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

CONFIDENTIAL

F.R. Note No. 6/1952

January, 1952.

SMOULDERING IN DUSTS AND FIBROUS MATERIALS
PART I. BEECH AND DEAL SAWDUSTS IN STILL AIR

by

F. E. T. Kingman and K. N. Palmer

Summary

The smouldering of beech and deal sawdusts in still air has been investigated. The dusts were formed into small trains and the linear rate of propagation of smouldering measured. This rate was slow and was not materially affected by variations in packing density, particle size, moisture content or size of train provided that the latter is greater than a certain critical value, depending chiefly upon the particle size of the sawdust. Practical applications of these results are discussed.

Introduction

A previous investigation (1) has disclosed an almost complete lack of information on the phenomenon of smouldering in common combustibles: in particular, the rate of propagation and the conditions necessary for sustained smouldering have not been determined. Apart from its value in the theory of solid combustion, such knowledge would be of the greatest assistance in the examination of the development of fires. Thus, there are many instances of considerable time intervals between the latest possible time of ignition and the observed outbreak of fire, especially with stacked materials. In such cases, spontaneous ignition is often recorded as the cause of fire, purely on the basis of the time lag between any possibility of ignition by an external source and the outbreak of fire. If sustained smouldering can occur at a very low rate of propagation, however, it offers an alternative explanation of such fires. It is, therefore, essential to know which materials are able to sustain smouldering and also the rate at which it can propagate in those materials.

An investigation of the properties of smouldering in some common combustible dusts and fibrous materials has been started and this note describes experiments upon sawdusts of English beech (Fagus sylvatica) and white deal (Picea excelsa). Wood sawdust was used as it is a very common combustible and following consultation with the Forest Products Research Laboratory, beech was chosen as a standard because:

(i) it is relatively homogeneous, there is little difference between sapwood and heartwood

(ii) it is not resinous and so sieving would not be seriously affected by cohesion of the particles

(iii) the sawdust particles are approximately cubic and so a given sieve fraction contains uniform particles.

The beech sawdust was formed into small trains and the effects of packing density, particle size, train size and moisture content upon the rate of smouldering were studied independently. Some experiments were repeated using deal sawdust, a softer resinous wood, in order to determine whether any marked differences in behaviour between hard and soft woods existed. All the experiments recorded here were carried out in still air, at atmospheric pressure and temperature.

Experimental

The beech sawdust was prepared and sieved from seasoned timber, by the Forest Products Research Laboratory, into the fractions shown in Table 1. The moisture contents of the various fractions, as received, are also given; they were determined by measuring the weight loss of 1 gm samples after heating to constant weight in a hot air oven at 105°C. Heating for 1 hr. was found to be sufficient.

Table 1

Characteristics of the beech sawdust

Sieve fraction I.M.M.	Mean particle diameter cm	Moisture content %
20 - 40	0·0476	9·4
40 - 60	0·0265	9·8
60 - 80	0·0185	9·4
80 - 100	0·0143	9·8
100 - 120	0·0116	9·7

For some experiments the moisture content of the beech was increased above that shown in Table 1 by leaving the sawdust over water for several days in an evacuated vessel; moisture contents up to 24% were obtained by this method.

The deal sawdust was produced by a fine-toothed circular saw and was then sieved into four fractions, details of which are given in Table 2; the portion which did not pass a mesh of 12 B.S. was discarded. The moisture contents of the various fractions were determined as before and are shown in Table 2, no experiments were carried out using deal sawdust with increased moisture contents.

Table 2

Characteristics of the deal sawdust

Sieve fraction B.S.	Mean particle diameter cm	Moisture content %
12 - 25	0·0992	11·9
25 - 60	0·0424	11·6
60 - 72	0·0231	9·0
72 - 120	0·0168	9·8

The beech and deal sawdusts were formed into small trains, from moulds, in order to facilitate measurement of the rate of propagation of smouldering; one of the moulds is shown in Plate 1 (left). The moulds were of sheet metal, with sloping ends, and their cross-sections were segments of circles. Each was 15 - 16 cm. in length; other dimensions are given in Table 3.

Table 3

Dimensions of the moulds used in the determinations of smouldering rates

Mould	Top width cm	Vertical depth along centre cm
A	1·35	0·30
B	2·35	0·80
C	3·55	1·00
D	5·10	1·65
E	7·25	2·40
F	9·85	3·70

Two wedge-shaped moulds with sloping bases were used, in addition, in order to determine the minimum thicknesses for sustained smouldering in layers of the various grades of sawdust; one of the moulds (Y) is shown in Plate 1 (right). The dimensions of these moulds, which were of trapezoidal cross-section, are given in Table 4.

Table 4

Dimensions of the wedge moulds

Mould	Base width cm	Vertical depths at ends cm
Y	5·70	1·70 and 0·00
Z	5·70	3·40 and 1·40

The same experimental procedure for determination of the rate of propagation of smouldering was used with both woods: the required amount of sawdust was weighed out, gently poured into the mould, and levelled by running a spatula along the top of the mould.

In order to produce the higher packing densities it was found necessary to use a considerable compressive force, this was obtained by placing a metal plate over the top of the mould and clamping in a small vice. The contents of the mould were turned out on to a strip of previously dried asbestos millboard, any vertical expansion or contraction of the train measured, and the smouldering was then initiated by a small gas flame. The combustion zone was allowed to advance 2-3 cm along the train before timing commenced; the time of travel was then measured at centimetre intervals over a total distance of 10 cm, the mean time per cm being taken as the "burning time." If the smouldering ceased before the 10 cm were completed the train was classified as "not smouldering."

The wedge moulds were filled with undried sawdust at a medium packing density and trains were formed as above; smouldering was initiated at the thicker end of the trains and the height of sawdust was measured, to the nearest mm, at the point where combustion ceased.

All experiments were carried out in a draught-free fume cupboard.

Results

In the determinations of the rates of smouldering, with moulds A-F (Table 3), it was found that the combustion zones advanced at uniform rates along the trains which underwent sustained smouldering, whether the sawdust was beech or deal; thus the burning time (mins/cm) was independent of the distance travelled along the train. The smouldering of a train of beech sawdust from mould D is shown in Plate 2: the sharp division between the burnt and unburnt portions is easily visible; Plate 3 shows a similar train that has burnt out, the sawdust being reduced completely to ash except at the edges of the train.

The combustion zones of trains which barely sustained smouldering were relatively narrower than that shown in Plate 2 and tended to wander laterally, an example of this behaviour is shown in Plate 4 where smouldering has ceased within the train. The burning times of these trains, calculated from measurements of the actual path of the smouldering, were in agreement with the results from the experiments in which combustion proceeded steadily.

The burning times of both the beech and deal trains were reproducible to within ± 5%; in any particular train, however, the variation over the 10 cm length was smaller and was less than that involved in the estimation of the position of the combustion zone.

<u>Effect of packing density</u> The effect of packing density upon the smouldering rate was investigated for all sieve fractions of the undried beech sawdust and the results are shown in fig. 1, where the burning time is plotted against the packing density (calculated on the dry weight basis). All trains were formed from the same mould (D, 5 cm in width), which was the smallest to give sustained smouldering in the coarsest fraction of sawdust: consequently the number of experiments with the finest fractions was restricted by the quantity of these grades available. The effect of packing density upon the smouldering of dried deal sawdust is shown in fig. 2, the trains being formed from mould E with the 12 - 25 B.S. sieve fraction; the sawdust was dried by heating in the oven at 105°C for 1 hour, accompanied by occasional stirring.

<u>Effect of train size and particle size of beech sawdust</u> Experiments were carried out on the undried beech sawdust to determine the effect of the particle size and train size on the rate of smouldering. These tests were carried out at two values of the packing density (high and low) and the results are shown in Table 5. In some experiments at the higher density however, the trains expanded after formation, so that the final density was intermediate between the high and low values, the results of these experiments are marked by an asterisk in the table. The results obtained from trains of low packing density and varying particle size from mould D are shown also in fig. 3; a similar curve was obtained with trains of high packing density.

Table 5

The burning times (mins/cm) of
trains of undried beech sawdust

Burning time with		Trains from mould					
Sawdust fraction I.M.M.	Packing density	A	B	C	D	E	F
20-40	Low	n.s	n.s	n.s	11.1	11.3	10.3
	High	n.s	n.s	n.s	11.1	11.6	-
40-60	Low	n.s	n.s	n.s	10.5*	11.0	-
	High	n.s	n.s	n.s	10.7	-	-
60-80	Low	n.s	n.s	n.s	9.9*	10.3	-
	High	n.s	n.s	11.9	10.4	-	-
80-100	Low	n.s	(9.5)	10.8	9.1	-	-
	High	n.s	9.5	10.2	9.8	-	-
100-120	Low	n.s	-	-	8.9	-	-
	High	n.s	9.0*	-	9.9	-	-

NOTES

Low packing density: $\ngtr$ 0.25 gm/ml
High " " $\nless$ 0.28 " "
*denotes measurement upon trains of medium packing density (0.26 - 0.27 gm/ml).
n.s denotes "no sustained smouldering"
- denotes "not determined"
( ) denotes measurements doubtful owing to lateral wandering of the combustion zone.

Many of the trains, including those which did not give sustained smouldering, were found to burn with a flame for periods up to 30 sec. after the initial application of the pilot gas flame. The gas flame was used as a source of ignition because it tended to give even zones of smouldering across the whole width of the trains. The flames appearing upon the sawdust, during ignition by gas, were blue in colour and slowly decreased in size as extinction was approached; they were probably caused by the ignition of the volatile materials evolved in the smoke during the initial application of the pilot light to the wood. Smouldering and flaming were initiated simultaneously by the pilot flame, but the former did not produce sufficient smoke to maintain flame after the initial evolution of volatiles had subsided; thus flaming was not sustained.

Smouldering in some trains could be initiated by a glowing cigarette-end, this method would not have produced flaming.

Effect of the moisture content of the beech sawdust A series of samples of beech sawdust with moisture contents varying from 0 - 24% were prepared as described earlier. The effect of the moisture content upon the burning times of two sieve fractions is shown in fig. 4, the relationship between burning time and moisture content being approximately linear. In these experiments the dry weight packing density of the trains was kept at a constant low value (0.21 gm/ml). Trains which sustained smouldering with difficulty (i.e. showed pronounced wandering), when constituted of beech sawdust with the original moisture content (Table 1), burned more strongly when dried sawdust was used; conversely, increased moisture contents often rendered them "non-smouldering". The minimum size of train able to sustain smouldering was, therefore, to some extent, dependent upon the moisture content of the sawdust.

Further experiments with deal sawdust The effects of train and particle sizes upon the rate of propagation of smouldering were also investigated with deal sawdust, both dried and undried, at low and high dry weight packing densities. The burning times observed are shown in Table 6; the values given are corrected for the extra distance travelled during the lateral wandering of the combustion zone in trains which only sustained smouldering with difficulty.

Table 6

The burning times (mins/cm) of trains of undried and dried deal sawdust

MOULD		A		B		C		D		E		F	
Sawdust fraction B.S.	Packing density	Un-dried	Dried	Un-dried	Dried	Un-dried	Dried	Un-dried	Dried	Un-dried	Dried	Un-dried	Dried
12 - 25	Low	n.s	n.s	n.s	n.s	n.s	n.s	n.s	n.s	n.s	n.s	11.8	9.3
	High	n.s	n.s	n.s	n.s	n.s	n.s	n.s	n.s	13.4	11.5	13.4	10.5
25 - 60	Low	n.s	n.s	n.s	n.s	n.s	n.s	n.s	7.8	9.0	8.5	10.2	7.4
	High	n.s	n.s	n.s	n.s	n.s	n.s	10.6	8.2	10.1	9.0	10.3	8.4
60 - 72	Low	n.s	n.s	n.s	n.s	n.s	n.s	5.7	5.7	6.6	5.6	-	-
	High	n.s	n.s	n.s	n.s	-	-	-	-	-	-	-	-
72 - 120	Low	n.s	n.s	n.s	4.6	6.2	5.1	6.2	5.1	-	-	-	-
	High	n.s	n.s	-	-	-	-	-	-	-	-	-	-

NOTES

Low packing density: 0.15 gm/ml
High " " 0.22 " "
The moisture contents of the sieve fractions of the undried sawdust are given in Table 2. The dried sawdust was prepared from undried sawdust by heating at 105°C to constant weight.
Other abbreviations as in Table 5.

The minimum height of train necessary for sustained smouldering to occur was investigated with the wedge moulds (Y, Z) using all sieve fractions of the beech and deal sawdusts; measurements were not taken upon trains in which the smouldering zone had wandered to the edge and extinguished since combustion might have continued if the train were wider. The results of these experiments with both types of wood, are shown in fig. 5; the point "M" was obtained from measurements upon a train composed of a mixture of equal weights of the 12-25 and 25-60 B.S. deal sawdust fractions in order to procure an approximate result for an intermediate particle diameter.

It was noticed during all the experiments with deal sawdust that the smoke evolved during the smouldering was considerably more resinous than that produced by beech sawdust and caused heavier condensation of tarry materials in the fume cupboard; the smoke from deal sawdust also seemed to ignite more readily than that from beech.

Discussion

As beech is a homogeneous wood it was expected that the various sieved fractions of the sawdust would have identical compositions; this was supported by the uniform results obtained in the moisture content determinations given in Table 1. Variations in the composition of different sieve fractions would be produced with less homogeneous woods, since during the sawing the harder portions would tend to yield finer sawdust than the softer parts; again, highly resinous parts may react to sawing in a different manner to the remainder. Consequently, the various sieve fractions of the deal sawdust were less uniform in composition than those of beech; also the particle diameter of the deal sawdust was known less precisely owing to the more acicular form of the particles. The variation in the sieve fractions of the deal sawdust is apparent in their non-uniform moisture contents (Table 2).

The effect of variation in packing density upon the burning time of beech sawdust, shown in fig. 1, was slight for all the sieve fractions; the maximum variation for a given particle size was not more than that to be expected from experimental error ($\pm$ 5%) and so the maxima obtained in the curves may not be significant. With the deal sawdust a linear relationship was obtained (fig. 2), although the burning time increased by only 13% of its lowest value throughout the entire range of packing density; that is from the lowest to the highest value that could be obtained by using a vice for compressing (an increase of 25%). Since the burning time is the reciprocal of the linear smouldering rate (cm/min), it follows for both beech and deal sawdust that as the packing density increases the mass rate of smouldering (gm/min) also increases and so the temperature of the combustion zone also probably rises.

The increase in the burning time of beech sawdust with increase in particle size is shown in Table 5 and fig. 3; it is also evident in fig. 1. The increase was small over the range of particles investigated, for example in trains from mould D it increased from 8·9 min/cm to 10·9 min/cm whilst the particle size was increased by 300% from 0·012 cm to 0·046 cm (fig. 3); however with very small particle sizes (less than 10^{-2} cm) the relative increase in burning time may be greater. The results of similar experiments with deal sawdust (Table 6) are less significant owing to the probable variations in composition of the sieve fractions but the general trend was similar to that observed with the beech.

The effect of the moisture content of the wood upon the burning times of beech sawdust was investigated and the results, given in fig. 4, show that the burning time increases approximately linearly with moisture content over a wide range; although an increase in moisture content from 0% to 24% produces only a small increase of 3 - 4 min/cm in the burning time. Experiments with deal sawdust showed that drying decreased the burning time (Table 6) but, as no exceptional behaviour was evident, a more detailed investigation was not undertaken.

With neither the beech nor the deal sawdust was there any indication that the size of the train had any material effect on the burning time: in Tables 5 and 6 there are slight variations in the burning time but they are haphazard and within the limits of experimental error. The size of the train did, however, determine whether smouldering could be sustained; thus no train formed from the smallest mould (A) with either beech or deal sawdust would support continuous smouldering, although initial, transient, flaming was possible. The results obtained from experiments with the wedge-shaped moulds (Y and Z) showed that a layer of sawdust would not sustain smouldering if its depth were less than a certain critical value, depending mainly upon the particle size of the sawdust; changes of packing density and moisture content produced only slight effects as may be seen from Tables 5 and 6. It is shown in fig. 5 that these critical depths are related linearly to the particle size over the range investigated, within the limits of experimental error ($\pm$ 1 mm); the position of the point M (obtained by mixing two sieve fractions) indicates that a mixture of sawdusts of various particle sizes will probably have a critical depth equal to the weighted mean of the critical depths of its components. The values obtained with the wedge moulds for the critical depths of the various sawdust fractions were consistent with those which may be deduced from Tables 5 and 6 and the dimensions of the moulds A - F. The smouldering of trains slightly deeper than the critical value was characterised by the wandering and narrowing of the combustion zones and it is probable that the critical depth is independent of the width in a horizontal layer. It is noteworthy that, within the limits of experimental error, the burning times of trains with erratic smouldering (wandering of the combustion zone) were the same as those of deeper trains in which smouldering was maintained without difficulty; thus a layer of sawdust will either not support sustained smouldering or will propagate it at a rate independent of the depth of the layer.

The experiments described in this note have shown that the burning time of either the beech or the deal sawdust was not materially affected by changes in packing density, particle size, moisture content or size of train provided that the latter is greater than a certain critical value, depending mainly upon the particle size. In the investigation of the initial stages of fires which may have resulted from smouldering, these properties have a considerable practical value because it is possible to obtain an approximate figure for the rate of propagation of smouldering which is independent of the condition of the sawdust. It was also shown with some trains that smouldering could be initiated by a glowing cigarette end.

The effect of variations in the conditions of combustion, especially the effect of draught and the transition from glowing to flaming combustion, remains to be investigated in detail. Preliminary experiments with a wind tunnel showed that the rate of smouldering of beech sawdust is markedly altered by a draught, a sevenfold increase being obtained with an airflow of 8 m.p.h. Future projects include measurements of the temperature of combustion and investigations of the smouldering of other dusts and jute cloth.

Conclusions

The work so far carried out has been concerned with smouldering in still air, the main points arising from the results are:

1. Steady smouldering may be initiated in beech and deal sawdusts and its rate of propagation is very slow compared to the rate of spread of flame.

2. The rate of smouldering is not appreciably affected by variations in packing density, particle size, moisture content or train size provided that the depth of the train is greater than a critical value which is related to the particle size of the sawdust.

3. Smouldering was easily initiated, e.g. by a cigarette end, and so it may be the first stage of development in many fires.

Acknowledgements

The late W. G. Campbell of Forest Products Research Laboratory, Princes Risborough, kindly arranged for the supply of the sieved beech sawdust. Miss M. Ward and Mr. G. Skeet assisted with the experimental work.

References

1. F.C. Note No. 42/1951.

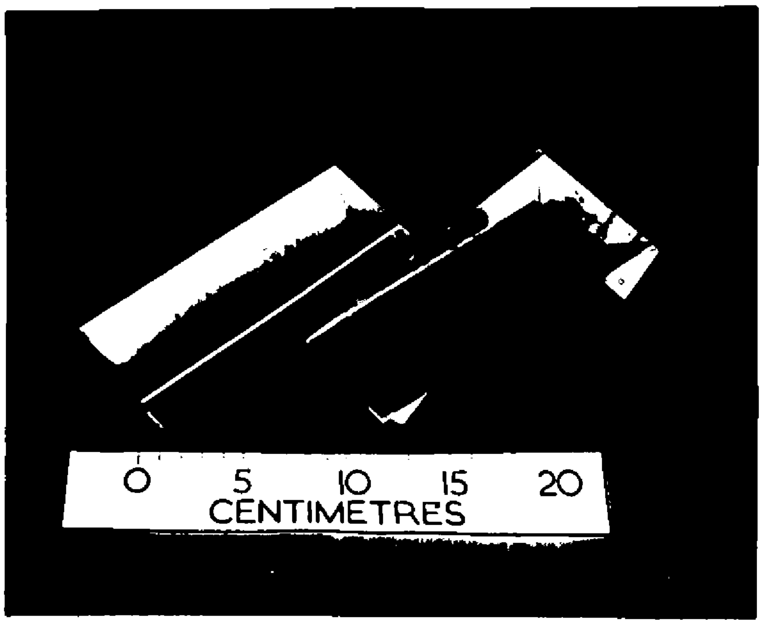

PLATE 1 TYPES OF MOULD USED IN TRAIN FORMATION

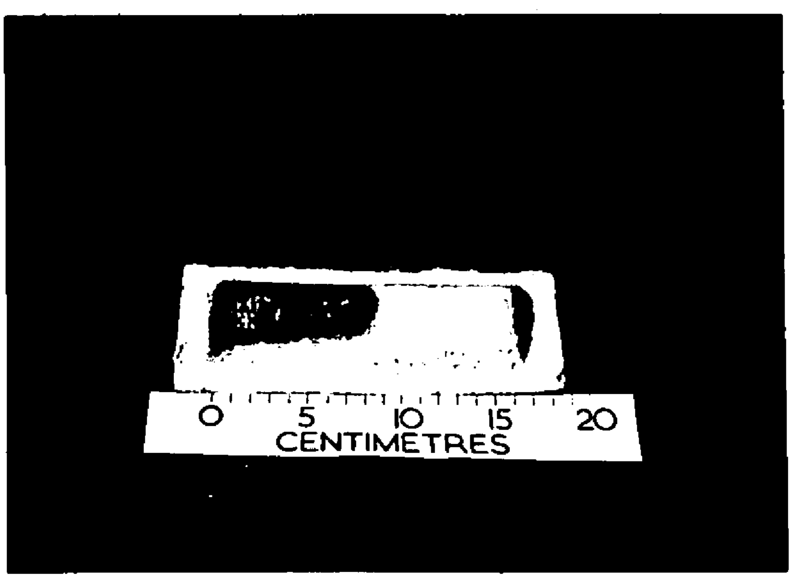

PLATE 2 THE SMOULDERING OF A TRAIN OF BEECH SAWDUST

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PLATE 3 A TRAIN OF BEECH SAWDUST IN WHICH SMOULDERING HAS BEEN COMPLETED

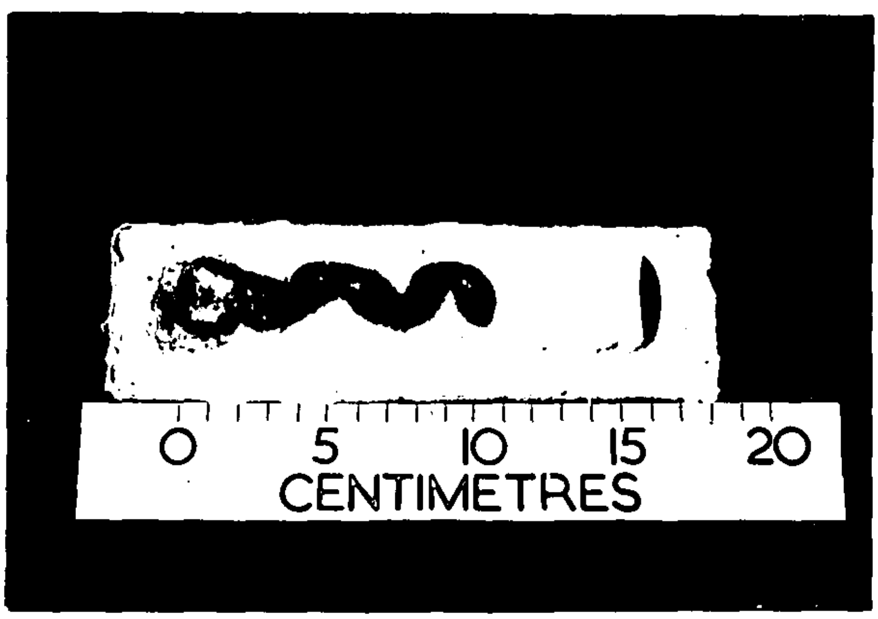

PLATE 4 WANDERING OF THE COMBUSTION ZONE IN A TRAIN OF DEAL SAWDUST

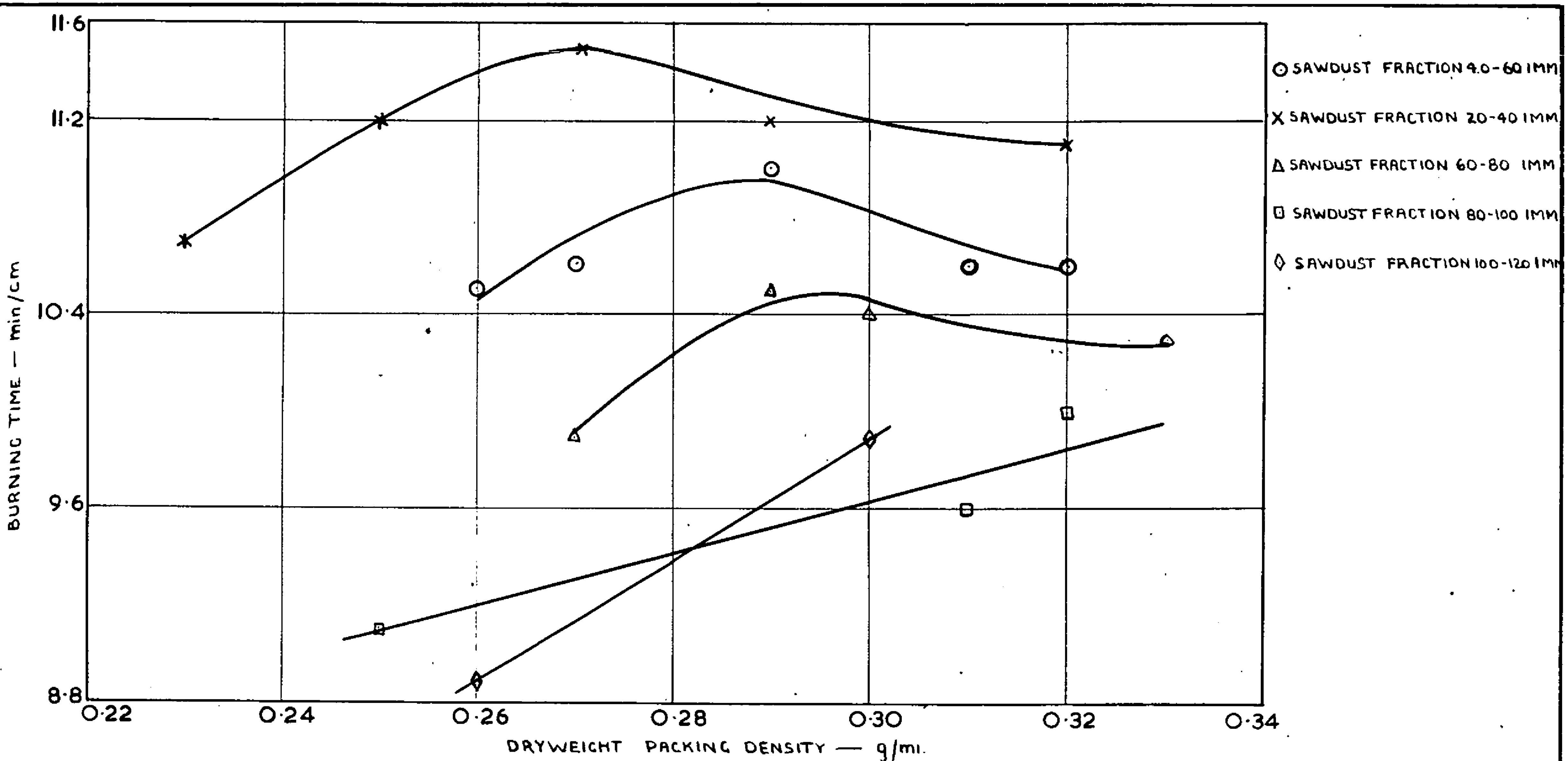

FIG. I. EFFECT OF VARIATION IN PACKING DENSITY UPON THE BURNING TIME OF BEECH SAWDUST

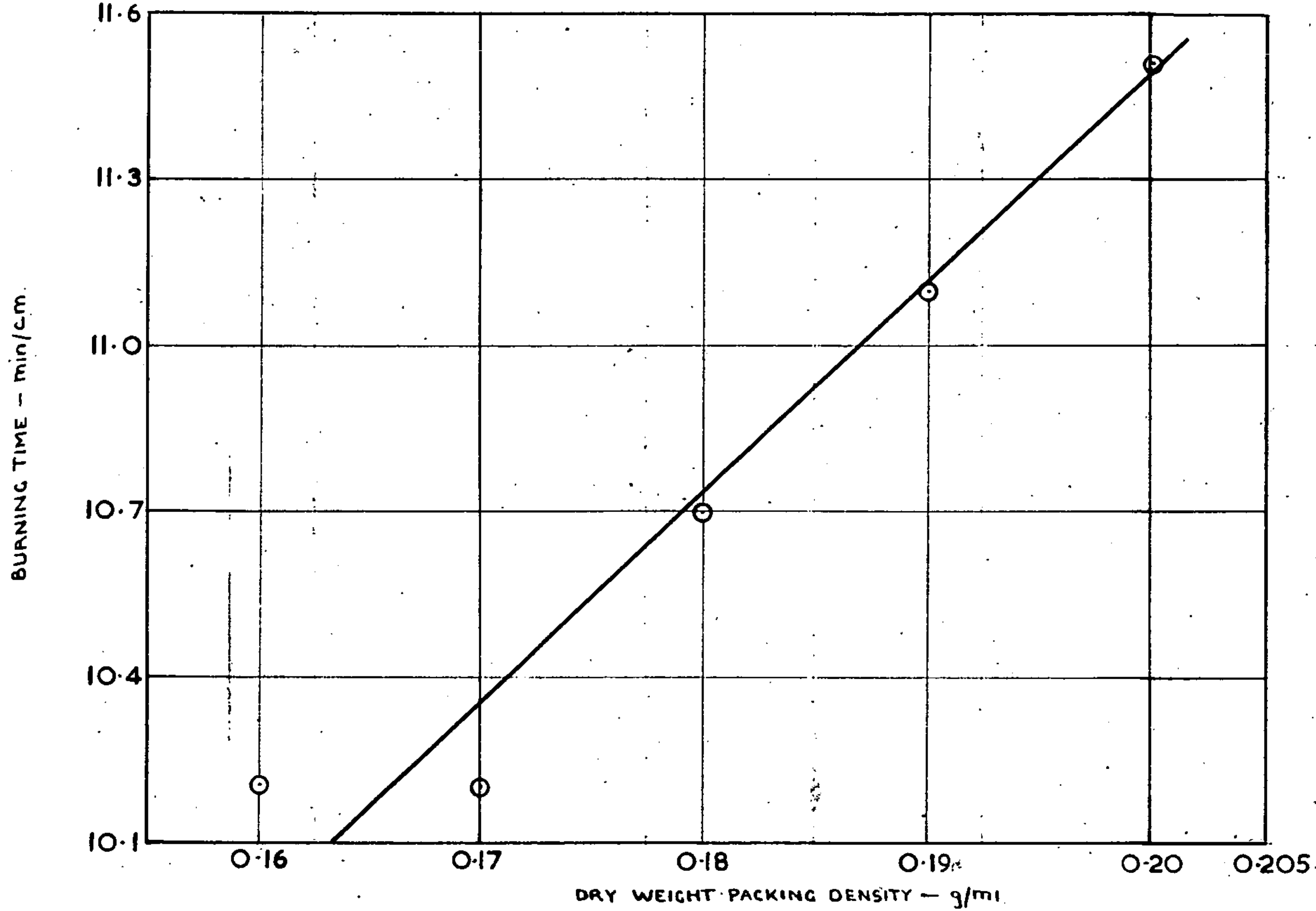

FIG. 2. EFFECT OF VARIATION IN PACKING DENSITY UPON THE BURNING TIME OF DRIED DEAL SAWDUST (12–25 B.S.)

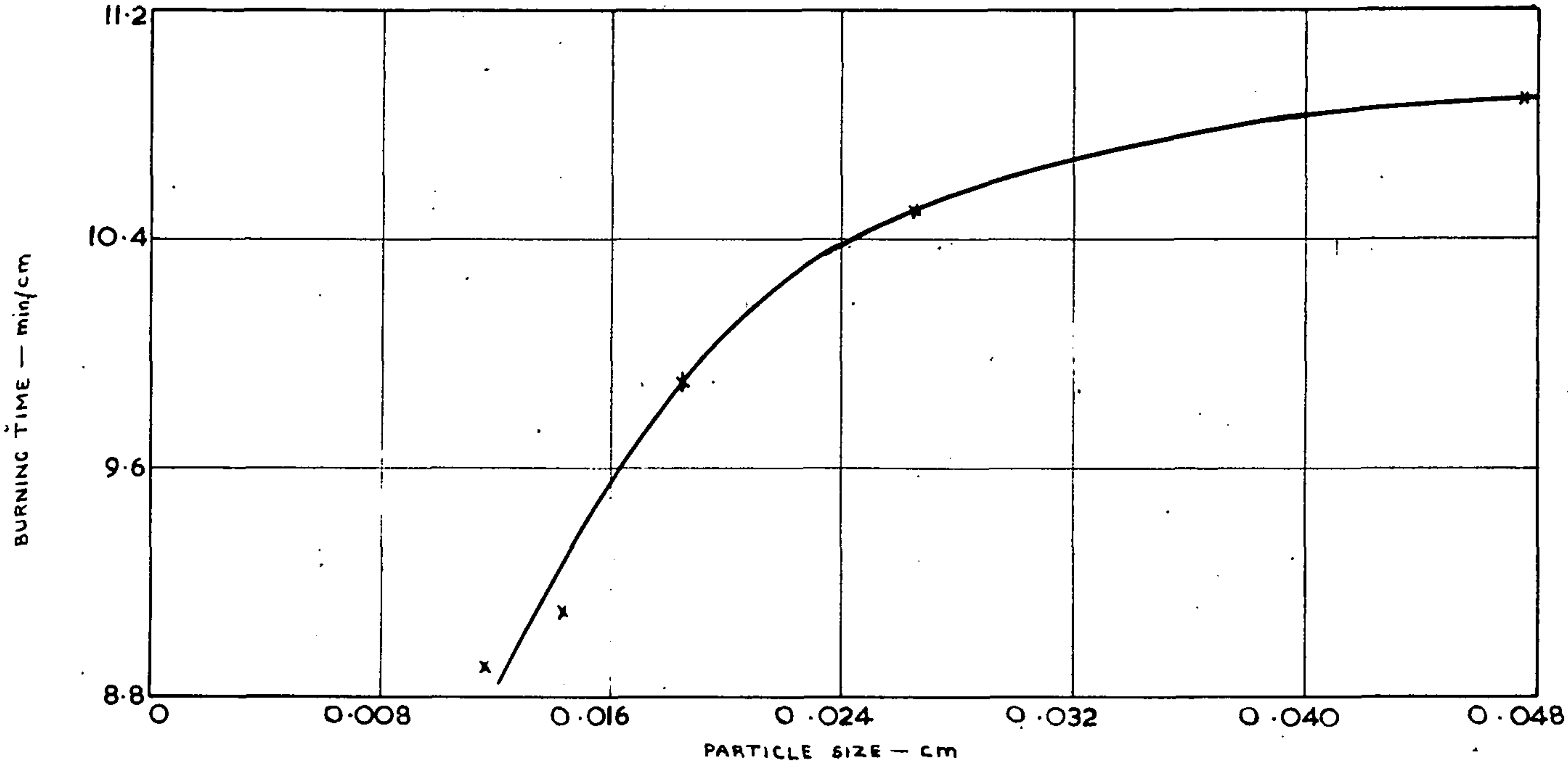

FIG. 3. RELATIONSHIP BETWEEN THE PARTICLE DIAMETER OF BEECH SAWDUST & ITS BURNING TIME

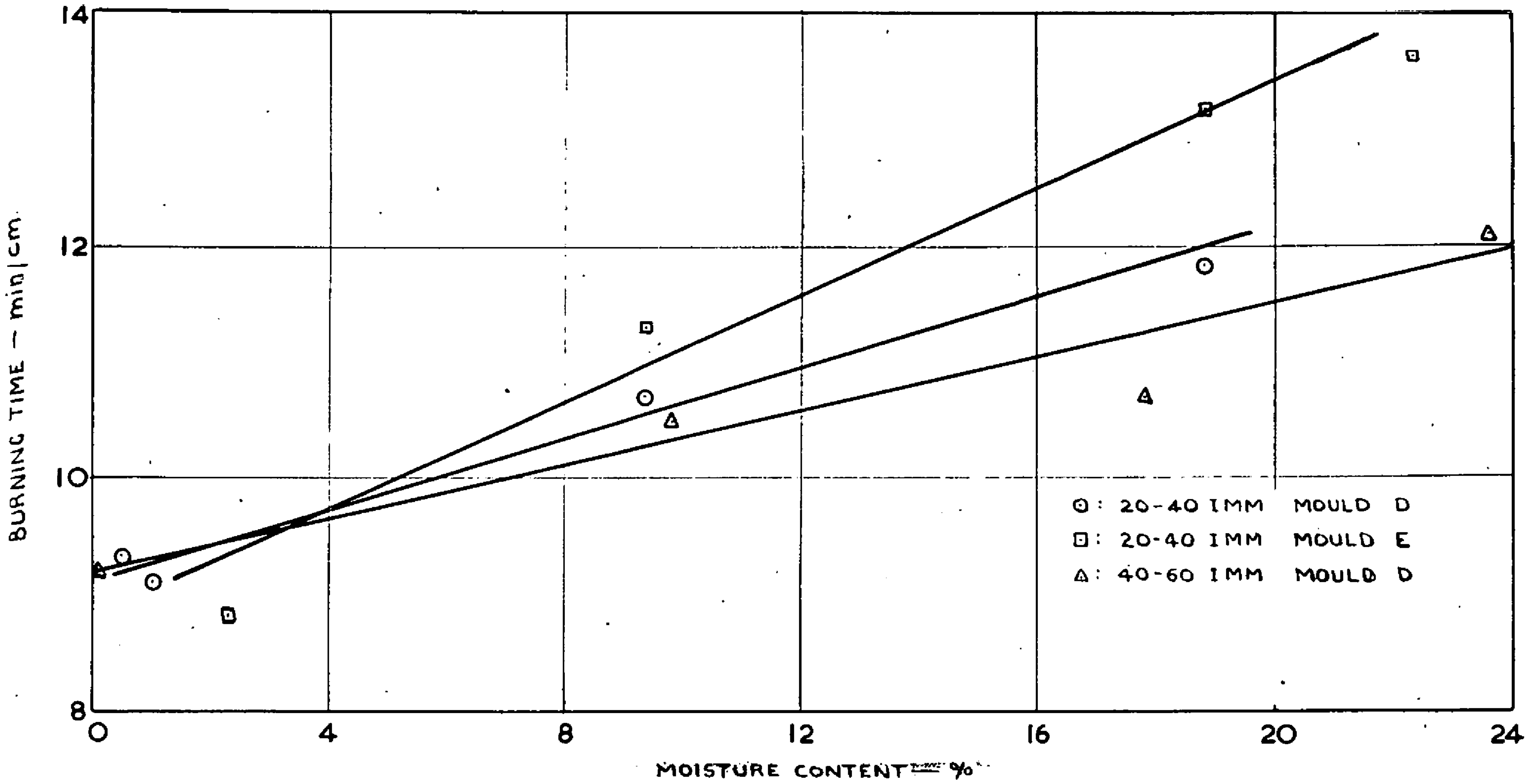

FIG. 4. EFFECT OF MOISTURE CONTENT UPON THE BURNING TIME OF BEECH SAWDUST

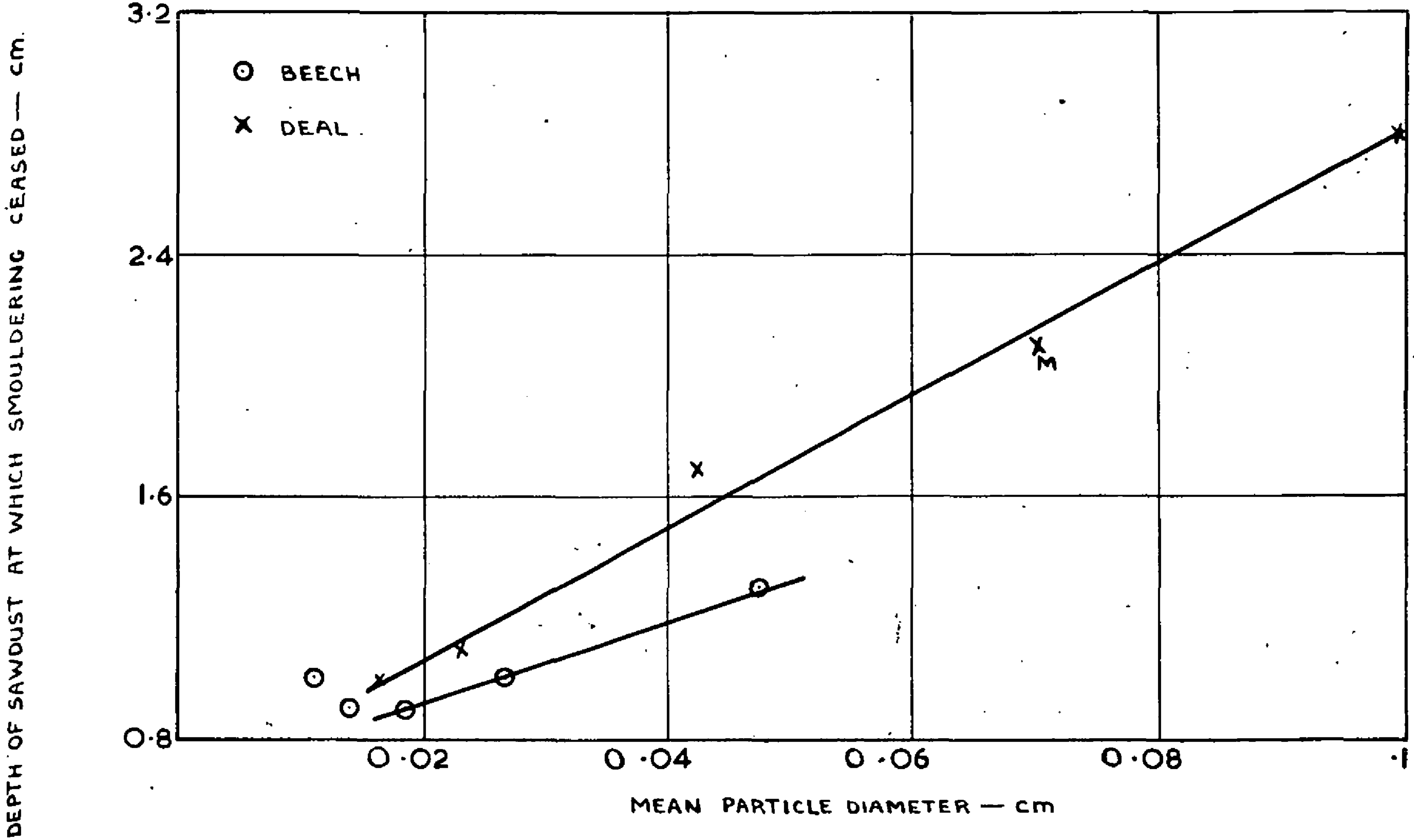

FIG. 5. RELATIONSHIP BETWEEN PARTICLE DIAMETER & MINIMUM DEPTH OF TRAIN FOR SUSTAINED SMOULDERING