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SMOULDERING IN DUSTS AND FIBROUS MATERIALS

PART VII. FIBRE INSULATING BOARDS UNDER AIRFLOW CONDITIONS

by

K. N. Palmer and M. D. Perry

Summary

A study has been made of the effect of an incident airflow upon the smouldering of several specimens of fibre insulation board. The board was cut into small strips and placed in a wind tunnel; smouldering was then initiated and the time of travel over unit distance (smouldering time) was determined. In general the smouldering time was inversely proportional to a fractional power of the air velocity; in some cases this relation was probably affected by cooling due to the airflow.

It was also shown that smouldering could be initiated by glowing cigarette ends under an air draught of 2 m.p.h.; this draught was also sufficient to cause flaming in the combustible ash formed by smouldering under still air conditions. As the flame subsequently spread rapidly across the board it was concluded that smouldering in fibreboard, under conditions of slight draught, may easily lead to a large scale fire.

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Fire Research Station,
Boreham Wood,
Herts.

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Introduction

The smouldering of several types of fibre insulation board, under still air conditions, has already been investigated. (1) It was found in experiments with the boards sawn up into strips that slow, but sustained, smouldering could occur and that the linear rate of smouldering depended upon the nature of the board, the size of the strip, and the angle to the vertical at which the strip was held.

The effect of an air draught upon the rate of smouldering of small trains of wood sawdusts has been investigated (2,3) and it was shown that the logarithm of the smouldering rate was approximately proportional to the incident air velocity. This relationship was markedly different from that obtained by Hottel et al for the combustion rate of carbon, a summary of this work has already been given (2); in the experiments of Hottel et al the rate of combustion of electrode carbon was found to vary as the 0.4-0.5 power of the air velocity. A similar result was predicted by means of the Reynolds analogy between heat and mass transfer.

In the present investigation, concerned with the effect of draught upon the smouldering of fibreboard, the relationship between air velocity and smouldering rate was determined. The effect of variation in strip size was also examined for various boards; further experiments were carried out upon the ease of initiation of smouldering and the production of flaming by an incident air draught.

Experiments and Results

Materials. Four specimens of board were investigated (Boards A-D); experiments upon the smouldering of Boards A-C had already been carried out under still air conditions (1). The fourth board (D) was used for the majority of the present experiments as it was more readily available; it was similar in appearance to Board A. Some characteristics of the boards are given below.

Table 1

Properties of the fibre insulation boards

Board	Moisture content %	Dry weight density gm/ml.	Calorific value (gross) of dry board cal/gm.
A	10·0	0.27	4370
B	6 6	0.22	4360
C	10·8	0·23	4760
D	9·3	0·29	4680

The experiments were carried out upon the boards sawn into strips 0·5 in. in thickness and of various widths; the strips of Boards A-C having been stored in sealed bins from the earlier investigation.

Measurement of rate of propagation of smouldering. In the determinations of smouldering rates the strips were supported along the axis of a horizontal wind tunnel (the construction of which has already been described (2)) usually so that the airflow and propagation of smouldering were in the same direction. Care was taken to ensure that the support did not interfere with the flow of air to the strips. The strips were marked with centimetre graduations on a face parallel to the laminations of the board and were held in the tunnel with the graduated face in either the horizontal plane (as in Plate 1) or in the vertical plane (Plate 2). Smouldering was then initiated by a small gas flame and the rate of propagation measured as in the experiments under still air conditions.

The first series of experiments was concerned with the effect of airflow upon the smouldering time of strips of Board D, 2 in. in width; the strips were held with the graduated face either vertical or horizontal, in these experiments the airflow and the propagation of smouldering were in the same direction. The results are shown in Figs. 1 and 2 (Lines I) where the air velocity and smouldering time are plotted on logarithmic axes.

When the airflow and the propagation of smouldering were in opposing directions the effect upon the smouldering time was comparatively small at air velocities less than 550 cm/sec (Fig.3). At higher velocities the smouldering zone did not extend across the entire width of the strip and at 900 cm/sec smouldering was barely sustained, so that measurements of the rate of propagation were not possible.

Effect of variation in strip size. The effect of airflow upon the rate of propagation of smouldering in Board D was studied with strips whose widths ranged between 0·5 in. and 4·0 in., all the strips were 0·5 in. in thickness. In each case the airflow and propagation of smouldering were in the same direction and the strips were usually held with their graduated face horizontal (as in Plate 1). The results of these experiments are shown in Figs. 1 and 2.

Smouldering of Boards A-C. The experiments so far described were upon strips cut from Board D only; a short investigation was, therefore, made with the Boards A-C, which had been used in the earlier experiments (under still air conditions). The results, for strips 0·5 in. in width, are given in Fig. 4 and whereas the values of smouldering time for Boards A and C fall approximately on straight lines, the results for Board B indicate a smooth curve. A similar curve was obtained with strips of 1·0 in. width from the same board. It was noted during the latter experiments that at high air velocities the smouldering zone did not extend over the entire cross-section of the strips and that the corners thus remained unburnt.

Effect of very high air velocities. Some further experiments on Boards A-D were carried out with air velocities in the range 1250-1450 cm/sec in order to determine whether smouldering could be extinguished by high airflows. In these experiments, upon strips 0·5 in. in width held with graduated face vertical, the wind tunnel was extended by a section of smaller cross-section; as the rate of airflow was measured only approximately the values for velocity are given below to the nearest 25 cm/sec.

Table 2

Results of experiments using high rates of airflow

Air velocity cm/sec	1275				1450			
Board	A	B	C	D	A	B	C	D
Smouldering time sec/cm	82	92	74	64	76	n.s.	n.s.	97

n.s. denotes "smouldering not sustained".

Low air velocities. Some experiments were carried out on 0·5 in. strips of Board A smouldering under very low air velocities (< 70 cm/sec; the results are given in Table 3. These results do not lie on the straight line for higher velocities (Fig.4 Line I) but fall consistently below.

Table 3

Results for low air velocities. Board A.

Air velocity cm/sec	50	30	20
Smouldering time sec/cm	251	281	306

The development of flaming from smouldering. When fibre insulation board smoulders under still air conditions an ash residue is formed which is combustible. It was found experimentally that if a slight draught were applied to board which had been smouldering in still air the ash residue might ignite and cause the board to burn with flame. In the experiments strips of Board D were allowed to smoulder in still air for periods up to 2 hr. before transferring to the wind tunnel; an extension of enlarged cross-section was added to the tunnel to permit experiments upon strips 12 in. in width. When the strips were transferred to the tunnel the airflow was started and the strips observed for 5 min.; if flaming occurred measurement was made of the time required. If no flaming was produced the experiment was repeated for a maximum of three attempts.

Table 4

Experimental details of the production of flaming from smouldering

Strip width in.	Duration of smouldering in still air Hr.	Air velocity cm/sec	Time in airflow before flaming sec.
0·5	1	266 180	- -
1·0	1	180 89	23·0 -
2·0	1	263 171 85 69	8·6 14·0 33·4 -
4·0	1	172 85 68	7·4 31·0 -
12·0	1	81 65 51	35·3 84 -
	2	51	-

44 7 cm/sec. = 1 m.p.h.

A series of photographs is reproduced in Plate 3 in which the various stages between the initiation of smouldering and the burning of the board with flame are shown.

Ease of initiation of smouldering. These experiments were restricted to Boards A, C, and D, since it had already been shown that a glowing cigarette end would initiate smouldering in Board B under still air conditions.(1) Glowing cigarette ends were placed in contact with broken edges of strips of the Boards A, C, and D, and an airflow of about 90 cm/sec (2 m.p.h.) was imposed. It was found that smouldering could be initiated in all three specimens of board.

Discussion

Effect of air flow upon the smouldering. The results given in Figs. 1 and 2 for Board D indicate that there is an approximately linear relationship between the logarithms of the smouldering time (S) and incident air velocity (V), within the air velocity range shown (70-1,000 cm/sec). The relationship is thus of the form

$$S = \frac{a}{V^n} \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (i)$$

where n and a are positive constants.

If the linear rate of propagation of smouldering is denoted by R, then

$$R = {}^1/S = {}^1/a \cdot V^n.$$

Similar relationships were obtained when strip sizes and the position of holding the strips were varied, the values of the constants a and n obtained are given below in Table 5. Experiments with Boards A and C (Fig. 4) also gave linear relationships and the respective values of a and n are included in Table 5 for comparison.

Table 5

Values of the constants a and n in the equation $S = aV^{-n}$ for various fibreboard strips

Board	Strip width in.	Position of graduated face of strip	n	a
D	4·0	horizontal	0·44	2030
	2·0	"	0·46	2350
	2·0	vertical	0·44	2250
	1·4	horizontal	0·48	2410
	1·0	"	0·47	2310
	0·5	"	0·39	1250
	0·5	vertical	0·44	1520
A	0·5	"	0·41	1420
C	0·5	"	0·38	1300

The scatter of the results shown in Figs. 1, 2, and 4 is markedly greater than that expected from the accuracy of measurement of smouldering time and air velocity; hence the variations in the values of n shown in Table 5 may not be significant. The values of the constant a in equation (i) varied with strip size, being dependent upon the separation of the lines in Figs. 1 and 2, but the variation was small and was comparable with the scatter of the individual results. Thus, although the lines fall approximately in order, the smouldering time at a given air velocity tending to increase with strip size (as under still air conditions [1]), no relationship was obtained between the values of a and strip size.

Experiments at low air velocities. As the smouldering time has been found experimentally to have a finite value under still air conditions it is obvious that equation (i) cannot apply when the incident air velocity (V) is zero. Equation (i) might therefore more strictly be of the form

$$S = \frac{a}{(c + V)^n} \quad \text{where } c \text{ is a constant.}$$

A value of c for 0·5 in. strips of Board A may be obtained from Fig. 6 where S^{-1}/n is plotted against V taking $n = 0{\cdot}41$ (Table 5). Thus, for the given sample of board, $c = 30$ cm/sec approximately and $S = 380$ sec/cm when the applied air velocity is zero. The latter value, although subject to considerable error, may be compared to a smouldering time of 390 sec/cm found for the board under still air conditions (1). The constant c was not evaluated for the other boards since the approximate relation given by equation (i) appeared to be adequate for the range of air velocities used with these boards.

Experiments at high air velocities. Cooling. The results for Board B, given in Fig. 4, are of a different form from those for Boards A and C in that at high air velocities the smouldering time did not decrease with increasing rate of air flow; for example, when the air velocity was 1,275 cm/sec (Table 2) the smouldering time was greater than at 865 cm/sec. A minimum value of smouldering time was also obtained with strips from Board D when the air flow and propagation of smouldering were in opposing directions (Fig. 3). As sufficiently high airflows may lead to the extinction of smouldering (Table 2) it is possible that the curvature of lines in Figs. 3 and 4 may result from cooling of the smouldering zones of the strips by the air draught; the board would thus smoulder less rapidly at high air velocities and in the extreme case would suffer extinction. Thus at high air velocities equation (i) would no longer hold. However, if equation (i) is extended to the form

$S = \frac{a}{V^n} + bV^m$ where b and m are positive constants and $a \gg b$

then the second term in V would only be appreciable at high air velocities; at very high velocities the second term would predominate and S would increase with V. Further, as the mass transfer of oxygen to the surface of the combustion zone and the transfer of heat away from the zone into the airstream are analogous processes, although acting upon the smouldering time in opposite senses, it is assumed that both are dependent upon the same function of the ambient air velocity

$$\text{i.e.}\quad m = n.$$

Equation (i) thus becomes

$$S = \frac{a}{V^n} + bV^n \quad \ldots\ldots\ldots\ldots \quad \text{(ii)}$$

The last assumption is not valid when the air flow is sufficiently rapid to cause diminution of the area of the smouldering zone, so that parts of the strip remain unburnt. When this occurs the transfer of heat from the smouldering zone to the airstream is not direct but involves conduction of heat through unburnt board.

If, as a further approximation, $n = 0{\cdot}5$ (Table 5)

$$\text{then}\quad S\sqrt{V} = a + bV \quad \ldots\ldots\ldots \quad \text{(iii)}$$

Values of $S\sqrt{V}$ are plotted against values of V in Fig. 5 for the results obtained with 0·5 in. strips of Board B (Fig. 4, line II) and for 2·0 in. strips of Board D in which the air flow and propagation of smouldering were in opposing directions (Fig. 3); the constants a and b were evaluated and are given in Table 6, values for other strips are also included for comparison.

Table 6

Values of a and b from equation (iii)

Board	Reference	a c.g.s. units	b c.g.s. units	a/b (= V_{min}) cm/sec	$2\sqrt{ab}$ (= S_{min}) sec/cm
B 0·5 in. strip	Fig. 4 Line II	1,500	1·19	1,260	85
A 0·5 in. strip	Fig. 4 Line I	2,080	0·80	2,600	82
D 2·0 in. strip	Fig. 2 Line I	2,900	0·70	4,130	90
2·0 in. strip) reverse flow)	Fig. 3	2,700	8·68	311	306

It may be seen from the above Table that always $a > b$ and the values of b are larger for strips in which cooling of the smouldering zone by the airstream has been postulated; in these cases the term bV^n in equation (ii) thus becomes more important. The values of a given in Table 6 differ for some boards from those in Table 5; this is due to the approximation in taking $n = 0{\cdot}5$ in evaluating Table 6.

A further point is that the value of S given by equation (ii) passes through a minimum value (i.e. most rapid smouldering rate) at an air velocity V_{min} given by

$$V_{min}^{2n} = a/b.$$

When $n = 0{\cdot}5$. $V_{min} = a/b$ and hence $S_{min} = 2\sqrt{ab}$.

Values of V_{min} and S_{min} are given in Table 6 and are in good agreement with experimental values when V_{min} is low. Higher values of V_{min} are obtained from results which appear to fall on approximately straight lines (Figs. 2 and 4, Lines I) so that it may be inferred that cooling effects were not important over the air velocity range investigated with these strips.

The main points contained in the sections above may be stated as follows:

1. The relationship given as equation (i) holds approximately for strips of Boards A, C, and D, within the air velocity range 70-1,000 cm/sec, when air flow and smouldering are in the same direction.

2. With Board B the air draught exerts a measurable cooling effect over the entire velocity range (70-900 cm/sec); at higher velocities (>1,000 cm/sec) the smouldering time may pass through a minimum value before smouldering is extinguished by the air flow. The reason for this behaviour is not clear but may be connected with the low density of Board B (Table 1). Board C is of similar density but the scatter of the results for this board (Fig. 4 Line III) is too great for detailed comparison with Board B to be made.

3. When the air flow and propagation of smouldering are in opposing directions the "cooling" term in equation (ii) becomes appreciable even at low air velocities. However, the "oxygen supply" term (a/V^n) remains very similar to that obtained under normal air flow conditions, this would be expected if the rate of combustion were controlled by diffusion of oxygen through a stagnant film of gas covering the smouldering zone. The thickness of the stagnant film would be affected equally for either direction of ambient air flow.

4. There are points of similarity between the results given above and those obtained with pure carbon by Hottel et. al., thus relations similar to equation (i) and values of n in the range 0·4-0·5 were obtained. For these results, however, upon pure carbon, ambient furnace temperatures of 1,100-1,700°K were necessary and small air velocities were used (up to 70 cm/sec). The rate of combustion of carbon may depend greatly upon the previous treatment of the carbon before it is brought into contact with oxygen; with the smouldering of fibreboard carbon is produced in the reducing atmosphere around the smouldering zone and reacts with oxygen very shortly after formation. The rate of reaction of this new surface with oxygen may therefore differ widely from the reaction rate of an old and machined surface as used by Hottel.

Practical considerations. The experiments upon the ease of initiation of smouldering in fibreboard by glowing cigarette ends, and the subsequent development of flaming, show that only slight air draughts (about 2 m.p.h.) are required. It may be seen from the photographs in Plate 3 that several hours can easily elapse between the initiation of the smouldering and the production of flaming; subsequently the flame spreads rapidly across the board. Smouldering in fibreboard, under conditions of slight draught, may thus easily lead to a large scale fire.

Conclusions

1. An incident air draught causes a marked increase in the rate of propagation of smouldering in fibreboard. It was shown that the smouldering time (sec/cm) varies inversely as a fractional power of the air velocity. The smouldering time is also dependent upon the nature and dimensions of the board.

2. The increase in the combustion rate of the board due to air flow may be appreciably reduced by the cooling effect of the draught.

3. Smouldering may be initiated easily by glowing cigarette ends under an air draught of 2 m.p.h., this air flow is sufficient to cause flaming of the ash residue formed by smouldering under still air conditions. There may thus be a long delay between the initiation of smouldering and the development of fire.

References

1 F.R. Note No. 24/1952
2 F.R. Note No. 48/1952
3 F.R. Note No. 50/1953

KC : PC.

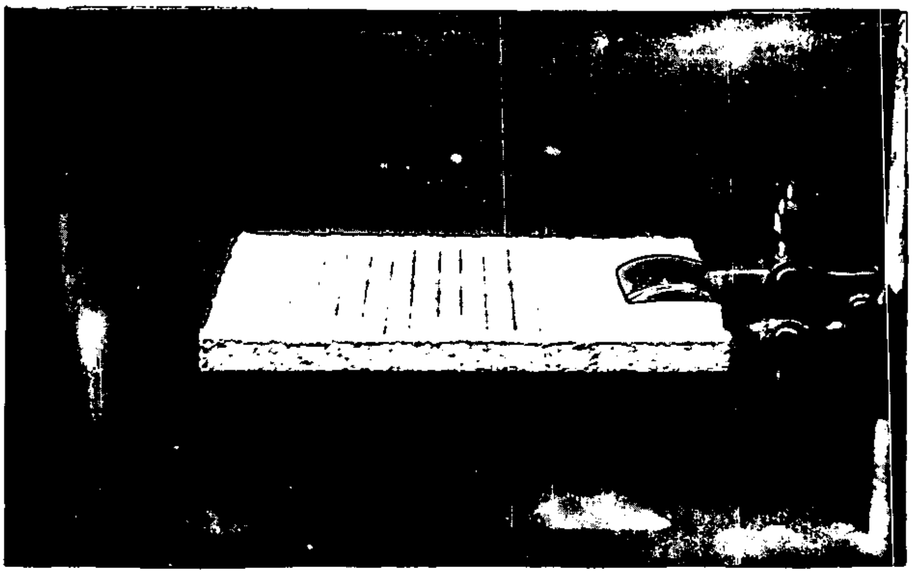


PLATE.1. POSITION OF STRIP HELD WITH GRADUATED FACE HORIZONTAL; SMOULDERING TO PROPAGATE HORIZONTALLY

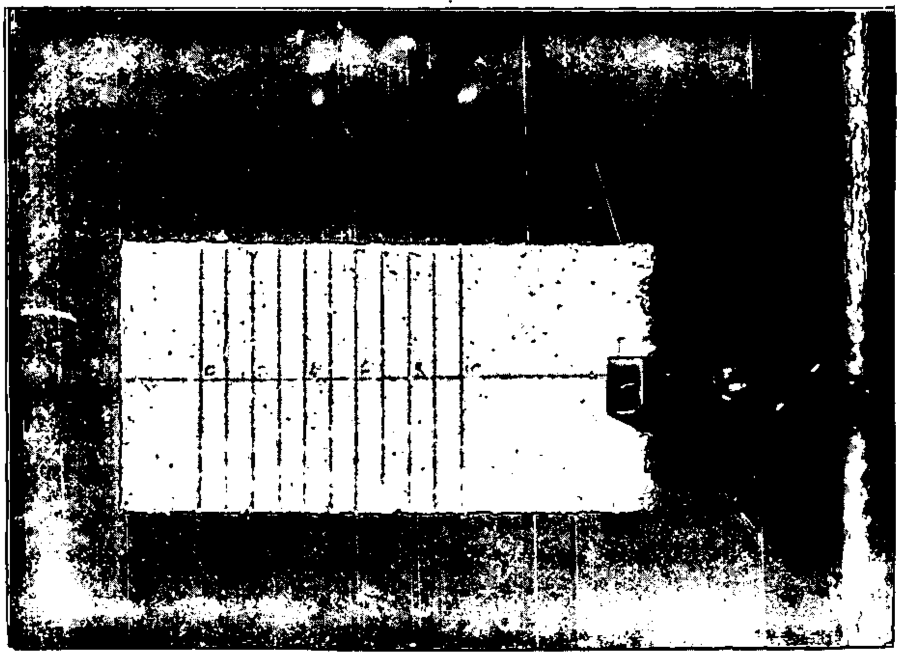
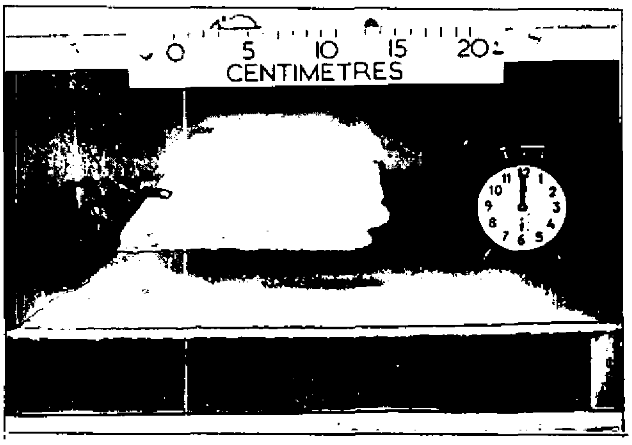
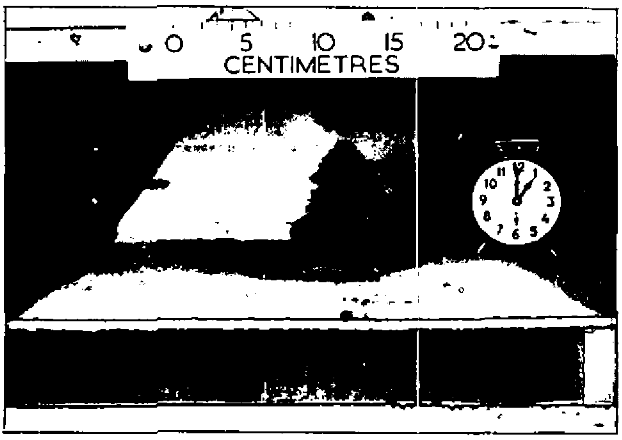


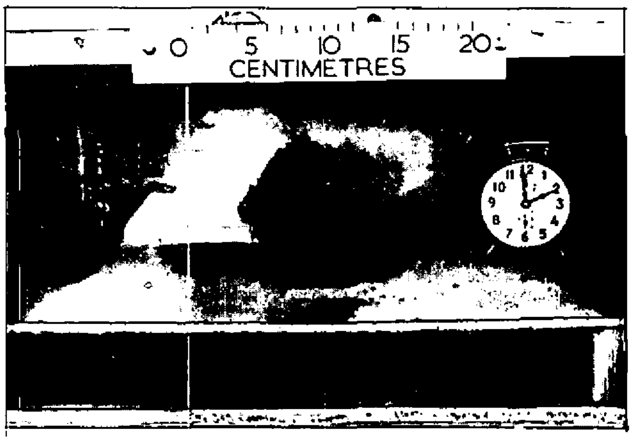
PLATE.2. POSITION OF STRIP HELD WITH GRADUATED FACE VERTICAL; SMOULDERING TO PROPAGATE HORIZONTALLY



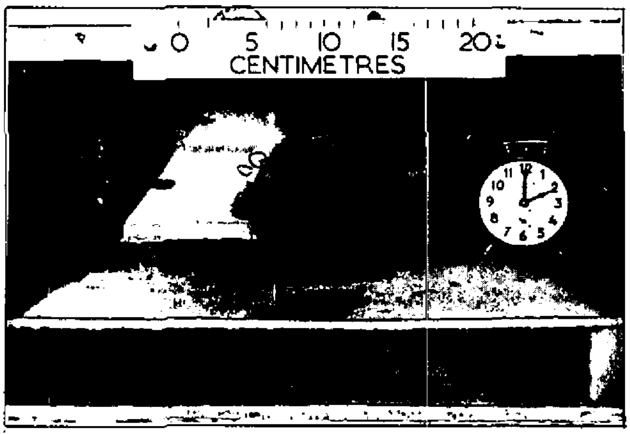
Omin. Smouldering started, still air



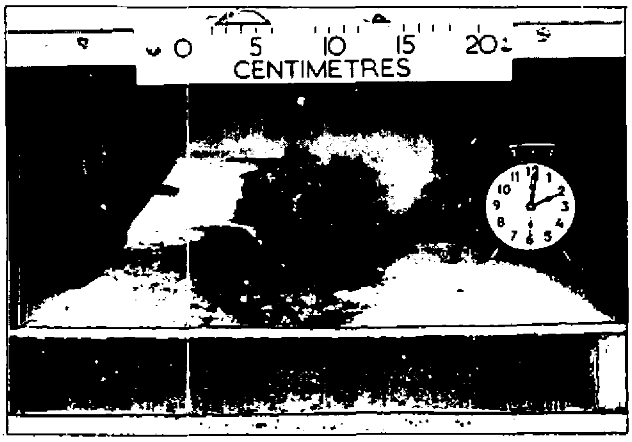
6Omin. Ash formation in still air



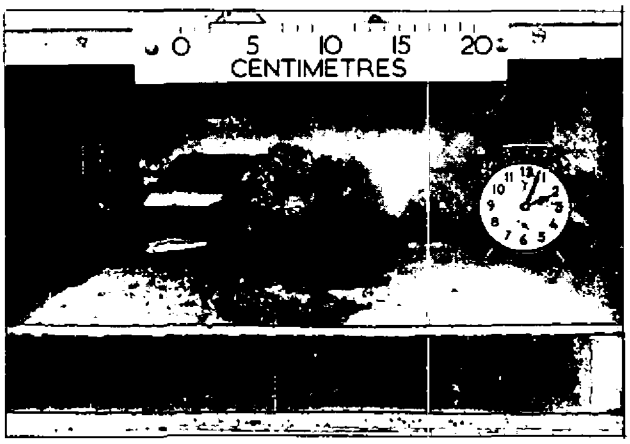
119min. Ash formation 1min. before application of draught



12Omin. 2O sec. First appearance of flame



122 min. 22 sec. Flame spread on board



123 min. 5O sec. Flame spread almost complete

PLATE. 3.

PRODUCTION OF FLAMING ON APPLYING A 2 m.p.h. DRAUGHT TO A FIBREBOARD STRIP SMOULDERING IN STILL AIR STRIP WIDTH 30 cm.

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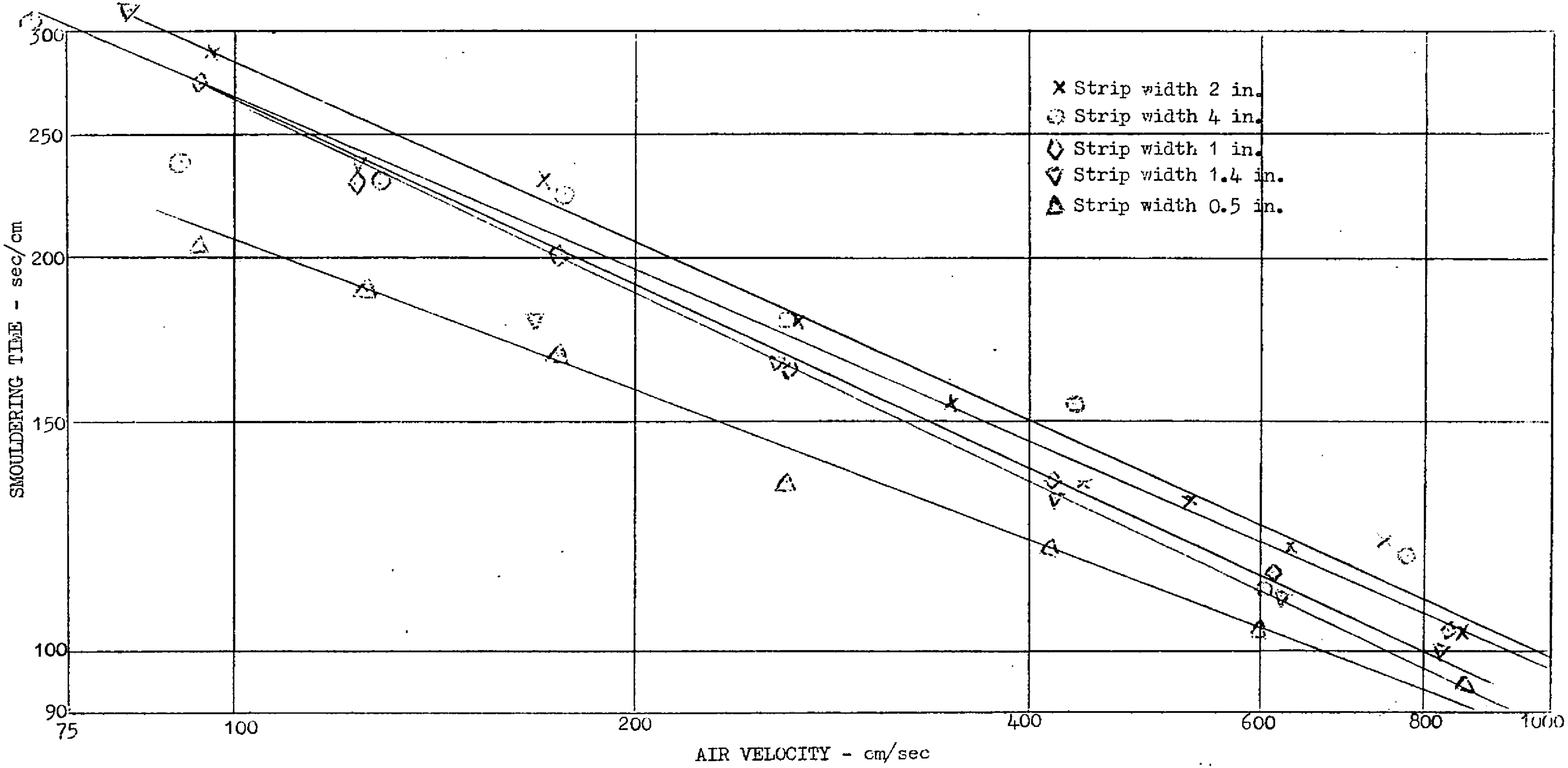

FIG. 1. EFFECT OF AIRFLOW UPON THE SMOULDERING TIME OF STRIPS FROM BOARD D

Airflow and propagation of smouldering in the same direction.
Strips held with graduated face horizontal.

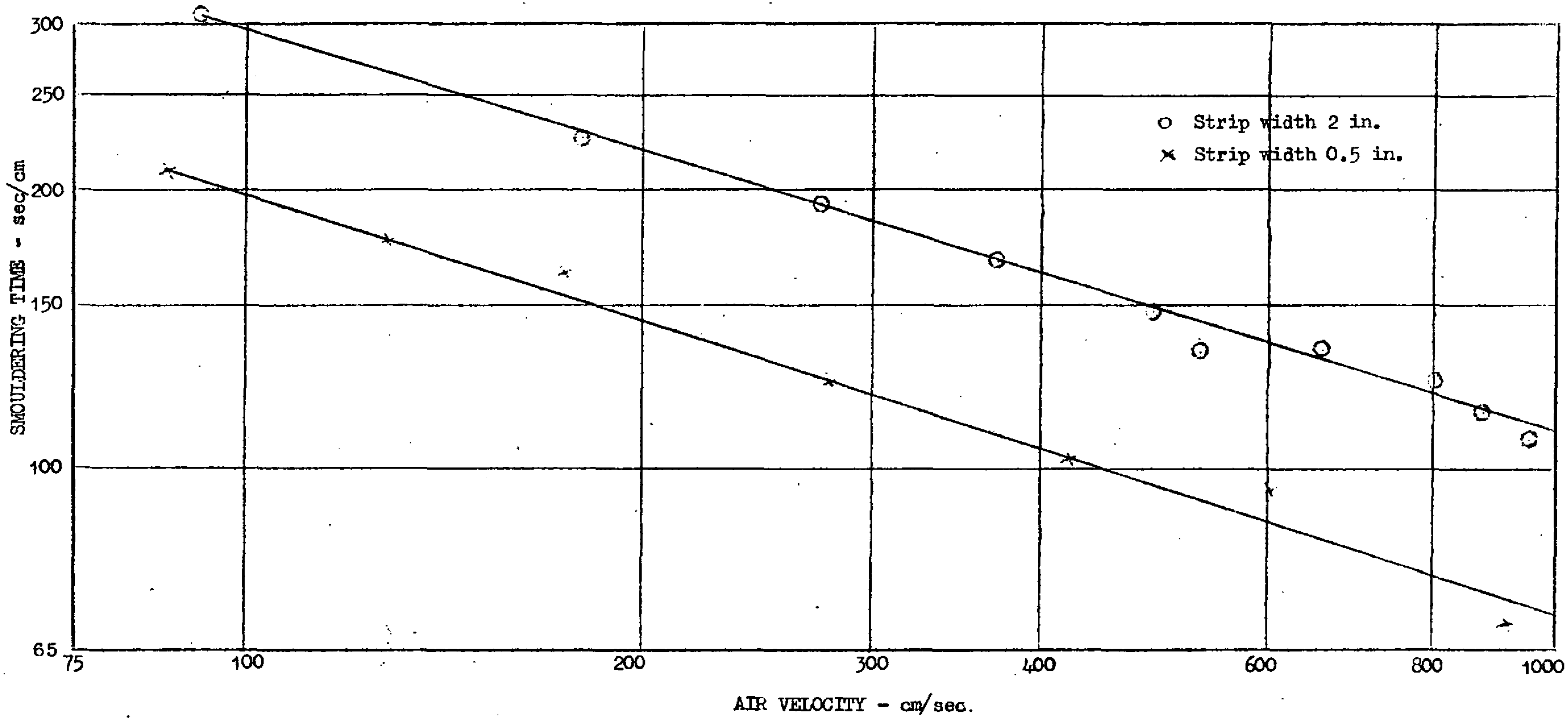

FIG.2. EFFECT OF AIRFLOW UPON THE SMOULDERING TIME OF STRIPS FROM BOARD D

Airflow and propagation of smouldering in the same direction.
Strips held with graduated face vertical.

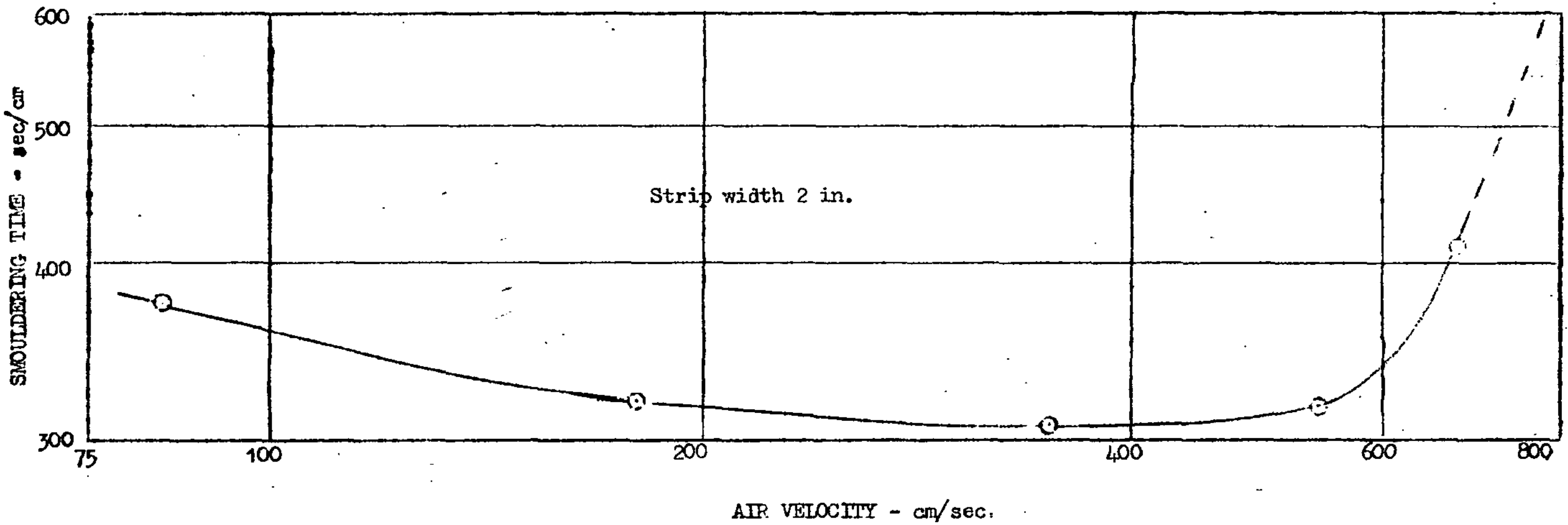

FIG. 3. EFFECT OF AIRFLOW UPON SMOULDERING TIME OF BOARD D

Airflow and propagation of smouldering in opposing directions.
Strips held with graduated face horizontal.

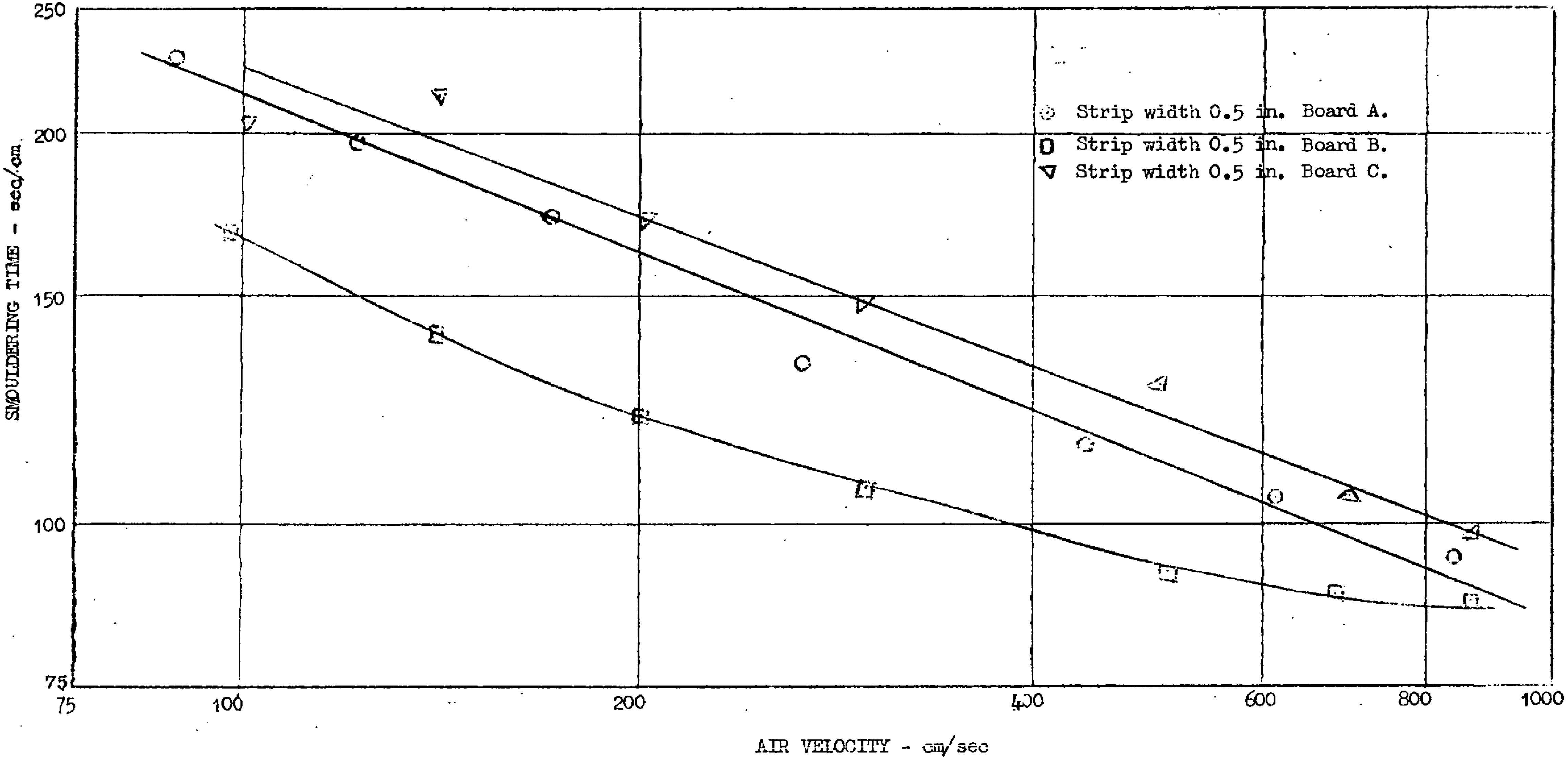

FIG.4. EFFECT OF AIRFLOW UPON THE SMOULDERING TIME OF STRIPS FROM VARIOUS BOARDS

Airflow and propagation of smouldering in the same direction.
Strips held with graduated face vertical.

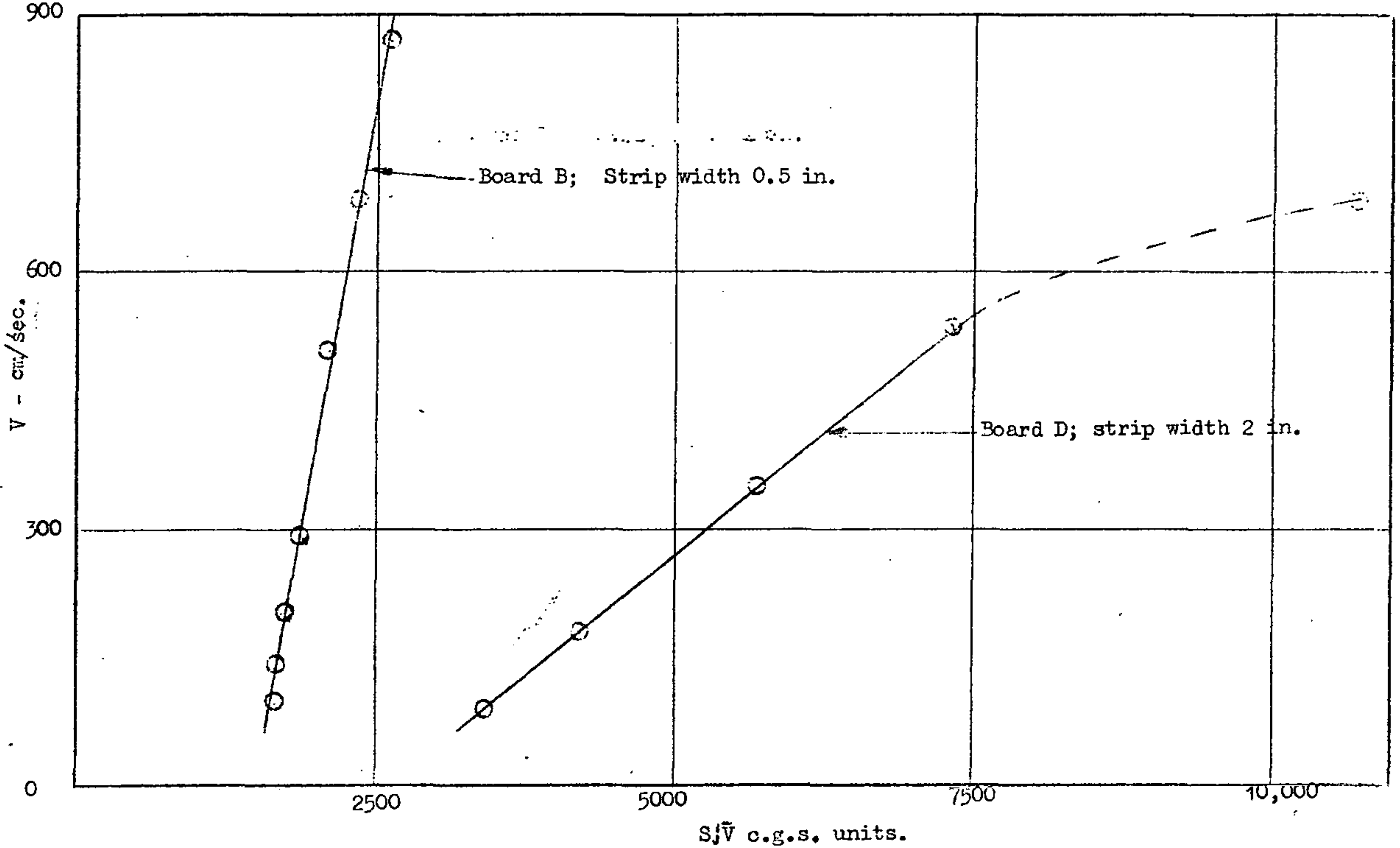

FIG.5. EVALUATION OF THE CONSTANTS a AND b IN THE EQUATION $S\sqrt{V} = a + bV$

Airflow opposing propagation of smouldering.

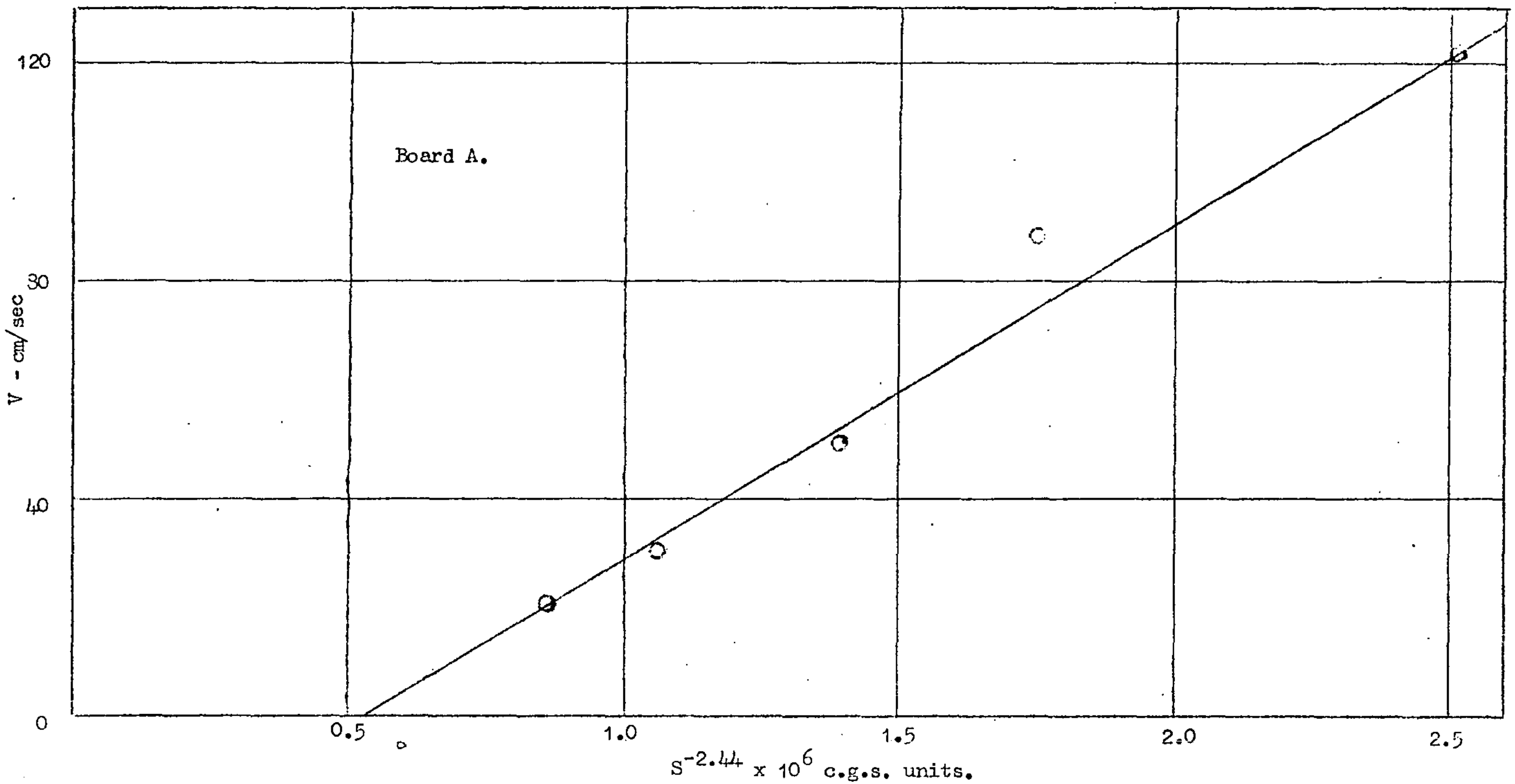

FIG. 6. EVALUATION OF THE CONSTANT C IN THE SMOULDERING TIME — AIR VELOCITY RELATION $S = \left(\frac{a}{c+v}\right) 0{\cdot}41$