F.R. Note No. 490

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

THE VENTING OF GASEOUS EXPLOSIONS IN DUCT SYSTEMS

PART IV - THE EFFECT OF OBSTRUCTIONS

by

D. J. Rasbash and Z. W. Rogowski

SUMMARY

Experiments have been carried out to ascertain the effect of obstructions on gaseous explosions in duct systems containing quiescent flammable mixtures. Obstructions in the form of orifice plates, strips and pipe fittings were used. It was found that these generated turbulence in the moving mixture, which increased the combustion rate within the duct. As a result there was a considerable increase in the pressure after the flame front had reached the turbulent region downstream of the obstruction. During this stage of the explosion, high flame speeds along the duct were observed. Simple correlations between the maximum pressure and the resistance of the obstacle to gas flow were obtained. Tests with supplementary vents at various positions have shown that the most efficient venting was obtained, when an extra vent was inserted near the ignition source. This reduced the velocity of the unburnt gases thus avoiding the turbulence.

January, 1962.

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INTRODUCTION

Previous work at the Joint Fire Research Organization on the venting of gaseous explosions in duct systems(4) showed the need for investigation into the effect of turbulence caused by obstacles on the maximum explosion pressures attained. This phenomenon has been recognised in the past; Thomas et al(1) and Simmonds et al(2), reported some effects of obstacles and turbulence on explosions in vessels of small length to diameter ratio. Although no results of such experiments using ducts are published, the possible effect of obstacles has been appreciated: this is reflected in industrial practice where advice has been given for vents to be inserted near industrial fittings(3). The object of the work described below was to ascertain the effect of various obstructions in ducts on the maximum pressure and flame speed and to obtain some indications of the most efficient method of venting.

APPARATUS

Ducts

The required lengths of ducting were assembled from 6 ft and 3 ft long sections of 6 in internal diameter carbon steel pipe, flanged at both ends. Each length of pipe had three 1 in B.S.P.T. bosses for the insertion of flame velocity measuring probes, one $1\frac{1}{2}$ in B.S.P.T. boss for the insertion of a pressure gauge and one $\frac{3}{8}$ B.S.F. boss for the insertion of the ignition source. In addition, any of these devices could be located in any one of the end blank flanges.

Ignition

The mixtures were ignited by the use of an inductive spark and the ignition source was located at the axis of the duct, 6 in from its end.

Obstructions

Three types of obstructions were used: (a) standard pipe fittings: tee, square elbow, and streamlined elbow, (b) central orifice plates with the following areas of orifice, 23 in^2, 20 in^2 and 14 in^2, (c) strips located along the vertical diameter of the duct; these were of the following areas: 10.4 in^2, 5.2 in^2, 2.6 in^2 and 1.3 in^2.

The orifice plates and the strips were made from $^3/_{16}$ in thick aluminium plate and could be clamped between two of any end flanges of the duct. In this note these orifice plates and strips will be referred to as obstacles. In all tests, the obstruction was followed by a 6 ft length of pipe.

Pressure measuring apparatus

Quartz crystal pressure transducers were used and these had a natural frequency of 60 000 c/s. The signal from these transducers, after preamplification, was displayed on the screen of a double beam cathode ray tube and photographed on a variable speed revolving drum camera. This operation was timed by displaying at the same time a sinusoidal wave of the required frequency on the other beam of the cathode ray tube. This apparatus had the advantage of providing a long time base with a large variation of the writing speed.

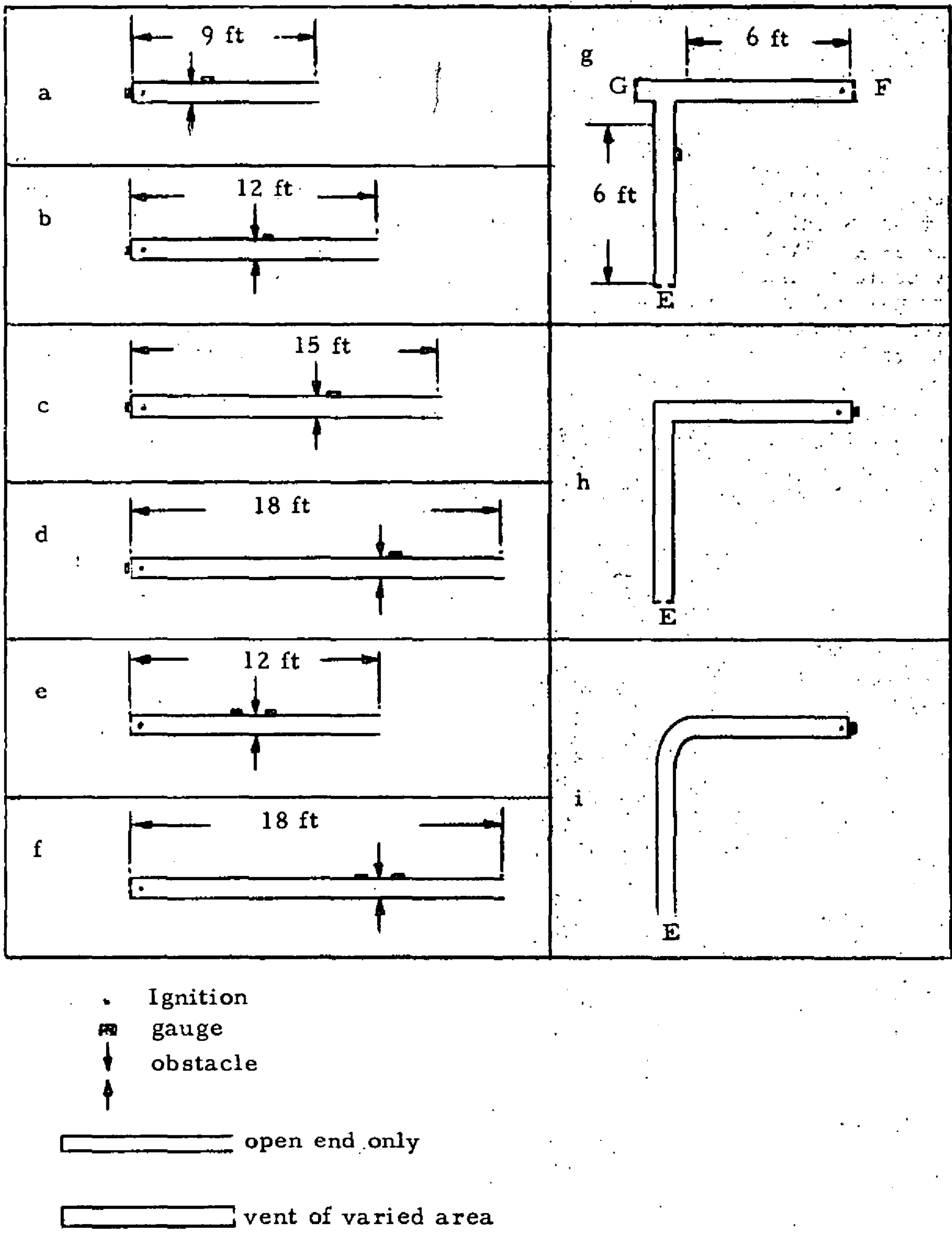

TABLE 1
ARRANGEMENTS OF DUCTS USED IN TESTS

The flame speed measuring apparatus

In earlier experiments the flame progress was followed by the use of the ionisation probes; these protruded 1 in approximately inside the duct. In this series of experiments however such a large distortion of the flame front occurred due to the presence of the obstacle that this type of probe gave misleading results, and a photocell system was therefore designed where the most advanced portion of the flame front could be detected. The probe was an infra red sensitive photocell and was located in a sealed brass chamber with a window made from polished quartz plate. The whole unit was screwed into the available boss on the wall of the duct. The signals from these photocells were fed into the transmitting circuit which included cold cathode triodes. The signal from the cell triggered the tube and this in turn delivered a signal which was superimposed on a sinusoidal timing wave. The use of these triodes had the advantage of blocking the signals which were caused by hot gases behind the flame front. These signals, if not removed, interfered seriously with the signals of the other photocells.

Apparatus measuring the friction loss caused by the obstructions

For these determinations the 24 ft long duct was used, with obstructions mounted in the middle of the duct length as in the explosion tests. Air was sucked into the pipe by a centrifugal blower. The smoothness of the flow was improved by the use of gauze and a 3 ft long flow straightener.

Vents

All vents were central square edge orifices machined from mild steel blank flanges, bolted to the end flanges of the duct. For convenience in some graphs the size of vent is expressed by factor $K = \frac{\text{cross-sectional area of duct}}{\text{cross-sectional area of vent}}$

EXPERIMENTAL

Test procedure

In all tests unless otherwise indicated, the duct was filled by displacement of air with a 5 per cent propane-air mixture. During that time the vent orifices were closed, but before ignition their closures were removed.

Test programme

Table 1 shows the duct arrangements used in these tests. This table also shows the position of the relief vents and the pressure gauges, except for arrangement with the Tee; with the latter arrangement when the vent F was closed the gauge was placed in the flange F and not 6 in beyond the T piece as shown. In the description of results and in the discussion below the part of the duct between the flange near the ignition source and the obstacle is regarded as being "upstream" of the obstacle; the rest of the duct is "downstream" of the obstacle.

RESULTS

Effect of obstacles in an open-ended straight duct

For these tests, ducts a, b, c and d were used. Typical pressure records are shown in Plate 1. In all cases, the maximum explosion pressures were recorded by the gauge located near the ignition source.

There were some general features common to all the pressure records obtained near the obstacles. The initial stages of these explosion records were similar to those obtained in a duct with no obstalces in that after ignition there was a small pressure rise due to the inertia of the volume of gas inside the pipe ahead of the flame front. However, soon after the flame front reached the obstacle another sudden increase in pressure took place. The shape of this part of the record varied and with some obstacles there were several peaks in the form of vibrations, the last one often occurring when the flame front was at the open end of the duct. The records of pressure measured near the ignition source, were initially similar to those measured near the obstacle. However, the pressure rise after the flame had passed the obstacle was different. This pressure rise took place a few milliseconds after the pressure rise near the obstacle and seldom was there more than one peak. Often records taken by both gauges showed very high rates of pressure rise.

Fig. 1 shows the maximum pressure for ducts of different lengths plotted against the distance from the ignition source to the obstacle. This graph shows, that for obstacles of larger area, increasing the distance between the ignition source and the obstacle had little effect on the maximum pressure. With obstacles of small area, however, this pressure tended to decrease as this distance increased. Maximum pressures recorded downstream of the obstacle were lower and Figs 2 and 3 show, for strips and central orifices respectively, the difference Δ Pm between the maximum pressures near the ignition source and downstream of the obstacle, plotted against the distance between the ignition source and the obstacle.

Flame speed measurements indicated that, for a given length of pipe, the flame speed from the ignition source to any obstacle did not differ greatly from that in an unobstructed pipe. However, when the flame front reached the obstacle, the flame accelerated within a 3 ft length of the pipe beyond the obstacle and then either continued to accelerate or decelerated. All the flame speeds downstream of the obstacle were higher than corresponding speeds in an unobstructed duct. Fig. 4 shows the flame speeds along the duct for different ducts with the same obstacle and shows that the flame speed at the obstacle increases with the increase of the distance between the ignition source and the obstacle up to and including a length of 8 ft 6 in. When this distance was 11 ft 6 in the flame front decelerated after travelling along two thirds of the duct. This phenomenon occurred with all obstacles and with the unobstructed duct.

Effect of a vent near the ignition source in a straight open ended duct

For these tests ducts e and f were used. Figs 5 and 6 show the maximum pressures plotted against the size of the vent near the ignition source for ducts e and f respectively. It is evident that insertion of even a small vent near the ignition source resulted in substantial reduction of maximum pressure. Figs 7 and 8 show the maximum pressures plotted against the maximum flame speed for ducts e and f respectively. These graphs show that for all obstructions pressures increased with an increase in maximum flame speed.

Pressure records obtained with vents near ignition source showed considerable reduction in the rates of pressure rise, and with vents of large area the pressures measured during the flame travel from ignition to the obstacle were very small. There was little difference between the pressures recorded upstream and downstream the obstacle, with the exception of orifice plates blocking 75 and 87 per cent cross-sectional area of duct where higher pressures were recorded downstream of the obstacle.

Effect of industrial pipe fittings

Three industrial pipe fittings were used: a tee, a square elbow and a streamlined elbow. Table 2 shows the maximum pressures and the maximum flame speeds obtained with each fitting using duct arrangements g, h and i, with the vent at E fully open and the others shut. (see Table 1).

TABLE 2

Duct arrangement	Maximum pressure lb in^{-2}	Pressure downstream of obstacle lb in^{-2}	Maximum flame speeds ft s^{-1}
g Tee	18.8	-	944
h Square elbow	15.2	9.6	1020
i Streamlined elbow	5.0	-	702

Pressure records obtained with the square elbow are shown in Plate 2. Pressure and flame speed records obtained in these tests were similar to those where strip and orifice plate obstacles were used. Similarly, maximum pressures occurred after the flame front emerged from the fitting. The flame speed records indicated that the flame front accelerated rapidly after emergence from the fitting, but the maximum flame speed occurred always in the last quarter of the duct. Fig. 9 shows the maximum pressures obtained with duct arrangements g and i for different areas of vent E, other vents in the system being closed. With both arrangements the maximum pressure increased with a decrease of vent area. On the other hand, the flame speeds along the duct decreased with a decrease of vent area. Fig. 10 shows the maximum pressures obtained with a number of vent systems using arrangement g. Evidently the lowest pressures for a given vent area were obtained when a supplementary vent was placed near the ignition source as in vent system d. It is worth noting that the addition of another vent to vent system c resulted in much higher pressures, as illustrated by the line showing the pressures for vent system b. Some of the pressure records obtained in these tests are shown in Plate 3.

Effect of concentration of propane on the maximum pressure

Some experiments were carried out to show the effect of the concentration of propane on the maximum pressure. Duct b was used both with an orifice plate obstacle and without an obstacle. Fig. 11 shows the relation between maximum pressure and maximum flame speed in the duct with and without an obstruction. These graphs show that highest pressures and highest flame speeds occurred with mixtures of compositions near the stoichiometric and that high pressures were accompanied by high flame speeds. However, in the unobstructed duct the maximum pressures did not vary as much as the maximum pressures in the duct with an obstruction. It is interesting that for a given flame speed in a duct with no obstruction, mixtures richer than stoichiometric gave lower maximum pressure than mixtures leaner than stoichiometric.

DISCUSSION

Effect of turbulence

The experimental results show that the violence of an explosion taking place in a duct may be considerably increased by the presence of an obstacle. The evidence from the explosion pressure and the flame speed records strongly suggests that this increase in violence is due to an increased rate of combustion in a pocket of turbulent gas caused by the obstacle. It has been recognised for some time that turbulence might increase the rate of combustion in an explosive gaseous mixture. Although the exact mechanism by which this occurs is not clear, probably the most important factor is an increase of the surface area of the flame resulting in a proportionate increase in the rate of combustion. If the turbulence is of very high intensity, the flame might even be disrupted and this would result in several flame fronts burning simultaneously.

There are a number of observations that illustrate qualitatively that turbulence downstream of the obstacle was responsible for the increased violence of the explosion. Thus the progress of the explosion between ignition and the flame arriving at the obstacle is the same as would be expected from a duct without an obstacle; rapid rises in the pressure and the flame speed occur only after the flame has passed the obstacle. Moreover, for a given duct system the pressure and flame speeds developed depend on the freedom with which the unburnt gases ahead of the flame may pass through the obstacle and create a pocket of turbulence. This is well illustrated in the experiments with the T-piece represented in Fig. 10. With vent system c, a limb leading away from the T-piece was closed at E but there was a relief vent in G in line with the ignition source. Under these conditions the maximum pressure and flame speeds were no different than would be expected in a straight length of ducting of the appropriate length. The provision of an extra vent at point E gave rise to a considerable increase in pressure for the larger vent sizes, presumably because a certain amount of the unburnt gas ahead of the flame could travel towards the vent at E instead of towards the vent at G.

The energy in the turbulent pocket downstream of the obstacle is probably related to the resistance to flow caused by the obstacle in the gases moving ahead of the flame. This resistance to flow may be expressed by equation 1

$$\Delta h = \frac{nVu^2}{2g} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where 'h is the pressure drop across the obstacle
Vu the velocity of unburnt gas moving towards the obstacle
n is a constant dimensionless factor for a given obstacle
and g is the acceleration due to gravity

n expresses the ratio of the resistance to flow across the obstacle, to the velocity head of the gas moving towards the obstacle. Assuming that the rate of combustion depends on the intensity of turbulence, it would be expected that for a given configuration of duct upstream and downstream of the obstacle, the maximum pressure should increase as the factor nV^2 increases. Figure 12 shows the maximum pressure obtained with different obstacles when using duct b plotted against the factor n for the different obstacles. The factor n was determined from separate experiments in which air was propelled at different velocities through each of the obstacles. In the tests represented in Fig. 12 the presence of the obstacle did not affect the progress of the flame towards the obstacle, and Vu was approximately constant. Figure 12 shows a power relation between the maximum pressures and n that covers all obstacles and fittings with the exception of the streamlined elbow. This particular fitting was found to produce a steep velocity gradient across the pipe diameter, extending for some distance downstream from the elbow. These characteristics of flow may well have caused a part of the turbulent combustion to take place nearer the open end of the duct, thus giving a lower maximum pressure. In Fig. 13 the maximum pressure is plotted against the factor nVu^2 for explosions in duct e with strip and orifice obstacles and with vents of different sizes close to the ignition source. Vu was estimated from the recorded flame speed across the obstacle in the manner indicated in the Appendix. Figure 13 shows that for any given obstacle, the maximum pressure increased as nVu^2 increased, and the results for all obstacles, although scattered, fell about a straight line indicating that the maximum pressure was proportional to the square root of the resistance to the flow of unburnt gas. The correlations shown in Figures 13 and 14 could not be extended to cover the experiments with ducts of different lengths. There are possible explanations for this limitation. Firstly, although the rate of burning in the turbulent pocket may have been similar for a given value of nVu^2, the maximum pressure which would have developed as a result of this rate of burning would depend on the geometry of the duct. Thus the distance between the closed end and the obstacle would affect both the volume upstream of the obstacle into which expansion could occur and the ability of the shock waves to reach and be reflected back from the closed end of the duct while the intensely turbulent combustion was still in progress. Secondly, the values of V_u obtained with ducts longer than 12 ft were generally higher than those occurring in the tests correlated in Figures 12 and 13; under these conditions it is possible that the turbulent pocket may have extended for a longer distance downstream of the duct and that the intense combustion took place nearer the open end.

Effect of concentration of flammable gas

Figure 11 shows that the composition of the flammable mixture had a much greater effect on the flame speed and maximum pressure when an obstacle was present than when no obstacle was present. The highest pressures and flame speeds occurred with mixtures of composition near the stoichiometric; this implied that the turbulent burning velocity was very much dependent on the concentration of the flammable gas. Figure 14 shows the maximum pressures plotted against the laminar burning velocity of the mixture[5] for duct b with and without the obstacle. The curves showed a very much steeper increase in maximum pressure with laminar burning velocity when an obstacle was present than when no obstacle was used.

The curves in Fig. 14 suggest that maximum explosion pressures in ducts containing obstacles are very much affected by the composition of the mixture and this in practice offers a certain margin of safety as explosible atmospheres will in practice tend to be near the limits. It is unknown whether similar increases in the maximum pressure would be obtained with a stoichiometric mixture of a different gas with a higher laminar burning velocity, and this may be worth further investigation.

Practical Implications

Obstacles similar to those tested in this work occur widely in duct systems. The above information indicates that the presence of these obstacles is a prime consideration in designing venting relief for these systems. The most effective way of providing explosion relief is for the combustion products of the explosion to be relieved before the flame reaches the obstacle. This method of relief reduces the velocity of the unburnt gases flowing through the obstacle, thus reducing the turbulence downstream of the obstacle, and the rise in pressure which follows when the flame reaches this turbulent pocket. Practical methods for providing this relief are discussed elsewhere[6].

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3. National Fire Protection Association. Code for Explosion Venting.

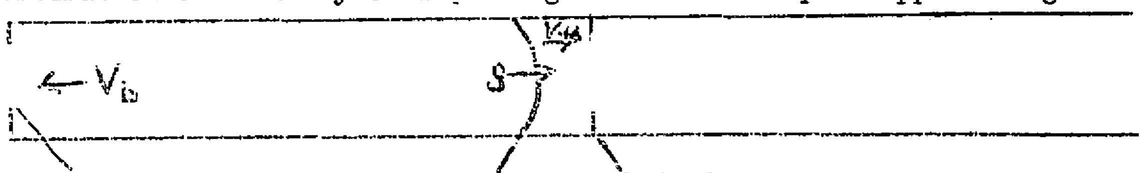
4. RASBASH, D. J. and ROGOWSKI, Z. W. Gaseous Explosions in Vented Ducts. Flame and Combustion. September, 1960.

5. BOTHA, J. P. and SPALDING, P. B. The Laminar Flame Speed of Propane-Air Mixtures with Heat Extraction from the Flame. Proc. Royal Soc.A. Vol. 225, 1954.

6. RASBASH, D. J. and ROGOWSKI, Z. W. F.R. Note No. 452.

APPENDIX

Estimation of velocity of unburnt gas from flame speed approaching the obstacle



Assume there is only one flame front approaching the obstacle.

Let S = flame speed approaching the obstacle

V_u = velocity of unburnt gas approaching the obstacle

V_b = velocity of burnt gas approaching the vent

T_u = absolute temperature of unburnt gas

T_b = absolute temperature of burnt gas

c_1 = discharge coefficient of burnt gas through vent

c_2 = discharge coefficient of unburnt gas through obstacle

A_1 = area of vent

A_2 = area of duct left unobstructed by obstacle

Assuming the pressure is uniform between the obstacle and the vent, i.e. the same pressure drives the unburnt gas through the obstacle as drives the burnt gas through the vent

$$\frac{V_b}{V_u} = \frac{c_1 A_1}{c_2 A_2}\sqrt{\frac{T_b}{T_u}} = a \qquad \ldots\ldots\ldots\ldots\ldots(1)$$

The flame speed relative to the unburnt gas is $(S-V_u)$. Therefore, assuming that the pressure rise is negligible compared with atmospheric pressure, the rate at which the gas expands is given by $(\alpha-1)(S-V_u)$ where α is the ratio of the volume of burnt gas to unburnt gas at atmospheric pressure. This expansion may be equated to the sum of $V_u + V_b$ thus

$$(\alpha-1)(S-V_u) = V_u + V_b \qquad \ldots\ldots\ldots\ldots\ldots(2)$$

Substituting for V_b from equation 1 gives

$$(\alpha-1)S = \alpha V_u + a V_u$$

$$\frac{(\alpha-1)S}{(\alpha+a)} = V_u \qquad \ldots\ldots\ldots\ldots\ldots(3)$$

In the calculations S was taken as the mean flame speed between points 6 in upstream and 6 in downstream of the obstacle. This flame speed differed somewhat from the flame speed approaching the obstacle but was the nearest approach to the true value of S for which data was available. c_1 was assumed to be equal to c_2 and a value of 7.0 was used for α.

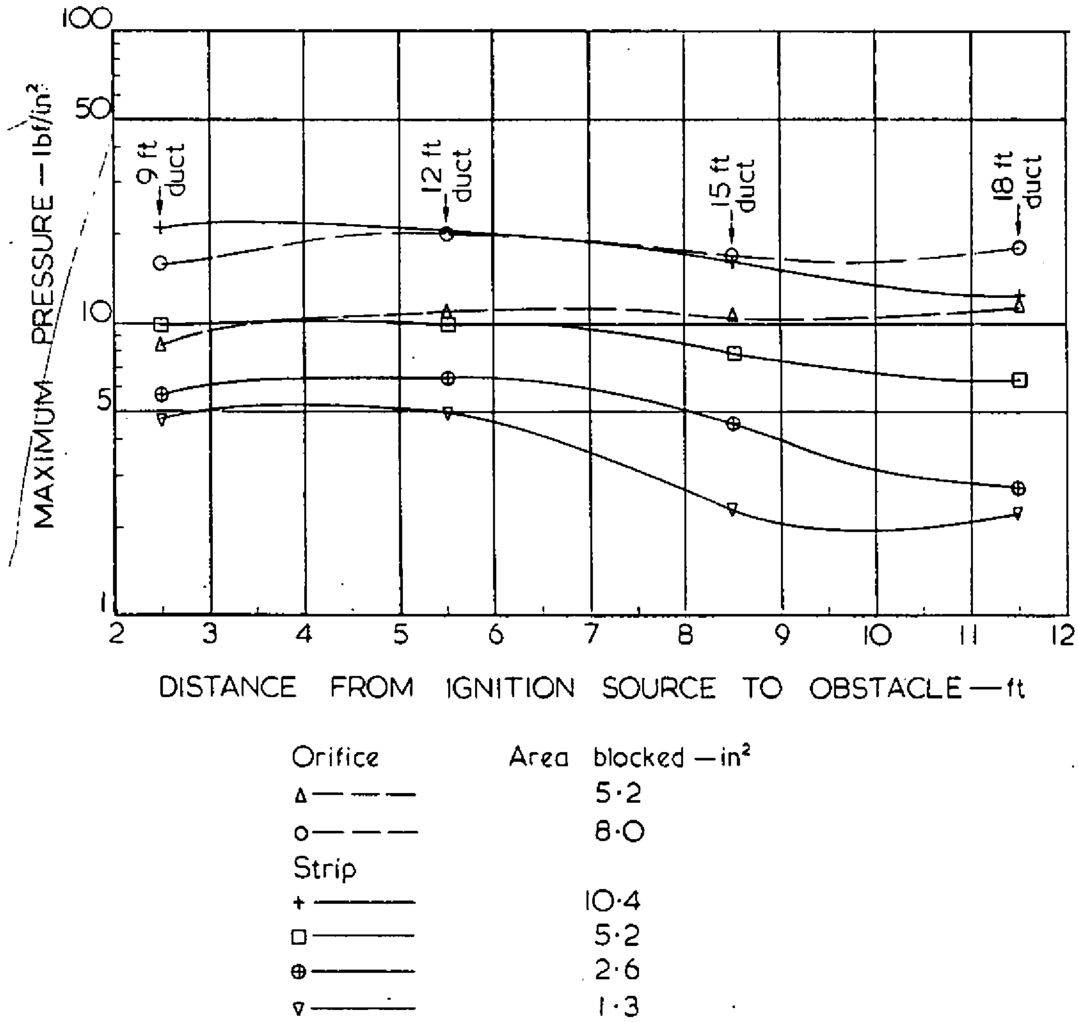


FIG. 1. RELATION BETWEEN DISTANCE BETWEEN IGNITION AND OBSTACLE AND MAXIMUM PRESSURE
(Pressure gauges near ignition source)

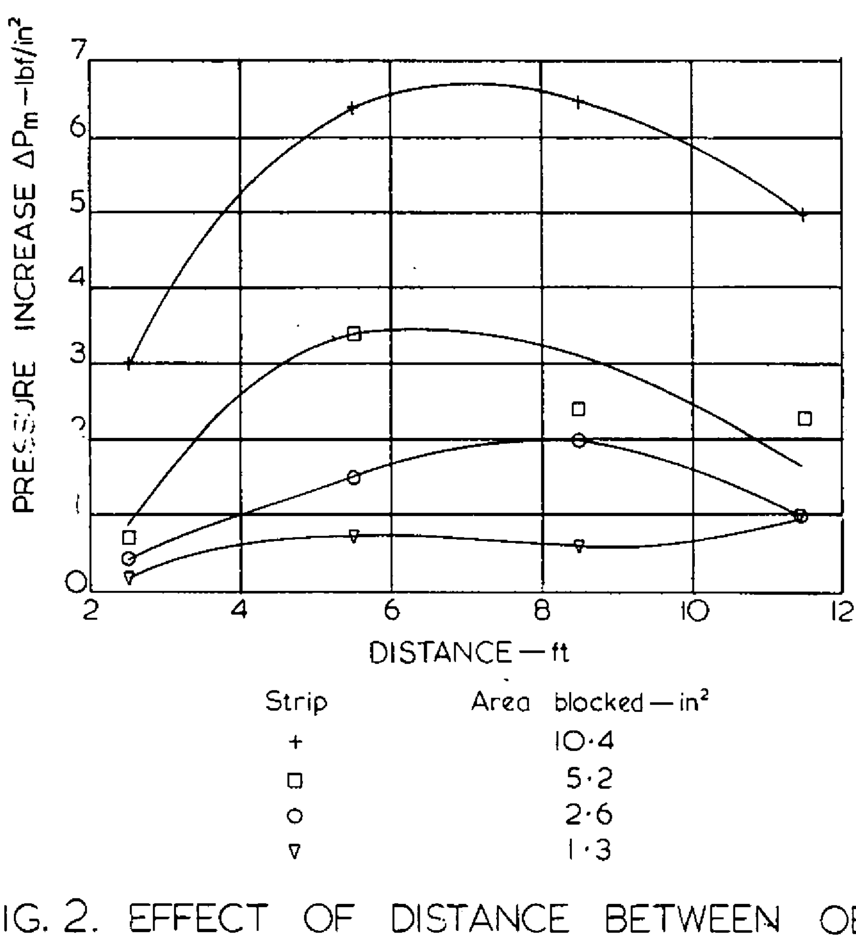


FIG. 2. EFFECT OF DISTANCE BETWEEN OBSTACLE AND IGNITION SOURCE ON ΔP_m

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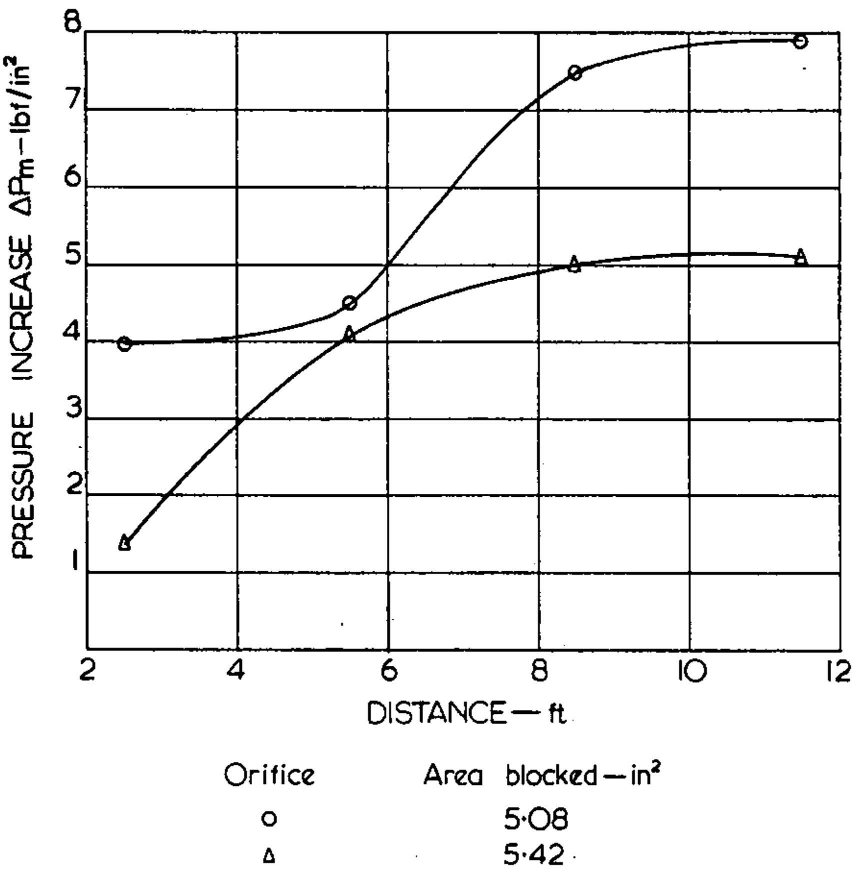


FIG. 3. EFFECT OF DISTANCE BETWEEN OBSTACLE AND IGNITION SOURCE ON ΔP_m

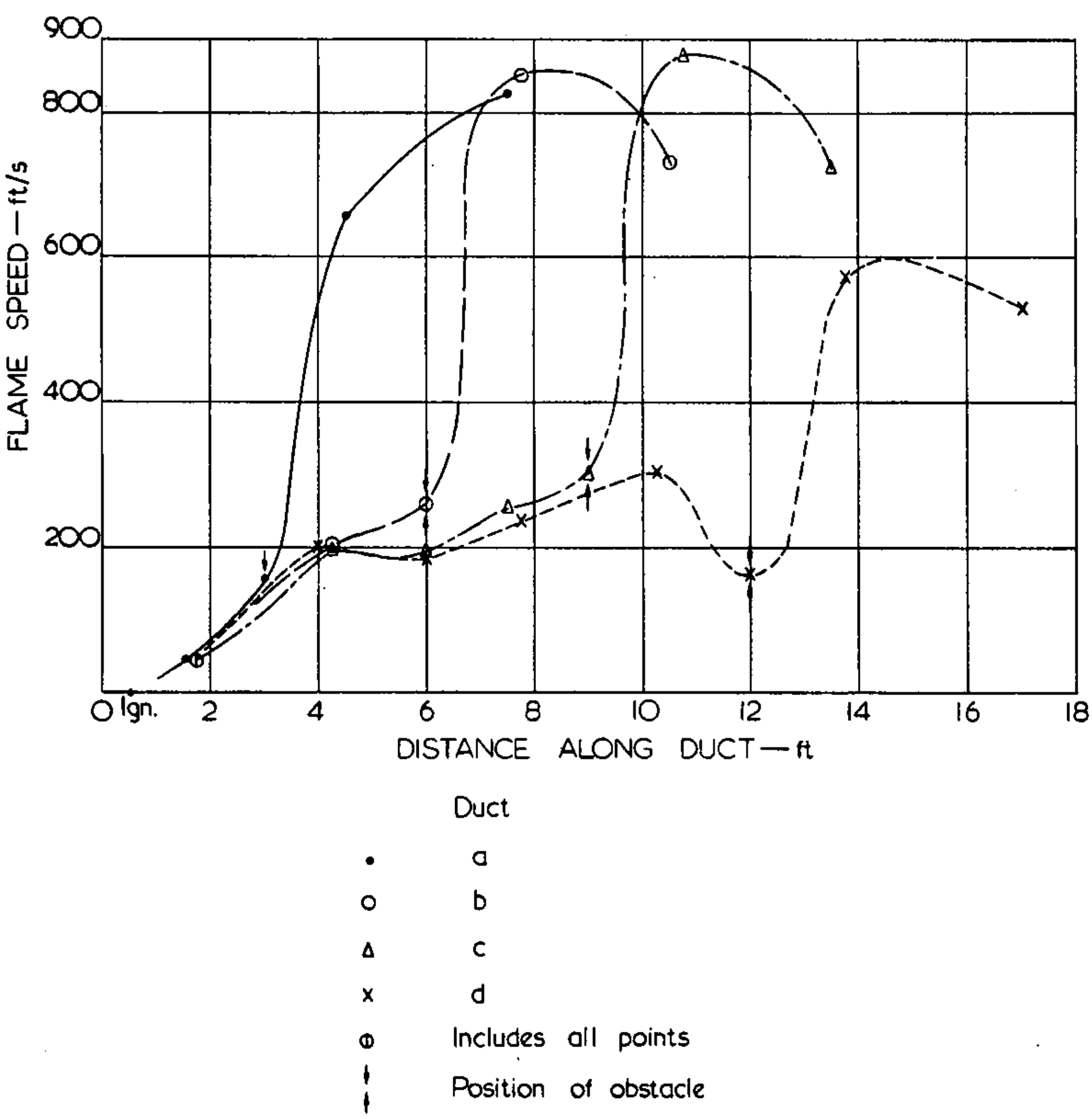
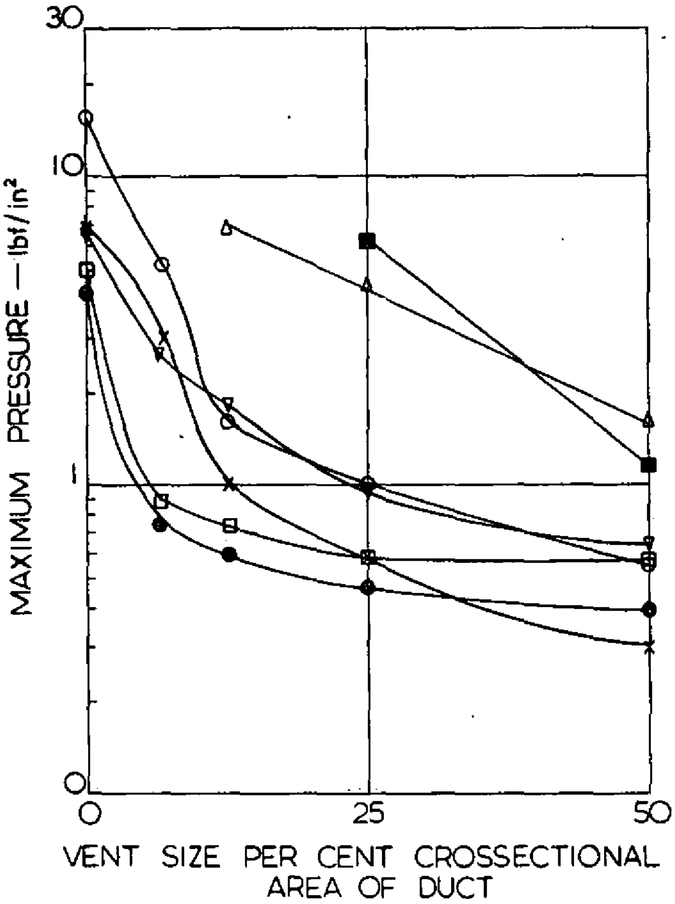
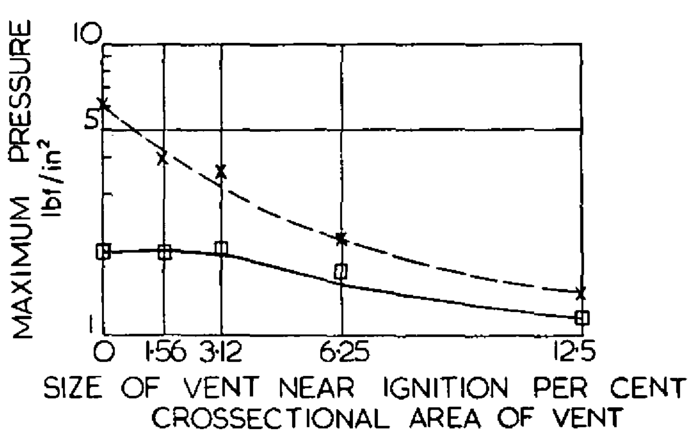


FIG. 4. FLAME SPEED ALONG DUCTS CONTAINING STRIP OF AREA 10·4 in²



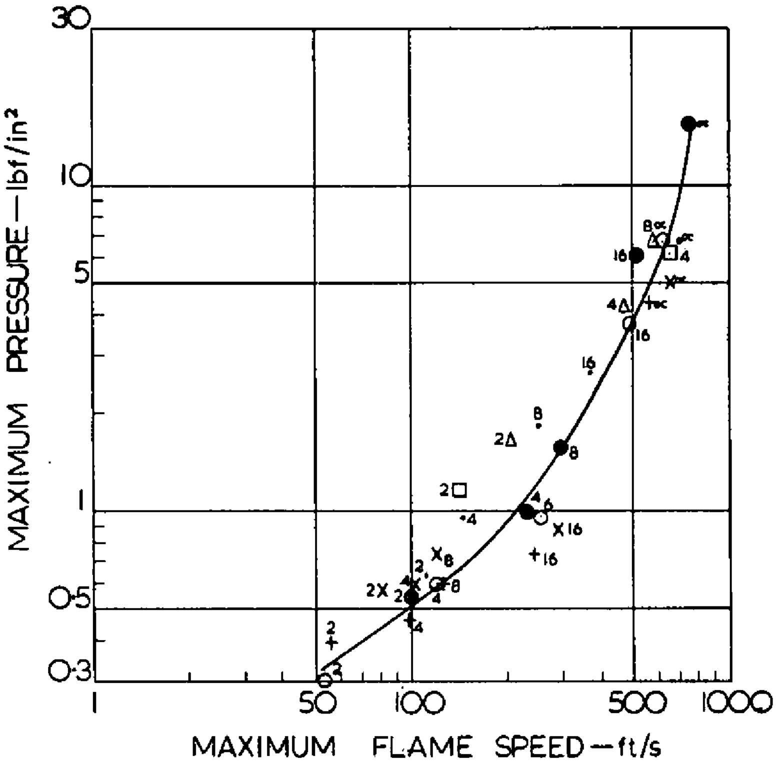
Obstacles	Area blocked in²
Orifice plate	
x	5·2
o	8·0
Δ	14·3
■	21·2
Strips	
●	1·3
□	2·6
▽	5·2

FIG. 5. EFFECT OF SIZE OF VENT NEAR IGNITION SOURCE ON MAXIMUM PRESSURE – DUCT e – 12 FT LONG (Pressure gauge near obstacle)



Obstacles	Area blocked in²
Orifice plate	
– – – x	5·2
Strips	
——— □	2·6

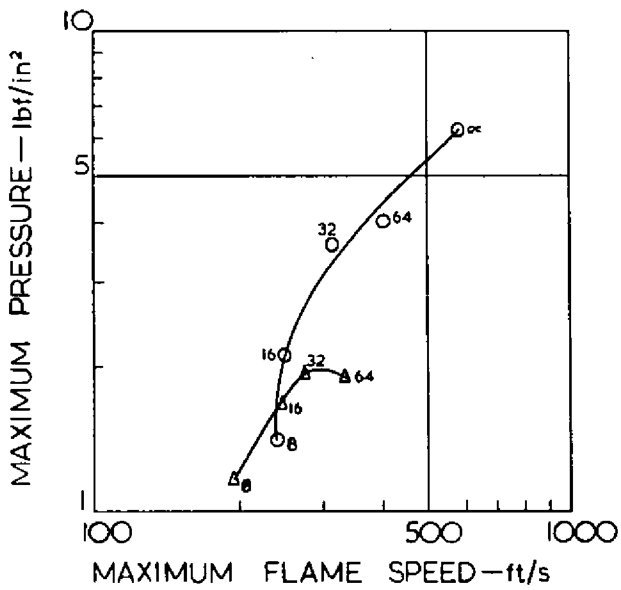
FIG. 6. EFFECT OF SIZE OF VENT NEAR IGNITION SOURCE ON MAXIMUM PRESSURE – DUCT f – 18 FT LONG (Pressure gauge near obstacle)



Obstacles	Area blocked in²
Orifice plates	
o	5·2
●	8·0
Δ	14·3
□	21·2
Strips	
+	1·3
x	2·6
•	5·2

Figure at each point indicates K factor of the vent near ignition source

FIG. 7. RELATION BETWEEN MAXIMUM PRESSURE AND MAXIMUM FLAME SPEED—DUCT e—12 FT LONG WITH VENT NEAR IGNITION SOURCE



Obstacles	Area blocked in²
Orifice—o	5·2
Strips —Δ	2·6

Figure at each point indicates the K value of the vent

FIG. 8. RELATION BETWEEN MAXIMUM PRESSURE AND MAXIMUM FLAME SPEED—DUCT f—18 FT LONG WITH VENT NEAR IGNITION SOURCE

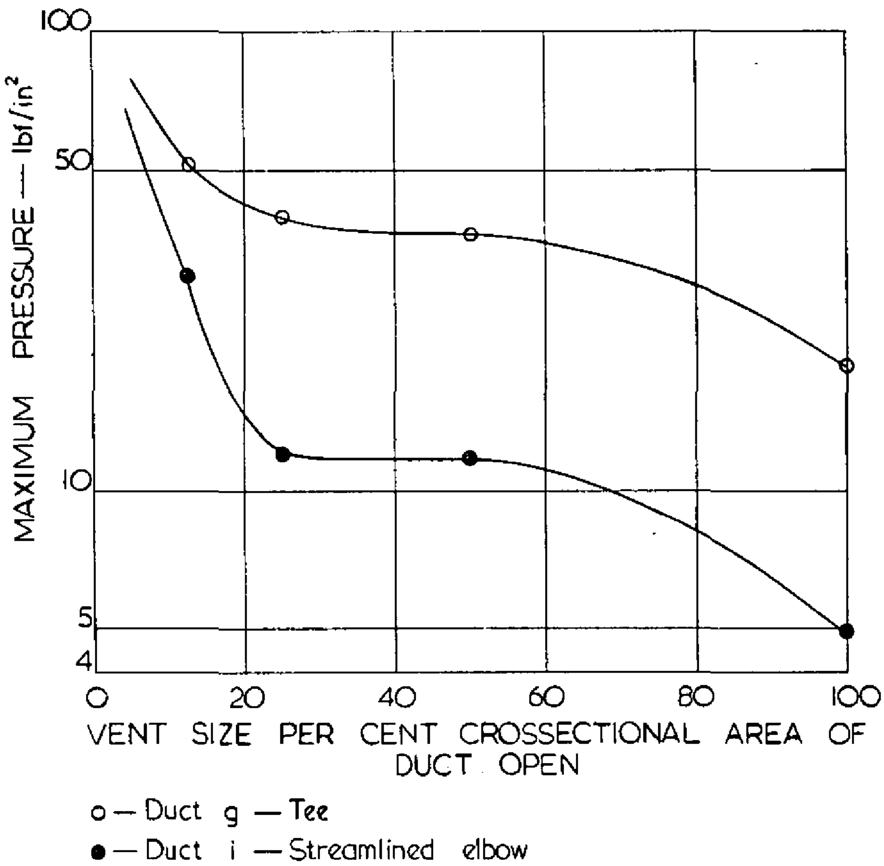
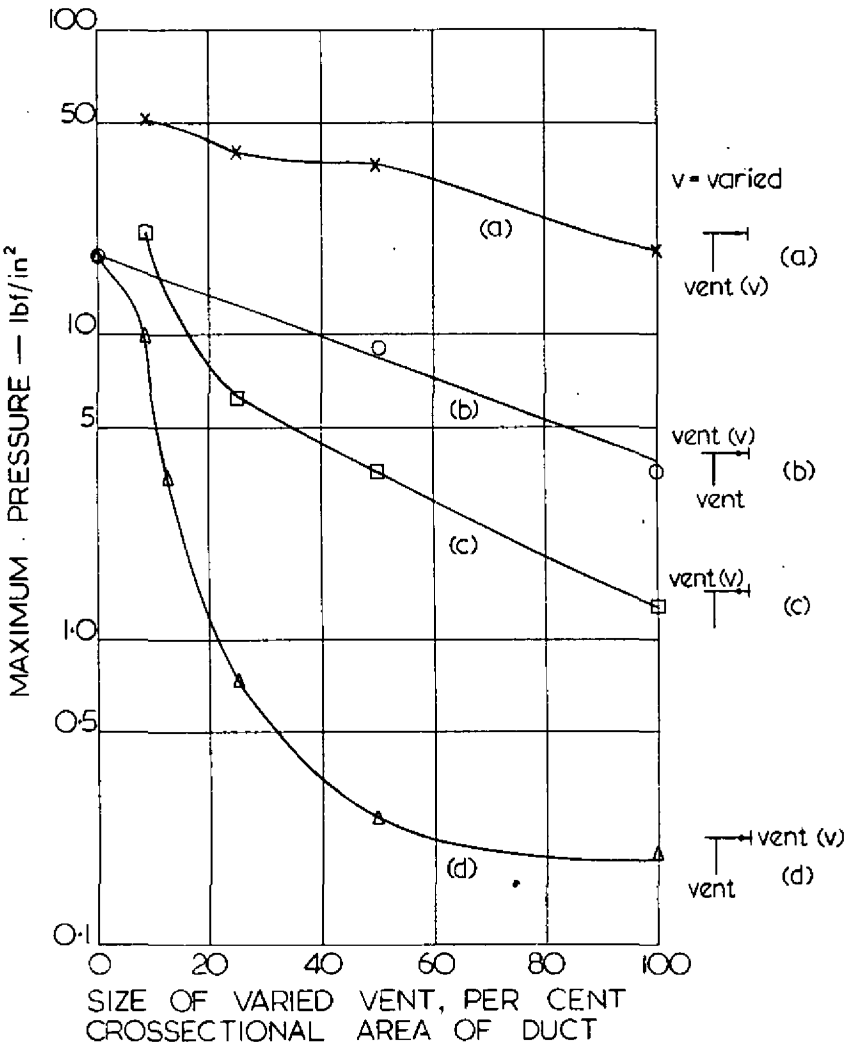


FIG. 9. EFFECT OF VENT SIZE ON MAXIMUM PRESSURE IN DUCT WITH FITTINGS



Vent System	Vents F	Vents G	Vents E
a X	Closed	Closed	Varied
b O	Closed	Varied	Open
c □	Closed	Varied	Closed
d Δ	Varied	Closed	Open

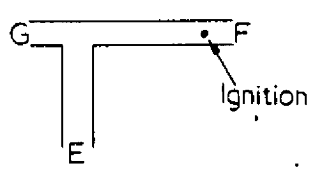
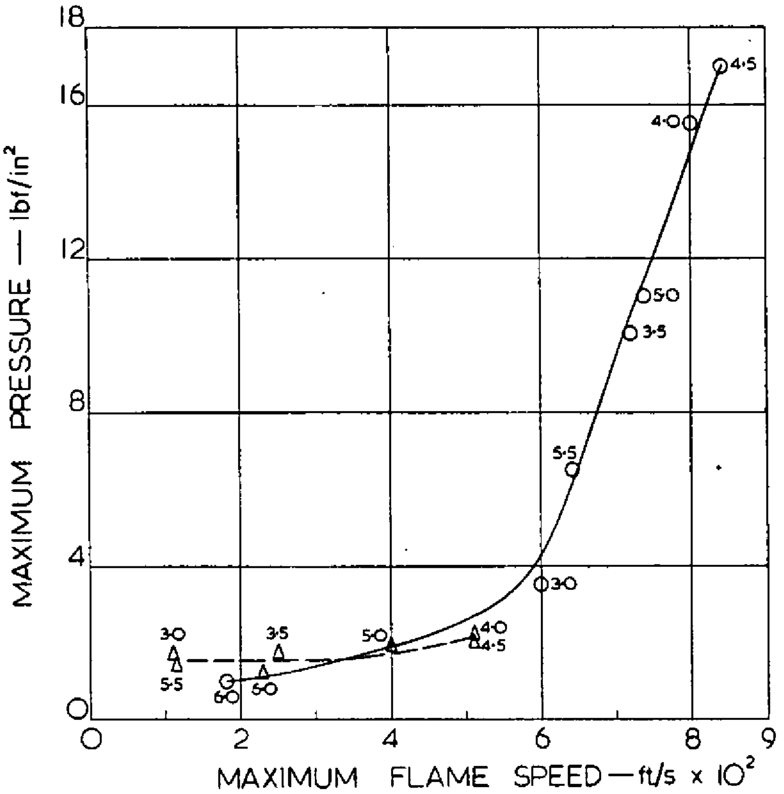


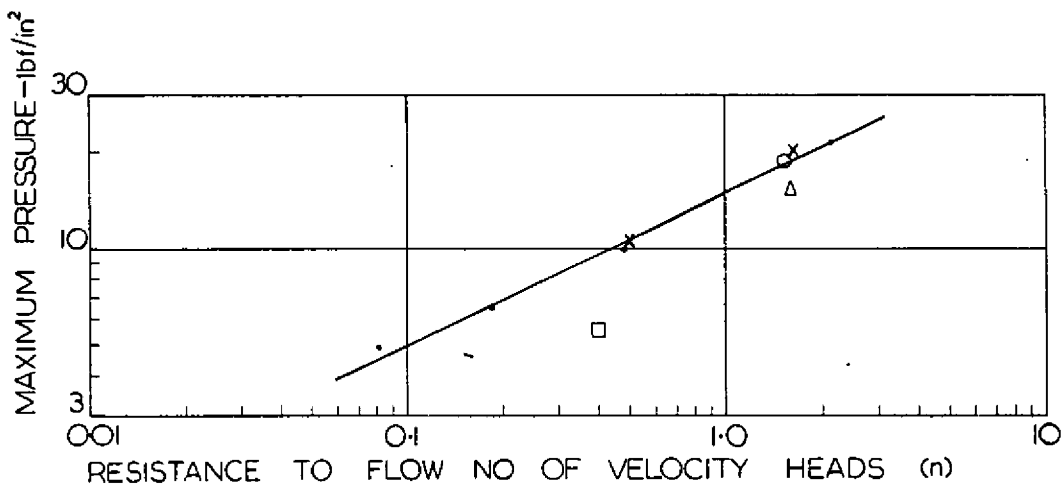
FIG. 10. EFFECT OF VENT SIZE AND VENT POSITION ON MAXIMUM PRESSURE IN DUCT WITH TEE



—o— Pipe with obstacle Area blocked 5·2 in²
---Δ--- Unobstructed pipe

Figure at each point indicates per cent propane in the flammable mixture

FIG. 11. RELATION BETWEEN MAXIMUM PRESSURE AND MAXIMUM FLAME SPEED FOR VARIOUS CONCENTRATION OF FLAMMABLE DUCT b — 12 FT LONG — PROPANE AIR MIXTURE



- • Strips
- x Orifices
- o Tee
- Δ Square elbow
- □ Streamlined elbow

Duct 12 ft long x 6 in diameter
Obstacle in centre
Pressure measured near ignition source

FIG. 12. RELATION BETWEEN MAXIMUM PRESSURE AND THE RESISTANCE TO FLOW CAUSED BY THE OBSTACLE

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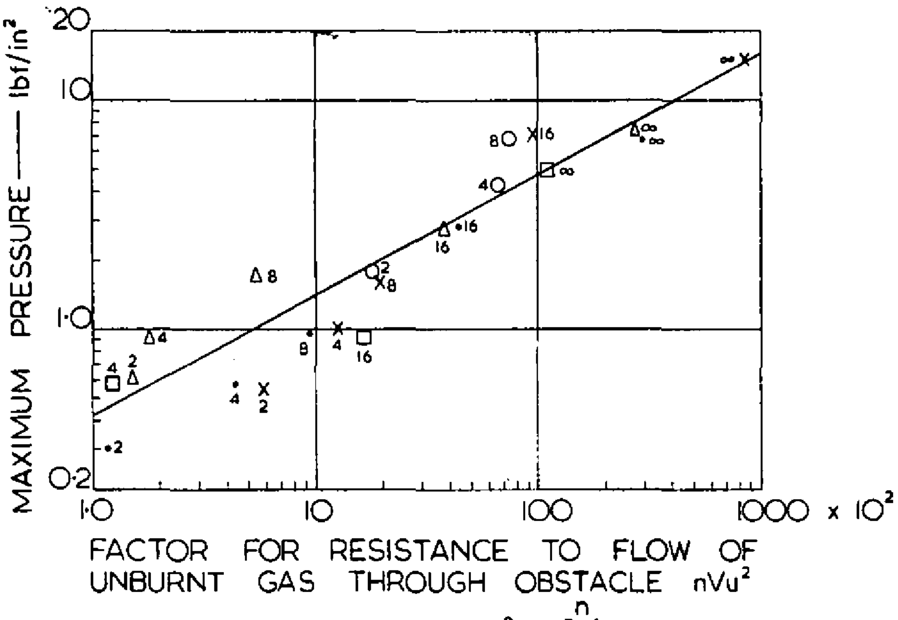
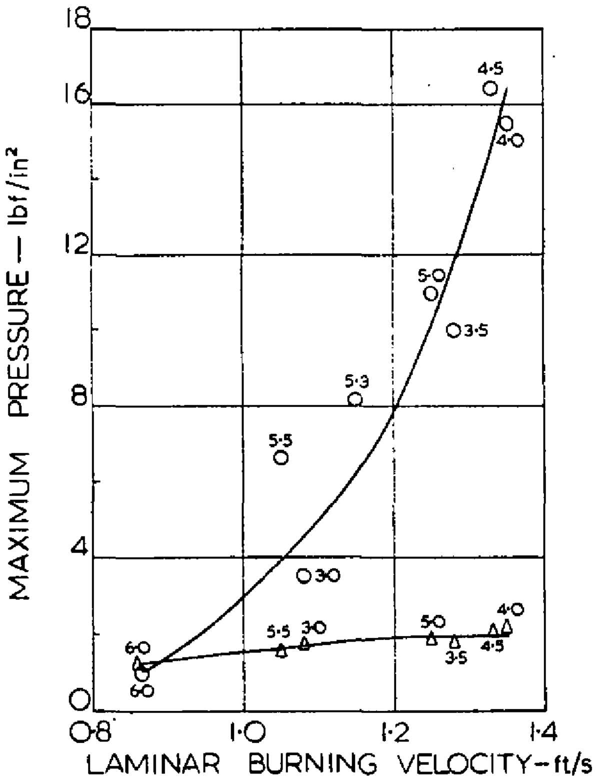


			n
o	Orifice obstructing	14·0 in²	8·6
x	Orifice obstructing	8·2 in²	1·65
•	Orifice obstructing	5·2 in²	0·51
Δ	Strip obstructing	5·2 in²	0·48
□	Strip obstructing	2·6 in²	0·19

Duct 12 ft long x 6 in diameter. Obstacles (strips or orifices) in centre
Vent near ignition (K factors shown). Pressure measured near obstacle

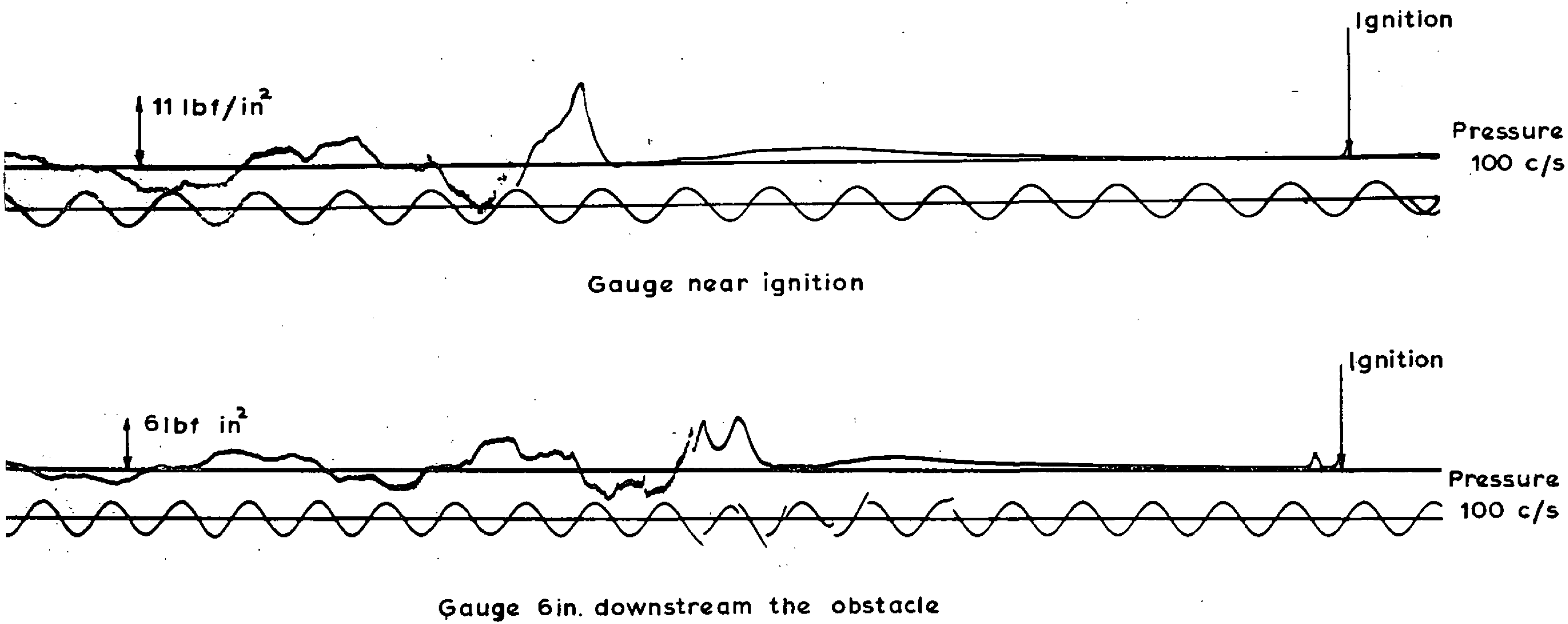
FIG. 13. RELATION BETWEEN MAXIMUM PRESSURE AND RESISTANCE TO FLOW CAUSED BY OBSTACLE



—o— Pipe with obstacle Area blocked 5·2 in
—Δ— Unobstructed pipe

Figure at each point indicates per cent propane in the flammable mixture

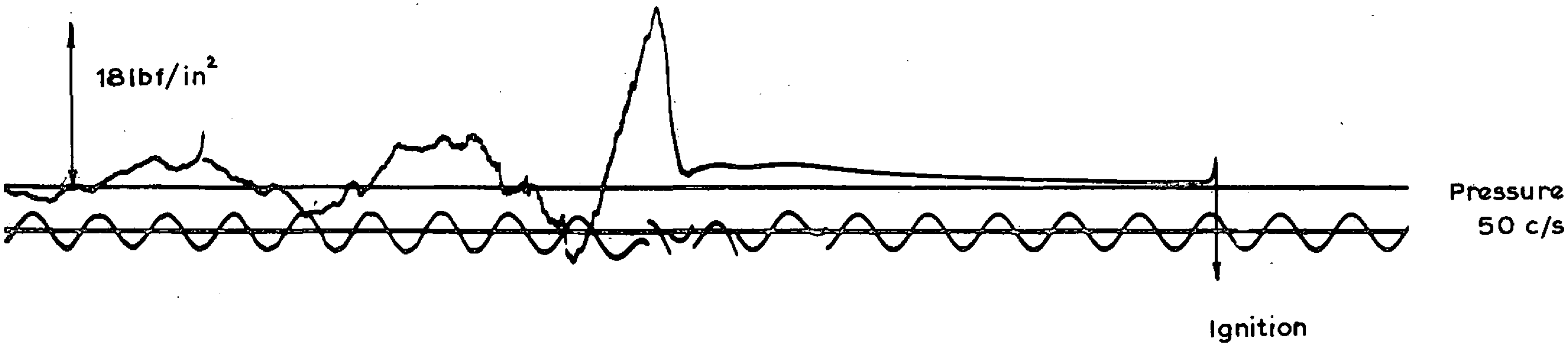
FIG. 14. RELATION BETWEEN LAMINAR BURNING VELOCITY AND MAXIMUM PRESSURE — DUCT b — 12 FT LONG PROPANE—AIR MIXTURE



Blips on the timing wave indicate the position of flame along the duct

PLATE. I.

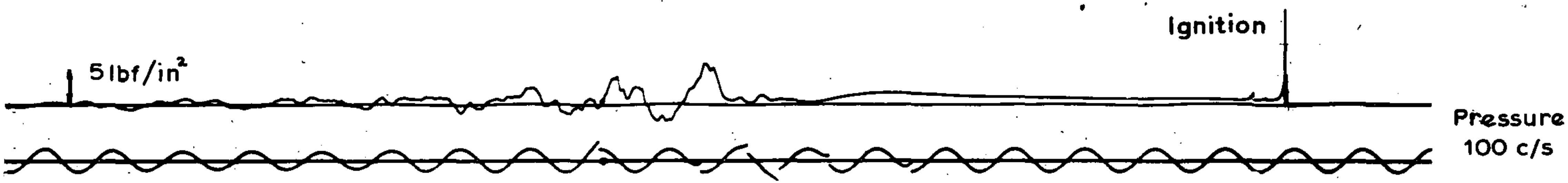
DUCT c OBSTACLE ORIFICE PLATE. CROSSECTIONAL AREA OF DUCT BLOCKED 5·2 in^2



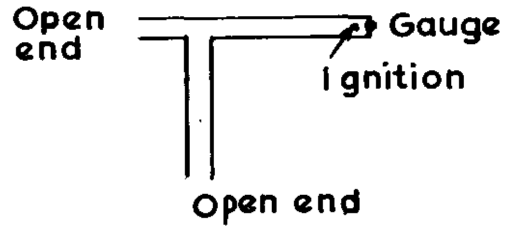
Blips on the timing wave indicate the position of flame along the duct

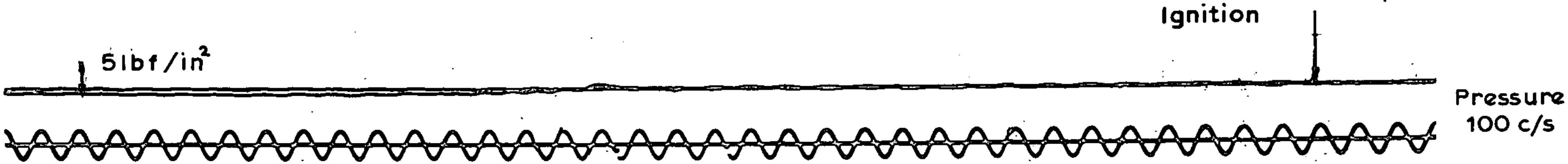
PLATE. II.

DUCT h WITH SQUARE ELBOW. GAUGE NEAR IGNITION

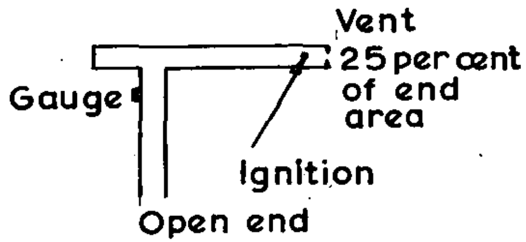


Vent arrangement b as shown below





Vent arrangement d as shown below



Blips on the timing wave indicate the position of flame along the duct

PLATE III

DUCT g WITH TEE