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Research Programme
Objective:

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

THE VENTING OF GAS AND VAPOUR EXPLOSIONS IN DUCT SYSTEMS

PART III

VENTED EXPLOSIONS IN STRAIGHT UNOBSTRUCTED SQUARE DUCTS

by

D. J. Rasbash and Z. W. Rogowski

Summary

Tests have been carried out on the effect of a number of factors on the venting of explosions in a straight unobstructed length of 1 ft^2 duct. It has been found that the efficiency of a given venting area for a given length of duct may be increased by a factor of about ten by distributing the venting area over the whole length of the duct. There was little difference if a vent of a given area was placed in the end of the duct or near the end in the side of the duct. Variation of the weight of the cover of the vent between 0 and 720 g/ft^2 of venting area gave rise to a variation in maximum pressure of about 50 per cent. The particular point in the pressure record where the maximum pressure occurred varied considerably between the tests. This suggested that the maximum pressure was controlled by one of the following factors: (1) the inertia of gas in the duct, (2) the inertia of the cover of the vent, (3) the increase in combustion rate produced by turbulence at the vent itself, (4) the pressure drop across the vent.

January, 1961.

Fire Research Station,
Boreham Wood,
Herts.

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INTRODUCTION

Previous work on the relief of gas and vapour explosions in ducts, using an open vent in the end of the duct[1] indicated that the explosions were vented most efficiently when the vents were situated near the source of ignition. This ensured least disturbance to the unburned gas and as a result low maximum pressures were obtained. It was evident that any practicable venting system should be based on venting the combustion products soon after ignition took place. However, before this principle could be applied in practice to straight unobstructed ducts it was necessary to have further information on the effect of certain factors on the progress of an explosion in a duct, in particular the effect of the position of the relief vent with regard to the source of ignition and the duct itself, the effect of multiple relief vents in a duct and the effect of closing the vent with covers of varying weight. Work on these problems is described in this note.

EXPERIMENTAL

Apparatus

The experiments were carried out in 1 ft square ducting constructed from $\frac{1}{8}$ in. steel and designed to withstand a maximum pressure of 10 lb/sq.in. Five 6 ft long flange sections were used and any number of these could be bolted together to give ducts up to 30 ft in length. Three of the sections had one side open and when these sections were used this open side was always situated at the top of the duct. Removable steel plate covers were used to block parts of the whole of these open sides leaving vents of the required area on the top of the duct. In one series of tests, relief vents in the shape of slots were used in the top of the ducting. This was achieved by bolting to the open sides steel plate covers from the centre of which a slot 5 ft long and 0.8 or 1.6 in. wide had been cut. Plates containing central square edged square orifices of different areas could also be bolted at the end of the duct.

A diagram of the apparatus used for filling the duct with flammable mixtures, is shown in Figure 1. The air was supplied by a fan with a capacity of 60 cu.ft/min., and was metered through a venturi into a mixing section where propane was introduced through a distributor containing five orifices. The gases mixed in a pipe 2 ft long and 3 in. diameter and passed through a gate valve into the square duct. The gate valve was so arranged that the flow of gas into the square duct and of propane into the air stream could be stopped in one operation. A deflecting baffle was placed $1\frac{1}{2}$ in. downstream of the point of entry of the gas mixture into the duct. This baffle was a 6 in. diameter plate containing a central hole $1\frac{1}{2}$ in. diameter and it served to facilitate the complete filling of the duct with the gas mixture.

Test programme and procedure

Experiments were carried out to investigate the effect of the following factors:-

(1) the weight of the vent cover within the range of 0-750 g/ft^2 of vent area,

(2) the position relative to the duct of vents of different size,

(3) the position of the ignition source over a short distance near the closed end of the duct, with a vent remote from the ignition source,

(4) the effect of a single supplementary vent of variable size placed at different positions along the duct,

(5) the distribution of a given vent area along the duct.

Table 1 gives an outline of the various duct arrangements used in the tests.

Before charging the duct with flammable mixture, the vent in the end was partially blocked and each top vent was covered with a loose cover of expanded polystyrene weighing 250 grams/sq.ft of vent area, except in the tests where the vent was varied. In the latter tests covers weighing either 250 g, 325 or 750 g. were used. The duct was purged 7 to 10 times with a 5 per cent propane - 95 per cent air mixture. The gate valve was then shut to stop the supply of mixture into the duct and the apparatus left for 1 min. to allow the mixture to become stationary. The blockage at the end of the duct was removed and the gas ignited. If more than one vent was employed, the loose covers on top of the duct were left in place prior to ignition, ~~except in the series where the effect of the weight of cover was investigat~~ed. It was necessary to do this, since otherwise the contents of the duct would become seriously diluted, even in the few seconds between removal of the covers and ignition of the gas.

The pressure was measured with capacity gauges stated by the makers to have a natural frequency of not less than 1000 cycles/sec. The flame speed was measured with ionization probes which were spaced at intervals of 2 ft 6 in. and 3 ft 6 in. alternately along the duct. The signal from each probe was fed to the grid of a cold cathode tube and this in turn delivered the signal which was superimposed on a sinusoidal timing wave. Both pressure and flame speeds were recorded by photographing the screen of a double beam cathode-ray tube on a variable speed revolving drum camera.

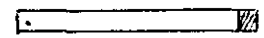
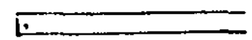
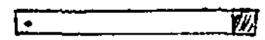
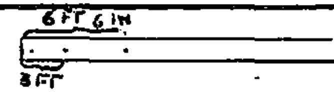
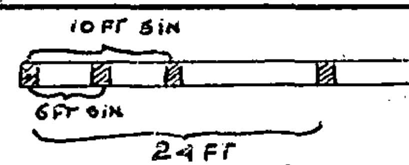
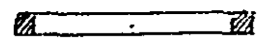
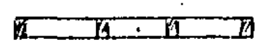
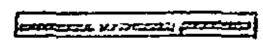
RESULTS

Effect of vent cover

Duct arrangement 'a' (Table 1) was used for these tests, the 1 ft^2 vent being either completely open or covered with a panel weighing 250, 325 or 720 g. Fig. 2 shows the effect of the weight of the vent cover on the maximum pressure. All the records obtained in these tests were characterised by the presence of three peaks in the pressure record. The first peak occurred when the flame had travelled one third of the total duct length, the second when the flame had travelled along two thirds of the duct and the third peak occurred within .01 sec. after the flame front had reached the end of the duct. Figures at each point on the graph indicate at which peak the maximum pressure occurred in a given test. Fig. 2 shows that with no cover or a very light cover the maximum pressure occurred at the third peak, whereas with heavier covers it occurred at the second peak. There was also a smaller maximum pressure when there was a light cover weighing 250 g. ft^{-2} than when the vent was completely open. Some experiments were also carried out in which one vent was closed with kraft paper weighing 10 g/ft^2. The paper was clamped to the edge of the vent but slit along the diagonals. The mean maximum pressure in four tests was 1.5 lb/in^2 and was higher than would be expected from a simple cover of the same weight. Moreover,

TABLE 1

Duct arrangements used in tests

Factors varied in Experiments	Duct Designation	Duct Length ft	End Vent	Position of Ignition	Number of Top Vents	Sketch plan of Duct
Weight of Vent Cover	a	18	None	6 in from Closed End	One 1.0 ft^2 Weight of Vent Cover varied	
Size of vents and position relative to duct	b	18	One 0.5 or 1.0 ft^2	6 in from Closed End	None	
	c	18	None	6 in from Closed End	One Area 0.5, 1.0 or 2.0 ft^2 No Closure	
Position of ignition source	d	24	One 0.25 ft^2	Varied	None	
Size and position of single supplementary vent	e	30	One	6 in from Closed End	One 0.125 to 1.0 ft^2 Position varied Light Cover	
Distribution of a given vent area	f	18	None	Centre	Two Total area 0.5, 1.0, 2.0 ft^2 Light cover	
	g	18	None	Centre	Four Total area 0.5, 1.0, 2.0 ft^2 Light cover	
	h	18	None	Centre	Slots Total area 1.0 or 2.0 ft^2 Light cover	

▨ Vent • Ignition

there was no consistency in the particular peak pressure at which the maximum occurred.

Fig. 3 shows the flame speed along the duct for these experiments. The presence of a cover over the vent brought about a slight reduction in the flame speed along the duct. The sudden reduction at the end is due to the fact that the flame reached the most remote ionisation gap from the ignition source after it had reached the vent, and the flame recorded was one which was propagating slowly towards the closed end of the duct which was 6 in. away from the gap. Plate 1 shows two typical records (a) for an open vent and (b) for a vent with a cover weighing 720 g.

Effect of vent position relative to the duct

These experiments were carried out using duct arrangements b and c shown in Table 1. Fig. 4 shows the maximum pressures for different vent areas. For a given vent area there was little difference in maximum pressure for both vent positions. Fig. 5 shows the flame speed along the duct for both vent positions while using different vent areas. There was little difference in flame speed when the area of the vent was 0.5 ft^2, but the difference was substantial when the vent area was 1 ft^2.

With the vent at the top of the duct the measurements of flame speed within 3 ft of the vent were unreliable because of distortion of the flame caused by the vent.

Effect of position of ignition source

For these tests duct arrangement d was used and the position of ignition was varied as shown in Table 1.

Fig. 6 shows the effect of the position of the source of ignition on the maximum pressure with vent opening equal to 25 per cent cross-sectional area of the duct. The maximum pressure was greatest when ignition took place 3 ft from the closed end of the duct. Examination of the pressure records in these tests showed that the peaks were not very pronounced. With ignition 6 in. and 3 ft from the closed end the maximum pressure occurred when the flame front was at the vent. When ignition was 6 ft 6 in. from closed end the maximum pressure occurred when the flame front had travelled approximately 8 ft along the duct; there was a second peak when the flame front arrived at the vent. A typical pressure record is shown in Plate 2.

Fig. 7 shows the flame velocity along the duct for the same series of experiments. In all tests the flame accelerated during first 6 ft of its travel and then attained a much steadier velocity between 90-140 ft sec^{-1}.

Effect of single supplementary vent in an open ended duct

These tests were carried out using duct arrangement e and the distance between the supplementary vent and the ignition source was varied as shown in Table 1. Fig. 8 shows the maximum pressure plotted against the distance between the ignition source and supplementary vent for the different supplementary vent areas. These curves show that, for a given vent the maximum pressure increases with an increase of distance between the supplementary vent and the source of ignition. Examination of the pressure records, some examples of which are given in Plate 3, showed that with vents 6 ft 3 in. from the source of ignition there was one peak only and after this oscillations developed. When the vent was 10 ft 6 in. away from the source of ignition the first peak was followed by a second peak, and this peak with the smaller vents gave the maximum pressure; after this oscillations in pressure followed.

With vents above the ignition source measurable pressures were obtained only with the smaller vents. There were two peaks, the first occurring when the flame was approximately 2 ft 6 in. from the source of ignition, and the second appearing soon after the flame reached the second half of the duct. Typical pressure records are shown in Plate 3.

Fig. 9 shows the effect of distance between the vent and the point of ignition on the maximum flame speed. This speed increased as the distance between the vent and the ignition source increased and decreased with increase in vent area. In all tests, with the exception of those where the vent was above the source of ignition, the flame decelarated after reaching the vent and then either maintained a steady velocity or accelerated. With a vent near the ignition source, there was a gradual increase in the flame speed throughout the duct length.

The effect of distributing the venting area over a duct closed at both ends

For these tests duct arrangements f.g.h. were used. Fig. 10 shows the maximum pressure plotted against the number of top vents for a given vent area; figures for one vent at the end of the duct obtained from Fig. 3 have been included in the curves. For any given area of vent the maximum pressure decreased as the number of vents increased. When using a continuous vent in the form of a slot of 1 sq. ft and 2 sq. ft total area, the maximum pressure was approximately 0.1 $lb.in^{-2}$ or less. The pressure records indicated that multiple vents relieved the pressure more speedily than a single vent of the same total area and invariably the pressure decreased after the flame arrived at the first vent orifice. Fig. 11 shows the maximum flame speeds obtained in these tests. The flame speeds were reduced as the number of vents increased; maximum flame speeds when slot vents were used were 20 ft/sec.

DISCUSSION

The results obtained above illustrate the importance of using distributed vents in a duct system. The reason for this is that the better the vents were distributed the nearer was there a vent to the source of ignition and as soon as the flame reached the vent there was a drop in pressure and flame speed. The use of distributed vents is, therefore, important where ignition might take place at any point in the system. The efficiency of the slot vents, compared with vents placed at intervals along the duct, is particularly noteworthy, thus in the 18 ft long duct the slot vents gave a maximum pressure less than $^1/_{10}$ of the maximum obtained with a single vent of equal area. With the slot vents a certain amount of venting area is present near the ignition source wherever the latter may be sited and for this reason the use of slot vents is, in principle, the most efficient way of distributing a given area for venting along the duct.

Compared with the effect of distributing the vents, factors such as the position of the vent relative to the duct, and within the limits investigated, the weight of the cover used to close the vents, were of minor importance. These factors did give rise to certain variations in the maximum pressure reached, but what is probably of greater interest is the variation in the particular point in the explosion at which the maximum pressure occurred. This variation suggests that any one of a number of factors might control the maximum pressure and great care is therefore required in extrapolating results of the present experiments to other conditions.

The nature of the pressure records obtained in the tests with covers of different weight (Plate 1) suggests that one of three factors corresponding to the three peak pressures may control the maximum pressure.

(1) The first peak shown on the record, occurs during the initial acceleration of the flame front and may be ascribed to the inertia of the gas inside the duct.

(2) The factor responsible for the second peak is not quite clear; this peak occurred with no cover and thus it cannot be entirely ascribed to the inertia of the cover. However, since the pressure at this peak was increased, when a cover was present, a possible explanation in that this peak was due to the combined effect of the inertia of the cover and the inertia of the air outside the duct.

(3) The third peak occurred when there was flame outside the duct and can be ascribed to a sudden increase in the rate of combustion when the flame reached the vent, combined perhaps with the explosion of a turbulent pocket of inflammable gas expelled from the vent.

Placing a vent at the side of a duct rather than at the end of a duct brought about an increase in the turbulence at the vent since the unburned gas was turned through a right angle, this resulted in an increase in the peak pressure due to the third factor. However, because of the slightly larger resistance of the side vent, compared with the end vent, the acceleration of the flame towards the vent was reduced and the peak pressures (1) and (2) due to inertia were reduced. The reduction in the maximum pressure when a light cover was placed over the vent was a consequence of the reduction in the velocity of the flame. This resulted in a smaller velocity of unburned gas passing through the vent and a reduction in the turbulence at the vent. For the heaviest covers, however, the inertia of the cover became the factor of greatest importance; the maximum pressure was greater than with the lightest cover and occurred at the second peak pressure.

When single vents are used which are appreciably smaller than the cross-sectional area of the duct, the maximum pressure inside the duct is controlled by the resistance of the vent to the flow of unburnt gases passing through it. This occurred in the explosions using the vent of 0.5 sq.ft area in series b and c and of 0.25 sq.ft area in series d. In the latter experiments the absence of pronounced peaks in the pressure records suggests that the velocity of unburnt gas approaching the vent reached a fairly uniform value and this is confirmed by the flame speed records for the flames in the second half of a duct (Fig. 7). However, when the flames were in the first half of the duct a fairly well defined peak in speed did occur and the flame speed at the peak diminished as the distance between the ignition source and the closed end increased. This was probably due to an increase in the ability of the combustion products to expand in two directions rather than in only a single direction towards the vents. This reduction in the initial flame speed would reduce the turbulence in the unburnt gas ahead of the flame approaching the vent and hence tend to reduce the rate of combustion at this flame and the maximum pressure. On the other hand the presence of an extra flame front travelling slowly towards the closed end would tend to increase the total rate of combustion occurring in the duct and thus to increase the pressure. Occurrence of a maximum value in the maximum pressure when the ignition source was 3 ft from the end of the duct may be ascribed to the combined effect of these two processes.

PRACTICAL APPLICATIONS

The information in Figure 8 may be applied to the design of distributed venting for long straight ducts. If ignition takes place at some point in such a duct flame will travel in opposite directions from the ignition source. It is unlikely that in the first 20 or 30 ft travelled by the flames the rate of combustion at either of these flame fronts will be greater than the rate of combustion that occurred in the experimental set up used in the present tests, provided of course that the gas was not initially highly turbulent or that the flammable gas mixture does not have a fundamental burning velocity in air substantially higher than propane. In these circumstances the ignition at the centre of a long duct open at both ends may be considered as giving rise to similar effects to ignition on both sides of a hypothetical blockage that stretches across a duct and the results shown in Figure 8 may be applied directly. Thus if it is desired to keep maximum pressures in a duct down to 1 lb/sq.in. by the use of vents of $\frac{1}{2}$ sq.ft placed at intervals along the duct, Figure 8 shows that a relief vent must be not more than 8 ft from any point of ignition. This implies that for a long length of ducting, relief vents should not be further than 16 ft apart. Available information on explosions in ducts of different diameter indicates that flame speeds are similar for a given ratio of $\frac{l}{d}$ where l is the distance between ignition source and the relief vent and d is the diameter of the duct. It would be expected, therefore, that distances between relief vents may be scaled directly with the diameter of a duct. Further investigation on this point is desirable.

The information in Figure 10 may be applied to the venting of duct shaped vessels. The following relationship has been given elsewhere (2) between the maximum pressure reached in an explosion and the size of a single vent in the end of a duct.

$$P = 1.75\ K \qquad \text{................(1)}$$

Figure 10 indicates that considerably smaller pressures may be obtained if the available venting area is distributed along the whole length of the duct rather than at one end of the duct. Thus if the venting area is calculated on the basis of equation 1 a considerable safety factor will be employed if the venting area estimated on this basis were distributed along the walls of the duct.

<u>References</u>

1. RASBASH, D. J. and ROGOWSKI, Z. W. "Gaseous Explosions in Vented Ducts" to be published in Flame and Combustion, December, 1960.

2. RASBASH, D. J. "Reliefs for Gaseous and Vapour Explosions", Department of Scientific and Industrial Research Joint Fire Research Organization, F.R. Note No. 416.

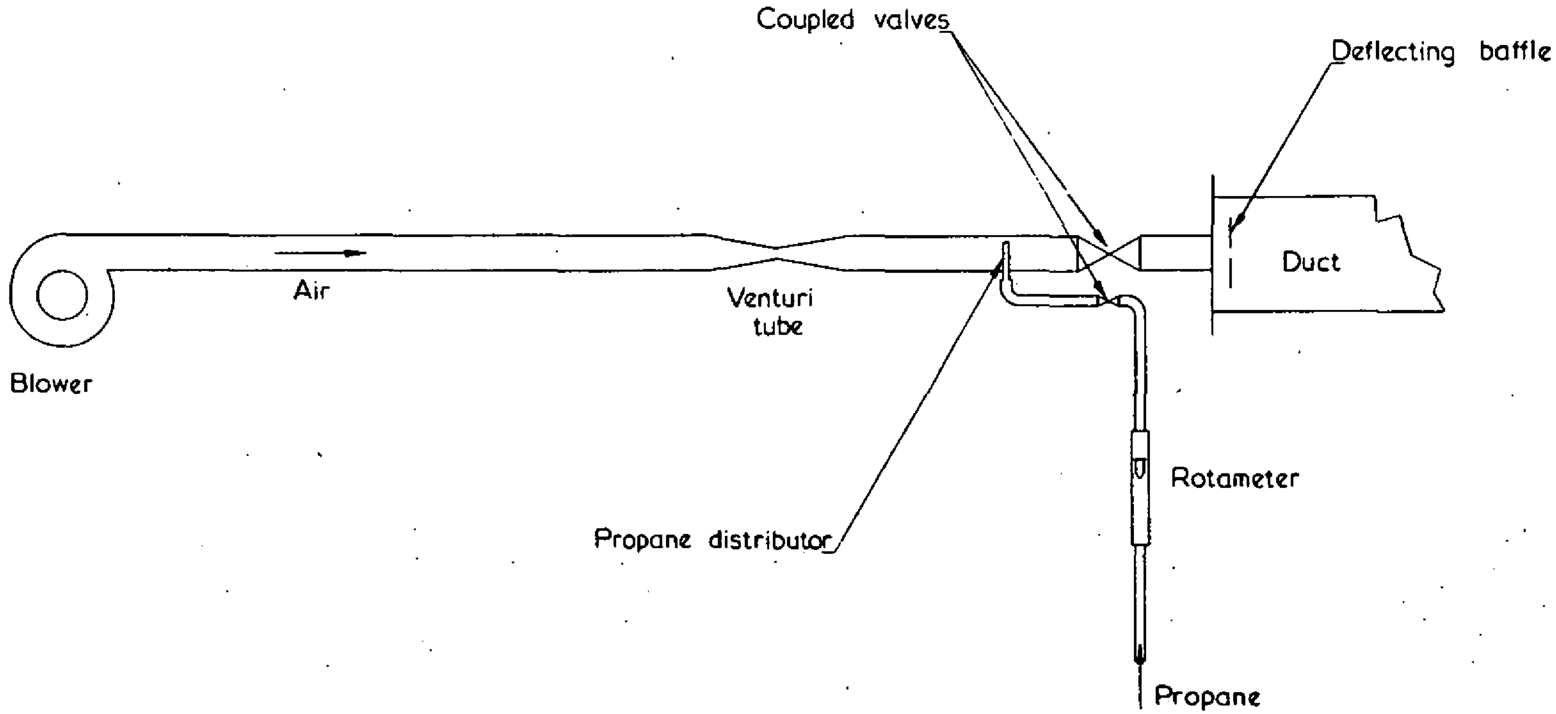
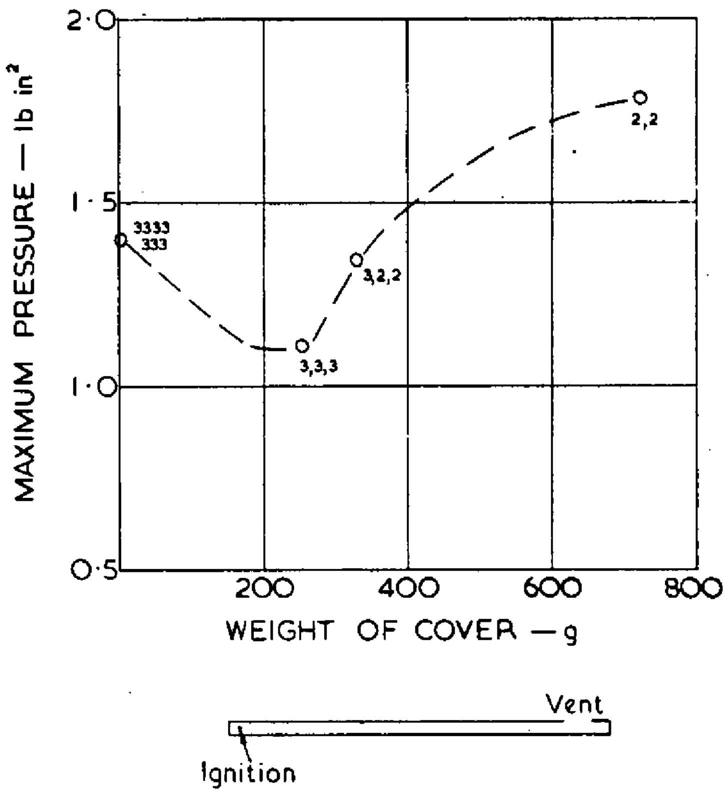


FIG. 1. DIAGRAM OF THE APPARATUS USED FOR FILLING THE DUCT WITH FLAMMABLE MIXTURES



Figures at each point indicate which peak determined the maximum pressure

FIG. 2. RELATION BETWEEN WEIGHT OF COVER AND MAXIMUM PRESSURE — 18 FT LONG DUCT

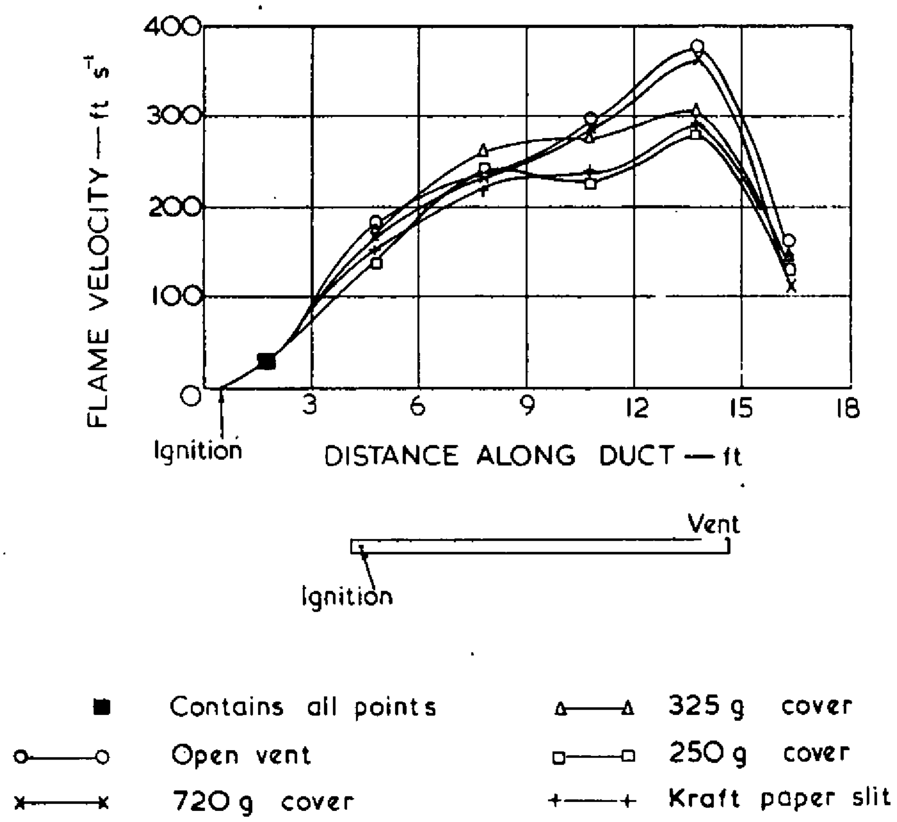


FIG. 3. RELATION BETWEEN THE WEIGHT OF VENT CLOSURE AND FLAME VELOCITY — 18 FT LONG DUCT

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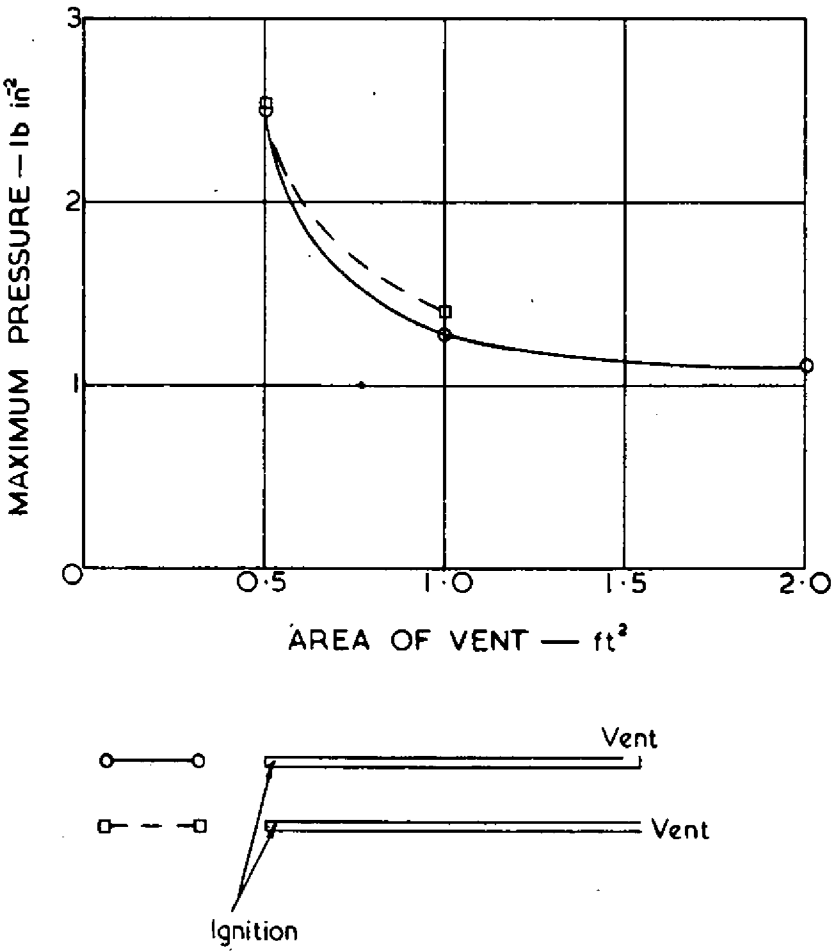

FIG. 4. EFFECT OF VENT POSITION ON MAXIMUM PRESSURE FOR DIFFERENT VENT SIZES 18FT x 1FT DUCT. VENTS REMOTE FROM IGNITION

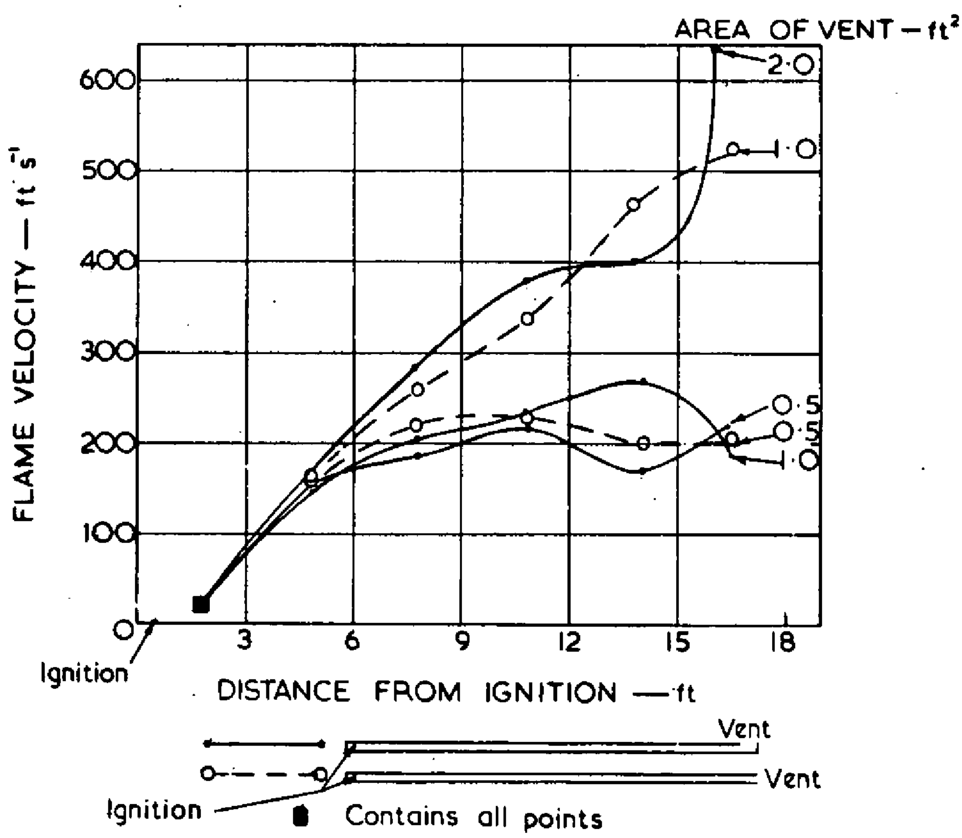

FIG. 5. EFFECT OF VENT POSITION ON FLAME VELOCITY FOR DIFFERENT VENT SIZES 18FT x 1FT DUCT

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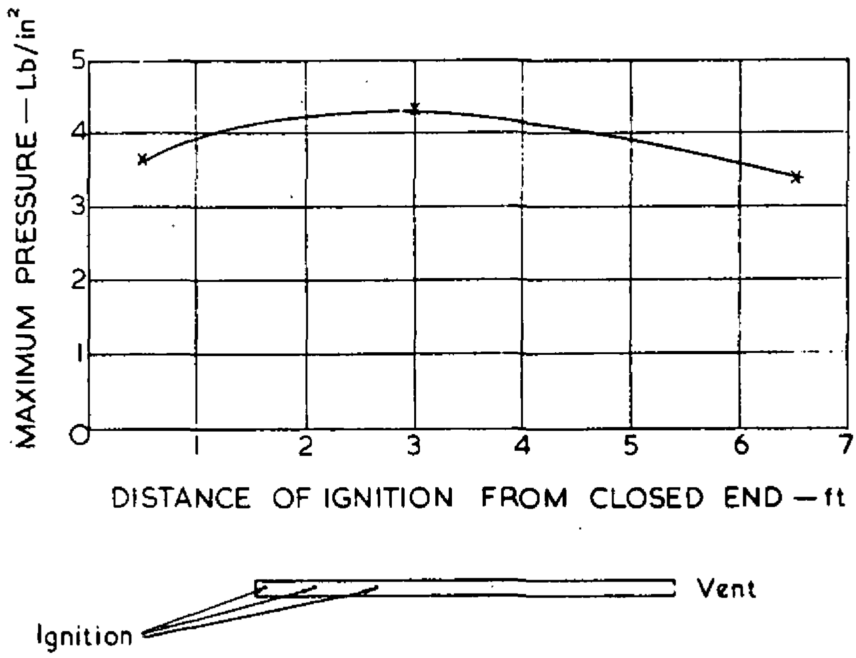

FIG. 6. EFFECT OF POSITION OF IGNITION ON MAXIMUM PRESSURE – 24 FT LONG DUCT VENT AT ONE END 25 PER CENT AREA OPEN

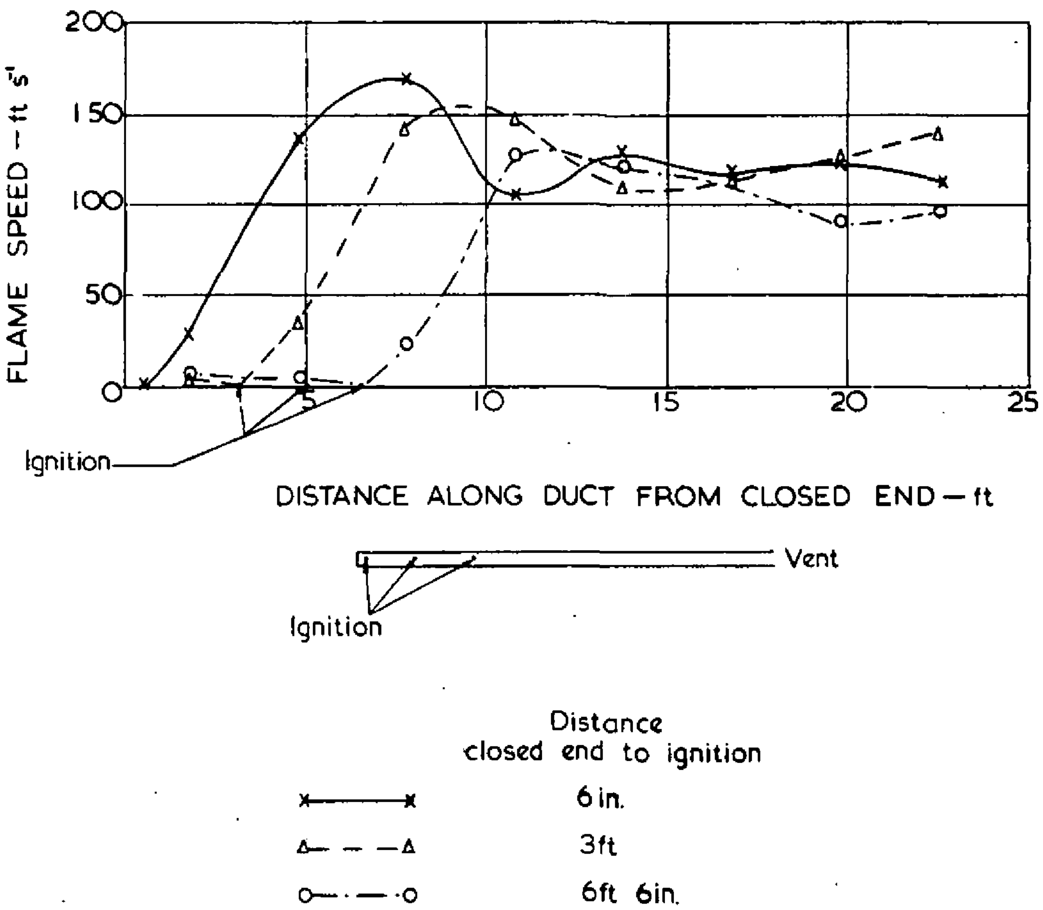

FIG. 7. RELATION BETWEEN POSITION OF IGNITION AND FLAME SPEED ALONG THE DUCT – 24 FT LONG DUCT VENT AT ONE END 25 PER CENT AREA OPEN

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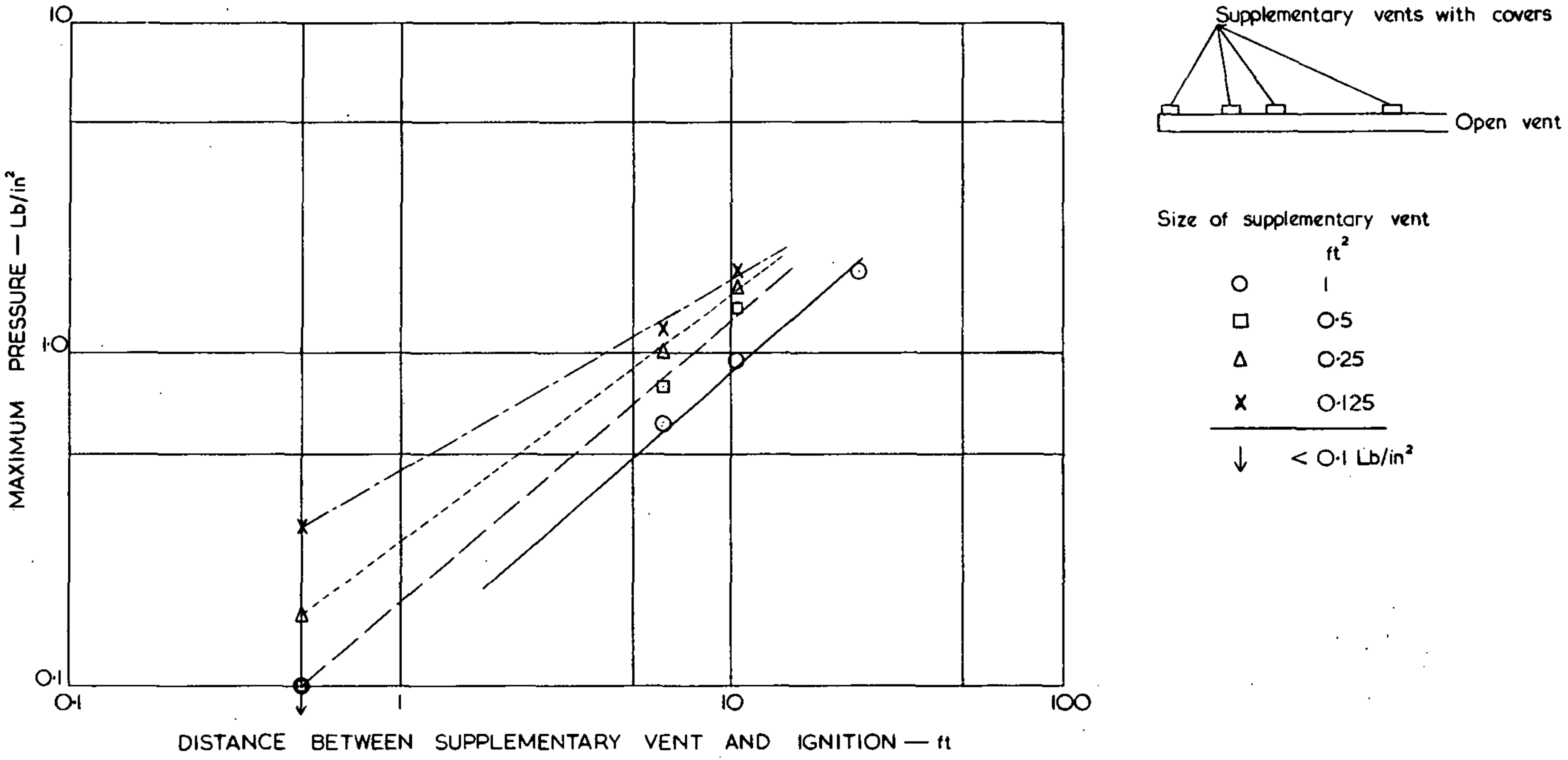

FIG. 8. EFFECT OF DISTANCE BETWEEN SUPPLEMENTARY VENT AND IGNITION ON MAXIMUM PRESSURE 30 FT X 1 FT DUCT — OPEN VENT AT THE END

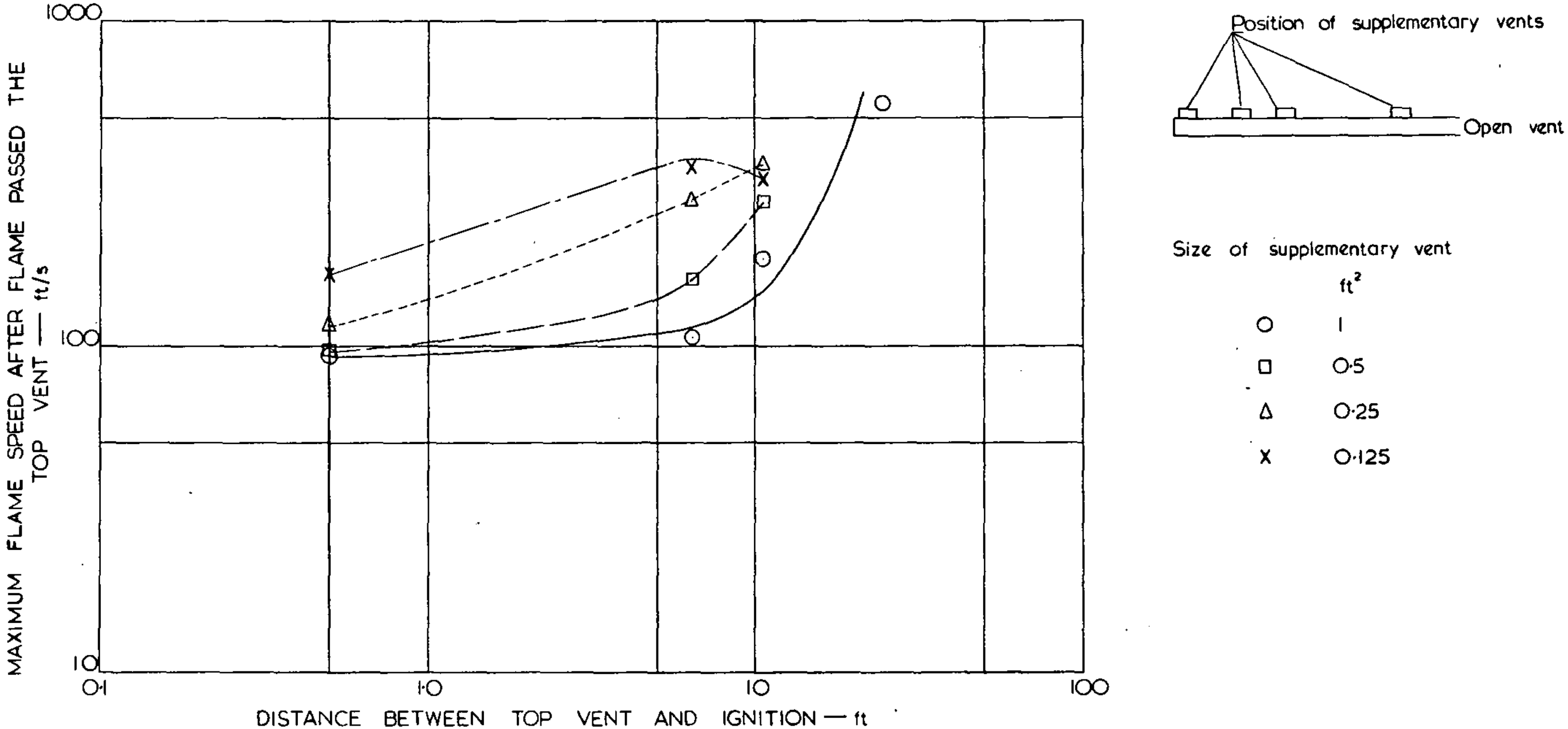

FIG. 9. EFFECT OF DISTANCE BETWEEN SUPPLEMENTARY VENT AND IGNITION ON MAXIMUM FLAME VELOCITY
30 FT X 1 FT DUCT — OPEN VENT AT THE END

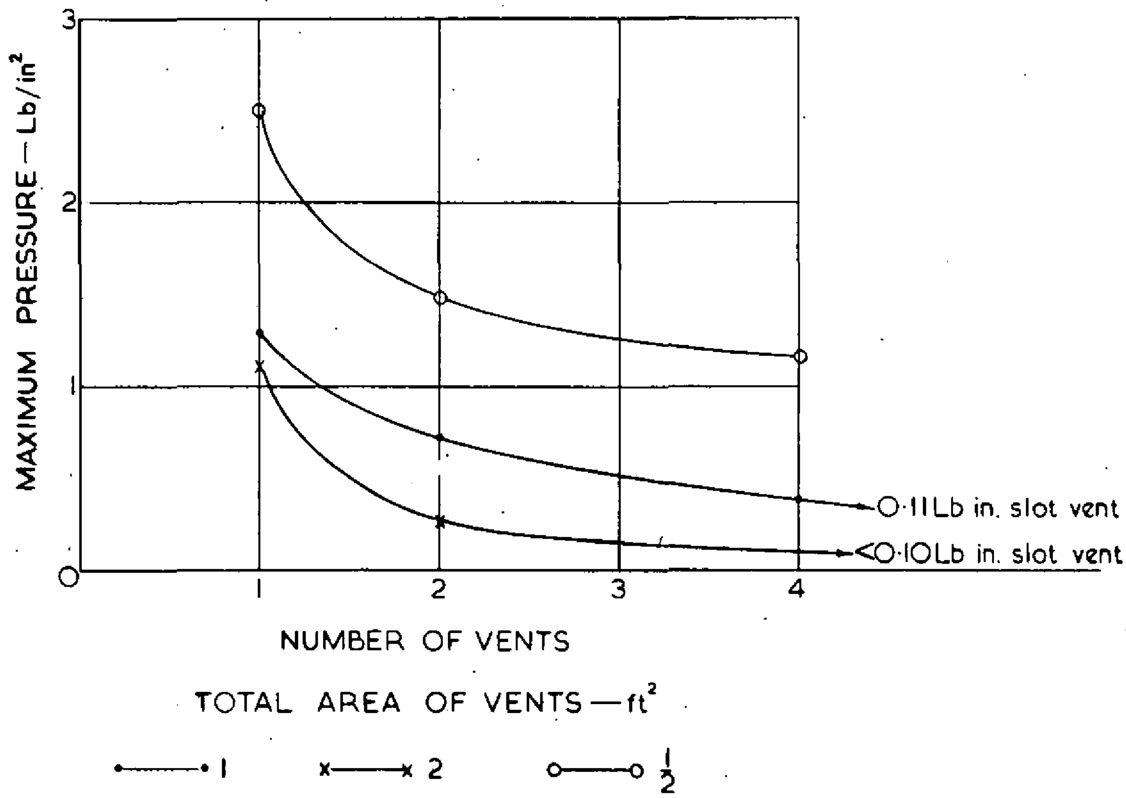

FIG.10. RELATION BETWEEN NUMBER OF VENTS AND MAXIMUM PRESSURE — 18 FT x 1 FT DUCT
IGNITION CENTRE WITH MORE THAN ONE VENT
IGNITION 6in. FROM CLOSED END WITH ONE VENT

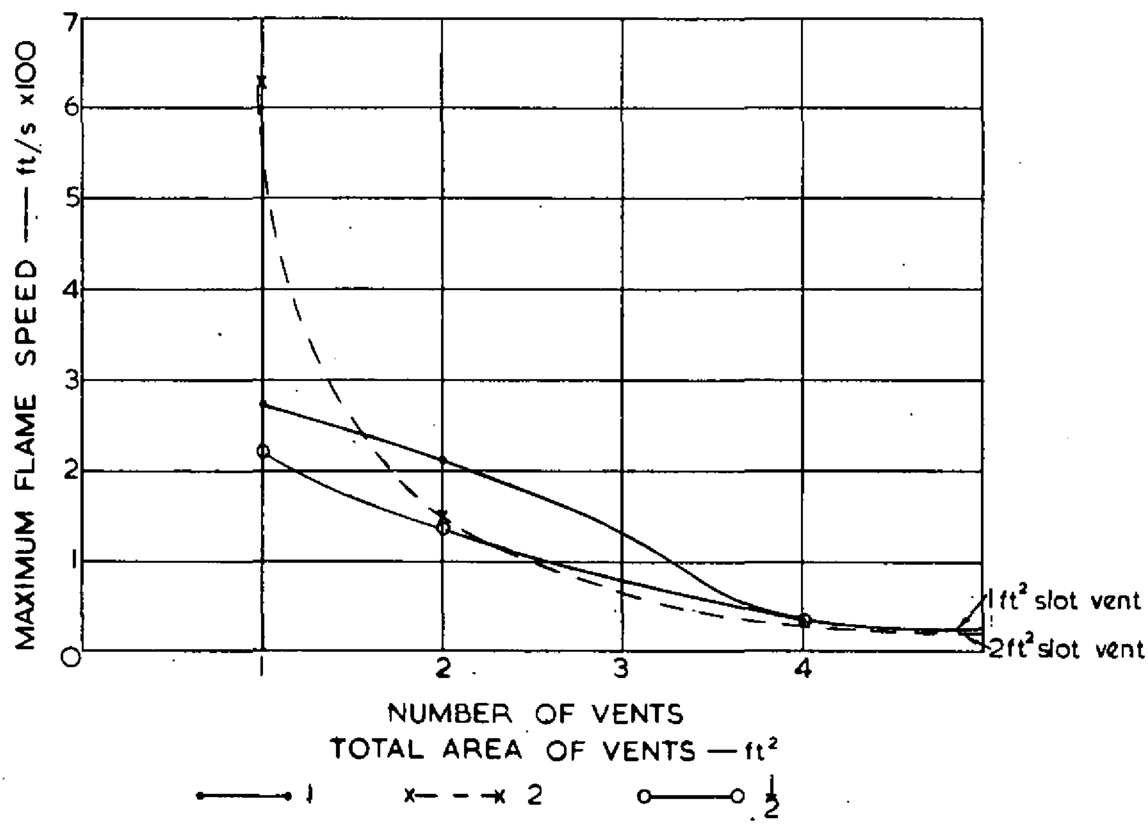

FIG.11. RELATION BETWEEN NUMBER OF VENTS AND MAXIMUM FLAME SPEED 18 FT x 1 FT DUCT
IGNITION CENTRE WITH MORE THAN ONE VENT
IGNITION 6in FROM CLOSED END WITH ONE VENT

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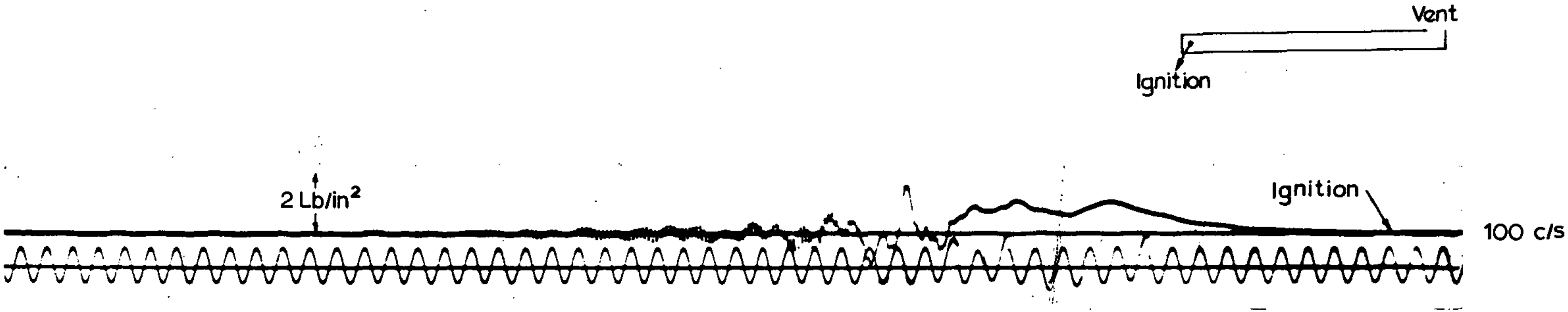
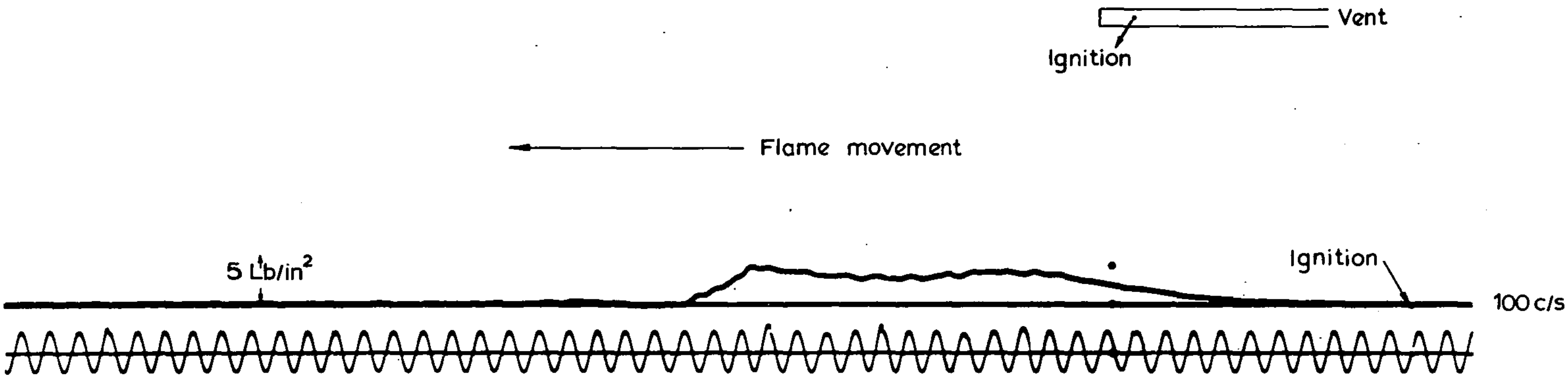


a. Open vent — area 1 ft^2

b. Vent with cover — area 1 ft^2
weight 720 g/ft^2

Blips on the timing wave indicate arrival of flame at the probe

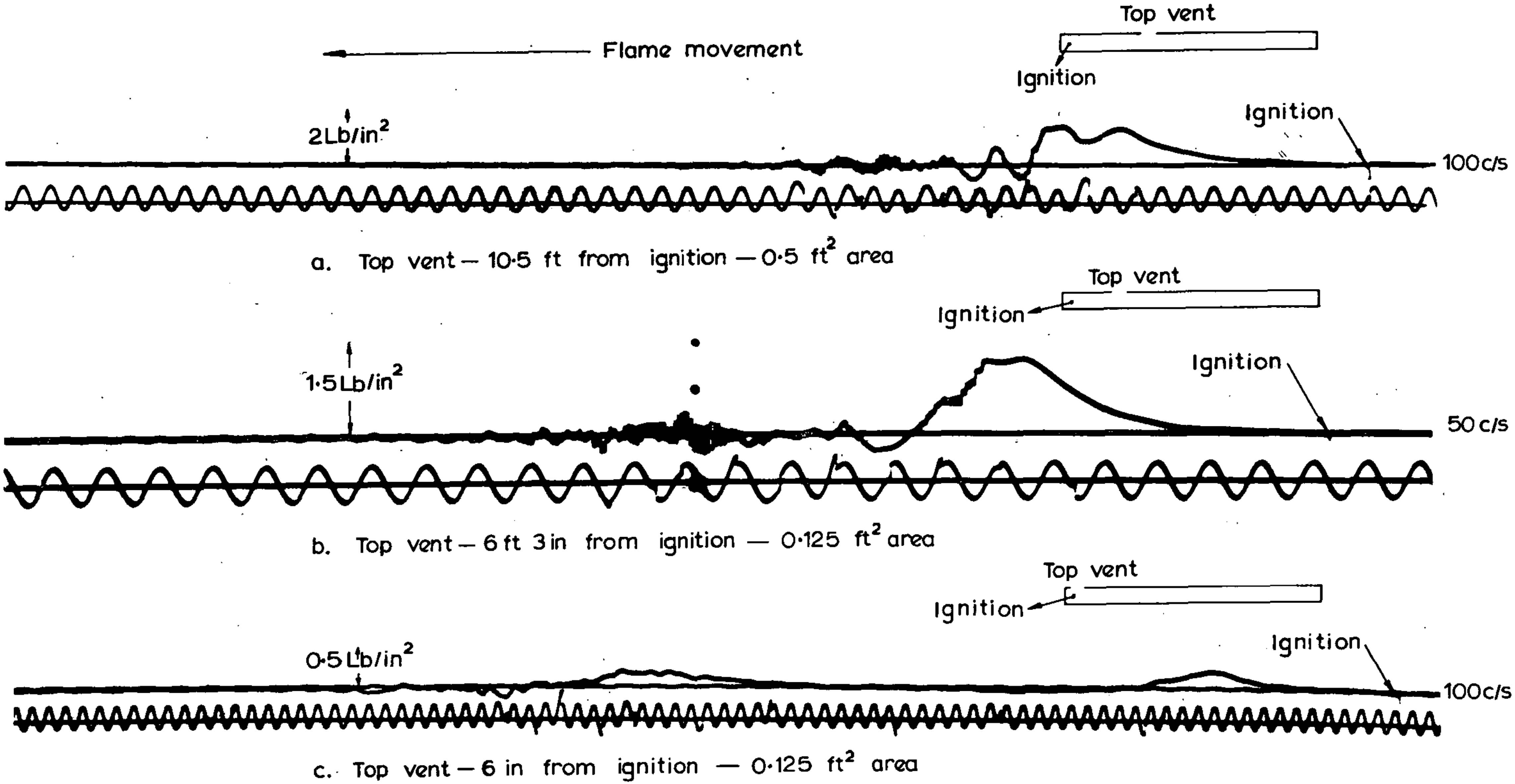
PLATE 1. 18 FT DUCT – VENT AT THE TOP – REMOTE FROM IGNITION



b. Vent area $\frac{1}{4}$ ft^2

Blips on the timing wave indicate arrival of flame at the probe

PLATE 2. 24 FT LONG DUCT—EFFECT OF VENT POSITION RELATIVE TO IGNITION
IGNITION 3 FT FROM CLOSED END



Blips on the timing wave indicate arrival of flame at the probe

PLATE 3. 30 FT DUCT — EFFECT OF DISTANCE BETWEEN VENT AND IGNITION ON MAXIMUM PRESSURE