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F.R.Note No.10/1952.

June, 1952.

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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

THE DETERMINATION OF THE IGNITION TEMPERATURE OF SOLIDS BY A RISING
TEMPERATURE METHOD

by

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Summary

The definition and utility of ignition temperatures of solid materials determined by a rising temperature method are investigated. Ignition temperature is a characteristic with definite, but limited, applications; except when extreme values occur it is not considered to be a valid index of fire hazard.

Introduction

The relative fire hazard associated with different solid materials depends, in the first place, on the ease with which they can be ignited. Attempts to assess ease of ignition have centred largely on the measurement of "ignition temperature". Broadly speaking, the ignition temperature is the temperature at which the ignition of the material can be regarded as certain to occur under a given set of experimental conditions; the precise definition and method of determination is subject to wide choice. To be of maximum use the ignition temperature must not only be capable of classifying materials in order of ease of ignition but must have some absolute significance for predicting the hazard due to a material in any situation.

The definitions of ignition temperatures and related temperatures, and the methods used to determine them, have been reviewed by Brown⁽¹⁾ who has proposed a definition based on the behaviour of a material when heated relatively slowly in a furnace. This "rising temperature" method with continuous observation of the specimen temperature appears capable of yielding most information on the ignition process. This note describes an investigation of the method and the definitions of ignition temperature based on it, and discusses briefly the application of these temperatures in general.

It has been shown that the moisture content of the specimen may influence the results but, otherwise, the effect of the character of the specimen itself (e.g. particle size) has not been investigated in the work described in this note.

Theoretical

In the rising temperature method of ignition temperature determination a specimen of the material to be tested is contained in a vessel inside an electric furnace. Air, preheated to near the furnace temperature, is passed through or round the specimen at a fixed rate and the furnace is heated from room temperature with (for the work described in this note) constant current.

The temperatures of the specimen and furnace are recorded at frequent intervals during the heating and the ignition temperature is deduced from the behaviour of these temperatures, or of their differences, in ways to be described.

It is possible, by using a simple model, to make a theoretical prediction of the form of the temperature-time curves which is of assistance in discussing the different definitions of ignition temperature which have been proposed and the effects of the variables in their experimental determination.

a. The form of the temperature-time curves

Let q_1 = rate of heat transfer from the furnace to the specimen,
 q_2 = rate of heat generation in the specimen,
 q_3 = rate of heat lost from the specimen to the atmosphere,
all at time t .

Then, if q is the rate of heat gain in the specimen at time t , we have

$$q = q_1 + q_2 - q_3$$

Since the specimen is, in practice, virtually surrounded by the furnace, q_3 is zero as long as the furnace temperature exceeds the specimen temperature and the specimen evolves no volatile products.

If S is the temperature of the specimen at time t (assumed uniform), and C is its thermal capacity, we have

$$\frac{dS}{dt} = \frac{q}{C} = \frac{q_1 + q_2 - q_3}{C} \dots\dots\dots(1)$$

The rate of heat transfer between the furnace and the specimen may be written formally as

$$q_1 = h A (F - S)$$

where F is the furnace temperature at time t , A is the area of the specimen boundary surface, and h is the overall coefficient for heat transfer to the specimen. In general, h will be a function of temperature, the rate of air flow, and the physical constants of the furnace and its contents.

Substituting the above expression for q_1 , in equation (1) we get

$$\frac{dS}{dt} = \frac{hA}{C} (F - S) + \frac{q_2 - q_3}{C} \dots\dots\dots(2)$$

Taking the simple case for which hA/C is constant equation (2) may be multiplied by $\exp. pt$, where $p = hA/C$, and integrated to give

$$S - F = e^{-pt} \left\{ S_0 - F_0 - \int_0^t e^{pt} \frac{dF}{dt} dt + \int_0^t \frac{q_2 - q_3}{C} e^{pt} dt \right\} \dots\dots(3)$$

where $F_0 = F$, and $S_0 = S$, when $t = 0$.

Equation (3) may be interpreted by considering first the case for a dry inert material, i.e. for which q_2 and q_3 are both zero throughout. With $F_0 = S_0$, as in practice, we then have

$$S - F = -e^{-pt} \int_0^t e^{pt} \frac{dF}{dt} dt \dots\dots\dots(4)$$

The furnace temperature may be expressed, sufficiently well for the present purpose, by the following equation which is based on constant power input to the furnace and on the assumption that the heat loss to the surroundings obeys Newton's law:-

$$F = F_{\infty} - (F_{\infty} - F_0) e^{-bt}, \dots\dots\dots(5)$$

where $F_{\infty} = F$ at $t = \infty$ and $b = \text{constant}$.

Differentiating (5) with respect to t , inserting in (4), and integrating, we obtain

$$S - F = -\frac{b}{p-b} (F_{\infty} - F_0) (e^{-bt} - e^{-pt}) \dots\dots\dots(6)$$

This expression has the following characteristics:-

$$\begin{aligned} S - F &= 0 && \text{when } t = 0 \text{ or } \infty \\ (S - F)' &= -b(F_{\infty} - F_0) && \text{when } t = 0 \\ &= 0 && \text{when } t = \infty \\ &= 0 && \text{when } t = \frac{\ln b - \ln p}{b-p} = t_m \text{ (} S - F = \text{minimum)} \\ (S - F)'' &= 0 && \text{when } t = 2t_m \text{ (inflexion)} \\ &= 0 && \text{when } t = \infty \end{aligned}$$

Substitution of (5) in (6) gives the equation for the specimen temperature as a function of time. This has the following characteristics:-

$$\begin{aligned} S' &= 0 \text{ when } t = 0 \text{ or } \infty \\ S'' &= 0 \text{ when } t = t_m \text{ (inflexion).} \end{aligned}$$

Using these data, and the experimental fact that t_m is small, the temperature and temperature difference curves have been sketched in Fig. 1; the temperature scale for the difference curve has been exaggerated.

When an exothermic reaction occurs (i.e. $q_2 - q_3 > 0$) the specimen temperature will begin to increase more rapidly than shown and may exceed the furnace temperature, but the complete temperature-time curve cannot be predicted from equation (3) without a knowledge of $q_2 - q_3$ as a function of time. However, with the furnace and materials used in the present work, and probably with all materials which merit investigation by this technique, $q_2 - q_3$ only becomes appreciably greater than zero at a time which is certainly later than the minimum of $S - F$ at t_m but which may be less than $2t_m$. Moisture in the specimen may cause $q_2 - q_3$ to be negative until it has been driven off, i.e. until the specimen temperature is in the neighbourhood of 100°C , and the minimum in the curve for $S - F$ will then not necessarily occur at t_m as given above.

The curves obtained in practice with a moist combustible material are indicated in Fig. 1 by chain lines; the case is shown in which the specimen temperature eventually rises continuously and very steeply to high values associated with glowing combustion. Flame does not normally appear since the volatile combustible products are driven off at temperatures too low to be ignited.

It will be seen that the exothermic reaction introduces a second inflexion into the specimen temperature and temperature difference curves. On the other hand, it is evident from inspection of Fig. 1 that the exothermic reaction will remove the inflexion on the theoretical curve of $S - F$ for a dry specimen if it begins appreciably before time $2t_m$.

b. Definitions of ignition temperature

Characteristics of the above curves which have been used as definitions of ignition temperature are described below.

(i) First occurrence of exothermic reaction Brown¹ emphasizes that the stage which is fundamental to the successful ignition of a solid is that at which the rate of heat development by the reactions leading to ignition first exceeds the heat loss to the surroundings; i.e., in the notation used above, $q_2 - q_3$ first becomes positive. He maintains that for a given set of conditions this occurs at a definite temperature which he terms the ignition temperature, and which he determines as the temperature of "downward break" in the curve for $F - S$; this corresponds to the point P on the curve for $S - F$ in Fig. 1.

Essentially Brown's method consists in locating the point at which a smooth curve drawn through the experimental points diverges by an arbitrary small amount from the tangent to the curve at the second inflexion. The distance of this point from the inflexion will be a variable quantity depending on $(S - F)'''$ and on the scatter of the experimental points and the thickness of the drawn lines.

It would seem that a better choice of temperature to define the occurrence of exothermic reaction is that at the second inflexion, either on the specimen temperature curve or on the difference curve. The latter is preferable since, with a smaller total range, a more open scale is possible on the measuring device. Provided the curve is fairly symmetrical about the inflexion it should be possible to locate the inflexion with reasonable accuracy, since errors in drawing the curve and tangent will tend to cancel out. The possibility of using this point is examined in this work.

Neither the inflexion nor Brown's point can give the temperature at which $q_2 - q_3$ first exceeds zero; this occurs at an unknown time before the inflexion.

(ii) Point of rapid temperature rise Determination of the point at which the rate of rise of the specimen temperature first increases is subject to the same difficulties as the determination of Brown's point. The most clearly defined point associated with the period of rapid temperature rise is that chosen by Swietoslawski, Roga, and Chorazy² and by Bardsley and Skeet³. It is, in terms of the above analysis, the temperature at the intersection of the tangents to the specimen temperature curve at the second inflexion and at the maximum gradient. In practice the curves are virtually linear for a considerable period containing the inflexion and during the steep rise, and determination of this point consists merely of producing these lines to intersection; this is shown in Fig. 3.

Although this point is artificial it has some practical justification as a definition of ignition temperature, and will be so used in this work. Thus, it is a temperature at which visible combustion will occur within a relatively short time (a few minutes only) in the continued presence of an external source of heat (in this case the furnace) and it is easily determined with precision. Further, its determination requires completion of the whole ignition process and it will be a function of all stages of the process. It differs from Brown's point in that it occurs near the end rather than the beginning of the self heating stage preceding ignition.

(iii) Crossing temperature The temperature at which the specimen temperature equals the furnace temperature was regarded by Wheeler⁴ as critical in the ignition of coals. It is evident from Fig. 1 that the point at which the specimen and furnace temperature curves cross (i.e. $S = F$) depends on the magnitude of $S - F$ in the early stages. Thus if the apparatus design and operating conditions are such that $S - F$ is small when $q_2 - q_3$ is near zero the curves will cross soon after an exothermic reaction begins; when $S - F$ is large the cross-over will occur near the rapid increase of specimen temperature.

It may be noted that at the cross-over we have, from equation (2),

$$\frac{dS}{dt} = \frac{q_2 - q_3}{C},$$

i.e. the gradient of the specimen temperature curve at the cross-over depends only on the properties of the material. But this quantity is of little use for comparative purposes unless it can be determined at the same temperature for different materials, which is normally not possible.

c. Effect of variables

It is evident that if the ignition temperatures are to be truly comparative for different materials the rate of furnace heating and the initial temperatures, S_0 and F_0 , must be approximately the same in all tests. If, further, hA/C could be maintained constant or, at best, the same for all specimens the ignition temperature and other points would vary only as the last term of equation (3) varied for different materials.

The thermal capacity of the specimen must be expected to vary as the temperature rises. But if, as was the case in this work, the specimen is in the form of a porous packing the initial value, at least, of A/C could be kept constant to some extent by adjustment of the packing density. Within the range of densities which do not affect the rate of reaction, dS/dt as a function of the ratio $(q_2 - q_3)/C$ alone, in equation (2), is independent of the packing density. Factors in the design and operation of the apparatus which affect the overall coefficient, h , for heat transfer between the furnace and the specimen can be kept constant. But the heat balance within the specimen itself will depend on its thermal conductivity and hence on the packing density. All that can be done initially, therefore, is to maintain A approximately constant. The ignition temperatures determined then apply to the materials at the packing density employed.

For a given packing density the ratio A/C is proportional to the boundary surface per unit volume of the specimen, and therefore depends on its size and shape. The larger the specimen the smaller this ratio will be for a given shape; consequently at a given rate of heat evolution the term involving A/C in equation (2) diminishes in importance as the size of the specimen increases.

For a given furnace the main variables which require testing for their effect on the ignition temperature determination are the rate of air flow, the rate of heating of the furnace, and the size and packing density of the specimen.

Experimental

The liner and internal fittings of the ignition furnace are shown in cross section in Fig. 2. The whole fits into an electric furnace with a winding graduated in the usual way to improve the uniformity of temperature along the length.

The apparatus is based on that used by Brown¹ and by Bardsley and Skeet³. The main modifications are that the furnace temperature is read from a mercury-in-glass thermometer inserted into a cavity in the thick aluminium liner, and the specimen is packed into a pyrex cylinder fitted by a standard ground joint. The specimen is supported in the tube on a disc of stainless steel gauze held by a split ring.

The temperature difference between the furnace wall and the centre of the specimen was determined with a calibrated platinum-rhodium thermocouple (34 S.W.G.) and galvanometer. The thermocouple wires were threaded through ceramic tubes but the junctions were exposed. The junction in the furnace wall was contained in a cavity parallel and close to that containing the

thermometer. A preliminary test was carried out with a junction inserted into each cavity; up to 208°C the temperature difference indicated did not exceed 1°C, but it varied systematically with the temperature and changed sign at about 120°C. No correction for this effect was applied to the determination of ignition temperature.

All the materials examined were either in the form of powders or short fibres. The supporting gauze was kept at 2.0 cm from the shoulder of the tube and the amount of material used was adjusted to give a packing length of 2.5 - 3.0 cm for the purpose of keeping A approximately constant (above). The internal diameter of the specimen tube was normally 1.9 cm.

The principal materials used for testing the effect of the different variables on the ignition temperatures were a sample of grass meal and a sample of beech sawdust size-graded to 20-40 B.S.; details on the nature of the grass meal were not available but, for the purposes of this work, they were not required. One series of tests was made using wood fibreboard disintegrated by hand rasping and a sample of Daisee jute (*Corchorus elitorius*) cut into lengths of about one cm. Ignition temperature determinations were also made on a number of other woods (Table V below). The samples of wood were reduced to powder by hand rasping.

Results

a. General

Fig. 3 illustrates the general behaviour of the materials tested; it shows the temperature curves for 2g of beech sawdust with a rate of air flow of 2.94 cm/sec., and the inset shows the final stages of the specimen temperature curve for the beech with an air flow of 0.59 cm/sec. The difference in temperature between the specimen and furnace wall is given in terms of the thermocouple e.m.f. in microvolts.

In all cases the first visible evolution of volatile products occurred in the early stages of exothermic reaction indicated by upward curvature of the specimen temperature curve; in this case it occurred at about 227°C, but in others it was noticed at slightly lower temperatures. The evolution increased slowly as the temperature rose further until, coinciding with the period of most rapid temperature rise, there was a rush of thick smoke which lasted for little more than one minute.

With the higher rates of air flow (velocities up to 2.9 cm/sec.) the diminution of the smoke was followed shortly by glowing of the specimen, but the behaviour of the registered specimen temperature then depended on the nature of the specimen. Thus, with grass meal, the combustion occurred fairly uniformly at the lower end of the specimen and the temperature rose steadily to values in excess of 500°C. But, with beech sawdust, glowing occurred intermittently at widely separated points and the registered temperature actually decreased while the glowing was in progress.

At low rates of air flow (velocities of 0.29 - 0.59 cm/sec.) the temperature rise was arrested during the rapid evolution of smoke. The temperature then fell until the evolution of smoke diminished, when it rose again at a steady but reduced rate (Fig. 3 inset). This effect at low rates of air flow was doubtless due to dilution of the oxygen supply, by the gases evolved, sufficiently to reduce the rate of oxidation; the subsequent temperature rise then corresponded to slow ignition of the carbonised residue. At intermediate rates of air flow, and depending on the material, interruptions of the steep temperature rise to glowing combustion occurred at higher temperatures than in Fig. 3 (inset) and were of shorter duration.

Beech sawdust with a moisture content of 9.2%, and beech after oven drying overnight at 105°C, were both heated in the ignition furnace in a current of nitrogen instead of air. The resulting curves for the temperature difference between the specimen and furnace, in terms of the thermocouple, e.m.f., are shown in Fig. 4. The rate of nitrogen flow was 1.76 cm/sec, and the furnace and specimen temperatures were taken to 300°C and 270°C respectively.

The curve for dry beech does not show the inflexion which should occur in the absence of reaction. It indicates, in fact, that there is a slow evolution of heat in the specimen during the later stages of the heating, i.e. after about 50 minutes. There is, however, no indication of the vigorous exothermic decomposition which occurs in the presence of oxygen. The amount of smoke produced was relatively small. These results were tested and confirmed for all the woods listed in Table V. It appears that the exothermic decomposition of wood which occurs at about 275°C during dry distillation⁵ does not make much contribution to the heat balance during ignition under the conditions of these tests.

It will be seen that the first inflexion in the curve for S - F, on which depends the occurrence of the second inflexion when an exothermic reaction begins (c.f. Fig. 3), in this case depends entirely on the presence of moisture. In general, the position of the second inflexion will vary with moisture content and, for comparative determinations of the inflexion, this must be kept constant. The moisture content will also affect the determination of Brown's point since this depends on drawing a tangent through the second inflexion.

In a test with beech at an air flow of 1.76 cm/sec it was found that, on applying a small gas flame, transient flames were obtainable in the gases in the specimen tube when the specimen temperature was about 265°C, and the first persistent flame at the mouth of the tube occurred at a temperature of about 290°C.

b. Effect of the rate of air flow

The effect of varying the rate of air flow is shown in Table 1 for duplicate determinations on beech sawdust and on grass meal. The beech was packed in a length of 2.5 cm at a density of 0.283 gm/cc and the grass meal in 3.0 cm at a density of 0.235 gm/cc. The furnace was heated at 400 watts. The rate of air flow is expressed in terms of the air velocity in the empty specimen tube (1.9 cm diameter).

Table 1. Effect of the rate of air flow

Material	Air Flow cm/sec	Ignition Temperature °C	Crossing Point °C	Brown's Point °C	Inflexion °C
Beech (20-40 I.M.M.)	0.59	244	272	218	185
	0.59	245	270	214	191
	1.76	248	271	204	166
	1.76	246	272	180	160
	2.94	249	272	168	149
	2.94	247	274	190	164
Grass meal	0.29	231	256	174	154
	0.29	228	256	184	168
	0.59	232	256	170	158
	0.59	231	256	180	160
	1.17	229	256	200	170
	1.17	230	255	180	158
	1.76	234	256	181	159
	1.76	230	255	183	148
	2.35	235	258	164	-
	2.35	240	258	178	148
	2.94	236	258	168	150
	2.94	236	260	172	158

- (i) Crossing point It will be seen from Table 1 that this point is closely reproducible; it increases very slightly with air velocity over the range covered.
- (ii) Ignition temperature The reproducibility of this point is also good and values tend to be slightly higher for the higher air velocities.
- (iii) Brown's point and inflexion For both points the results are not sufficiently reproducible to be conclusive, but with beech these points tend to occur at lower temperatures as the air velocity increases.

The variation in the temperatures at the inflexion of the temperature difference curves is greater than can be accounted for by uncertainty of location and indicates a real difference between the duplicates. In some cases this is true also for Brown's point.

The rate of air flow will influence the results through its effect both on $q_2 - q_3$ in equation (2) and on the overall heat transfer coefficient, h . In the temperature range $100^\circ - 200^\circ\text{C}$, when all the moisture will have evaporated and $q_2 - q_3$ is small, the effect of air flow on h will be important. That this is so is indicated by the correlation between the rate of temperature rise at the inflexion in the temperature curve for the grass meal and the rate of air flow, Fig. 5. Since they occur in or near this temperature range Brown's point and the inflexion in the temperature difference curve may be expected to be sensitive to variations in h and, hence, also to factors other than air flow which affect h ; the most important of these are likely to be differences in the porosity and thermal conductivity of the specimen which can arise from local density variations during the original packing and from changes in porosity of the specimen during a test. It is suggested that these factors, rather than variation in $q_2 - q_3$, are responsible for the large variability of duplicate determinations of these points.

In the neighbourhood of the ignition temperature and, especially, the crossing point, when $F - S$ approaches zero and q_2 is becoming large, the term involving $q_2 - q_3$ will become the most important in equation (2). Then, except at the low rates of air flow which were found to limit the reaction rate, the air flow will influence the results mainly through q_3 ; the results show that either this effect, or q_3 itself, is relatively small.

Fig. 5 indicates an inverse relationship between the rate of increase of the specimen temperature at the inflexion and the air flow; but a ten-fold increase in the air flow produces a decrease of less than 1°C per minute, i.e. less than 20% of the rate of temperature rise. This suggests that the temperature of the air reaching the specimen decreases as its rate of flow through the pre-heater increases, but, also, that the air flow plays a minor part in the transfer of heat from the furnace to the specimen, which therefore takes place mainly through the walls of the specimen tube. It follows that if specimen tubes are to be interchangeable they must be of similar material and wall thickness.

It is concluded that the main requirement of the air supply is that it should be sufficient to ensure a largely uninterrupted progress of the specimen to glowing ignition but otherwise it need not be closely controlled.

c Effect of the packing density of the specimen

Tests were carried out on the beech sawdust and grass meal packed at the highest and lowest densities obtained by ordinary hand packing; the lowest was just sufficient for the central thermocouple to be supported when inserted. In order to cover the wider range of packing densities obtainable with fibrous materials tests were also carried out on the disintegrated wood fibreboard

and the jute fibre. Considerable force was required to pack the fibres at densities approaching those of the beech and grass meal.

The air pressure necessary to maintain the required air velocity with fibreboard at the higher densities was sufficient to blow the specimen out of the tube when it carbonised and contracted. A piece of stainless steel gauze was therefore wedged above the specimen in all but two of the tests with fibreboard. In all tests the air velocity was 1.76 cm/sec in the open tube.

Table II. The effect of packing density

Material	Packing length cm	Packing density g/cc	Ignition temperature °C	Crossing point °C	Brown's point °C	Inflexion °C
Beech (20-40 I.M.M.)	3.0	0.235	242	271	204	175
	3.0	0.235	244	269	195	177
	3.0	0.293	242	266	197	176
	3.0	0.293	244	268	200	189
Grass meal	3.0	0.200	232	255	179	158
	3.0	0.200	234	256	183	166
	3.0	0.235	234	256	181	159
	3.0	0.235	230	255	183	148
Fibreboard	2.9	0.085	285	300	174	-
	2.9	0.085	280	295	172	148
	2.9	0.085	280	299	170	-
	3.2	0.110	281	282	198	161
	3.2	0.110	285	290	196	-
	3.2	0.165	275	273	200	167
	3.2	0.165	270	273	206	182
	3.5	0.201	249	271	178	165
	3.5	0.201	253	267	205	170
	3.5	0.201	254	272	194	164
	3.2	0.110	270	286	175	153
	3.2	0.110	263	285	183	144
Jute	3.0	0.094	290	304	207	-
	3.5	0.212	266	290	193	175
* No top gauze						

The results for beech sawdust and grass meal (Table II) shows that the initial packing density has no effect on any of the temperatures determined. With fibreboard and jute, however, the ignition temperature and crossing point show a marked inverse variation with packing density. With fibreboard there is a tendency for the higher values for Brown's point to be associated with the higher packing densities.

It is concluded that the packing density should always be controlled and specified in determinations of ignition temperature by the rising temperature method.

It is suggested that, when a comparison is being made of the ignition temperature of powdered materials which differ in particle density, the packing densities should be adjusted to give equal porosities; except when the ignition temperature is known to be independent of packing density over ranges which overlap for the different materials.

Comparing the results for fibroboard at a density of 0.110 g/cc it will be seen that the presence of the top retaining gauze leads to a higher ignition temperature.

In view of the results for beech and grass meal it is probable that the variability of Brown's point and the inflexion observed with these materials does not, in fact, depend on variation in the initial packing density but is due to variable changes of porosity during a test. Changes in porosity were indicated by the need to make small adjustments to the air flow during a test. On one occasion the pressure difference across the specimen (beech) was measured. It was found that the pressure rose fairly steadily to 2.6 times its initial value and then began to fall sharply just before the specimen temperature reached the crossing point when, presumably, the specimen began to shrink from the walls of the specimen tube.

The reason for the difference in behaviour of the powdered and fibrous materials is not obvious; but it is possible that, in the case of the former, the changes of porosity during a test were such as to cancel the effect of initial differences in porosity. A particulate packing would presumably have greater freedom for self-adjustment than a packing of interlaced fibres.

d. Effect of the dimensions of the specimen

Determinations were carried out on beech sawdust in two tubes of different diameters and with different lengths of packing. In most cases the packing density was the same. With the larger diameter tube the air pump delivery was sufficient to give only 90-95% of the air velocity used in the narrow tube. The results are given in Table III.

Table III. Effect of the dimensions of specimen (Beech)

Diameter cm	Length cm	Packing density gm/c.c.	Air flow cm/sec	Ignition temperature °C	Crossing point °C	Brown's point °C	Inflexion °C
1.9	1.2	0.294	1.76	255	276	203	167
1.9	3.0	0.293	1.76	242	266	197	176
1.9	3.0	0.293	1.76	244	268	200	187
1.9	3.7	0.286	1.76	245	269	201	175
1.9	3.7	0.286	1.76	244	271	190	168
2.6	3.0	0.293	1.67	217	263	186	164
2.6	3.0	0.293	1.63	216	267	192	175
2.6	4.5	0.293	1.61	219	260	191	177

The Table shows that there is a large decrease in the observed ignition temperature when the diameter of the specimen is increased from 1.9 cm to 2.6 cm.; the crossing point is also lowered but to a less extent. Brown's point appears to be lowered slightly but the inflexion is not significantly affected.

Except for the one case where the length of the specimen was less than its diameter, variation of the length does not influence any of the temperatures.

The reduction in ignition temperature with increase in specimen size cannot be accounted for by the consequent decrease in the ratio A/C in equation (2); decrease in this ratio will reduce the proportion of heat lost when the specimen temperature exceeds the furnace temperature, but at this stage the graph of the specimen temperature rises almost vertically and the effect on the intersection of the tangents will be small. The reduction must be due to the effective reduction of radial heat loss from the interior which occurs in the larger specimen during the stage of spontaneous heating; this permits higher temperatures and greater acceleration of the reaction in the centre.

In the simplest case in which the temperature distribution is not uniform the highest temperatures in the specimen will always occur on the cylinder axis. But, as the diameter of the specimen is increased, the radial temperature gradient set up during the initial heating of the specimen may lead to initiation of the exothermic reaction in an annular region increasingly removed from the centre; ultimately ignition may occur before it is indicated by a thermocouple situated at the centre.

With the rising temperature method it is preferable to employ fairly narrow specimens and so reduce to a minimum complications which may be introduced by non-uniform temperature distribution.

e. Effect of the rate of heating

The effect of rate of heating of the specimen was determined on the grass meal only, packed into a length of 3.0 cm at a density of 0.235 gm/cc and with an air velocity of 1.76 cm/sec. The results are shown in Table IV where the rate of heating of the specimen is expressed in terms of the rate of temperature rise at the second inflexion of the specimen temperature curve; values of the temperature difference at the second inflexion in the difference curve are included as a measure of the "closeness" of the specimen and furnace temperature curves.

Table IV. Effect of the rate of heating (Grass meal)

Furnace power watts	Rate of Temperature rise °C/min.	Temperature difference °C	Ignition temperature °C	Crossing point °C	Brown's point °C	Inflexion °C
144	0.77	13	248	223	187	160
196	1.55	20	232	235	180	153
400	4.45	44	238	259	174	146
400	4.45	45	230	255	183	148
529	6.43	60	232	272	158	158

As the rate of heating is reduced the specimen temperature becomes closer to the furnace curve. This has the effect of lowering the crossing point which, at the lowest rate of heating, is lower than the ignition temperature. Except at the lowest rate of heating the ignition temperature does not vary much with the rate of heating.

There is not sufficient replication of experiments to draw conclusions on the behaviour of Brown's point and the inflexion.

f. Ignition temperatures of woods

Ignition temperatures and other data determined for raspings of a number of different woods are given in Table V. All determinations were carried out with an air velocity of 1.76 cm/sec and furnace power of 400 watts. The moisture contents were determined on the raspings and sawdust.

Table V. Ignition temperature of woods

Wood	Moisture content %	Packing length cm	Packing density gm/cc.	Ignition temperature °C	Crossing point °C	Brown's point °C	Inflexion °C
Beech (<i>Fagus sylvatica</i>)	9.2	2.5	0.28	248 246	271 272	204 180	166 160
Western Red Cedar (<i>Thuja plicata</i>)	6.2	2.9 3.0	0.18 0.18	245 244	269 268	190 192	156 155
American Whitewood (<i>Liriodendron tupilifera</i>)	8.6	3.0 2.9	0.18 0.18	246 246	272 272	185 187	155 158
African mahogany (<i>Khaya ivorensis</i>)	9.7	3.0	0.18	244	270	196	182
Oak (<i>Quercus robur</i>)	8.1	3.1 3.2	0.23 0.22	238 238	261 262	150 175	150 154
Iroko (<i>Chlorophora excelsa</i>)	8.1	3.2 3.1	0.22 0.23	240 243	264 264	175 168	149 160

The ignition temperatures of the different woods do not vary widely. This suggests a similarity in the exothermic reactions preceding ignition.

Discussion

It has been found that the ignition temperature adopted is a reproducible characteristic of the behaviour of a combustible material heated in the ignition furnace described. It is necessary that the diameter of the specimen should be kept constant, that the length should exceed the diameter, and that the air supply should be sufficient for unretarded reaction. The ignition temperature is then satisfactorily insensitive to variations in the rates of air flow and heating and to the length of the specimen. The packing density of the specimen should always be specified.

The crossing temperature varies with the rate of heating but otherwise has similar properties.

Brown's point and the second inflexion in the temperature difference curve, as a suggested alternative, were not found to be reproducible; the variability was, in fact, too great to allow any dependence on the factors tested to be established. At the low rates of heat evolution near these points the change in the specimen temperature will be sensitive to small changes in factors affecting the heat balance, notably the heat transfer to and through the specimen, so that the variability observed might, perhaps, be expected. Brown's results show better reproducibility than was obtained in this work. This may depend on the fact that in Brown's apparatus the specimens were not in contact with the walls of the containing vessel; contact cannot, however, be avoided when the specimens consist of powders.

In spite of the poor reproducibility, the order of magnitude of the temperatures at which exothermic reactions are first appreciable is of importance and the determination is always worth making on a material of unknown properties. But the detailed study of ignition from these low temperatures may be more satisfactorily carried out by exposing the material to constant temperatures for long periods; e.g. as recently carried out by Mitchell⁶ who obtained ignition in a solid octagonal prism of wood fibre-board sheets, 22 inches between faces, exposed to an ambient temperature of 228°F (109°C) for 150 hours.

The ignition temperature may be used for studying the effect of different treatments on the self-heating stage preceding ignition in a given material, and should give an indication of corresponding changes in ease of ignition.

Except in so far as a solid which ignites in a short time in the furnace at a temperature of, say, 200°C will in most circumstances be more readily ignitable than one which requires heating to 300°C the use of ignition temperature is unsound for comparing the ease of ignition of different materials. This follows from the results of Landt and Hausmann⁷ and of Lawson and Simms⁸ who have shown that the time to ignition of different woods exposed to a source of heat is fundamentally related to the density and the thermal properties. In particular, Lawson and Simms found that for ignition by radiation of intensity in excess of a certain minimum, which was the same for all the woods tested, the time to ignition was related to the product of the density, the specific heat, and the thermal conductivity of the wood for both spontaneous and pilot ignition. A measure of the ease with which a solid may be ignited must take account of these properties of the solid, in addition to the temperature to which its surface must be raised for ignition to occur; this temperature is not necessarily simply related to the ignition temperature as measured here.

Conclusions

1. The ignition temperature introduced by Swietoslawski et al.² is a reproducible characteristic of the behaviour of a combustible material

heated in the furnace described.

2. The ignition temperature may be used for studying the effect of different treatments on the self-heating stage preceding ignition in a given material, and may be expected to indicate a corresponding change in the ease with which the material may be ignited by a given source.
3. Except when extreme values are found it is considered that the ignition temperature cannot be used to compare the ease with which different materials may be ignited by a given source; it is not a valid index of fire hazard.
4. A reproducible characteristic temperature associated with the beginning of exothermic reaction in the material tested was not found, but reaction was detected in most cases between 150°C and 200°C. The possibility of self-heating to ignition in materials exposed to temperatures of this order, and lower, is of great importance; but it is more suitably studied by methods employing constant or slowly rising, ambient temperatures rather than by the method described in this note, in which the temperature is raised comparatively rapidly.

Acknowledgements

The experimental work described in this note was carried out by Mr. G. Skeet and Miss M. Ward.

References

1. Brown C. R., "The determination of the ignition temperatures of solid materials", Dissertation, The Catholic University of America, Washington, D.C. 1934.
2. Swietoslawski W., Roga B., and Chorazy M., "Researches on the inflammation temperatures of solid fuels.", Fuel, 1930, IX (2), 93-96.
3. Bardsley H. and Skeet G., "The effect of preheating on the ignition temperature of wood.", F.C. Note No. 30/1950.
4. Wheeler R. V., "The oxidation and ignition of coal.", J.C.S., 1918, 113, 945.
5. Bunbury H. M., "The destructive distillation of wood." London, 1923.
6. Mitchell N. D., "New light on self-ignition.", National Fire Protection Association (U.S.A.), Quarterly, 1951, 45 (2), 165.
7. Landt G. E. and Hausmann E. O., "Initial inflammability of construction materials", Ind. Eng. Chem., 1935, 27 (3), 288.
8. Lawson D. I., and Simms D. L., "The ignition of wood by radiation." Department of Scientific and Industrial Research and Fire Offices' Committee Joint Fire Research Organization, F.P.E. Note 33/1950.

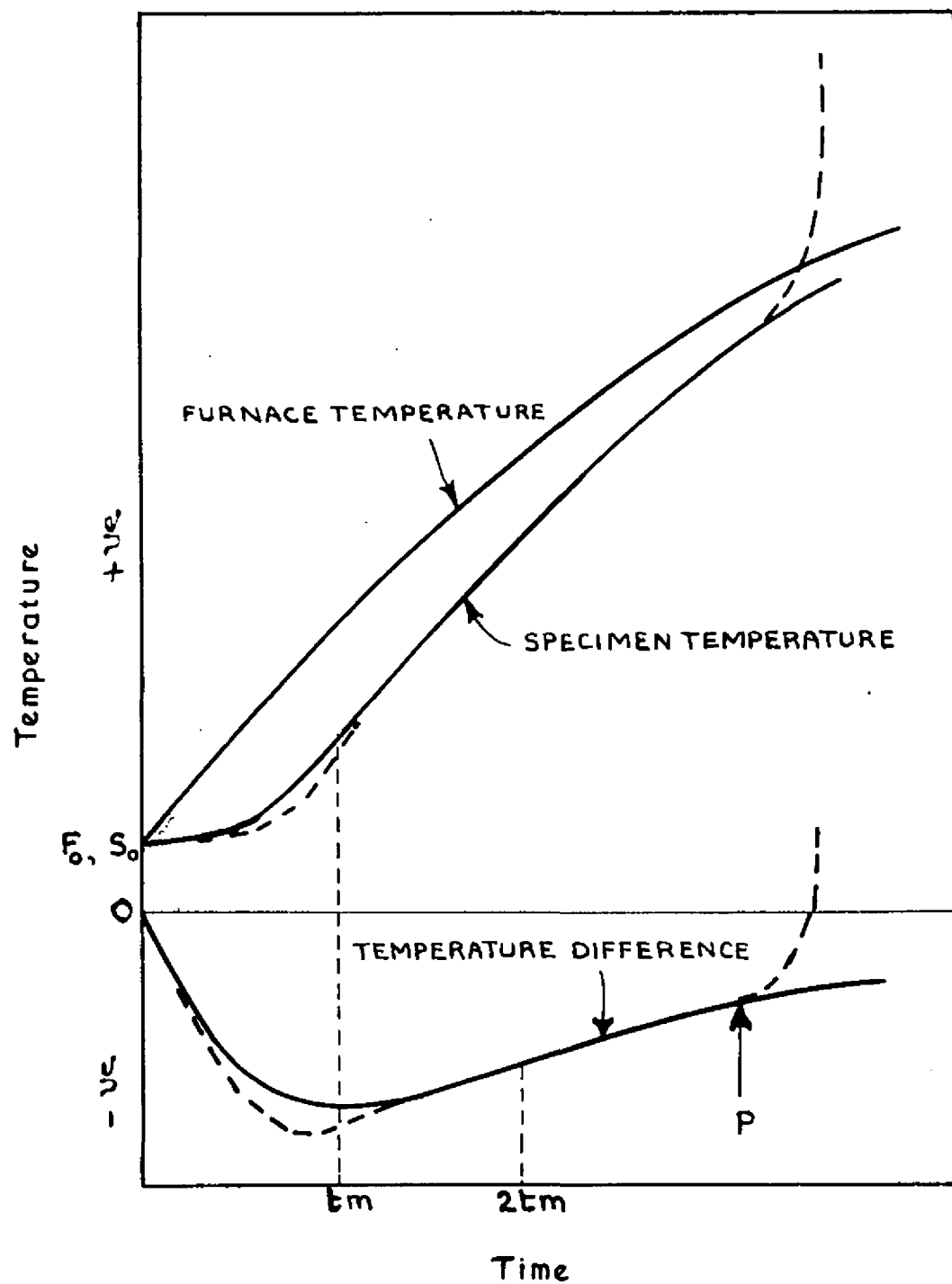


FIG. 1. THEORETICAL TEMPERATURE-TIME CURVES FOR DRY INERT MATERIAL

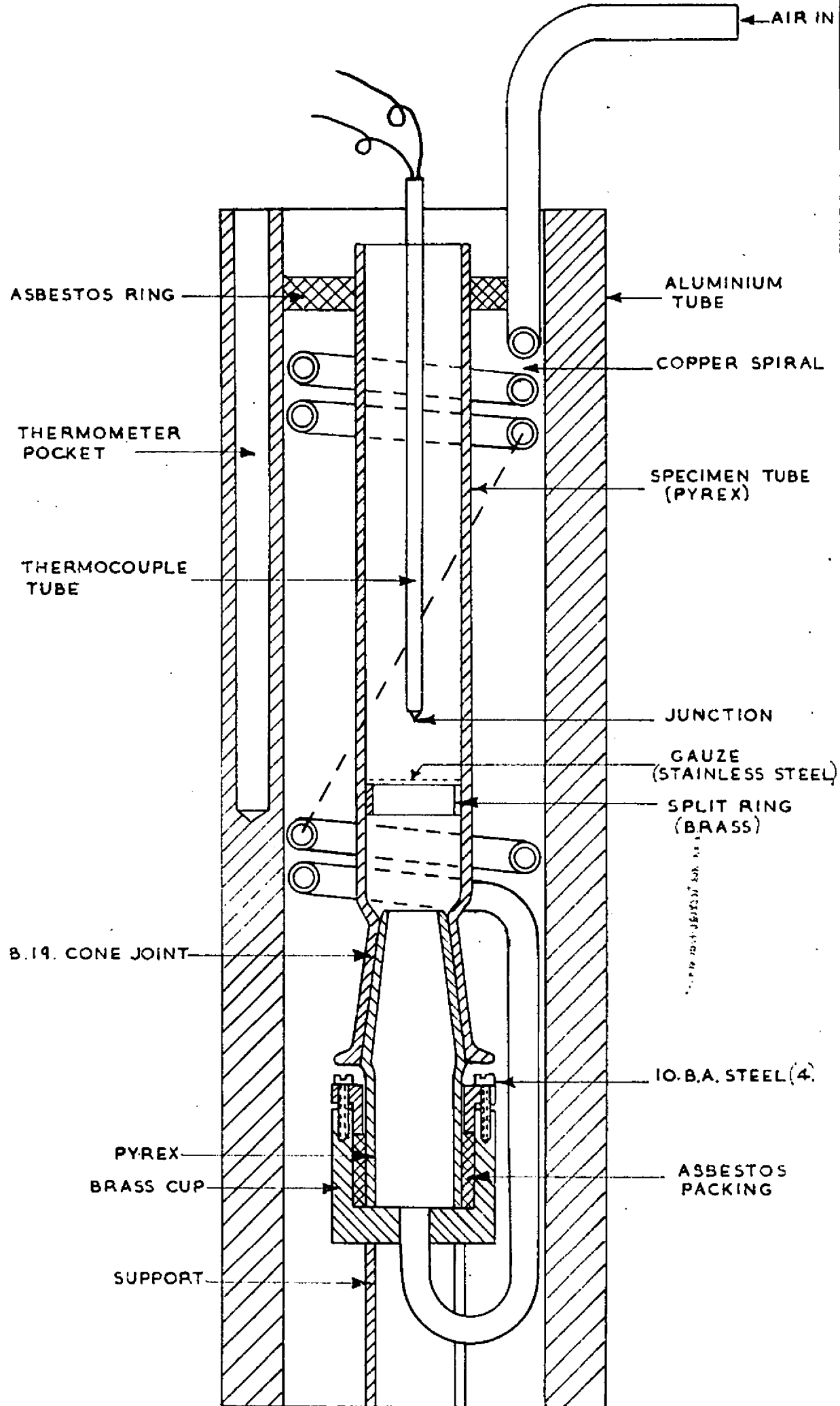


FIG. 2. INTERNAL FITTINGS OF IGNITION FURNACE

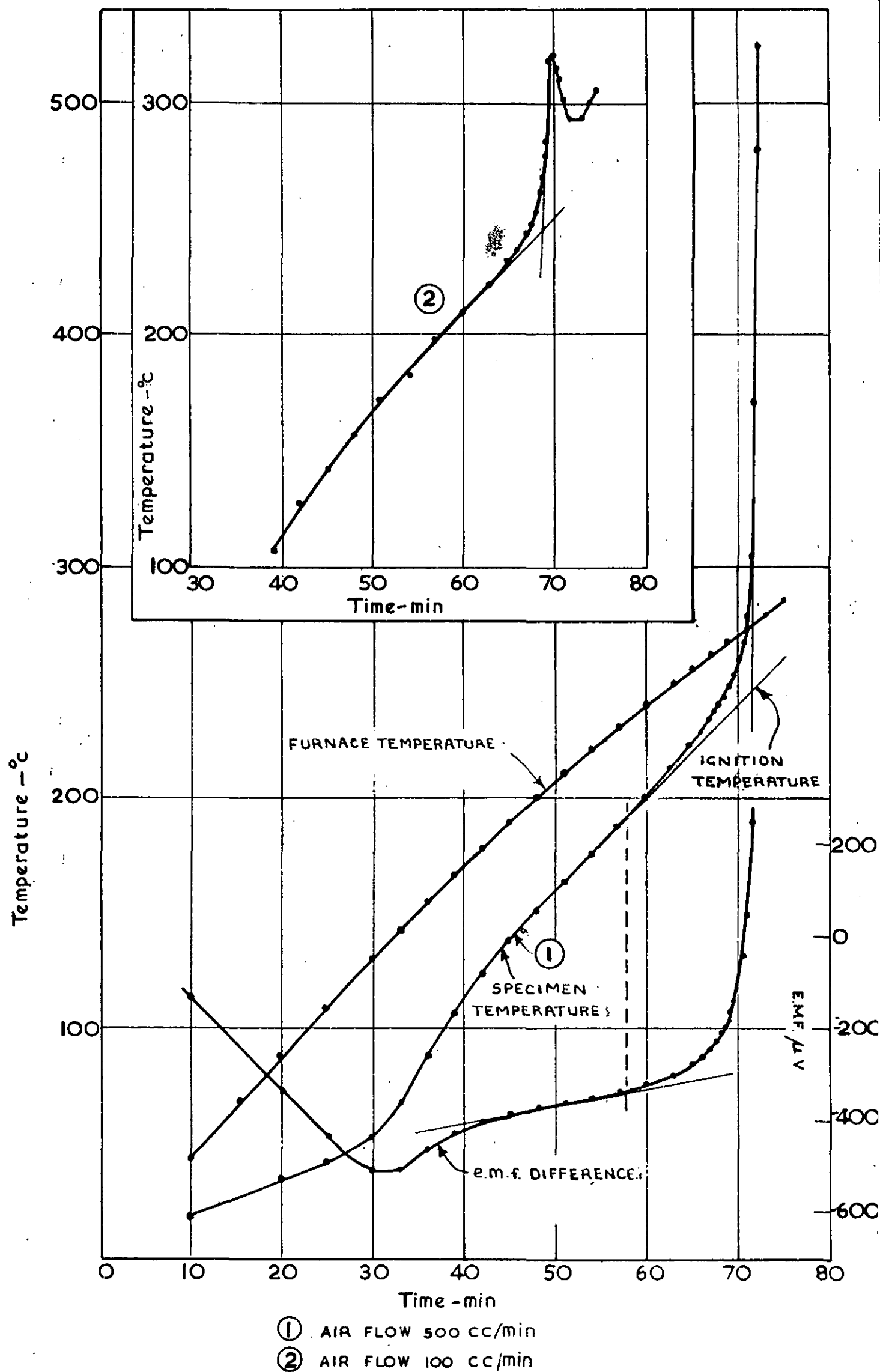


FIG. 3. HEATING OF BEECH SAWDUST IN IGNITION FURNACE

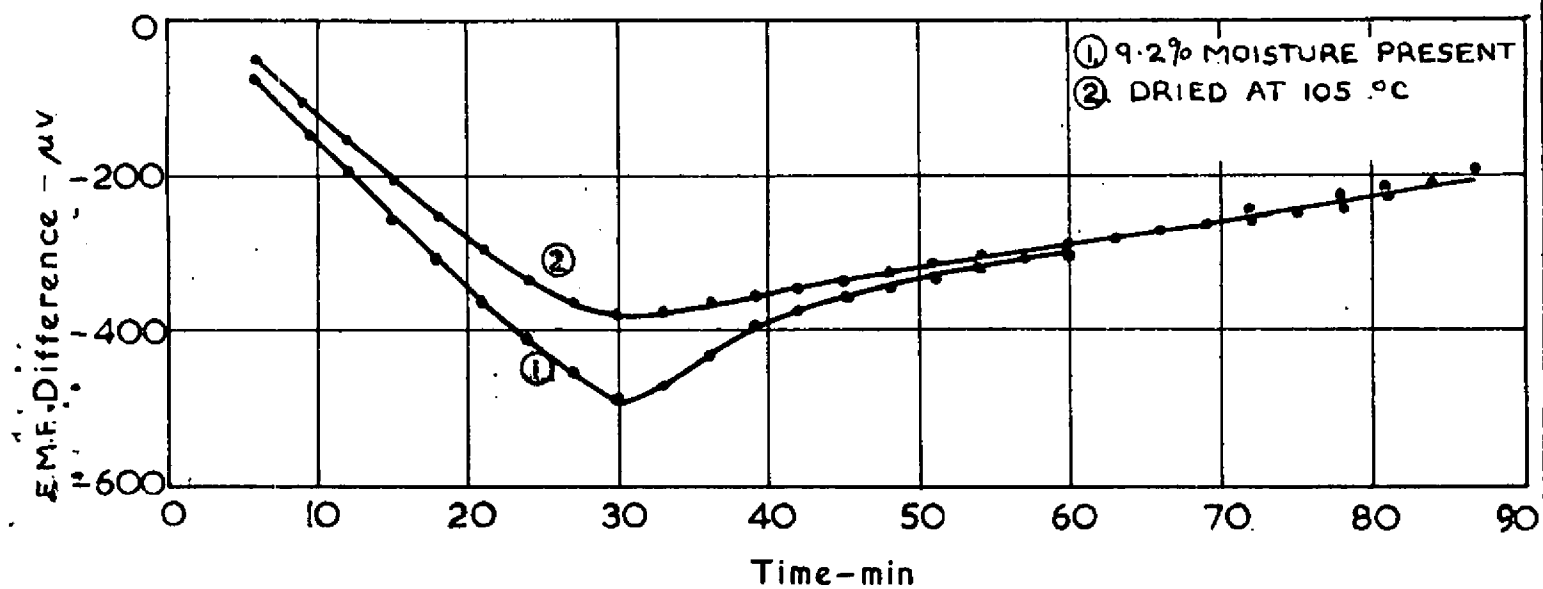


FIG. 4. BEECH SAWDUST HEATED IN NITROGEN

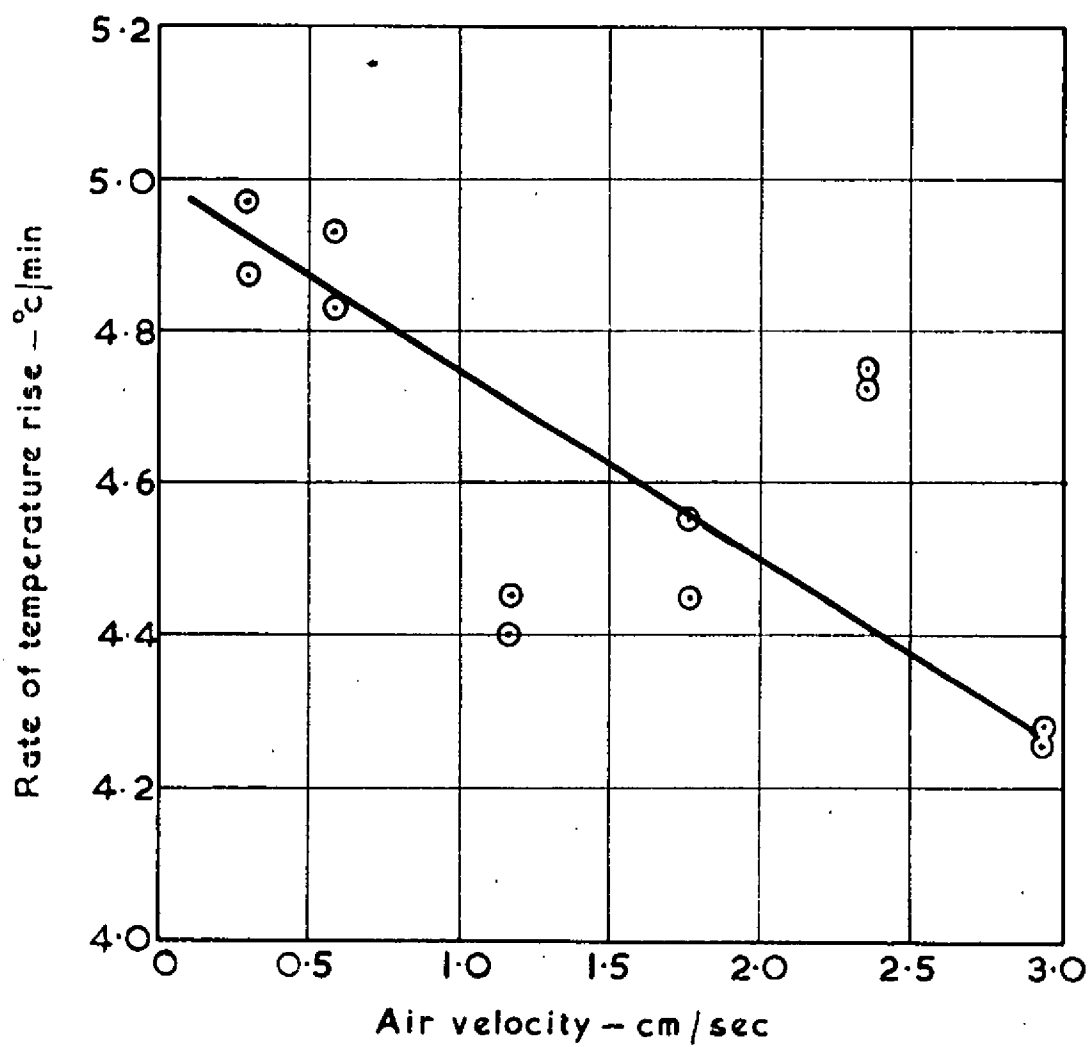


FIG. 5. CORRELATION OF TEMPERATURE RISE AND AIR VELOCITY