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SMOULDERING IN DUSTS AND FIBROUS MATERIALS

PART V BEECH SAWDUST WITH AN INCIDENT AIR DRAUGHT

by

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SUMMARY

The effect of an incident airflow upon the smouldering of beech sawdust has been investigated in detail. The sawdust was formed into small trains, as in earlier experiments under still-air conditions, and placed in a small wind tunnel; smouldering was then initiated by a small gas flame and the time of travel over unit distance (smouldering time) was determined. A logarithmic relationship was found between the smouldering time and incident air velocity; the effects of variations in train size, sawdust particle size, and moisture content upon this relationship were comparatively slight. The reduction in the minimum depth of sawdust necessary for sustained smouldering was also investigated and it was shown that this depth could be reduced easily to less than 3 mm. by an incident draught.

Some further experiments, described in an Appendix, showed that flaming could be produced in wood shavings or newspaper in contact with the smouldering sawdust and that only gentle airflows are necessary. From these results it is concluded that an outbreak of fire could be a direct consequence of the initiation of smouldering in beech sawdust.

Introduction

This investigation is one of a series concerned with the properties of smouldering in common combustibles. The work was undertaken in order to determine whether smouldering could be an intermediate stage in the development of certain types of fire; in particular, fires in which there is a considerable delay between the time of ignition and the observed outbreak. It was suggested that in such cases smouldering could have been initiated unnoticed and that it could continue for long periods, if the rate of propagation were slow, before developing into flame. The first experiments upon smouldering were carried out with beech sawdust (1) and they showed that slow, but sustained, smouldering could occur in still air in trains of this dust and that it could be initiated by a small source of ignition such as a glowing cigarette end. The linear rate of propagation was found to be not greatly affected by changes in the particle size, density of packing, moisture content, or size of heap of the sawdust. Similar results were obtained later with deal sawdust (1) and some industrial dusts (2): with all the dusts it was found that there was a minimum depth of layer necessary for sustained smouldering, this depth varied with the nature of the material and for some of the finer dusts was only a few mm (2).

In all these experiments the smouldering was allowed to propagate under still-air conditions, the only airflow affecting the combustion zone was that due to the combustion itself; the effect of draughts upon the rate of propagation of smouldering is the subject of the present note. The effect produced by a flow of air upon smouldering is of considerable importance as it not only increases the rate of propagation but is also the most probable method by which the transition from glowing to flaming may occur, either in the dust itself or in other combustible material near the smouldering zone. As the smouldering of beech sawdust under still-air conditions had been studied earlier in detail, the same material was used in the present investigation; thus enabling direct comparisons to be made of smouldering rates under differing air conditions.

The relationships between air velocity and combustion rate have been studied by several earlier workers, a recent summary was given by Hoy and Whittingham (3); detailed investigations of the combustion of single carbon particles have been carried out by several workers, notably Tu, Davis, and Hottel (4) and Smith and Gudmundsen (5). In these experiments carbon spheres were suspended in furnaces through which metered airstreams were passed, either continuously or intermittently, and measurements were made of the rates of combustion and surface temperatures of the spheres. The experimental results indicated that the combustion of carbon involved two rate-determining processes:

1. chemical resistance (temperature sensitive)
2. diffusion (comparatively independent of temperature)

Tu et al inferred that, with carbon spheres, chemical resistance ceased to affect the combustion rate at temperatures greater than 1100°K; at these higher temperatures the counter diffusion of oxygen and carbon dioxide (assumed to be the main combustion product) through the stagnant film around the sphere was believed to be the rate-determining process. It was found that in the temperature range within which chemical resistance was the controlling factor the effect of changes in the ambient air velocity was totally overshadowed by that of temperature. When diffusion was the controlling process, however, the rate of combustion was found to vary as the 0.4 - 0.7 power of the air velocity and was only slightly dependent upon the ambient temperatures.

Concise accounts of present knowledge of the combustion of fuel beds in furnaces have been given by Lowry (6) and Thring (7). It is pointed out that measurements upon the rate of combustion of single particles cannot be applied directly to fuel beds by multiplying the combustion rate per unit area by the specific surface of the bed. Experiments showed that the specific reaction rate was dependent upon the velocity of air flow but more precise relationships were not obtained because the air velocity in a porous bed varies from point to point and is not uniformly turbulent; a further complication is that the pressure drop due to friction loss through the bed may cause disturbance of the individual particles. Another series of experiments, upon coke beds, indicated that the mass rate of absorption of oxygen per unit partial pressure was proportional to the 0.5 power of the mass rate of flow of oxygen. In these experiments, however, the beds were overfed and so the entering air was exposed to the residue from fuel which had been partly consumed during its passage through the bed; fluctuations in the size, ash content, and reactivity could thus occur and combustion rates near the point of air admission to such beds were variable.

It is evident from the above remarks that few systematic quantitative results are available, probably owing to the lack of satisfactory theoretical relations for conditions inside furnace beds. More knowledge is also required of the initial products of combustion so that the experimental observations and deductions for single fuel particles may be linked more closely to those obtained with the more complex system of a fuel bed.

The experiments described in this report were carried out in a small wind tunnel, of square cross-section, through which air was drawn by an electric fan. The beech sawdust was made up into small trains, as in the still-air experiments, and the linear rates of propagation of smouldering were measured. The effects produced by variations in train and particle size, packing density and moisture content of the sawdust were investigated, usually with the airflow in the same direction as the propagation of smouldering. Further experiments were carried out concerning the variation with airflow of the minimum depth of dust layer necessary for sustained smouldering. Finally, in an appendix, the details are given of experiments showing the spread of smouldering from beech sawdust trains into other materials and the subsequent production of flame.

Apparatus

The beech sawdust used in these experiments was taken from the same samples used in the earlier work carried out in still-air; details of the mean particle diameters and moisture contents of the different sieve fractions have already been given (1). The trains of sawdust were formed with the small metal moulds used before; some dimensions of these moulds are given in Table 1 for reference. Further details may be obtained from the earlier report, together with measurements of the mould Y used in the determinations of minimum depths of dust required for sustained smouldering.

Table 1

Dimensions of the moulds used in the determinations of smouldering rates

Mould	A	B	C	D	E	F
Top width cm.	1.35	2.35	3.55	5.10	7.25	9.85
Vertical depth along centre cm.	0.30	0.80	1.00	1.65	2.40	3.70

The wind tunnel, which was 15 ft. in length, was mounted horizontally; detailed measurements of the tunnel are given in Fig. 1. The construction was in four sections, as follows:

I - long duct containing combustion chamber, and observation panels, leading to II.

II - pipe with airflow regulator.

III - connecting pipe between II and IV

IV - electric fan drawing air through duct and pipes.

The air entered at the open end of the long duct I (Fig. 1) and travelled several feet before entering the combustion chamber. The chamber (Plate 1) was of the same cross-section as the duct (5 in. square) and transparent plastic observation panels were mounted in the asbestos side walls. A third panel was set in a detachable lid which formed the roof of the combustion chamber. This panel was marked out in centimetre divisions and another graduated scale was fixed to the floor of the combustion chamber to facilitate the measurement of smouldering rates. A metal bridge with an asbestos wood covering stood upon the lower scale and supported the train in the centre of the airstream (Plate 2).

On leaving the combustion chamber the air flowed through further ducting before entering a circular, sheet metal, pipe II containing a metal damper used as a means of fine adjustment of the air flowing through the tunnel. After passing through a conical, sheet metal, pipe III the air was finally expelled through the fan IV. As a means of coarse adjustment of the airflow, the outlet of the fan could be partially reduced in area. In order to maintain constant the voltage supply of the fan motor (0.072 BHP, 2800 RPM) a variable transformer and an A.C. voltmeter were introduced into the electrical supply circuit.

Particular care was taken to ensure that the interior of the tunnel was as smooth as possible, to prevent disturbance of the airflow, and that no leakage of air took place. The apparatus was situated in a large building with little bulk movement of air; consequently external disturbance of the air passing through the tunnel was reduced to a minimum.

Method

The method used in the formation of the trains was the same as in the earlier work carried out in still-air (1). Before the trains were placed in the combustion chamber of the tunnel the airflow was adjusted to the value required, using a moving vane anemometer for measurement of the air velocity; check determinations of the velocity were made at the end of each experiment. When the required airflow was obtained the trains, supported upon asbestos millboard, were placed upon the bridge in the combustion chamber; smouldering was then initiated by a small gas flame. In the experiments concerning the measurement of smouldering rates the combustion zone was allowed to advance 2-3 cm along the train before timing commenced. Measurements of the time of travel of the combustion zone at centimetre intervals, over a total distance of 10 cm, were made without parallax errors by using the graduated scales on the lid and the floor of the combustion chamber. The mean time per centimetre was taken as the "smouldering time".

The first investigation was concerned mainly with the effect of variation in air velocity upon the rate of smouldering in trains of 20-40 IMM sawdust formed from mould D. Two series of experiments were undertaken in which the airflow was either in the same direction as the propagation of smouldering (positive air velocities) or in the reverse direction (negative air velocities) further experiments in the former series were concerned with variation in the density of packing of the trains. The effect of variation in train size upon the relation between smouldering rate and air velocity was next investigated. In these experiments, restricted to positive air velocities, moulds B-E were used and trains were made from both the 20-40 IMM and the 40-60 IMM sawdust fractions. Studies were also made of the effects produced by variation of particle size and of moisture content of the sawdust; in both series of experiments the trains were formed from mould B and the air velocity restricted to positive values. In the particle size investigation the complete range of sawdust fractions was used (20-40 IMM to 100-120 IMM), but in the moisture content series only the three coarse sieve fractions were employed. The methods used for changing the moisture contents of the sawdust from normal values were identical with those described in the earlier report (1).

Finally, an investigation was made of the effect of air velocity on the minimum depth of dust layer required for sustained smouldering of the three coarse fractions of sawdust. Instead of obtaining minimum depth by direct measurement, as in the earlier work, a more precise method was adopted. Thus measurement was made of the distance down the train from the point where smouldering ceased to the shallow end of the train; the minimum depth was then calculated from this distance and the slope of the train, the latter quantity being obtained directly from the dimensions of the mould Y.

All experiments were carried out at atmospheric temperature.

Results

Appearance of the smouldering

The visible effect produced upon smouldering in trains of beech sawdust by an incident air draught was usually most marked when the air velocity was above 150 cm/sec. (1 m.p.h. = 44.7 cm/sec.). Thus, when the velocity of flow was below 100 cm/sec. the appearance of the trains was very similar to those smouldering under still-air conditions; when the air velocity was approximately 150 cm/sec, however, the ash residue was

was removed in the airstream and the smouldering trains glowed visibly. The brightness and extent of this glowing increased at higher air velocities and hence the division between the unburnt and burning portions of the trains became very marked; the position of the smouldering front could therefore be estimated with greater accuracy within the air velocity range 150-450 cm/sec. than at lower velocities or in still air. At greater velocities, outside this range, serious disturbance of both the smouldering zone and the unburnt sawdust particles occurred; under these conditions measurement of smouldering rates became difficult and hence detailed investigations were not undertaken.

Incident air flow

The results obtained in the initial experiments, devoted mainly to the effect of airflow upon the smouldering rate, are shown in Figs. 2 and 3. In both Figs. the smouldering time is plotted on a logarithmic scale whereas the air velocity scale is linear, in Fig. 2 the results are for positive air velocities (airflow and propagation of smouldering in the same direction) and in Fig. 3 are for negative velocities. All the results shown in Figs. 2 and 3 are for trains packed to a medium density of 0.28 gm/ml. In both Figs. the graphs are extrapolated to zero air velocity by means of dashed lines, these are used to indicate that sustained smouldering occurs within this velocity range (since smouldering is sustained in still air [1]). In addition to the above, attempts were made to determine the effect of variation in packing density upon the smouldering rate, using an air velocity of 250 cm/sec. It was found, however, that packing to an initial dry weight density of 0.30 gm/ml, or more, resulted in the expansion of the trains immediately ahead of the smouldering front; thus changing both packing density and size of train. Since this method proved unsuitable for detailed investigations the experiments were discontinued; the results that were obtained, however, indicated that any alteration of the smouldering rate caused by change in the packing density was small compared to that produced by variation in airflow. In all subsequent experiments the packing density was maintained at 0.28 gm/ml, unless otherwise stated.

Train size

The results obtained in the investigation of the effect of train size upon the smouldering rate, under airflow conditions, are summarised in Figs. 4 and 5 (for 20-40 and 40-60 IMM fractions respectively); in Fig. 4 the results previously obtained with mould D, and shown in Fig. 2, are included for comparison. Each of the lines shown in Figs. 4 and 5 was initially drawn as a separate graph before being added to the group; the individual points are omitted in both Figs. for clarity, since the scatter of the results was in all cases similar to that shown in Fig. 2. Extrapolations to zero air velocity were again made using dashed lines for trains which sustain smouldering in still-air (D,E); the results for the smaller trains not sustaining smouldering under these conditions (B,C) are extrapolated by dotted lines. Thus sustained smouldering in these smaller trains ceases in the air velocity range represented by the dotted lines. The measurement of smouldering rates was restricted at high air velocities by disturbance of the trains; the results shown in Figs. 4 and 5 are for experiments in which little or no disturbance occurred. No experiments were carried out with the mould F as the trains formed were too large for convenient measurement; with the smallest mould (A) no measurements could be taken as smouldering was not sustained by trains from any of the sawdust fractions. Similar results to those described above for trains of intermediate size formed from the 20-40 and 40-60 IMM fractions were obtained with 60-80 IMM sawdust, using moulds B and C only; further experiments with this and finer dusts were restricted in number by the limited quantities of sawdust available.

Sawdust particle size

The effect of particle size and airflow upon the smouldering time was next investigated; a summary of the results is given in Fig. 6 and includes those already shown in Figs. 4 and 5 for trains formed from mould B and the two coarse fractions of sawdust. Individual points are again omitted in Fig. 6 from the family of results and the lines are extrapolated to zero air velocity, with broken lines, using the same convention as before. It is noteworthy that the results given in Fig. 6 show that at high air velocities the most rapid smouldering (i.e. smallest smouldering time) occurred with the coarsest fraction of sawdust, but that the effect was reversed at lower velocities and this fraction then produced the least rapid smouldering. Also, the other sawdust fractions behaved similarly and remained in the same relative sequence throughout the air velocity range investigated.

Moisture content

The experiments concerning the effect of variation in moisture content of the sawdust were carried out upon several fractions, using extreme values of moisture content (approximately 0% and 22% respectively). The results given in Fig. 7, for 20-40 IMM sawdust, also include those for sawdust in the normal condition (moisture content 9.4%) and shown earlier in Figs. 4 and 6. The packing density of the trains was not maintained throughout at 0.28 gm/ml since the sawdust particles expanded considerably on increasing their moisture content to 22.3%; trains of sawdust in this condition were thus packed at a dry weight density of 0.19 gm/ml. It is again noteworthy that the fraction smouldering least rapidly at low air velocities (that with moisture content of 22.3%) was also that which smouldered most rapidly at higher velocities; similar behaviour was observed on varying the particle size (Fig. 6).

Minimum depth

Experiments showed that the minimum depth of dust layer necessary for sustained smouldering is reduced when a draught is incident upon the layer. The effect of airflow upon the minimum depth of the 20-40 IMM sawdust fraction was therefore studied and the results are shown in Fig. 8, for the air velocity range 45-250 cm/sec; at higher rates of flow the minimum depths were very small and were not measurable even though the method used was more precise than in the earlier work (see Experimental). The results shown in Fig. 8 are for experiments upon trains formed from the wedge-shaped mould Y, in which smouldering had ceased at a point within the trains and not at an edge; however, the scatter of the results was wide compared to those given in Figs. 2-7. Similar variations were obtained with the 40-60 and 60-80 IMM. sawdust fractions.

Ease of ignition

The initiation of smouldering by a small source of ignition, such as a glowing cigarette end, became much easier under even a small airflow (100 cm/sec) than described earlier for still-air conditions(1). In addition, the smouldering zone produced initially by a source of small area spread rapidly across the entire width of the trains; it then proceeded in the same manner as in trains in which smouldering was initiated by the small gas flame. In none of the experiments described above was the smouldering transformed into flaming by the action of draught; this was not entirely unexpected since, as stated in the earlier report (1), none of the beech sawdust fractions sustained flaming in still-air. Some experiments were carried out, however, to determine whether smouldering beech sawdust trains could induce flaming in other materials under the action of draught; as these experiments involved the use of combustibles other than beech sawdust, and as the conditions were not rigorously controlled, the method and results of these experiments are given in an Appendix.

Discussion

Appearance and effect of airflow upon trains

The experiments described above have shown that an incident air draught produces marked changes in both the appearance and the rate of propagation of smouldering in beech sawdust trains. It is apparent from Fig. 2 that, within the positive air velocity range investigated (50-500 cm/sec), there is an approximately exponential relationship between the smouldering time and the incident air velocity; in this air velocity range the smouldering time can decrease to about one tenth of its value at very low air velocities. When the airflow was in the opposite direction to the propagation of smouldering (i.e. negative air velocities) the relationship between the smouldering time and incident air velocity was more complex (Fig. 3); this may be due to the air stream not impinging directly on to the smouldering zone but forming an eddy in the lee of the train. The air velocity in this eddy may not be equal to that in the main air stream and would probably be affected by the geometrical shape and roughness of the surface of the train; since the effect of negative airflows upon the smouldering time was small compared to that of positive velocities, particularly with gentle air flows, the number of experiments was restricted to that shown in Fig. 3.

The mathematical relationship between smouldering time (S) and positive air velocity (V) for the results given in Fig. 2 is of the form:

$$\log (S/S_o) = -mV \quad \text{.........................} \quad (i)$$

where m is a +ve constant, and S_o is the smouldering time with zero incident air velocity.

The substitution of numerical values in this equation leads to:

$$\log_{10} S = -2.6 \times 10^{-3} V + 2.8$$

It should be noted that an alternative formulation of equation (i) is

$\log (R/R_o) = mV$ where R is the linear rate of propagation of smouldering (cm/sec)

whence $\frac{dR}{dV} \propto R$ so that as R increases $\frac{dR}{dV}$ also increases.

Since this relationship is unlikely to be valid for large values of R, it is probable that equation (i) holds over a restricted air velocity range only; with the beech sawdust however, this range is greater than that imposed by the tendency of the dust to be disturbed in high velocity air streams (above 500 cm/sec). The results shown in Fig. 2 give no indication that the relationship between smouldering time and incident air velocity does not hold for airflows only slightly less than those necessary for serious removal of the dust; in addition, when the air velocity was increased above a certain critical range (100-150 cm/sec), the ash formed during combustion was removed by the draught without affecting the logarithmic relation between smouldering time and air velocity. It is thus unlikely that ash formation takes a significant part in regulating the rate of smouldering of beech sawdust under the airflow conditions employed.

The relationship given in equation (i) differs considerably from those obtained by earlier workers and summarised in the Introduction; in particular, the effect of airflow upon the combustion rate of single carbon spheres is usually markedly less than upon the smouldering rate of beech sawdust, especially at the higher airflows. There are, however, considerable differences in the experimental conditions of the two cases since the combustion of the carbon spheres resembles the smouldering of a solid block of material over its entire surface.

Comparison of the results obtained upon the smouldering of beech sawdust trains with measurements upon furnace beds also has limited value because the air is blown through fuel beds whereas it flowed over the sawdust trains. Further experiments are needed to determine whether logarithmic relationships similar to that in equation (i) are obtained with smouldering in other materials such as trains of different dusts and strips of fibre insulation board. As the visible glowing of the beech sawdust trains brightened with increasing airflow, it is probable that the temperature of the smouldering zone was increased; at present, however, the relation between incident air velocity and smouldering zone temperature is unknown.

Effect of train size

The results given in Figs. 4 and 5 show that logarithmic relationships, as in equation (i), still hold for various train sizes but that for a given sawdust fraction the value of the constant m is dependent upon the mould size; thus under the same conditions small trains tend to smoulder more rapidly than larger trains. The effect of train size is most marked at the higher air velocities and it may possibly be caused by the reduction in air velocity at the centre of the smouldering zone, since most of the air incident upon the train does not flow through it but is deflected past. A greater reduction in air velocity would be expected with trains of greater cross-sectional area and hence the smouldering of these trains would be less rapid than with those formed from smaller moulds. No simple relationship was obtained between the dimensions of the moulds and the separation or differences in gradient of the lines shown in Figs. 4 and 5; any further examination of this aspect would entail experiments with a series of moulds whose widths and depths could be varied independently.

The results obtained for the smouldering of beech sawdust trains under still-air conditions[1] indicated that within the limits of experimental error the smouldering time was independent of the train size; the values of these earlier smouldering times are tabulated below together with those obtained from Figs. 4 and 5 by extrapolation to zero air velocity (S_o in equation (i)). It should be noted that zero incident air velocity is not exactly equivalent to still-air conditions since with the latter there is an airflow at the smouldering zone, due to natural convection, which is perpendicular to the direction of the applied airflow.

Table 2

Comparison of smouldering times (min/cm) obtained in still air with extrapolated values for zero air velocity.

Mould	20-40 I.M.M. fraction		40-60 I.M.M. fraction	
	Still air	Zero air velocity	Still air	Zero air velocity
B	n.s.	(10.8)	n.s.	(10.5)
C	n.s.	(11.3)	n.s.	(10.5)
D	11.1	11.3*	10.7	11.0
E	11.6	11.3	-	11.5

*12.3 min/cm on extrapolating results for negative airflows (Fig.3)

n.s. denotes "no sustained smouldering".

The values of the smouldering time given for trains from the smaller moulds B and C are of theoretical interest only, as these trains do not sustain smouldering in still-air, but there is close agreement with the larger trains between the measured smouldering times in still-air and the values obtained by extrapolation.

Effect of particle size

The family of results given in Fig. 6 for particle size experiments is notable in showing the existence of an air velocity range within which the smouldering time of trains from a given mould is approximately independent of the particle size of the sawdust. The limits of this range will, however, probably be affected by the train size. With some fractions the extrapolated values of smouldering time at zero incident air velocity can be compared directly to values obtained earlier in still-air with trains from mould B; with the coarser fractions, however, trains from mould B did not sustain smouldering and the values given in Table 3 are for trains from the larger mould D. It has already been demonstrated that variation in train size causes no measurable change in smouldering time under still-air conditions.

Table 3

Comparison of still-air and extrapolated values of smouldering time for various sawdust fractions.

Sawdust fraction	Smouldering time (min/cm)	
	still-air	extrapolated
20-40 I.M.M.	11.1*	10.7
40-60 "	10.7*	10.5
60-80 "	10.4*	8.8
80-100 "	9.5	8.6
100-120 "	9.0	8.4

*trains from mould D; all others from mould B.

There is again fair agreement between the still-air and extrapolated values of the smouldering time, and although the latter values are slightly less than in still-air, this difference may not be significant because small changes in the positions of the lines in Fig. 6 could result in comparatively large variations in the values of the intercepts owing to the condensed scale. It may be seen from Tables 2 and 3 that the extrapolated values of smouldering time of trains not supporting smouldering in still-air were approximately equal to experimental determinations made upon larger trains under these conditions; this indicates that the transition to a non-smouldering state occurs abruptly without affecting the logarithmic relationship between smouldering time and incident air velocity.

The results given in Fig. 6 show that the slopes of the lines increased with particle size and although no direct relation was obtained it is probable that coarser particles would give even greater reductions in smouldering time per unit increase in air velocity. If this were so, the rate of production of volatile combustible gases distilled from the sawdust by the smouldering zone would increase more rapidly than the rate of removal in the air stream; this would render more probable the direct production of flaming from glowing in trains of beech sawdust.

Effect of moisture content

The dispersion of the results obtained upon varying the moisture content of the sawdust trains (Fig. 7) was smaller than that for variation in particle size; but, as before, an air velocity range was found within which the smouldering time of a given sawdust fraction was approximately independent of its moisture content. The sawdust sample which smouldered least rapidly under small airflows (that with high moisture content) was also that giving the greatest change in the logarithm of the smouldering-time per unit air velocity change; this behaviour was similar to that observed in the previous experiments (Fig. 6). It is possible that the factors which determine the smouldering time of the sawdust in still-air are also those which control the rate of change of smouldering time with incident air velocity; the measurement of temperature distributions in the trains may provide further information upon this aspect.

Minimum depth for sustained smouldering

The decrease in minimum depth with air velocity is shown in Fig. 8, for the 20-40 IMM sawdust fraction; it may be seen that only slight air velocities are necessary for considerable reductions in the minimum depth. Thus the still-air value of 1.3 cm is reduced to about 0.2 cm by an airflow of 5 mph. (223 cm/sec). As with the experiments upon smouldering time there again appears to be a logarithmic dependence upon air velocity although the scatter of the results is greater than in the earlier experiments. This scatter was too large to be accounted for by the error in the determination of the minimum depth (± 0.1 mm); it may be caused by chance local variations in the sawdust trains affecting the position at which smouldering ceases. It should be noted that these experiments measure the depth of layer at which smouldering ceases in a wedge-shaped train; this depth may be slightly less than that required for sustained smouldering in a uniform layer.

As with the smouldering times there is fair agreement between minimum depths measured under still-air conditions and extrapolated values for zero incident air velocity; there is thus a marked similarity in the relations of minimum depth and smouldering time to airflow.

Practical considerations

The possibility of fires developing by the mechanism suggested in tho Introduction has been demonstrated in the experiments described above and in the Appendix. Thus, although the effect of airflow upon the smouldering time of beech sawdust is much greater than any other factor investigated, only small changes are produced at the low air velocities required for the flaming of wood shavings or newspaper. Smouldering may therefore proceed at a very slow rate in still-air or slight draught for long periods before flame appears; further experiments are required, however, upon the latter aspect. The decrease in the minimum depth of dust required for sustained smouldering under airflow conditions also has practical significance in that a layer of sawdust only 2-3 mm. in thickness may be able to support smouldering for considerable periods. The fire hazard of such very shallow deposits of combustible dust has not, perhaps, been fully realised.

Conclusions

The main points arising from this work are:

1. The smouldering times (min/cm) of beech sawdust trains are greatly reduced by an air draught in the same direction as the propagation of smouldering; the effect is much more marked than with any of the factors investigated under still-air conditions.

2. In the air velocity range investigated a relationship of the form $\log (S/S_o) = -mV$ was found between the smouldering time (S) and incident airflow (V). This relationship was affected only slightly by variations in train size, particle size and moisture content of the sawdust.

3. The minimum depth of sawdust layer necessary for sustained smouldering was also found to decrease approximately logarithmically with incident air velocity. In consequence, very shallow layers of beech sawdust are able to sustain smouldering under airflow conditions; such layers therefore present a fire hazard.

4. If the measurements of smouldering times and minimum depths are extrapolated to zero incident air velocity, the intercept values are in approximate agreement with the results of experiments carried out under still-air conditions.

5. The incidence of draught upon beech sawdust increases the ease of initiation of smouldering by sources such as glowing cigarette ends. Although smouldering in the beech sawdust trains does not develop into flaming under a constant air draught, flaming may be produced in materials such as wood shavings or newspaper in contact with the smouldering dust. The rapid development of fire may thus occur a considerable time after the initial ignition if the propagation of smouldering in the dust has proceeded unnoticed.

Acknowledgment

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References

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NOTE

Since this report was produced a systematic error has been discovered in the measurement of the air velocity incident upon the trains. In consequence, the values of air velocity shown in Figs. 2-8 are too large by a constant factor; corrected values are given below.

Air velocity shown cm/sec	40	80	120	160	200	240	280	320	360	400	440	480
Corrected air velocity cm/sec	35	70	105	140	175	210	245	280	315	350	385	420

Appendix

As subjecting the beech sawdust trains to an air draught at constant velocity had failed to produce flaming in this dust, some further experiments were carried out involving materials which would support flaming viz. thin wood shavings and newspaper. In these experiments a beech sawdust train (from mould C or D) was made up in the normal manner and placed in the wind tunnel; it was then covered, except for about 6 cm. at one end, to a depth of approximately 5 cm. with either the wood shavings (a mixture of cedar and deal) or crumpled quarter sheets of "The Times" newspaper (July 1952). Smouldering was then initiated at the exposed end of the train and timing was started after the smouldering front had travelled about 2 cm. Measurements were made of the smouldering time over a 3 cm. length of train in addition to the period of time required for flaming; the results are tabulated below:

Table 4

Experimental details of the production of flame.

Mould	Layer material	Air velocity cm/sec	Time for 3 cm. smouldering mins.	Time for flaming mins.
C	Wood shavings	284	9.8	20.3
"	" "	217	12.0	19.0
"	" "	180	14.5	23.8
"	" "	124	22.3	48.5
"	" "	88	25.3	65.8
D	" "	90	ca 27	38.3
"	" "	64	30.5	48.0
"	" "	43	-	> 60
"	" "	still-air	-	No flaming
C	Newspaper	119	ca 21	31.8
"	"	85	-	39.0

(44.7 cm/sec = 1 m.p.h.)

A series of photographs from a demonstration experiment, on a larger scale, is given in Plate 3.

It may be seen from the results given above that although trains of the beech sawdust were not able to produce flaming in themselves, they could cause other materials to inflame under very small airflows. Thus the minimum air velocity required to produce flaming in wood shavings from a smouldering beech sawdust train (mould D) is less than 43 cm/sec; in addition, the total time required is over 1 hr. which could be greatly lengthened by increasing from 6 cm. the distance travelled by the smouldering front along the uncovered portion of the train.

In view of the obvious practical importance of these results it is considered that more detailed investigations are required, with particular regard to the relative sizes of the train and covering layer as well as the nature of the latter material.

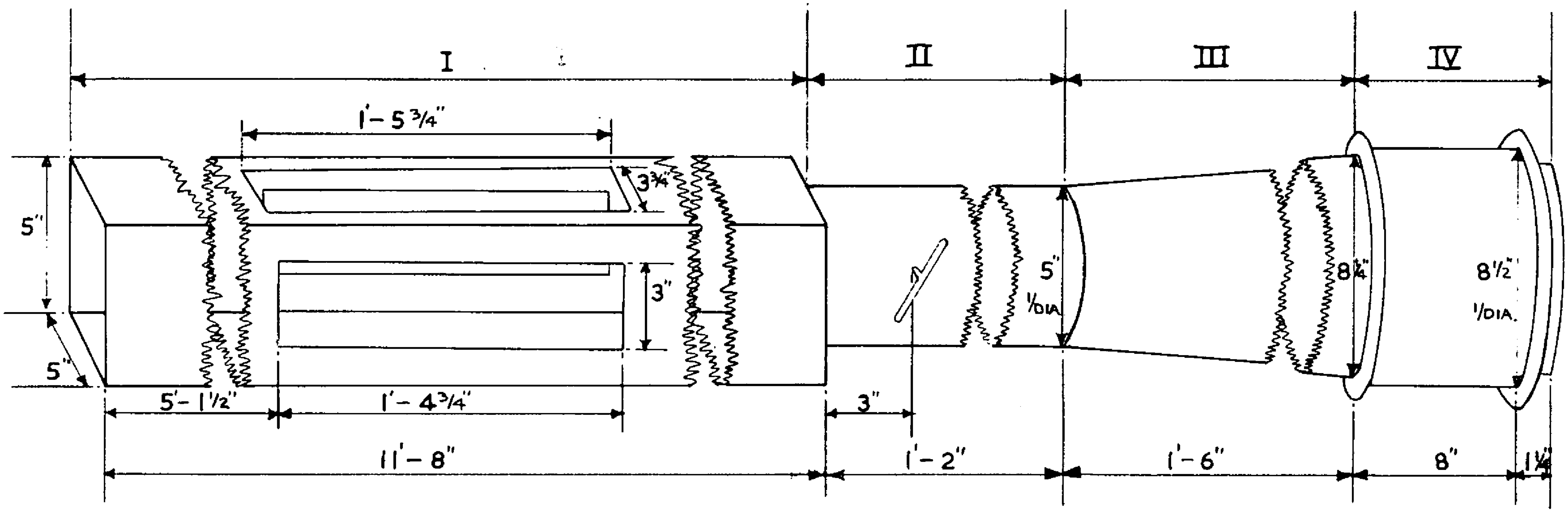


FIG. 1. THE WIND TUNNEL

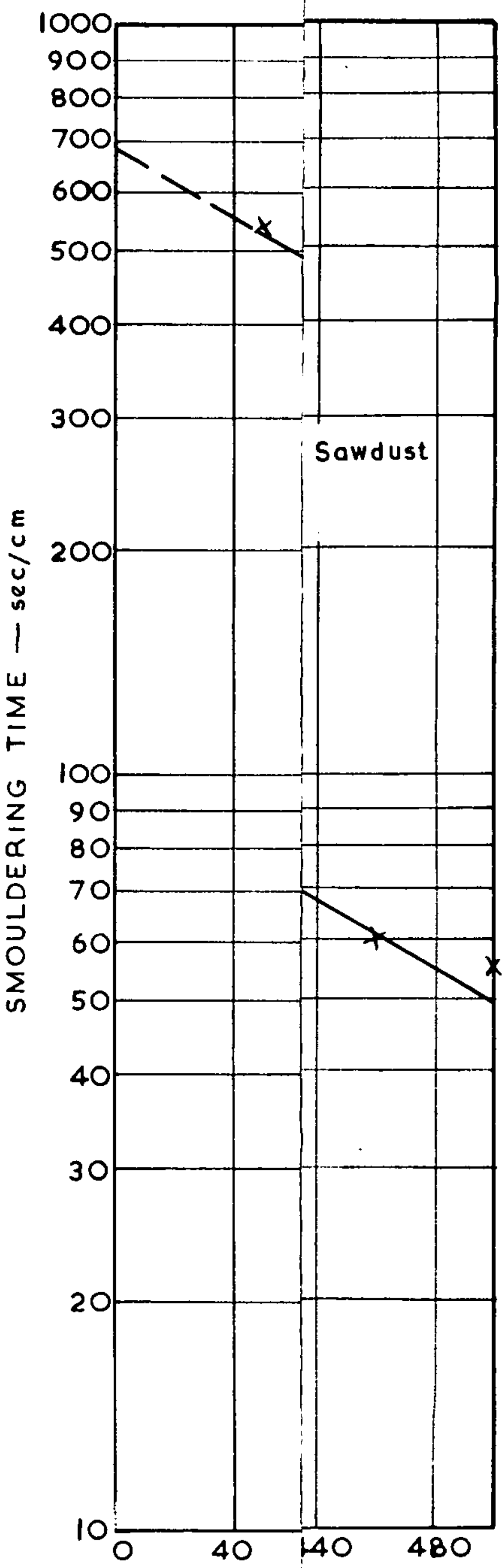
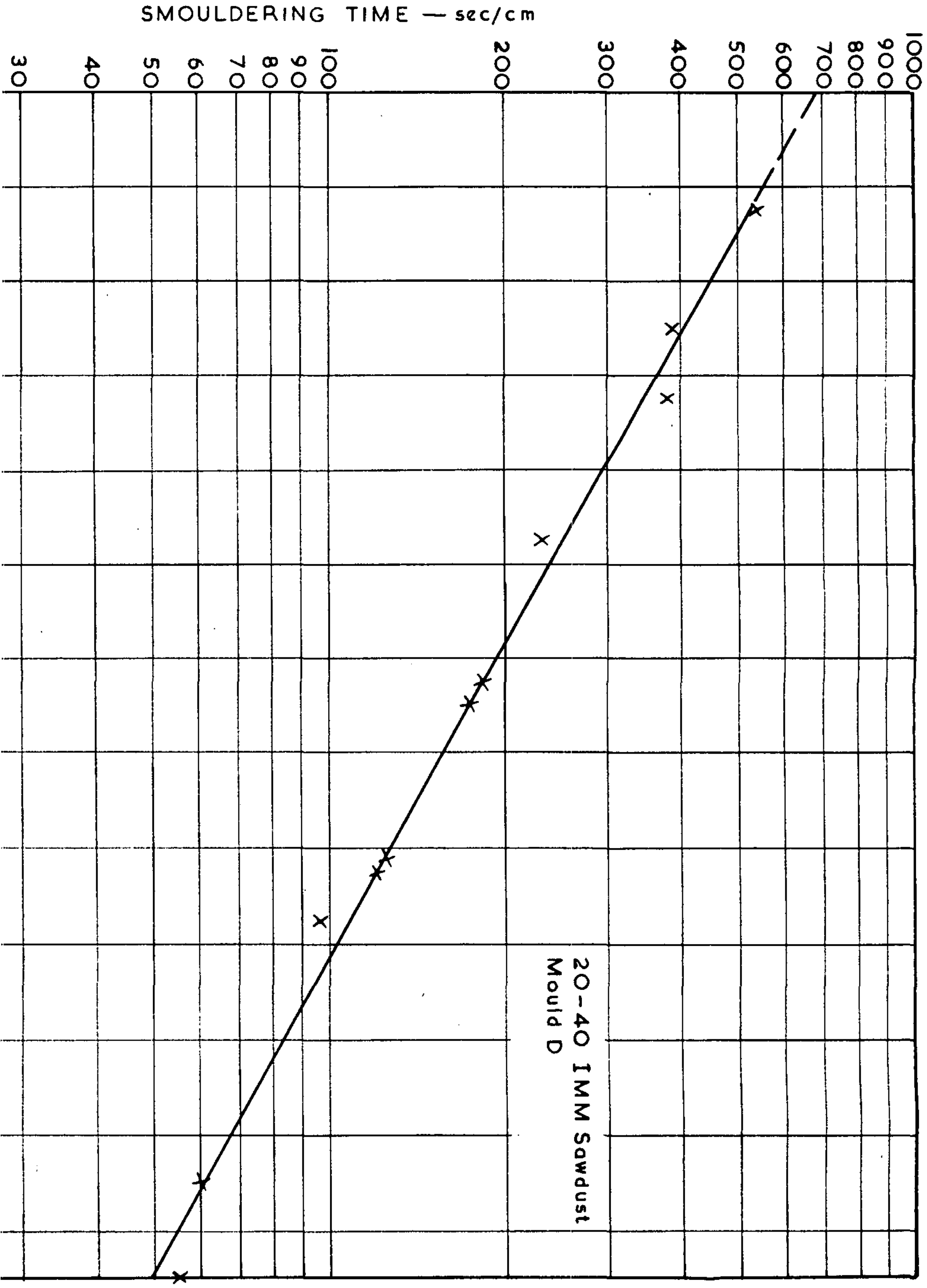


FIG. 2. THE REL IR VELOCITY
(AIRFLOW DIRECTION)


SMOULDERING TIME — sec/cm
30
40
50
60
70
80
90
100
200
300
400
500
600
700
800
900
1000
20-40 IMM Sawdust
Mould D

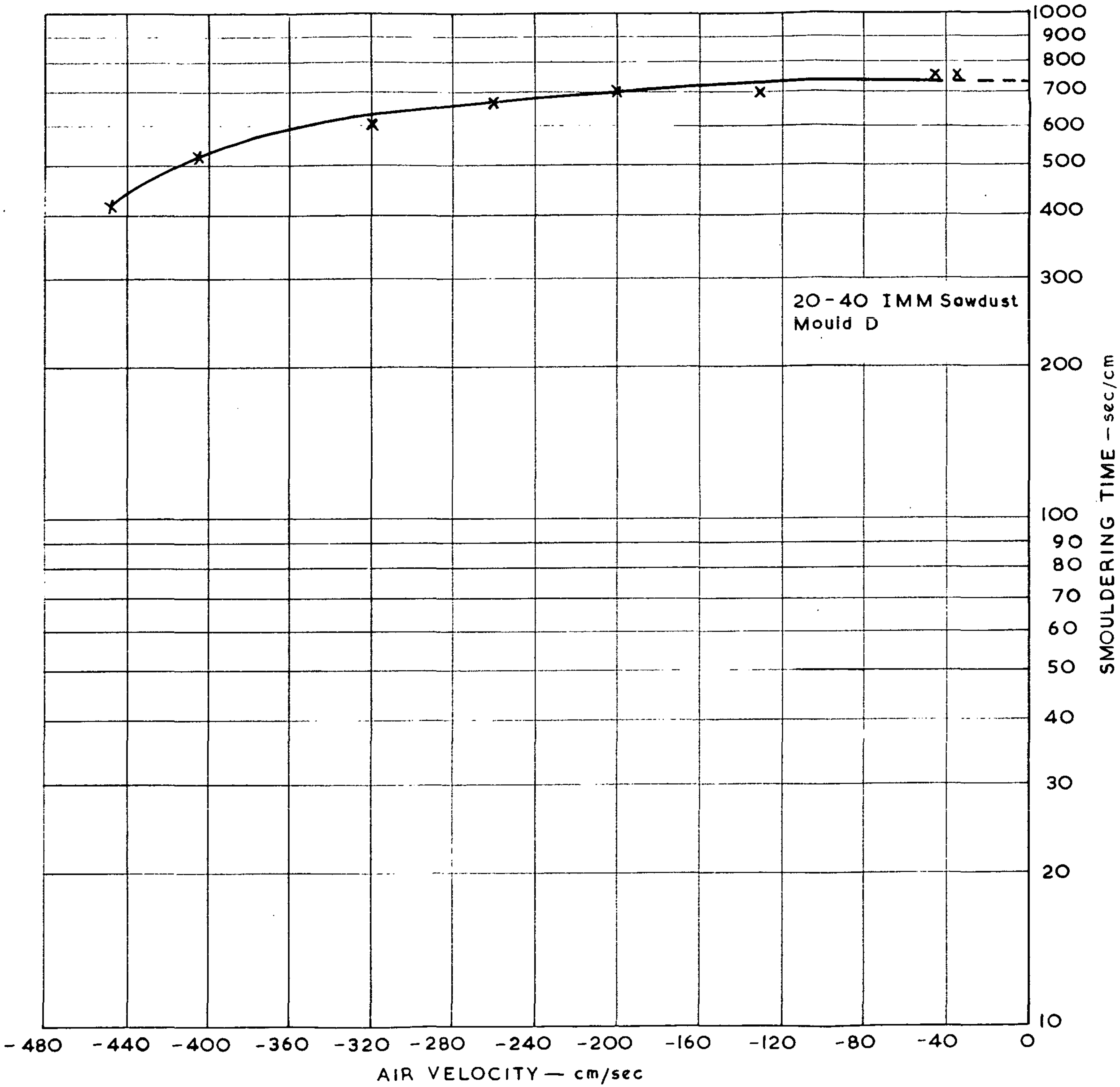


FIG. 3. THE RELATION BETWEEN SMOULDERING TIME AND INCIDENT AIR VELOCITY (AIRFLOW AND PROPAGATION OF SMOULDERING IN OPPOSING DIRECTIONS)

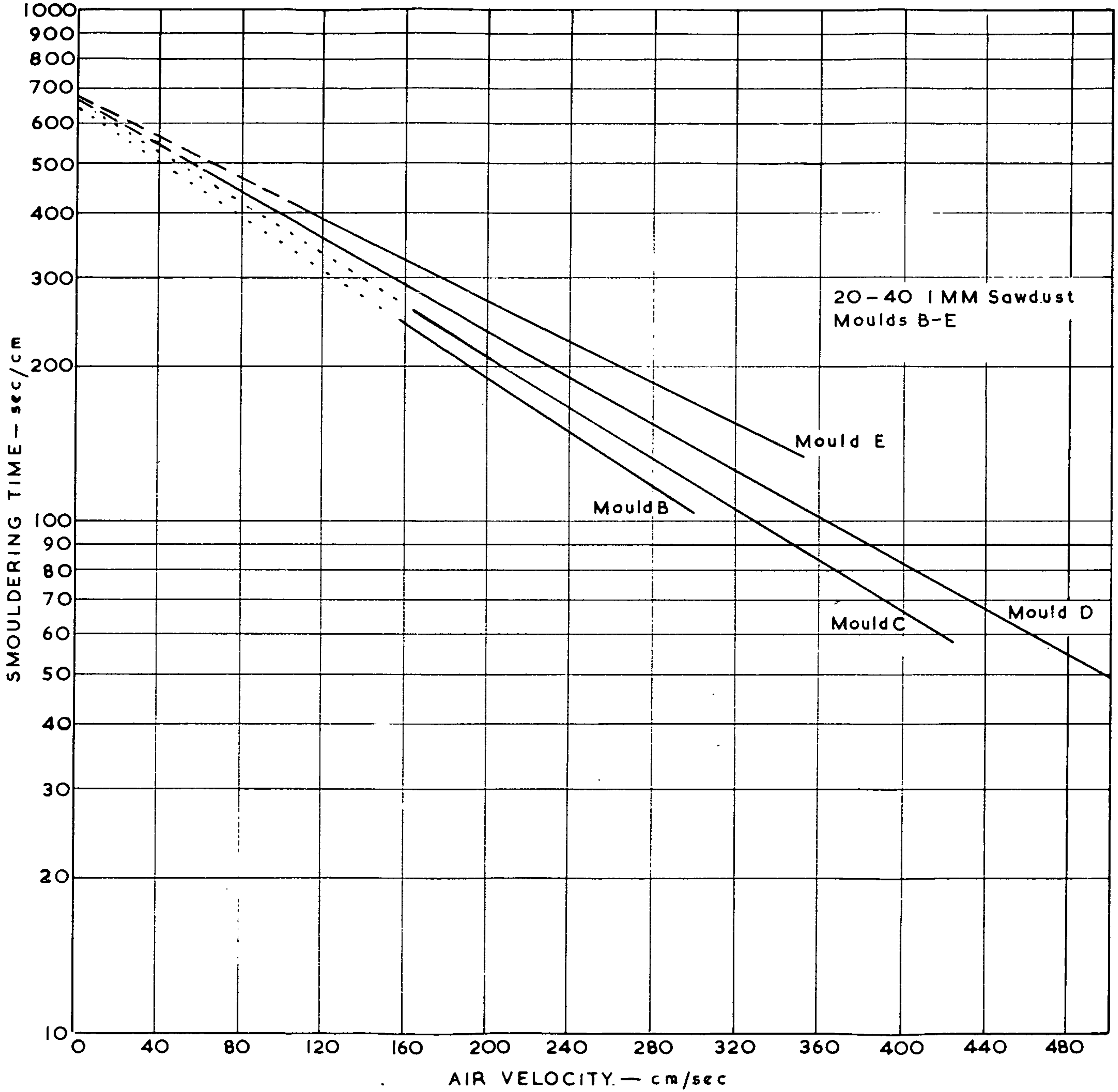


FIG. 4. THE EFFECT OF TRAIN SIZE AND AIRFLOW UPON SMOULDERING TIME

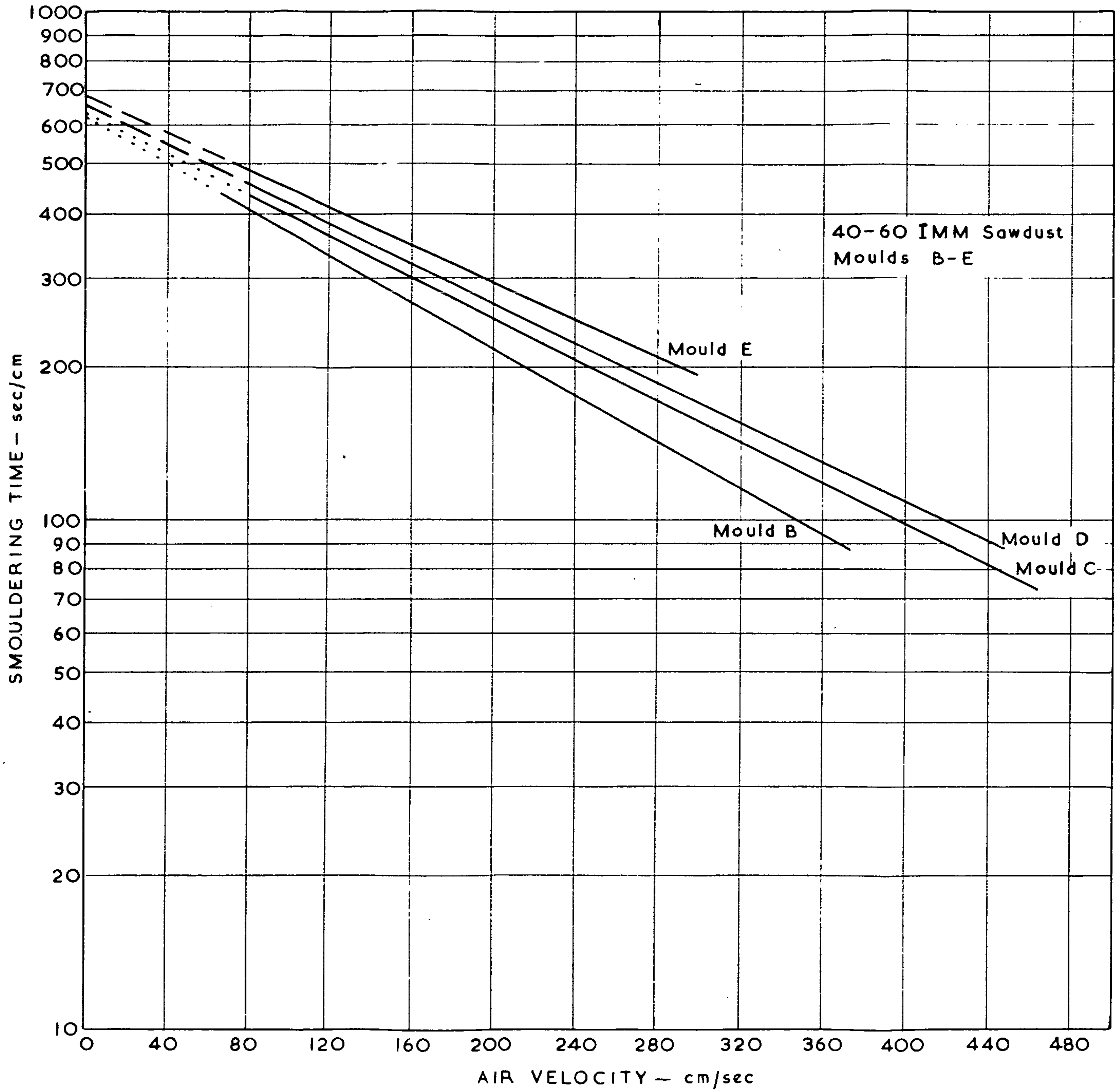
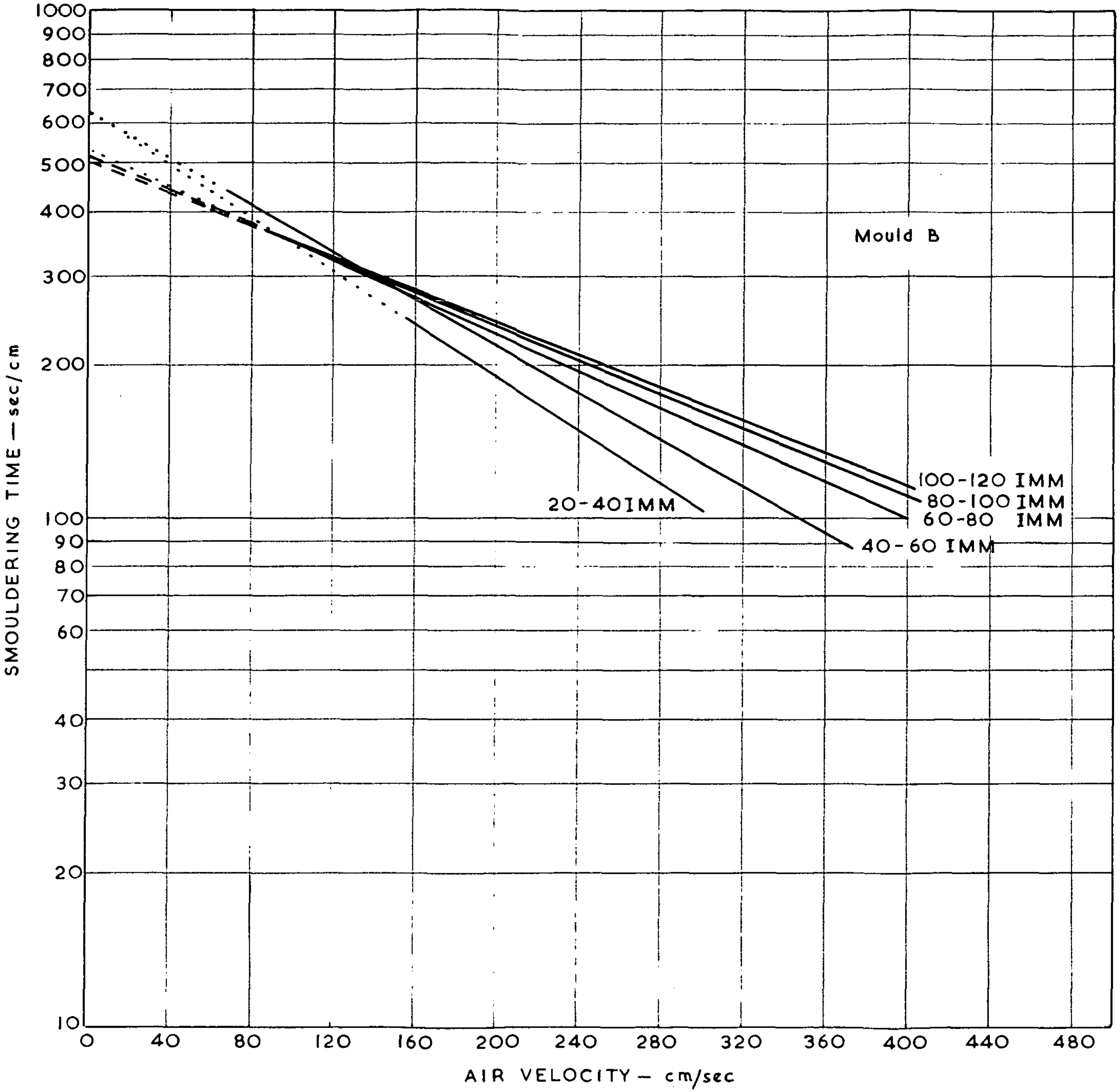
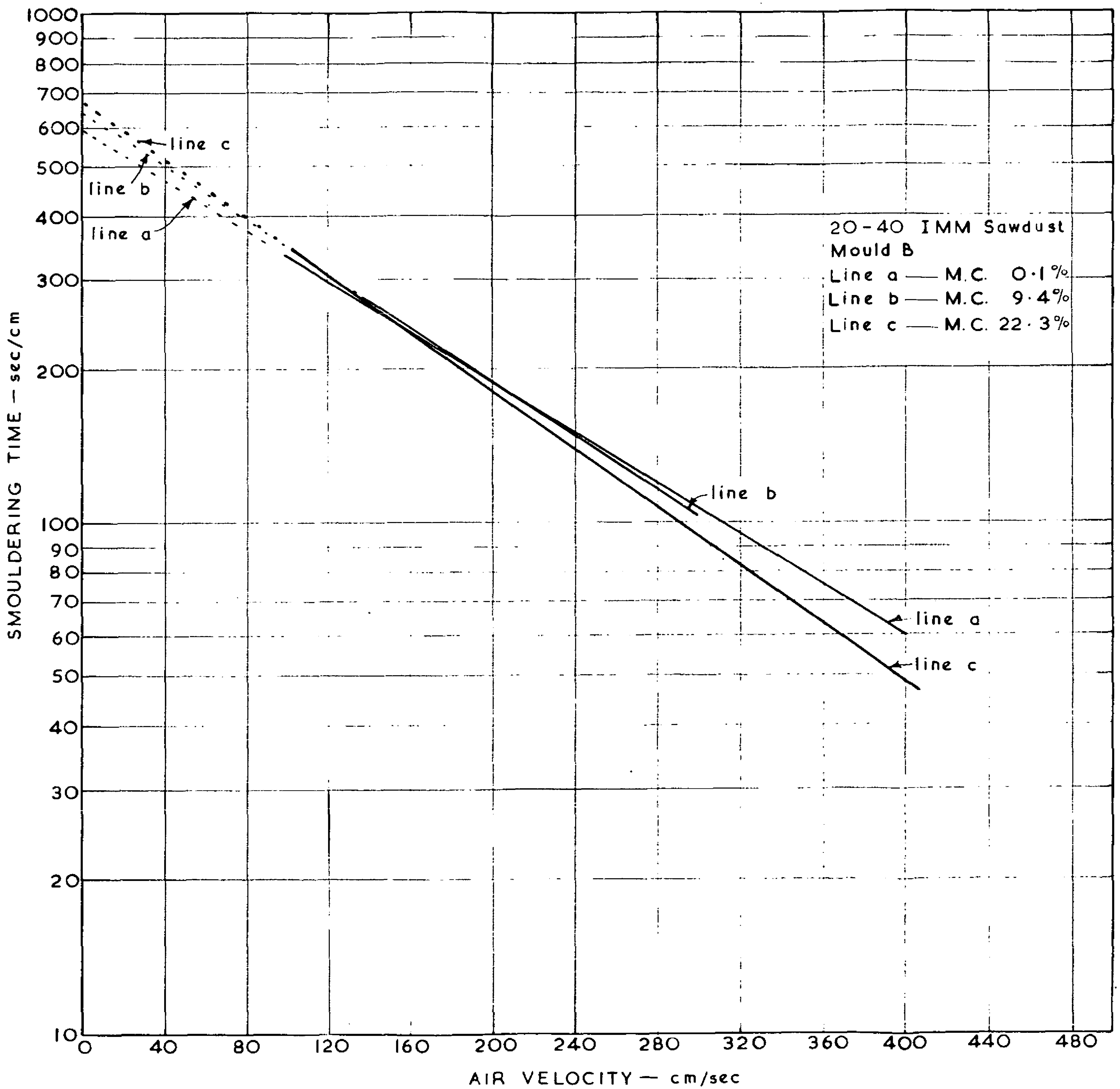


FIG. 5. THE EFFECT OF TRAIN SIZE AND AIRFLOW UPON SMOULDERING TIME


Mould B
100-120 IMM
80-100 IMM
60-80 IMM
40-60 IMM
20-40IMM
SMOULDERING TIME — sec/cm
AIR VELOCITY — cm/sec
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
40
30
20
10
0
40
80
120
160
200
240
280
320
360
400
440
480



1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10
SMOULDERING TIME — sec/cm
0
40
80
120
160
200
240
280
320
360
400
440
480
AIR VELOCITY — cm/sec
line a
line b
line c
20-40 IMM Sawdust
Mould B
Line a — M.C. 0·1%
Line b — M.C. 9·4%
Line c — M.C. 22·3%

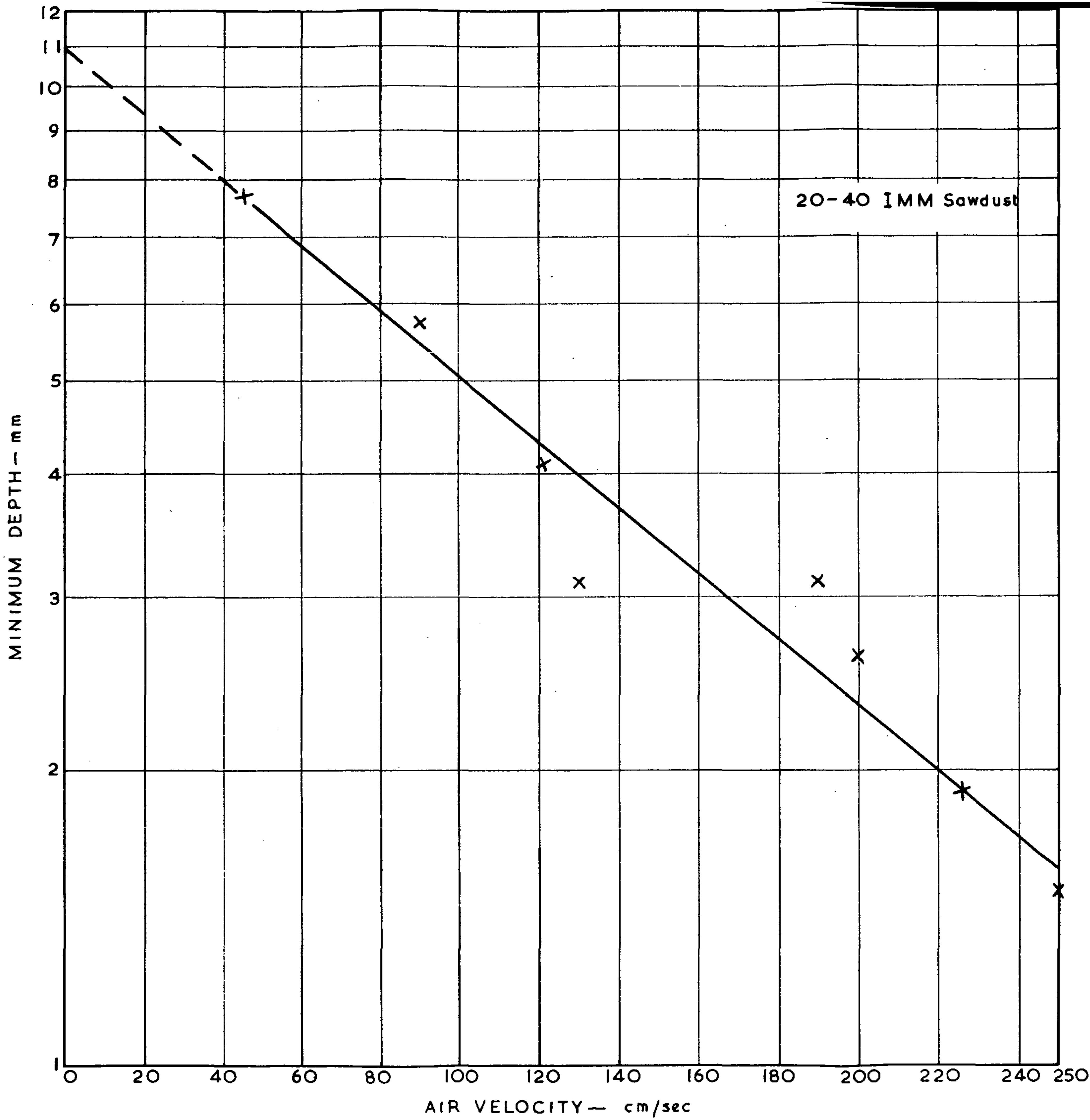


FIG. 8. VARIATION OF MINIMUM DEPTH FOR SUSTAINED SMOULDERING WITH INCIDENT AIR VELOCITY

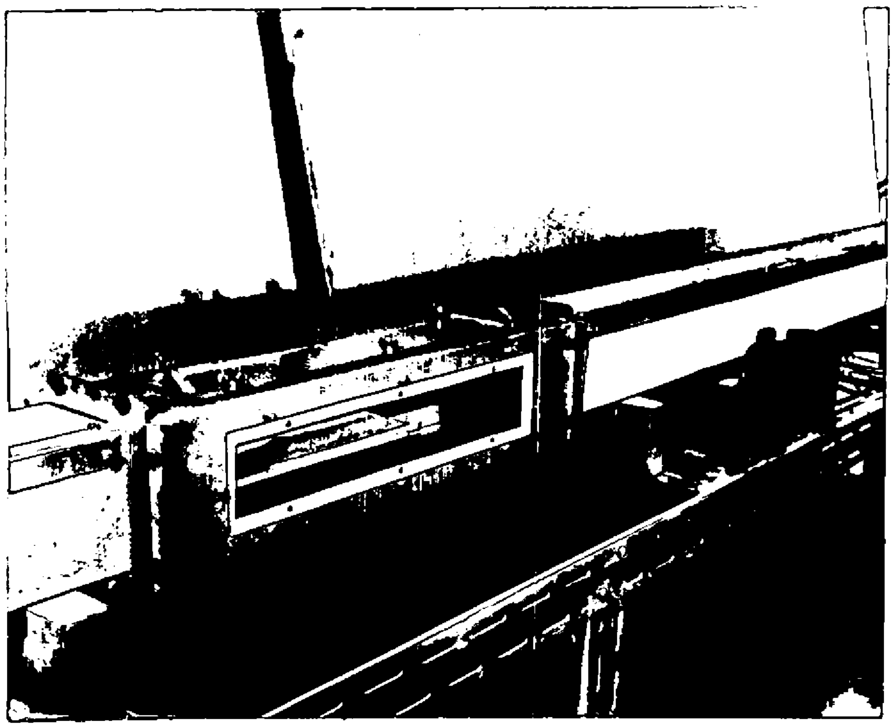


PLATE. I. COMBUSTION CHAMBER AND ADJOINING SECTION OF WIND TUNNEL

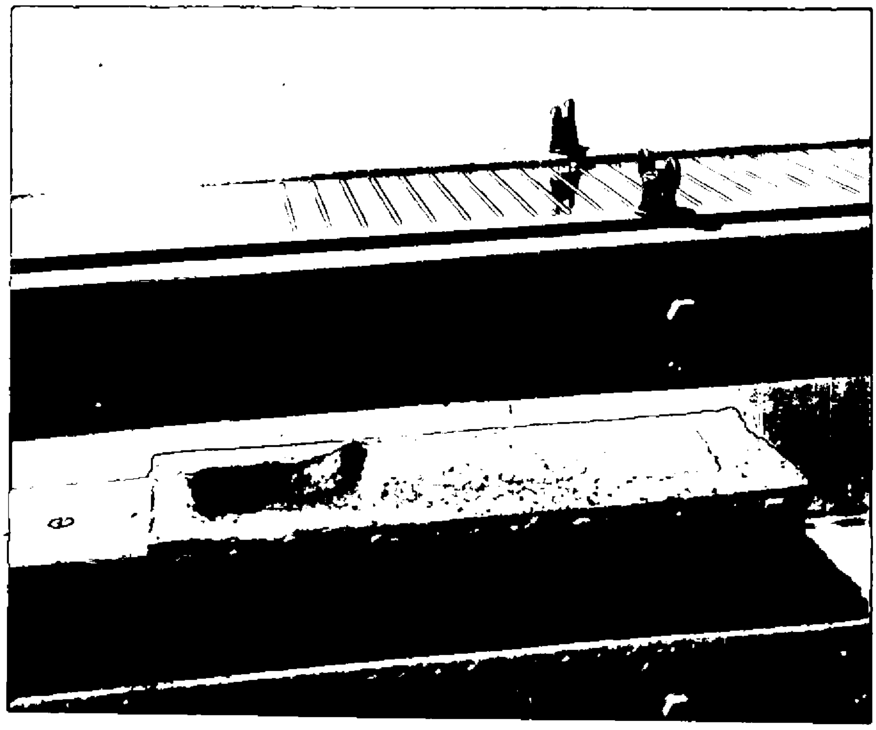
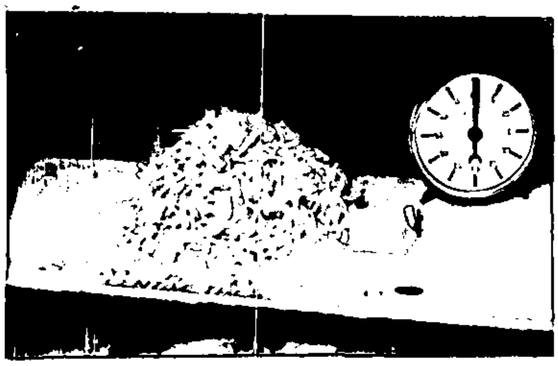
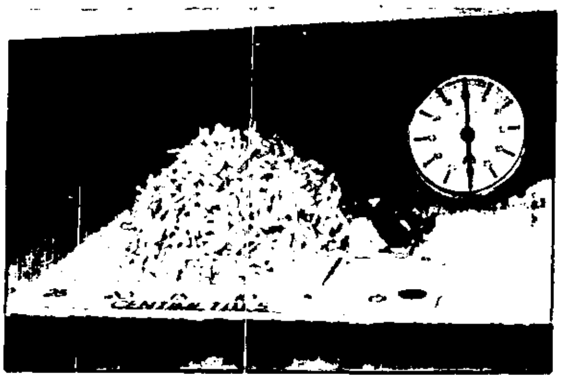


PLATE.2. SMOULDERING TRAIN IN POSITION



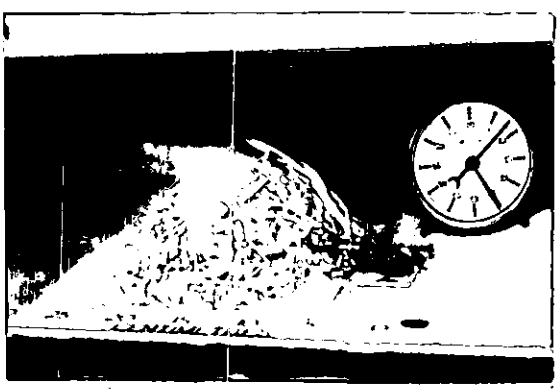
Glowing cigarette end dropped upon sawdust train
(0min)

Spread of smouldering into sawdust
(15min)

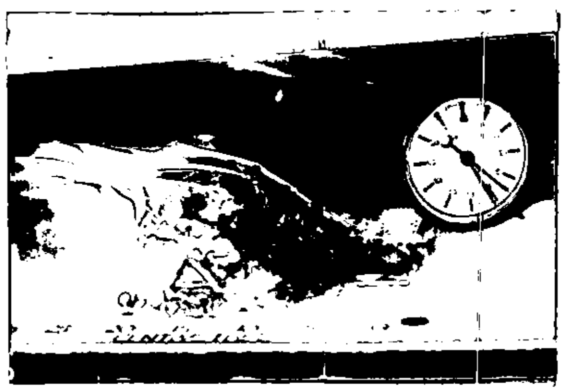


Smouldering zone advancing along train
(30min)

Smouldering zone entered heap of shavings
(60min)



Flame appeared in shavings
(85min 8sec)



Shavings well alight
(85min 22sec)

PLATE. 3. DEVELOPMENT OF FIRE IN A TRAIN OF BEECH SAWDUST COVERED WITH DEAL WOOD SHAVINGS UNDER AN AIR DRAUGHT OF 2 M.P.H.