F.R. Note No. 149/1954
Research Programme
Objective B3/(1).

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

SMOULDERING IN DUSTS AND FIBROUS MATERIALS
PART XI. PROPAGATION OF SMOULDERING INSIDE DUST HEAPS

by

K. N. Palmer and M. D. Perry

Summary

This note gives an account of some experiments carried out in still air on smouldering fires resulting from small sources of ignition buried in heaps of dust of up to 85 cm in depth. The heaps were either formed from flat-topped conical moulds or contained in lidless boxes, and the smouldering was initiated at the bottom and propagated upwards.

The results have shown that a small source of ignition when buried in a heap of dust can initiate and propagate smouldering upwards through the heap for many days without visible signs of combustion; an 85 cm. depth of mixed wood sawdust, for example, was found to take over 12 days for the smouldering to penetrate to the surface. The time for the smouldering to penetrate varies approximately as the square of the depth of dust; the rate of smouldering is consequently inversely proportional to the depth and is, in general, appreciably slower than when under open conditions, and for large heaps may become very slow.

When the smouldering penetrated the top surface of a heap the smouldering was observed to spread out over the surface and the smoke produced inflamed above the smouldering region, even in still air. Larger but transient flames occurred as a result of disturbing the smouldering heap and allowing the core of carbonized dust to fall in fine suspension through the air.

Some practical aspects of this work are briefly discussed.

September, 1954.

File No. F.1020/4/1

Fire Research Station,
Boreham Wood,
Herts.

Introduction

Earlier work in this series has been concerned with the behaviour of certain common combustibles smouldering in shallow layers in the open, either under conditions of still air or of uniform draught. Although smouldering under these conditions is probably the form which is most frequently encountered, an alternative process could develop from a source of ignition which had become buried in the combustible. Smouldering might then spread outwards from this source through the heap of combustible until the zone reached the external surface, after which it could propagate under open conditions and spread over the surface of the heap.

It was not known whether a small buried source of ignition could initiate and propagate smouldering in a heap of combustible. If smouldering fires could occur in this way, it is important to know the order of the times taken under specified conditions to penetrate known depths of combustible, as these times may be very different from those for the open propagation of smouldering.

The development of smouldering from a buried source of ignition was investigated in a series of experiments in which only dusts were considered; the dusts were either formed into heaps or contained in lidless boxes up to about 90 cm in depth. All the experiments were carried out in still air.

Experimental

Materials. Four dusts were used in these experiments: two samples of cork dust taken from the same supply but stored separately, elm sawdust and a commercial mixed wood sawdust. The dusts were used because it was believed that their behaviour may be typical of other closely packed materials in which bulk storage fires are known to occur. The 15 cwt supply of mixed wood sawdust was specified as being homogeneous throughout but there was evidence of some of the sacks of dust being damp in places; in consequence, the contents of each sack were exposed to an indoor atmosphere and mixed before using but some variation in moisture content was found to remain. The distribution of particle size in a random sample of each of the dusts is shown in Figure 1; further characteristics of the dusts are tabulated below.

Table 1

Details of the dust samples

Experiments	Still air smouldering time* sec/cm	Moisture content % wet weight	Dry weight packing density g/ml
Cork dust in conical heaps	210	8·6	0·14
" " " 1 ft box	-	8·0	0·14
Elm sawdust in conical heaps	252	11·3	0·18
Mixed wood sawdust in 1 ft box	456	18·0	0·20
" " " " 2 ft box	395	15·3	0·20
" " " " 3 ft box	354-405	10·7-12·5	0·20

*Determinations made on trains of dust formed from a mould 1·65 cm in depth and 5·10 cm base width.

Apparatus. The moulds were of sheet metal and were frustra of cones; some dimensions of these moulds are given in Table 2. It will be seen that in the series M-Q the base and top diameters are very approximately $\frac{3}{2}$ h and $\frac{7}{2}$ h, and for mould NN $\frac{9}{2}$ h and $\frac{13}{2}$ h respectively, where h is the vertical depth.

Table 2

Mould dimensions

Mould	Base diameter cm	Top diameter cm	Vertical depth cm
M	3·3	8·9	2·5
N	7·5	17·7	5·2
O	10·9	26·5	7·6
P	15·0	35·4	10·5
Q	22·5	53·5	14·9
NN	22·6	33·0	5·6

The boxes were approximately 1 ft, 2 ft and 3 ft cubes internally, the smallest of which had walls and floors of ½ in. asbestos wood, the remainder had floors of the same material but their walls were of sheet metal.

Procedure (i) Using heaps of dust formed from moulds. In each experiment a mould was filled with a weighed amount of dust so that it was level with the top of the mould and at the required packing density. A ½ in. long flame from a small gas jet was then applied to the centre of the dust for 1 minute, causing a charred area of about 1 in. diameter. After allowing the smouldering to proceed undisturbed for a further 5 minutes, a square piece of asbestos millboard was placed over the mould, the whole inverted, the mould removed and any change in the height of the heap noted.

In these experiments the times for the smouldering to penetrate were measured from the time of formation of the heaps to the time at which the smouldering burnt through to produce a ½ in. diameter black spot on the top surface of the heap (i.e. the total time minus 6 minutes for the preburn). One exception to this is the result for heaps of cork dust formed from mould Q, when the time given is for an automatic recording instrument connected to a thermocouple, whose hot junction was in grazing contact with the centre of the top of the heap, to register the maximum temperature. With the larger piles, economy of dust was achieved by supporting the sides of the heap, by having the dust contained on lidless boxes.

(ii) Using dust contained in boxes. A smouldering heap of dust formed from one of the two smaller moulds used previously was employed as the buried source of ignition in the experiments of this type. The heap was prepared and ignited as before and placed in the centre of the bottom of one of the boxes. After the smouldering had nearly propagated to the top surface of the heap, a weighed amount of dust was rapidly put into the box, burying the heap, and the dust was then levelled and packed down to the required depth. Table 3 gives the time schedule for these operations, also the size of source. The times for the smouldering to penetrate were measured from the commencement of filling to the emergence of the smouldering at the top surface of the dust, usually as determined by the sudden rapid rise in temperature of a thermocouple placed centrally.

The depths of dust recorded below for experiments of both classes are the distances between the top of the asbestos millboard supporting the heap, or the ignition heap, to the top exposed surface of the dust.

In no experiment were thermocouple wires or sampling tubes etc. introduced into the dust; the possibility of leakage of air along the leads to the interior of the heap was thus avoided.

Table 3

Details of experiments with dust contained in boxes

Experiments	Source of ignition. Heap from mould	Time of flame application min.	Further time of undisturbed smouldering min.	Further time in box before commencement of filling min.
Cork dust in 1 ft box	M	1	5	9
Mixed wood sawdust in 1 ft box	M	2	10	8
" " " 1 ft box	N	2	10	68
" " " 2 ft box	N	2	10	68
" " " 3 ft box	N	2	10	68

Results

In the first investigation the times for the smouldering to propagate vertically to the surface of heaps of cork dust formed from the moulds M-Q were measured. The results are given in Figure 2 where the times and depths are plotted on logarithmic scales. In addition, it was found that, using heaps formed from mould N, the effect of increasing the packing density of the dust from 0·14 g/ml to 0·16 g/ml was to increase the average time for the smouldering to emerge from 50 min. to 60 min. Similarly, drying the dust and leaving the packing density at its original value was found to reduce the average time to penetrate to 39 min. In contrast, variation of the width of heap was found (using mould NN) to have less effect: a heap 5·6 cm in depth whose top diameter was three times that used normally required 63 min. for the smouldering to penetrate, whereas the usual heaps would require 58 min.

The first investigation was repeated using heaps of elm sawdust for comparison with cork dust heaps; the results are given in Figure 3, the scales on both axes being again logarithmic.

As already stated the larger heaps were contained in lidless boxes. The results obtained earlier had suggested that the depth of layer rather than its width was the chief factor governing the time required for the smouldering to propagate through the heap, so that it was expected that similar results might be obtained with both dust arrangements. This was tested using five different depths of cork dust in the 1 ft box and the results are shown in Figure 2 together with those obtained earlier for moulded heaps of cork dust.

Finally a series of experiments using dust depths considerably greater than those hitherto, up to 85 cm, was carried out using the mixed wood sawdust in the 1 ft, 2 ft and 3 ft boxes. The division of the results in Figure 4 for this investigation is made according to the size of the box and the initiating source.

Appearance. The appearance of a typical dust heap at various stages of the propagation of the smouldering is shown in Plate 1. It will be seen that for the greater part of the duration of the smouldering there was no visible sign of the combustion. Within a few minutes of the smouldering emerging, the surface became damp near the centre, shortly afterwards the centre of the damp patch dried out, and this was soon followed by charring, the centre of which being usually within 1 cm of the centre of the top surface of the heap. It was only during these latter stages that steaming and the evolution of an acrid smoke occurred; previously the combustion was accompanied only by a faint smell quite unlike that characteristic of the open smouldering of the dust.

There was little change in volume of the dust during the course of the experiments, and the carbonized material formed in the cork dust heaps was sufficiently rigid to enable the heaps to be cut open for inspection (as shown in Plate 1). On exposure to the air the black carbonized mass started to glow over its entire depth, thus indicating that at no point was combustion within the heap near to completion. It was also noticed that there was always a sharp division between the carbonized and the unburnt dust.

The appearance of the smouldering in the experiments in which the dust was contained in boxes was, for depths less than 60 cm, very similar to that described above: thus a faint smell was again produced during the combustion and there was little visible sign until the smouldering had almost emerged. However, in the experiment carried out with an 85 cm depth of mixed wood sawdust, pronounced surface cracking occurred, and although the smouldering finally emerged from a crack, the total time of propagation (over 12 days) was close to the extrapolated value. Plate 2 contains six photographs (including some close-ups) taken at different stages of this particular experiment.

In the experiments in which the dust was contained in boxes, the rate of transfer of heat to the sides of the boxes was so slow that only a very slight elevation in temperature occurred at the sides. The width of the core of carbonized dust produced in the combustion seldom exceeded about half that of the box during the timed part of the experiments; and on excavation at the end of the experiments it was found that the dust surrounding the core was quite damp.

It was found that flaming could occur in two ways. The smoke produced, after the smouldering had penetrated to the surface and expanded part way across, was found to inflame above the smouldering region, even in still air. The flame did not, however, spread across the unburnt surface of the dust but remained stationary over the smouldering region. Larger but transient flames also occurred when the smouldering heap was disturbed and the core of carbonized dust allowed to fall in fine suspension through the air.

Discussion

The variation of the time for the smouldering to emerge (t hr.) with the depth of dust (y cm) can for all the conditions and materials studied in the present investigation be represented approximately by the equation:

$$t = Ky^n$$

Where K and n are empirical constants having the values given in the table below.

Table 4

Values of the constants in the equation $t = Ky^n$

Experiments	Source of ignition. Heap from mould	10^2K	n
Cork dust in conical heaps	-	3·6	1·90
" " in 1 ft box	M	2·5	2·05
Elm sawdust in conical heaps	-	3·5	1·95
Mixed wood sawdust in 1 ft box	M	6·5	2·05
" " " in 1 ft box	N	3·2	2·15
" " " in 2 ft box	N	2·5	2·15
" " " in 3 ft box	N	2·1	2·15

The time required is thus approximately proportional to the square of the dust depth, and the rate of propagation consequently varies inversely as the depth of dust overlying the smouldering zone, and is in general, appreciably slower than when under open conditions, and for large heaps may become very slow.

Although no systematic work was carried out on the effects of changes in moisture content and packing density, two brief investigations suggested that both have a noticeable influence on the times of upward propagation of smouldering through heaps of dust. This may be compared with the earlier findings that the rate of open smouldering in still air of a dust is affected by variations in moisture content but little affected by variations in packing density. In practice the packing density might be expected to have a wider range with large heaps than with small trains.

The width of a dust heap was found to have little effect on the times for smouldering to penetrate. This is indicated by the results obtained with heaps of cork dust from mould NN, the marked similarity of the results for cork dust in conical heaps and in the 1 ft box, and by the small relative displacement in the lines for the mixed wood sawdust resulting from changing from a box of one width to one of another.

Experiments in which the mixed wood sawdust was used have shown, in addition, that deep layers can sustain smouldering for many days without visible signs of combustion, and although a larger initiating source was required for deep layers the size of the source was negligible compared with that of the layer. There was no indication that a dust layer could be too deep for smouldering to penetrate upwards through it.

In view of the observed propagation of flame in the carbonized dust when in aerial suspension, standard dust inflammability tests (1) were conducted on samples of the carbonized and original dusts. The classifications which the samples received, original dust Class I, carbonized dust Class II, (i.e. the carbonized dust was less hazardous than the original), indicate that the activity of the carbonized dust when the propagation of flame was observed was probably connected with the dust being at an elevated temperature.

Slight packing errors occurred in the preparatory stages of the experiments and also developed as a result of the subsequent combustion; an explanation of the high general consistency of the results in view of these known errors may be that the effects of increases in packing density of the dust and consequent decreases in the depth of dust tend to balance each other. A numerical example of this is provided in the results quoted above for cork heaps at two different packing densities formed from mould N. A layer 5·2 cm in depth at a packing density of 0·160 g/ml contains the same weight as a layer 5·8 cm deep at a density of 0·144 g/ml.

The time measured for the smouldering to penetrate the first heap (1·00 hr.) is very close to that obtained by interpolation in Figure 2 for the second (1·02 hr.). Furthermore, it would appear from the similarity of the results for cork dust in conical heaps and in the 1 ft box that the time for the smouldering to penetrate is not particularly sensitive to variations in the initiating process.

Practical aspects. This work emphasizes even more the fire hazards associated with dust deposits of common occurrence in industrial practice. Earlier work in this series has shown, in particular, that smouldering can be initiated in heaps of dust a few centimetres in depth by a glowing cigarette end, and it has been shown above that such small heaps can ignite considerable depths of dust and thereby initiate fires requiring several days before any visible sign of the combustion is given. If a fire of this type occurred in practice it is probable that the development in its late stages would be unexpected; in addition, considerable difficulty might then be experienced in extinguishing such a fire.

There is an obvious parallel between the type of fire studied in the present work and those fires known to occur in closely-packed materials in bulk storage or transport and in tip heaps; it may therefore be argued that such fires may be started by the burying of small sources of ignition.

Conclusions

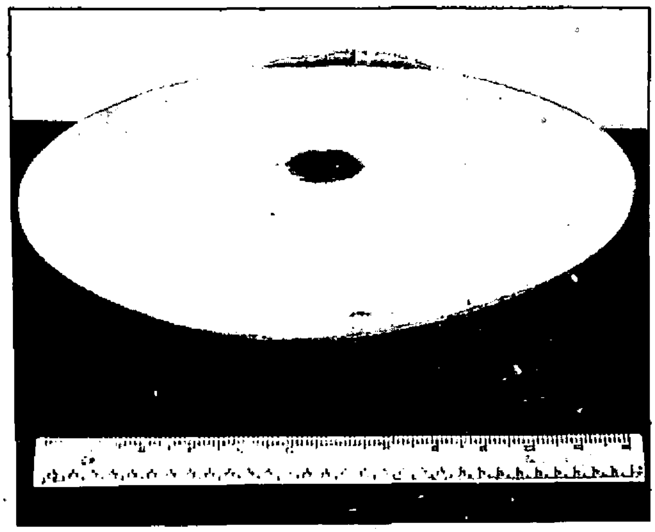
The main points arising from the results of this work are:-

1. A small source of ignition when buried in a heap of dust can initiate and propagate smouldering upwards through the heap.
2. The smouldering can then continue without visible signs of combustion for many days; the time for the smouldering to penetrate varying approximately as the square of the depth of the dust heap.
3. Increases in moisture content and packing density produce noticeable increases in the time for the smouldering to penetrate, whereas increases in the width of the dust heap have less effect.
4. When the smouldering penetrates to the surface of the heap the smouldering zone spreads out over the surface, and, if left unattended, the smoke produced can inflame above the smouldering region, even in still air. Larger but transient flames can occur as a result of disturbing the smouldering dust heap and allowing the core of carbonised dust to fall through the air in fine suspension.

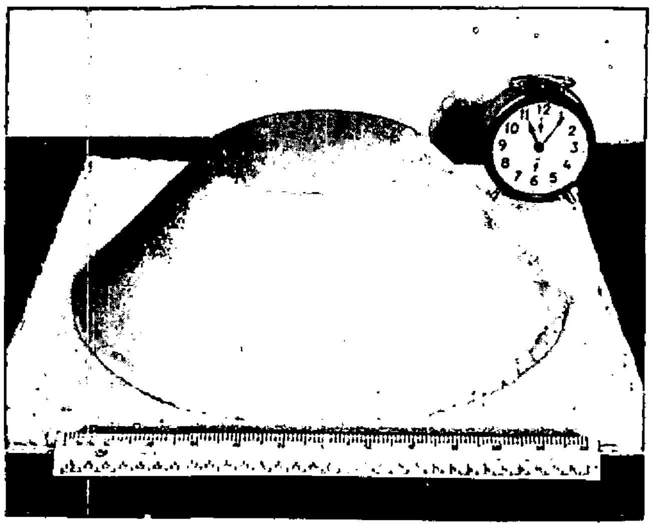
Acknowledgment. The authors wish to express their thanks to Mr. K. C. Brown, H.M. Inspector of Factories, Safety in Mines Research Establishment, Harpur Hill, Buxton for arranging the supply of cork dust used in this work and for carrying out the standard dust inflammability tests.

References. 1. K. C. Brown "A review of the present methods of testing industrial dusts for inflammability", S.M.R.E., Research Report No. 21.

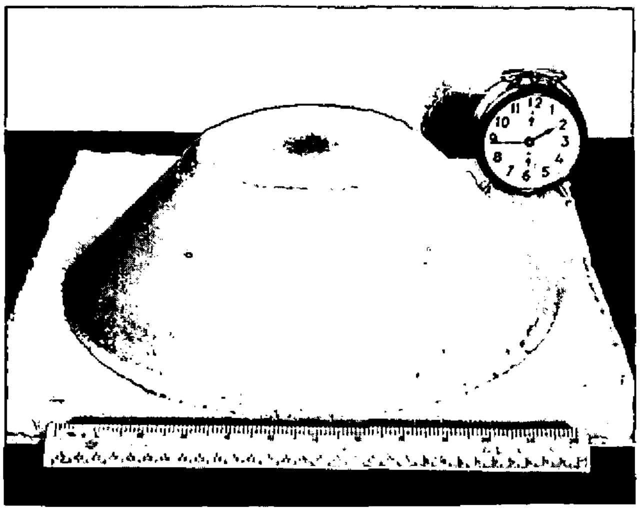
EPH



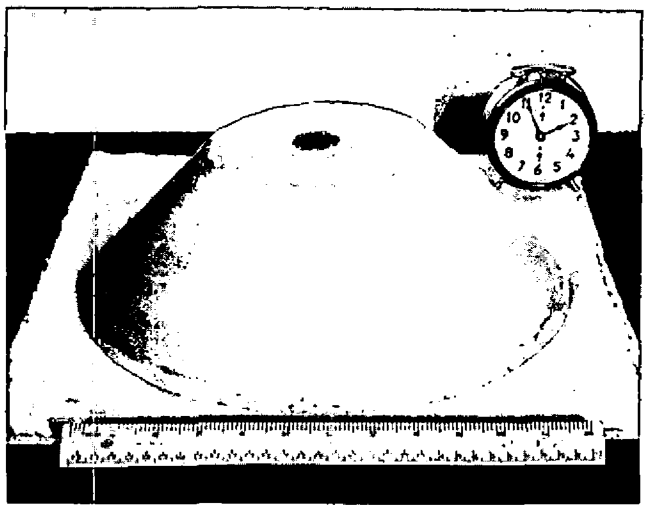
0-1 min Flame application
1-6 min Preburn



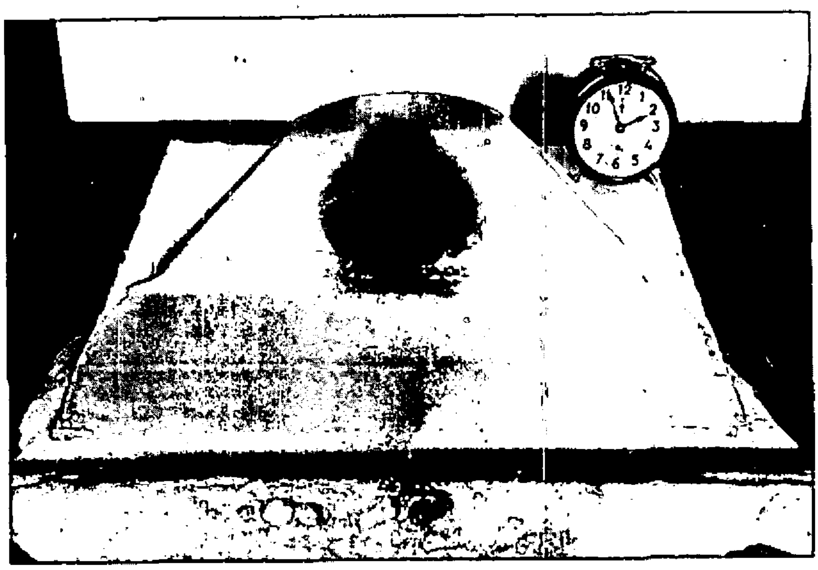
6 min Heap formation on asbestos millboard



2 hr 44 min Discolouration on top surface

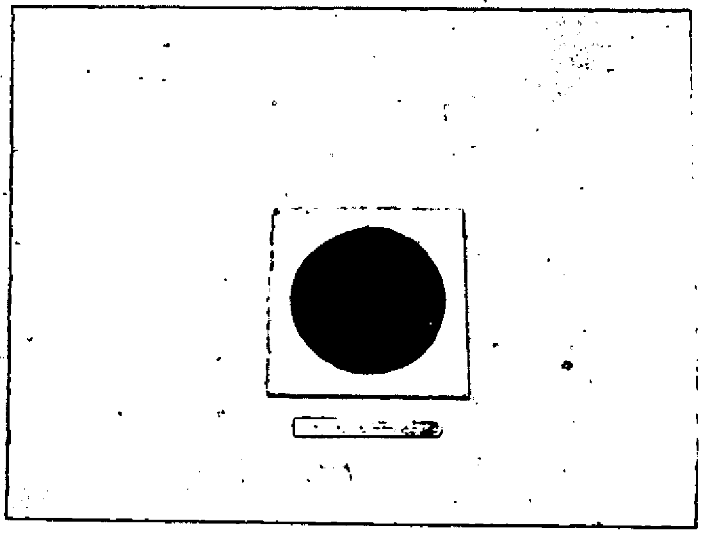


2 hr 55 min Penetration of the smouldering

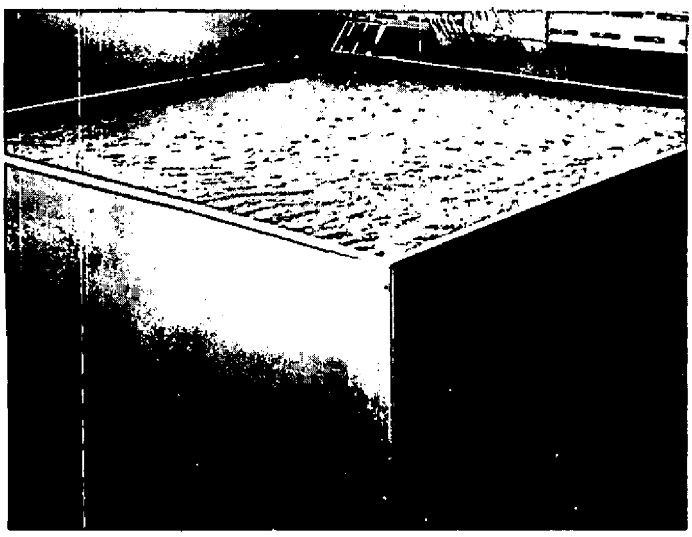


Section of heap showing carbonized core

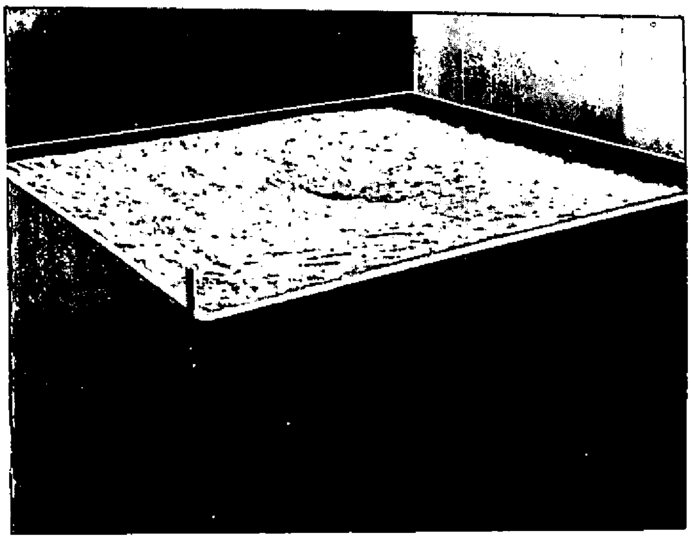
PLATE I. STAGES IN DEVELOPMENT OF SMOULDERING FIRE IN A CONICAL HEAP OF CORK DUST.



0 days (9·30am.)
Initiator in position.

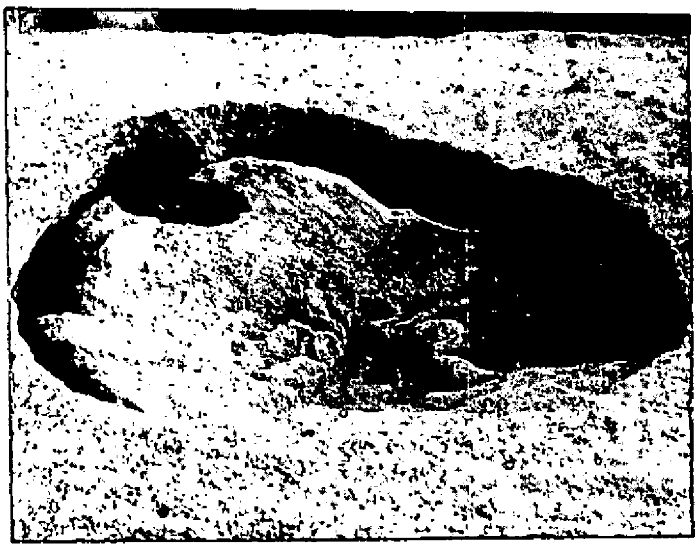


7 days
Sawdust appearance normal.

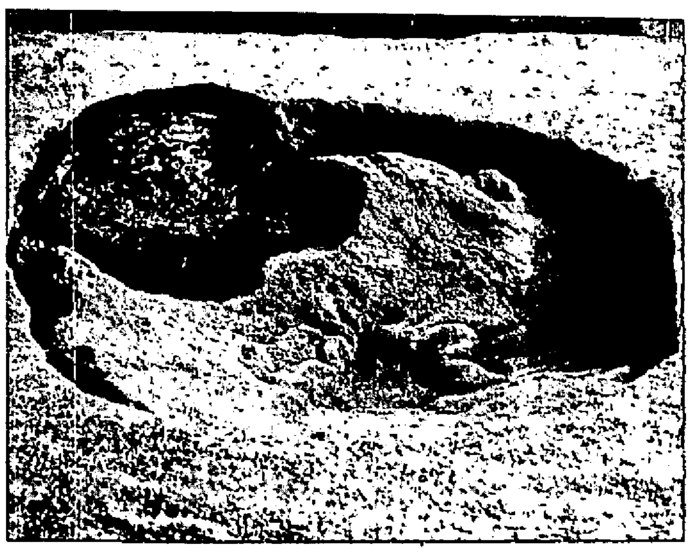


10 days
Central cracking and subsidence.

12 days (2 pm.)
Steam issuing from crack.



12 days (3·30 pm.)
Penetration of the smouldering.



12 days (4·30 pm.)
Smouldering spread to main surface.

PLATE 2. STAGES IN DEVELOPMENT OF SMOULDERING FIRE OF MIXED WOOD SAWDUST IN 3 FT. BOX.

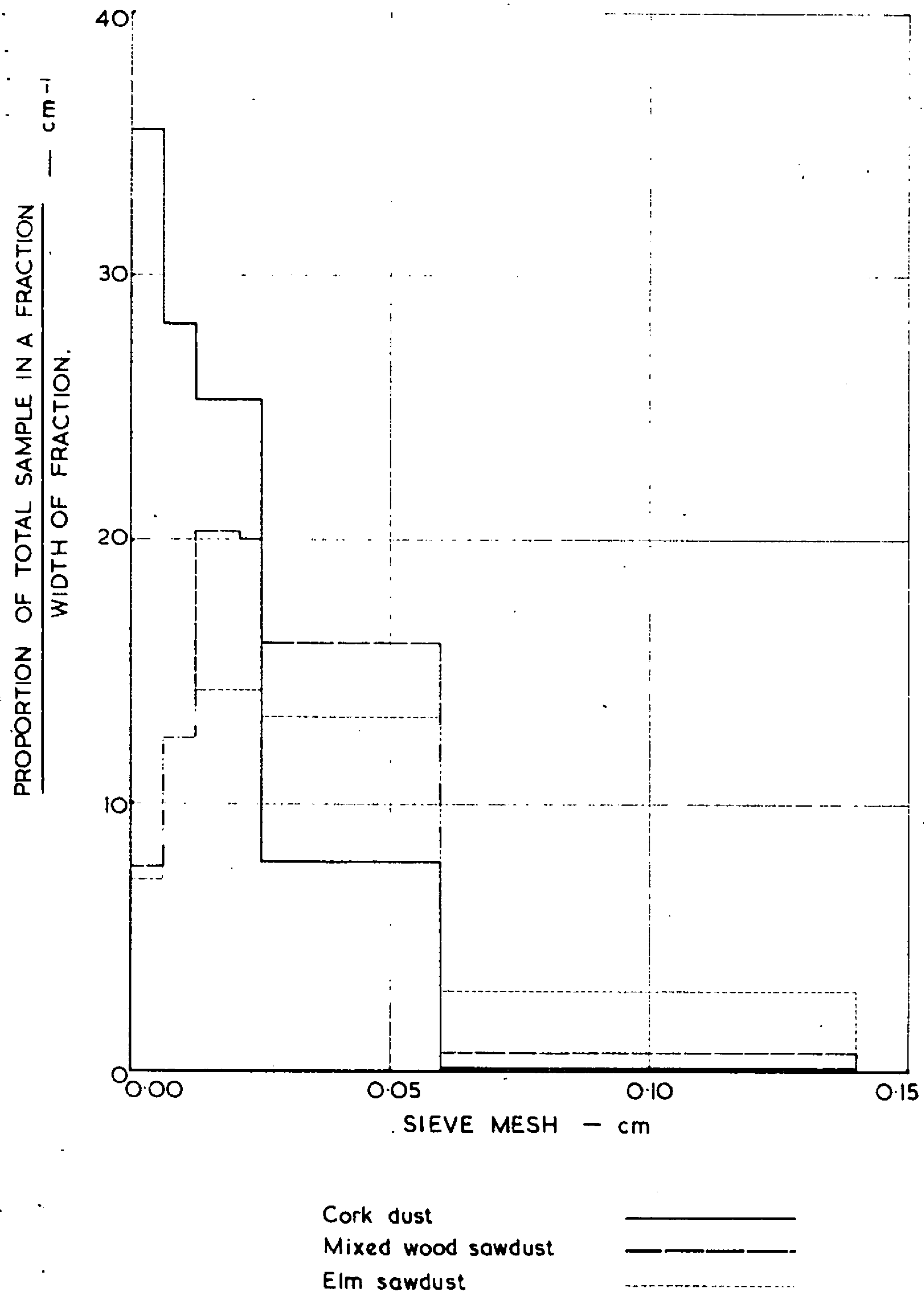


FIG. 1. THE DISTRIBUTION OF PARTICLE SIZES.

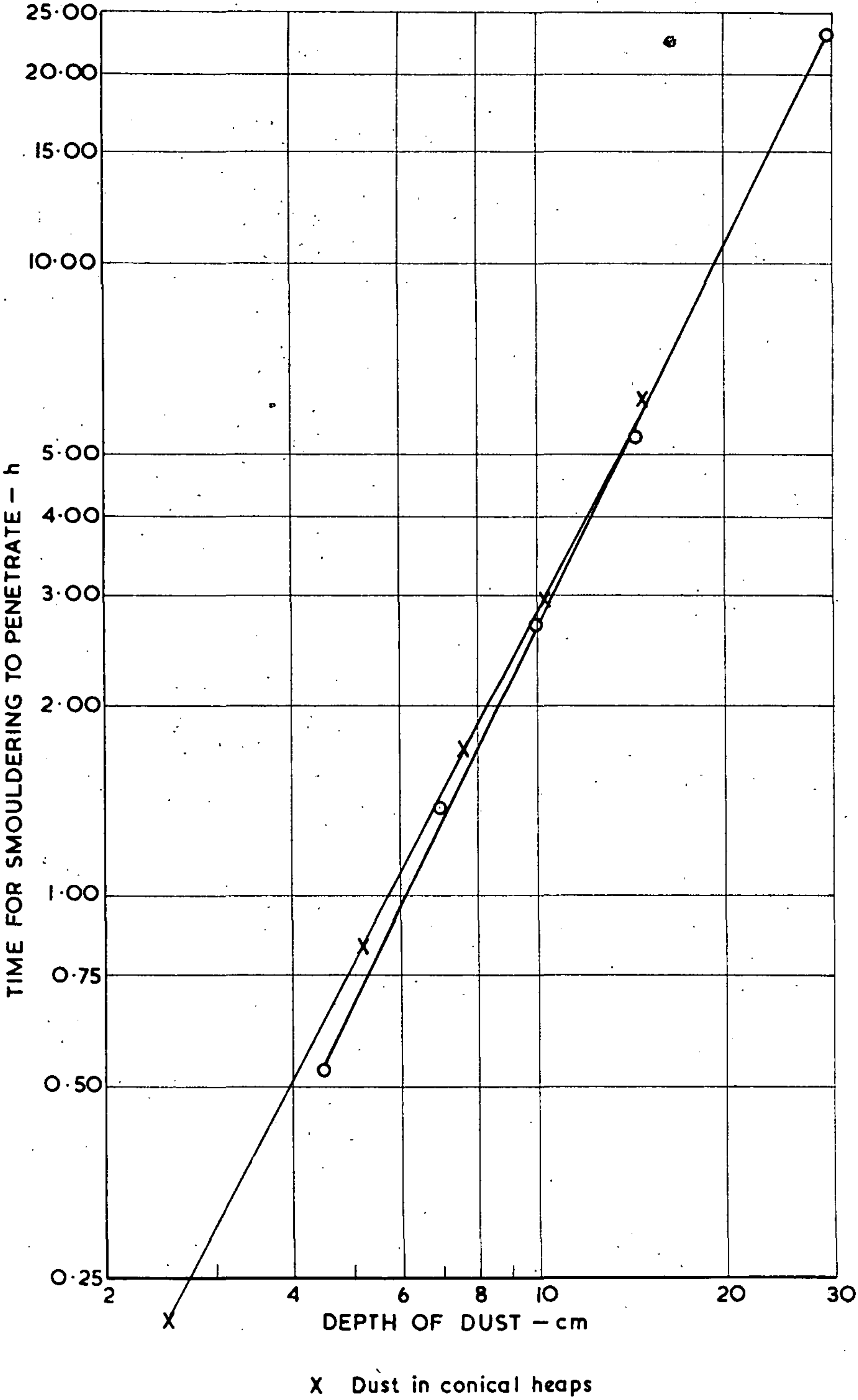


FIG. 2. SMOULDERING WITHIN LAYERS OF CORK DUST

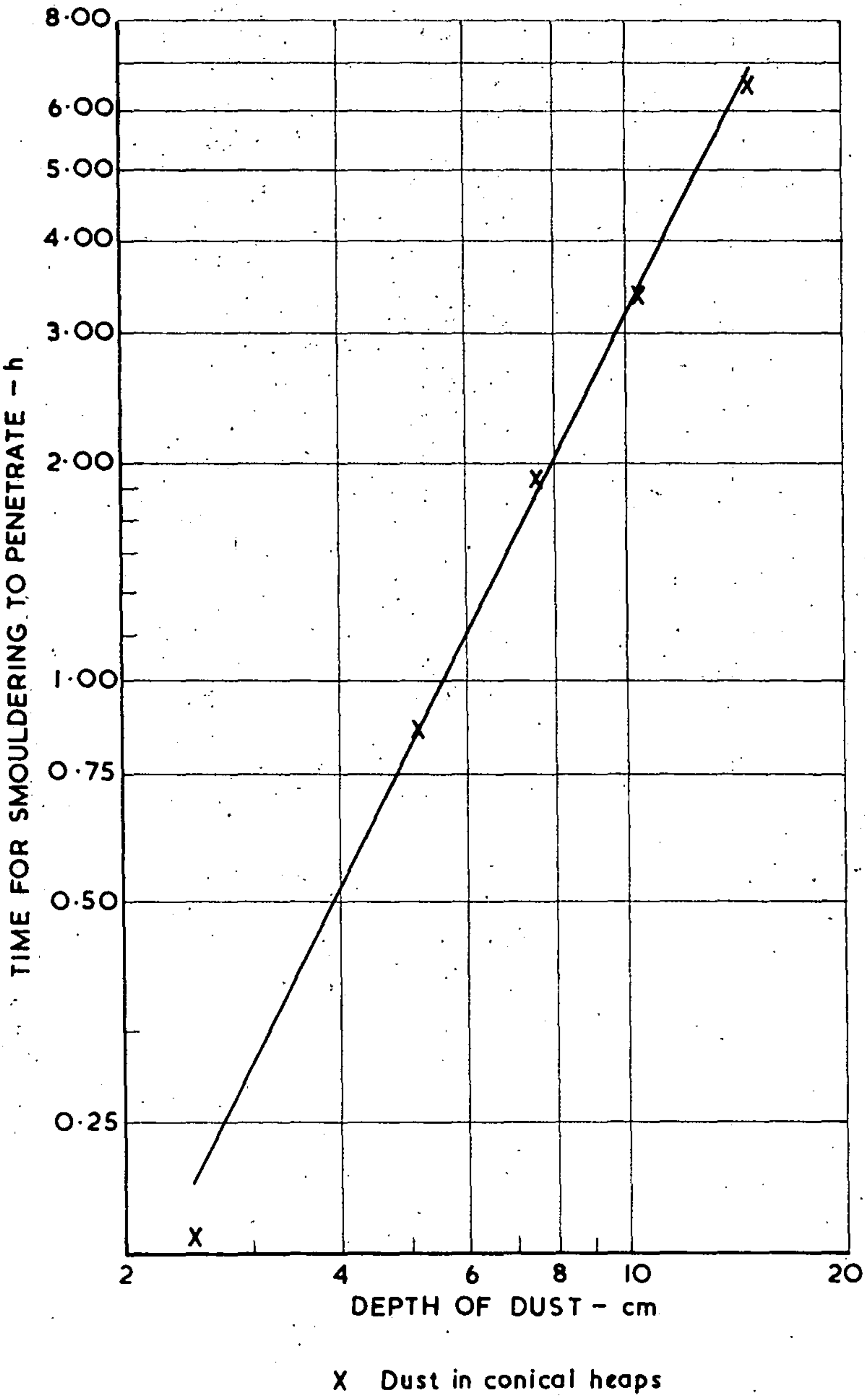
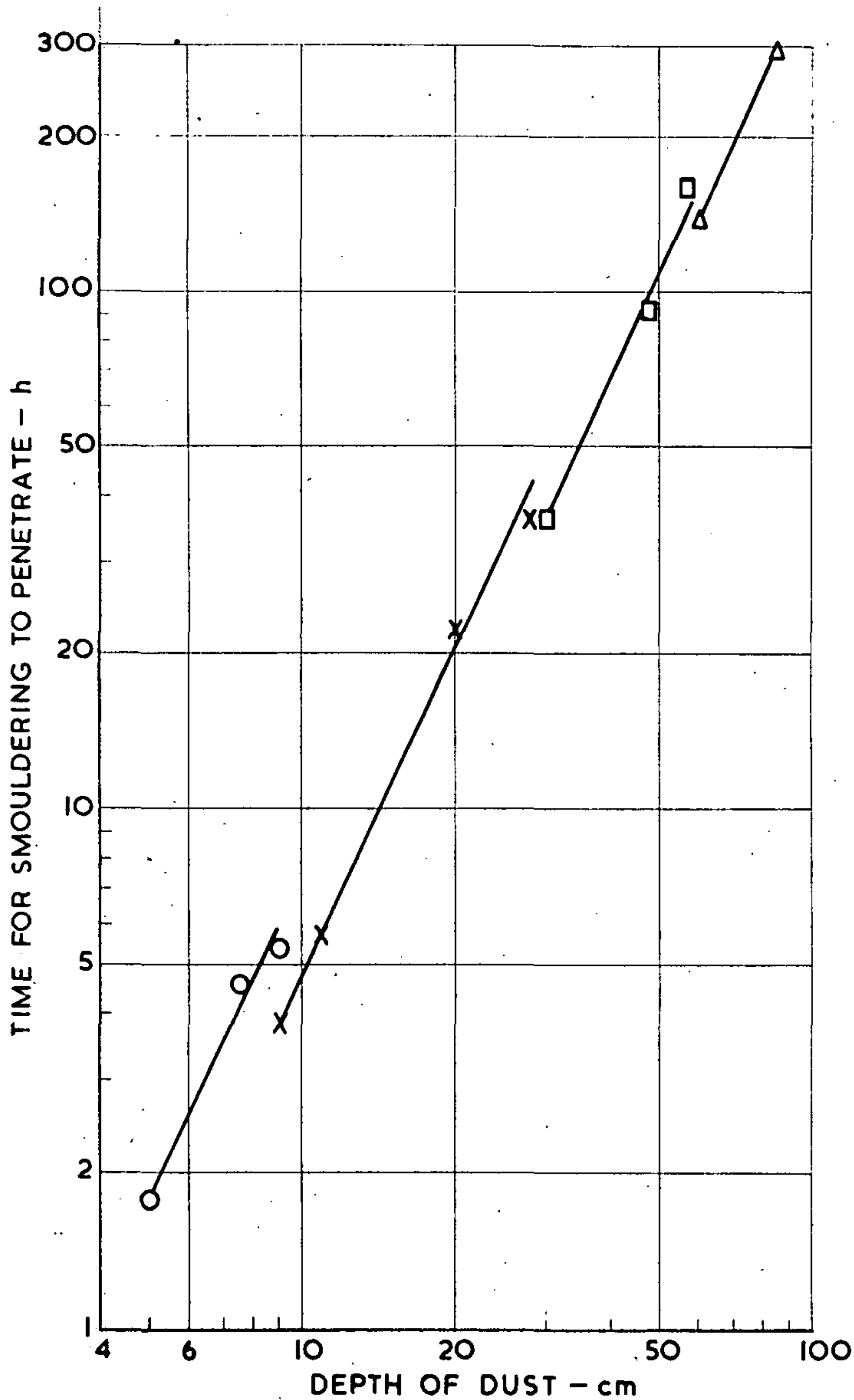


FIG. 3. SMOULDERING WITHIN LAYERS OF ELM SAWDUST



O	Heap	from	mould	M	as	initiating	source	to	layer	in	1 ft	box.
X	"	"	"	N	"	"	"	"	"	"	1 ft	"
□	"	"	"	N	"	"	"	"	"	"	2 ft	"
Δ	"	"	"	N	"	"	"	"	"	"	3 ft	"

FIG.4. SMOULDERING WITHIN LAYERS OF MIXED WOOD SAWDUST