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THE PROTECTION OF EQUIPMENT WITH FLAME ARRESTERS

1. CUBICAL ENCLOSURES WITH COMMERCIAL ARRESTERS.

by

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Summary

Flame arresters have been applied to the protection of industrial equipment which may be used in a flammable atmosphere and which may cause an explosion hazard. The arresters would release pressure resulting from ignition of the gas in the equipment, but would prevent flame emerging through the vents. Cubical enclosures up to 3 ft^3 in volume have been tested, in a propane-air mixture, and were safely protected with commercial crimped ribbon arresters.

The vent area required depended on the volume of the enclosure and needed to be sufficient to prevent thermal damage to the arresters. It was usually about 25 per cent of the area of one side of the enclosure. The maximum explosion pressure was low, often less than 2 lb in^{-2}. The vent area required and explosion pressure could be reduced by distributing the vents on two opposite walls of the vessel. Protection of arresters against mechanical damage was obtained with an external shield.

The maximum explosion pressure was related by theory to the vent area and the dimensions of the flame arresters.

MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

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Introduction

Industrial equipment may cause an explosion risk if it is used in situations where flammable gases or vapours may be present. The risk would arise because gas penetrated to a source of ignition within the equipment; the resulting explosion would then be able to propagate to the outside of the equipment unless adequate precautions were taken. A new method of obtaining safety is at present being investigated. The method involves installing flame arresters in the outer casing or cover of the equipment, to relieve the explosion pressure but to prevent the emission of flame. Because of the venting of the explosion the maximum pressure developed within the equipment would be considerably less than that which could otherwise occur, and relatively light construction of the casing could be used. The advantages of this method of protection are that it may be applied cheaply and that increased weight is minimised, which is especially important with portable equipment. In addition the method is easily adapted to allow ventilation of the equipment if this is required.

There are several existing methods by which equipment is customarily protected against explosion risk in flammable atmospheres. The methods include flameproofing of electrical equipment [1], design of electrical circuitry to ensure intrinsic safety [2], pressurising or purging with air or inert gas, encapsulation. Each of the methods suffers from one or more limitations which restrict their application. The limitations include protection from electrical sources of ignition only, increased weight of equipment, relatively small maximum permissible operating currents, the necessity for the permanent installation of pressurised air or gas lines with associated equipment. If protection is obtained by installing flame arresters these limitations are avoided or minimised. Hence the use of flame arresters is an additional method of protection with sufficient advantages to be of practical importance.

To ensure adequate protection by means of flame arresters the maximum pressure developed in an explosion must be no greater than an acceptable level. There must also be no cumulative mechanical or thermal damage to the arresters after a series of explosions. The experiments have therefore initially been concerned with the variation of explosion pressure with size of vent for enclosures of practical dimensions, and the determination of the type and size of flame arresters that gave protection without being damaged. The explosible gas mixture was propane-air, taken as representative of Group II gases [1].

Apparatus and Materials

Explosion vessels

Four cubical explosion vessels were used, having capacities of $^1/_{10}$, $^1/_3$, 1 and 3 ft^3. Each vessel had two open flanged ends with provision for bolting on covers provided with vents. Each cover had circular openings which could be fitted with flame arresters or closed individually by bolting on blank circular plates. Fig 1 (a) shows the $^1/_3$ ft^3 explosion vessel with covers attached; the top cover was fitted with two flame arresters and the remaining three vents were blanked off. Fig 1 (b) shows the same vessel with cover removed. For experimental purposes the explosion vessels were constructed with substantial flanges. It is envisaged that for industrial applications enclosures would be designed to incorporate adequate venting, and lighter forms of construction could safely be used. The dimensions and number of vents used with each vessel are shown in Table 1; all the vents were situated in one cover unless stated otherwise, below.

Table 1

Numbers and diameters of vents used

Diameter of vents in.	Volume of explosion vessel (ft^3) $^1/_{10}$	$^1/_3$	1	3
1.15	1	1-5	-	-
2.25	1	1	1-5	-
4.30	1	1	2-4	1-4

The amount of venting is usually specified by the ratio K , where

$$K = \frac{\text{cross-sectional area of vessel}}{\text{total area of vents}}.$$

This ratio is only applicable when all vents are in the same cover of the explosion vessel.

All explosion vessels had provision for the insertion of a pressure gauge and an igniting source. The pressure gauge was always situated in the middle of a side of the vessel. The igniting source could be situated either in the centre of the vessel or on the axis of the vessel, 1 in away from either cover of the smallest vessel or 2 in away in the other vessels. Thus when all the vents were in one cover the igniting source could be near the vents, central, or remote from the vents.

Usually the explosion vessels were tested inside a 15.6 ft^3 cubical box having one open side. When the vents were fitted with flame arresters the open side of the outer box was sealed with a polythene diaphragm, consisting of two layers of 0.0015 in thick film. The diaphragm was not used in experiments with open vents i.e. no arresters. The 3 ft^3 explosion vessel was tested outside the box, as spurious pressure effects were otherwise obtained.

The outer box, with the $^1/_3$ ft^3 explosion vessel in position, is shown in Fig. 2.

Flame arresters

Three types of arrester were used:

Crimped ribbon

Perforated metal sheeting

Wire gauze.

The crimped ribbon arresters were a commercial product and they consisted of a crimped and a flat metal ribbon wound on a central core and then inserted within a brass mounting (Fig 3). The ribbons were of cupronickel brass-based alloy, were 0.002 in thick and were crimped in three sizes. Further dimensions of the arresters are given in Table 2, where nominal crimp heights are shown. Sample measurements of the crimps showed that the respective crimp heights were 0.044 ± 0.004 in, 0.023 ± 0.001 in, and 0.015 in.

The perforated sheeting arresters were of brass, with circular holes spaced in a regular pattern. Other details are shown in Table 3. The wire gauze was of steel and was a normal commercial product. The dimensions are given in Table 4.

Flammable gas and igniting source

A 4 per cent by volume propane-air explosive mixture was used in all experiments. It was ignited by an induction spark 1 mm in length.

Measurement of explosion pressure and flame speeds

Pressures were determined using variable electrical capacity gauges in conjunction with a cathode ray oscilloscope. The arrival of the flame front at the arresters, or at the centre of a blank cover, was also recorded. Each vent was fitted with an ionisation gap and all the gaps on a cover were wired in parallel, thus recording the most advanced part of the flame.

Table 2

Crimp heights (in) of arresters

Diameter of arrester in	Thickness of arrester (in) 1.5	0.75	Fraction of crimped area open to gas flow
1.15	0.017	-	0.79
	0.024	-	0.82
	0.045	-	0.90
2.25	0.045	-	0.90
	-	0.024	0.82
	-	0.017	0.79
4.30	0.045	-	0.90

Table 3

Perforated sheeting arresters

Diameter of arrester in	Diameter of perforations in	Thickness of arrester in	Area of aperture per unit area of sheeting
1.15	0.10	0.03	0.44
1.15	0.03	0.02	0.26

Table 4

Wire gauze arresters

Diameter of arrester in	Mesh number	Wire gauge s.w.g.	Mesh width in	Wire diameter in	Area of aperture per unit area of gauze
1.15	28	28	0.021	0.015	0.35
1.15	60	37	0.010	0.007	0.35

Procedure

Apart from some experiments with the 3 ft^3 explosion vessel, all vessels were tested inside the 15.6 ft^3 cubical box (Fig 2), which was sealed with a polythene diaphragm in tests with flame arresters.

A 4 per cent by volume propane-air mixture was metered into the explosion vessel and flowed through the vents into the outer cubical box, from which it passed to waste. When this box was fitted with a diaphragm the contents were stirred by a fan, and ten changes of mixture were passed. The fan was then switched off. The gas mixture inside the explosion vessel was ignited, and if the explosion did not pass into the outer box the contents were ignited subsequently by a second spark.

Visual examination was made of the arresters after every sequence of tests with a given position of the igniting source and, in a few cases, after each test. No explosion pressures are quoted for tests in which the arresters suffered structural damage.

Results

Dependence of explosion pressure on vent area

(i) Open vents

Maximum explosion pressures were measured with a range of explosion vessels having open vents, with no flame arresters. The maximum explosion pressures obtained in the $^1/_{10}$ - 3 ft^3 vessels with vents in the top surfaces are shown in Fig 4-7. With the $^1/_{10}$ ft^3 vessel the explosion pressures with the two larger vent areas were largely determined by intense acoustic vibrations, but in the remaining tests with this and the other explosion vessels no such vibrations were evident and the pressure/time curves were smooth. Typical examples are shown in Fig 8.

When single vents were used there was little difference between the maximum pressures obtained with the igniting source remote from the vent or in the centre of the vessel; often the central position gave the highest pressure. With multiple vents the highest maximum pressures occurred with the igniting source remote from the vents, and the lowest maximum pressures were obtained with the igniting source near the vents. The central position gave intermediate values.

In the tests represented in Fig 5-7 in which three vents were used, each vent was in a corner of the vessel cover. Some further tests were carried out using $^1/_3$ ft^3 vessel having three vents situated diagonally across the cover. A comparison is given in Table 5 of the two sets of results.

Table 5

Maximum explosion pressures (lb in^{-2}) in $^1/_3$ ft^3 vessel with three vents on diagonal or at corners of cover

Position of vents	Position of igniting source Near to vents	Remote from vents
On diagonal	1.8	2.4
In corners	1.7	3.0

The effect of distribution of vents over two covers was investigated with the $^1/_3$ ft^3 vessel. The maximum explosion pressures with 4 vents, 1.15 in diameter, in one cover are listed in Table 6 together with the pressures for two vents of the same diameter in each of two opposite covers. Distribution of the vents reduced the maximum explosion pressure obtained with the most unfavourable position of igniting source.

Table 6

Maximum explosion pressures (lb in^{-2}) in $^1/_3$ ft^3 vessel with different vent distributions

Distribution of vents	Position of igniting source Near vents	Central	Remote from vents
One cover with four vents	1.0	1.5	2.4
Two covers, each with two vents	1.8	2.0	

(ii) Vents fitted with arresters

Each of the explosion vessels was tested when protected with crimped ribbon arresters of thickness 1.5 in and crimp height 0.045 in. The results for the $^1/_{10}$ ft^3 vessel are shown in Fig 9; in these tests only single vents were used. The pressure records showed intense acoustic vibrations and with the two larger vents the vibrations largely determined the maximum explosion pressure. With the smallest vent (K = 30) the vibrations were either absent or were of small amplitude. Multiple vents were used in experiments with the $^1/_3$ ft^3 vessel, and in Fig 10 the maximum exmplsion pressures are plotted against the venting ratio, K. In these tests all vents were in the vessel cover. The variation of pressure with K was similar to that for open vents

(Fig 5), but the pressures were about three times as high. Further results were obtained when two opposite walls of the $^1/_3$ ft^3 vessel were vented, and are given in Fig 11. The shaded area on the graph indicates the limits of maximum pressures obtained with the same number of arresters in a single cover. All the maximum explosion pressures for distributed vents fell within the shaded area. A relatively large amount of venting was required with the 1 ft^3 vessel to avoid thermal damage to the arresters; this type of damage is considered in more detail below. The results for the 1 ft^3 vessel are given in Table 7, all vents were in the cover of the vessel and the diameter of each arrester was 4.3 in. A limited number of experiments was carried out with the 3 ft^3 vessel, and to avoid thermal damage to the arresters the vents were situated in two opposite covers of the vessel. Two 4.3 in diameter arresters, of crimp height 0.045 in and thickness 1.5 in, were mounted in either cover. The maximum explosion pressure was 0.3 lb in^{-2}, with the igniting source central or near one pair of vents, and no thermal damage to the arresters was obtained.

Table 7

Maximum explosion pressures (lb in^{-2}) in 1 ft^3 vessel with arresters of thickness 1.5 in, diameter 4.3 in, and crimp height 0.045 in.

Number of arresters	K	Position of igniting source		
		Near vents	Central	Remote from vents
4	2.45	1.4 a	1.1 a	0.50 a
3	3.30	1.4 a	0.40	0.45
2	4.90	0.45	0.50	0.50

('a' indicates that maximum pressures were caused by acoustic vibrations)

The effect of variation of crimp height on the maximum explosion pressure was investigated. The results given in Table 8 are for the $^1/_3$ ft^3 vessel fitted with five small arresters. Further tests were done with the 1 ft^3 vessel and these results are given in Tables 9 and 10. In all experiments the arresters were mounted in the cover of the vessel.

The possibility was investigated of ignition very close to the crimp allowing a slow flame to propagate through the arrester to the external gas mixture. An arrester of crimp height 0.045 in, diameter 4.3 in, was mounted in the $^1/_3$ ft^3 explosion vessel. A series of tests was carried out in which the igniting spark was at the periphery of the arrester. The spark passed directly from an electrode to the arrester ribbon in 10 tests; and between electrodes sited 1/8, 1/4, ½ and 1 in below the arrester (8 tests in each position). In another 8 tests the spark passed directly from an electrode to the ribbon 1 in from the periphery of the arrester. In no tests did the flame propagate through the arrester.

Some exploratory tests were carried out with wire gauze and perforated metal sheeting arresters, using the 1/3 ft^3 explosion vessel fitted with four 1.15 in diameter vents in the cover. Both types of arrester failed to contain the explosion within the vessel when the igniting source was remote from the vents. In addition, both the 28- and the 60-mesh gauzes were seen to glow during and after the explosion. Because of the unfavourable results the experiments with gauze and perforated metal sheeting were not continued.

Table 8

Maximum explosion pressures (lb in^{-2}) in 1/3 ft^3 vessel with five arresters of thickness 1.5 in, diameter 1.15 in, and various crimp heights.

crimp height in	K	Position of igniting source		
		Near vents	Central	Remote from vents
0.045	12	1.3	2.3	3.3
0.024	12	1.0	1.8	2.5
0.017	12	0.95	1.5	2.8

Table 9

Maximum explosion pressures (lb in^{-2}) in 1 ft^3 vessel with arresters of thickness 0.75 in, and diameter 2.25 in.

crimp height in	Number of arresters	K	Position of igniting source		
			Near vents	Central	Remote from vents
0.024	5	7.2	0.60	0.65	0.75
0.017	4	9.0	1.0	1.4	2.2

Table 10

Maximum explosion pressures (lb in^{-2}) in 1 ft^3 vessel with arresters of diameter 2.25 in. Igniting source control

Crimp height in	Arrester thickness in	Number of arresters	K	Maximum explosion pressure (lb in^{-2})
0.045	1.5	4	9.0	1.0
0.024	0.75	4	9.0	1.2
0.017	0.75	4	9.0	1.4

Thermal damage to arresters

For an enclosure to be successfully protected with flame arresters it is essential that the maximum explosion pressure should be reduced to an acceptable value and also that the arresters should not suffer structural damage due to mechanical or thermal effects, even after repeated exposures to the explosions. The importance of the thermal damage effect (melting, oxidation etc.) increased as the volume of the explosion vessel was enlarged. With crimped ribbon arrestors constructed from the alloy used for the experiments the acceptable vent area for the two large explosion vessels was in fact governed by the problem of avoiding thermal damage to the arresters.

The thermal damage increased in a somewhat stepwise manner as the area of the arresters was reduced. The smallest detectable damage was a yellow discoloration, which was followed by discoloration to a dark blue shade sometimes accompanied by a loss of lustre. The next stage of damage was classified as structural and was noticeable at the leading edge of the metal ribbon, exposed to the explosion. The edge was eroded and it curled over in places. Further reduction of arrester area resulted in melting of the ribbon edge and beads of molten metal or oxide were observed, accompanied by a reduction in arrester thickness. In all explosion vessels damage was greatest when the ignition source was situated near the vents.

With the 1/10 ft^3 explosion vessel no structural damage was observed in the 4.3 in and 2.25 in diameter arresters, but a 1.15 in diameter arrester showed erosion and curling of the ribbon edge after two explosions. All these arresters were of 0.045 in crimp height. Five 1.15 in diameter arresters fitted to the 1/3 ft^3 explosion vessel oxidised heavily at the edge of the ribbons, with crimp heights of 0.045, 0.024 and 0.017 in. A single arrester of 4.3 in diameter was however only slightly discoloured, and it is likely that a smaller diameter could be used safely. With the 1 ft^3 vessel two arresters, each 4.3 in diameter and crimp height 0.045 in, appeared to be the smallest area that could be safely applied to avoid structural damage. Even so, considerable surface erosion and discolouration was evident after the tests and this indicated that there was little scope for a substantial reduction of vent area without structural damage occurring. The vent area could be reduced by using arresters of smaller crimp height. Five arresters of diameter 2.25 in and crimp height 0.024 in were found to be adequate, as were four arresters of the same diameter and of crimp height 0.017 in.

Table 11

Minimum areas of arresters to avoid structural damage

Volume of explosion vessel ft^3	Number of arresters	Diameter of arresters in	Crimp height in	Total area of arresters in^2	Arrester area per ft^3 of vessel in^2	Corrected arrester area per ft^3 of vessel in^2	Maximum explosion pressure $lb\ in^{-2}$	Distribution of arresters
1/10	1	2.25	0.045	4.0	40	29	1.9	In one cover
1/3	1	4.3	0.045	14.6	44	38	0.3	In one cover
1/3	4	1.15	0.045	4.2	12.5	11	2.0	In two covers
1	2	4.3	0.045	29.2	29	24	0.5	In one cover
1	5	2.25	0.024	20.0	20	16	0.8	In one cover
1	4	2.25	0.017	16.0	16	13	2.2	In one cover
3	4	4.3	0.045	58.4	20	17*	0.3	In two covers

* No flammable mixture outside vessel.

A summary of the results is included in Table 11 which gives approximate values for the minimum safe areas of arrester, within the size intervals available from commercial production. Later tests with crimped ribbon arresters made of different metals has given evidence that arresters can readily be constructed to be more resistant to thermal damage than those used in the investigations reported in this Note. The results will be reported later.

Flame speeds

Measurements were usually made of flame speeds in at least one test for each vent area and each position of the igniting source. The measurements were omitted in a few tests with the 1/10 and 3 ft^3 explosion vessels. The highest flame speeds always occurred when the igniting source was remote from the vents; the speeds with the igniting source in the centre of the vessel were lower. The minimum flame speeds were measured between the igniting source and the wall opposite to the vents. The ranges of flame speeds given in Table 12 are for open vents in the cover of the explosion vessels. In most cases the maximum explosion pressure developed when the flame front arrived at the vent; in some tests with smaller vessels the maximum pressure occurred after the flame arrived at a vent, but before it had propagated to the bottom of the vessel.

Table 12

Ranges of flame speeds with open vents

Volume of explosion vessel ft^3	Minimum flame speed ft s^{-1}	Maximum flame speed ft s^{-1}
1/10	2.7	20
1/3	3.7	19
1	1.7	19
3	4.4	19

The insertion of flame arresters in the vents made little difference to the flame speeds. Table 13 shows the ranges of flame speeds obtained with arresters of crimp height 0.045 in and thickness 1.5 in.

Table 13

Ranges of flame speeds with vents fitted with arresters

Volume of explosion vessel ft^3	Minimum flame speed $ft\ s^{-1}$	Maximum flame speed $ft\ s^{-1}$
1/10	4.4	20
1/3	3.7	18
1	2.8	18

Mechanical protection of arresters

In industrial use some form of protection may be required on the exposed face of the arresters to prevent mechanical damage. A simple method of protection would be to fix a protective shield a short distance away from the arresters. Some experiments were carried out to investigate the effect of such a shield on the maximum explosion pressures developed in the 1/3 ft^3 vessel. A mild steel plate was placed in front of four 1.15 in diameter arresters, of crimp height 0.045 in and thickness 1.5 in, and the position of the plate was varied so that the area on the periphery of each arrester was between one half and double the cross-sectional read of the arrester. The results summarised in Table 14 include values of explosion pressures when no shield was in position.

Table 14

Maximum explosion pressures ($lb\ in^{-2}$) for shielded arresters

Position of igniting source	No shield	Peripheral area half cross-sectional area	Peripheral area equal to cross-sectional area	Peripheral area double cross-sectional area
Remote from vents	2.8	5.0	3.3	2.9
Central	1.5	2.4	1.9	1.3
Near vents	0.95	1.3	1.1	0.80

Discussion

Use of flame arresters

The experiments have shown that enclosures up to 3 ft^3 in volume can safely be protected with flame arresters against propane-air explosions. The ignition of flame from the enclosures was prevented, the explosion pressures could be reduced to low values, and thermal or mechanical damage to the arresters could be avoided. Adequate precautions could readily be obtained with crimped ribbon arresters, which are commercially available, but arresters made from wire gauze or perforated metal were not successful and were not considered further. In assessing the adequacy of an arrangement of the commercial crimped ribbon arresters, two principal factors have to be considered. These were the maximum explosion pressure developed and the avoidance of thermal damage to the arresters.

Thermal damage to arresters

With the commercial arresters used, and with propane-air explosions, the avoidance of thermal damage governed the area of arresters required. The necessary areas of arresters, per unit volume of the vessel, were shown in Table 11 and diminished as the crimp height decreased. The area of arrester could also be reduced if it were divided equally between two opposite walls of the vessel. Because of restrictions on the available diameters of the arresters, the relationship between area of arresters required and the volume of vessel could not be established precisely.

Some previous large-scale work had been reported [3] using 66 and 200 ft^3 vessels, mainly with wire gauze arresters and with one crimped ribbon arrester. On the basis of these results it was shown that the mass of the arrester, rather than the areas of vent, determined the volume of vessel that could be protected without the arrester being thermally damaged. The arresters were not tested under the most severe conditions. It was assumed in the calculations that the heat absorbed by the arrester was distributed uniformly throughout the metal. Evidence in support of the assumption was that when damage was caused to the gauze arresters, it regularly penetrated to the side of the arrester remote from the flame. Insufficient information was available to establish whether the same criterion applied to the crimped ribbon arrester in the large-scale test. However, using the available data, it may be shown 3, 4, that the volume of crimped ribbon arrester expected per cubic foot of vessel volume would be 16.1 in^3, for a crimp height of 0.045 inch. If the arrester thickness were 1.5 in, the area of arrester would be 10.7 in^2. The area is substantially less than the range of values reported in Table 11 (22-33 in^2/ft^3) for the present work.

As this work was with small-scale vessels, the explosions would be of shorter duration; usually the time required to attain maximum explosion pressure varies with the cube root of the vessel volume. In addition, visual observation of the arresters showed that damage to the ribbon commenced at the leading edge exposed to the flame. The heat absorbed by the arresters was thus unevenly distributed, and the simple treatment applied in large-scale tests, would underestimate the required area of vents. By using the area of arrester required per unit volume of vessel, as in Table 11, the experimental results can be applied directly to practical situations for small enclosures. A detailed analysis of the heat transfer to the arrester ribbon has not been carried out, because experiments to be reported subsequently showed that arresters made from other metals were considerably more resistant to thermal damage. With the new arresters, which are not yet commercially available, the area of venting could be so reduced that the pressure developed during the explosion became the dominant factor.

Maximum explosion pressures

The relation between the vent area and the maximum explosion pressure, was determined for open vents (Fig.4-7) and for vents protected with arresters (Fig 9-11). In each figure the explosion pressure was plotted as a function of the ratio K, on logarithmic scales, and approximately linear relationships were obtained. All vents were in the cover of the explosion vessels.

Relationships of this type may be derived on simple theoretical grounds. Considering firstly open vents, it is assumed that the maximum explosion pressure was governed by the resistance to gas flow caused by the vents, and that the pressure gradient within the explosion vessel was relatively small. It is also assumed that the flame front acted as a piston expelling unburnt gas through the vent. The latter assumption is an approximation, because the flame front was of complex shape, but the experiments showed that pressures were higher when the igniting source was sited at a distance from the vents. The maximum explosion pressure usually occurred when the flame front arrived at the vents. For the isothermal flow of an ideal gas[5]

$$G = Ca \sqrt{2\rho_o (P - P_o)} \quad \text{approximately}$$

where
- a = area of vent
- C = discharge coefficient
- G = mass rate of flow through vent
- P = absolute explosion pressure inside vessel
- P_o = atmospheric pressure
- ρ_o = density of gas at atmospheric pressure

Now

$$G = VA\rho_1 = VA\rho_o \frac{P}{P_o}$$

where
- A = cross sectional area of explosion vessel
- V = gas velocity in explosion vessel
- ρ_1 = density of gas in explosion vessel

Hence

$$\frac{V^2 A^2 \rho_o}{C^2 a^2} \cdot \frac{P^2}{P_o^2} = 2 (P - P_o)$$

$$\frac{A}{a} = K$$

$$P^2 - \frac{2\,C^2\,P_o^2}{V^2\,K^2\,\rho_o} \cdot P + \frac{2\,C^2\,P_o^3}{V^2\,K^2\,\rho_o} = 0$$

$$P = \frac{C^2\,P_o^2}{V^2\,K^2\,\rho_o}\left[1 \pm \sqrt{1 - \frac{2\,V^2\,K^2\,\rho_o}{C^2\,P_o}}\right] \quad \ldots\ldots\ldots \quad (1)$$

For the present work, in practice interest concerns explosions in which the maximum explosion pressure is low, i.e. $\rho_1/\rho_o = 1$ approximately. As a further simplification

$$G = V\,A\,\rho_o = C\,a\sqrt{2\,\rho_o\,(P - P_o)}$$

i.e. $$\frac{V^2\,A^2\,\rho_o}{2\,C^2\,a^2} = (P - P_o)$$

$$\Delta P = P - P_o = \frac{V^2\,K^2\,\rho_o}{2\,C^2} \quad \ldots\ldots\ldots \quad (2)$$

The maximum flame speed for each vessel was about 19 ft/sec (Table 12); but the corresponding gas velocity would be slightly less because the flame was propagating through the gas mixture. With no heat losses, the maximum flame temperature would be 2260° K and the expansion ratio based on an initial temperature of 300° K would be 7.5, approximately. That is, one volume of initial gas mixture would yield 7.5 volumes of hot combustion products. For a vent ahead of the flame, the maximum gas velocity would then be 19 x 6.5 ÷ 7.5 = 16 ft/sec approximately. The Reynolds Number with this gas velocity in a vessel of 1 ft sq cross-section is approximately 10^5; hence, c = 0.6 and is relatively insensitive to variation in the vessel dimensions and numbers of vents, over the range studied. ρ_o = 0.0808 lb/cu ft

$$\text{Hence } \Delta P = \frac{128 \times 0.0808}{0.36 \times 32 \times 144}\,K^2 \text{ lbf in}^{-2}$$

$$= 0.0062\,K^2 \text{ lbf in}^{-2} \quad \ldots\ldots\ldots \quad (3)$$

Equation (3) is represented by a broken line in Fig 12, which summarises the maximum pressures measured with a range of explosion vessels. The equation is in good agreement with the results over the relevant low pressure range (that over which compression of the gas could be neglected). This agreement is of interest, because the maximum pressure varied with the square of K, and also appears to vary with V^2. These findings differ from the behaviour observed in the explosion venting of industrial drying ovens [6] in which the maximum pressure with no vent cover varied directly with K, and with the standard burning velocity. The values of K were usually small, less than 4, and hence the pressure drop across the vent may not have been the principal effect governing the explosion pressure. The smallest oven of 8 ft^3 volume and the largest, for which results were reported, was 98 ft^3, i.e. the volumes were much greater than in the present work. The lack of agreement with the results for drying ovens will be examined again when a faster burning gas is used in the small explosion vessels.

When vents were covered with flame arresters, the increase in explosion pressures should be related to the structure of the arresters. For crimped ribbon arresters, the relation between pressure drop ($\Delta P'$), gas velocity (U), fraction of area open to gas flow (e), thickness of arrester (L), hydraulic diameter of aperture (d), is of the form [7]

$$\Delta P' = 4.1 \times 10^{-6} \left(\frac{U}{e} \right)^{1.082} \frac{L^{0.665}}{d^{1.583}}$$

For an arrester of crimp height 0.045 in, (Table 2), d = 0.045 x 0.83 = 0.037 in, L = 1.5 in, e = 0.90, $U \doteq VK = 16\ K$ ft/sec, because maximum flame speed was the same as with open vents.

$$\text{Hence} \quad \Delta P' = 2.2 \times 10^{-2}\ K^{1.082}\ \text{lbf in}^{-2} \quad \ldots\ldots\ldots \quad (4)$$

The contribution of the arresters to the explosion pressure, given by equation (4) was comparable with that from the vents, given by equation (3). For example, when K = 10,

eq. (3) gave $\Delta P = 0.62$ lbf in^{-2}

and eq. (4) gave $\Delta P' = 0.26$ lbf in^{-2}

Thus total calculated explosion pressure = 0.88 lb/sq in, in reasonable agreement with the experimental results (Fig 9 and 10). As $\Delta P'$ was approximately proportional to K, whereas ΔP varied with K^2, the contribution of the arresters to the total pressure would be relatively greater at low values of K. With fast burning gases, the contribution of the vents appears likely to dominate, with ΔP varying with V^2 and $\Delta P'$ varying only with $V^{1.082}$.

The use of an external shield to protect the arresters from mechanical damage, was shown to be feasible, (Table 14). To prevent the explosion pressure from being significantly increased, the peripheral area round the shield should be twice the vent area; but only a slight increase in pressure was found when the two areas were equal. The external shield did not appear to affect the maximum flame speeds, but an internal shelf or other obstacle would be expected to affect the explosion. Explosion vessels containing various obstacles have been tested in further work, to be reported later.

As the maximum flamespeed was only 19 ft/sec, the crimped ribbon arresters were easily able to quench flames. For instance, it may be calculated [4], that an arrester of thickness 1.5 in, crimp height 0.045 in, and free area 0.90, would be able to quench propane-air flame with velocities up to 490 ft/sec. The arresters of smaller crimp height, used in the present work, would be even more effective. Failure of equipment due to the passage of flames through the crimps may therefore be discounted for propane and other gases of similar burning velocity.

Conclusions

1. Enclosures up to 3 ft^3 volume could be safely protected by flame arresters. Factors controlling the vent area required, were the maximum explosion pressure and thermal damage to the arresters.

2. With crimped ribbon arresters, which were commercial products, the required vent area was governed by the avoidance of thermal damage to the arresters. In no case did flame propagate through an arrester.

3. The required area of vent depended upon the volume of the enclosure. For cubical enclosures, the area was about 25 per cent of the area of one side of the enclosure.

4. With adequate areas of vent to protect the arresters, the maximum explosion pressure was low, often less than 2 lb in^{-2}.

5. If the vents were distributed on two opposite walls of the vessel, then the total area could be reduced.

6. Approximate relations between maximum explosion pressure, area of vent, and dimensions of the flame arresters, could be accounted for by a simple theory.

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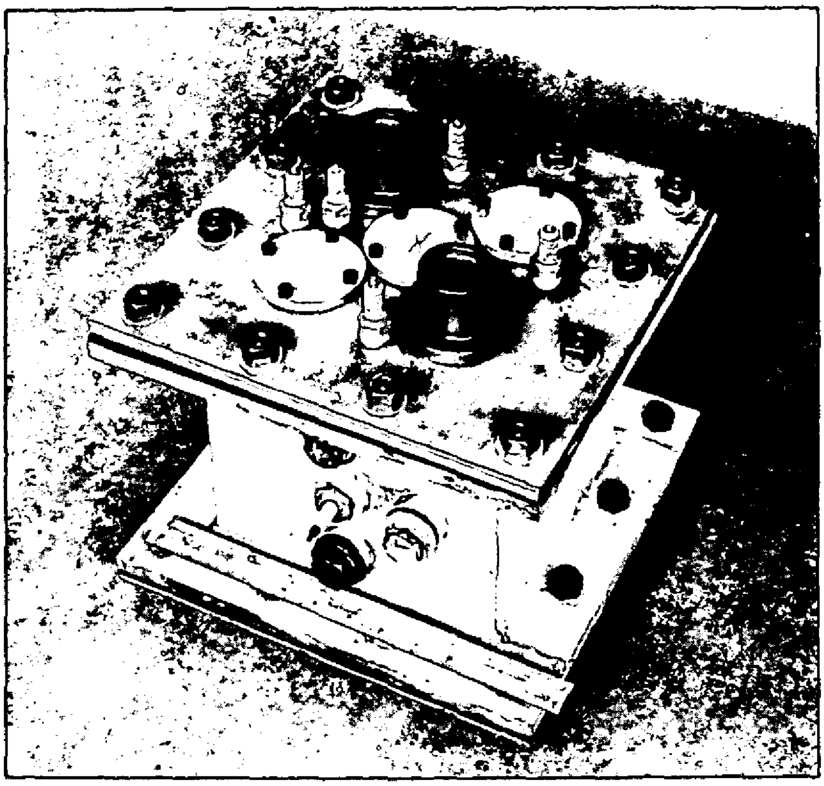


FIG. 1. a) $\frac{1}{3}ft^3$ EXPLOSION VESSEL WITH THE COVER BOLTED ON

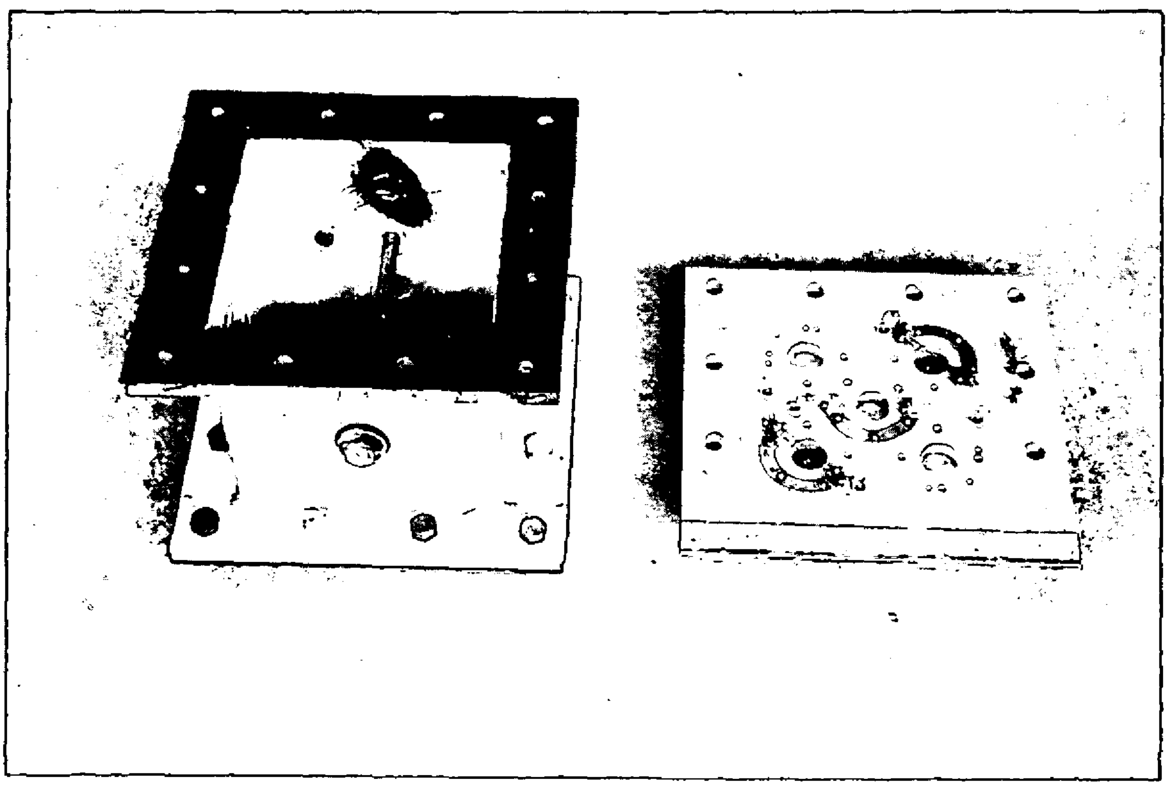


FIG. 1. b) $\frac{1}{3}ft^3$ EXPLOSION VESSEL WITH THE COVER REMOVED

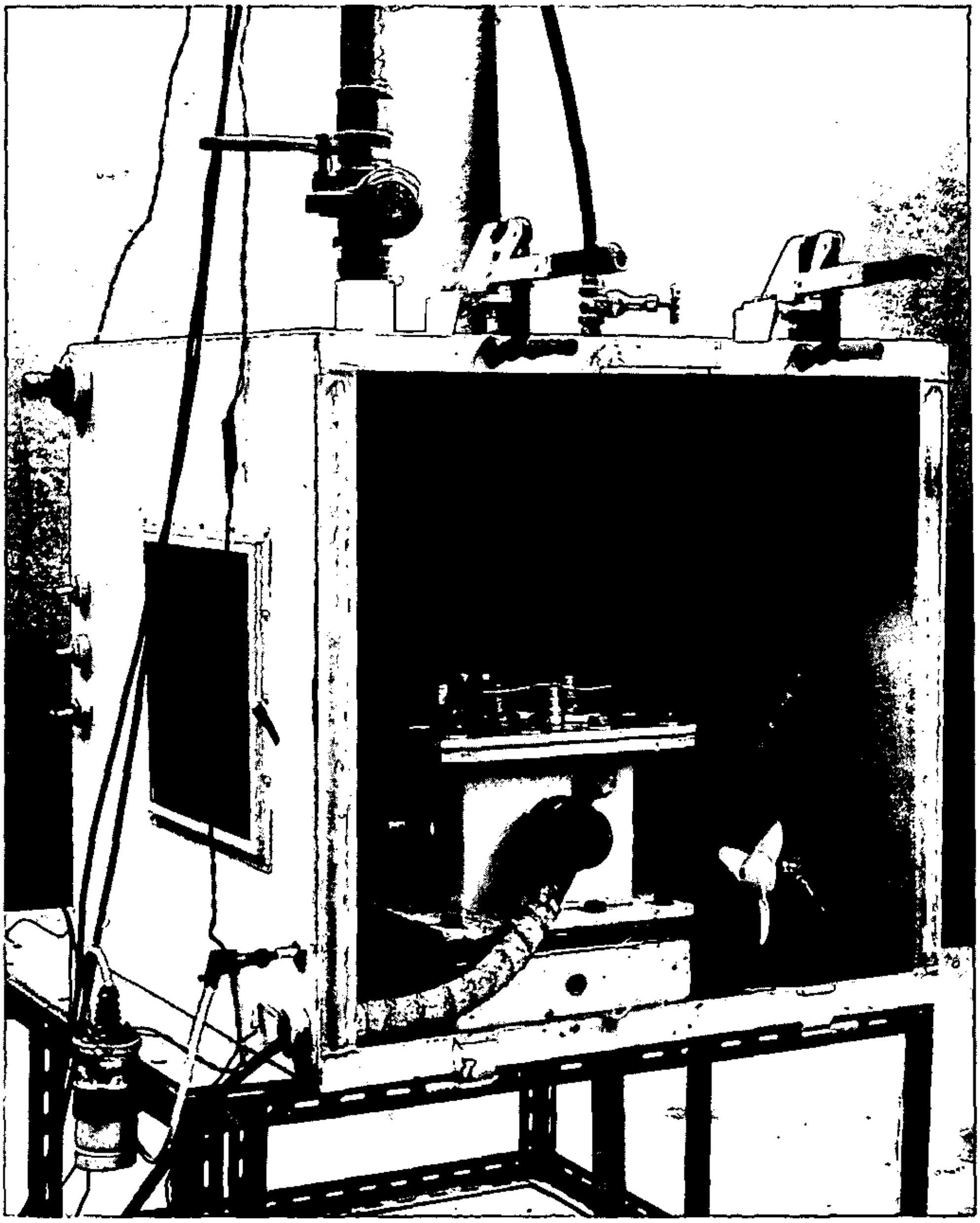


FIG. 2. 15·6ft^3 CUBICAL BOX WITH 1/3ft^3 EXPLOSION VESSEL IN POSITION

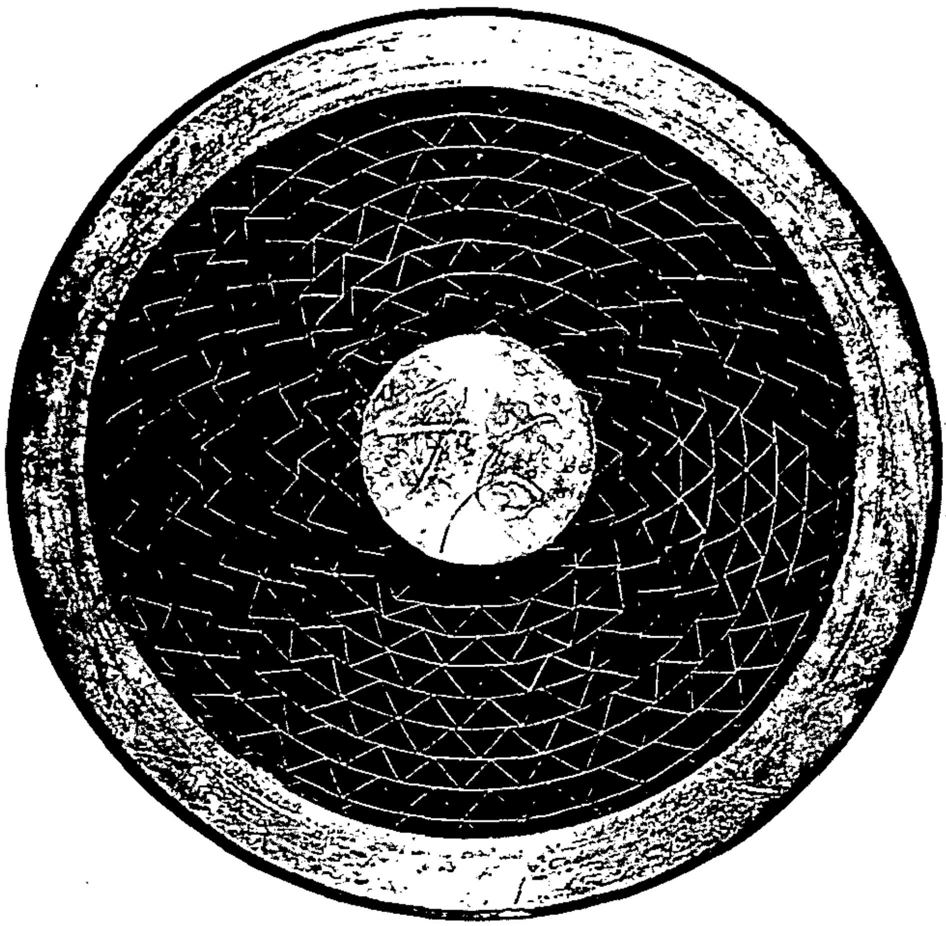


FIG. 3. CRIMPED RIBBON FLAME ARRESTER
(CRIMP HEIGHT 0·045 in.)

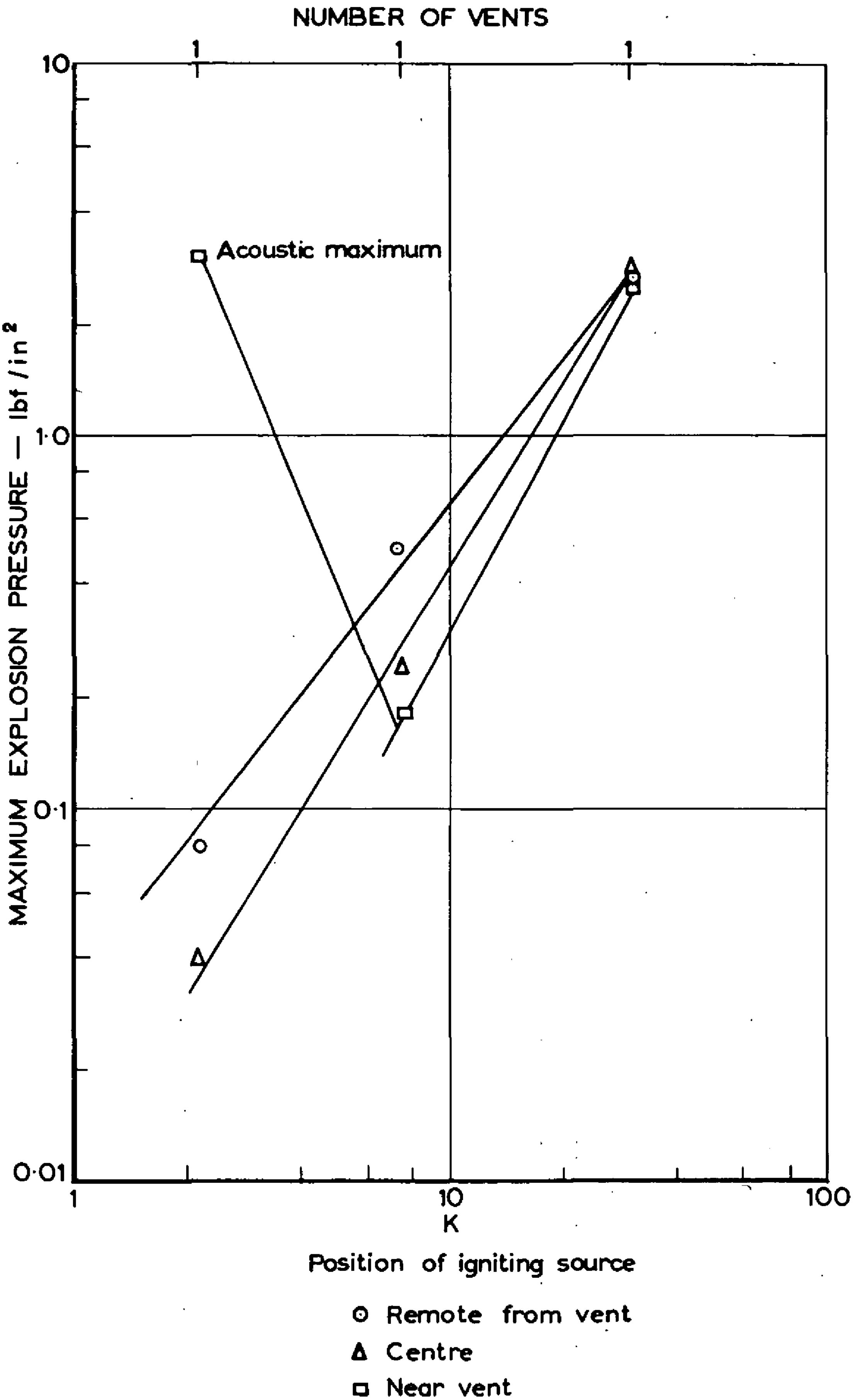


FIG. 4. RELATION BETWEEN VENT AREA AND THE MAXIMUM EXPLOSION PRESSURE—1/10-FT³ VESSEL (OPEN VENTS)

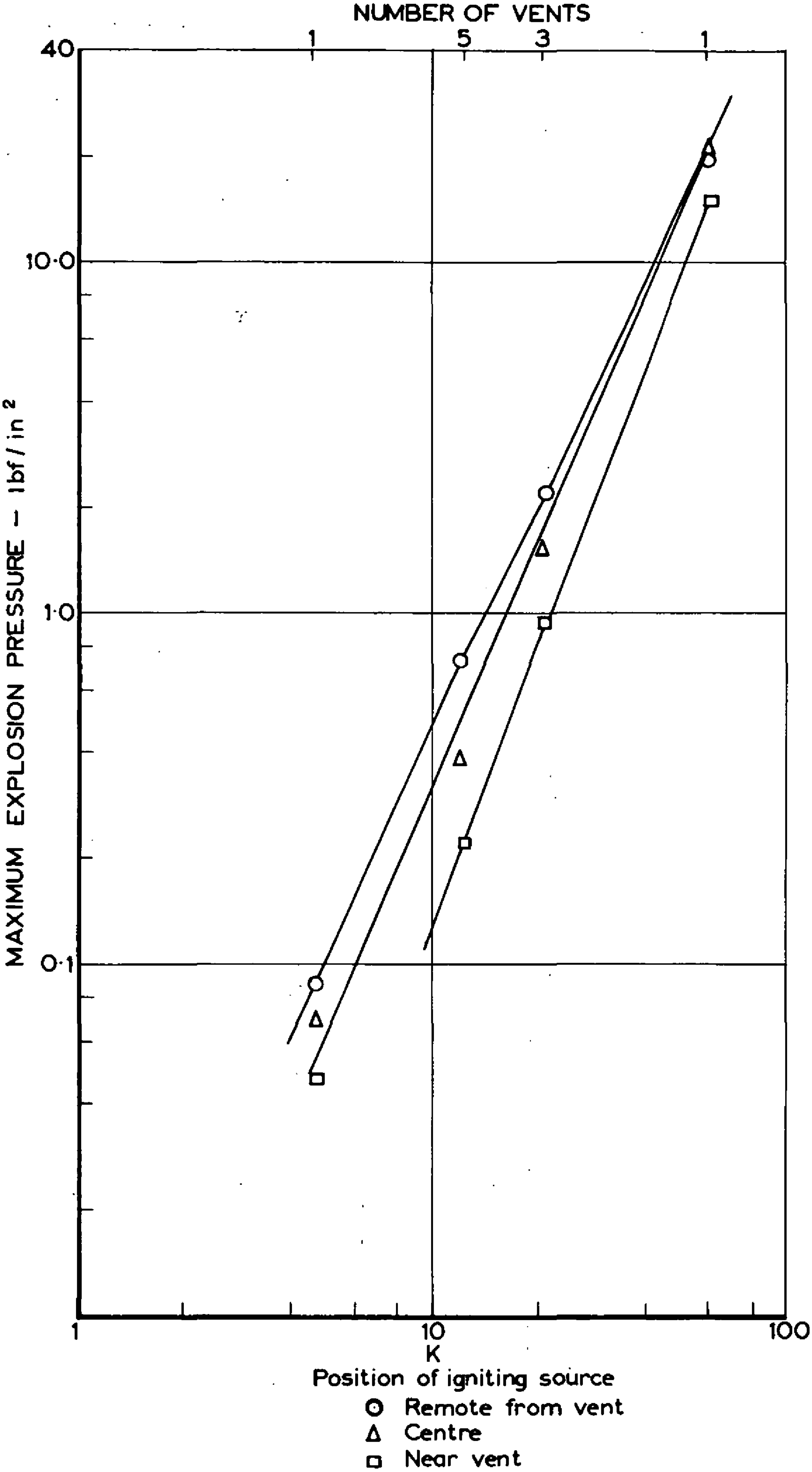


FIG. 5. RELATION BETWEEN VENT AREA AND THE MAXIMUM EXPLOSION PRESSURE — 1/3 - FT³ VESSEL (OPEN VENTS)

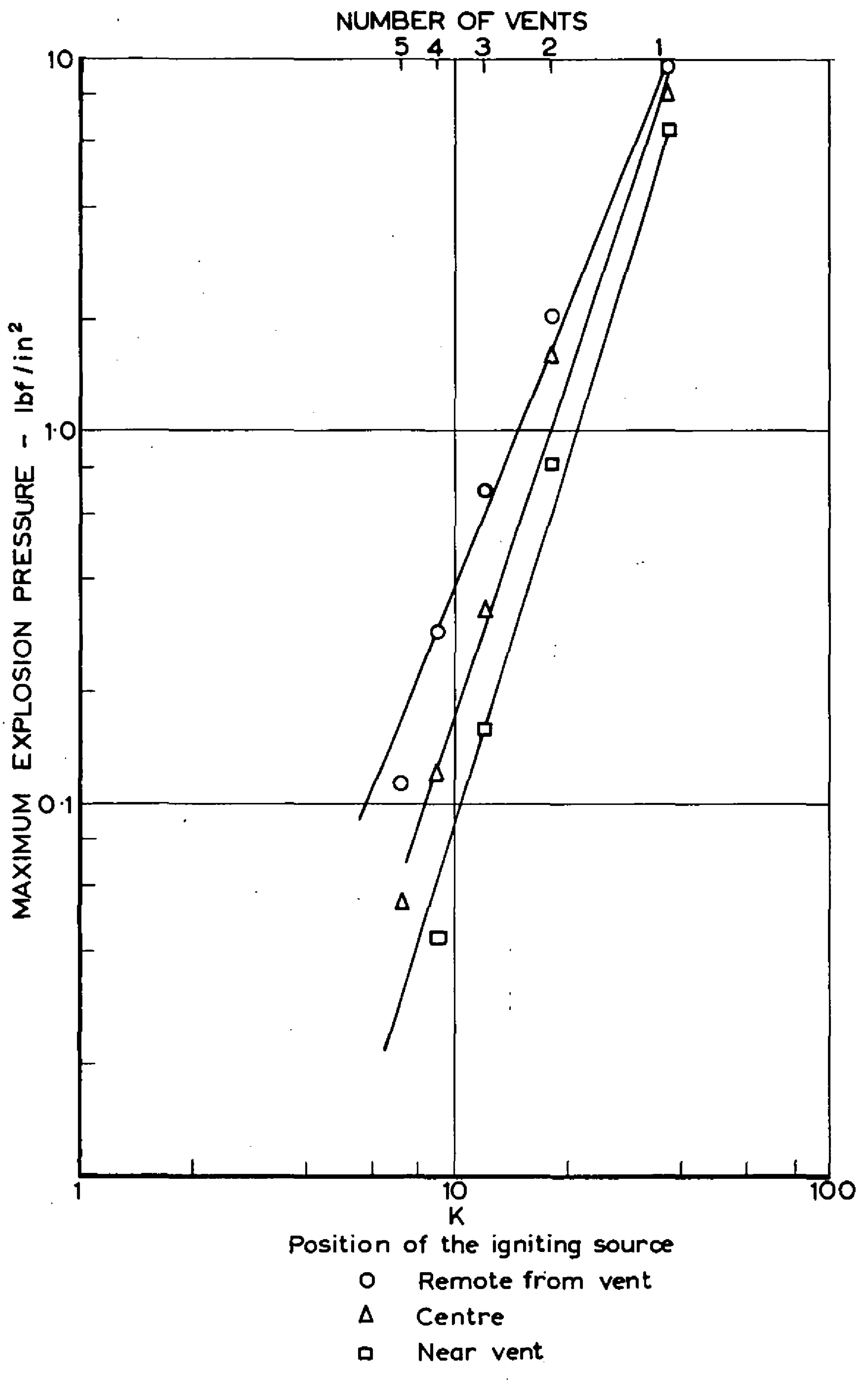


FIG. 6. RELATION BETWEEN VENT AREA AND THE MAXIMUM EXPLOSION PRESSURE—1-FT³ VESSEL (OPEN VENTS)

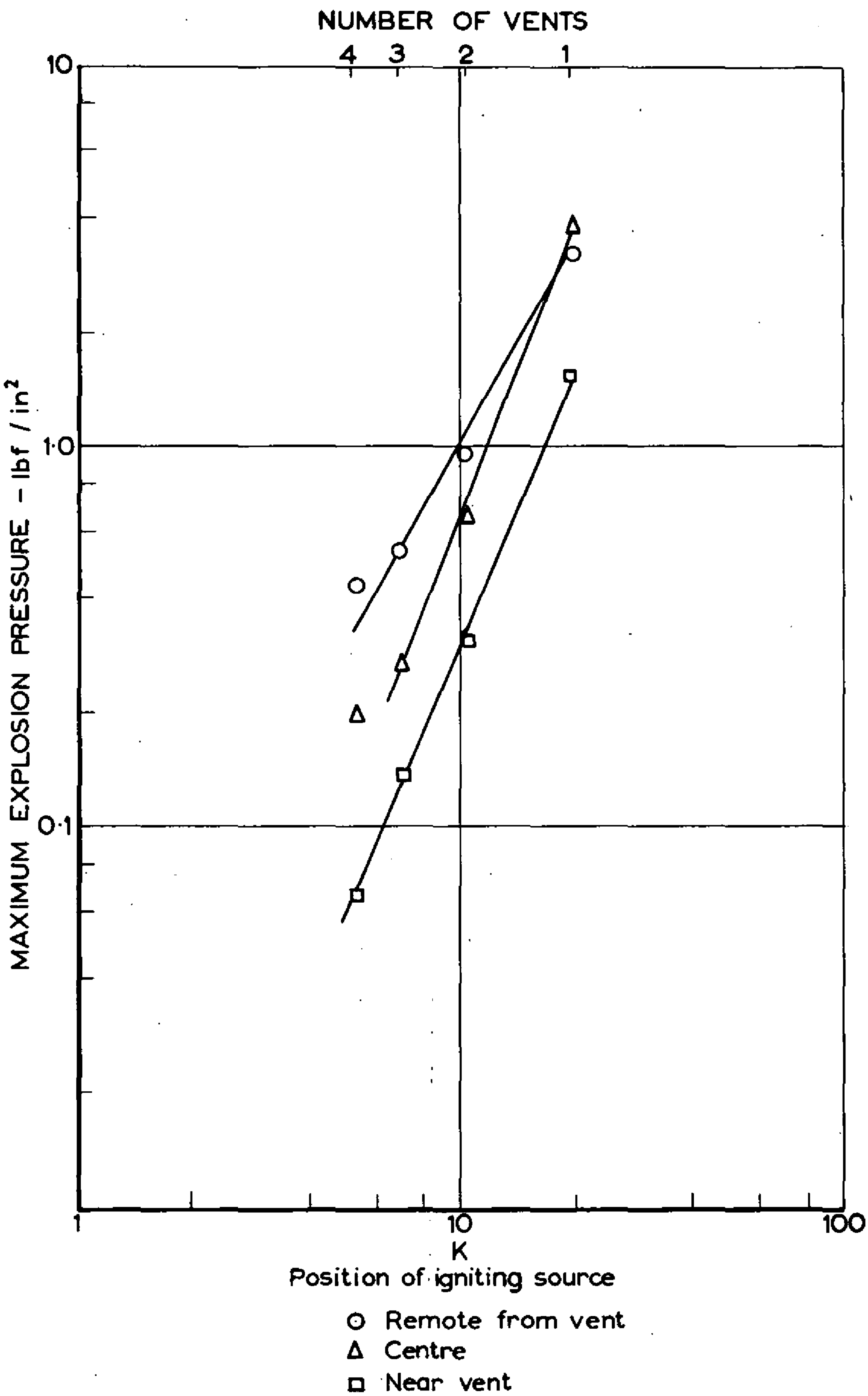
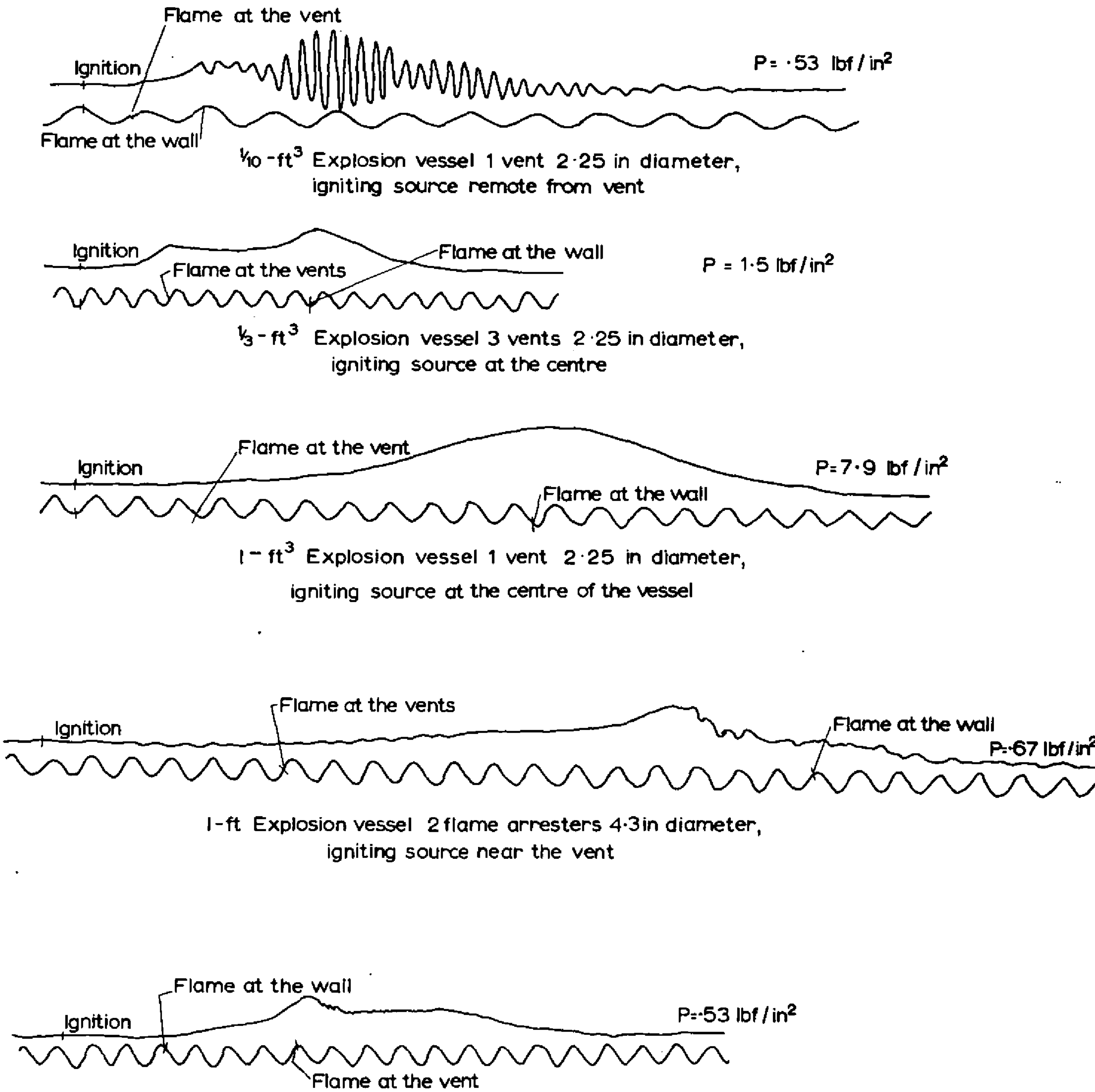


FIG. 7. RELATION BETWEEN VENT AREA AND THE MAXIMUN EXPLOSION PRESSURE—3 - FT³ VESSEL (OPEN VENTS)



$\frac{1}{10}$-ft³ Explosion vessel 1 vent 2·25 in diameter, igniting source remote from vent

$\frac{1}{3}$-ft³ Explosion vessel 3 vents 2·25 in diameter, igniting source at the centre

1-ft³ Explosion vessel 1 vent 2·25 in diameter, igniting source at the centre of the vessel

1-ft Explosion vessel 2 flame arresters 4·3 in diameter, igniting source near the vent

3-ft³ Explosion vessel 3 vents 4·3 in diameter, igniting source remote from vent

P–Maximum pressure
Timing wave 100c/s

FIG. 8. EXAMPLES OF PRESSURE RECORDS

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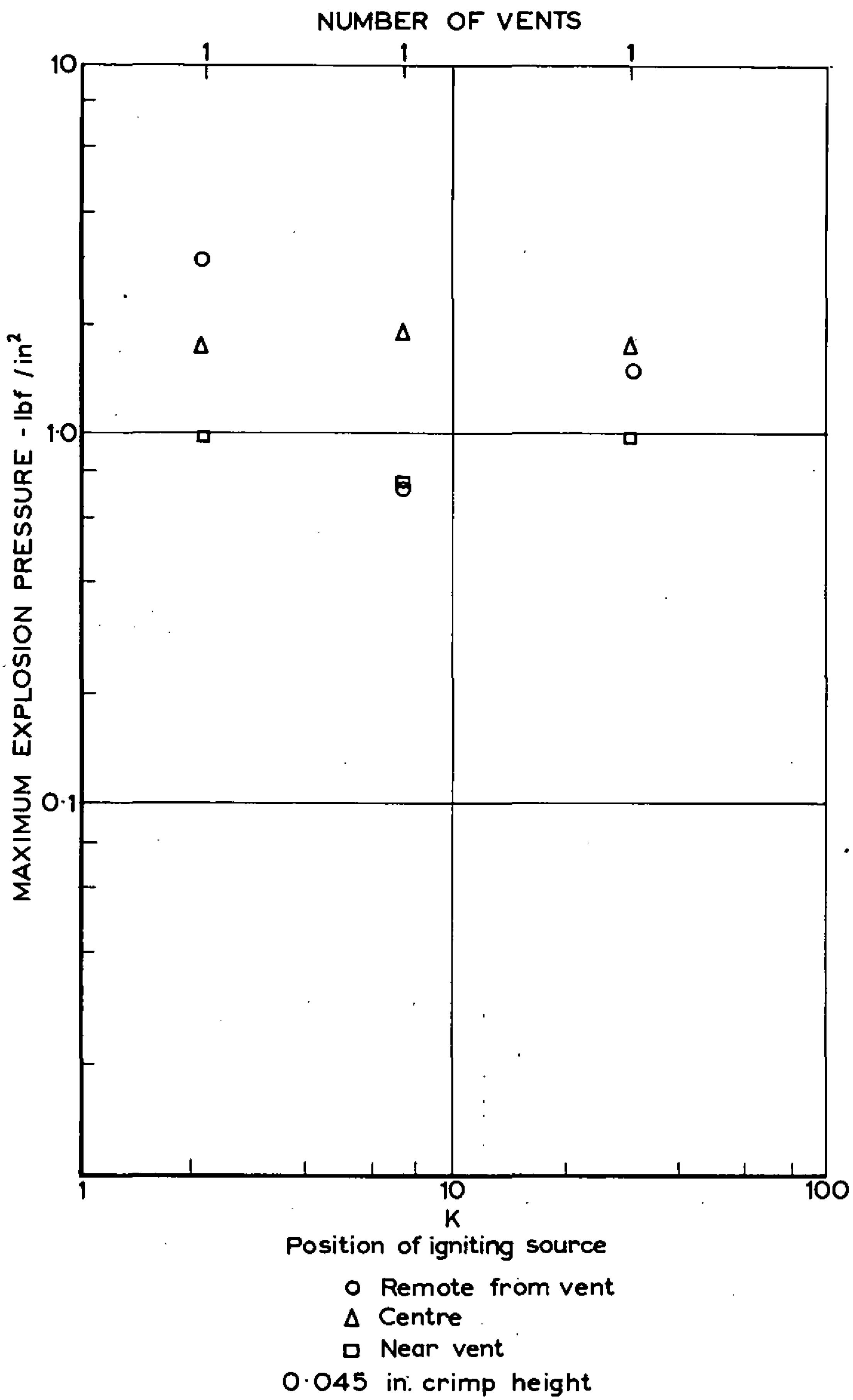

FIG. 9. RELATION BETWEEN VENT AREA AND THE MAXIMUM EXPLOSION PRESSURE–1/10-FT³ VESSEL FITTED WITH CRIMPED RIBBON ARRESTERS.

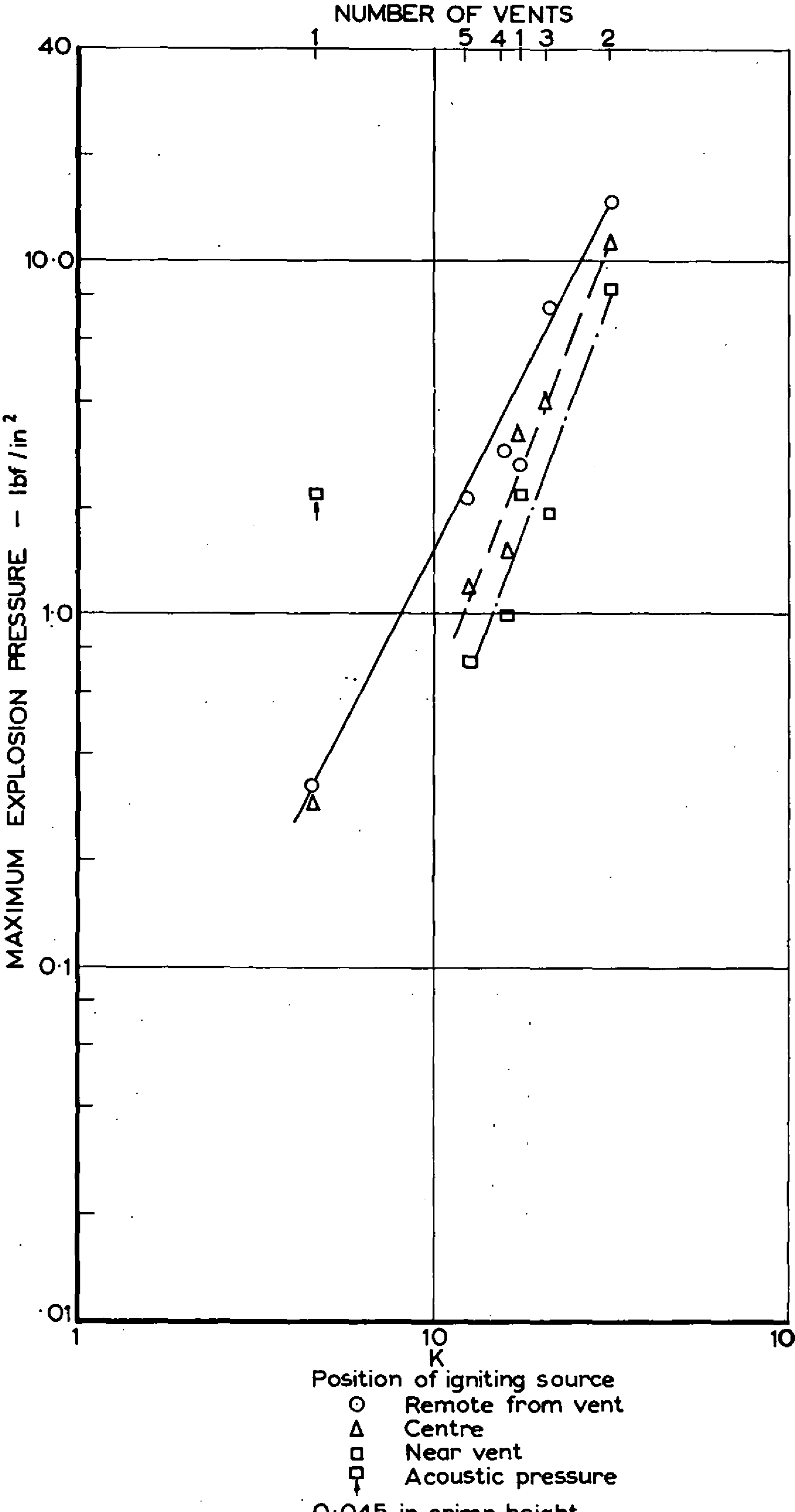

FIG.10. RELATION BETWEEN THE VENT AREA AND THE MAXIMUM EXPLOSION PRESSURE–1/3-FT³ VESSEL VENTS FITTED WITH CRIMPED RIBBON ARRESTERS.

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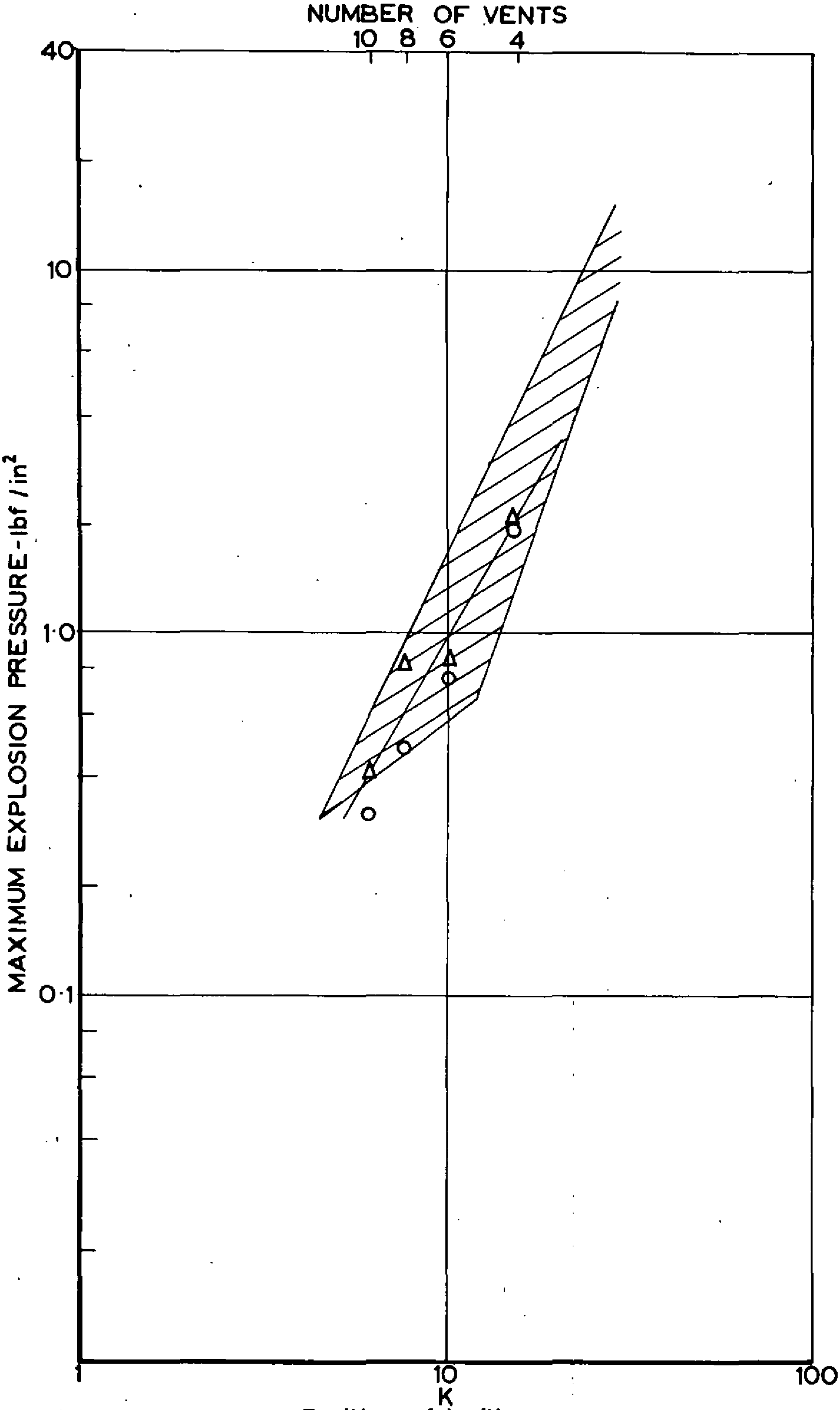

Position of igniting source
Δ Centre
O Near a wall with arresters
0·045 in. crimp height
Shaded area indicates the limits of curves obtained with vents in one cover

FIG. 11. EFFECT OF SPACING OF THE VENTS ON THE TWO OPPOSITE WALLS OF THE VESSEL–1/3-FT³ VESSEL FITTED WITH CRIMPED RIBBON ARRESTERS

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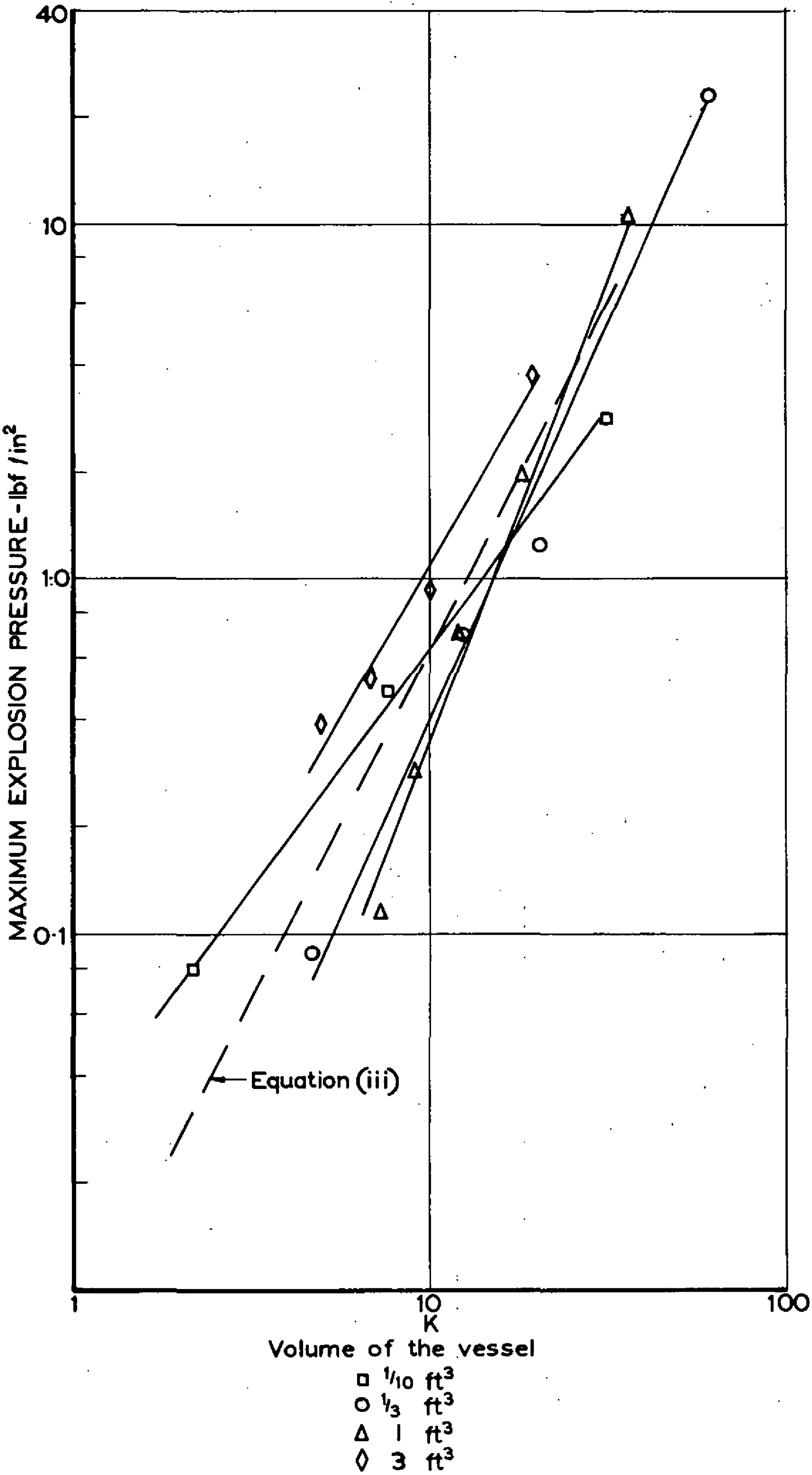

FIG. 12. RELATION BETWEEN VENT AREA AND THE MAXIMUM EXPLOSION PRESSURE (OPEN VENTS)