially similar to the one used by Myer.

For a number of the runs, a composite sample of anthracite was used, the majority of the samples being of two sizes: through 20 on 28-mesh and through 28 on 35-mesh. It was realized that the selection of coal particles of a definite size from a crushed sample would not furnish a true measure of the ignition temperature of the coal as a whole, but since the runs were made solely for purposes of comparing methods of determination these convenient sizes were used. Solid pieces of anthracite also were used.

Experimental results.—When determining the resistance of a sample of screened anthracite, it is evident that the contact resistance between the faces of the individual coal particles will determine the major part of the total resistance of a sample at a given temperature. Consequently, in order to obtain a firm contact between the two electrodes through the coal sample, a steady pressure must be exerted on the electrodes. The effect of varying the weight load on the resistance of particular samples is shown in figures 11 and 12. A solid piece of

anthracite was used in obtaining the curve shown in figure 12 while the composite fraction through 20 on 28-mesh was used for obtaining the data shown in figure 11. The effect of contact resistance is readily apparent, since the weight of coal used in each case was the same. After making these tests it was decided to use a total load of 6 kg. upon the top electrode since this weight was thought to be sufficient to cause the necessary contact between the electrodes. The two lower curves in figure 11 show the effect of increasing the load at tempera-

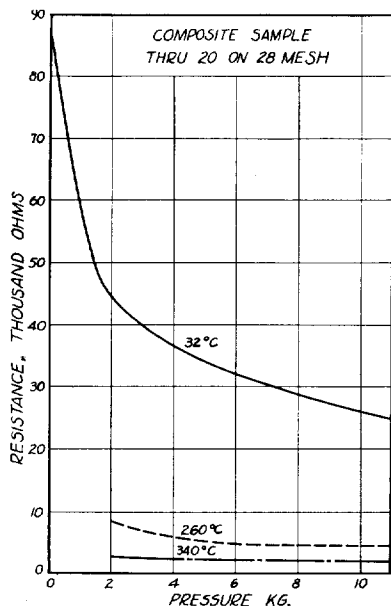


Figure 11.—Effect of pressure on resistance of sized anthracite at various temperatures.

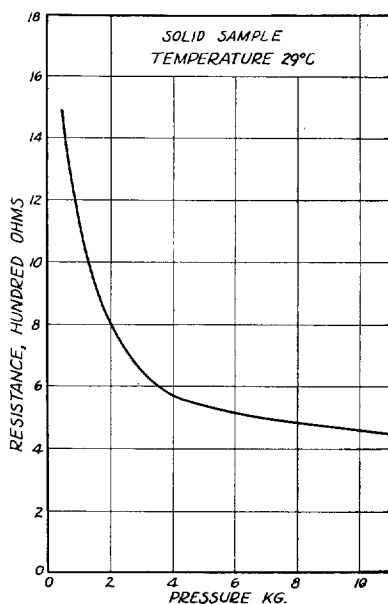


Figure 12.—Effect of pressure on resistance of solid sample of anthracite.

tures above that of the room. At these elevated temperatures the effect of pressure on the resistance readings is noticeably less, the higher temperature showing the lesser effect.

Solid pieces of anthracite were used for the first set of experimental runs. Most of the pieces were cut with the laminations parallel to the contact faces, a few being cut with the ignition surface at right angles to the laminations. When resulting data for these runs were plotted, the curves were all found to be similar to those shown in figure 13. In this figure the curves to the left have resistance values plotted against temperature readings for the duration of the entire run, the individual points being at five-minute intervals. The curves to the right are plotted from the portion of the data at temperatures above 300° C with the resistances plotted on an enlarged scale. In this case the individual points on the curves represent data taken at one-minute intervals. It will be observed that there are no definite breaks in the curves which might be accepted as an indication of an ignition point

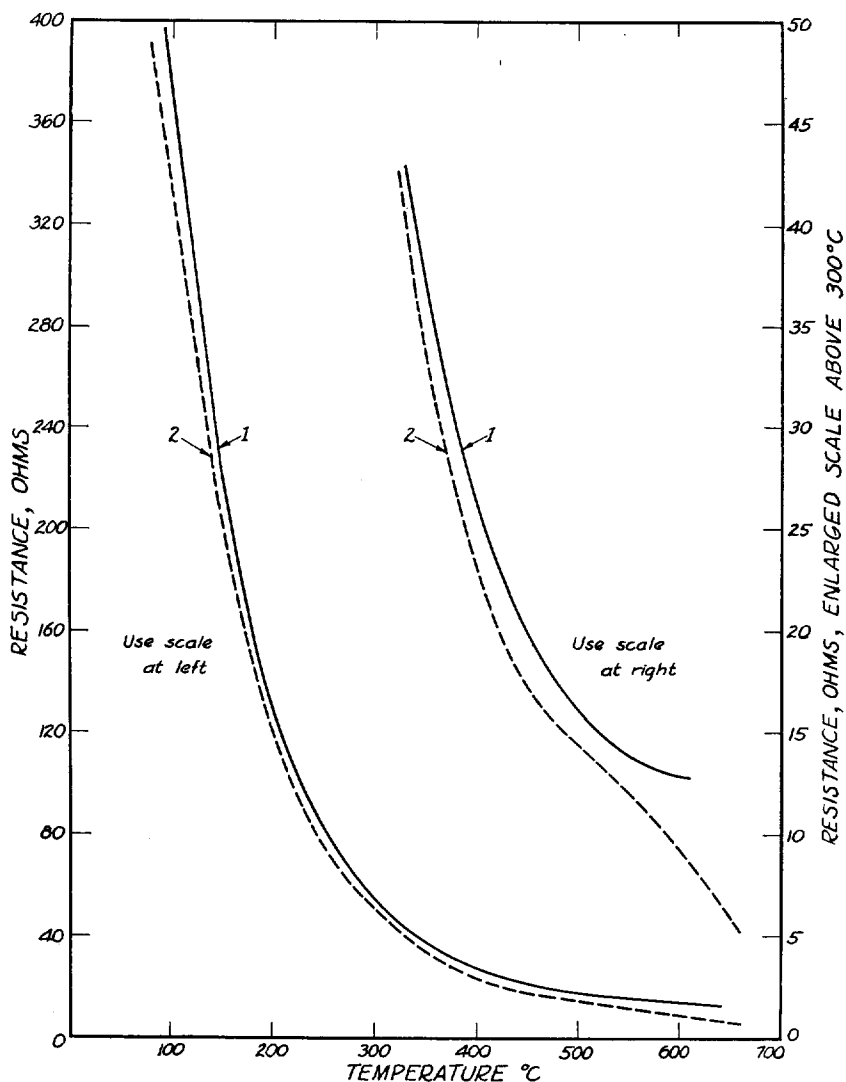


Figure 13.—Temperature-resistance curves for solid pieces of anthracite. (1) Solid sample, laminations perpendicular to face. (2) Solid sample, laminations parallel with face.

or critical temperature such as Myer describes. Upon removal of the test samples from the container, a thin coating of ash over the surface gave evidence that oxidation of the coal had taken place.

The next set of experiments was made with the same apparatus using screened samples of the composite anthracite. Curves representing the data obtained when using samples of through 20 on 28-mesh

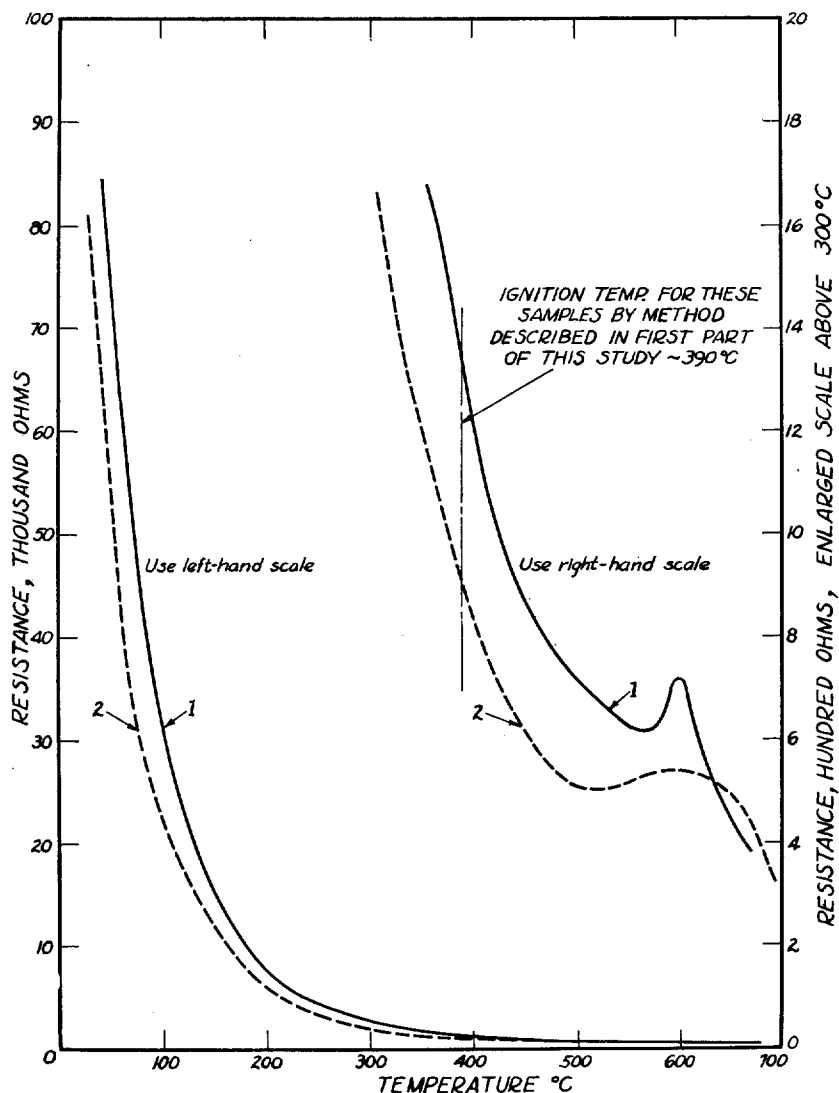


Figure 14.—Temperature-resistance curves for composite anthracite samples, through 20 on 28-mesh.

coal are shown in figure 14. In this case it will be observed that the rate of change of the resistance with increasing temperature decreased gradually to a zero value after which the resistance increased for a time and again decreased as the temperature was raised further. The same phenomenon was noticed in eight or more runs using the screened fraction of coal but the significance of the upward swing of the curve

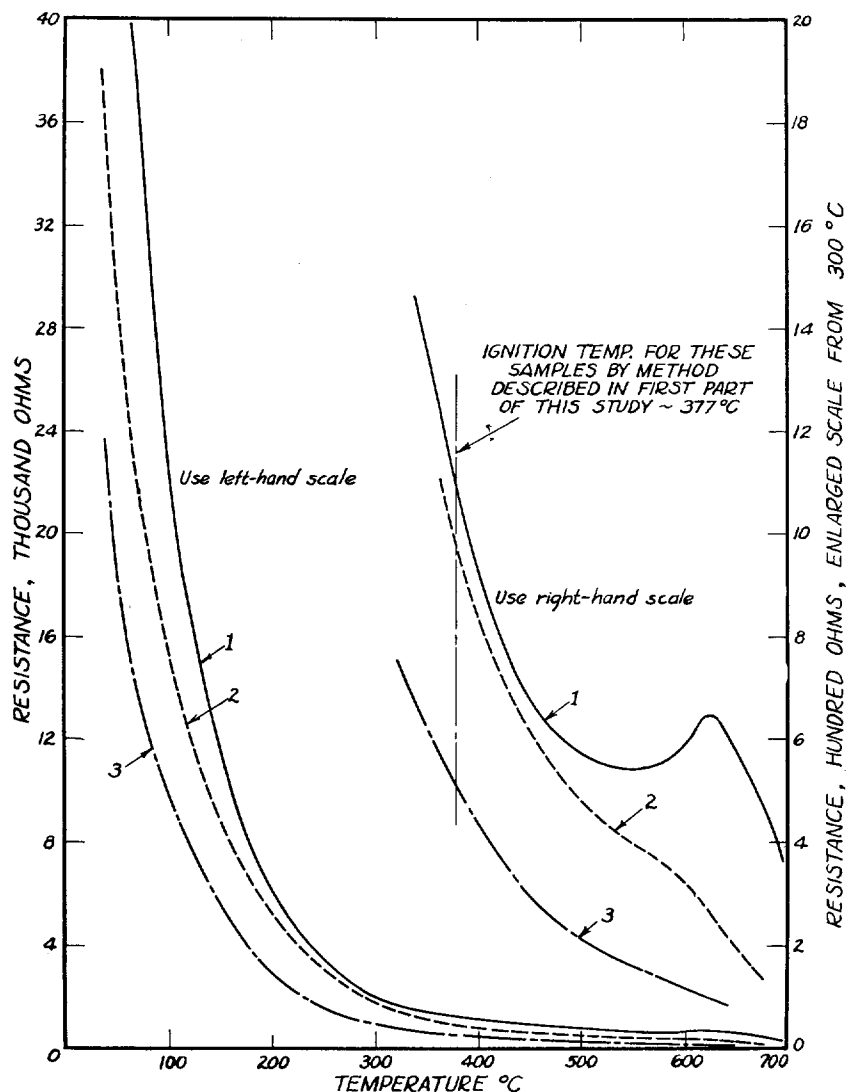


Figure 15.—Temperature-resistance curves for composite anthracite samples, through 20 on 28-mesh, with atmosphere of oxygen and nitrogen. (1) Oxygen, 200 cc. per minute. (2) No oxygen flowing; air only in tube. (3) Nitrogen, 200 cc. per minute.

could not be correlated with a factor such as the ignition temperature. The ignition temperature of this screened sample as determined by the method proposed in the first part of this investigation was found to be 390° C. At or near this temperature there is no indication of a break in the curve for any set of the plotted data.

Similar results were obtained using samples of through 28 on 35-

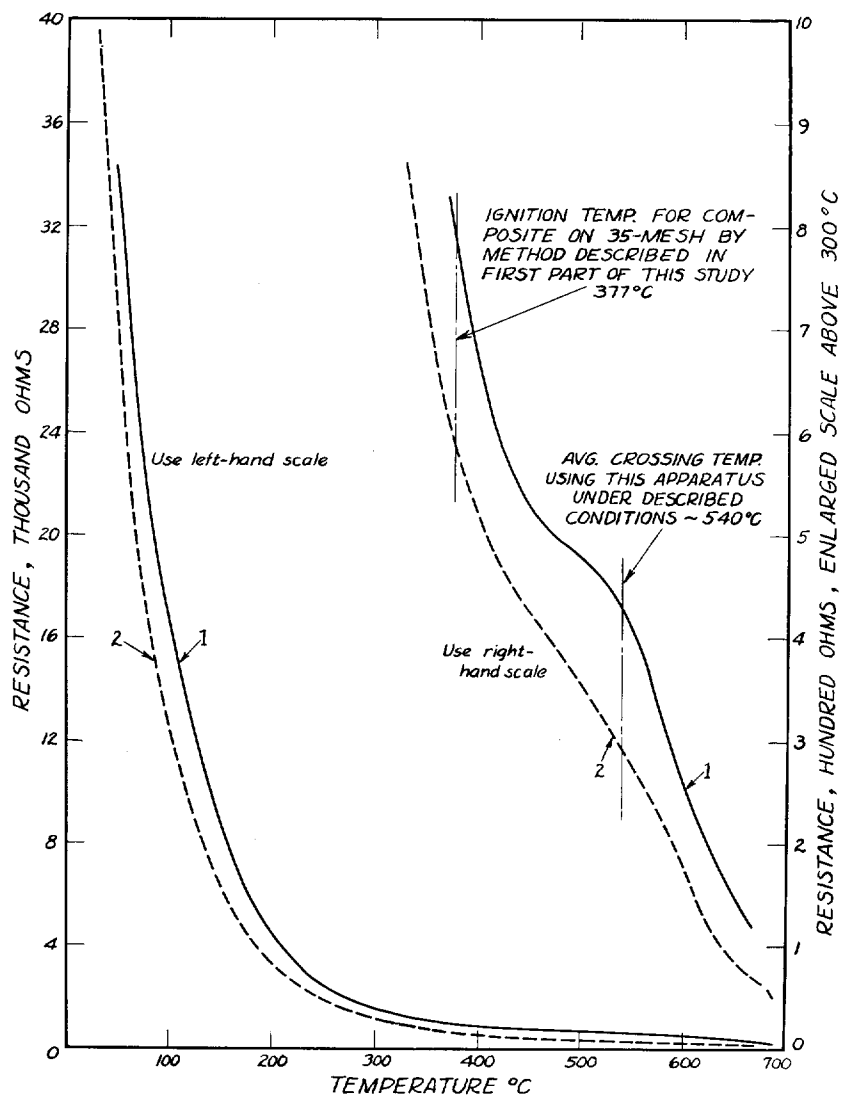


Figure 16.—Temperature-resistance curves for composite anthracite samples, through 28 on 35-mesh.

mesh composite anthracite. A curve has been plotted from the data of a typical run and is shown as curve (1) in figure 15. Again the minimum in the curve can be seen with a subsequent increase and decrease in the resistance. Curve (2) represents data from a run using the same mesh coal with no oxygen flowing over the test sample. The only oxygen present came from the air present in the sample container and

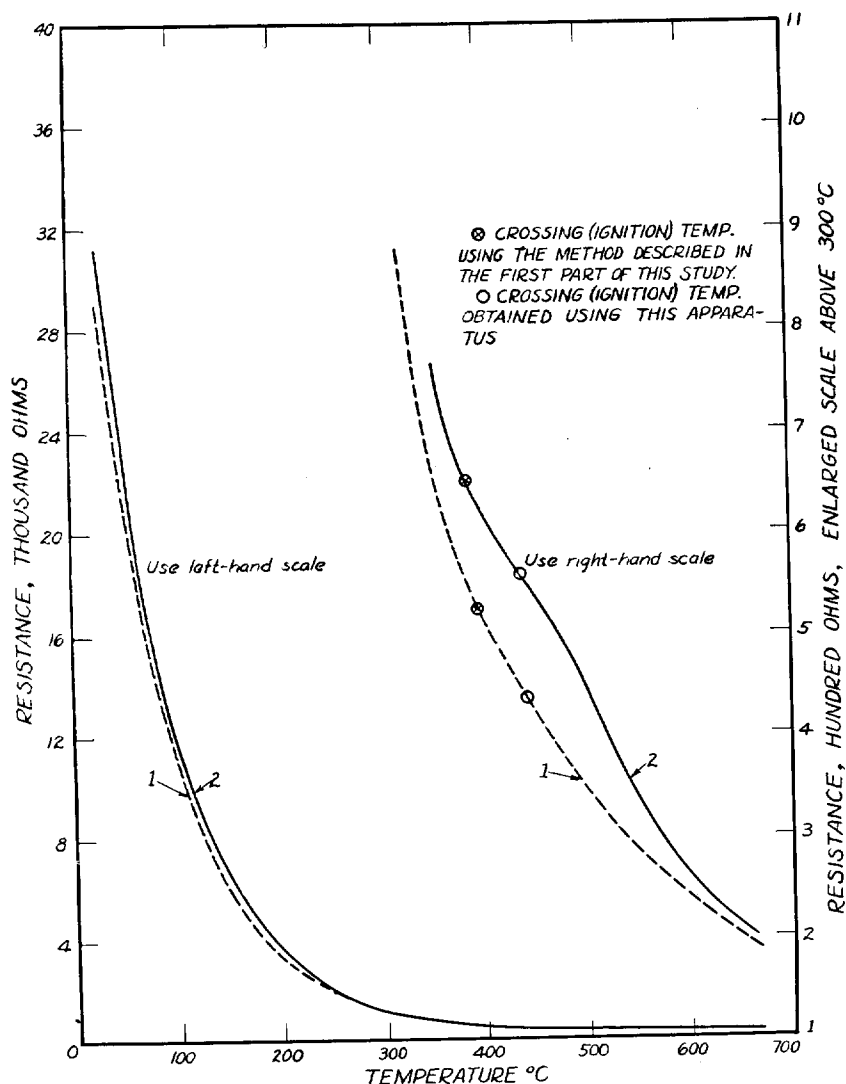


Figure 17.—Temperature-resistance curves for composite anthracite samples, modified apparatus with oxygen entering from below. (1) Sample, through 20 on 28-mesh. (2) Sample, through 28 on 35-mesh.

that which filtered through to the charge. Curve (3) was plotted from data obtained in the usual manner using a flow of nitrogen of 200 cc. per minute instead of oxygen. Curve (2) shows a very small change in rate of resistance drop while curve (3) is a smooth curve with a more or less uniform resistance change. These curves, when considered together, would seem to indicate that the resistance changes taking

place in the neighborhood of 540°C are a result of oxidation of the coal but these changes do not seem to be connected with the ignition temperature of 377°C found for this screen fraction using the method described in the first part of this paper.

A number of experimental runs were made several months later in order to check the results of the runs referred to above. The same apparatus and original coal sample were used (composite anthracite, through 28 on 35-mesh). Curves plotted from data of representative runs were shown in figure 16. In this instance it may be seen that the rate of change of resistance does not decrease to a zero value followed by an upward swing in resistance values as the temperature is increased. The platform load, oxygen flow, rate of rise of the temperature, size and weight of the sample, position of the coal thermocouple and all other factors conceivably affecting the results of the tests were kept the same as in the case of the first series of runs. When making these runs the furnace temperature was recorded and the ignition temperature found by means of the furnace-crossing method. An average ignition temperature using this apparatus was found to be 540°C , a very high value when compared to the ignition temperature of 377°C found for this sample using the method described in the first part of this report. Again it will be seen, however, that there is no sharp break in the resistance curve which could be used as an index of the ignition temperature.

The apparatus was then modified slightly so that the oxygen entered from below and passed up through the perforated electrodes and the coal sample. A circular piece of fine nickel gauze *C* was placed over the bottom perforated electrode so as to prevent particles of the coal from obstructing the holes through which the oxygen was passed. The apparatus was made to resemble Myer's as closely as possible. All experimental conditions with the exception of the direction of flow of oxygen were the same as in the previous runs.

Experimental runs were then made with this apparatus, using several sized fractions of the composite anthracite. The curves plotted from the results of two of the runs are shown in figure 17. Curve 1 was plotted from data obtained from a run using through 20 on 28-mesh coal while curve 2 represents data of a run using through 28 on 35-mesh coal. No minimum in the temperature-resistance curves was found in these cases. The ignition temperature (furnace-crossing method) was determined in each case concurrently with the temperature and resistance readings and was found to be an average value of 437°C for the on-35-mesh coal and 448°C for the on-28-mesh coal. These values are a little more than 100 degrees higher than the values obtained for the respective screen sizes by the method proposed in the first part of this study, which illustrates the importance of external test conditions in any determination of the ignition temperature. Hence, using this apparatus with the conditions external to the test sample being what they were, if a break in the resistance curve is to be observed it should occur at approximately 440°C for the on-35-mesh coal and 450°C for the on-28-mesh coal, since these temperatures are the points at which the rapid oxidation reactions have made some

progress. The temperature of the coal was increased very rapidly in the few minutes after the crossing temperature had been reached, but from the resistance readings there is no indication of ignition having occurred.

V. SUMMARY

Studies of the oxidation of anthracite in the temperature range at which the reactions are rapidly accelerated to active combustion have led to the following results and conclusions:

(1) A method and apparatus were developed which were useful in determining the minimum temperature of sustained combustion of fuels of the anthracitic type.

(2) The method was applied in a comparative study of 50 samples of anthracite, representative of the important producing seams of the whole region.

(3) Comparison of temperature of sustained combustion with certain properties of these anthracites showed that no fixed relationship existed and that a number of other variables complicated the oxidation reaction.

(4) When the volatile matter of each sample was plotted against the hydrogen content and the points thus defined were grouped into regions of equal crossing temperatures by drawing boundary lines, a series of iso-ignition bands resulted. The peculiar curvature and trend of these bands permitted a separation of these anthracites into two groups, corresponding to the free- and hard-burning anthracites differentiated in combustion practice.

(5) The temperature-resistance measurements were found to be of no value for determining the ignition temperature of anthracite.

(6) In no case was there found a break in the temperature-resistance curve corresponding to the sharp break found by the author of the proposed method in his investigation.

(7) The explanation given by Myer for the distinct break which he obtained in the temperature-resistance curve is that a much lower resistance drop is prevented at that point by the rapid formation of an ash which has a high resistance. In many of the runs described in the latter part of this paper, ignition is known to have occurred since ignition temperatures by the furnace-crossing method were made and some ash was found to be present at the completion of the run. In spite of ignition having occurred, the resistance values did not react in any manner whereby a definite point could be picked as the ignition temperature. It is unlikely that the small quantity of ash formed after the ignition temperature has been known to have been reached would affect the resistance readings sufficiently to show a definite effect.

VI. BIBLIOGRAPHY

- (1) Arms, R. W., "Ignition Temperature of Coals," Univ. Illinois Eng. Exp. Sta. Bull. **128** (1922).
- (2) Berl, E., and Weingartner, E., "Über Entzündungspunkte von Aktiven Kohlen," Z. Physik. Chem., (A), **161**, 315 (1922).
- (3) Boegehold, A. L., "Quality of Pig Iron and Castings as Affected by Blast Furnace Practice," Foundrymen's Assoc., **37**, 91 (1929).

- (4) **Brown, C. R.**, "The Determination of the Ignition Temperatures of Solid Materials," *Fuel*, **14**, 14, 56, 80, 112, 149, 173 (1935).
- (5) **Bunte, K.**, "Zündpunkte und Reaktionsfähigkeiten von Verkokungsprodukten," *Gas- und Wasserfach*, **69**, 192, 217 (1926); *Z. angew. Chemie*, **39**, 132 (1926).
- (6) **Davis, J. D.**, and Byrne, J. F., "An Adiabatic Method for Studying Spontaneous Heating of Coal," *J. Am. Ceram. Soc.*, **7**, 809 (1924). Also see *Ind. Eng. Chem.*, **17**, 125 (1925); **18**, 233 (1926).
- (7) **Davis, J. D.**, and Reynolds, D. A., "Spontaneous Heating of Coal," *U. S. Bur. Mines Tech. Paper*, **409** (1928).
- (8) **Dennstadt, M.**, and Schaper, L., "Die Gefahren der Steinkohle, III. Die Beurteilung der Selbstentzündlichkeit," *Z. angew. Chemie*, **25**, 2625 (1912).
- (9) **Eaton, W. C.**, Brady, G. A., Gauger, A. W., Lavine, I., and Mann, C. A., "Critical Oxidation Temperature of Lignite," *Ind. Eng. Chem.*, **23**, 87 (1931).
- (10) **Griffen, H. K.**, Reed, D. L., and Hargen, F. A., "Relative Ignitibilities and Ease of Flame Propagation of Powdered Coal and Semi-coke," *U. S. Bur. Mines—Carnegie Tech. Bull.*, **50** (1931).
- (11) **Hack, W.**, "Relation between Swelling Point and Ignition Point of Coal," *Brennstoff-Chemie*, **13**, 361 (1932).
- (12) **Kreulen, D. J. W.**, "Ein neuer Apparat zur Bestimmung der Neigung zur Selbstentzündlichkeit von Steinkohlen und andern Stoffen," *Brennstoff-Chemie*, **11**, 261 (1930). Also see *Brennstoff-Chemie*, **12**, 107 (1931); *Fuel*, **5**, 345 (1926); **13**, 55 (1934).
- (13) **Lange, T.**, "Ignition Temperature of Coal Dust," *Z. oberschles. berghüttenmänn. Ver.*, **67**, 630, 688 (1928).
- (14) **Masson, H. J.**, and Hamilton, W. F., "Auto-Ignition Temperatures," *Ind. Eng. Chem.*, **19**, 1335 (1927).
- (15) **Moore, B.**, "The Behavior of Solid Fuels during Oxidation," *Fuel*, **10**, 205, 344, 394 (1931); **11**, 267 (1932).
- (16) **Myer, J. L.**, "Proposed Method for Determining the Oxidation Temperature of Anthracite," *Trans. Am. Inst. Mining Met. Engrs., Coal Division*, **101**, 215 (1932).
- (17) **Parr, S. W.**, and Coons, C. C., "Carbon Dioxide as an Index of the Critical Oxidation Temperature for Coal in Storage," *Ind. Eng. Chem.*, **17**, 118 (1925).
- (18) **Parr, S. W.**, and Staley, W. D., "Reactivity of Coke," *Ind. Eng. Chem.*, **19**, 820 (1927).
- (19) **Rosin, P.**, Fehling, R., and Kayser, H. G., "Die Zündung Fester Brennstoffe auf dem Rost," *Arch. Wärmewirt.*, **12**, 97 (1931).
- (20) **Schaper, L.**, "Zur Prüfung auf Selbstentzündlichkeit," *Chem. Zeit.*, **43**, 401 (1919).
- (21) **Sinnatt, F. S.**, and Moore, B., "Ignition of Solid Fuels," *Fuel*, **4**, 194 (1925); **5**, 377, 557 (1926).
- (22) **Spicer, T. S.**, "Temperature-Resistivity Curves of Anthracite," Unpublished Senior Thesis, Department of Fuel Technology, The Pennsylvania State College.
- (23) **Steinbrecher, H.**, "Die Selbstentzündungstemperaturen des Kohlenstaubes," *Braunkohle*, **25**, 937 (1927).
- (24) **Swietoslawski, W.**, Roga, B., and Chorazy, M., "Research on the Inflammation Temperatures of Solid Fuels," *Fuel*, **9**, 93 (1930).
- (25) **Turner, H. G.**, "Constitution and Nature of Pennsylvania Anthracite with Comparison to Bituminous Coal," *Trans. Am. Inst. Mining Met. Engrs., Coal Division*, 1930: 627; *Fuel*, **11**, 254 (1932).
- (26) **Wheeler, R. V.**, "Oxidation and Ignition of Coal," *J. Chem. Soc.*, **113**, 945 (1918); *Fuel*, **3**, 366 (1924).
- (27) **Winmill, T. F.**, "The Absorption of Oxygen by Coal. VI. The Rate of Spontaneous Heating of Coal," *Trans. Inst. Min. Eng. (London)*, **48**, 535 (1914-15).