F.R. Note No. 298/1957
Research Programme
Objective

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



# THE VENTING OF EXPLOSIONS IN DUCT SYSTEMS

## PART II

## THE VENTING OF EXPLOSIONS IN A PENTANE-AIR MIXTURE IN A DUCT 6 FT. LONG x 6 IN. DIAMETER

by

D. J. Rasbash and Z. W. Rogowski

Summary

The effect has been studied of relief vents on the maximum pressure reached in explosions in a mixture containing 3.37% pentane in air in a steel tube 6 ft. long x 6 in. diameter. Ignition was near one end of the tube and the vents could be placed at either end of the tube. The maximum pressure reached when open vents were used decreased inversely as the 0.75 to 1.5 power of the vent area. This pressure was 3 - 5 times greater when the vent was remote from the ignition source than when it was near this source. However with large open vents near the ignition source, vibrations with a large amplitude became established; the maximum pressure in these vibrations increased as the vent area increased. Calculations have been made of the venting requirements of the explosions on the assumption that the rate of combustion when a vent is present in the tube is the same as when no vent is present. When the vent was covered by a disc of thin material the maximum pressure reached depended on the static bursting pressure of the disc if this pressure was larger than the pressure reached with the open vent. Cross shaped cutters gave a large reduction of the maximum pressure reached with brown paper and aluminium discs but a negligible reduction with polythene discs.

File No.
February, 1957.

Fire Research Station,
Boreham Wood,
Herts.

# THE VENTING OF EXPLOSIONS IN DUCT SYSTEMS

## PART II

## THE VENTING OF EXPLOSIONS IN A PENTANE-AIR MIXTURE, IN A DUCT 6 FT. LONG x 6 IN. DIAMETER

by

D. J. Rasbash and Z. W. Rogowski

## INTRODUCTION

The need often arises in industry to lessen the damage caused by gas and vapour explosions which might take place in duct systems by providing relief vents in these systems. However there is little information available which allows the venting requirements to be reliably estimated. In this report results are presented of the effect of relief vents on explosions in a short straight length of tube. This investigation was a necessary first step before explosions in more complicated duct systems could be examined.

## EXPERIMENTAL

### Apparatus

The explosion tube was a steel tube 6 ft. long and 6 in. diameter and flanged at both ends. The vents which were used were essentially, square edged, circular holes in the centre of flanges which could be bolted at either end of the tube, either directly or as part of a bursting disc assembly. The diameter of the holes used as vents, their area and their area per unit volume of the tube, are given in table I. Each of the largest four vents was part of a bursting disc assembly which allowed the vent to be closed by discs of various thin materials pressed tightly against the flange. The assembly for one of the vents is shown in figure 1.

Three sheet materials were used as bursting discs - aluminium, polythene and brown paper. The thickness and weight of these materials are listed in table II. Typing paper was used to cover the vent during preparation for most of the tests with open vents, in these tests the typing paper was slit immediately prior to explosion. Figure 2 shows the static bursting strength of the aluminium and polythene discs plotted against the area of the disc. These bursting strengths were obtained by clamping the disc, in its appropriate assembly, onto the explosion tube and increasing the pressure in the tube with air in a standard manner recommended by Philip[1], until the disc burst. The pressure was measured on a Bourdon gauge. The brown paper did not give reproducible results by this method since it was slightly porous.

In some of the tests cutters were placed immediately outside the bursting disc to expedite the bursting. Sketches of the five cutters used are shown in figure 3, A was a cylindrical brass rod sharpened at the end, B and C were brass rods 7/16 in. diameter on which were soldered two and three sharp blades respectively in the manner shown, D and E were similar to B and C but had larger blades. Plate 2 shows photographs of the five cutters.

### Test procedure

A standard method was used in the tests, of introducing a uniform mixture, containing 3.37% pentane in air into the explosion tube and of igniting this mixture by means of an induction spark at a point on the axis of the tube 6 in. from one end. The pressures in the explosions were recorded by means of a piezo-electric gauge. In a majority of tests the emergence of flame at the vent was also recorded by means of a lead

sulphide photo-conductive cell which had a response time of 75 micro seconds. In a few tests the flame emerging from the vent was also recorded directly by a drum camera.

Figure 4 shows the relative positions of relief vent, pressure gauge and ignition source with which the tests were carried out. In all tests the ignition source was 6 in. from the end of the tube. At least two tests with each vent diameter using each of the three materials and also open vents were carried out with the arrangement shown in figure 4A; in this arrangement the vent was in the flange remote from the ignition source and the pressure gauge was near the vent. With the exception of tests using bursting discs of brown paper, all the tests were also repeated with the arrangement shown in figure 4B; here the vent was in the flange near the ignition source and the position of the pressure gauge unchanged. A few tests were carried out with the arrangement shown in figure 4C; this was identical to the arrangement in figure 4A, with the exception that the pressure gauge was placed in the flange near the ignition source and was therefore remote from the vent.

The tests with the cutters were carried out with the arrangement shown in figure 4A using aluminium and brown paper in the 6 in. and 3 in. vents and polythene in the 6 in. vent. Tests were also carried out using two sheets of the aluminium and brown paper with this arrangement.

## RESULTS

### Aural and Visual Phenomena

The flame which appeared at the vents and the sound made by the explosion varied considerably. When the vent was 5 ft. 6 in. from the ignition source the flame appeared as a flash of short duration over a length of 3 ft. A drum camera record of a flame emerging from a vent in this position is shown in Plate 3. The sound in these tests was sharp and its loudness increased as the maximum pressure reached in the explosion increased. However, when the vent was 6 in. from the ignition source, a flame often persisted at the vent. These tests were accompanied by a muffled note of increasing pitch. A few tests were carried out in which a polythene vent was used 5 ft. 6 in. from the ignition source, and an open vent 6 in. from the ignition source. This test showed that a flame travelled along the tube at the same time as a flame persisted at the open vent.

It was noted that after explosions with the aluminium and brown paper bursting discs, nearly all the disc material was removed from the vent; in general the material was torn by the explosion into small pieces. The polythene discs however, remained in position in the vent. The passage of the explosion gases took place through a slit-shaped rupture which was formed in the disc.

### Explosion pressure records

Bursting discs. In tests with bursting discs the pressure records followed the normal course of an explosion in a closed tube until rupture of the disc took place. This rupture was identified by the first break on the pressure record dissimilar to discontinuities occurring in explosions with a closed tube.

The course of the pressure record after the rupture of the disc varied considerably as the size, the position and the material of the disc varied. Broadly speaking, seven different patterns of behaviour could be distinguished.

For completeness, details of all these patterns are given below; reference to some of them will be made in the later discussion.

(a) The pressure dropped rapidly to atmospheric pressure accompanied by vibrations of small amplitude.

(b) The pressure dropped almost immediately to atmospheric and was followed by vibrations at atmospheric pressure.

(c) There was a rapid drop in pressure accompanied by sharply peaked vibrations in which the peaks did not reach a value equal to the pressure at burst.

(d) As in (c) but with at least one peak of a vibration giving a pressure higher than the pressure at burst.

(e) Several vibrations occurred with a mean pressure either somewhat less or equal to the pressure at burst before the pressure dropped to atmospheric.

(f) A decrease of pressure was followed by an increase of pressure before the pressure dropped.

(g) The pressure continued to rise and reached a peak before dropping to atmospheric.

Examples of patterns a, c and e are shown in Plate 4 and of patterns b, f and g in Plate 5.

In table 3 the characteristics of the pressure records in the various tests with bursting materials have been classified according to the above scheme.

Open events. The pressure records of tests with open vents could be classified into five main forms (A to E) when the vents were 5 ft. 6 in. from the ignition source and three further forms (F, G, H) when the vent was 6 in. from the ignition source. Again for completeness the main features of these forms have been summarised below.

(A) The pressure rose to a peak, vibrations of small amplitude or no vibrations appeared at the commencement of the pressure rise to disappear within 0.1 second after pressure within the tube had returned to atmospheric.

(B) The pressure rose to a peak at which pressure vibrations developed which disappeared when atmospheric pressure was regained.

(C) There was a rapid rise in pressure followed by a slow rise in which vibrations were established. The amplitude of the vibrations increased and at the same time the pressure rose sharply to a peak. The pressure dropped to atmospheric and the vibrations stopped.

(D) The pressure developed as with (C) but with vibrations of smaller amplitude and there was no sharp peak.

(E) The pressure rose gradually to a flat maximum with the accompaniment of small amplitude vibrations which disappeared within 0.1 seconds after the pressure returned at atmospheric.

(F) The pressure rose slowly to a flat maximum. After the maximum pressure was reached vibrations were established which continued with an increase in frequency for more than 0.8 seconds.

(G) The pressure rose to a peak, dropped to rise again to a value less than the first maximum. The rise and fall in pressure was repeated 2 or 3 times.

(H) There was no definite peak or maximum on the pressure record. Vibration developed shortly after ignition and continued for about 0.8 seconds. The amplitude and the frequency of the vibrations varied.

Examples of patterns A, B, C are shown in Plate 6 and D, F, G, H in Plate 7. Table IV shows the various tests carried out with open vents classified according to the above scheme. The record used to illustrate patterns C and D both appertained to tests in which a 1.06 in. vent was used 5 ft. 6 in. from the ignition source, but there was a difference in that in the test in which record C was obtained there was no slit typing paper covering the vent whereas there was this covering with record D. The records indicate that when the slit typing paper was used the vibrations were of smaller amplitude. There is also little doubt that the vibrations which occurred in the tests having the patterns F and H were due to the vibration of the gas column within the tube. Thus in most of these tests the frequency increased from 50 to 100 as the combustion proceeded. Assuming that the 6 ft. pipe may be considered to constitute 1/4 of the wavelength of the vibrations it may be estimated that the frequency should increase from 45 to 110 as the combustion proceeded and the temperature of the gases increased. A microphone recording of the sound of the explosion also gave the same frequency sound waves. Finally when tests which gave these records were repeated with a polythene disc covering the end of the pipe remote from the open vent and the ignition source, the pressure record obtained showed that the vibrations were almost completely damped.

Relation between the Bursting Pressure, the Maximum Pressure reached and the Vent Area

Figures 5A and 5B show respectively the pressure at burst and the maximum pressure obtained in those tests in which bursting discs were used plotted against the vent area. The maximum pressure recorded was the highest pressure shown in the record; and in a number of cases this occurred at the top of a vibration. In all cases, the points fell about straight lines of a slope of about -0.5 which indicated that the pressure was inversely proportional to the square root of the area of the vent or inversely proportional to the vent diameter. The results for polythene however are very scattered. Figures 5A and 5B also show the static bursting strength for the aluminium and polythene bursting discs. It will be noted that the maximum pressure and the bursting pressure in the explosions using aluminium discs were only slightly higher than the static bursting pressure of the disc, but for polythene, there was a large difference. There was no difference in the pressures developed when the bursting disc and the pressure gauge were placed in the different arrangements shown in figure 4 and no distinction between the tests on this basis has been made in figure 5.

Figure 6 shows the maximum pressure developed in the explosions using open vents, also plotted against the vent area. The curve for explosions in which the vent area was near the source of ignition is in two parts. Up to a vent area of 7 in.$^2$ the maximum pressure was recorded during a steady increase in pressure soon after ignition (pressure record pattern G); under these conditions the maximum pressure diminished as the vent area increased and was 1/3 to 1/5 of that which occurred when the vent was remote from the ignition source. When the vent area was greater than 7 in.$^2$ the maximum pressure was at a peak of an accoustic vibration about atmospheric pressure which occurred late in the explosion (pressure record pattern H). This maximum pressure increased with the vent size and with the largest vent used it was very much higher than the pressure which developed when the vent was remote from the ignition source. The smallest vents when remote from the ignition source, gave slightly higher pressures when completely unrestricted than when they were covered with a slit typing paper. Finally figure 6 does not show any difference in the maximum pressure reached between arrangements A and C.

In figure 7 the mean lines representing maximum pressure using the open vents, the bursting pressure with bursting discs and the maximum pressure with bursting discs have been assembled. Figure 7 shows that the pressures obtained with the bursting discs were generally much higher than those obtained with open vents. The reason for this is that the pressure was controlled very largely by the bursting pressure of the discs which was in most cases much higher than the maximum pressure obtained with open vents. This was not so with the smaller polythene vents; with these vents the pressure continued to rise after the burst to a value slightly higher than those obtained with open vents of the same size.

The Effect of Cutting and Puncturing Tools

The maximum and bursting pressures which occurred when a cutting or puncturing tool was mounted outside the bursting disc, are given in table 5. This table shows

(1) The cutting tools reduced the bursting pressure to $\frac{1}{4}$ to $\frac{1}{2}$ of the value required when no tools were used when aluminium and brown paper vents were used; with polythene, there was no difference. The corresponding reduction in the maximum pressure was to about $\frac{1}{3}$ to $\frac{1}{2}$ of the original maximum pressure.

(2) There was little difference between the various cutting tools, although perhaps tool ~~No~~ D4 with the 1 in. cutting blades gave the greatest reduction in the maximum pressure.

(3) There was a smaller reduction in bursting pressure when the puncturing tool was used.

(4) Under given conditions, the maximum pressure reached when two sheets of material were used to form the ~~max~~ disc was approximately twice as great as that reached when one sheet of material was used.

Flame movement

Most of the records in Plates 4, 5, 6 and 7 also show traces which represent the appearance of flame and hot gases at the vent. From these traces the time which elapsed between the bursting of the disc and the first appearance of the flame at the vent was determined. Figure 8 shows this time plotted against the pressure in the tube when the disc was 5 ft. 6 in. away from the ignition source and indicates a reduction in this time as the bursting pressure increased and as the vent size decreased. When the vent was 6 in. from the source, there was in almost every test an immediate appearance of flame when the disc burst.

DISCUSSION

Bursting Discs

The results show that the maximum pressure and the bursting pressure obtained in the tests when bursting discs were used were determined mainly by the static bursting strength of the disc. Thus all the experiments showed that for a given disc material, the maximum and bursting pressures were approximately proportional to the square root of the vent area, a relation which is similar to that correlating static bursting strength and the area. For polythene discs however, the absolute values of the bursting and the maximum pressures obtained in the explosions were more than twice as great as the static bursting pressure of the same disc, and the scatter of the results was large. The strength of the polythene depended very much on the direction in which force was applied. As a result the bursting of the disc was likely to be sensitive to the way the disc was clamped; the burst also resulted in the formation of slit shaped openings. This phenomenon can account for the scatter of the results and also the lack of effect which the puncturing and cutting tools had in reducing the maximum pressure when this material was used. By using thinner materials than those used in the tests, it is likely that the maximum pressure obtained would be reduced, at least under conditions in which the pressure was determined by the bursting strength of the materials used. The potential use of such materials in industry is limited since they would be too flimsy to withstand general mechanical damage. Another way of reducing the maximum pressure is by using cutters; the present tests show that with at least two materials (brown paper and aluminium) a substantial reduction in the maximum pressure may be achieved by using suitable cutters. With the smallest diameter vents with polythene, the flow of gases through the vents rather than the bursting strength of the material determined

the maximum pressure. However, the maximum pressure reached was not very much higher than the maximum reached with the open vents and this disparity can be readily accounted for by the fact that with the polythene the gases were forced through the slit produced by the burst rather than the full bore of the hole. These observations are somewhat dissimilar to those of Wilson [3] who carried out measurements on pentane-air explosions taking place in an approximately spherical chamber of 60 cu.ft. capacity. Wilson found that covering the vent with a light bursting disc under these conditions brought about a substantial increase in the maximum pressure reached by the explosion.

Open Vents

Comparison with previous work Figure 9 and 10 show the results of investigations by different authors of the maximum pressure obtained in vented gaseous explosions; for convenience the maximum pressures have been plotted against the ratio of the vent area to the volume of the vessel. Some of the experimental details of these investigations have been given in Table VI. All the results in figure 9 refer to vessels with elongated shapes in that the ratio of the maximum to minimum linear dimensions is greater than 2; in figure 10 this ratio is less than 2. Figure 9 which contains results of the present work, show the results to fall broadly about one curve, with the exception of those tests carried out in the present series with ignition near the vent. However too much emphasis should not be placed on this curve since the method of plotting does not take into account the different sizes of the vessels or the different gases used, and the number of investigations which are represented in figure 9 are so few that the agreement might be fortuitous. This comment is borne out by the information presented in figure 10 which summarises the results for explosions in volumes of comparatively regular shape. The results of the work of Cubbage and Simmonds [7] show that the size of the vessel and the composition of the gaseous mixture have a substantial effect on the maximum pressure. It is also interesting to note that Wilson's work suggests that with low vent area ratios much higher pressures are obtained with a spherical volume than with tubes.

The fact that much lower pressures obtained in the present series when the vents were close to the source of ignition is somewhat at variance with results obtained by Freestone et al [6] who found that the position of the ignition source made little difference to the maximum pressure. However, it agrees qualitatively with work carried out by Brown on the venting of dust explosions [8].

Calculation of the flow rate of gases through vents. It may be expected that the maximum pressure reached with the open vents would be a direct function of the rate of expansion of the gases in the pipe as a result of the combustion process, and that this rate may be equaled to the rate at which gases are ejected from the orifice under the particular conditions of the experiments.

The rate at which gas is ejected from an orifice placed centrally in a tube is given in standard books on aerodynamics. Thus for square edged orifices Perry [9] gives

$$\frac{dV}{dt} = C\,Y\,S_2 \sqrt{\frac{2g_c\,(P_1 - P_2)}{(1 - \beta^4)}} \qquad \text{.....(1)}$$

Where $\rho_1$, $P_1$, = density and absolute pressure of upstream gases.

$P_2$ = absolute pressure of downstream gas.

$\beta$ = ratio of orifice to pipe diameter.

$g_c$ = gravitational constant.

$C$ = coefficient of discharge

$Y$ = $1 - \left(\frac{P_1 - P_2}{P_1\,\gamma}\right)(0.41 + 0.35\,\beta^4)$

$\gamma$ = specific heat ratio for the gas.

Equation 1 applies only up to a certain critical pressures beyond which the gas is ejected through the orifice at sonic velocity and the flow rate is independent of the downstream pressure.

For rounded orifices Perry gives the critical pressure ratio $\frac{P_2}{P_1}$ for air as 0.53 and the flow rate as through the orifices at lower values of this ratio as

$$W = 0.533 \frac{C_v S_2 P_1}{\sqrt{T_1}} \text{ lb. mass/sec.} \qquad \ldots\ldots\ldots\ldots(2)$$

Where $T_1$ = upstream temperature

$C_v$ = velocity coefficient

However Schiller [10] states that this relationship does not hold for square edged orifices for which the flow rate continues to increase beyond the critical ratio. In the present work most of the pressures obtained with open vents were below 15 lb/in$^2$ (gauge) which is the limiting pressure for rounded orifices; a few higher pressures were obtained up to 35 lb/in$^2$ for the smallest vents. For simplicity and in view of Schiller's findings for square edged orifices only equation 1 has been used in calculating the flow rates through the orifices.

Equation 1 shows that the volume flow rate of gas through a vent at a given pressure will depend on the density and therefore the temperature of the gas. Broadly speaking, the gases expelled through the vents in the present experiments were either unburned gas at approximately atmospheric temperature, apart from a small temperature rise due to the adiabatic compression when the vent was remote from the ignition source, or burned gas at a very much higher temperature when the vent was near the ignition source. As a first approximation the temperature of the burned gas may be estimated on the basis of the maximum pressure reached in the tube to be 2090° K (Appendix II). For practical purposes of the calculation the gas ejected through the vents in all cases may be considered to be air.

Figures 12 and 13 show curves (a) which give, as a function of the pressure, the flow rates of unburned and burned gases respectively through vents of the diameter used in the present tests. The curves were calculated from equation 3 using a discharge coefficient of 0.61 for the unburned gas and 0.84 for the burned gas [3].

Calculation of maximum pressure reached with open vents

When the pressure in a vented vessel reaches the maximum pressure, for a very brief interval of time the combustion may be considered as taking place at constant pressure. Under these conditions it may be shown that if the perfect gas law is obeyed the rate of increase in volume of the gas is given by equation (1) (See Appendix I)

$$\left(\frac{dV}{dt}\right)_P = \frac{R}{P}\left\{\frac{dN_u}{dt}(T_u - k\,T_b) + \frac{N_u dT_u}{dt} + \frac{N_b dT_b}{dt}\right. \qquad \ldots\ldots\ldots\ldots(3)$$

Where V = volume of gases

t = time

N = No. of mols present

T = absolute temperature

P = pressure

R = gas constant

Subscripts u, b for unburned and burned gases respectively

k = No. of mols of burned gases obtained from 1 mol of unburned gases.

Equation 3 does not apply when the maximum pressure occurs as a peak in an accoustic vibration about atmospheric pressure.

Equation 3 can be applied most simply if it is assumed

(1) that $T_b$ and $T_u$ remain unchanged during the explosion and are independent of the particular venting conditions used.

(2) the rate of combustion $\frac{dN_u}{dt}$ is also independent of the presence of vents.

With these assumptions it may be shown that

$$\left(\frac{dV}{dt}\right)_P = \frac{Vo}{P} \frac{dp}{dt} \qquad \text{..... (4)}$$

Where $\left(\frac{dV}{dt}\right)_P$ = rate of expansion of the gases at the maximum pressure.
P occurring in the vented explosion

Vo = Volume of the tube

$\frac{dp}{dt}$ = rate of pressure rise in an unvented explosion

However, there is some difficulty in applying equation 4 since the pressure record in an unvented explosion in the tube shows sharp changes in the value of $\frac{dp}{dt}$ at certain specific times after ignition. This is shown in figure 11 which gives a mean pressure record for the unvented tube calculated from a number of separate records. Up to a point A at a time after ignition of 0.046 seconds the pressure increased approximately as the cube of the time. However between points A and B, B and C, C and D the pressure increased in direct proportion to the time but at rates which decreased in succeeding portions of the record. After point D the pressure rose at an increasing rate and in non-reproducible manner to the peak value. It is possible that the changes at two of the points A, B and C are associated with two changes occurring (1) when the flame first meets the tube and (2) when the pocket of gas between the ignition source and the near flange has been completely burned. Although approximate calculations suggest that these changes take place at A and B respectively this is by no means certain. However, these changes must take place whether the tube is vented or not and the only working assumption which one can reasonably make is that in a vented tube they take place at the same time after ignition as in an unvented tube. This assumption is probably valid when the vent is remote from the source of ignition since as the most pronounced motion of the gases and the flame takes place towards the end remote from the ignition source, then the pattern of the flame behaviour in the initial stages of the explosion is probably approximately independent of the presence of the vent. It is less valid when the vent is near the ignition source as in this case the motion of the combustion gases towards the vent is in a different direction to the motion of the flame along the tube.

In figures 12 and 13 curves (b) represent the rate of increase of the volume of the gas which may be expected to occur as a result of the combustion process at the moment of maximum pressure in the vented tubes; these curves are based on equation 4. It will be noted that in both figure 12 and 13 there are two limbs to curves b ; the reason is that in both cases the times at which maximum pressure was reached corresponded to two different rates of pressure rise in figure 10. It might be expected that the point at which curves (b) cross curves (a) represents the maximum pressure which would occur with the particular vent appropriate for curve (a). Maximum pressures obtained in this way have been compared with the experimental maximum pressures in figure 14. It will be seen that the calculated maximum pressures are about the same as the experimental ones. In particular the calculated values predict a difference between the effect of vents near to and remote from the ignition sources which was very similar to that which actually occurred. It may be concluded from this

agreement that under the particular conditions of these experiments the rate of combustion with the vented tubes was approximately the same as that which occurred with the unvented tube, and in particular the presence of the vents did not increase the rate of combustion. Further evidence to support this conclusion is given in figure 15 in which the maximum rate of pressure rise that occurred in the explosions with vents remote from the ignition source are plotted against the vent size. The maximum rate of pressure rise was reduced consistently as the vent size increased and in no case was this rate greater than the maximum rate obtained when no vents were used. However this conclusion cannot be expected to hold for other explosion systems. For example Wilson found (loc cit) that the rate of pressure rise in an approximately spherical shaped vessel increased considerably when vents were placed in the vessel.

Equation 1 which gives the flow rate through an open vent obviously breaks down when the vent diameter is the same as the pipe diameter ( $\beta = 1$) since it predicts that a positive pressure behind the orifice should give an infinite flow rate. It is likely therefore that the positive pressure registered for the 6 in. vent 5 ft. 6 in. from the ignition source was not associated through the relationship given in equation 1 with any definite flow rate, but rather that this was a measure of the inertia of the outside atmosphere to the movement of the given combustion coming from within the tube. A similar effect may be deduced from results given by Cubbage and Simmonds.[7]

## Conclusions

With open vents it has been found that a simple equation based on information on the rate of combustion in a closed vessel, may be used to calculate venting requirements. It remains to be seen to what extent this formula can be applied to other duct systems and even if it does apply it will still be necessary to estimate this rate of combustion from first principles if tests on every individual ducting arrangement which has to be vented are to be avoided. Moreover, in the present tests the friction of the gases flowing along the pipe was not a major factor as shown by the fact that the same pressure was recorded whether the pressure gauge was near or remote from the vent. However, as the length of the pipe is increased, this factor must become of increasing importance.

The use of bursting discs to cover the vents did not have the disadvantage of increasing the rate of burning that was found to occur with a vessel of even dimensions [3]. Moreover it seems likely from the present tests that as long as the right materials are used it is possible to produce a large reduction in the bursting strength of the disc by the provision of cutting tools. It is necessary to test these conclusions further for pipes of larger diameter and length than used in the present work.

Finally the finding that vibrations of high amplitude occurred when large open vents were placed in the end near the ignition source is most important practically (since it is generally recommended at the moment that vents should be placed near a potential ignition source and also in line with a length of tubing (12)). It is therefore important to establish whether the destructive effect of these vibrations is comparable to that of the explosion. In the present tests an attempt to determine this was made by placing a polythene disc at the opposite end from the open vent. If the vibrations had occurred, the maximum pressure reached should have been sufficient to burst the disc. However the polythene disc damped the vibrations. The effect however can be further investigated by placing a bursting disc on a side vent which can be formed by adding a T-piece to the 6 ft. tube. In this position the damping effect of the disc should be much less.

ACKNOWLEDGMENT

Mr. A. Kelly helped to carry out the experimental work.

## SYMBOLS

| | |
|---|---|
| $C$ | coefficient of discharge |
| $g_c$ | gravitational constant |
| $k$ | No. of mols. of burned gas obtained from 1 mol of unburned gas |
| $n$ | fraction of initial gas burned |
| $N$ | No. of mols. |
| $P$ | Pressure in vented combustion tube |
| $P_1$ | Pressure on upstream side of vent or orifice |
| $P_2$ | Pressure on downstream side of vent or orifice |
| $p$ | Pressure in inverted combustion tube |
| $R$ | Gas constant |
| $S_2$ | Area of vent or orifice |
| $T$ | Temperature of gases |
| $t$ | Time |
| $V$ | Volume of gases |
| $V_o$ | Initial volume of unburned gases or volume of tube |
| $Y$ | Coefficient for flow rate equation |
| $\beta$ | Ratio of vent to pipe diameter |
| $\gamma$ | Specific heat-ratio for the gas |
| $\rho$ | Density of gas |

Subscripts

| | |
|---|---|
| 0 | initial condition in tube |
| e | final condition in closed tube immediately after explosion |
| u | unburned gases |
| b | burned gases |
| 1 | upstream of vent |
| 2 | downstream of vent |

References

(1) T. B. Philip. Trans. Inst. Chem. Eng. 1953 31 p.149

(2) D. J. Rasbash and Z. W. Rogowski. F.R. Note 257

(3) M. J. G. Wilson. Relief of Explosions in closed vessels. Ph.D. Thesis. London Univ. June 1954

(4) E. W. Cousins and P. E. Cotton. Chem.Eng. 1951 58 p33-37

(5) G. W. Jones, E. S. Harris and B. B. Beattie. U.S. Bur. of Mines. Tech. paper 553

(6) H. G. Freestone, J. D. Roberts and A. Thomas. Paper read to Inst.Mech.Eng. April 1956

(7) P. A. Cubbage and W. A. Simmonds. The Gas Council Research Communication G.C. 23. November 1955

(8) K. C. Brown. S.M.R.E. Research Report No. 22

(9) J. H. Perry. Chemical Engineers Handbook. 3rd Edition. p403.

(10) W. Schiller. Forsch. Ing. Weis. 1933 4 (3) 128-37.

(11) B. Lewis and G. Van Elbe. Combustion in Flames and Gases. New York 1951 p455.

(12) See e.g. National Fire Codes Vol.II. Dust explosions 1955. N.E.P.A. Boston.

## Appendix I

### Rate of expansion in combustion at a constant pressure

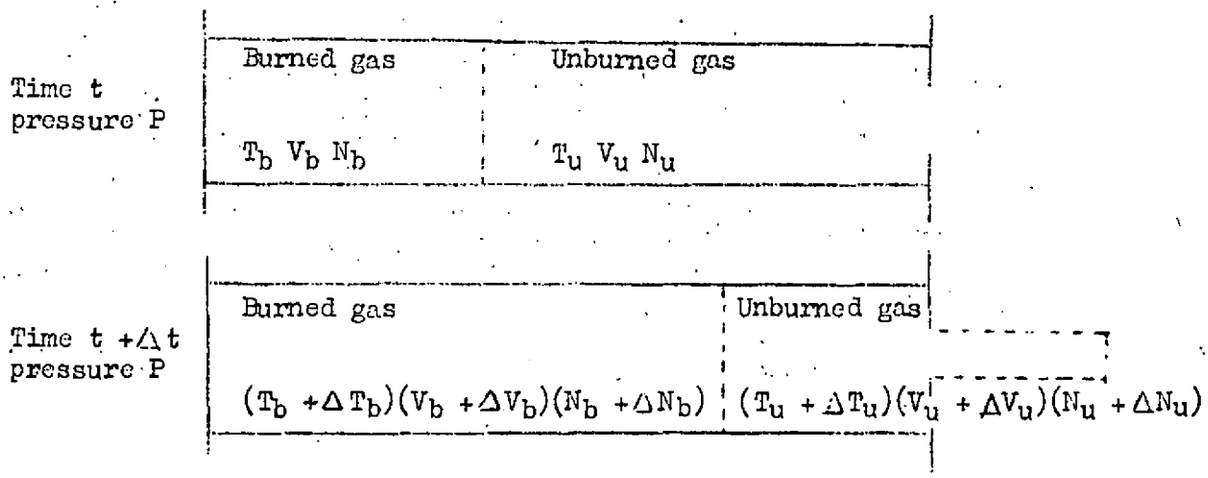



Fig.1. Combustion in vented pipe at constant pressure

Consider the combustion of gas in the vented pipe at maximum pressure. For a short time, $\Delta t$, the combustion may be considered as taking place at a constant pressure P (see figure 1). Let $T_b$, $V_b$, $N_b$ and $T_u$ $V_u$ and $N_u$ be respectively the temperature volume and number of mols of burned and unburned gas present at time t in the pipe (see figure 1) and $\Delta T_b$, $\Delta V_b$, $\Delta N_b$, $\Delta T_u$, $\Delta V_u$, $\Delta N_u$ be the changes which take place within time $\Delta t$. Then from the perfect gas laws,

$$P\,(V_b + V_u) = R(N_b T_b + N_u T_u) \qquad \ldots\ldots\ldots\ldots (1)$$

$$P\,(V_b + V_u + \Delta V_b + \Delta V_u)$$
$$= R\left\{(N_b + \Delta N_b)\ (T_b + \Delta T_b) + (N_u + \Delta N_u)\ (T_u + \Delta T_u)\right\} \ldots\ldots (2)$$

Subtracting equation (1) from (2) and omitting second order quantities gives

$$P\,(\Delta V_b + \Delta V_u) = R(T_b \Delta N_b + T_u \Delta N_u + N_b \Delta T_b + N_u \Delta T_u) \qquad \ldots\ldots (3)$$

If the combustion processes can be represented by a given equation throughout the reaction then the relation between $\Delta N_b$ and $\Delta N_u$ is given by equation (4)

$$\Delta N_b = -k \Delta N_u \qquad \ldots\ldots\ldots\ldots (4)$$

Where k is a constant depending on the combustion equation. Substituting for $\Delta N_b$ in equation 3 and dividing by $\Delta t$ gives

$$P\,\frac{\Delta(V_b + V_u)}{\Delta t} = R\left\{\frac{\Delta N_u}{\Delta t}\ (T_u - kT_b) + \frac{N_b\,\Delta T_b}{\Delta t} + \frac{\Delta T_u}{\Delta t} N_u\right\} \ldots\ldots\ldots (5)$$

In the limit $$\frac{dV}{dt} = \frac{R}{P}\left\{\frac{dN_u}{dt}\ (T_u - kT_b) + N_u \frac{dT_u}{dt} + N_b \frac{dT_b}{dt}\right\} \ldots\ldots\ldots (6)$$

Equation 6 represents the rate at which the volume of the gas is increasing and therefore the rate at which it is being forced through the vent under conditions of maximum pressure in the tube. On the downstream side of the vent there is a further increase in volume because of expansion to a lower pressure.

Equation 6 may be applied if some simplifying assumptions are used. Assumptions which together give rise to a substantial simplification are as follows.

(1) $T_u$ and $T_b$ remain unchanged during the explosion and are independent of the position or size of the vents. With this assumption $\frac{dT_u}{dt}$ and $\frac{dT_b}{dt}$ are both zero, $T_u$ equals $T_o$ and $T_b$ equals $T_e$, where $T_o$ and $T_e$ are the temperatures of the gas before and after the explosion. In fact $T_u$ will vary somewhat because of adiabatic compression and $T_b$ will vary because of the varying amount of work done by the expanding gases.

(2) The rate of combustion $\frac{dN_u}{dt}$ under the conditions of the experiment are the same as the rate of combustion taking place inside a closed tube. With these assumptions equation 6 becomes

$$\frac{dV}{dt} = \frac{R}{P}\left(\frac{dN_u}{dt}\right)_c (T_o - k\,T_e) \qquad \text{..... (7)}$$

where $\left(\frac{dN_u}{dt}\right)_c$ is the rate of combustion in the closed vessel.

$$\text{but} \quad p_o V_o = N_o R\, T_o \qquad \text{..... (8)}$$

$$\text{and} \quad p_e V_o = N_e RT_e = k\, N_o\, RT_e \qquad \text{..... (9)}$$

Where $p_o$, $T_o$, $V_o$ and $N_o$ are the initial pressure, temperature, volume and number of mols of the gas in the tube and $p_e$, $N_e$, $T_e$ is the final pressure, number of mols and temperature after combustion has taken place in a closed tube.

$$\therefore \frac{dV}{dt} = \frac{R}{P}\left(\frac{dN_u}{dt}\right)_c \left(\frac{p_o V_o}{N_o R} - \frac{p_e V_o}{N_o R}\right) \qquad \text{..... (10)}$$

$$= \frac{V_o}{P N_o}\left(\frac{dN_u}{dt}\right)_c (p_o - p_e) \qquad \text{..... (11)}$$

It has been shown that for practical purposes when combustion takes place in a closed system (11) then

$$n = \frac{p - p_o}{p_e - p_o} \quad \text{where } n = \text{fraction of initial gas burned} \quad \text{....(12)}$$

$$\text{Now } N_u = (1 - n)\, N_o \qquad \text{..... (13)}$$

$$\therefore \left(\frac{dN_u}{dt}\right) = -\frac{dn}{dt} N_o = \frac{N_o}{p_o - p_e} \frac{dp}{dt} \qquad \text{..... (14)}$$

Substituting equation 11 gives

$$\frac{dV}{dt} = \frac{V_o}{P} \frac{dp}{dt} \qquad \text{..... (15)}$$

TABLE I. Sizes of Vents Used

| D in. | A $in^2$ | A/V $in^2/ft^3$ |
|---|---|---|
| 1.06 | 0.881 | .75 |
| 1.50 | 1.77 | 1.5 |
| 2.12 | 3.53 | 3.0 |
| 3.00 | 7.05 | 6.0 |
| 4.24 | 14.1 | 12.0 |
| 6.00 | 28.3 | 24.0 |

TABLE II. Properties of Bursting Materials

| Material | Wt/Area $g/ft^2$ | Thickness in x $10^{-3}$ |
|---|---|---|
| Brown Paper | 7.979 | 5.5 |
| Aluminium | 16.492 | 2.6 |
| Polythene | 3.252 | 1.6 |

TABLE III. Classification of pressure records obtained when bursting discs were used

| Material | VENT DIAMETER in. | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Vent 5' 6" from Ignition | | | | Vent 6" from Ignition | | | |
| | 6.00 | 4.24 | 3.00 | 2.12 | 6.00 | 4.24 | 3.00 | 2.12 |
| Aluminium 2 sheets | c | c | | a | | | | a |
| Aluminium 1 sheet | c | f | e | a | c | cd | a | a |
| Brown Paper 2 sheets | c | | | | | | | |
| Brown Paper 1 sheet | c | c | c | e | | | | |
| Polythene | cea | | | | d | d | d | a |

TABLE IV. Classification of pressure records obtained when open vents were used

| VENT POSITION | | VENT DIAMETER ins. | | | | | |
|---|---|---|---|---|---|---|---|
| | | 6.00 | 4.24 | 3.00 | 2.12 | 1.50 | 1.06 |
| 5 ft. 6 in. from ignition | Imperial Typing paper cut | E | A | A | B | D | CD |
| 6 in. from ignition | Imperial Typing paper cut | H | H | F | G | G | G |
| 5 ft. 6 in. from ignition | Open | - | - | - | - | D | C |

## Appendix II

### Estimation of temperature of Combustion Gases

By dividing equation 9 in Appendix I by equation 8 one obtains

$$\frac{P_e}{P_o} = \frac{k\,T_e}{T_o} \qquad \ldots\ldots\ldots\ldots (1)$$

Tests on the closed tube in which $P_e$ was measured gives the value of $\frac{P_e}{P_o} = 7.45$ when the mean value of $T_o$ was 290°K. If it is assumed that there was no dissociation then it may be estimated that $k$ was approximately 1.03. Substitution in equation (1) gives a value of $T_e$ 2090°K.

TABLE V

Bursting pressures and maximum pressures with various cutters.
Vent 5 ft. 6 in. from the igniting source

| Type of material | Diameter of disc in. | Normal pressures (mean) | | Pressures with puncturing cutter | | Pressures with two blade cutter $\frac{5}{8}$ in. diameter | | Pressures with three blade cutter $\frac{1}{2}$ in. diameter | | Pressures with two blade cutter 1 in. diameter | | Pressures with three blade cutter 1 in. diameter | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | At burst p.s.i. | Maximum p.s.i. | At burst p.s.i. | Maximum p.s.i. | At burst p.s.i. | Maximum p.s.i. | At burst p.s.i. | Maximum p.s.i. | At burst p.s.i. | Maximum p.s.i. | At burst p.s.i. | maximum p.s.i. |
| Aluminium two sheets | 6.00 | 32.3 | - | n.d. | n.d. | 11.4<br>10.2 | 12.1<br>12.3 | n.d. | n.d. | 7.6<br>9.9 | 10.3<br>10.5 | 12.0 | - |
| Aluminium | 6.00 | 16.9 | - | 7.8<br>8.4 | - | 4.9<br>5.0 | 5.7<br>6.7 | 5.8 | 6.9 | 4.3<br>4.2 | 5.8<br>5.8 | 4.8<br>7.3 | - |
| Aluminium | 3.00 | 29.4 | 30.9 | n.d. | n.d. | 10.8 | 12.5 | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| Brown Paper two sheets | 6.00 | 12.5 | - | n.d. | n.d. | n.d. | n.d. | 5.3<br>4.8 | n.d. | n.d. | n.d. | n.d. | n.d. |
| Brown Paper | 6.00 | 6.5 | - | 4·4<br>5.2 | - | 2.4<br>2.5 | - | 3.0<br>3.7 | n.d. | 2.3 | - | 2.2 | - |
| Brown Paper | 3.00 | 14.2 | - | n.d. | n.d. | 6.0<br>5.2 | 10.8<br>10.2 | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| Polythene | 6.00 | 3.1 | - | n.d. | n.d. | n.d. | n.d. | 3.1<br>3.0 | - | n.d. | n.d. | n.d. | n.d. |

TABLE VI

Details of investigations into venting requirements for gas and vapour explosions

| Series | Ref. no. | Type of vessel | Linear dimensions in. | Length to maximum width ratio | Gas used | *Mixture composition ratio | Fundamental burning velocity of gas mixture used cm/sec | Position of ignition source | Position of vent | Covering of vent |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 4 | Cylinder | 32.5 x 14 | 2.3 | Propane | 1.26 | 38 | Not known | | Not known |
| B | 5 | Cylinder | 38 x 4 | 9·5 | Acetone | 1.12 | | Near the end of cylinder | Away from ignition | Open hole |
| C | 6 | Cylinder | 132 x 18 | 7.3 | Petroleum spirit | 1.25 | 35 | Near the end of cylinder | Away from ignition | Open hole |
| D | Present work | Cylinder | 72 x 6 | 12 | Pentane | 1.31 | 32.5 | Near the end of cylinder | Away from ignition | Paper cut |
| E | | Cylinder | 72 x 6 | 12 | Pentane | 1.31 | 32.5 | Near the end of cylinder | Near ignition | Paper cut |
| F | 3 | Cylinder | 52 x 50 | 1.25 | Pentane | 1.06 | 37 | Centre of cylinder | Top | Waxed paper |
| G | 3 | Cylinder | 62 x 50 | 1.25 | Pentane | 1.37 | 30 | Centre of cylinder | Top | Waxed paper |
| H | 3 | Cylinder | 62 x 50 | 1.25 | Pentane | 1.06 | 37 | Centre of cylinder | Top | Relief-spring valve |
| K | 3 | Cylinder | 62 x 50 | 1.25 | Pentane | 1.37 | 30 | Centre of cylinder | Top | -do- |
| L | 7 | Cube | 24 | 1.00 | Coal gas | 1.38 | 118 | Centre | Top | Relief loose panel |

*RATIO $\frac{\text{per cent wt. oz. per cent volume of gas used in mixture}}{\text{per cent wt. oz. per cent volume of gas in stoichometric mixture}}$

TABLE VI (contd.)

| Series | Ref. no. | Type of vessel | Linear dimensions in. | Length to maximum width ratio | Gas used | *Mixture composition ratio | Fundamental burning velocity of gas mixture used cm/sec | Position of ignition source | Position of vent | Covering of vent |
|---|---|---|---|---|---|---|---|---|---|---|
| M | 7 | Cube Approx. | 72 x 48 x 49 | 1.47 | Coal gas | 1.38 | 118 | Centre | Top | Relief loose panel |
| N | 7 | Cube | 24 | 1.00 | Methane and carbon disulphide | Not given | 36 and 49 resp. | Centre | Top | Relief loose panel |

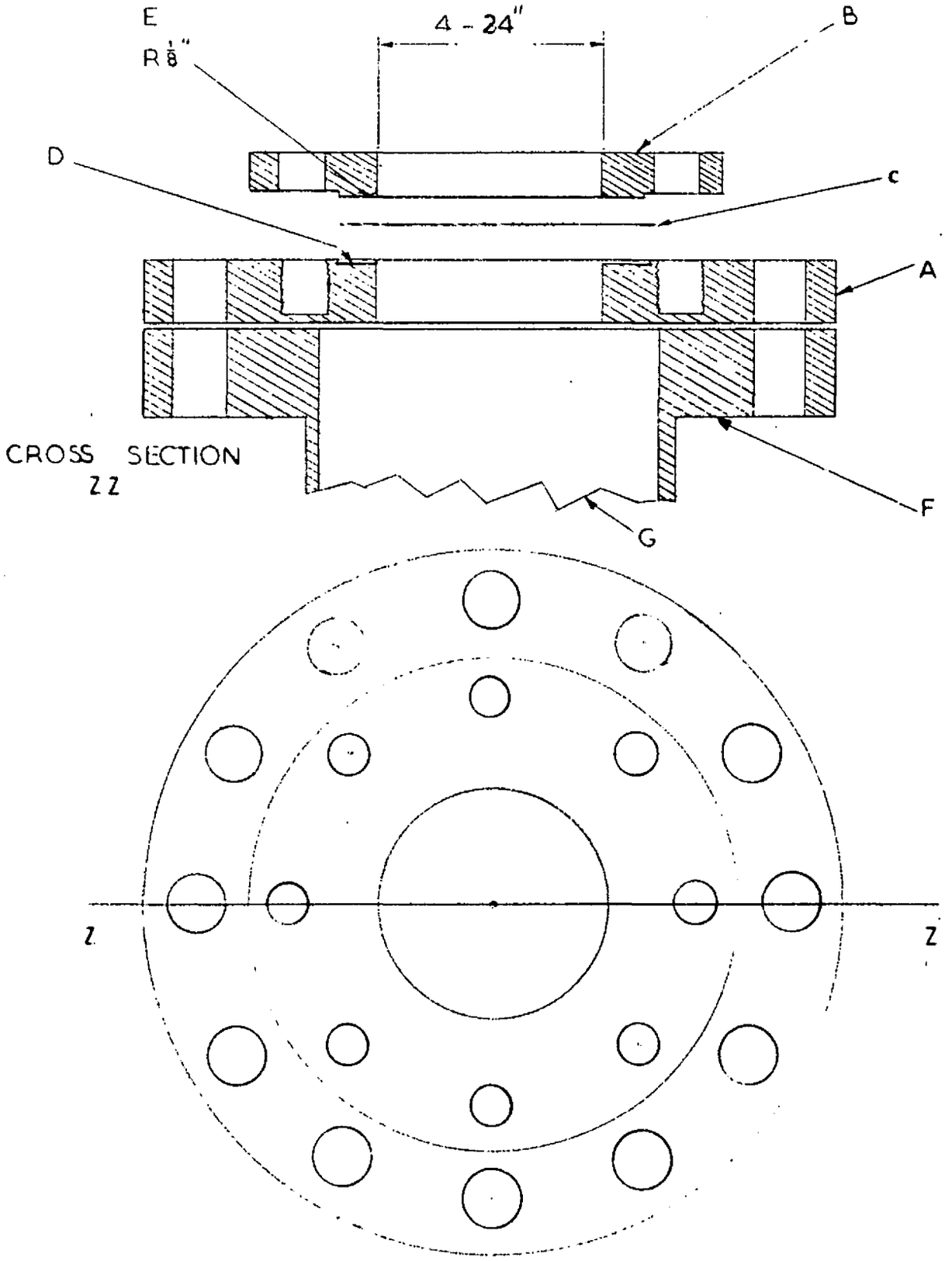



FIG. I. BURSTING DISC ASSEMBLY

SCALE 1cm:1in

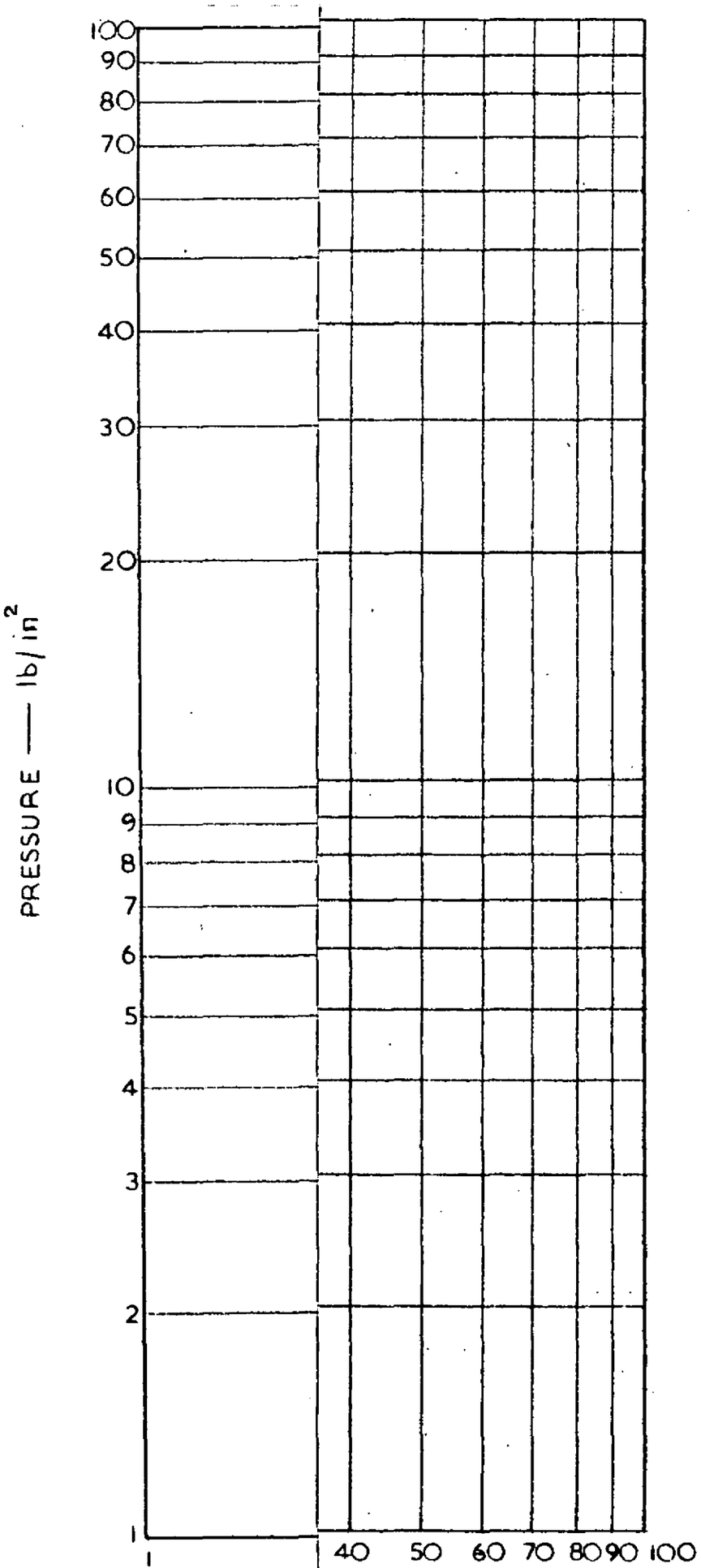



FIG. 2. STATIC BURS POLYTHENE DISCS

FR 398 2/240

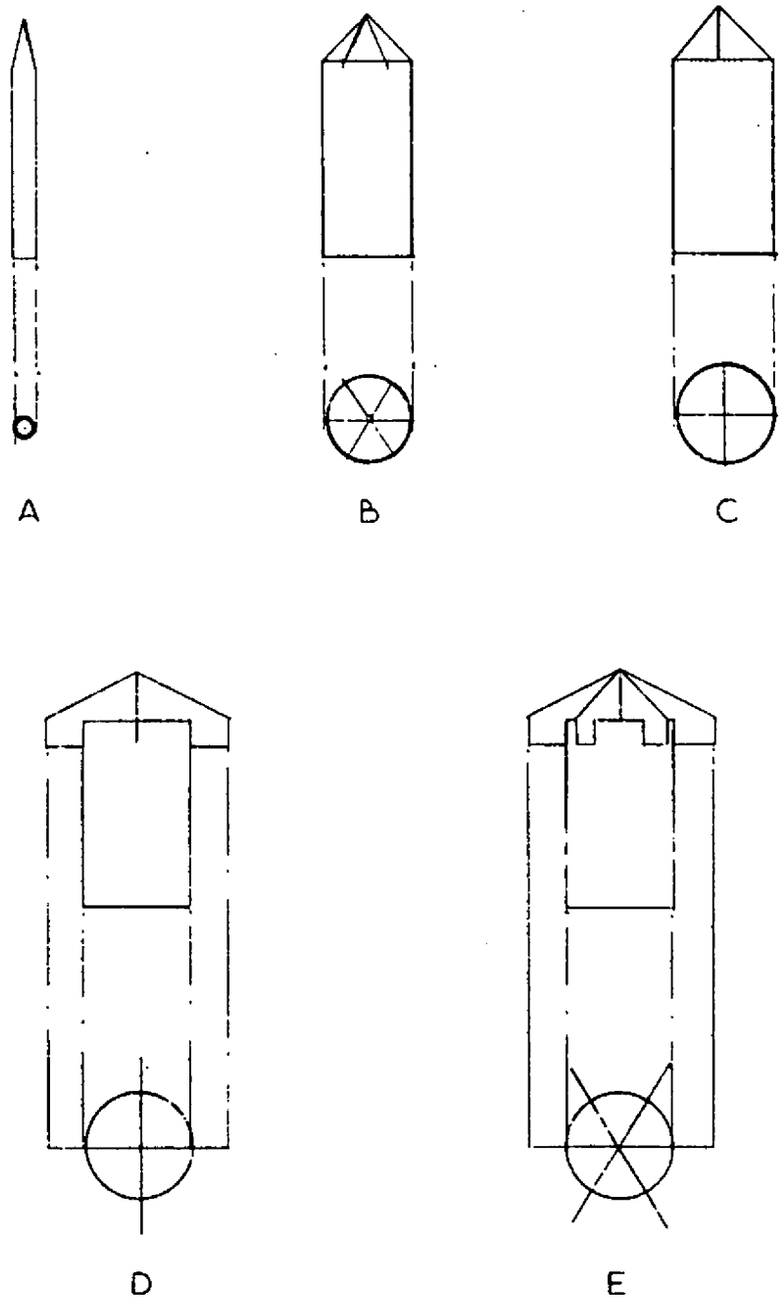
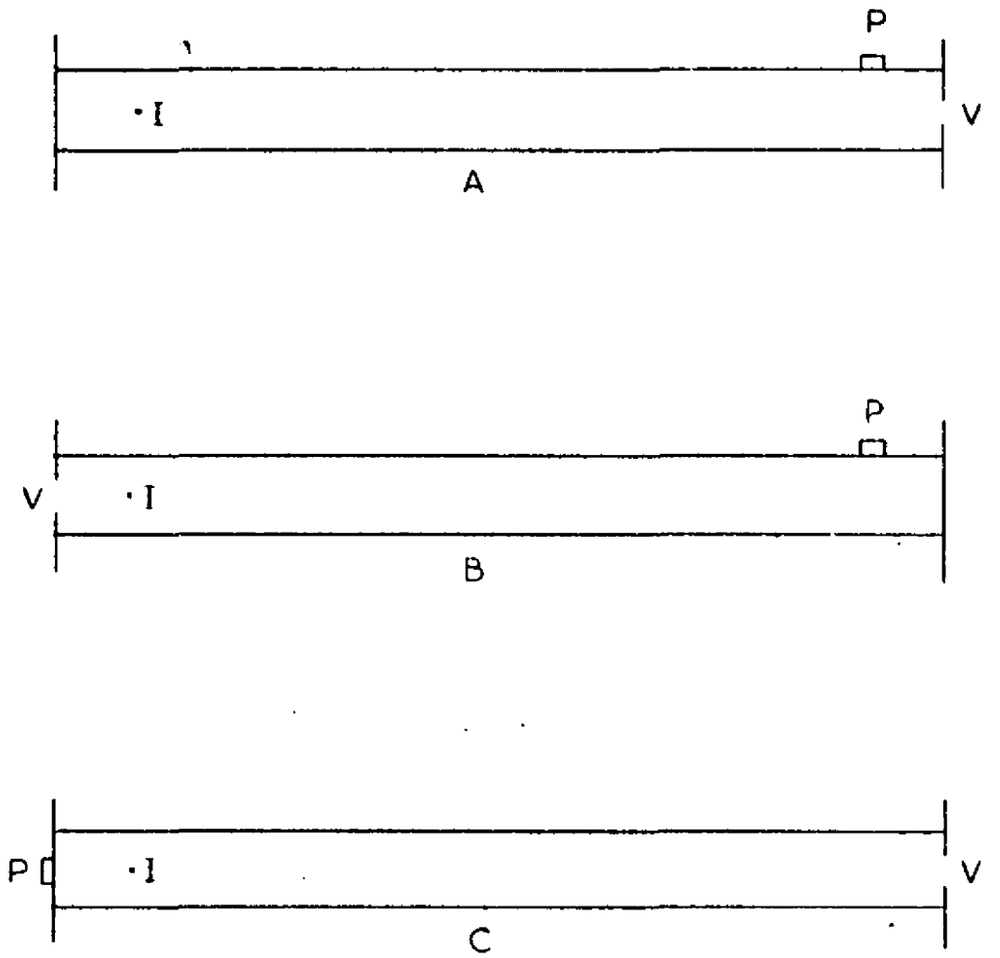



FIG.3. VARIOUS TYPES OF CUTTERS

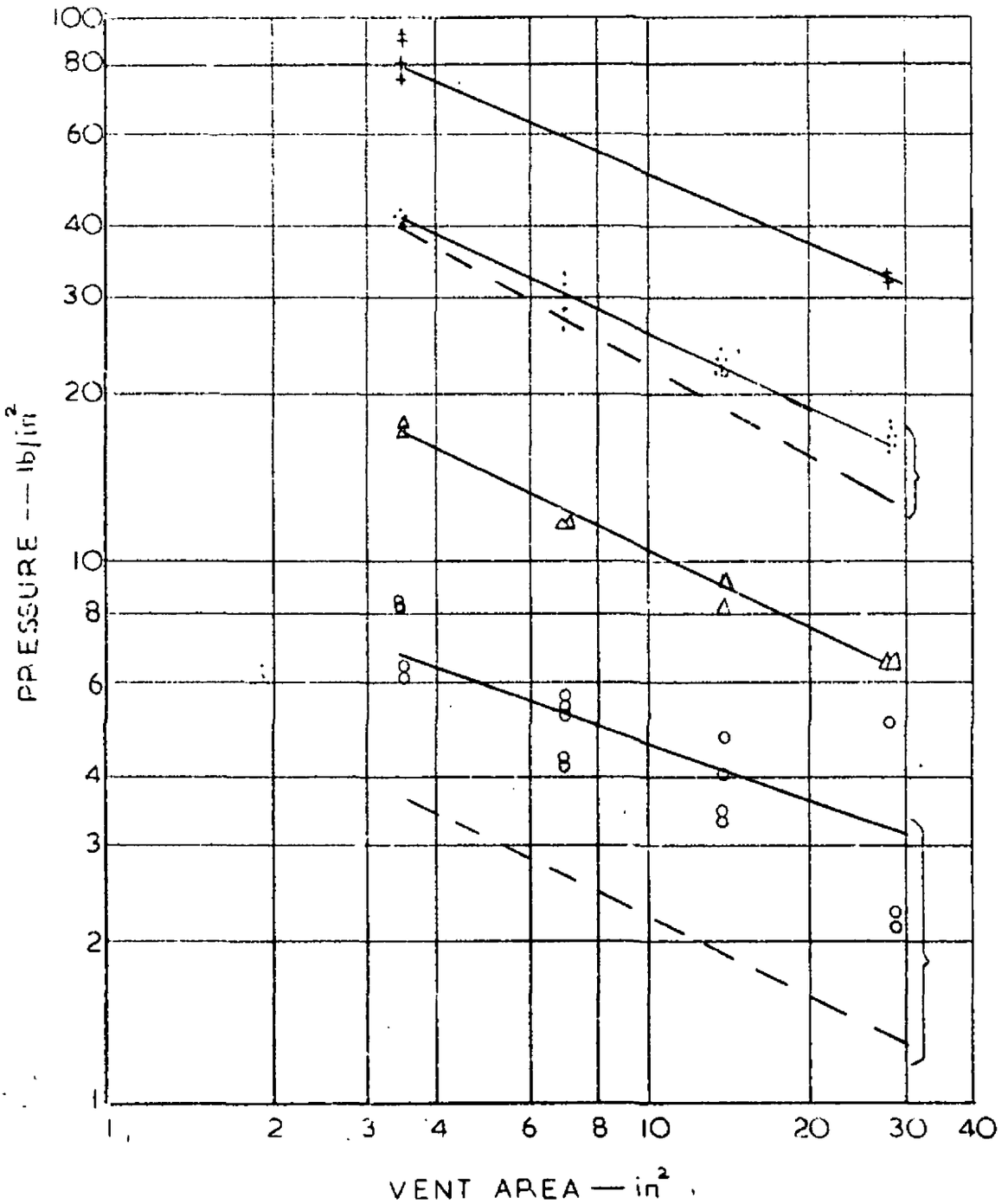



I Ignition

P Pressure gauge

V Vent

FIG. 4. THREE RELATIVE POSITIONS OF VENT, IGNITION AND PRESSURE GAUGE




Aluminium one thickness

Aluminium two thicknesses

Polythene

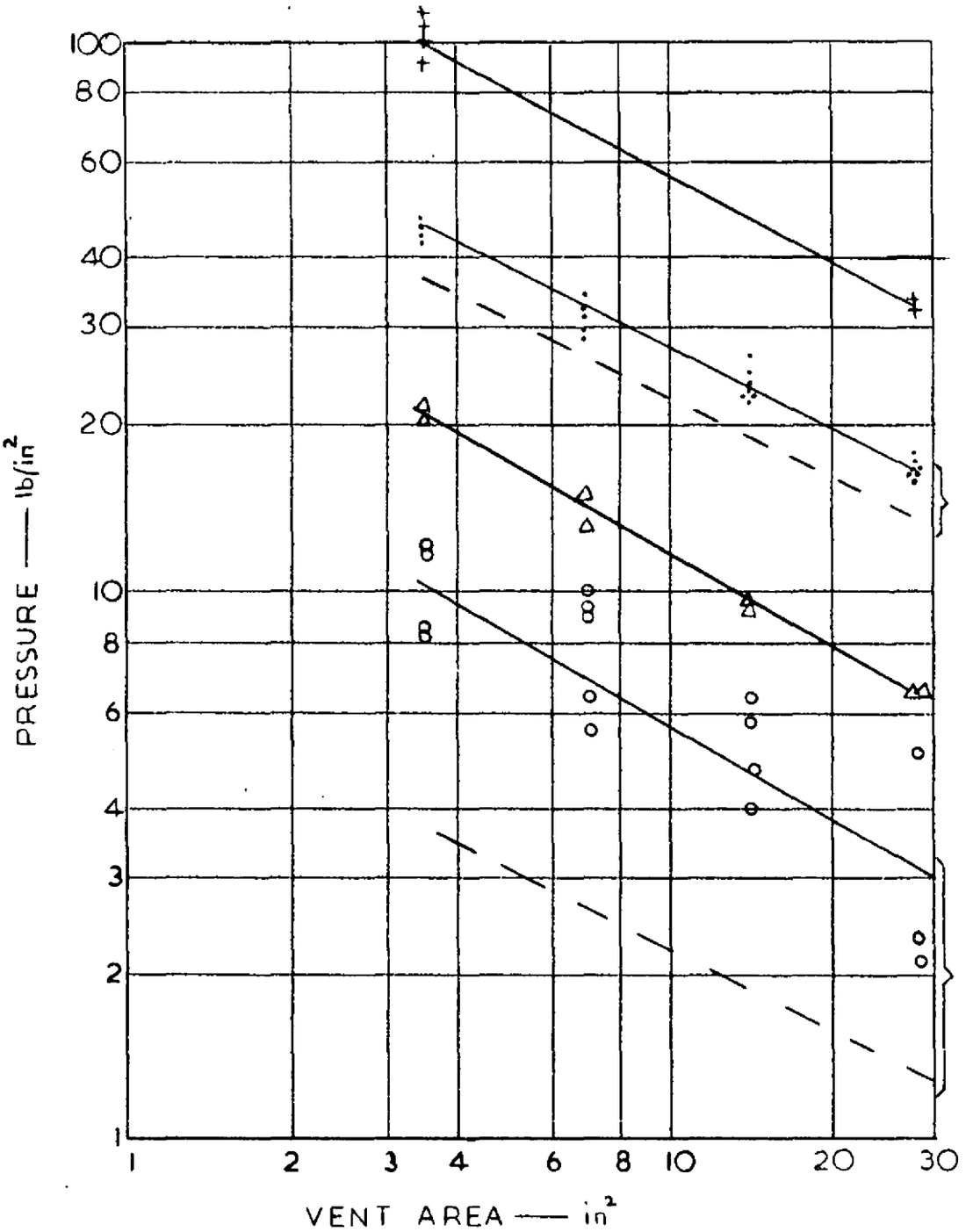
Brown paper

Explosion pressure

Static bursting pressure

FIG. 5a. EXPLOSION BURSTING PRESSURES AND STATIC BURSTING PRESSURES FOR DIFFERENT VENT AREAS

F.R.298. 1/2629




• Aluminium one thickness

+ Aluminium two thicknesses

o Polythene

Δ Brown paper

——— Explosion pressure

– – – – Static bursting pressure

FIG. 5b. MAXIMUM EXPLOSION PRESSURES AND STATIC BURSTING PRESSURES FOR DIFFERENT VENT AREAS

F.R. 248 17/2630

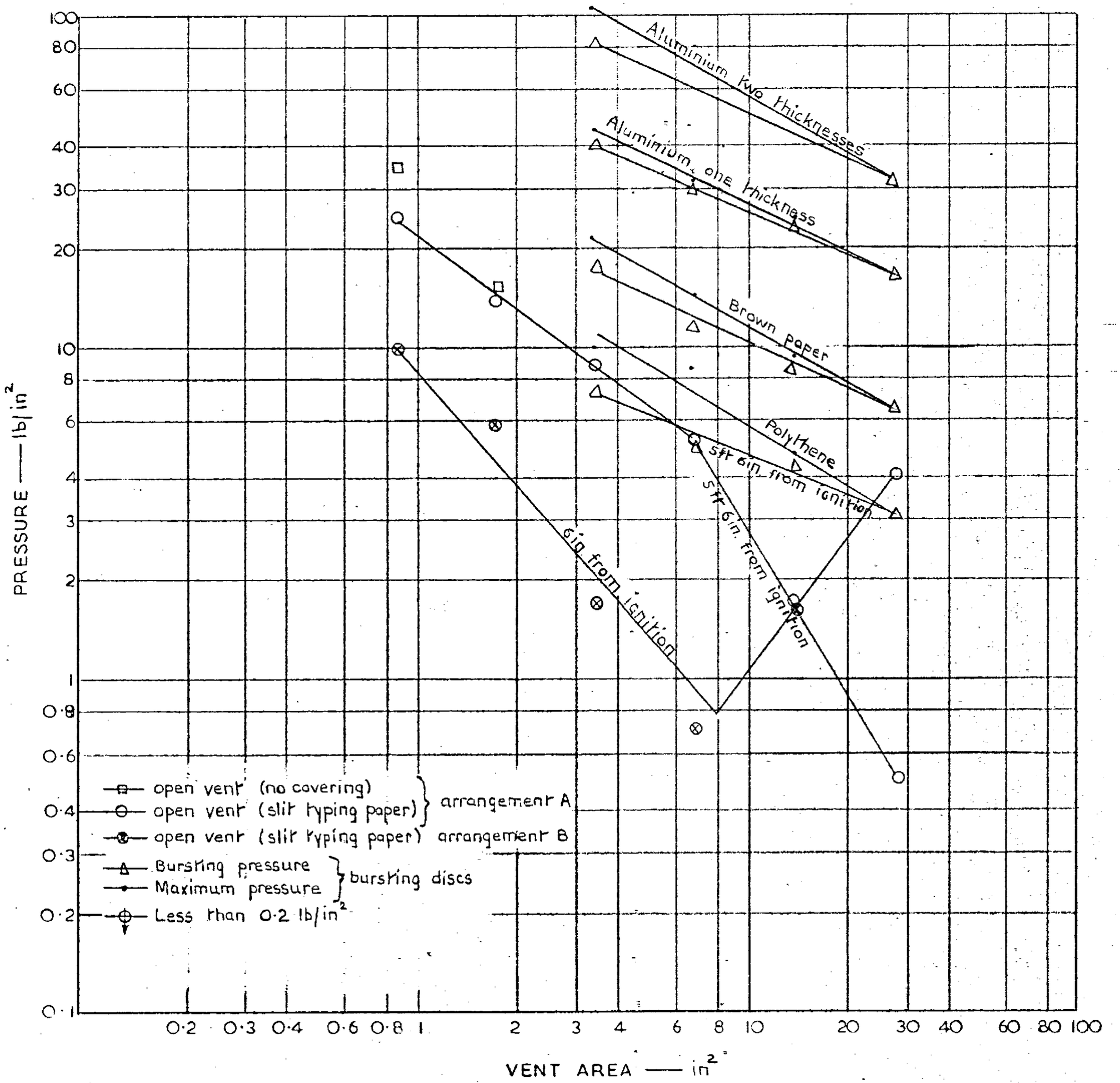
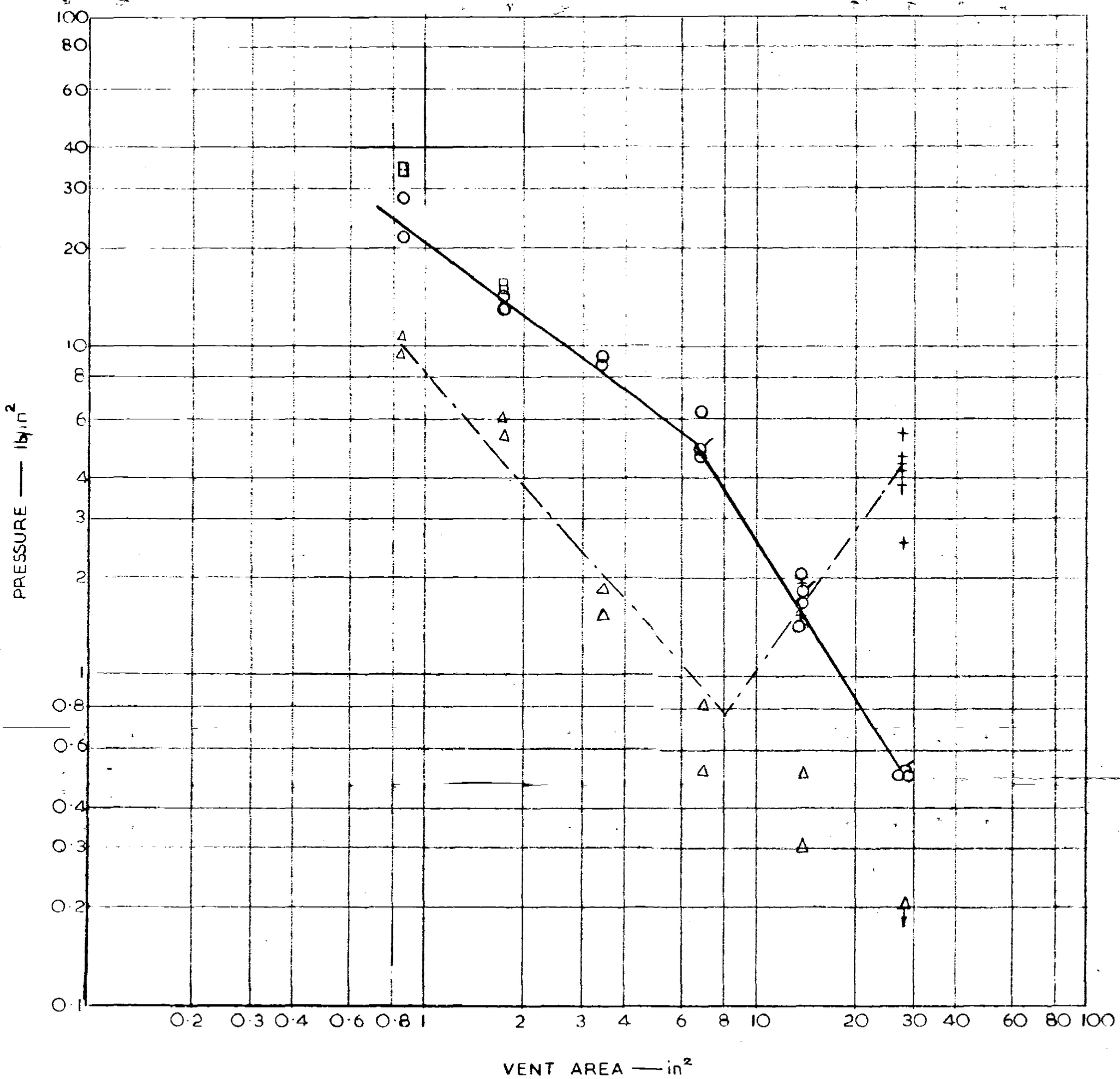



FIG. 7. MEAN VALUES FOR MAXIMUM AND BURSTING PRESSURES FOR DIFFERENT VENT AREAS. IGNITION 5ft 6ft AND 6in FROM VENTS




Vent 5ft 6in from ignition, gauge near vent

Vent 5ft 6in from ignition gauge away from vent

Vent 6in from ignition gauge near the vent (maximum pressure of initial pressure (RISE

Vent 6in from ignition gauge near the vent (maximum pressure of vibrations about atmospheric pressure)

No slit type paper covering vent

Less than 0·2 lb/in²

FIG.6. MAXIMUM EXPLOSION PRESSURES WITH OPEN VENTS FOR DIFFERENT VENT AREAS

FR 298 2/241.

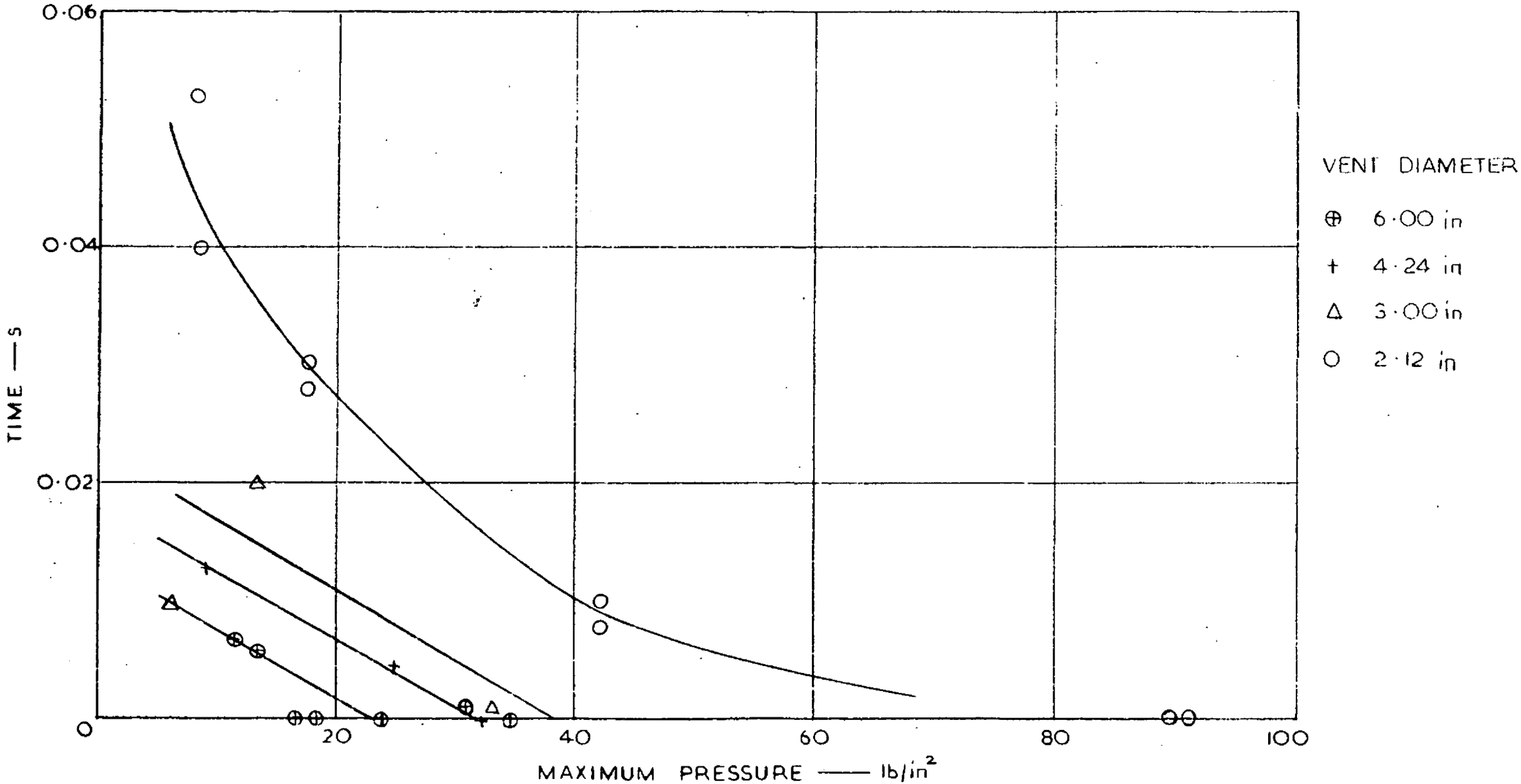



FIG.8. TIME INTERVAL BETWEEN RUPTURE OF THE DISC AND THE APPEARANCE OF FLAME AT THE VENT.

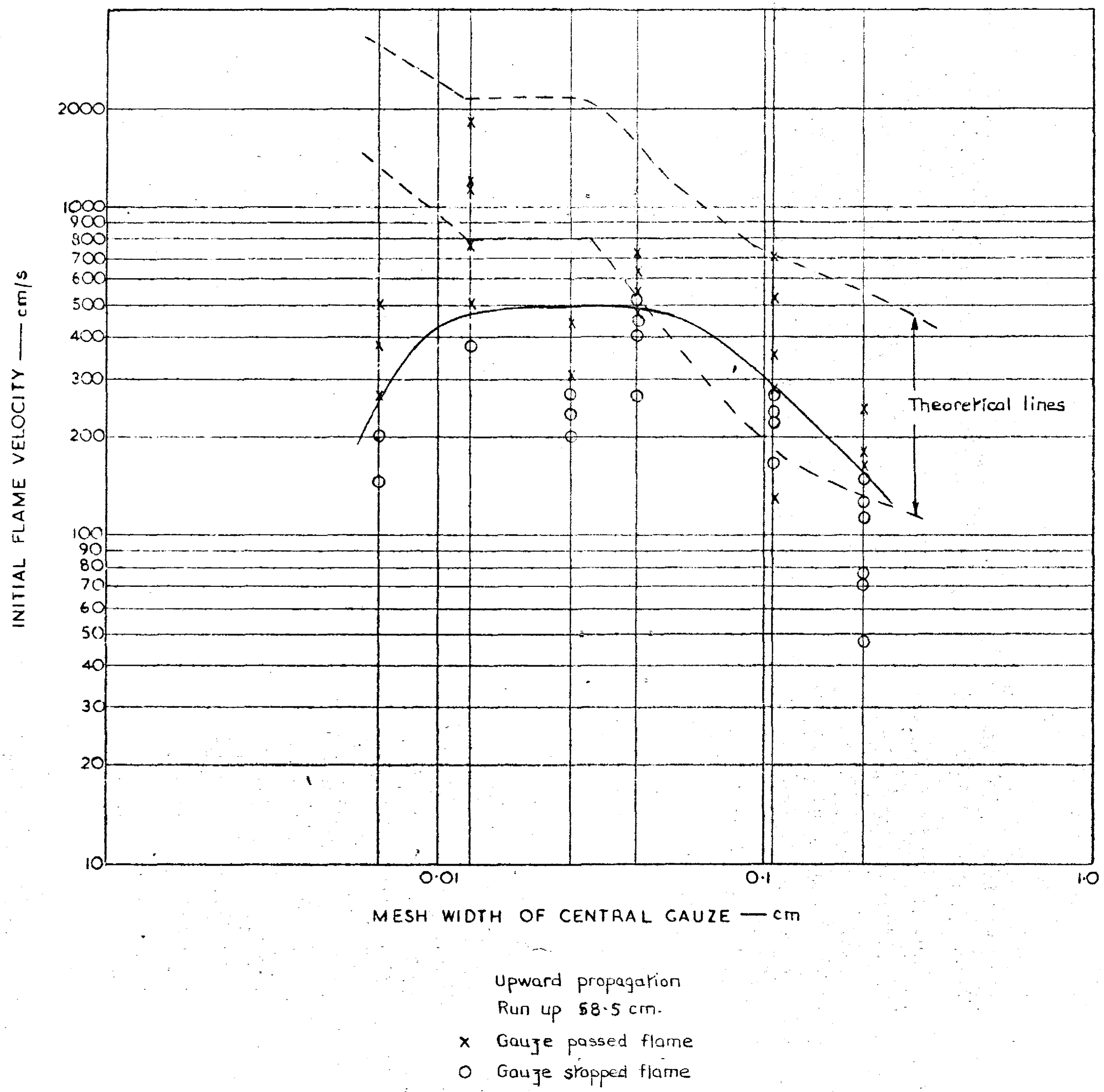



FIG. 9. THE ARRESTING OF PROPANE FLAMES BY SINGLE GAUZES SANDWICHED BETWEEN TWO 6-MESH BRASS GAUZES

F.R. 309 2/2.54

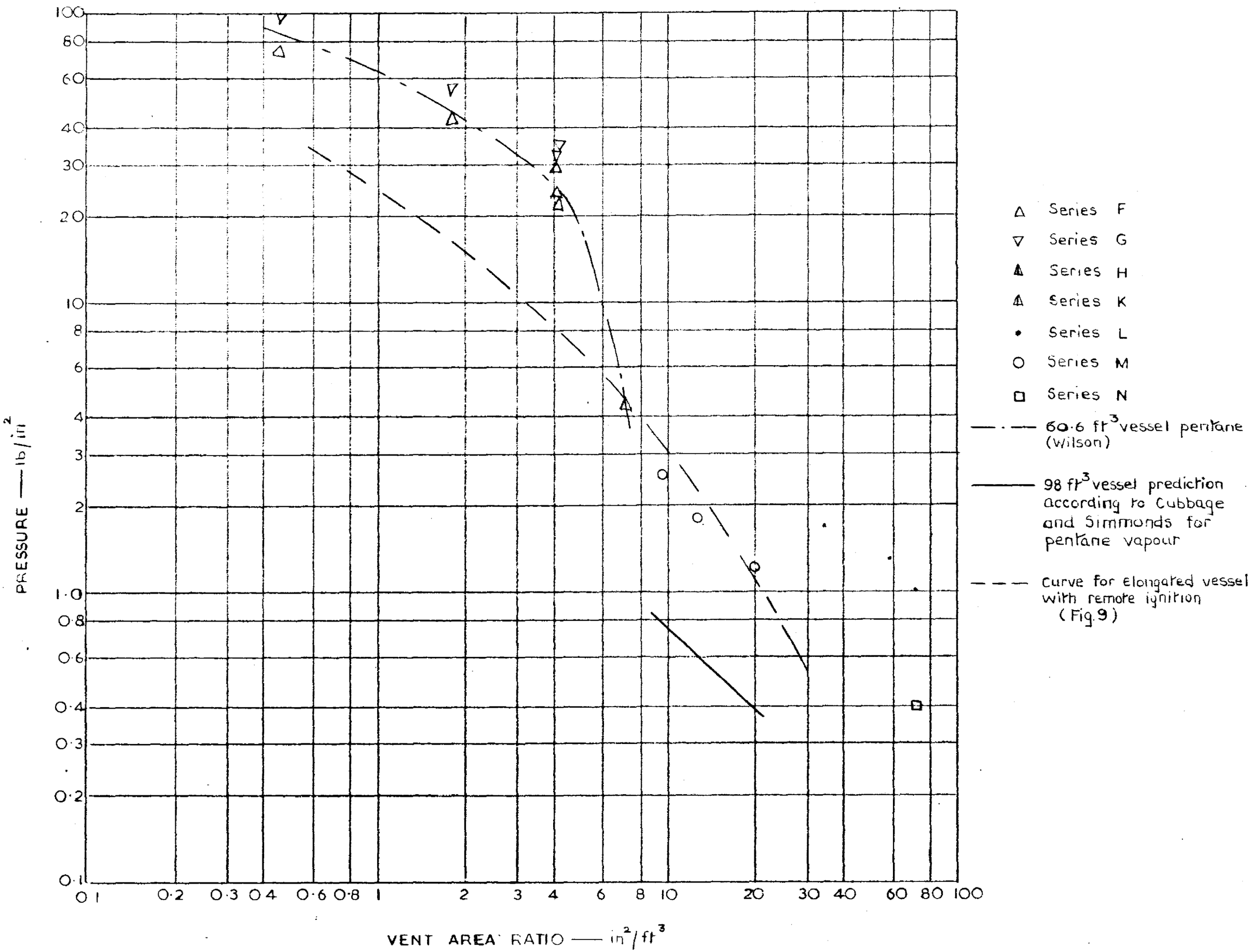



FIG. 10. RELATION BETWEEN PRESSURE AND VENT AREA FOR GASEOUS EXPLOSIONS. LENGTH/WIDTH RATIO OF VESSELS <2·0

F.R298 1/2632

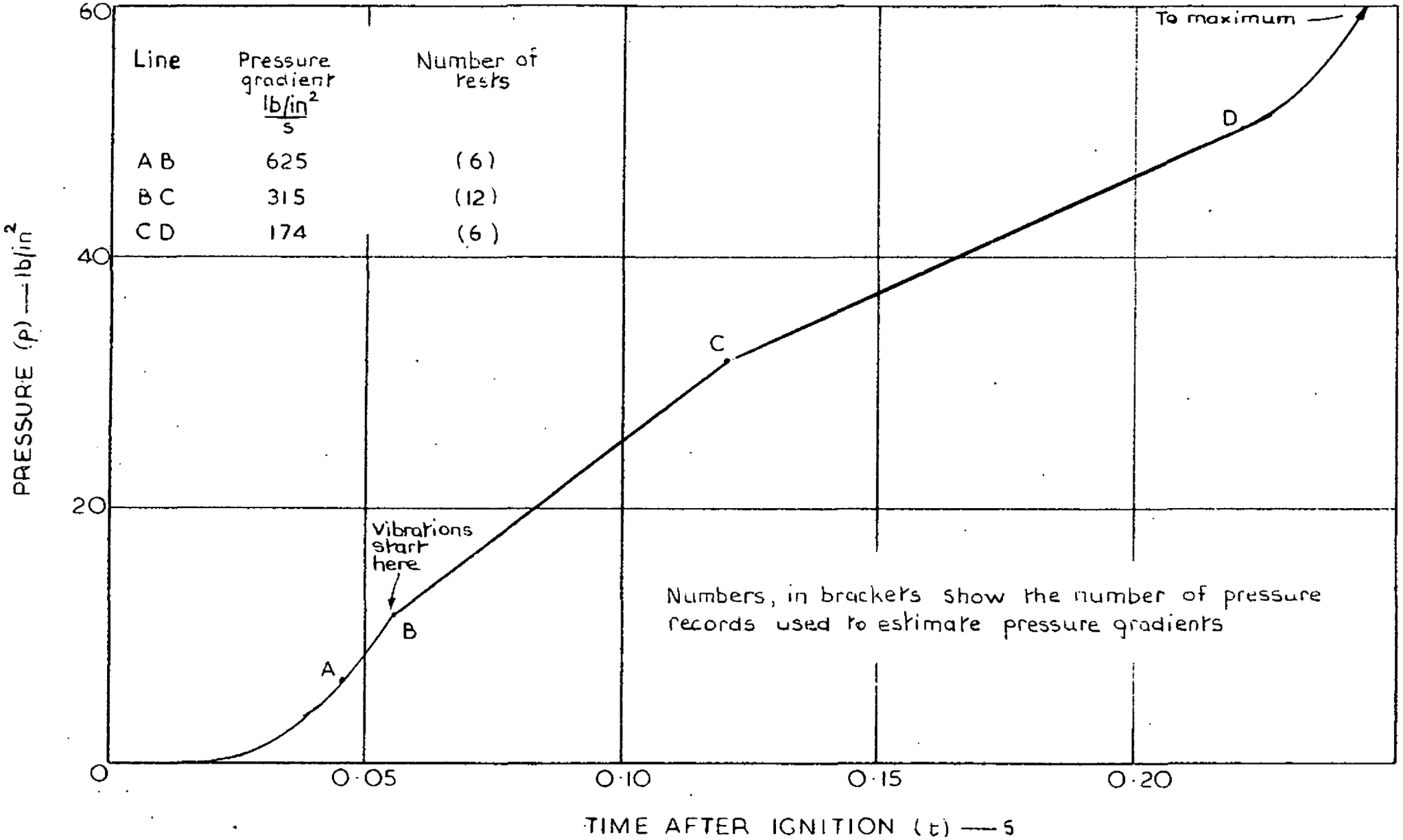



FIG.11, MEAN PRESSURE RECORD IN UNVENTED EXPLOSION

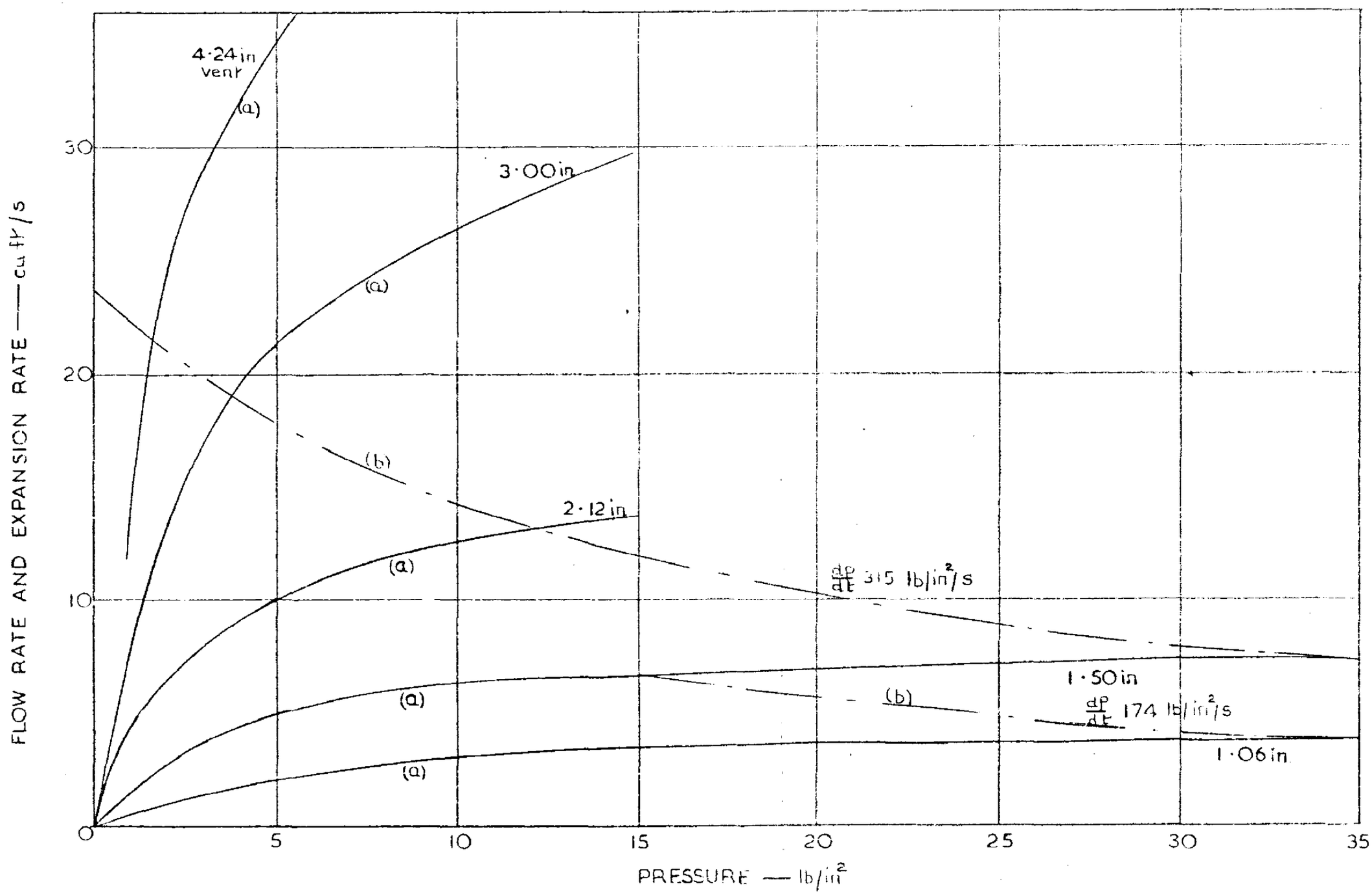



FIG. 12. FLOW OF GASES IN VENTED EXPLOSIONS — UNBURNED GAS

(a) ESTIMATED FLOW RATE THROUGH VENTS

(b) ESTIMATED RATE OF EXPANSION OF GAS IN PIPE DURING COMBUSTION AT CONSTANT PRESSURE

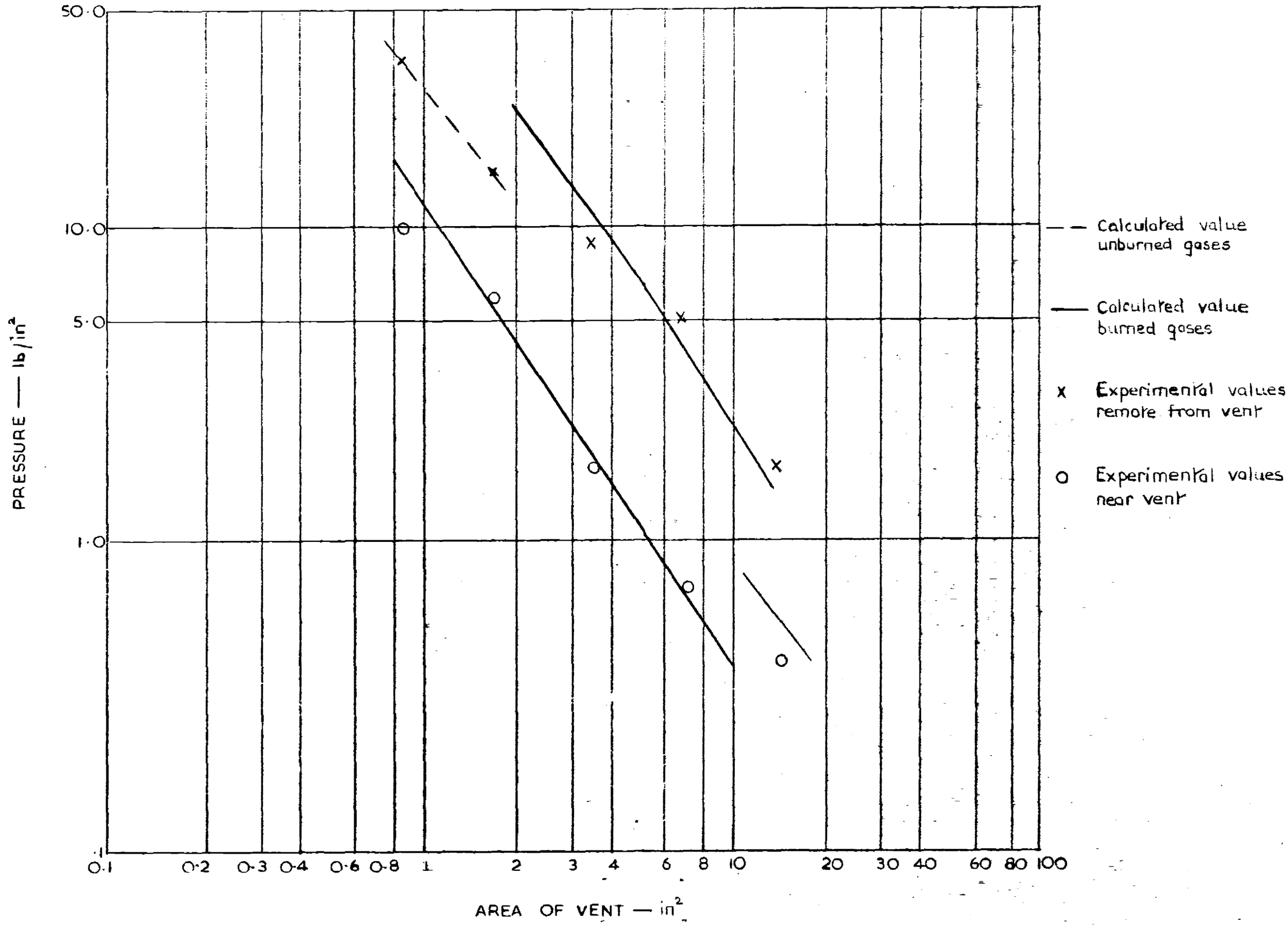
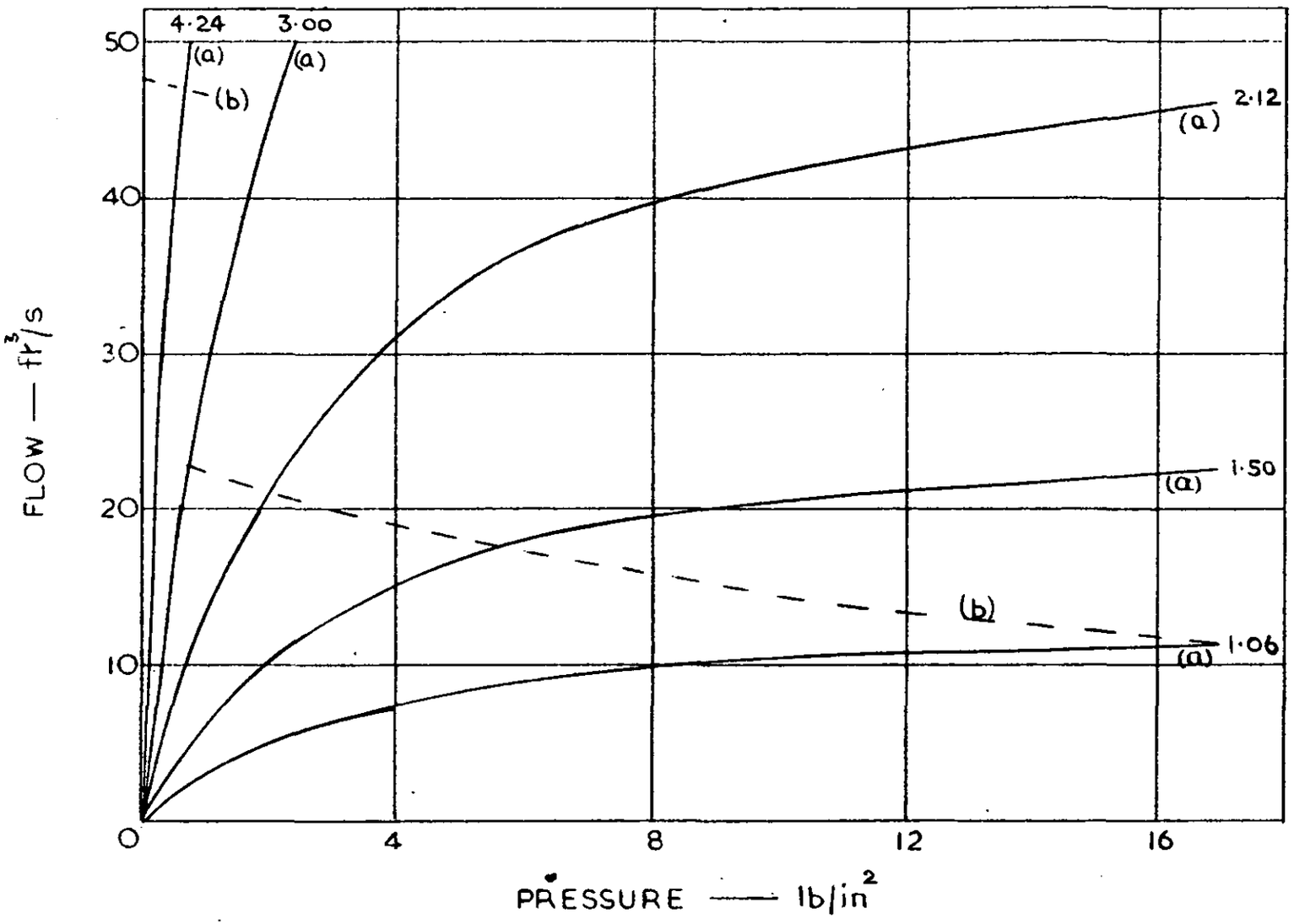



FIG. 14. COMPARISON OF CALCULATED AND EXPERIMENTAL VALUES OF THE MAXIMUMUM PRESSURE IN VENTED EXPLOSIONS

F.R. 298. 24246




(a) Estimated flow rate through vent

(b) Estimated rate of expansion of gas in pipe during combustion at constant pressure

FIG. 13. FLOW OF GASES IN VENTED EXPLOSIONS — BURNED GAS

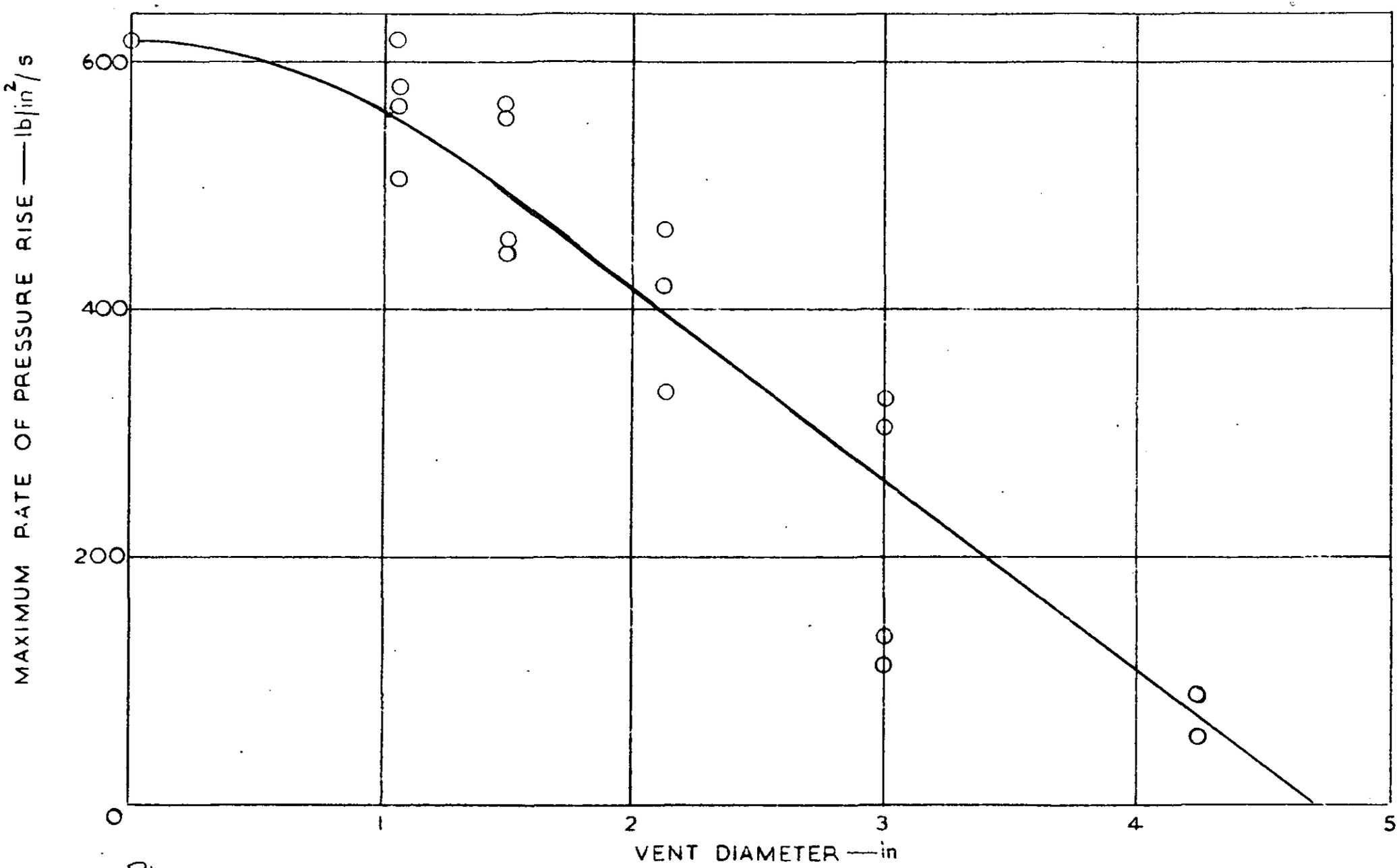



FIG.15. MAXIMUM RATE OF PRESSURE RISE FOR VARIOUS DIAMETER OPEN VENTS. SITUATED AT 5ft 6in. FROM THE IGNITION. (6ft x 6in. TUBE)

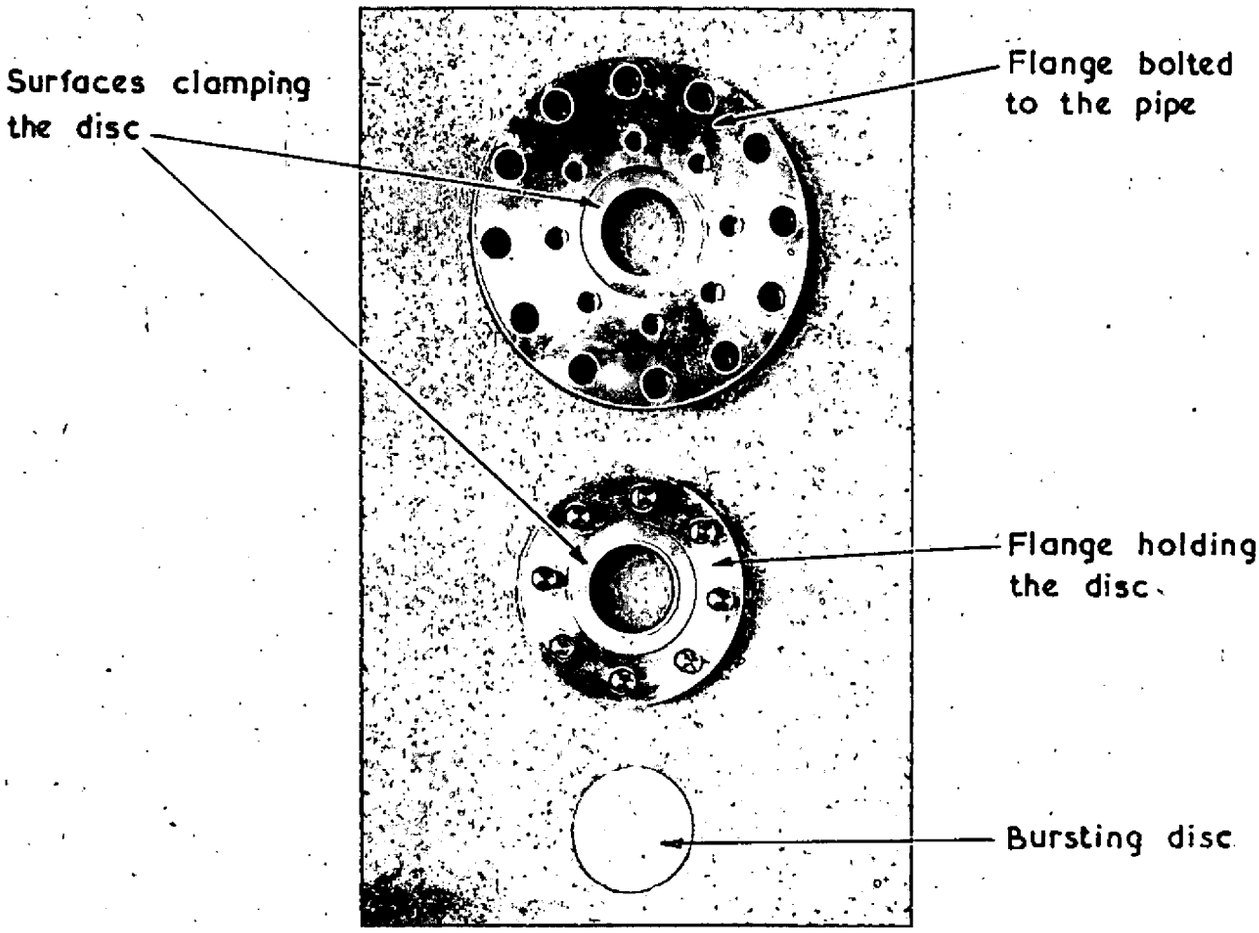



PLATE.1. BURSTING DISC ASSEMBLY

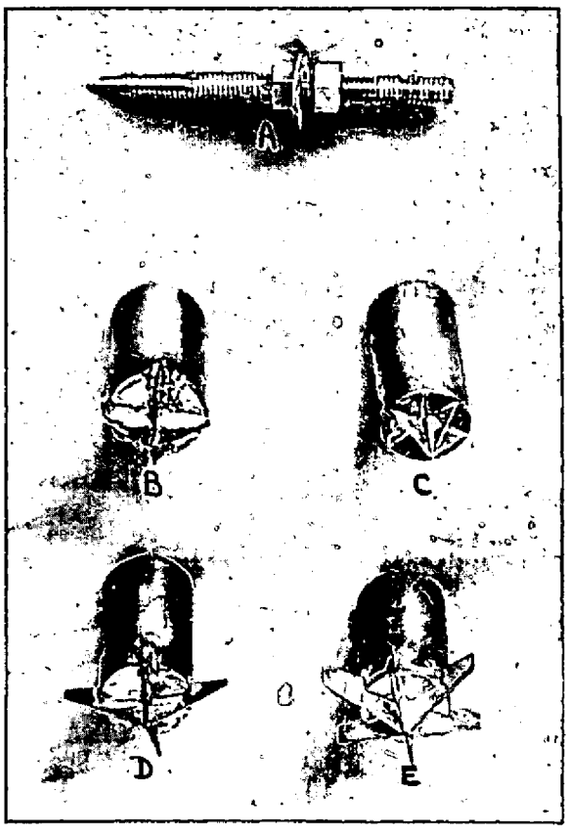
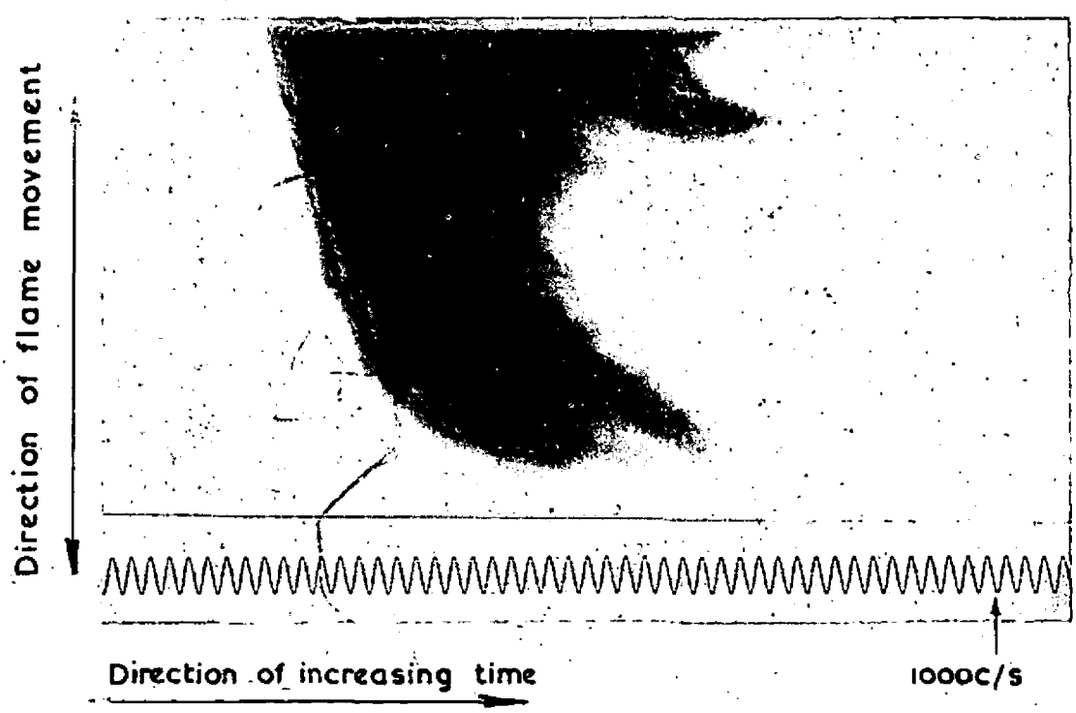


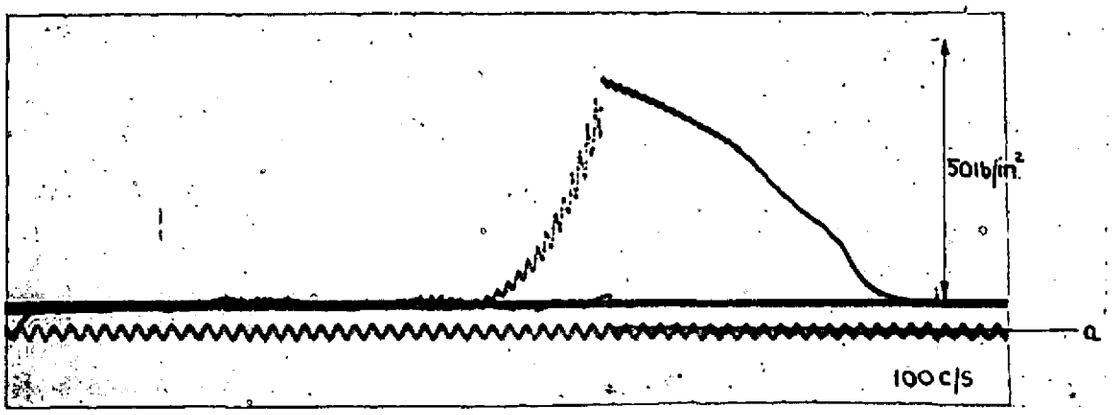

PLATE.2. PUNCTURING AND CUTTING TOOLS




Open vent 4·24 in. dia. 5ft. 6in. from ignition source

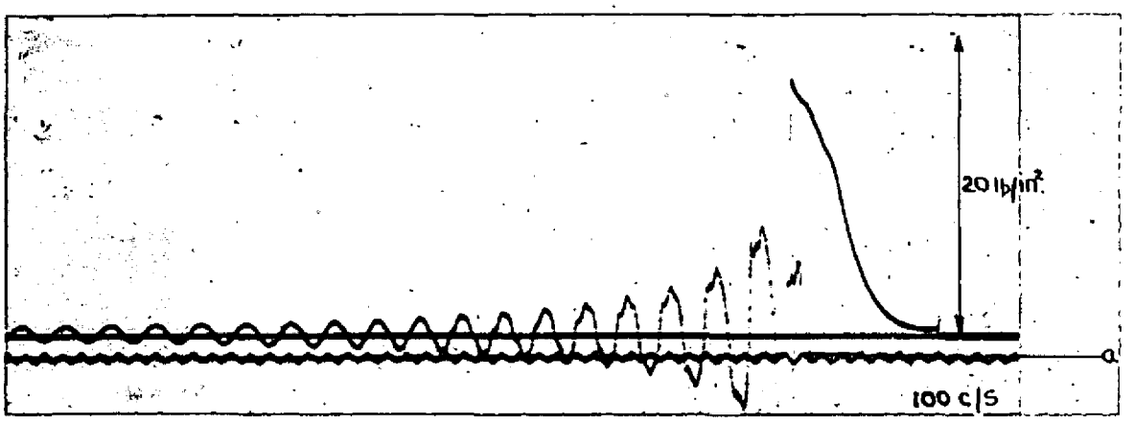
Flame velocity 193 m/s

PLATE.3. DRUM CAMERA PHOTOGRAPH OF THE FLAME EMERGING FROM THE VENT ORIFICE



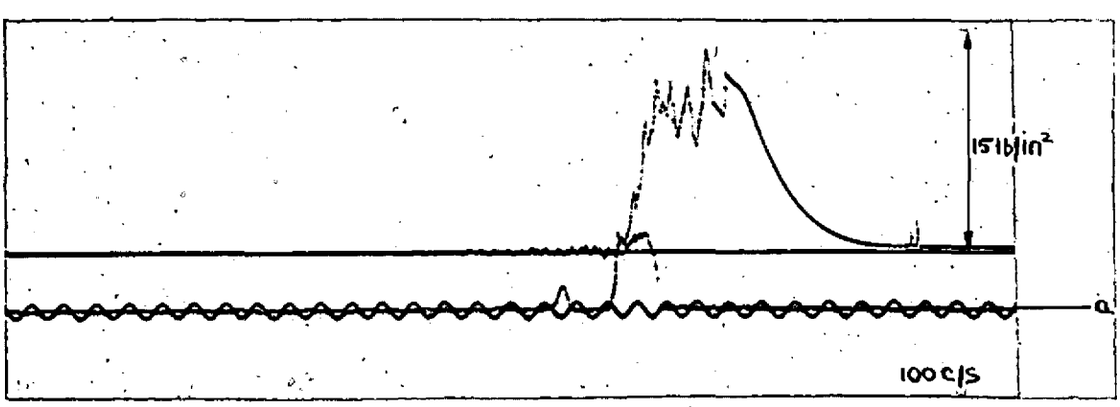

PATTERN ~~A~~ a

Aluminium 2·12 in. dia. 6 in from ignition




PATTERN ~~E~~ c

Aluminium 6 in. dia. 6 in from ignition

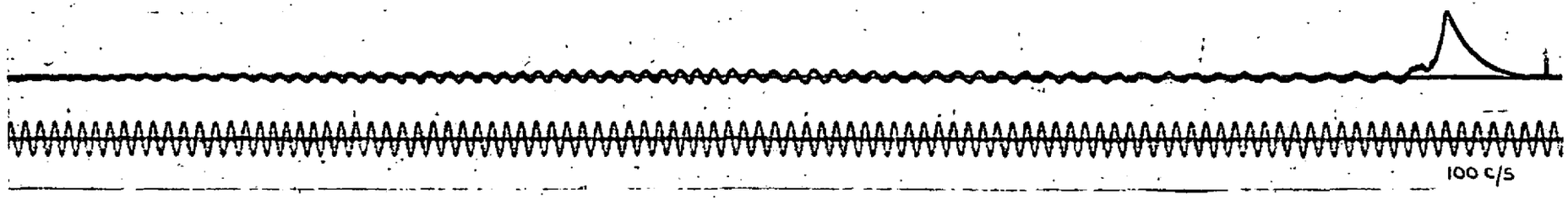



PATTERN ~~E~~ e

Brown paper 3 in. dia. 5 ft 6 in from ignition

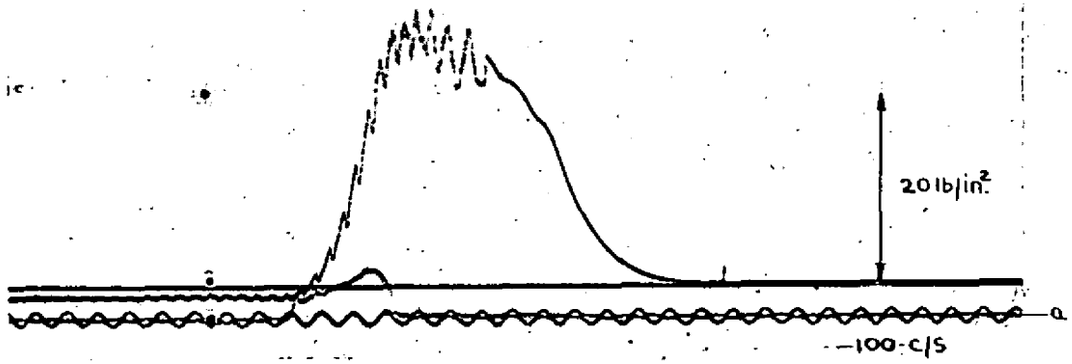
a A commencement of deflection on this trace indicates the emergence of the flame from the vent

PLATE. 4. PRESSURE RECORDS FOR BURSTING DISCS.
PATTERNS ~~A, C, E~~. a, c, e,




PATTERN ~~B~~ b

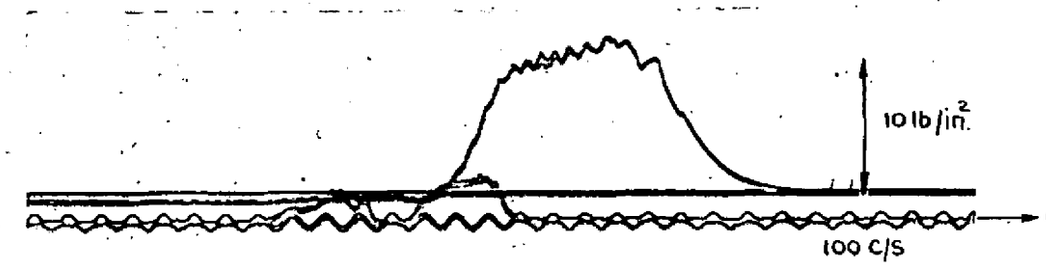
Polythene 3·00 dia. vent 6in. from ignition




PATTERN ~~F~~ f

Brown paper 2·12 in. vent dia.

Vent 5ft 6in. from ignition



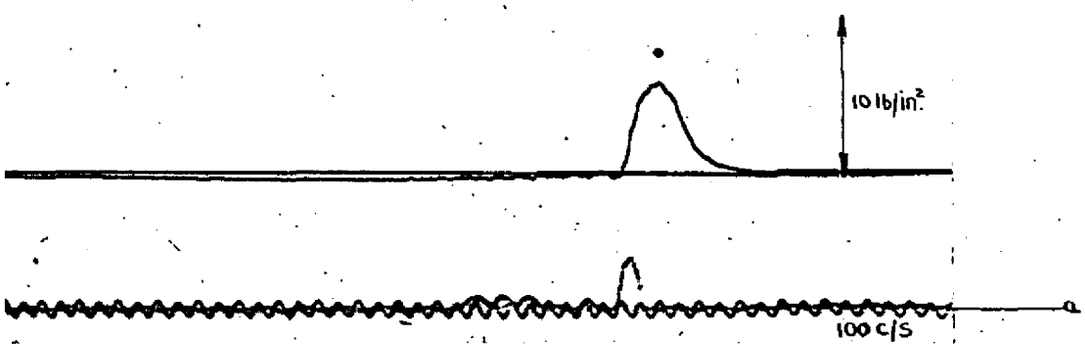

PATTERN ~~G~~ g

Polythene 2·12 in. vent dia.

Vent 5ft 6in. from ignition

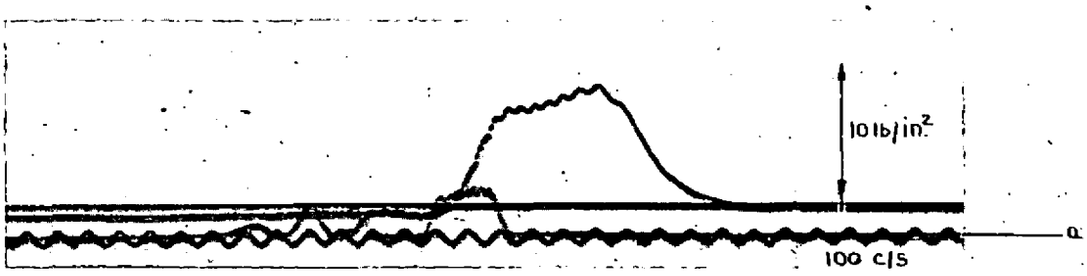
a A commencement of deflection on this trace indicates the emergence of the flame from the vent

PLATE.5. PRESSURE RECORDS FOR BURSTING DISCS. PATTERNS ~~B, F, G~~. b, f, g.



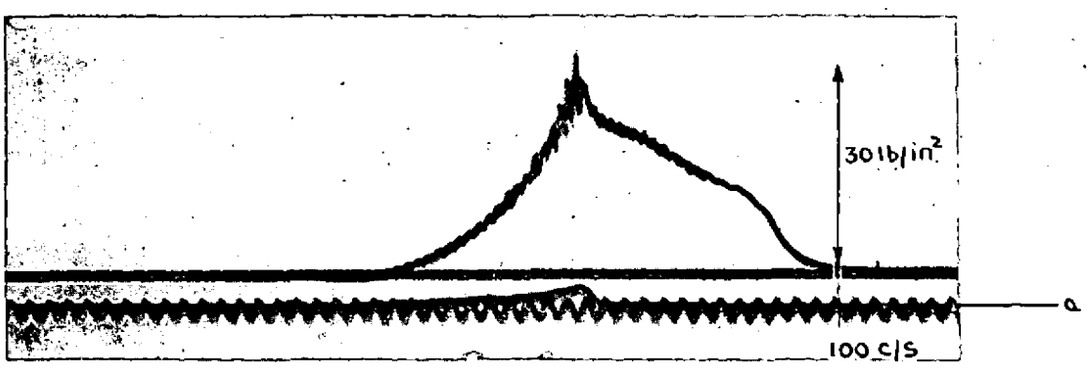

PATTERN ~~A~~ a

3in. dia. vent 5ft 6in. from ignition




PATTERN ~~B~~ c

2·12 in. dia. vent 5ft 6in. from ignition

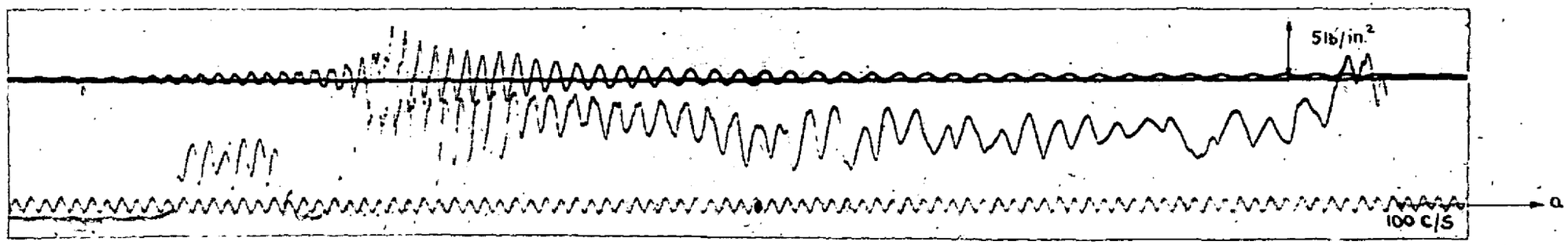



PATTERN ~~C~~ e

1·06 in. dia. vent 5ft 6in. from ignition:
open orifice

a A commencement of deflection on this trace indicates the emergence of the flame from the vent

PLATE. 6. PRESSURE RECORDS WITH OPEN VENTS.
PATTERNS A, B, C.

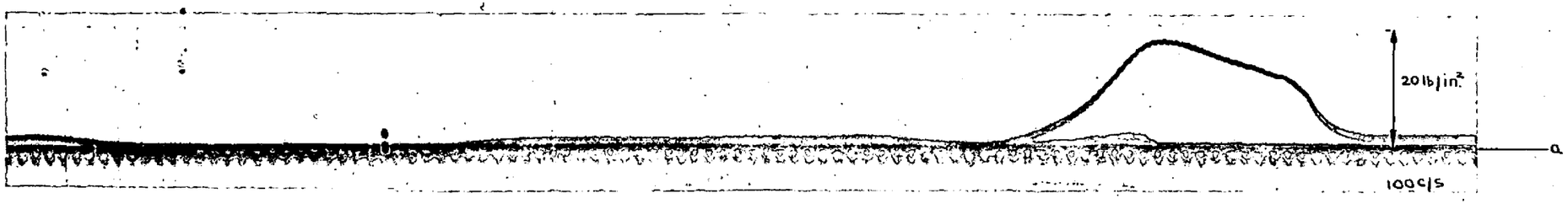



PATTERN H

6in dia. vent 6in. from ignition

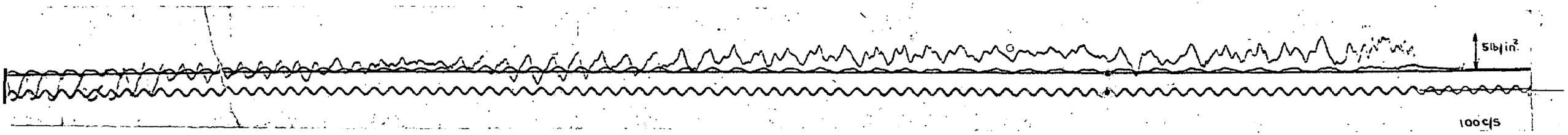
a A commencement of deflection on this beam indicates the emergence of the flame from the vent

PLATE. 7. CONTINUED



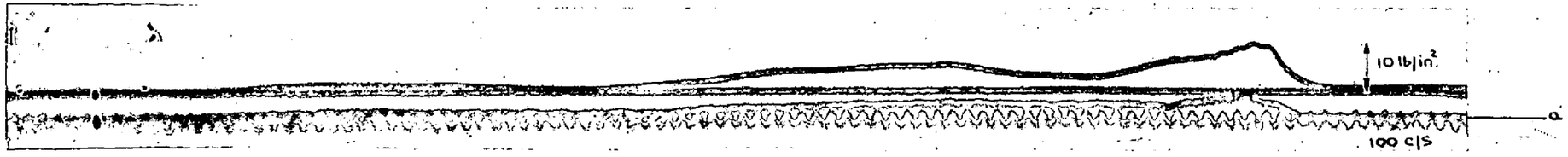

PATTERN D

1·06 in. dia. vent 5ft 6in. from ignition




PATTERN F

3·00 in. dia. vent 6 in. from ignition




PATTERN G

1·06 in. dia. vent 6in. from ignition

a A commencement of deflection on this trace indicates the emergence of the flame from the vent

DS 56402/P. 218 60 5/57 CL

PHATE

~~FIG.~~ 7. PRESSURE RECORDS WITH OPEN VENTS. PATTERNS D, F, G, H