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THE IGNITION TEMPERATURE OF COAL

BY

RAY W. ARMS

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REPLACING

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1. *Outline of Work.*—There is no definite temperature at which coal bursts into flame. The phenomenon of flame from coal is due to the combustion of volatile matter driven off from the coal, the character of such matter varying under different conditions; hence, the temperature at which the coal flames varies widely and is dependent upon surrounding conditions, and therefore the flaming temperature of a coal does not serve as an indication of the ignition point. Strictly speaking, it is the true ignition point, but since it varies so widely its evaluation is meaningless. Moreover, any definition of ignition temperature based on the spontaneous emission of heat from coal is equally unsatisfactory, because experiments have proved that coal is giving off heat of combustion or some phenomenon akin to combustion at all temperatures. To be sure, the combustion at low temperatures is slow, but it is nevertheless evident. As the coal is raised in temperature by an outside source of heat it produces more and more heat from its own combustion, but there is no point in this process where the change in rate of heating is sufficiently abrupt to be regarded as indicating a definite ignition temperature.

The first purpose of this investigation, therefore, was to establish some definite point along the line of this process of heating which could be called the ignition temperature. In the effort to locate such a temperature heating curves were drawn to show the rate at which the coal increased in temperature when assisted by an outside source of heat. After a study of these curves the point at which the coal assumed a uniform glow was chosen as the most logical ignition temperature, not only because this point was found to be rather definite in the heating curve, but also because it could be checked in various types of apparatus by different means of temperature measurement and control, and by different operators.

With this glow point chosen as the ignition temperature the method for the determination became comparatively simple. The sample of coal was heated gradually in a normal air supply until the glow appeared, the temperature of the coal itself being measured by means of a thermocouple. The furnace was shielded from air currents, but sufficient opening was left in the shields to provide an adequate air supply for the combustion of the coal. This apparently crude method is open to many objections, but it is surprising how closely the results can be made to check. Out of thirty runs by this method on the same coal, twenty-four agreed within ten degrees.

The accuracy of the method was next tested by experiment on several representative coals. Among the samples tried were bituminous coal, coke, anthracite, and lignite. The values for the glow points of these coals are shown in the following table:

TABLE 1

VALUES OF GLOW POINTS FOR DIFFERENT COALS

Kind of Coal	District	Glow Point	
		Deg. C.	Deg. F.
Bituminous	Georgetown, Ill.	456	853
Bituminous	Bennett Station, Ill.	496	925
Bituminous	Herrin, Ill.	440	824
Lignite	Manitoba	526	979
Semi-bituminous	Castle Gate, Utah	528	982
Anthracite	Pennsylvania	600	1112
Coke		606	1123

2. *Influence of Various Factors on Ignition.*—Finally an attempt was made to determine the influence of various factors such as ash, moisture, sulphur, size of particles, air supply, etc., upon the temperature of ignition. The results of this work may be briefly summarized as follows:

Ash

The amount of ash present in the coal has no apparent influence on the temperature of the glow point. The ash influences the distribution of heat throughout a mass of coal and may change the time required to bring the coal up to a definite temperature, but, the proper temperature once reached, the coal will glow no matter what the ash content may be.

Moisture

Moisture has a great deal to do with the rate at which the coal is heated up to the point where it will burn, consequently with the shape of the heating curve; but, as the moisture is driven off before the glow point is approached, the actual temperature of the glow point can in nowise be affected by the quantity of moisture present.

Size of Particles

The glow point for all sizes of coal is the same, but in the process of determining this fact some difficulty was experienced in observing the glow points on the fine sizes. The air passages through finer mesh coal are so confined that the interior of such coal is not reached by the air. Furthermore, as its temperature rises, a pile of fine coal begins to cake on the surface, forming a crust that interferes still more with the passage of air to the interior. This made it rather difficult to determine the glow point of fine coal, but the results obtained indicate that there is no difference between its glow point and that of coarser sizes.

Quantity of Air

Glowing of coal is a form of combustion which requires oxygen, but the actual temperature of the glow point is independent of the quantity of oxygen supplied. Obviously, if the coal were heated in an atmosphere devoid of oxygen it would not glow at all, but would undergo destructive distillation. On the other hand, if an atmosphere of pure oxygen were supplied, the rapidity of the combustion would be increased but the temperature of the glow point itself would not be altered.

Sulphur

Separate runs were made on pure pyrite in the effort to determine its ignition temperature, which was found to depend much on its rate of heating. If heated very slowly practically all the sulphur can be driven off in the form of SO_2 without producing any visible flame. If the rate of heating is increased, a blue flame appears at a comparatively low temperature. Unquestionably, therefore, the combustion of sulphur adds to the mass of coal a heat which slightly increases the tendency of this coal to fire, but, as the heat of combustion of sulphur and the percentage of pyritic sulphur present are comparatively low, the total effect of sulphur on the tendency of coal to fire is relatively small.* The experiments appeared to indicate that the presence of pyrite does not alter the glow point of the coal substance itself, but that its only effect is to add its heat of combustion to that of the coal.

Rate of Heating

Coal has a comparatively low heat conductivity, so that, in order to insure a uniform distribution of the heat throughout the sample, external heat must be applied slowly. If the sample is heated too rapidly it will burst into flame before the glow point is reached, due to the ignition at the edge of the pile of small pieces of coal which are at a higher temperature than the average of the pile itself. The best results in the present experiments were obtained when the sample was heated up to the glow point in about twenty minutes' time.

Volatile Products

The ignition points of the various gases volatilized from coal during distillation are fairly well known. In all cases the ignition points of these gases are higher than the glow point of the coal, so that no flame should be observed before the glow point is reached. However, if even a very small particle of coal is heated above the ignition temperature of any of the gases, a flame will result. Thus, in order to successfully determine the temperature of the glow point, it is first necessary to drive off most of the volatile products.

Residual Carbon

It is a well-known fact that various forms of carbon differ in the ease with which they may be ignited. Beyond a doubt the character of the carbon or coke resulting from the partial distillation of the coal has more to do with the temperature of the glow point than any other single factor. The exact reason for this was not determined, nor was any attempt made to differentiate the forms of carbon or coke resulting from various coals tested. Furthermore, when a coal starts to glow it is not yet completely coked. Samples of coal quenched at the glow point show that the individual particles have lost their angular shape and are only partly cemented together.

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* "The Spontaneous Combustion of Coal." Univ. of Ill. Eng. Exp. Sta., Bul. 46, 1910.

3. *Acknowledgments.*—The author wishes to express his appreciation of the manner in which MR. FRANK STAMBERG carried on the work of the investigation in the laboratory. Several of the samples of coal were furnished by PROFESSOR S. W. PARR of the Department of Chemistry of the University of Illinois, who also made valuable suggestions both regarding method of procedure and interpretation of results. PROFESSOR H. H. STOEK of the Department of Mining Engineering of the University of Illinois also furnished many helpful suggestions, and it was through his encouragement and assistance that the work progressed.

The work was done in the laboratory of the Department of Mining Engineering of the University of Illinois.

II. Ignition Temperature

4. *General Significance.*—Under ordinary conditions the ignition temperature of a fuel is less important than the maintenance of combustion. No matter how large the mass of fuel may be, whether it is in a blast furnace, under a boiler, or in an ordinary household furnace, the origin of the heat necessary to raise this fuel to the ignition temperature is in the kindling which starts the fire. The flame of the match which ignites the kindling is at a much higher temperature than the ignition point of the coal; hence, the starting of an ordinary fire is a process depending upon the application of an outside source of heat, always at high temperature, to some portion of the mass of coal until a part of the coal itself burns and propagates heat to the remainder. At some time during this process the outside source of heat may be removed as, for example, when the kindling is completely burned. At all times during this process there is a zone of heat production at a temperature well above the ignition point. Whether this source of outside heat is in the form of kindling or in a form similar to the heat in the walls of a coke oven, it is only necessary to supply the heat until a certain part of the coal is burning and raising the temperature of the rest of the mass by its own combustion.

It is possible that the ignition temperatutre of fuel might assume a greater significance than this in connection with problems involving burning of pulverized coal. For example in the cement industry, where pulverized coal is used largely for heating the kilns, trouble is sometimes experienced when the supply of coal is temporarily cut off and the kiln allowed to cool. In resuming the supplying of coal to the cooled kiln, an explosive atmosphere, apt to cause damage, is sometimes produced. It is suggested that this may be prevented by supplying temporarily a fuel with a lower ignition temperature.

It is, however, in connection with the storing of coal in piles that the ignition temperature takes on a real significance. According to Professor S. W. Parr* and others, coal is actually burning at all times and

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* "The Spontaneous Combustion of Coal." Univ. of Ill. Eng. Exp. Sta., Bul. 46, p. 50, 1910.

even at low temperatures. If the heat thus produced is sufficiently confined and air is supplied to the coal at the proper rate, the temperature of the interior of the mass will rise. As the temperature rises the rate of combustion also rises, and, after a certain safe temperature is passed, the process goes on quite rapidly until burning or flame results.

One of the original objects of this investigation was to determine the influence of the temperature of ignition of the various coals upon their liability to fire while in storage. At first thought it would seem that the ignition point would have a very important bearing on the tendency to fire. As a matter of fact, however, the glow points determined, with a few notable exceptions, bear no relation to the liability to fire. The same is true if some point on the heating curve other than the glow point is assumed to be the temperature of ignition. For example, the point at which the coal burns with a blue flame is a rather definite point which shows some variation with different coals; but even this variation bears no relation to the liability of the coal to fire.

However, these results are not in any sense conclusive, since several factors known to affect the firing qualities were not considered. For example, Wheeler has found* that the relative ignition temperature of coal depends upon the total oxygen content. Furthermore, experience shows that after coal has been stored for a certain time it becomes more or less immune from firing. Neither the oxygen content of the coal nor the time elapsed since it was mined was considered in the present experiments.

The temperature at which coal bursts into a yellow flame depends so much upon the rate of heating and other conditions, and varies so widely, that it is impossible to establish any quantitative relationship between it and the firing qualities of the coal.

The rate of heating or the shape of the heating curve of various coals differs widely, and this rate is far more important than any temperature which may be chosen as the ignition temperature. The shape of this heating curve is influenced by the volatile matter present, percentage of ash, moisture, sulphur, and oxygen, the air supply, the form of carbon in the partially coked residue, the size of the sample, and, perhaps, by other factors.

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* See Table 7.

5. *Discussion of Ignition Temperature.*—In order to arrive at any satisfactory conclusion regarding the ignition point, some idea must first be obtained as to how ''ignition temperature'' may be defined.

At first thought it would seem that ignition point is the temperature at which self-heating begins and is maintained, but this, in the case of coal, seems to be a very indefinite point.

In the words of Wheeler:*

> ''If one adopts the generally accepted definition of Ignition Temperature as applied to gaseous mixtures, (that is, the temperature at which self-heating of the mixture begins to take place) the ignition temperature of most coals is the normal atmospheric temperature.
>
> ''A distinction between one coal and another could, no doubt, be made by determining the time taken for this self-heating from atmospheric temperature to result in flame under standard conditions.
>
> ''It may also be of value to know at what temperature a given coal must be heated in air, under specific conditions, in order that it shall burst into flame, and this temperature may, perhaps, be regarded as the 'ignition temperature,' the preliminary self-heating (corresponding with the 'fire-flame period' with gases) being ignored. Experimental difficulties, however, stand in the way, both of determining accurately the moment when flame appears in a mass of coal, and of ensuring that in a comparative test with different coals all the factors, on which the appearance of flame depends, are maintained constant.
>
> ''From a practical, as well as a theoretical point of view, it is sufficient to know at what temperature, under standard conditions, different coals begin to react with oxygen so rapidly that the ultimate appearance of flame is assured.''

Again J. F. Cosgrove† states that the ignition temperature of coal ''is, of course, the temperature of ignition for the fixed carbon of the coal, because the gases are roasted out of the coal before the coke burns.''

J. S. S. Brame in his book on ''Fuels'' discusses the matter as follows:

> ''For active combustion to be initiated, a definite temperature, at least, must be maintained. The ignition point of all substances occurs no doubt at a

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* "The Oxidation and Ignition of Coal." Jour. Chem. Soc., Vol. 113, p. 949, 1918.

† "Coal, Its Economical and Smokeless Combustion."

fixed temperature, but many conditions influence the ease with which the combustion may be started, mass and fineness of division being the most important. While a given coal, in a finely divided condition, may ignite at a low temperature, a lump of the same coal will require considerable heating before it will take fire, due to the smaller surface exposed to the air in proportion to the mass, which carries away the heat.''

F. H. Sinnatt and Burrows Moore* give the following definition: ''Temperature of ignition in oxygen is defined as that temperature to which fuel must be raised for its ignition to take place without the aid of external agents of inflammation.'' In this definition, as in some of the others, the temperature to which the coal is heated is used as the ignition point, but no account is taken of the heat due to the coal itself burning. In the experiments carried on by Sinnatt and Moore the time required to heat the samples of coal to glowing, flaming, and exploding temperatures was recorded, but in all cases these temperatures applied to the external source of heat and not to the temperature of the coal itself. As a matter of fact, if the coal is heated to a certain temperature it will carry on oxidation and combustion at an increased rate without any visible sign of such combustion, such as glowing or flaming. The temperature to which coal must be raised in order that it may carry on its own increase in temperature up to the ignition point is generally considered to be the ignition temperature.

6. *Various Suggested Ignition Temperatures.*—In the small amount of experimental work and printed discussion on ignition temperature of coal, several distinct points have been mentioned as possible criteria for comparing various coals.

(1) The temperature at which self-heating begins.

(2) The temperature to which coal must be raised in order that it may unite with oxygen and burn.

(3) The temperature (zone) at which rapid self-heating begins.

(4) The temperature to which coal must be raised in order that it may maintain its own combustion.

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* Jour. Soc. Chem. Ind., Vol. 39. pp. 72-78. March 31, 1920.

(5) Definitions on a time basis, such as the time required for a given external temperature to ignite the coal or cause it to glow.

(6) The temperature of the glow point.

(7) The blue flame temperature.

(8) The crossing point of the outside heat, coal-heat curves. (Wheeler.)

The following objections may be raised to all of these methods of defining the ignition temperature.

(1) The temperature at which self-heating begins is actually atmospheric temperature, since coal is combining with oxygen even at low temperatures and producing small amounts of heat.

(2) A definition referring to the temperature at which coal will unite with oxygen and burn in reality defines the flaming temperature, as flaming is the usual visible evidence of combustion. The flaming of a coal, however, depends upon the character of the volatile matter driven off, which varies with the conditions of the heating. The flaming temperature, therefore, is very uncertain.

(3) The heating curves of all coals show an abrupt rise in the neighborhood of 200 deg. C; but there is no definite temperature during this change which may be assumed as the point where rapid self-heating begins. Hence this zone must be noted by its upper and lower limits or by its average temperature, either one of which would be rather indefinite.

(4) The temperature to which coal must be raised in order that it may sustain its own combustion without outside heat is one of the most logical points which could be chosen as an ignition temperature. However, as has already been pointed out, this temperature depends much on the size of the particles and on the air supply. In addition to the necessity of providing different values for different sizes of coal, there would probably be grave experimental difficulties in measuring the exact temperature at which combustion of the coal would be self supporting.

(5) Any definition based on time would not be a true definition but would simply serve as a criterion for comparing various coals.

(6) The glow points were found to be much easier to check with a fair degree of precision than was at first expected. As they are independent of variables such as heating rate they may be measured in various kinds of furnaces with the assurance that the results obtained will check any other operator's figures on the same coal. On the other hand the principal objection to the glow point as a definition lies in the fact that, before it is reached, a large portion of the volatile combustible matter has been driven off: and some of this matter driven off at the very lowest temperatures may have an ignition temperature lower than the glow point. In the experience of all investigators on the subject of ignition point, however, the semi-coked residue has been found to have a lower ignition temperature than any of the evolved gases. The temperatures of ignition of such gases as CH_4, CO, etc., which are known to be given off by coal at low temperatures, are all higher than the glow points observed. True, it was found that the glow point bore practically no relation to the liability to fire while in storage, but this corresponds with the experience of Winmil and Graham,* who state that the most inflammable coal is not necessarily the most liable to spontaneous combustion.

(7) If after all the volatile matter has been driven off from a coal, the residue is brought up to a sufficiently high temperature it will flame with a non-luminous flame. Athough this matter has not been investigated thoroughly it is probable that coals differ very slightly in the temperature at which this blue flame will appear. This is asserted in view of the fact that, in order to obtain the blue flame, practically all the volatile matter must be driven off previously.

(8) Wheeler has shown that the crossing point of the outside heat curve and the coal heating curve as a relative ignition temperature can be easily checked in his type of apparatus.† The objection to any methods of this kind, however, is that the results cannot be duplicated except in identical apparatus and perhaps by the same observer. Furthermore this "relative temperature" marks no definite event in the heating process. It occurs some-

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* I. & C. Tr. Rev., Vol. 89, p. 336.

† See page 35 for a description of Wheeler's work.

time after the coal has begun to heat rapidly enough to cause the curve to cross the furnace curve but it does not mark the beginning of this rapid rise.

7. *Explanation.*—It is highly probable that the ultimate explanation of ease of firing, temperature of the glow point, or ignition temperature, however it is defined, must be sought in the chemical composition of the volatile products and the semi-coked residue. Brame in "Fuels" states: "Generally the proportion of hydrogen present is the determining factor in ignition point of fuel, this being well illustrated in the case of charcoal, which, if carbonized below a visible red heat, ignites at 427 deg. C., while if carbonized at a bright red heat, 900 deg. C., it ignites at approximately 537 deg. C."

In Wheeler's opinion adsorbed oxygen is the determining factor. Having made various tests on coal of different total oxygen percentages, he states that the relative ignition temperatures decrease as the oxygen content increases, but that no relationship exists between ignition temperature and other analytical data. Wheeler also makes the statement that the oxygen content given in his figures must be regarded as that of the saturated coals, because the treatment to which they had been subjected involved exposure. He also shows that a coal which takes up a large amount of oxygen shows self-heat at a lower temperature than low oxygen coals. He says, "The term self-heat may be seen to have its true significance so far as the highly oxygenated saturated coal is concerned if one considers that the loosely combined oxygen may, at a higher temperature, desire a more permanent attachment. If a reaction of the kind does take place, evolution of heat should be observed on a saturated sample if heated in an atmosphere of nitrogen."

Professor Parr suggests, in personal communication, that it is probable that oxygen adsorbed after the coal is mined has an important bearing on the glow point and the firing qualities of the coal. In his opinion, also, the nature of the gases given off just previous to the glow point will have an important bearing on the temperature of the glow, and these gases will probably show some alteration after the coal has been stored for some time. He therefore suggests that one series of experiments be undertaken to determine the chemical composition of such gases and the effect of storage upon the glow point; and another to compare the glow points of freshly mined samples with those of samples saturated with oxygen.

Hollings and Cobb* obtained heating curves which show a marked exothermic reaction in nitrogen between 150 deg. and 250 deg. It is significant that the range 150 to 250, over which exothermic reactions in an inert atmosphere are manifest, should correspond so closely with the range over which rapid self-heating occurs in a stream of air.

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* Jour. Chem. Soc., Vol. 107, p. 1109, 1915.

III. Description of Methods Used by Others

8. *Method of Sinnatt and Moore.*—Fig. 1 shows the apparatus used by F. S. Sinnatt and Burrows Moore for the determination of the relative temperatures of spontaneous ignition of solid fuels.

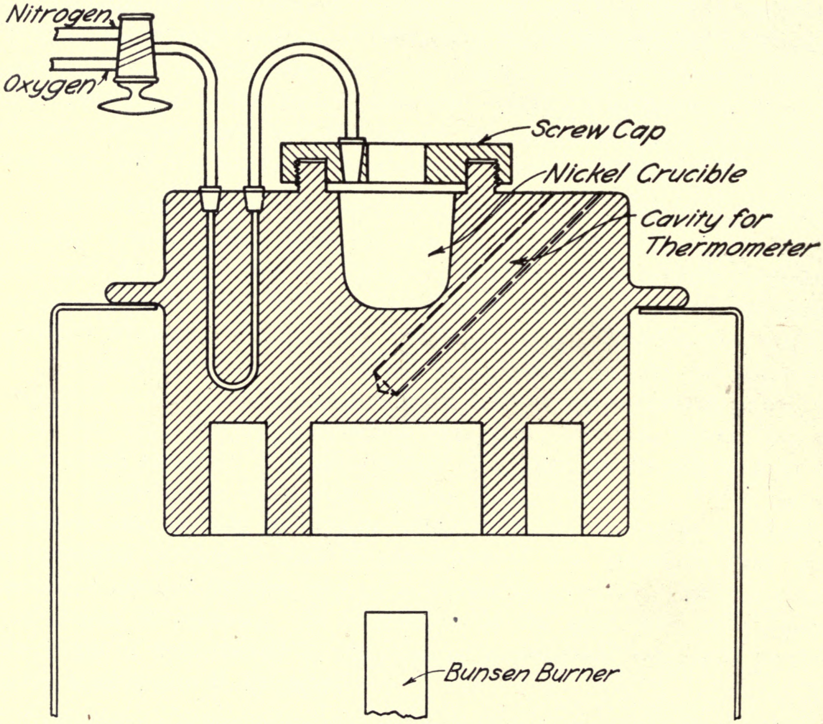

Fig. 1. Apparatus Used by Sinnatt and Moore for Determining Ignition Temperature

The apparatus consists of a heavy cast iron vessel in which an enclosed nickel crucible may be raised to any desired temperature. The whole apparatus is enclosed in an asbestos-lined box to eliminate the influence of drafts. Before entering the combustion chamber the oxygen or other gas traverses the U-shaped tube bored into the casting.

The length of this pre-heating tube is sufficient to raise the temperature of the oxygen to that of the casting before it comes into the combustion chamber. A thermometer is placed in a cylindrical chamber arranged so that the mercury bulb is immediately below the combustion chamber. The casting is deeply grooved at the bottom in order to increase the surface exposed to the flame of a large bunsen burner which is used as a source of heat. The oxygen is dried by passing it through concentrated sulphuric acid. In certain experiments nitrogen was used to sweep out the crucible and a three-way tap was attached to the ignition meter so that nitrogen or oxygen can be passed into the combustion chamber as required.

Pulverized fuel was used in all these experiments and in each case a measured amount was dropped into the nickel crucible by means of a dropper made of glass tubing.

After the introduction of the sample a time record was kept of the following phenomena: first, commencement of visible active combustion, glowing of the mass; second, ignition as manifested by an explosion or production of flame; and third, extinction of the visible combustion. The special points noted were the time interval before visible combustion or glow occurred and the time interval before explosive or inflammatory ignition occurred. The progress of the combustion was watched through a central hole in the lid and the residue after visible combustion had ceased was examined preparatory to the introduction of a fresh charge. Tests were made on the same coal under various temperature conditions in the apparatus, and Tables 2 and 3 show some representative results obtained by these experiments.

The investigators, Sinnatt and Moore, make the following remarks regarding some of the coals:

> ''In the coals examined, with the exception of the two which are known to be liable to gob fires, there appear to be zones of temperature in which spontaneous ignition occurs after a much longer interval. It would appear that the coals yield volatile compounds at these ranges of temperature, which compounds have a higher temperature of ignition. It is suggested that such coals may possess the property at these temperatures of tending to extinguish any heating which may be taking place especially where the coal is in masses and the oxygen only in contact with the surface. Where, however, coal does not evolve such compounds, no such self-damping action is possible, and the result of the oxidation

TABLE 2

COMBUSTION PHENOMENA OBSERVED WITH COAL LIABLE TO PRODUCE GOB FIRES

Time in Seconds for			Temp. Deg. C.	Remarks
Extinction	Glow	Ignition		
52	29	35	228	
55	20	35	230	
45	13	15	243	Very powerful explosion.
44	13	14	250	Powerful explosion, yellow flame.
40	11	14	267	Very powerful explosion, yellow flame.
40	10	14	278	
38	10	14	290	
39	10	14	300	Very powerful explosion, yellow-white flame.
38	9	13	310	
38	8	14	320	
25	6	9	330	
37	4	10	340	
35	3	3-14	350	Very powerful explosion at 14.
36	5	10	362	Very powerful explosion, yellow-blue-white flame.
30	2	2	378	
40	1	1	386	

TABLE 3

COMBUSTION PHENOMENA OBSERVED WITH ANTHRACITE

Time in Seconds for			Temp. Deg. C.	Remarks
Extinction	Glow	Ignition		
..	..	..	246	
..	..	..	248	
113	45	..	250	
125	32	32	256	
140	31	31	258	Yellow flame.
136	29	29	267	
120	23	23	278	
130	17	17	287	
90	19	..	296	
105	17	20	300	
110	15	45–50	310	
100	12	41	321	Yellow-white flame.
110	12	14	332	
108	9	12	342	
90	6	6	350	
100	6	28–35	362	
102	6	..	368	
120	7	50–58–70	384	Yellow-white flame at 50; blue flame at 70.
83	4	38	388	
106	5	52	390	Yellow-white-blue flame.
121	4	35	394	
111	6	17	400	Very powerful explosion.
90	5	5	412	

would be an additive one, consisting of the glowing of the solid substance and the ignition of the volatile constituents.

''In order to obtain an idea of the minimum temperature at which substances would either glow or ignite a time limit of four minutes was adopted, and the lowest temperature at which substances would either glow or ignite within this period was taken as the temperature of glowing or ignition. The time decided upon was sufficiently long for most practical purposes.''

The values obtained for a number of substances are given below.

TABLE 4

MINIMUM TEMPERATURES FOR IGNITION IN OXYGEN

Substance	Minimum Temperatures in Oxygen, Deg. C.			
	Glowing	Ignition	Holm's Figures	Brame's Figures
Anthracite coal	250	258	440	500
Hoo cannel coal	225	230	....	....
Wigan Arley coal	184	188	....	370
Wigan yard coal	219	219	....	to
Indian coal	242	242	....	425
Coal liable to gob fires, No. 1	228	228	....	....
Coal liable to gob fires, No. 2	228	228	....	....
Gas coke	Above 398	Above 398		
Coalite	Above 396	Above 396	....	....
Wood charcoal	248	248	....	....
Irish peat	300	300	....	....
Cellulose	324	324	360	....
Fusain	367	367	....	....
Paraffin wax	....	246	310	....

The investigators continue:

''Early in the experiments it was found that the degree of fineness of the particles of the fuel had a considerable influence upon the minimum temperature at which spontaneous glowing would occur, and preliminary observations have been made to ascertain broadly the influence of the fineness of the fuels examined. The results are recognized as being quite preliminary but, as they show that the degree of fineness is a most potent factor, it is desirable to place them on record.''

An attempt was likewise made to ascertain the influence of the volatile matter present in the fuels on the temperature at which spontaneous ignition occurs. In order to do this the apparatus was

TABLE 5

MINIMUM TEMPERATURE AT WHICH SPONTANEOUS GLOWING OCCURS

Description	Degree of Fineness		
	1/200	1/100 to 1/200	Mixture of 2 parts 1/200 and 1 part 1/100–1/200
	Temp. Deg. C.	Temp. Deg. C.	Temp. Deg. C.
Indian coal	240	Above 380	242
Hoo cannel	229	Above 390	277
Yard coal	219	Above 396	233
Coal liable to gob fires, No. 1	232	348	...
Coal liable to gob fires, No. 2	225	298	...

arranged so that nitrogen could be passed into the combustion crucible through the three-way tap shown in the diagram, until the volatile matter had been driven off from the coal. The procedure was as follows: The ignition meter was raised to any desired temperature, the nitrogen turned on, and a charge of coal introduced from the dropper. The coal was kept for 15 minutes in the atmosphere of nitrogen. At the end of this period the supply of nitrogen was interrupted and oxygen introduced into the crucible. The time interval before glowing or ignition occurred was then determined. The crucible was at once emptied of any residue and a fresh charge or blank was dropped in, having the oxygen continually flowing. The process was repeated for different temperatures and the results are given in Table 6.

Sinnatt and Moore say further:

> ''It may be observed that at temperatures only slightly above the minimum temperatures previously recorded for the occurrence of glowing, all the fuels, except the Hoo cannel, which had been previously exposed to nitrogen failed subsequently to glow or ignite in oxygen within the time interval of four minutes whereas the control samples examined immediately afterwards behaved exactly as previously recorded. The conclusion to be deduced from these observations is that the volatile matter in the coal has considerable influence upon the liability of the fuel to glow. The non-appearance of the glowing in the nitrogen-treated charges appears especially important where the material has only been

heated to temperatures not appreciably above the minimum temperatures previously recorded for glowing to occur. It would therefore appear that the oxidation of the volatile constituents evolved contributes very largely to the heating effect, which leads to the mass of coal becoming heated, and consequently to the production of a glow.''

TABLE 6

TIME INTERVAL BEFORE GLOWING OCCURS IN NITROGEN AND OXYGEN

Exposed to Nitrogen for 15 Min. before Admission of Oxygen				No Previous Exposure to Nitrogen before Admission of Oxygen	
Air Dried Sample	No. of Seconds before Glowing	Remarks F—flame E—explosion	Temp. Deg. C.	No. of Seconds before Glowing	Remarks
Arley coal 200 mesh	20	Feeble E at 20 sec. Yellow F.	398	1	More powerful E at 43 sec. Blue F.
	10	Feeble E at 10 sec.	378	1	
	35	Residue partly ash	285	3	More powerful E at 25 sec.
		No glowing	240	13	Explosion at 25 sec.
		No glowing	226	25	
		No glowing; unburnt residue	260	8	
Anthracite coal 200 mesh		No glowing	388	7	Yellow F.
		No glowing	362	12	Feeble E.
		No glowing	325	22	
		No glowing	300	30	
Hoo cannel 200 mesh	8	Feeble E at 12 sec.	382	1	Fairly powerful E.
	10	Very feeble E at 12 sec.	363	3	Fairly powerful E.
	11	Very feeble E.	340	3	No ignition
		No glowing	270	16	No ignition
Irish peat 200 mesh	20	No glowing; residue charred	390	1	
		No glowing; residue charred	385	1	
		No glowing; residue charred	350	2	
Cellulose 200 mesh	15	No glowing; residue charred	396	1	
		No glowing; residue charred	369	1	
		Feeble E at 15 sec	340	30	Powerful E at 30.
Fusain 200 mesh		No glowing	389	6	Yellow F.
		No glowing	370	10	

9. *Remarks on Method of Sinnatt and Moore.*—In the method just described for obtaining the ignition temperature it is obvious that the temperatures obtained are those of the external source of heat and not of the coal itself. The very small sample used, about 0.0052 g., did not in any way affect the temperature of the apparatus

to an extent which could be measured. It is impossible with this type of apparatus to measure the temperature of the coal itself at any stage in the process. The chief value of the method lies in the possibility of determining the relative ease with which coals fire while in storage, but the reasons for the ease of firing are not made known. It is to be noted in Tables 2 and 3 that the glow points are in all cases reached before ignition takes place.

The results obtained by these men, although taken in a manner very different from that of the present investigation correspond in every way with those recorded later in this paper.

Present experiment, however, determined that the glowing temperatures were far above those recorded by Sinnatt and Moore in their table. This explains why these investigators obtained no glow after the volatile matter had been driven off, as shown in Table 6. It has been found by several investigators that the giving off of the volatile products in an atmosphere of oxygen or air is accompanied by exothermic reactions which add their heat to the mass of the coal. Therefore the explanation of the failure to obtain the glow point is that, after the volatile matter had been driven off in an atmosphere of nitrogen, very little heating effect could be obtained from the exothermic reactions, while the semi-coked residue which was later submitted to the action of oxygen was at too low a temperature to glow, and its combustion in oxygen was going on too slowly to raise the temperature of the coal mass to the glow point. Had the oxygen been admitted at a trifle more rapid rate, the glow would undoubtedly have appeared. In Tables 2 to 6 the temperatures indicated are those of the apparatus. Undoubtedly if the temperature of the coal sample had been measured it would have been found to be considerably above that of the apparatus when the coal glowed.

10. *Method of Wheeler.**—The apparatus used by Wheeler is shown in Fig. 2. It consists of a tube holding the sample of coal, and an electrically heated sand bath surrounding the sample tube. Air is drawn through the sample at a constant rate; the temperature of the coal mass itself and the external sand bath being taken simultaneously. Experiments were made on 40-g. samples of 150-mesh and 240-mesh coal. The temperature of the sand bath was slowly raised

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* Jour. Chem. Soc., Vol. 113, p. 949, 1918.

at a uniform rate and the temperatures inside and outside the coal taken at intervals.

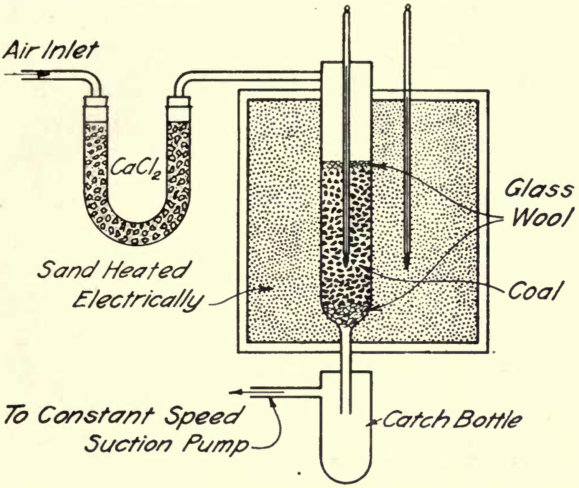

FIG. 2. APPARATUS USED BY WHEELER FOR DETERMINING IGNITION TEMPERATURE

The results of these experiments were plotted as two time-temperature curves, one showing the heating rate of the coal sample and the other showing the heating rate of the external sand bath. In all cases the temperature within the coal eventually began to rise rapidly above that of the sand bath, but, due to the kind of thermometers used, it was impossible to carry the experiment to very high temperatures. It may, however, be assumed that after the heating curve began to rise rapidly it would only be a matter of time before the coal would flame. A curve, characteristic of these results, is shown in Fig. 3.

Wheeler says:

> "It will be seen that the temperature at which the reaction velocity becomes so rapid that inflammation of the coal is imminent is clearly indicated to be at about 205 deg. C. It is evident also from the gradual approach of the two curves that the heat due to the oxidation of the coal was sufficient, despite the loss to outgoing air, to raise the temperature of the coal above that normally due to the heat received from the sand bath when the reaction was proceeding at a temperature of 125 deg. C. The latter temperature might be regarded as

the ignition temperature of the coal, (that is, the temperature at which self-heating begins) under the conditions of the experiment.

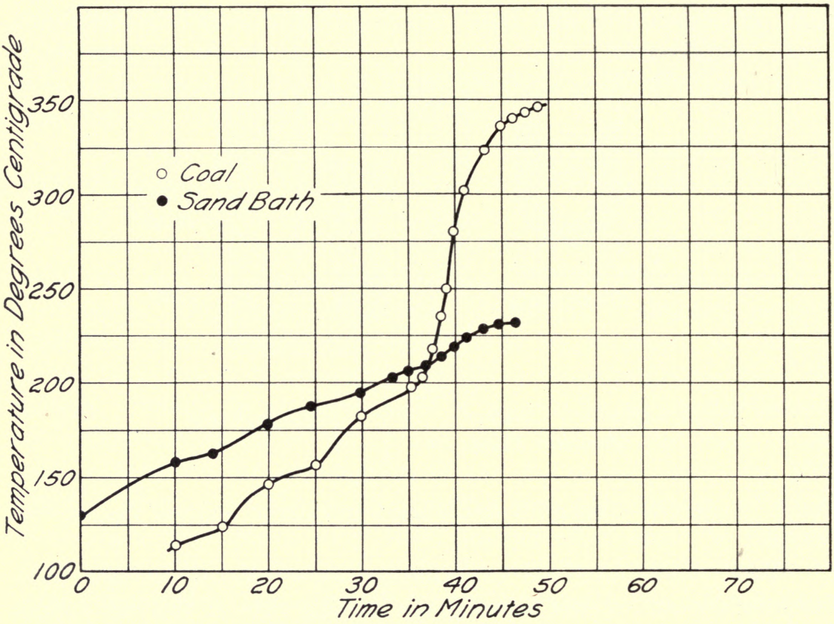

Fig. 3. Heating Curves of Coal and Sand Bath (Wheeler)

> "For comparative purposes, however, it was found preferable to record as the relative ignition temperature the point at which the coal temperature curve and the sand bath curve cross, as this point is clearly defined. It is the temperature at which rapid self-heating begins and is therefore in conformity with Nernst's definition of the ignition temperature for gaseous mixtures."

Wheeler treated several samples of coal having various oxygen contents and determined that the most highly oxygenated fuels are those most liable to self-heat. His results are shown in the following table, in which the oxygen contents were taken on the basis of ash-free, dry coal and must be regarded as those of the "saturated" coals as the treatment to which the coals had been subjected involved exposure.

11. *Remarks on Method of Wheeler.*—The heating curves obtained by Wheeler are similar to those obtained here except for the fact that much higher temperature readings could be obtained by the

use of the thermocouple than with glass thermometer. Wheeler proved unquestionably that the crossing point of the coal-heat, outside-heat curves is a definite point and that he is justified in using this point as a means of comparison for different coals. It is to be noted, however, that these results can be duplicated only in the identical apparatus used by Wheeler, as the shape of the heating curve is affected by the characteristics of the furnace and the conditions under which the experiment is run. Similar to Wheeler's experience, present experiments obtained heating curves showing abnormal tendencies between the range 150-250 deg. C. Fig. 13, page 54, shows this bulge in the heating curve very markedly.

TABLE 7

RELATIVE IGNITION TEMPERATURES FOR VARIOUS OXYGEN CONTENTS

Oxygen Content Per Cent	Rel. Ig. Temp. Deg. C.	Oxygen Content Per Cent	Rel. Ig. Temp. Deg. C.
11.1	165	8.3	182
11.1	165	8.1	180
11.1	167	8.0	183
10.6	177	7.6	192
10.5	176	7.4	188
10.3	176	7.3	185
9.9	177	7.0	192
9.9	179	6.7	195
9.9	179	6.6	206
9.5	178	6.4	200
9.2	178	5.6	210
8.8	183	5.4	200
8.8	187	5.1	217
8.7	186	4.9	195
8.6	183	4.7	220
8.5	185	3.9	200

IV. GLOW POINT

12. *Glow Point as Ignition Temperature.*—If a sample of coal is heated carefully so that the rate of heating is uniform throughout the sample it will be found that at a certain very definite temperature the sample will assume a uniform glow. This glow takes place rather suddenly, if one neglects the occasional glowing particles on the edge of the pile, and it is quite certain that it is not entirely due to incandescence of carbon alone, since the color of the glow is much brighter than black bodies assume at this temperature. Furthermore the change from the black coal to the brightly glowing mass is too rapid to be explained by incandescence. After coal has been heated for about twenty minutes under the conditions of the experiment, the change from black to glowing coal takes place sometimes within a half minute of time. With much sulphur present a rather confusing glow occurs earlier than this, but with low sulphur coals the appearance of the glow is quite abrupt. With a few unexplained exceptions the temperatures observed for the glow points of samples of the same coal check fairly closely.

Strange to say there is no very abrupt rise in the heating curve beyond the glow point. To be sure the sample of coal is still rising in temperature, but the rather abrupt rise that might be expected after rapid combustion begins is not apparent. Professor Parr suggests that this might be explained by assuming that at this point adsorbed oxygen, which is probably already partly combined with the coal substance, completely combines with the carbon to form carbon dioxide. The additional heat thus produced is probably not sufficient to alter the temperature at a rate which can be measured by this method. Whatever the explanation of the glow point may be, it occurs at a very definite place in the heating curve and may therefore be accepted definitely as the ignition temperature.

13. *Determination of Nature of Glow Point.*—An attempt to determine the intensity of the action at the glow point was made by submitting a sample of coal above the glow point and one below the glow point to a blast of oxygen. No definite statements can be made regarding the results of this experiment because of the difficulty of

handling a single small particle of coal, determining its temperature, and keeping it from being blown away by the blast. The procedure was to place a small sample of coal in a wire cylinder, raise it above the glow point, and then allow it to cool until the glow just disappeared. As nearly as could be determined the sample was always cooled by the blast of oxygen if its temperature was below that of the glow point, but if it was glowing in but a small part its combustion would rapidly accelerate until it was burning fiercely.

Another experiment made to determine the exact nature of the glow point was to heat a sample of coal in the furnace to about 300 deg., at which time the furnace current was shut off and temperature readings continued. The results of several trials indicated that the coal heated to a temperature just short of the glow point, then the rise stopped. It must not on that account be supposed that further heating is necessary to carry on combustion; indeed, if the concentration of oxygen be increased but slightly the heating will continue even beyond the glow point. The experiment does indicate, however, that the glow point is reached only with a certain amount of difficulty, and that, even if the heating is started, the glow point will not be reached unless a certain concentration of oxygen is exceeded.

These experiments to ascertain the nature and characteristics of glow point furnish in nearly all cases added argument for establishing the glow point as the ignition temperature. The glow point is, moreover, the first visible evidence of combustion, as it occurs in all cases before flame or explosion takes place.

Professor Parr believes that the temperature of the evolved gas has something to do with the glow point and advises a further series of tests to determine the nature of this gas and the influence of weathering on the ignition temperature.

V. DESCRIPTION OF APPARATUS

14. *General Discussion.*—The apparatus used in these experiments is shown in Figs. 4, 5, and 6. It consists of an electric furnace of the resistance type, a motor generator set furnishing direct current, a method of regulating the voltage of this generator by means of shunt field resistance, a Hoskins thermocouple, and a millivoltmeter.

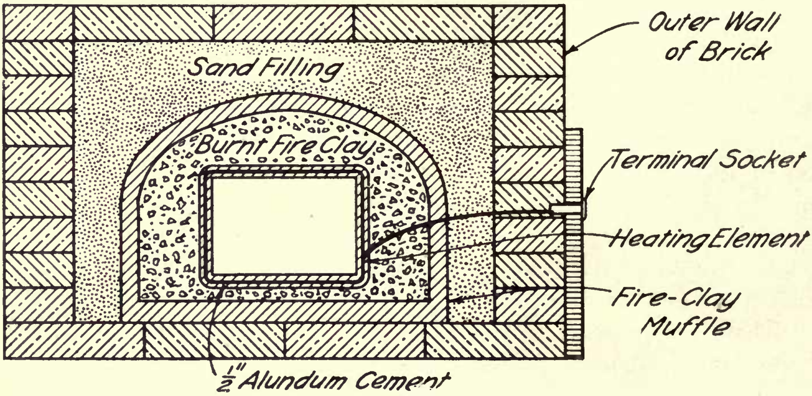

FIG. 4. SECTION OF FURNACE

15. *The Furnace.*—The furnace that was used was made purposely for these experiments and is shown in Figs. 4 and 6. The heating element was made by wrapping 70 feet of special resistance wire, No. 14 B. & S. gauge, having a resistance of 625 ohms per mil-foot and a total resistance of 10.78 ohms, on a reinforced paper form. After the element was wound it was cemented with alundum cement which was allowed to dry before the form was removed. The element was then placed in an ordinary muffle and the space between the wires and the muffle filled in with burned fire-clay. The ends of the wire were brought through holes bored in the muffle to terminals placed on the outside of the furnace. The muffle was then set on a stand and walled in with brick.

A thin layer, ¼ in., of alundum cement was spread on the wires inside the furnace as a lining, and this construction brought the

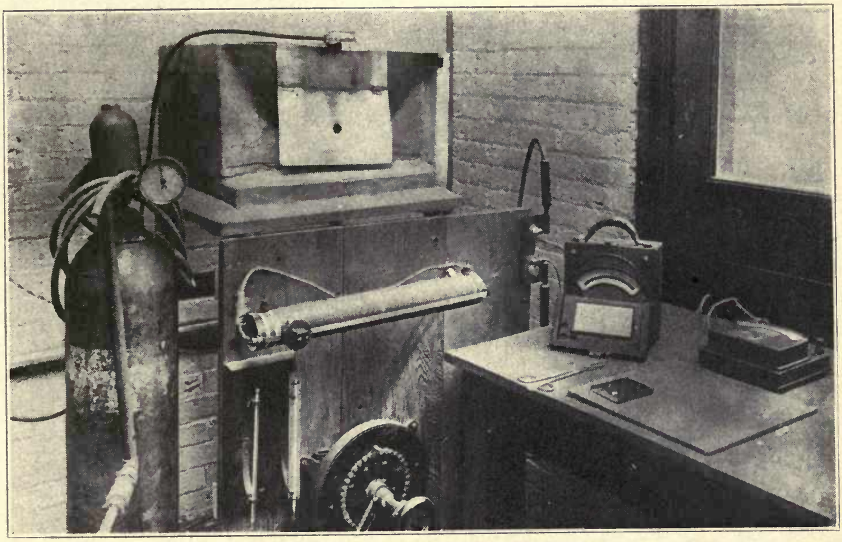

FIG. 6. APPARATUS USED IN PRESENT INVESTIGATION

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heating element very close to the interior surface. Because of this the furnace heated rapidly. As the inside was worn off it had to be plastered up occasionally to avoid danger of short circuiting the wires inside the furnace.

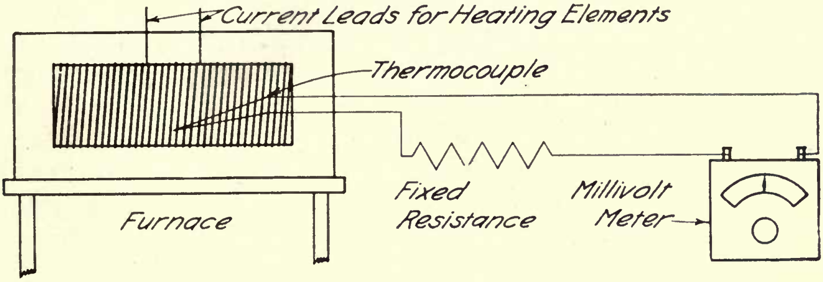

FIG. 5. WIRING DIAGRAM OF FURNACE

16. *Power Required.*—Because of its ease of measurement and control direct current was chosen as the power for the heating element. The laboratory was already equipped with a 250 volt D. C. compound generator driven by a 440 volt A. C. motor. The voltage of this generator could be regulated by the shunt field control. The switchboard of this set was provided with a field rheostat, but it was found that the successive points on this rheostat gave jumps in the voltage which were larger than desired. A smaller field rheostat, shown in Fig. 6, was therefore wired in series with the switchboard rheostat for the purpose of giving finer adjustments of the voltage. With this auxiliary rheostat it was possible to regulate the voltage so that the current flowing through the heating element was constant at all times.

It was found that 15 amperes gave the best results in the experiments, heating the coal sample as rapidly as possible without showing any great amount of lag due to the low conductivity of the coal. In order to get 15 amperes through the furnace a voltage of about 160 was required, depending somewhat upon the temperature of the heating element. An ammeter was placed in the circuit as shown in the wiring diagram.

VI. Temperature Measurement

17. *Method Employed.*—The thermocouple used was a Hoskins base metal couple, the negative side of which is an alloy called Chromel, composed of chromium and nickel, and the positive side Alumel, made of aluminum and nickel. Within the range of temperature desired, this couple has a guaranteed millivoltage of approximately 40 mv. As the millivoltmeter used has a maximum scale reading of 20 mv., it was necessary to use the couple in series with a resistance in order to reduce the scale reading. The couple, resistance, and millivoltmeter were standardized against the melting points of three pure metals.

The placing of a resistance in series with the couple gave the added advantages of high resistance temperature measurements. When the resistance of the couple circuit is extremely low the millivoltmeter reading is affected by the variation of the resistance of the hot wire, imperfect connections, a change in the length of the connections, and many other things. If a high resistance in the circuit is kept at a constant temperature the above mentioned factors will not affect the result appreciably.

The gases produced from the burning of the coal were very corrosive and the couple frequently broke. However, due to the high resistance mentioned above, frequent re-calibrations proved that after the wire was re-welded there was very little difference in the reading for any given temperature.

18. *Calibration of Thermocouple.*—The metals used in the calibration of the couple were aluminum, melting point 659 deg. C., lead, melting point 327 deg. C., and tin, melting point 232 deg. C. These three metals were used because their melting points fell within the limits of temperature most used in this work, and because they gave the most satisfactory calibration points. It was found that zinc gave an uncertain calibration point.

19. *Fixed Junction Correction.*—No attempt was made to keep the fixed junction of the thermocouple at zero degrees, but room temperatures were observed on all the tests and the correction for

room temperature made by the method described by L. H. Adams before the A. I. M. E., September, 1919. In this method the millivolts corresponding to room temperature are added to the observed millivoltmeter reading, giving a value of the voltage which will correspond with the true temperature of the hot end of the couple. In this same paper Adams includes a table showing temperature difference per millivolt with this type of couple. This difference varies slightly for different temperatures, but there is less variation than in noble metal couples or "Constantan" combinations. In other words the calibration curve is nearer a straight line for the Chromel-Alumel couple than for the other types.

TABLE 8

TEMPERATURES FOR VARIOUS MILLIVOLTMETER READINGS
DEGREES CENTIGRADE

M. V.....	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
00........	0	46	90	134	179	223	268	312	358	404	451	498	543	587	630
05........	2	48	92	136	181	225	270	314	360	406	453	500	545	589	632
10........	5	50	94	138	183	227	272	317	363	409	456	503	548	591	634
15........	7	53	97	141	186	230	275	319	365	411	458	505	550	594	636
20........	9	55	99	143	188	232	277	321	367	414	460	507	552	596	638
25........	12	57	101	145	190	234	279	324	369	416	463	510	555	598	641
30........	14	59	103	147	192	237	281	326	372	418	465	512	557	600	643
35........	16	61	105	149	194	239	283	328	374	421	467	514	559	602	645
40	18	64	108	152	197	241	286	330	376	423	469	516	561	605	647
45........	21	66	110	154	199	243	288	333	379	426	472	519	564	607	649
50........	23	68	112	156	201	246	290	335	381	428	474	521	566	609	651
55........	25	70	114	158	203	248	292	337	383	430	476	523	568	611	653
60........	28	72	116	161	205	250	294	340	386	433	479	525	570	613	655
65........	30	75	119	163	208	253	297	342	388	435	481	528	572	615	657
70........	32	77	121	165	210	255	299	344	390	437	484	530	574	617	659
75........	35	79	123	168	212	257	301	347	392	440	486	532	577	620	.....
80........	37	81	125	170	214	259	303	349	395	442	488	534	579	622	.....
85........	39	83	127	172	216	261	305	351	397	444	491	536	581	624	.....
90........	41	86	130	174	219	264	308	353	399	446	493	539	583	626	.....
95........	44	88	132	177	221	266	310	356	402	449	496	541	585	628	.....

The table of temperature differences just mentioned could not be employed directly because of the high resistance used, but a similar table was prepared based on Adams's temperature differences and our own calibration, and is given above as Table 8. This table was used in connection with all temperature determinations of the glow points of the various coals. In making the experiments on the heating curve of the furnace and the heating curves of the standard coal a slightly different resistance was used and a separate calibration was made. The table calculated from this is not included. Several recalibrations of the thermocouple during the tests on coals showed practically no deviation from the values given in the above mentioned tables.

Taking all factors into consideration, such as the accuracy of the calibration, loss of heat, lag of the couple, approximations in the calculations, and similar sources of error, the readings are thought to be correct to about 5-8 degrees.

VII. Method of Making Tests

20. *General Procedure.*—The method used in these experiments was as follows: a sample was placed in a flat pan and the thermocouple inserted in the top of the coal so that the junction was entirely submerged, see Fig. 7; the shields were then placed over the furnace and the current turned on; observations of the temperature were made at half-minute intervals and temperatures of glowing, flaming, or other phenomena, were noted.

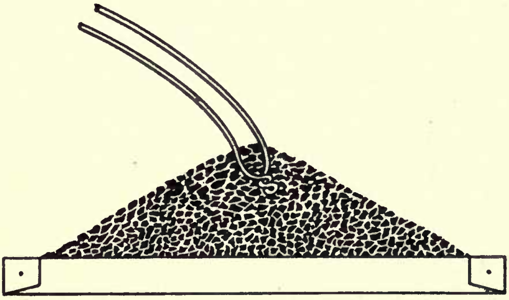

Fig. 7. Depth of Immersion of Thermocouple

21. *Weight of Sample.*—For the determination of glow point alone it was unnecessary to standardize the weight of the sample as the glow point is independent of the weight. In order to get the heating curves of various coals for purposes of comparison, all the conditions, including the weight of the sample, were standardized. It was found that about 35 g. of coal could be heated at a fairly uniform rate without any great amount of lag in any part of the pile; furthermore this weight was large enough to make possible a good immersion for the couple.

The pan in which the sample was placed was rather flat, with low sides, so that the air had free access to the sample and all parts of the pile could be observed from the front of the furnace.

22. *Setting of Thermocouple.*—It was found rather important to have the proper immersion of the thermocouple in the sample in order to check results. The object of course was to get the

average temperature of the sample itself, or more properly to observe what happened to that coal which immediately surrounded the couple. If the point of the couple was too deep it was in no way certain that what was observed on the surface was also taking place within the pile. On the other hand if merely the tip of the couple was placed in the coal, temperatures observed applied to the gases coming off the coal rather than to the interior of the pile itself.

23. *Distribution of Heat and Temperature Lag.*—In starting these experiments it was uncertain just how much dependence could be placed on temperature measurements made in this manner. The number of degrees by which the thermocouple lagged, the temperature of the coal itself, the distribution of temperature throughout the sample, the lag of the top of the coal pile behind those individual particles next to the hot furnace floor and the difference in temperature between the surface of any particle and its interior were all uncertain factors. In order to eliminate some of the uncertainty regarding the lag of the couple and the distribution of the heat throughout the pile, a cooling curve was taken on a given coal sample whose heating curve had previously been observed, and the glow point on the cooling curve noted. In observing this the temperature at which the coal lost its glow and returned to its black aspect was noted. In every case these cooling curve glow points were the same as those observed on the heating curves. These results indicate that the lag of the couple was very slight and that under the conditions of the experiment the distribution of the heat throughout the sample was fairly even.

The lag of various parts of the coal pile depends on the rate of heating. The first work done was to determine the proper rate of heating and the proper size of particles. It was found that with 35 g. of sample, 15 amperes supplied to the furnace heated the sample at a fairly uniform rate and the glow observed on low sulphur coals was fairly uniform throughout the pile.

No attempt was made to determine the lag of the interior of the individual particles behind the surface because this is relatively unimportant: that is, if we assume that glow point and flame, and as a matter of fact all oxidation, are superficial phenomena, it matters very little what the temperature of the interior of the particle may be. Experiments on large and on very small particles showed that the total amount of surface exposed to the action of oxygen bore no relation to the temperature of the glow point. This fact also gives some weight to the statement that the temperature of the interior of the particle is of no importance.

Some error is probably introduced by radiation of heat from the walls of the furnace to the thermocouple, especially during the early stages of the heating when the furnace is at a higher temperature than the coal. About 8 in. of the couple was exposed in this way, protected only by small, two-holed, porcelain sleeves ⅝ in. long, extending to within an inch of the coal sample. At the glow point, however, the error introduced by radiation is probably small, inasmuch as the walls of the furnace and the sample of coal are both at a temperature higher than the air temperature represented by the heating curve of the furnace.

VIII. Description of Experiments

24. *Heating Curve of Furnace.*—The first work that was done was to compare the heating rate of various currents on the empty furnace. After several quantities of current were tried, both on samples of coal and on the empty furnace, it was concluded that 15 amperes gave the most satisfactory heating curve. To determine the heating curve of the furnace, six runs were made under exactly similar conditions. The furnace was allowed in each case to cool to room temperature and the temperature of the room itself was kept fairly constant by steam heat. The shield on the front of the furnace was in the form of a door hinged at the top, so that, when lowered, it always assumed the same position. This door was made of sheet metal having in the center a ¾-in. hole through which the action within the furnace could be observed. The shield was not tight

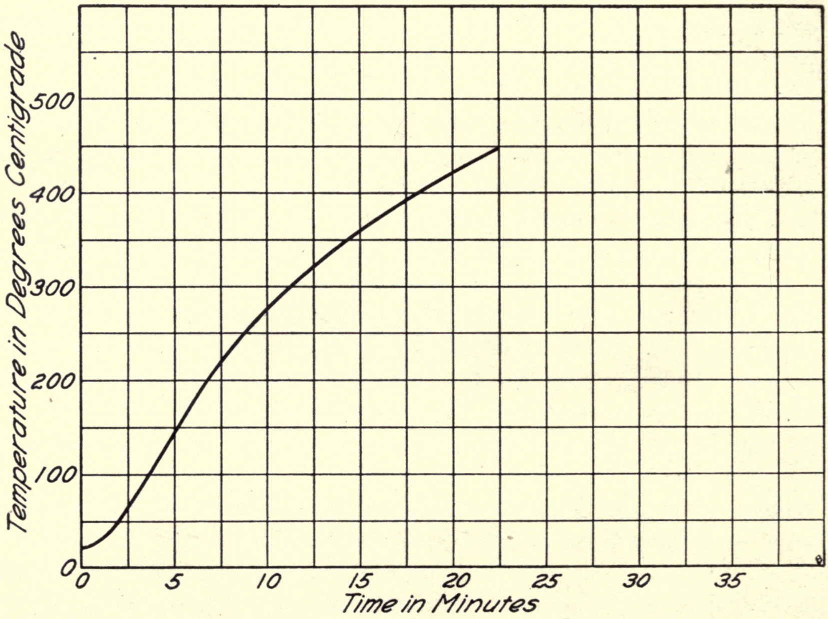

Fig. 8. Average Heating Curve of Empty Furnace

fitting; air could enter the furnace around the edges and through the hole, and also by an opening provided in the back of the furnace for the admission of the couple. The furnace was placed in a corner of the laboratory away from air currents, so that even with openings through which air might pass to cool the furnace, individual observations of heating curves differed but slightly from the average. The maximum deviation of any single heating curve from the average of all was less than 15 deg. The heating curve of the furnace calculated from these six runs is shown in Fig. 8.

25. *Work on Standard Coal.*—A low sulphur and ash coal was hand sorted from available samples in order to provide a relatively pure coal which could be used in standardizing a method for the determination of the glow point. On analysis this coal was found to contain 8.60 per cent ash and 1.25 per cent sulphur. This coal was prepared by crushing to a maximum size ¼ in. and then screening through the following screens: ¼ in. and ⅛ in., and 14, 28, 48, 100, 150, and 200 mesh. Thirty-five gram samples were then heated at a constant rate based on a 15 ampere supply of current to the furnace. Care was exercised to give the same immersion to the couple in every case. Three or four check runs were made on each size to determine the effect of size of particles on the glow point. The results of these runs are shown in the following tables:

TABLE 9

GLOW POINT TEMPERATURES, STANDARD COAL

DEGREES CENTIGRADE

Size of Coal	Run No.				
	1	2	3	4	5
¼ in.—⅛ in.	469	469	463	469	454
⅛ in.—14 mesh	469	473	445	...	...
14—28 mesh	466	467	471	435	...
28—48 mesh	517	510	456	501	...
48—100 mesh	472	470	472	480	...
100—150 mesh	466	468	...	...	...
150—200 mesh	470	466	468	477	...
Through 200	466	472	469	478	...

Average Temperature—472 deg. C.

TABLE 9A

GLOW POINT TEMPERATURES, STANDARD COAL

DEGREES FAHRENHEIT

Size of Coal	Run No.				
	1	2	3	4	5
¼ in.—⅛ in.	876	876	865	876	849
⅛ in.—14 mesh	876	883	833	...	...
14—28 mesh	871	873	880	815	...
28—48 mesh	963	950	853	934	...
48—100 mesh	882	878	882	896	...
100—150 mesh	871	874	...	...	...
150—200 mesh	878	871	874	891	...
Through 200 mesh	871	882	876	892	...

In at least one run on each of these sizes the furnace was started from the room temperature and observations of the temperature made at half-minute intervals to determine the heating curves. As these heating curves vary but little they were averaged to represent the heating curve of the standard coal. This heating curve was plotted against the average heating curve of the furnace and is shown in Fig. 9.

The results obtained for the glow point on the sizes finer than 100 mesh were uncertain because there soon formed over the pile a crust of glowing coal which made it impossible to determine just what was going on around the thermocouple. This is explained by the fact that in the smaller sizes very much more surface is exposed to the action of oxygen, and the surface of the pile is actually at a higher temperature than the interior. The temperature of this crust, however, is not transmitted to the thermocouple; hence results on the finer sizes are apt to be false. No attention was paid to this initial glow of the crust but as soon as it seemed that the pile was glowing to a depth equal at least to the immersion of the thermocouple the temperature was noted. In every case the results on the fine coal were very uncertain and it would require a great deal of practice before an operator could distinguish the proper point and check himself.

The most consistent results were obtained on the larger sizes from ¼ in. to ⅛ in., and ⅛ in. to 14 mesh. With this method any one of these sizes could be adopted for use as a standard, and in the subsequent work on individual coals these sizes were used.

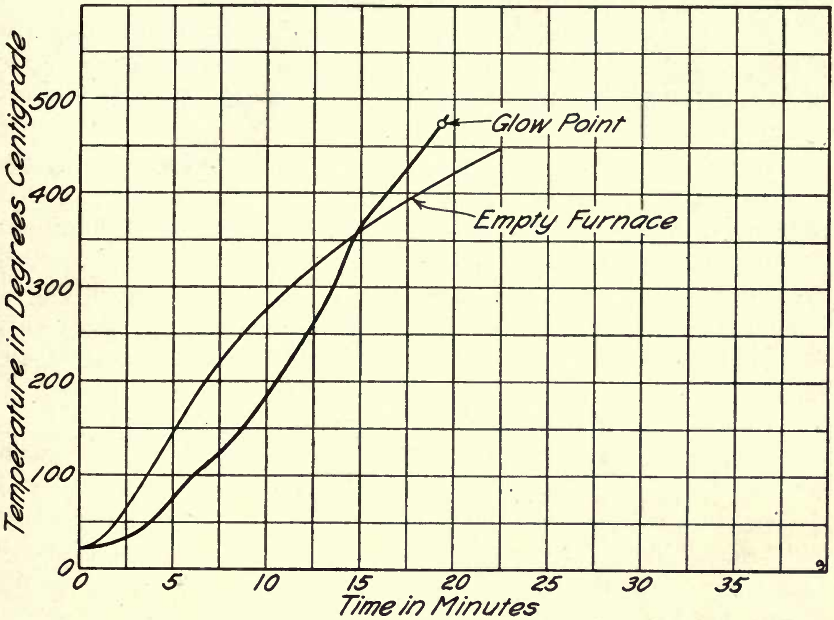

FIG. 9. AVERAGE HEATING CURVE OF STANDARD COAL

26. *Effect of Air Supply.*—To test the influence of various oxygen percentages on the temperature of the glow point the coal was heated under various conditions.

Case I.

The furnace was heated in the ordinary manner but a small stream of oxygen was admitted through the shield. This was done to give the same effect as a larger air supply, without the objectionable cooling effects of a blast of air.

Case II.

The furnace was heated in the usual manner to a temperature of about 300 deg., at which point the current was shut off. Oxygen was then admitted slowly to determine if the glow point could be reached without the action of outside heat.

Case III.

Conditions of Case III were similar to those of Case II except that a blast of oxygen was played on the sample.

In all three cases the action of oxygen was to increase the heating rate. This, however, was done at the expense of accuracy, inasmuch as the pile heated locally and a uniform glow was difficult to obtain.

In Case I a satisfactory glow point was observed by keeping the quantity of oxygen admitted very low. This glow point was found to be the same as when the coal was heated under ordinary conditions.

In Cases II and III when the current was shut off at about 300 deg., it was found that if sufficient oxygen was admitted to the sample the glow could be produced without the assistance of external heat, but if insufficient oxygen was admitted, or no oxygen at all, the coal would heat to some extent but the glow would not appear.

In Case III if the blast of oxygen was strong enough and the coal sample had not yet reached the glow point the latter would actually be cooled off, but if the glow point was first obtained and the coal then submitted to the blast of oxygen it would burn fiercely. This would indicate that the rate at which coal is raised to the temperature of the glow point is largely dependent upon the air supply, but that the actual temperature of the glow point, no matter how it is approached, is not altered.

27. *Effect of Ash.*—To determine the effect of ash on the glow point a sample of coal was mixed with pure shale washed from coal, and run under standard conditions. The following table of results

TABLE 10

EFFECT OF ASH ON GLOW POINT

Glow Points of Coal 35 g. Sample		Glow Points. 25 g. Coal Mixed with 10 g. Shale	
Deg. C.	Deg. F.	Deg. C.	Deg. F.
525	977	526	979
521	970	524	975
512	954	520	968

shows that the temperatures for the glow points under the two conditions were practically the same.

One peculiar feature of this experiment is illustrated in the heating curves shown in Fig. 10. It will be seen that high refuse coal heated more rapidly in the early stages than clean coal, but at a retarded rate towards the end of the process. This retardation was due to the fact that the quantity of coal in this experiment was less by 10 g. than in the other test; hence the quantity of heat derived from the coal after self-heating began was less. The rapid heating of the high refuse material early in the experiment may be explained by all or any of the following considerations:

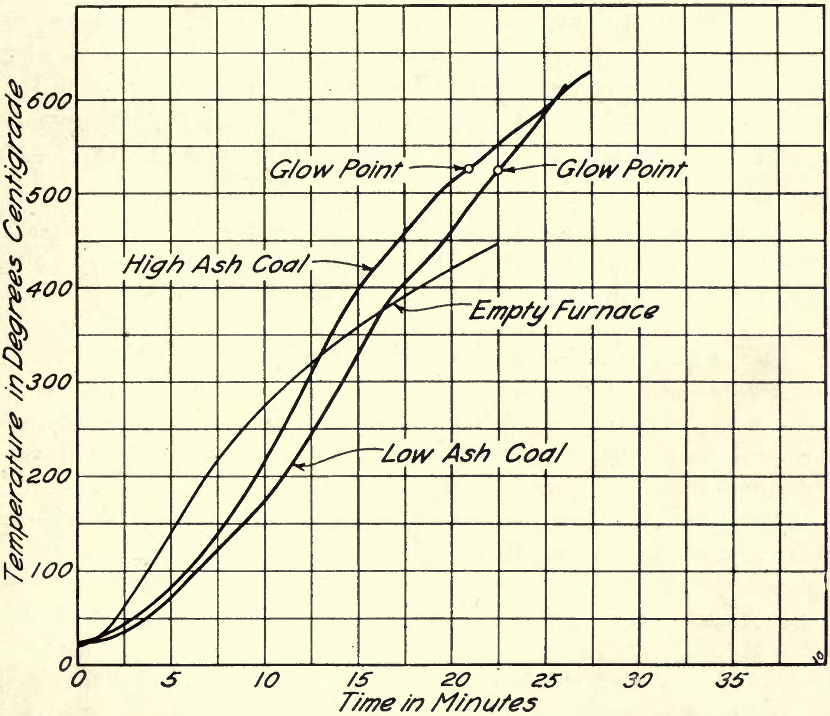

FIG. 10. EFFECT OF HIGH ASH ON HEATING CURVE

(1) Shale has a lower specific heat than coal. No figures on the specific heat of shale are known, but similar substances, such as

brick, kaolin, and ashes, have specific heats ranging from 0.120 to 0.224, whereas that of coal is given by the same authorities as 0.314. To be sure the relative thermal conductivities of these substances enter into the discussion to some extent since it is a rate of heating that is being observed. From the best figures obtainable the conductivity of coal is approximately double that of shale, which fact would tend to offset the opposite relation of the specific heats to some extent.

(2) Pure coal requires more heat in the early stages to drive off moisture and other volatile matter.

(3) In the high refuse samples, more air is supplied to the individual particles or the air which reaches any particular piece is higher in oxygen than in the case when the coal particles are more concentrated.

If the true explanation for this rapid heating of high ash coal could be found it might explain the prevalence of gob fires, refuse pile fires, and fires in piles of dirty coal.

28. *Effect of Sulphur.*—The effect of sulphur was tested in like manner by adding to the coal an amount of pyrite equivalent to about 6 per cent sulphur in the sample, the particles of pyrite being the same size as the particles of coal. As this sample was heated, the individual particles of pyrite and the coal just adjoining them glowed at a comparatively low temperature. Undoubtedly these individual particles were at or above the temperature of the glow point but their accumulated heat had a negligible effect on the temperature of the entire mass. From this it was assumed that the glow point of the coal substance proper is independent of the percentage of sulphur. It must be admitted, however, that this constitutes an objection to the use of the glow point as a criterion for ignition temperatures since it is well known that sulphur in pyrite burns at a lower temperature than coal and consequently assists in its combustion and ignition.

29. *Effect of Moisture.*—The effect of moisture was studied by saturating a 35 g. sample of coal and running it under standard conditions. As in the case of the experiments on the high ash coals the tabulated results show that the glow points for the high moisture samples are practically the same as for the original coal.

TABLE 11

EFFECT OF MOISTURE ON GLOW POINT

Glow Points of Coal		Glow Points of Coal Saturated with Moisture	
Deg. C.	Deg. F.	Deg. C.	Deg. F.
526	979	515	959
525	977	529	984
512	954	526	979

Fig. 11 shows the heating curve under these conditions. In this curve the evaporation of the moisture is clearly indicated at 100 deg., but in spite of this retardation in heating the coal reaches the glow point sooner than that which was not dampened. In this

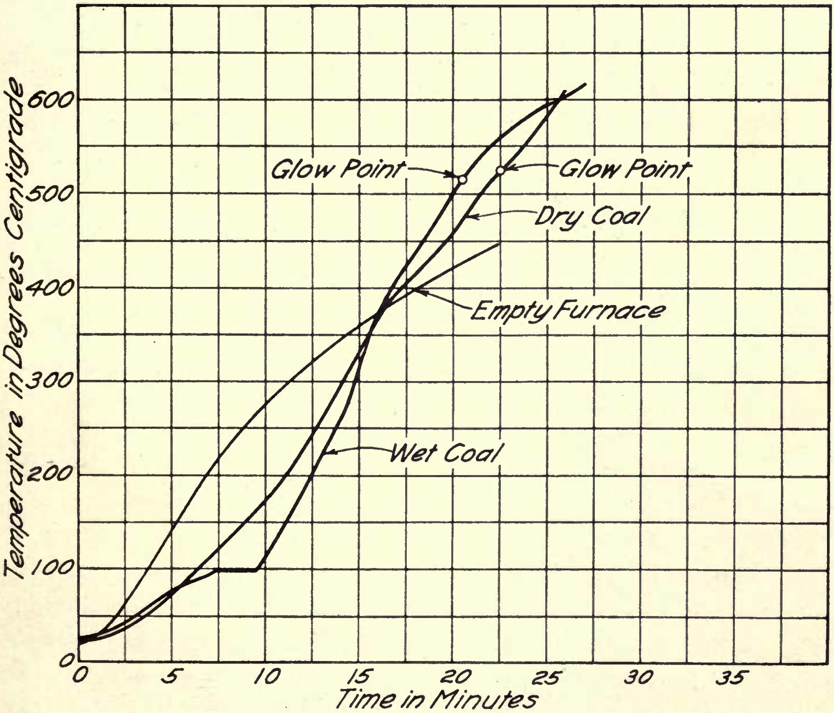

FIG. 11. EFFECT OF HIGH MOISTURE ON HEATING CURVE

experiment the coal showed an unusual tendency to flame before the glow point was reached. Several trials had to be made before the glow point could be obtained prior to the flame. It would seem, therefore, that there is some weight to the contention that better combustion is obtained from coal which has been previously moistened. Certainly in these experiments the moistened coal was more inflammable.

IX. Results and Discussion

30. *Tests on Ten Different Coals.*—In addition to the standard coal ten different coals were tested and their glow points determined as shown in Table 12.

Table 12

Glow Points of Coals Tested

Coal from	Glow Points		Average		Difference in Deg. from Average
	Deg. C.	Deg. F.	Deg. C.	Deg. F.	Deg. C.
Herrin, Williamson County	433	811	440	824	—7
	451	844	...	...	11
	437	819	...	...	—3
Georgetown, Vermilion County	453	847	456	852	—3
	453	847	...	...	—3
	466	871	...	...	10
	451	844	...	...	—5
Bennett Station, Vermilion County	498	928	496	925	2
	494	921	...	...	—2
Old Ben No. 8	526	979	521	970	5
	525	977	...	...	4
	512	954	...	...	—9
Lignite, Manitoba, Canada	535	995	526	978	9
	522	972	...	...	—4
	520	968	...	...	—6
Castle Gate, Utah	535	995	528	982	7
	524	975	...	...	—4
	525	977	...	...	—3
Lovington, Moultrie County	526	979	530	986	—4
	534	993	...	...	4
Lincoln, Logan County	559	1038	558	1036	1
	557	1035	...	...	—1
Anthracite, Pennsylvania	598	1108	600	1112	—2
	598	1108	...	...	—2
	605	1121	...	...	5
Coke	607	1125	606	1123	1
	607	1125	...	...	1
	605	1121	...	...	—1

The average glow points shown in Table 12, with the exception of those for anthracite and coke, show no apparent relation between the glow point and the liability to fire while in storage. For example the lignites and the coal from Castle Gate, Utah, which acts very much like a lignite in coking experiments, both have a comparatively high glow point, whereas the coal from Herrin, Williamson

County, Illinois, which ordinarily shows no unusual tendency to fire while in storage, has the lowest glow point of all the coals.

31. *Determination of Various Glow Points.*—So far in these experiments no attempt had been made to determine the oxygen of the coals nor the amount of oxygen absorbed after the coal was mined. It had been attempted simply to develop a method for the determination of ignition temperatures and to show that this method would give consistent results. Wheeler had shown that relative ignition temperature varied with the total oxygen content. Before making any positive statements, therefore, particularly concerning the relation between the glow point and the tendency to fire in storage, it was necessary to make a series of tests determining the glow point of the same coal both freshly mined and after it had been exposed to the action of oxygen for various periods.

Coal No. 1.

(Herrin-Watson Coal Co., Herrin, Williamson County, Illinois.)

This coal had the lowest glow point temperature of any of the coals tested. Three runs were made on the ¼-⅛-in. size, giving results as shown in the table. The heating curve showed no unusual characteristics and is not included.

Coal No. 2.

(Sharon Coal Company, Georgetown, Vermilion County, Illinois.)

In taking the heating curve of this coal it was observed that apparently strong exothermic reactions were taking place before the glow appeared. In order to be sure of this fact and to see how nearly the heating curves could be duplicated, a second curve was taken on this coal. The two heating curves plotted against the furnace heating curve are shown in Fig. 12.

Coal No. 3.

(Bennett Station, Vermilion County, Illinois.)

The peculiarity of this coal may be seen in the heating curve, Fig. 13, which displays rather unusual evidence of exothermic reactions before the glow point is reached. In this particular coal the glow appears on a rather steep portion of the curve, whereas in most of the other samples the glow point marks a flattening of the curve rather than a steeper inclination.

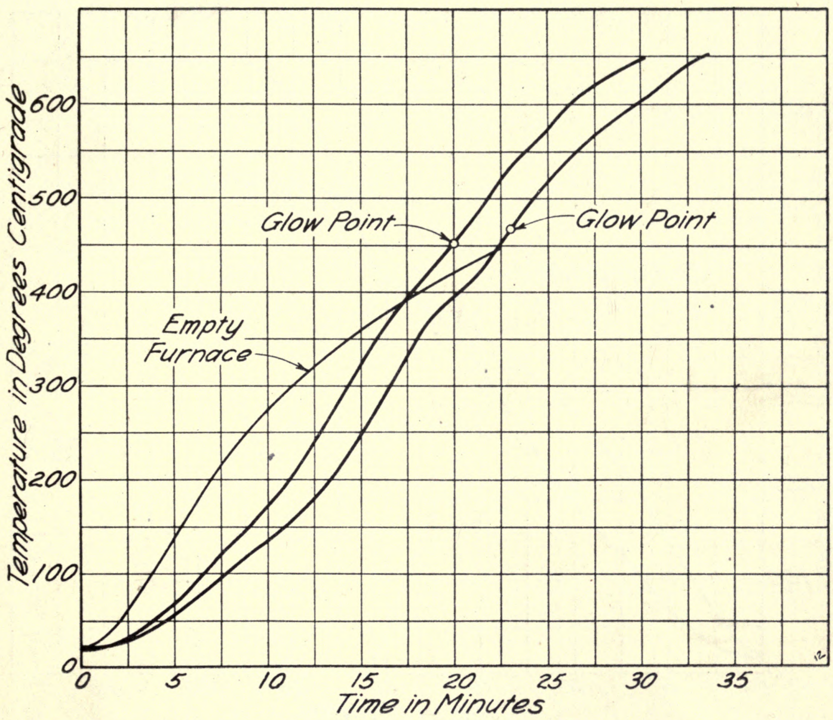

FIG. 12. HEATING CURVES OF COAL NO. 2, SHOWING SIMILARITY OF CURVES FOR CONSECUTIVE RUNS

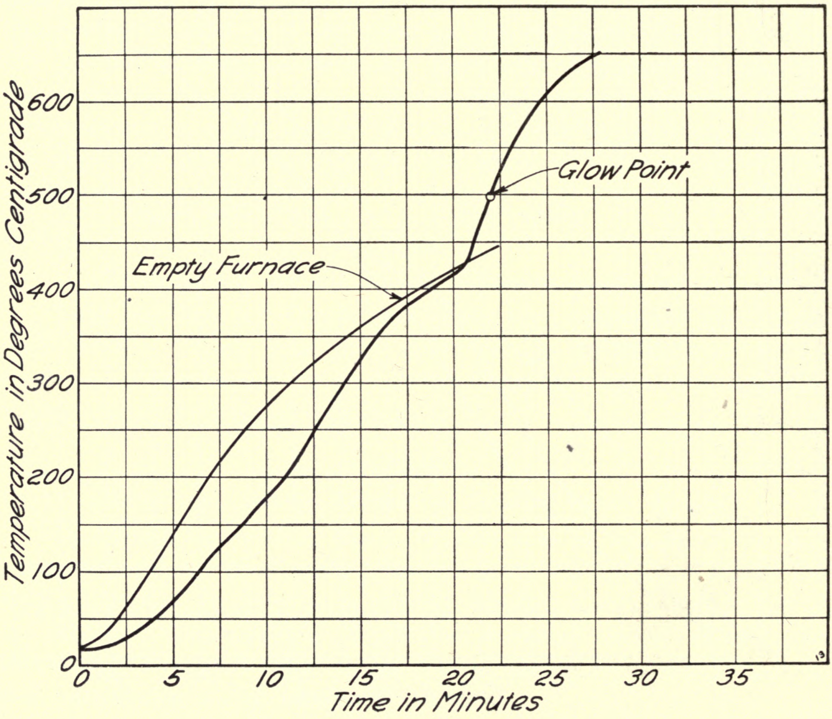

Fig. 13. Heating Curve, Coal No. 3

Coal No. 4.

(Old Ben Corporation, Mine No. 18, Johnson City, Illinois.)

This coal was used in the experiments to show the effect of high ash and high moisture on the heating curve. The heating curve may be seen in Figs. 10 and 11.

Coal No. 5.

(Lignite from Manitoba, Canada. Heating Curve, Fig. 14.)

Up to a temperature of about 150 deg. this curve is comparatively flat, as could be expected from the nature of the coal. During this range moisture and other volatile matter requiring heat for vaporization were being driven off. After this process was complete, however, there was a large discrepancy in temperature between the coal and the furnace; consequently the coal heated rapidly to the glow point.

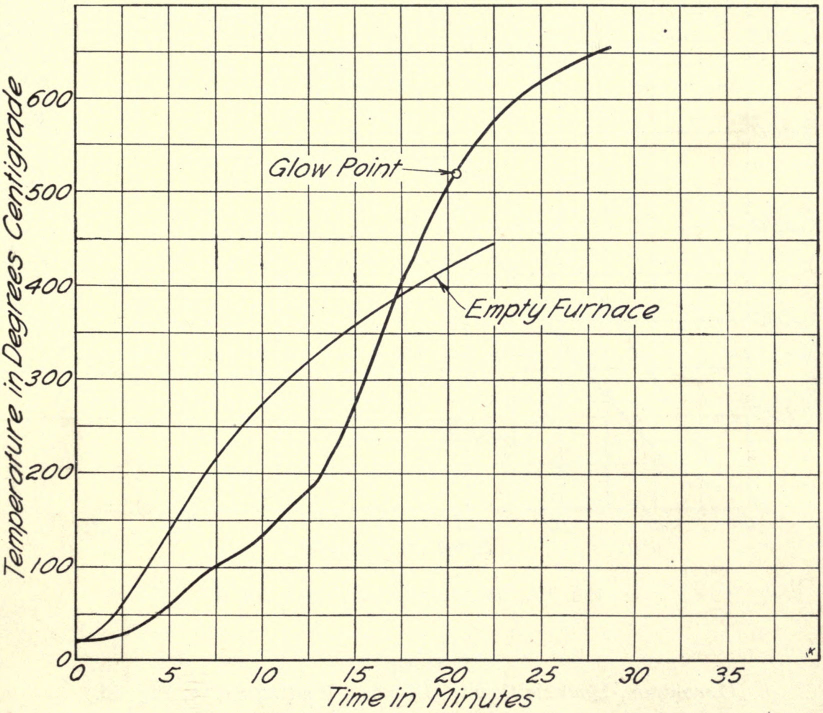

FIG. 14. HEATING CURVE, COAL NO. 5

Coal No. 6.

(Bituminous Coal. Castle Gate, Utah. Heating Curve, Fig. 15.)

In coking experiments made under the direction of Professor Parr this coal acted very much as a lignite. The moisture content, however, is only 3.5 per cent, which is much less than that of lignite; consequently the lower range of the curve does not show the flattening tendency that is apparent in the lignite curve. As may be seen in Table 12, the glow point of this coal was practically the same as that of the lignite.

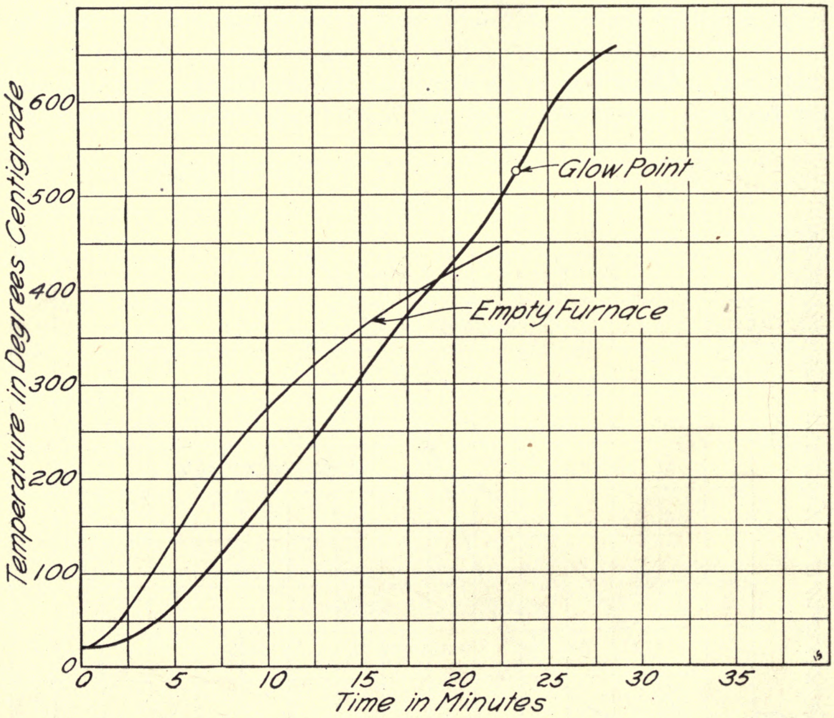

FIG. 15. HEATING CURVE, COAL NO. 6

Coal No. 7.

(Lovington, Moultrie County, Illinois. Heating Curve, Fig. 16.)

Coal No. 8.

(Lincoln, Logan County, Illinois. Heating Curve, Fig. 17.)

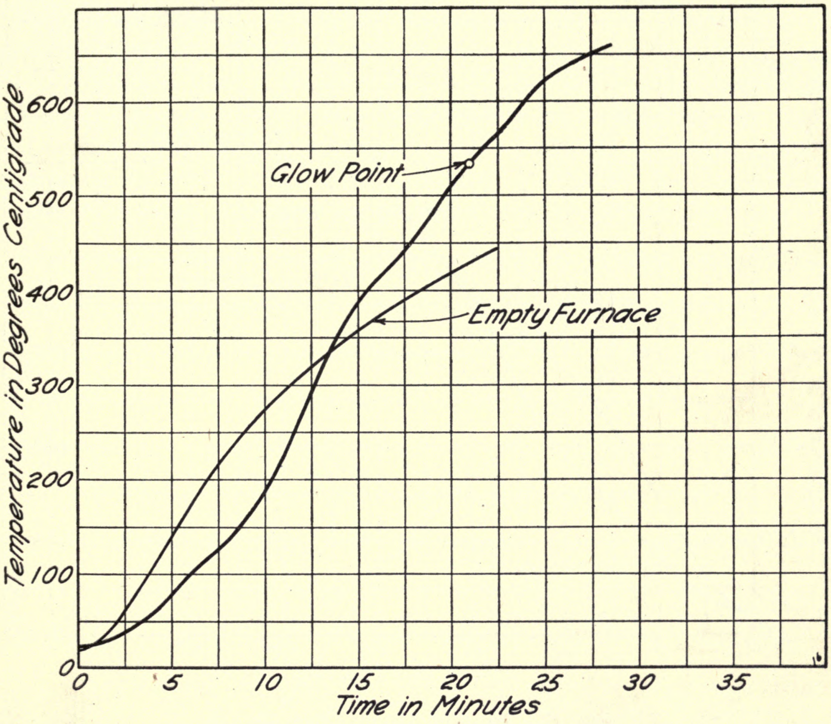

FIG. 16. HEATING CURVE, COAL NO. 7

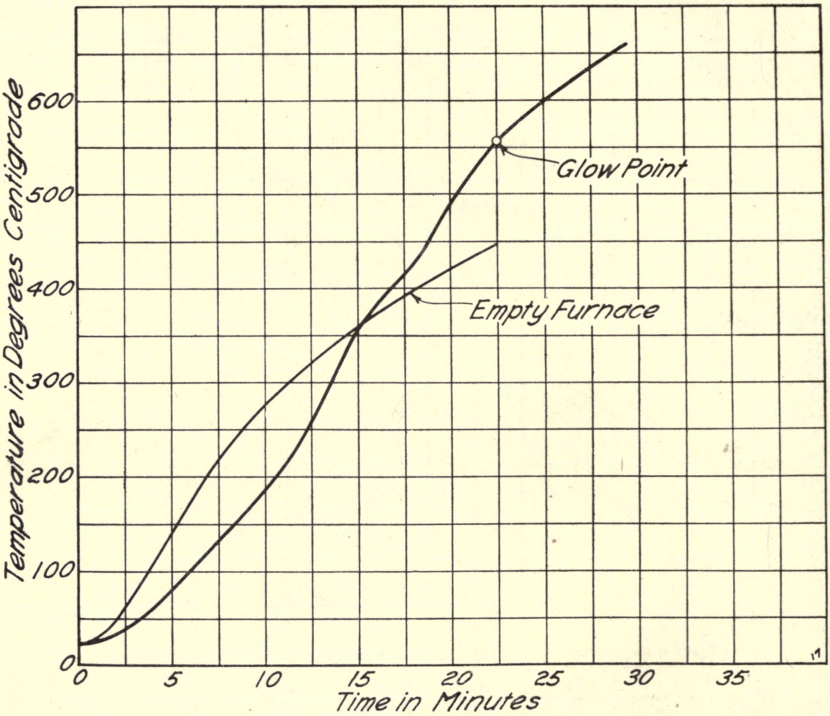

FIG. 17. HEATING CURVE, COAL NO. 8

Coal No. 9.

(Anthracite. Pennsylvania.)

The glow point of this coal was much higher than any of the bituminous coal or the lignite, as might be expected if the glow point is any criterion of ignition temperature. The heating curve as shown in Fig. 18 is an extremely smooth curve from the lower temperatures to the glow point, showing no exothermic reactions because of the relatively small amount of volatile matter present. As the heating of anthracite coal to the glow point was more a process of furnishing heat to a substance with a definite specific heat than heating something which contains certain volatile constituents requiring heat for their vaporization, its heating curve more nearly parallels that of the empty furnace. To be sure at a temperature of about 200 deg., anthracite began to furnish heat and its heating curve to gain on the furnace

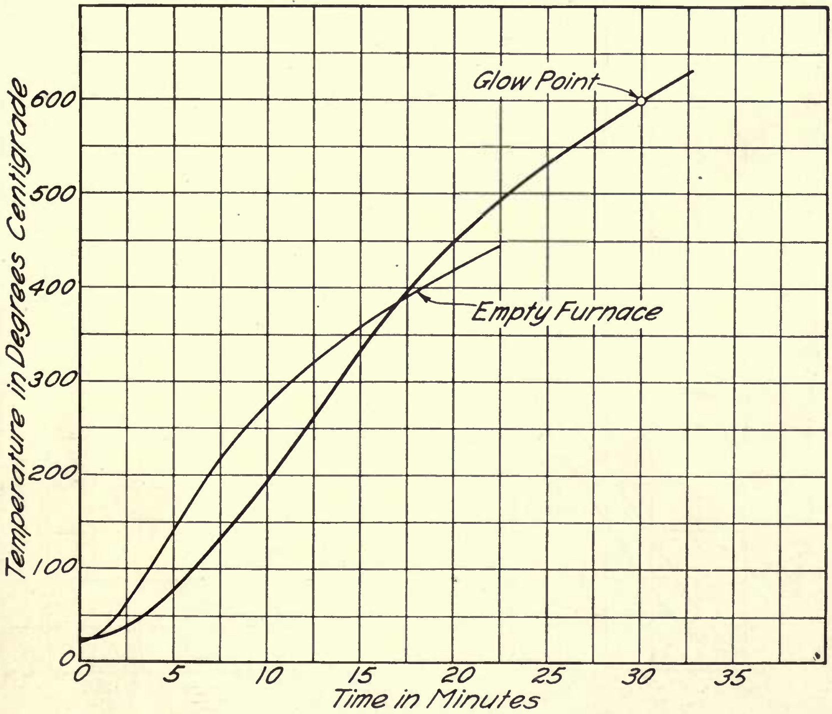

Fig. 18. Heating Curve, Coal No. 9 (Anthracite)

curve, but this gain is not as abrupt nor as well marked as in the case of the higher volatile substances illustrated in the previous diagrams. It is more apparent than ever in this heating curve and in that of coke, Fig. 19, that the glow point was merely an incident in this heating and did not mark a noticeable change in the heating rate.

Coke.

(Heating Curve, Fig. 19.)

This heating curve is even smoother and closer to the curve of the furnace than that for anthracite. However, at approximately the same temperature, 200 deg., self-heating began, causing a gain in the coke heating curve over the furnace curve.

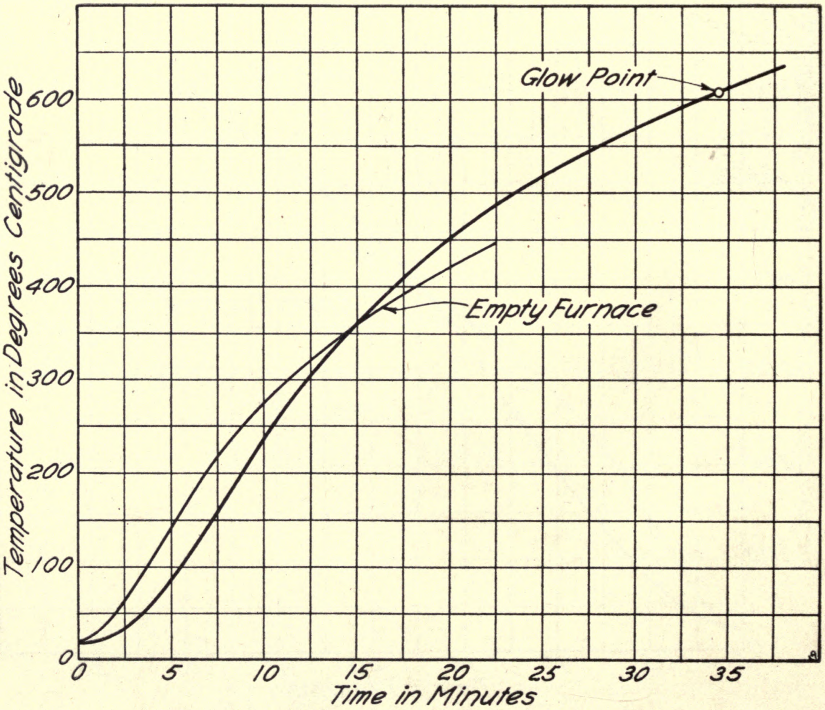

FIG. 19. HEATING CURVE, COKE

X. CONCLUSIONS.

32. *Summary.*—

(1) The "Ignition Temperature" of coal means nothing unless it is applied to some definite point in the process of heating the coal, which can easily be determined and duplicated.

(2) The temperature at which the coal glows seems to be the most logical point to choose as the ignition temperature. It is easily observed, can be duplicated with a fair degree of accuracy, and marks the beginning of visible combustion.

(3) The glow point is probably affected by the oxygen content of the coal, and perhaps by other agencies made active by weathering.

(4) The glow point is not affected by ash, moisture, size of particles, slight variations from the normal air supply, or rate of heating.

(5) There is no indication at present that the glow point bears any direct relation to the liability to fire while in storage. Perhaps if a series of tests were made on the glow points of freshly mined coal new information would be brought to light which would lead to the discovery of some more definite relation between glow point and the firing qualities of the coal.

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