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THE PROTECTION OF EQUIPMENT WITH FLAME ARRESTERS. (2) EFFECT OF CONTENTS, AND USE OF IMPROVED ARRESTERS

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SUMMARY

The use of flame arresters to prevent the emission of propane-air explosions from cubical vessels has been further investigated. External protection of the arresters with bursting diaphragms or magnetic panels has been shown to be practicable, and the effect of the covers on the explosion pressures was measured. The presence of two-dimensional contents within the vessels, such as a shelf or partition, increased the pressure particularly when more than 25 per cent of the cross-section of the vessel was blocked. Three-dimensional obstacles, such as bulky components, increased the pressure to a lesser extent. Means of minimising the increases were described. Flame arresters made from thermally resistant metals showed marked improvement over those reported previously, and permitted reduction in the required vent area; the area would then usually be governed by the maximum pressure permissible rather than by the need to prevent thermal damage to the arresters. Increased explosion pressures were also caused by multiple ignition sources, but the increases were relatively small in the presence of obstacles.

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INTRODUCTION

In industry, equipment able to generate a source of ignition such as a flame or an electric spark may be used where flammable gases or vapours could be present. If the flammable material penetrated into the equipment it could ignite, propagate flame outside the equipment, and cause an external explosion or fire. The initiation of flame is usually accompanied by an increase in pressure within the enclosure. A method of protecting such equipment using flame arresters is being investigated; the arresters cover vents in the casing of the equipment, thus preventing the emission of flame, but permitting relief of the explosion pressure. The method has several advantages including cheapness, relatively light construction of the casing, and minimizing increased weight.

The first part of an investigation of the method has already been reported[1]. Cubical containers up to 3 ft^3 (85 l) were fitted with explosion reliefs protected with flame arresters, and filled with a propane-air mixture which was then ignited. The two main factors affecting the suitability of the method were:

1. the maximum explosion pressure, and
2. the extent of thermal damage to the flame arresters on repeated tests.

With the commercial arresters used the second factor was dominant, so that the area of vent required was governed by the avoidance of oxidation and melting of the arresters. In addition, for simplicity, the containers were tested without any equipment content.

Before the method of protection could be applied to industrial conditions, further information was required and some of this is given in the present Note. The factors reported on here are:

1. The effect of external covers over the flame arresters.
2. The effect on the performance of the flame arresters of contents within the enclosures such as shelves, baffles and other obstacles, and three-dimensional contents.
3. Whether improved performance of the arresters could be obtained by changing the metal of which they were constructed, and using ribbon of higher melting point and greater resistance to oxidation.
4. Simultaneous ignition by several sources.

The flammable gas used was again propane, which is a typical group II gas.

The results given in the present Note, together with those reported previously[1] enable the venting requirements of group II gases and vapours to be assessed for a wide range of industrial equipment of volume up to 3 ft^3 (.85 l). Information is now available on the economic size and distribution of vents, possible types of vent covers, and the influence on the explosion pressure of the layout of the equipment contents. Flame arresters capable of quenching propane flames without sustaining thermal damage may now be specified; these arresters are commercially available. A reasonably precise specification may now be drawn up for prototypes of equipment protected with flame arresters, within the limitations outlined above.

APPARATUS AND MATERIALS

Explosion vessels

Three sizes of cubical vessel were used, with capacities of $\frac{1}{3}$ ft^3 (9 l), 1 ft^3 (28 l) and 3 ft^3 (85 l). Each vessel had two open flanged ends giving provision for bolting on covers usually provided with four or five circular vent openings to which flame arresters could be fitted; unused vents were closed by bolting on blank plates. One cover for the $\frac{1}{3}$ ft^3 (9 l) vessel had only one central circular opening 4.3 in (11 cm) in diameter.

Table 1 shows the sizes and the number of vents used with each vessel.

Table 1
Number and diameters of vents

Diameter of vents in	cm	Volume of explosion vessel $\frac{1}{3}$ ft^3 (9 l)	1 ft^3 (28 l)	3 ft^3 (86 l)
1.15	2.9	1 - 5	-	-
2.25	5.7	-	2	-
4.30	11.0	1	-	1 - 2

When all vents are situated on one cover it is useful to follow previous practice[1] and to define the area of the vents by the ratio

$$K = \frac{\text{Cross-sectional area of the explosion vessel}}{\text{Area of vent or vents}}$$

All vessels had provision for the insertion of pressure gauges and the ignition source. In tests other than those with obstacles, one pressure gauge was used and this was always situated in the centre of one vertical wall of the vessel. When obstacles were present, the pressure was measured on both sides of them. One gauge was situated in a vertical wall 2 in (5 cm) away from the top cover, the other gauge being in the opposite wall the same distance away from the bottom cover. In the majority of the tests the igniting source was either situated in the centre of the vessel or on the vertical axis of the vessel 2 in (5 cm) away from either cover.

Except in the majority of the tests with obstacles and with protective covers over the arresters, the explosion vessel rested inside a 15.6 ft^3 (440 l) cubical enclosure, the open side of which was sealed with two layers of 0.0015 in (0.0038 cm) thick polyethylene film.

Flame arresters

The arresters were made from crimped ribbon and were of three types of construction (Fig.1): commercial arresters consisting of a length of crimped and flat ribbon wound round a brass central core, thus forming a circular arrester, which was cased in brass. This type of arrester is designated as type a. Nickel arresters were constructed as packs of alternate crimped and flat ribbons sandwiched between two brass plates with appropriate central holes; the plates were soldered to the edges of the ribbons. These arresters are designated as type b. "Incoloy" arresters were assembled similarly to the nickel arresters but had no brass plates on the outside and the ribbon was held together by welds made outside the venting area. These are designated as type c. "Incoloy" is a nickel-chromium-iron alloy. Table 2 gives the details of all types of arresters used.

Table 2

Details of arresters

Diameter of arrester		Type	Ribbon metal	Ribbon thickness		Crimp height		Thickness of arrester	
in	cm			in	cm	in	cm	in	cm
1.15	2.9	a	Cupro-nickel	0.0025	0.0063	0.045	0.11	1.5	3.8
		b	Nickel	0.003 0.005 0.007	0.008 0.013 0.018	0.020	0.05	1.0	2.5
		c	Incoloy	0.0076	0.019	0.020	0.05	1.0	2.5
2.25	5.7	b	Nickel	0.003 0.005 0.007	0.008 0.013 0.018	0.020	0.05	1.0	2.5
4.30	10.9	a	Cupro-nickel	0.0025	0.0063	0.045	0.11	1.5	3.8
		b	Nickel	0.003 0.007	0.008 0.018	0.020	0.05	1.0	2.5
		c	Incoloy	0.0076	0.019	0.020	0.05	1.0	2.5

Pressure measurement and flame movement

Explosion pressures were determined using variable-capacity or quartz-piezo gauges and the pressure-time curves were recorded by photographing the screen of a cathode ray tube to which the amplified signals were fed. At least two tests were carried out with each set of experimental conditions.

The arrival of the flame at the arrester and at the opposite cover was timed using ionisation gaps, in the tests with the arrester protective coverings only.

Flammable gas

A four per cent by volume propane-air mixture was used throughout the tests; the explosion vessels were filled by the displacement of air.

Obstacles

Several types of obstacles were used as simulated equipment contents:

a) orifice plate

b) shelf

c) perforated metal

d) wire gauze

e) solid cube

f) solid bar

The orifice plates and the shelves were made from $\frac{1}{8}$ in (0.3 cm) thick mild steel sheet. The sides of the obstacles were secured to the wall of the explosion vessel by two or three set screws. Figure 2 shows orifice and shelf obstacles each obstructing 25 per sent of the cross-sectional area of the explosion vessel. These obstacles were used for several series of tests. In one series the obstacles were mounted parallel to the arresters and were situated either 0.8 in (2.0 cm) above the centre of the vessel or $1\frac{1}{2}$ in (3.8 cm) away from top cover or $2\frac{1}{2}$ in (6.3 cm) away from the bottom cover. With each position of the obstacles the igniting source was either in the centre of the vessel or on its vertical axis 2 in (5.1 cm) away from the top or bottom cover. When the obstacle and the igniting source were both nominally at the centre of the vessel the igniting spark was produced on the side of the obstacle remote from the arresters This arrangement is shown at Fig.3. and it is designated as arrangement A. In a further series of tests the obstacles were at right angles to the arresters; central obstacles are shown in arrangements B and C (Fig.3). Arrangements D and E, also shown in Fig.3, are similar to arrangements B and C but with the obstacles $2\frac{1}{2}$ in (6.3 cm) away from one wall and the igniting source 2 in (5.1 cm) away from the same wall. Some tests were also carried out with vents distributed between the two covers of the explosion vessel and central obstacles parallel or at right angles to the arresters. These are arrangements F and H (Fig.3.). In all these tests the igniting source was at the centre of the vessel.

The perforated metal obstacles consisted of brass sheet perforated with 0.22 in (0.56 cm) holes and mounted in a light aluminium frame (Figure 4a). Two obstacles were used, covering respectively 100 and 90 per cent of the cross sectional area. The same frame could hold, when required, 6-mesh 20-gauge steel wire gauze (Figure 4b). Both of these obstacles were tested with arrangement A only.

The cube and bar, three-dimensional obstacles were constructed of wood blocks covered with aluminium foil. The proportions of the bar were 1 : 1 : 2. The obstacles were attached to the walls of the vessel by brackets of negligible area.

Tables 3 and 4 give details of the obstacles used for the 1 ft^3 (28 l) and $\frac{1}{3}$ ft^3 (9 l) explosion vessels respectively.

Table 3

Details of the obstacles used in 1 ft^3 (28 1) explosion vessel

Type of obstacle	Per cent of cross-sectional area of the explosion vessel blocked	Volume of obstacle ft^3	Volume of obstacle 1
Shelf	25	-	-
	50	-	-
	75	-	-
	90	-	-
Orifice plate	25	-	-
	50	-	-
	75	-	-
	90	-	-
Perforated metal	56	-	-
	50	-	-
Wire gauze	38	-	-
Cube	25	$\frac{1}{8}$	3.5
Bar	50	$\frac{1}{4}$	7

The plastic-backed magnetic ferrite covers were made from $^1/_{16}$ in (0.15 cm) thick 6 in (15 cm) square sheets. The covers were anchored at one side of the flame arrester, so that the sheets rested flat on the mild steel mounting frame of the arrester, and were thus held by magnetic force over the whole upper surface of the frame. When the explosion took place the ferrite sheet was deflected, bending occurring near the anchoring line.

PROCEDURE

Except in the majority of tests with the obstacles and all tests with protective covers, the explosion vessel rested inside the larger 15.6 ft^3 (440 l) enclosure. The propane-air mixture was fed into the explosion vessel and passed into the outer enclosure through the flame arresters and from there ran to waste. A volume of gas equal to ten changes of the larger enclosure was used for each experiment; throughout the charging period the gas in the outer enclosure was stirred by a fan. After charging was completed the flammable mixture in the explosion vessel was ignited. Absence of explosion in the outer enclosure indicated that the arresters contained the explosion within the explosion vessel. Finally, the flammability of the gas mixture in the outer enclosure was proved by igniting it.

Visual examination of the arresters was made with every rig after the completion of the tests. With arresters which were expected to suffer damage, inspection was carried out after each test.

For experimental convenience in the majority of the tests with the obstacles and in all the tests with protective covers, no polyethylene diaphragm was used in the outer enclosure and the charging was terminated after ten volumes of the explosion vessel had passed. In these tests the gases escaping through the arresters were dispersed by a fan.

RESULTS

Tests with protective covers

The maximum bursting pressures obtained with vents covered with plastic diaphragms are shown as a function of the diameter of the vents in Fig. 7. These tests were carried out in the $\frac{1}{3}$ ft^3 (9 l) explosion vessel with central ignition. All the diaphragms were clamped to the periphery of the vents with mild steel flanges having $^1/_{16}$ in (0.15 cm) rubber gaskets. Three vents were used with the smallest diameter diaphragm, but only a single vent for the other diaphragms (Fig.7).

Table 4

Details of the obstacles used in $\frac{1}{3}$ ft^3 (9 l) explosion vessel

Type of obstacle	Per cent cross-sectional area of the vessel blocked
Shelf	25
	50
	75
Orifice plate	25
	50
	75

Ignition

In all experiments with a single igniting source the flammable gas was ignited by an inductive spark. This was delivered from a 12 volt car induction coil across a 1 mm gap.

In experiments with the multiple igniting source three shrouded "Nobel Safety Fuses" were used. These were situated on the axis of the vessel at distances 1.5, 6.5 and 10.5 in (3.8, 16.4, and 27 cm) from the bottom of the vessel, and were initiated simultaneously with a 12 volt accumulator.

Protective covers

Three different types of protective covers were tested: a) plastic diaphragms; b) solid covers either resting on the top of the arresters or held by magnets; c) plastic-backed magnetic ferrite sheet.

The diaphragms were made from polyethylene film 0.0015 in (0.0038 cm) thick or polystyrene film 0.014 in (0.036 cm) thick. These were tested without arresters in position and were either clamped around the periphery of the vent opening, or were clipped on the outside of the arrester holder. This method is illustrated in Fig.5. The solid covers were made from fibreboard skinned with aluminium foil, the weight of these covers was varied by attaching lead sheets. The solid covers held by magnets were of similar construction but four mild steel plates were attached at each corner, to engage the magnets situated on the periphery of the arrester holder. Figure 6 shows the magnetic cover assembly with the cover removed, and with a type of arrester.

All the pressure-time records obtained with polyethylene diaphragms, and also the records with the largest polystyrene diaphragm, showed a single pressure peak. The pressure declined sharply after the peak. The remaining polystyrene diaphragms gave records with two peaks, the second peak appearing at the time when the flame reached the bottom of the explosion vessel. All the second peaks showed vibrations superimposed on the pressure-time curves, and the maximum values of the vibrations were two to three times the values of the first peak, which is that shown in Fig.7.

A comparison of two different methods of mounting was made with the polyethylene diaphragms. Results for polyethylene clipped round the periphery of the arrester holder may be compared with the results for the diaphragm clamped round the vent, from Fig.8. Usually with the clipped diaphragms, only one peak was obtained on the pressure-time record. However, on two occasions with the 2.25 in (5.7 cm) diameter vent, a second peak appeared and gave maximum pressures up to 12 lb/in^2 (0.85 kg/cm^2).

The results given in Figs.7 and 8 were for vents not fitted with arresters. Comparison of the maximum pressures, for vents with and without arresters, may be made in Table 5. The arresters were Type a.

Table 5

Maximum bursting pressures with arresters covered by clipped polyethylene diaphragms

Diaphragm diameter		No arrester on vent		Arrester on vent	
in	cm	lb/in^2	kg/cm^2	lb/in^2	kg/cm^2
1.80	4.5	6.3 6.3 5.8	0.44 0.44 0.41	6.7 6.0	0.47 0.42
5.0	12.5	2.1 2.3 2.4	0.15 0.16 0.17	1.5 2.3 2.4	0.11 0.16 0.17

Tests with rigid protective covers were carried out in the $\frac{1}{3}$ ft^3 (9 l) vessel with central ignition. The covers were either held magnetically or were loose and rested under their own weight. Maximum explosion pressures are shown in Fig.9 for the vent 4.3 in(11 cm) in diameter for both loose covers and covers held by magnetic forces of 40 lb/ft^2 (2 x 10^{-2} kg/cm^2) and 80 lb/ft^2 (3.9 x 10^{-2} kg/cm^2). The increase in maximum pressure with magnetic covers was directly additive to the pressures with identical loose covers. A few tests were carried out with a (Type a) flame arrester covering the vent; the maximum explosion pressures are shown in Fig.9. The presence of an arrester slightly increased the maximum pressure with loose covers, but had no effect with magnetically held covers. Tests with plastic-backed magnetic ferrite covers, over a flame arrester on the same explosion vessel, gave a maximum pressure of 1.6 lb/in^2 (0.11 kg/cm^2) similar to that for rigid covers (Fig.9). The ferrite covers closed after the explosion, showed no damage after repeated tests.

Further tests were carried out with the 2.25 in (5.7 cm) diameter vent, and the results are shown in Fig.10. The magnetic force holding the covers was kept constant, but the maximum explosion pressures were scattered and were not markedly dependent upon the weight of the cover. The pressure records for the magnetically held covers showed only one peak, whereas with loose covers two peaks appeared. The second peak determined the maximum pressure, and it occurred towards the end of the explosion.

Effect of obstacles

Various types of obstacle, simulating equipment contents, were tested in the 1 ft^3 (28 l) and $\frac{1}{3}$ ft^3 (9 l) explosion vessels. A summary of the results is given in Table 6, fuller results are given in Tables in the Appendix which include versions both in British and in metric units. The results in Table 6 show that obstacles such as shelves or orifice plates covering a substantial cross-section of the explosion vessel do cause marked increases in explosion pressures. It should be emphasized that the results in Table 6 are for the most adverse conditions of test, and that explosion pressures were lower for more favourable conditions (see Tables 12-24). The increases in pressure may be mitigated by distributing the vents favourably relative to the obstacles and also by varying the position of the igniting source. With a single shelf, obstacle arrangement A, the

Table 6

Summary of results for explosion vessels containing obstacles

Type of obstacle	Area blocked by obstacle, per cent	Obstacle arrangement (Fig. 3)	K	Volume of explosion vessel		Maximum pressure without obstacle		Maximum pressure with obstacle		Further details Table number
				ft^3	l	lb/in^2	kg/cm^2	lb/in^2	kg/cm^2	
Shelf	90	A	4.9	1	28	0.6	0.04	4.0	0.28	12
	90	B-E	4.9	1	28	0.3	0.02	1.6	0.11	17
	90	A	4.8	1/3	9	2.3*	0.16	4.7*	0.33	14
	90	B-E	4.8	1/3	9	0.2	0.01	3.4	0.24	16
	90	F	-	1/3	9	2.3	0.16	2.9	0.20	19
	90	H	-	1/3	9	2.3	0.16	10.1	0.70	19
Orifice plate	75	A	4.9	1	28	0.6	0.04	2.6	0.18	13
	75	B-D	4.9	1	28	0.3	0.02	0.4	0.03	17
	75	B-D	4.8	1/3	9	0.2	0.01	0.5	0.04	16
	75	F	-	1/3	9	2.3	0.16	2.1	0.15	19
	75	H	-	1/3	9	2.3	0.16	2.1	0.15	19
Shelf and orifice plate	75	-	4.9	1	28	0.6	0.04	6.8	0.48	20
Perforated metal	56	A	4.9	1	28	0.6	0.04	1.2	0.08	21
	50	A	4.9	1	28	0.6	0.04	1.2	0.08	22
Wire gauze	38	A	4.9	1	28	0.6	0.04	0.8	0.06	23
Cube	25	-	4.9	1	28	0.6	0.04	1.1	0.08	24
Bar	50	-	4.9	1	28	0.6	0.04	0.6	0.04	24

*acoustic maxima

highest pressures were obtained with the ignition source remote from the arrester, and under these conditions alteration of the position of the obstacle had little effect. The pressure gradient across the obstacle did not exceed 1 lb/in^2 (0.07 kg/cm^2), the main pressure drop being across the vents. This pattern was repeated for other obstacles and vent arrangements. When two obstacles were mounted in the vessel, the maximum explosion pressures were further increased. A shelf and an orifice plate obstacle of various sizes were placed in the 1 ft^3 (28 l) vessel, and the maximum explosion pressures were higher than in experiments with single obstacles, with the same venting arrangements. The pressure gradient across the explosion vessel was again small.

The other two-dimensional obstacles, perforated metal and wire gauze, produced relatively small increases in explosion pressure. Both obstacles were used in the horizontal position and the ignition source was remote from the vents in all tests. Variation of the position of these obstacles had little effect on the maximum explosion pressure. Pressure gradients within the explosion vessels were again small. From the practical point of view the use of perforated shelves, chassis etc. in equipment would be much preferable to unperforated alternatives.

The three-dimensional obstacles, cube and bar, were supported so that their centres were in the centre of the explosion vessel. The sides of the obstacles were parallel to the walls of the vessel. The maximum explosion pressures were obtained when the ignition source was remote from the vents.

Thermally resistant arresters

Because of the thermal damage reported earlier[1] to the cupro-nickel arresters, the use of metal ribbons having higher resistance to thermal damage was investigated. Table 2 gives details of arresters fabricated in nickel (Type b) and incoloy (Type c).

With nickel arresters the maximum explosion pressures obtained with the thinnest and thickest ribbons are shown in Figs.11 and 12 respectively. Results for the ribbon of intermediate thickness, obtained with one vent area only, are summarized in Table 7. All these tests were carried out with the $\frac{1}{3}$ ft^3 (9 l) explosion vessel and, as reported previously, the lowest explosion pressures were obtained when the igniting source was near the vents. With multiple vents the

Table 7

Explosion pressures for nickel arresters, ribbon thickness 0.005 in (0.013 cm) ($1/3$ ft^3 [9 l] explosion vessel, K = 65)

Position of igniting source relative to vent	Maximum explosion pressure	
	lb/in^2	kg/cm^2
Remote	30	2.1
Centre	33	2.3
Near	27	1.9

Table 8

Variation of explosion pressure with ribbon thickness, nickel arresters (1 ft^3 [28 l] explosion vessel, K = 40)

Ribbon thickness		Maximum explosion pressure	
in.	cm	lb/in^2	kg/cm^2
0.003	0.008	16	1.1
0.005	0.013	17	1.2
0.007	0.018	19	1.3

highest pressures were obtained with the igniting source remote from the arresters, but with single vents similar values were obtained with the igniting source either remote from the arrester or in the centre of the vessel. This behaviour was similar to that reported previously[1]. The maximum explosion pressures did not depend markedly upon the thickness of the ribbon. When two or more arresters were used (i.e. K not greater than 34) no damage to any of the ribbons was evident for any ribbon thickness. With single arresters of the two thinner ribbons, some distortion was evident after two tests with the igniting source near the arrester, and therefore a further six tests were carried out with each ribbon. Subsequent inspection showed that some sections of the crimped and the straight ribbon were distorted and gaps up to 0.02 in (0.05 cm) opened up between the ribbons (Fig.13 and 14). In no case did an arrester fail and transmit the explosion. For the single arresters, the value of K was large (65), so that the area of vent was only about 1.5 per cent of the area of the cover of the explosion vessel and the maximum explosion pressure was impracticably high for industrial equipment generally. Within a practical range of explosion pressures, no thermal damage to the arresters was obtained.

Nickel arresters were also tested with larger explosion vessels. Results with each ribbon thickness are summarised in Table 8 for arresters attached to the 1 ft^3 (28 l) explosion vessel. There was evidence that the maximum pressure increased with ribbon thickness. In all tests the explosion was contained within the vessel, and no structural damage was observed to the two thicker ribbons. With the thinnest ribbon, some distortion was noticeable (Fig.15). The area of vent was again small, being about 2.5 per cent of the cover of the explosion vessel, and the explosion pressures were again impracticably high. A larger area of vent would be needed for practical purposes. Protection of the 3 ft^3 (85 l) explosion vessel was readily obtained without structural damage to arresters; details are summarized in Table 9. The maximum explosion pressures again increased with ribbon thickness.

Incoloy arresters (Type c) were tested with the $\frac{1}{3}$ ft^3 (9 l) explosion vessel. The results are shown in Fig.16, only one thickness of ribbon being available. No thermal damage to the arresters was evident after the tests.

Table 9

Explosion pressures for nickel arresters on 3 ft^3 (85 l) vessel

Ribbon thickness in.	Ribbon thickness cm	Number of vents	K	Position of igniting source	Maximum explosion pressure lb/in^2	Maximum explosion pressure kg/cm^2
0.003	0.008	1	21	Remote	8.0	0.56
				Centre	7.5	0.53
				Near	5.3	0.37
		2	10	Remote	2.2	0.15
				Centre	1.6	0.11
				Near	0.9	0.06
0.007	0.018	1	21	Remote	11.1	0.78
				Centre	12.6	0.88
				Near	8.7	0.61
		2	10	Remote	2.9	0.20
				Centre	2.2	0.15
				Near	1.2	0.08

Table 10

Explosion pressures with multiple ignition source and obstacles
(Ignition remote from vent, K = 4.9, cupro-nickel arresters)
1 ft^3 (28 l) explosion vessel

Ignition source	Obstacle types, and percentage obstruction	Maximum explosion pressure lb/in^2	Maximum explosion pressure kg/cm^2
Multiple	None	1.1	0.08
	Shelf and orifice, 75	4.2	0.30
Single	None	0.5	0.04
	Shelf and orifice, 75	3.8	0.27

Multiple ignition sources

The maximum explosion pressures obtained on simultaneous ignition with three large sources, may be compared with the values for ignition with a single inductive spark, in Table 10. The 1 ft^3 (28 l) explosion vessel was used, with and without internal obstacles. The pressure increase caused by the multiple ignition source was relatively small in the presence of the obstacles.

DISCUSSION

Performance of protective covers

There is a clear need for some form of protective cover for flame arresters in certain environments. The covers would be required to prevent accidental damage to the arresters, and the ingress of moisture and dust into the equipment casing. The necessary protection must be obtained without increasing the maximum pressure to such an extent as to adversely affect the performance of the arresters. In addition, the covers should be designed so that damage or lack of maintenance would reduce rather than increase the pressure required for operation, and preferably the performance of the covers should be predictable enough to facilitate design. It would also be desirable that covers should be robust enough not to be removed or damaged accidentally. The types of cover examined, bursting diaphragms and magnetic panels, appeared to satisfy most of the requirements, either directly or in conjunction with an external mechanical shield.

Both the polyethylene and the polystyrene diaphragms showed that the bursting pressure was inversely proportional to the diameter, a convenient relation for design purposes (Fig.7). However, polystyrene showed disadvantages which would restrict its usefulness; it was brittle and under some conditions tended to produce fluctuations in the explosion pressure. These fluctuations caused the maximum pressure to be higher than the pressure at which the diaphragm burst. Over the range of explosion pressures likely to be encountered in practice, up to 2 lb/in^2 (0.14 kg/cm^2), the polyethylene film behaved similarly whether clamped or clipped. In practical use this type of diaphragm would, of course, require some form of external protection; although it is possible that for vents of larger diameter, on larger enclosures, stronger plastic materials could in fact be used.

As alternatives to bursting diaphragms, magnetically held covers may be used. Their performance depends upon two factors; a) the weight of the cover and b) the strength of the magnetic force holding the cover (Fig.9 and 10). The maximum explosion pressure was related directly to the weight of the cover, and with large vents the increment in pressure caused by the magnets was proportional to the magnetic force. The design formulae are thus simple and convenient. With smaller vents a more complex pressure-time curve was obtained, and the maximum pressure appeared to be dependent on disturbances to the flame caused by movement of the covers. (Fig.10).

Before either bursting diaphragms or magnetic covers could be used on an item of equipment, further development work would of course be necessary. In particular it would be important that the action of the covers should not be affected by accidental damage or by normal maintenance operations, including painting, but the effectiveness of the principle of vent covers has been demonstrated. The design of covers for a particular piece of equipment is likely to require, at least initially, individual tailoring of the design to that of the equipment and its usage.

Effect of obstacles

The main purpose of the tests with obstacles was to assess broadly the explosion pressure increments brought about by various types of obstacles, in order to obtain some estimate of any limitations their presence might impose on the method of protecting equipment with flame arresters. For this purpose, the obstacles used were stylised, with varying area and distribution of obstruction, to represent some of the principal types of obstacle likely to be encountered in practice.

Obstacles may interfere with the development of an explosion within equipment by a number of means. Because gas is expelled through the arresters during the explosion, and is therefore set in motion within the vessel, obstacles may generate additional turbulence in the gas. It has been established that turbulence generated by solid objects placed in the path of expanding gases in an explosion in a duct can considerably increase the maximum explosion pressure[2]. The principal factors contributing to the increased pressure, were the area of the obstacle and the velocity of the gas in the neighbourhood of the obstacle before the arrival of the flame front. This velocity was largely dependent on the length of the duct and the relative positions of the vent, the obstacle, and the igniting source. The vessels used in the present investigations were compact, the length to diameter ratio being 1, and the distance available for generating turbulence was relatively less than in ducting. A further effect caused by 3-dimensional obstacles was the reduction in internal free volume of the vessel. Because of the reduction the rate of discharge of gas through the vents would be less than from an empty vessel and hence the maximum explosion pressure would be reduced. The effects of reduction in free volume and the generation of turbulence would affect the pressure in opposing senses, to an extent which could not be prejudged.

The maximum explosion pressures obtained with various obstacles are given in the Appendix and summarised in Table 6, and show that under certain circumstances substantial increases in explosion pressure were obtained. The obstacle arrangement tested in most detail was that in which a shelf was placed parallel to the vents in the lid of the vessel (arrangement A, Fig.3). The highest explosion pressures were obtained when the ignition source was remote from the vents, as in vessels without obstacles, and the pressure was affected more by the area of the shelf than by its position. During all tests, the pressure difference across the shelf was usually small compared with that between the inside and outside of the vessel. A shelf perpendicular to the plane of the vents (arrangements B to E, Fig.3), generally produced slightly lower explosion pressures than arrangement A. With any of the arrangements, pressures of 3-4 lb/in^2 (0.21-0.28 kg/cm^2) could be obtained under conditions where in the absence of obstacle, the maximum pressure would be less than 1 lb/in^2 (0.07 kg/cm^2). The increased explosion pressure due to the presence of a shelf obstacle could be lessened by distributing the vents over two walls of the vessel (arrangements F and H, Fig.3), particularly if the shelf were perpendicular to the vents (arrangement F).

The increases in pressure obtained with orifice obstacles were similar to those with shelves although the flame propagated through the explosion vessel rather than at the edges as with shelf obstacle. The pressure difference across the orifice was again small compared with that between the interior and exterior of the vessel.

The explosion pressure was further increased when two obstacles were present in the same vessel (Table 6); in these tests a shelf and an orifice obstacle were used. As with single obstacles the principal pressure difference was between the interior and the exterior of the vessel, the pressure differences across the pair of obstacles being relatively small. Sub-division of the obstructed area, as with wire gauze or perforated metal, led to lower explosion pressures than with the sheet-metal shelf obstacles; clearly, shelving within vessels should be recommended to have sub-dividing apertures as this could reduce the venting requirements.

All the obstacles considered so far were two-dimensional in form; a cube or a bar gave considerably lower explosion pressures than flat obstacles having the same cross-sectional area.

No simple relationship between the geometries of the obstacles and the vessel and the increase in explosion pressure was found. Taken as a whole, the results indicated that the effect of sheet-metal obstacles was to generate turbulence within the enclosure leading to enhanced explosion pressures. As mentioned above, the principal pressure difference occurred across the vent, rather than across the obstacle, indicating that accelerated burning rates occurred within the vessel as would be expected if the flame entered a turbulent region on propagating past the obstacle. When the position of the ignition source was such that movement of gas within the vessel was minimized, as when the ignition source was near to the vent, then explosion pressures tended to be considerably lower than when ignition source was remote from the vent. With perforated metal and wire gauze obstacles, the turbulence generated would be of different, smaller, scale and range and clearly had a less marked effect on the burning rate of the gas. With three-dimensional obstacles, the turbulence produced by their presence was again probably of different scale, and the increase in pressure due to turbulence would be reduced by the smaller free volume of gas within the vessel.

In considering the results for practical application, the following points may be made. Two-dimensional obstacles obstructing a high proportion of the cross-section of the vessel may lead to substantially increased explosion pressures throughout the entire volume. The effect of the obstacles may be reduced by their careful positioning relative to the vents, and also by sub-dividing the area of obstruction. In particular, the use of perforated metal sheeting, instead of solid metal shelving, would appear to be beneficial. Three-dimensional obstacles, such as bulky contents of the vessel, produce smaller effects on the explosion pressure and, it may be anticipated, would not present difficult problems in the arrangement of the contents of equipment casings. It is not yet possible from available data to predict the maximum explosion pressure in vessels containing obstacles, and at present it is still necessary to carry out tests with each individual item of equipment. However, the results obtained with various two and three-dimensional obstacles give a broad picture of the likely increases in maximum pressure, and possible methods of reducing the pressure have been illustrated.

Thermally resistant arresters

The results obtained previously with arresters made from cupro nickel ribbon[1] indicated that the satisfactory performance of these arresters was governed by their ability to resist thermal damage. The minimum area of these arresters that could be safely applied to 1 ft^3 (28 l) of propane-air ranged between 24 in^2 (155 cm^2) and 13 in^2 (84 cm^2), depending upon the crimp height. Both nickel and incoloy alloys gave a much better performance at an intermediate crimp height. A comparison is given in Table 11 of the minimum areas of nickel and incoloy ribbon arresters required per unit volume of propane-air mixture exploded in various vessels. The minimum areas shown in the Table were approximate because only a limited number of arrester areas were available. With arresters of ribbon thickness 0.003 and 0.005 in (0.008 and 0.013 cm) an arrester area of 3 in^2/ft^3 (0.68 cm^2/l) was inadequate, but the performance was satisfactory when the area was doubled. With ribbon thicknesses of 0.007 and 0.0076 in (0.018 and 0.019 cm) an arrester area of 3 in^2/ft^3 (0.68 cm^2/l) was satisfactory and it was not possible to test smaller areas of arrester. The arrester areas of 4 and 5 in^2/ft^3 (0.9 and 1.2 cm^2/l) obtained with the larger explosion vessels, were the smallest available for test; with suitable arresters the areas could probably be further reduced.

Table 11

Minimum areas of arresters required to avoid structural damage

Volume of the vessel		Ribbon metal	Arrester ribbon thickness		Diameter of arrester		Number of arresters	Area of arresters		Area of arresters per unit volume of flammable gas		Maximum explosion pressure	
ft^3	l		in	cm	in	cm		in^2	cm^2	in^2/ft^3	cm^2/l	lb/in^2	kg/cm^2
1/3	9	nickel	0.003	0.008	1.15	2.9	2	2	13	6	1.4	10.0	0.7
1/3	9	nickel	0.005	0.013	1.15	2.9	2	2	13	6	1.4	n.d.	n.d.
1/3	9	nickel	0.007	0.018	1.15	2.9	1	1	6.5	3	0.7	30.0	2.1
1/3	9	incoloy	0.0076	0.019	1.15	2.9	1	1	6.5	3	0.7	27.0	1.5
1	28	nickel	0.005	0.013	2.25	5.7	1	4	26	4	0.9	18.5	1.3
1	28	nickel	0.007	0.018	2.25	5.7	1	4	26	4	0.9	20.0	1.4
3	85	nickel	0.007	0.018	4.3	10.9	1	14.5	95	5	1.2	12.5	0.9
3	85	nickel	0.003	0.008	4.3	10.9	1	14.5	95	5	1.2	8.0	0.6

n.d. not determined

In no test was there any melting of the metal ribbon but in some cases distortion of thin ribbons occurred, caused by thermal expansion of the metal. This type of damage may be prevented by careful design of the arresters. The point may become particularly important with gases having high fundamental burning velocities because it would be necessary to use thin ribbons in the arresters in order to reduce the resistance to flow caused by small crimp heights.

There was no marked difference in the performance of arresters made from nickel or incoloy alloy, although their melting points differed, indicating that resistance to oxidation and not only elevation of melting point is a necessary property for the metal ribbons.

Multiple ignition sources

Three relatively large ignition sources were used simultaneously, both with an empty explosion vessel and a vessel containing obstacles (Table 10). The maximum explosion pressures were higher than with a single small ignition source, an electric spark, and were approximately doubled in the empty vessel. However, the presence of obstacles reduced the relative increase, possibly indicating that the maximum pressure in the presence of obstacles occurred when the flame area was governed by turbulence, and variation in the area of flame at the time of ignition was no longer dominant.

Practical aspects of technique

Sufficient laboratory work has now been carried out to show that it would be practicable to use flame arresters to protect equipment for use in propane-air atmospheres. As propane may be regarded as a typical Group II gas, the same conclusion will apply to other gases in this Group. From the information reported previously[1], and in this Note, the dimensions of vents required to keep the maximum explosion pressure down to any pre-determined value may be obtained directly. For many applications a useful working maximum explosion pressure would be several lb/in^2, in many cases this would allow construction from sheet metal either by pressing or by welding of the casing. Arresters able to safely protect such vents are described in this Note; these arresters would not permit passage of flame through their apertures and would not suffer thermal damage from repeated explosions. For vessels with a small amount of internal partitioning, and with all vents in one side, the total vent area would need to be between 7 and 10 per cent of the area of the largest side of the vessel. It is foreseen that this amount of venting could readily be provided for most industrial equipment in rectangular casings; if difficulty were experienced in accommodating all the venting on one side, then it may be sub-divided between several sides and experiments have shown that some reduction in total area of vent may then be permissible. All the data obtained has been for cubical vessels, which is the worst case, and if the same venting is applied to rectangular vessels, with one dimension appreciably less than the others, then a safety margin is again introduced provided that the vents are on the largest side of the vessel.

For vessels containing delicate industrial equipment handled with care, protection of the arresters against mechanical damage may not be necessary. However, should protection be required it may be easily obtained by mounting an external strong metal shield over the vents[1] and this may be enhanced by close-fitting vent covers which would open if an explosion should occur. These covers may either be self-closing after the explosion, or may burst and then need replacing. Both types have their advantages in that either the equipment reverts to its pre-explosion state, or an external visual sign is given of the occurrence of the explosion. The type of vent cover chosen would depend upon the circumstances of use.

The presence of contents within the equipment casing may increase the maximum explosion pressure, particularly if partitioning or shelving is in position. The increase in explosion pressure is particularly marked if more than 25 per cent of the cross-section of the vessel is obstructed. There are a number of ways of overcoming the effect; the vents may be enlarged to deal with the higher pressures, the relationship between vent area and explosion pressure has been discussed in detail[1]. Alternatively, the distribution of the vents on the casing may be adjusted to reduce pressures, and if the position of the likely igniting source is known, the shelving may be situated so as to minimize its effect. The use of perforated sheeting, instead of sheet metal, is also beneficial and may be useful for some applications. Bulky contents within the casing have a lesser effect on explosion pressure than partitions, and may in fact lead to a reduced pressure if the free-volume is substantially less. At present the amount of venting required for equipment with a substantial amount of contents would still need to be found by direct experiment.

If a number of ignition sources appear simultaneously, because of multiple failures of the equipment, then the maximum explosion pressure is increased; but with shelving or partitioning present their effect is likely to overshadow that of the multiple ignitions.

By using flame arresters for protection the explosion pressure is vented safely and the casing does not have to be so constructed as to withstand the full pressure of an unvented explosion. By suitable adjustment of vent areas and flame arresters, the maximum explosion pressure can be lowered sufficiently to permit a relatively light form of construction for the casing. It is envisaged for many applications that a modified standard type of construction for equipment not designed for hazardous atmospheres may be used, and the cost may be assessed accordingly. The cost of such equipment protected with flame arresters would be approximately that of the standard item, plus the cost of flame arresters and fittings. The latter would be a fairly standard cost directly additive to the original cost of the equipment. In the absence of venting the costs would be increased by the heavier form of construction needed for the casing, accompanied by accurate machining, the cost of which increases approximately in proportion to the original cost of the standard casing. The cost would then probably be of the order of 50 per cent over that of the standard casing. The flame arrester technique clearly becomes particularly advantageous when the initial cost of equipment is high, there is then a large difference between the fixed and proportionate extra charges.

In designing equipment casings protected with flame arresters it is not only important to consider the contents of the equipment, for which information given in this Note is applicable, but also the necessity to allow shafting etc. to pass through the casing to the exterior and also to consider the type of lid required. The amount of clearance permissible for shafting and lids is clearly important and at present relatively little information is available. Also, because the flame arresters are an open structure to allow passage of gas, they may also permit the discharge of hot metal particles should a wire or other metal component fuse inside the equipment. The emission of hot particles might then lead to ignition of the external gas mixture. The extent to which this phenomenon may occur with copper and with aluminium wires is being investigated.

CONCLUSIONS

1. Flame arresters on equipment casings may be covered effectively with bursting diaphragms or magnetic panels.
2. The increase in pressure due to the covers, in propane-air explosions, was directly related to their strength or weight.
3. The presence of two-dimensional obstacles, such as shelves or orifice plates, within the casings increased the explosion pressures. The effect became important when more than about 25 per cent of the cross-section was blocked.
4. Three-dimensional obstacles, such as bulky components, increased explosion pressures to a lesser extent than shelves etc.
5. Increased explosion pressures caused by obstacles could be minimised by distribution and sub-division of the vents, by increasing their area, or by using perforated shelves.
6. Flame arresters made from nickel, or a nickel-chromium-iron alloy, were markedly more resistant to oxidation and melting than when cupro-nickel was used.
7. With the nickel arresters, the vent area required would usually be governed by the maximum pressure permissible in an explosion, rather than by the need to prevent damage to the arresters.
8. Several large ignition sources, firing simultaneously, caused higher explosion pressures than a single small source. The increase was relatively small in the presence of obstacles.

REFERENCES

1. PALMER, K. N. and ROGOWSKI, Z. W. Fire Research Note No. 613.
2. ROGOWSKI, Z. W. and RASBASH, D. J. Second Symposium on Chemical Process Hazards 21-28. Institution of Chemical Engineers, 1963. London.

ACKNOWLEDGEMENTS

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APPENDIX

Table 12 (British Units)

Effect of shelf obstacles on the maximum explosion pressure

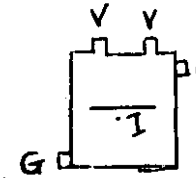
1 ft^3 Explosion vessel

Two (Type a) arresters 4.3 in diameter (K = 4.9)

Obstacle arrangement A

Maximum explosion pressure lb/in^2

(means of two tests)



V Vent
G Gauge
I Ignition

Ignition position	No obstacle	Position of obstacle blocking 25 per cent of the area			Position of obstacle blocking 50 per cent of the area			Position of obstacle blocking 75 per cent of the area			Position of obstacle blocking 90 per cent of the area			
		Remote	Centre	Near	Remote	Centre	Near	Remote	Centre	Near	Remote	Centre	Near	
Remote	0.5	0.7	0.8	0.6	1.0	0.8	0.9	1.3	2.0	1.6	4.0	4.0	3.3	Pressure above obstacle
	0.6	0.9	0.9	0.8	1.1	1.0	1.0	1.6	2.4	1.9	3.6	4.0	2.7	Pressure below obstacle
Centre	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.2	0.6	0.8	0.2	1.7	1.8	
	0.3	0.3	0.4	0.3	0.3	0.5	0.5	0.3	0.8	1.0	0.3	1.7	1.8	
Near	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.3	0.4	0.2	0.3	1.0	
	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.5	0.2	0.3	0.9	

Table 12 (Metric Units)

Effect of shelf obstacles on the maximum explosion pressure

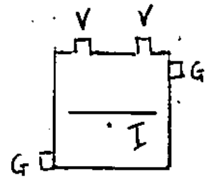
28 l Explosion vessel

Two (Type a) arresters 11 cm diameter (K = 4.9)

Obstacle arrangement A

Maximum explosion pressure kg/cm^2

(Means of two tests)



V Vent
G Gauge
I Ignition

		Position of obstacle blocking 25 per cent of the area			Position of obstacle blocking 50 per cent of the area			Position of obstacle blocking 75 per cent of the area			Position of obstacle blocking 90 per cent of the area			
Ignition position	No obstacle	Remote	Centre	Near	Remote	Centre	Near	Remote	Centre	Near	Remote	Centre	Near	
Remote	0.04	0.05	0.06	0.04	0.07	0.06	0.06	0.09	0.14	0.11	0.28	0.28	0.23	Pressure above obstacle
	0.04	0.06	0.06	0.06	0.08	0.07	0.07	0.11	0.17	0.13	0.25	0.28	0.19	Pressure below obstacle
Centre	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.01	0.04	0.06	0.01	0.12	0.13	
	0.02	0.02	0.03	0.02	0.02	0.04	0.04	0.02	0.06	0.07	0.02	0.12	0.13	
Near	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.01	0.02	0.07	
	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.04	0.01	0.02	0.06	

Table 13 (British Units)

Effect of orifice obstacles on the maximum explosion pressure

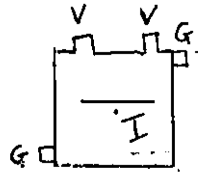
1 ft^3 explosion vessel

Two (Type a) arresters 4.3 in diameter (K = 4.9)

Obstacle arrangement A

Maximum explosion pressure lb/in^2

(means of two tests)



V Vent
G Gauge
I Ignition

Ignition position	No obstacle	Position of obstacle blocking 25 per cent of the area			Position of obstacle blocking 50 per cent of the area			Position of obstacle blocking 75 per cent of the area			
		Remote	Centre	Near	Remote	Centre	Near	Remote	Centre	Near	
Remote	0.5	0.6	0.6	0.6	0.5	1.0	0.2	0.7	2.0	2.1	Pressure above obstacle
	0.6	0.5	0.7	0.6	0.6	1.3	0.2	0.8	2.3	2.6	Pressure below obstacle
Centre	0.3	0.3	0.3	0.4	0.3	0.3	0.5	0.4	0.3	0.6	
	0.3	0.3	0.4	0.4	0.3	0.4	0.6	0.3	0.4	0.7	
Near	0.1	0.2	0.3	0.3	0.2	0.2	1.3	0.2	0.1	0.2	
	0.2	0.2	0.3	0.3	0.2	0.3	1.5	0.2	0.2	0.3	

Table 13 (Metric Units)

Effect of orifice obstacles on the maximum explosion pressure

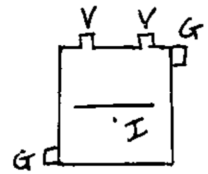
28 l explosion vessel

Two (Type a) arresters 11 cm diameter (K = 4.9)

Obstacle arrangement A

Maximum explosion pressure kg/cm^2

(means of two tests)



V Vent

G Gauge

I Ignition

Ignition position	No obstacle	Position of obstacle blocking 25 per cent of the area: Remote	Centre	Near	Position of obstacle blocking 50 per cent of the area: Remote	Centre	Near	Position of obstacle blocking 75 per cent of the area: Remote	Centre	Near	
Remote	0.04	0.04	0.04	0.04	0.04	0.07	0.01	0.05	0.14	0.15	Pressure above obstacle
	0.04	0.04	0.05	0.04	0.04	0.09	0.01	0.06	0.16	0.18	Pressure below obstacle
Centre	0.02	0.02	0.02	0.03	0.02	0.02	0.04	0.03	0.02	0.04	
	0.02	0.02	0.03	0.03	0.02	0.03	0.04	0.02	0.03	0.05	
Near	0.01	0.01	0.02	0.02	0.01	0.01	0.09	0.01	0.01	0.01	
	0.01	0.01	0.02	0.02	0.01	0.02	0.11	0.01	0.01	0.09	

Table 14 (British Units)

Effect of shelf obstacles on maximum explosion pressure

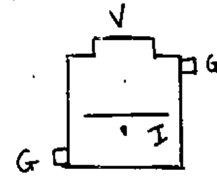
$\frac{1}{3}$ ft^3 explosion vessel

One (Type a) arrester 4.3 in diameter (K = 4.8)

Obstacle arrangement A

Maximum explosion pressure lb/in^2

(means of two tests)



V Vent
G Gauge
I Ignition

		Position of obstacle blocking 25 per cent of the area			Position of obstacle blocking 50 per cent of the area			Position of obstacle blocking 75 per cent of the area			Position of obstacle blocking 90 per cent of the area			
Ignition position	No obstacle	Remote	Centre	Near	Remote	Centre	Near	Remote	Centre	Near	Remote	Centre	Near	
Remote	0.3	0.6	0.6	0.6	0.8	0.8	0.8	1.3	1.5	1.2	3.3	3.2	4.2	Pressure above obstacle
	0.3	0.6	0.6	0.5	0.8	0.8	0.9	1.2	1.6	1.2	2.9	3.1	4.2	Pressure below obstacle
Centre	0.2	0.3	0.3	0.2	0.3	0.4	0.4	0.2	0.7	0.8	0.3	1.8	1.5	
	0.2	0.3	0.3	0.3	0.3	0.4	0.5	0.3	0.7	0.8	0.3	1.9	1.5	
Near	2.3a	1.9	1.1	0.3	1.7	0.8	0.2	5.5	0.9	0.3	4.5	1.0	0.9	
	2.3a	1.5	1.1	0.3	2.0	0.8	0.3	6.0	0.9	0.3	4.7	0.8	0.9	

a Acoustic

Table 14 (Metric Units)

Effect of shelf obstacles on maximum explosion pressure

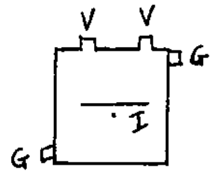
9 l explosion vessel

One (Type a) arrester 11 cm diameter (K = 4.8)

Obstacle arrangement A

Maximum explosion pressure kg/cm^2

(means of two tests)



V Vent

G Gauge

I Ignition

		Position of obstacle blocking 25 per cent of the area			Position of obstacle blocking 50 per cent of the area			Position of obstacle blocking 75 per cent of the area			Position of obstacle blocking 90 per cent of the area			
Ignition position	No obstacle	Remote	Centre	Near	Remote	Centre	Near	Remote	Centre	Near	Remote	Centre	Near	
Remote	0.02	0.04	0.04	0.04	0.06	0.06	0.06	0.09	0.11	0.09	0.23	0.23	0.30	Pressure above obstacle
	0.02	0.04	0.04	0.04	0.06	0.06	0.06	0.08	0.11	0.09	0.20	0.22	0.30	Pressure below obstacle
Centre	0.01	0.02	0.02	0.01	0.02	0.03	0.03	0.01	0.05	0.06	0.02	0.13	0.11	
	0.01	0.02	0.02	0.02	0.02	0.03	0.04	0.02	0.05	0.06	0.02	0.13	0.11	
Near	0.16a	0.13	0.08	0.02	0.12	0.06	0.01	0.39	0.06	0.02	0.32	0.07	0.06	
	0.16a	0.11	0.08	0.02	0.14	0.06	0.02	0.42	0.06	0.02	0.33	0.06	0.06	

a Acoustic

Table 15 (British Units)

Effect of shelf obstacles on maximum explosion pressure

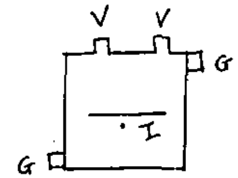
$\frac{1}{3}$ ft^3 explosion vessel

Five (Type a) arresters 1.15 in diameter (K = 13)

Obstacle arrangement A

Maximum explosion pressure lb/in^2

(means of two tests)



V Vent
G Gauge
I Ignition

Ignition position	No obstacle	Position of obstacle blocking 25 per cent: Remote	Centre	Near	Position of obstacle blocking 50 per cent: Remote	Centre	Near	Position of obstacle blocking 75 per cent: Remote	Centre	Near	
Remote	2.6	9.3	4.0	3.7	6.2	5.8	5.8	7.8	7.6	8.4	Pressure above obstacle
	2.5	7.2	3.7	3.2	5.4	4.8	5.0	7.2	7.0	8.1	Pressure below obstacle
Centre	1.5	2.1	2.0	1.8	2.1	2.8	2.9	1.3	4.1	4.8	
	1.4	1.9	1.9	1.7	1.9	2.4	2.7	1.2	3.8	4.4	
Near	0.9	1.2	1.5	0.9	1.1	1.2	1.2	0.9	1.0	1.9	
	0.9	1.1	1.4	1.0	1.0	1.2	1.2	1.0	1.3	1.7	

Table 15 (Metric Units)

Effect of shelf obstacles on maximum explosion pressure

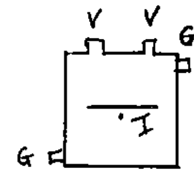
9 l explosion vessel

Five (Type a) arresters 2.9 cm diameter (K = 13)

Obstacle arrangement A

Maximum explosion pressure kg/cm^2

(Means of two tests)



V Vent

G Gauge

I Ignition

Ignition position	No obstacle	Position of obstacle blocking 25 per cent of the area			Position of obstacle blocking 50 per cent of the area			Position of obstacle blocking 75 per cent of the area			
		Remote	Centre	Near	Remote	Centre	Near	Remote	Centre	Near	
Remote	0.18	0.66	0.28	0.26	0.44	0.41	0.41	0.55	0.54	0.59	Pressure above obstacle
	0.18	0.51	0.26	0.23	0.38	0.34	0.35	0.51	0.49	0.57	Pressure below obstacle
Centre	0.11	0.15	0.14	0.13	0.15	0.20	0.20	0.09	0.29	0.34	
	0.10	0.13	0.13	0.12	0.13	0.17	0.19	0.09	0.27	0.31	
Near	0.06	0.08	0.11	0.06	0.08	0.08	0.08	0.06	0.07	0.13	
	0.06	0.08	0.10	0.07	0.07	0.08	0.08	0.07	0.09	0.12	

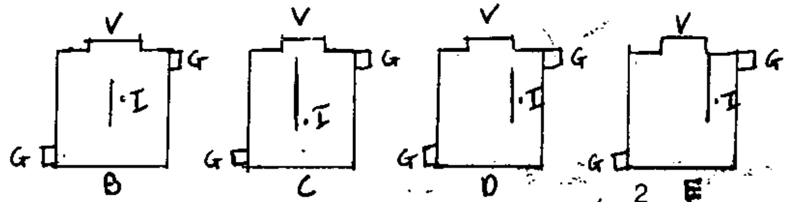
Table 16 (British Units)

Effect of shelf and orifice obstacles on the maximum explosion pressure

$\frac{1}{3}$ ft^3 explosion vessel

One (Type a) arrester 4.3 in diameter (K = 4.8)

Obstacle arrangements



V Vent

G Gauge

I Ignition

Maximum explosion pressure lb/in^2

(means of two tests)

No obstacle ignition		Orifice obstacle blocking 50 per cent area			Orifice obstacle blocking 75 per cent area			Shelf obstacle blocking 75 per cent area				Shelf obstacle blocking 90 per cent area				
Centre	Side	Obstacle arrangement			Obstacle arrangement			Obstacle arrangement				Obstacle arrangement				
		B	C	D	B	C	D	B	C	D	E	B	C	D	E	
0.17	0.17	0.2	0.2	0.2	0.5	0.2	0.2	0.3	0.3	0.6	0.5	0.3	0.3	2.6	1.1	Pressure above ignition
		0.2	0.2	0.2	0.5	0.2	0.2	0.4	0.2	0.8	0.5	0.3	0.3	3.4	1.2	Pressure below ignition

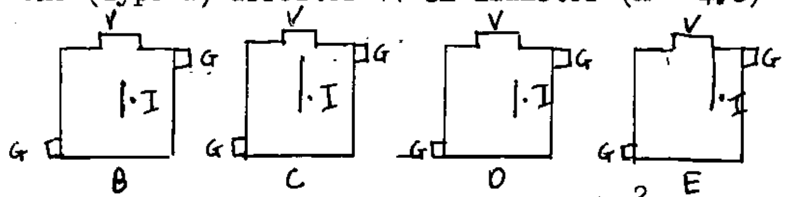
Table 16 (Metric Units)

Effect of shelf and orifice obstacles on the maximum explosion pressure

9 l explosion vessel

One (Type a) arrester 11 cm diameter (K = 4.8)

Obstacle arrangements



V Vent

G Gauge

I Ignition

Maximum explosion pressures kg/cm^2

(means of two tests)

No obstacle ignition		Orifice obstacle blocking 50 per cent area			Orifice obstacle blocking 75 per cent area			Shelf obstacle blocking 75 per cent area				Shelf obstacle blocking 90 per cent area				
Centre	Side	Obstacle arrangement			Obstacle arrangement			Obstacle arrangement				Obstacle arrangement				
		B	C	D	B	C	D	B	C	D	E	B	C	D	E	
0.01	0.01	0.01	0.01	0.01	0.04	0.01	0.01	0.02	0.02	0.04	0.04	0.02	0.02	0.18	0.08	Pressure above ignition
		0.01	0.01	0.01	0.04	0.01	0.01	0.03	0.01	0.06	0.04	0.02	0.02	0.24	0.08	Pressure below ignition

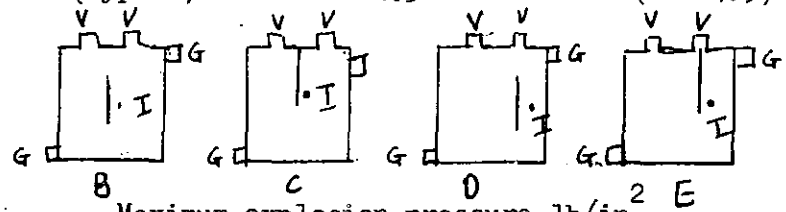
Table 17 (British Units)

Effect of shelf and orifice obstacles on the maximum explosion pressure

1 ft^3 explosion pressure

Two (Type a) arresters 4.3 in diameter (K = 4.9)

Obstacle arrangements



V Vent

G Gauge

I Ignition

Maximum explosion pressure lb/in^2

(means of two tests)

No obstacle ignition		Orifice obstacle blocking 50 per cent area			Orifice obstacle blocking 75 per cent area			Shelf obstacle blocking 75 per cent area				Shelf obstacle blocking 90 per cent area				
Centre	Side	Obstacle arrangement			Obstacle arrangement			Obstacle arrangement				Obstacle arrangement				
		B	C	D	B	C	D	B	C	D	E	B	C	D	E	
0.3	0.2	0.2	0.2	0.3	0.2	0.2	0.3	0.4	0.3	0.3	0.3	1.1	0.5	1.1	1.6	Pressure above ignition
		0.3	0.3	0.3	0.3	0.3	0.4	0.5	0.4	0.4	0.4	1.3	0.6	1.3	1.6	Pressure below ignition

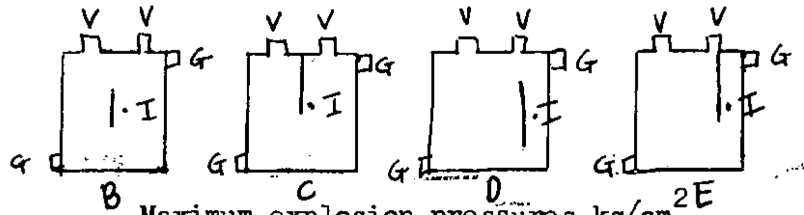
Table 17 (Metric Units)

Effect of shelf and orifice obstacles on the maximum explosion pressure

28 l explosion vessel

Two (Type a) arresters 11 cm diameter (K = 4.9)

Obstacle arrangements



V Vent

G Gauge

I Ignition

Maximum explosion pressures kg/cm^2

(means of two tests)

No obstacle ignition		Orifice obstacle blocking 50 per cent area			Orifice obstacle blocking 75 per cent area			Shelf obstacle blocking 75 per cent area				Shelf obstacle blocking 90 per cent area				
Centre	Side	Obstacle arrangement			Obstacle arrangement			Obstacle arrangement				Obstacle arrangement				
		B	C	D	B	C	D	B	C	D	E	B	C	D	E	
0.02	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.03	0.02	0.02	0.02	0.08	0.04	0.08	0.11	Pressure above ignition
		0.02	0.02	0.02	0.02	0.02	0.03	0.04	0.03	0.03	0.03	0.09	0.04	0.09	0.11	Pressure below ignition

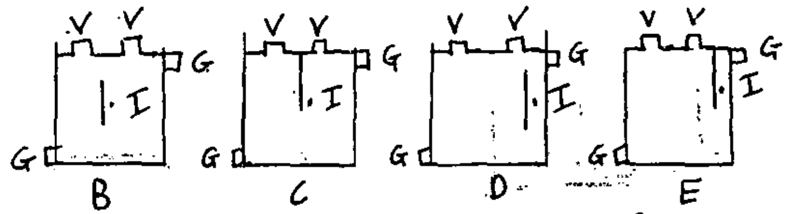
Table 18 (British Units)

Effect of shelf and orifice obstacles on the maximum explosion pressure

$\frac{1}{3}$ ft^3 explosion vessel

Five (Type a) arresters 1.15 in diameter (K = 13)

Obstacle arrangement



V Vent

G Gauge

I Ignition

Maximum explosion pressure lb/in^2

(means of two tests)

No obstacle ignition		Orifice obstacle blocking 50 per cent area			Orifice obstacle blocking 75 per cent area			Shelf obstacle blocking 75 per cent area				Shelf obstacle blocking 90 per cent area				
Centre	Side	Obstacle arrangement			Obstacle arrangement			Obstacle arrangement				Obstacle arrangement				
		B	C	D	B	C	D	B	C	D	E	B	C	D	E	
1.6	0.8	0.9	0.9	0.7	0.9	0.9	0.8	2.1	1.4	2.3	1.6	3.7	2.1	5.7	2.6	Pressure above ignition
		1.1	1.1	0.8	1.1	1.1	0.8	2.3	1.6	2.5	1.7	4.5	2.4	6.6	2.5	Pressure below ignition

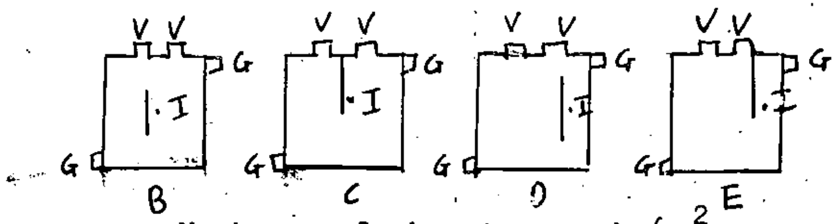
Table 18 (Metric Units)

Effect of shelf and orifice obstacles on the maximum explosion pressure

9 l explosion vessel

Five (Type a) arresters 2.7 cm diameter (K = 13)

Obstacle arrangements



V Vent

I Ignition

G Gauge

Maximum explosion pressure kg/cm^2

(means of two tests)

No obstacle ignition		Orifice obstacle blocking 50 per cent area			Orifice obstacle blocking 75 per cent area			Shelf obstacle blocking 75 per cent area				Shelf obstacle blocking 90 per cent area				
Centre	Side	Obstacle arrangement			Obstacle arrangement			Obstacle arrangement				Obstacle arrangement				
		B	C	D	B	C	D	B	C	D	E	B	C	D	E	
0.11	0.06	0.06	0.06	0.05	0.06	0.06	0.06	0.15	0.10	0.16	0.11	0.26	0.15	0.40	0.18	Pressure above ignition
		0.08	0.08	0.06	0.08	0.08	0.06	0.16	0.11	0.18	0.12	0.31	0.17	0.47	0.18	Pressure below ignition

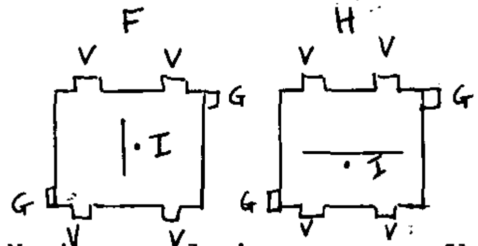
Table 19 (British Units)

Effect of shelf and orifice obstacles on the maximum explosion pressure

$\frac{1}{3}$ ft explosion vessel

Four (Type a) arresters 1.15 in diameter

Obstacle arrangements



V Vent

I Ignition

G Gauge

Maximum explosion pressure lb/in^2

(means of two tests)

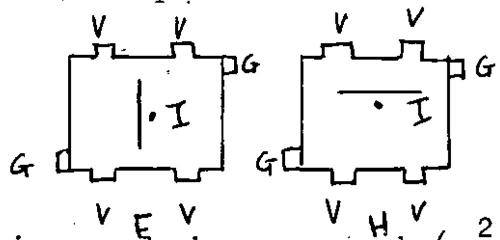
	Orifice obstacle blocking 50 per cent area	Orifice obstacle blocking 75 per cent area	Shelf obstacle blocking 75 per cent area	Shelf obstacle blocking 90 per cent area	No obstacle	
Obstacle arrangement F	2.2	2.1	2.4	2.3	2.3	Pressure above ignition
	2.0	1.8	2.2	2.9		Pressure below ignition
Obstacle arrangement H	1.7	1.8	3.3	9.4		Pressure above ignition
	2.0	2.1	4.0	10.1		Pressure below ignition

Table 19 (Metric Units)

Effect of shelf and orifice obstacles on the maximum explosion pressure

9 l explosion vessel

Obstacle arrangements



V Vent
I Ignition
G Gauge

Maximum explosion pressure kg/cm^2

(means of two tests)

	Orifice obstacle blocking 50 per cent area	Orifice obstacle blocking 75 per cent area	Shelf obstacle blocking 75 per cent area	Shelf obstacle blocking 90 per cent area	No obstacle	
Obstacle arrangement F	0.15	0.15	0.17	0.16	0.16	Pressure above ignition
	0.14	0.13	0.16	0.20		Pressure below ignition
Obstacle arrangement H	0.12	0.13	0.22	0.66		Pressure above ignition
	0.14	0.15	0.28	0.71		Pressure below ignition

Table 20 (British Units)

Effect of two obstacles on maximum explosion pressure

1 ft^3 explosion vessel

Two arresters (Type a) 4.3 in diameter (K = 4.9)

Maximum explosion pressure lb/in^2

(means of two tests)

Type of obstacle and area obstructed per cent	Obstacle position	Ignition position	Pressure above obstacles	Pressure below obstacles
Orifice 25 Shelf 50	Remote Near	Remote	1.3	1.3
Orifice 75 Shelf 75	Remote Centre	Remote	2.6	2.8
Orifice 75 Shelf 75	Centre Remote	Remote	4.2	4.3
Orifice 75 Shelf 75	Near Centre	Remote	6.6	6.8
Orifice 75 Shelf 75	Centre Near	Remote	3.5	3.8

Table 20 (Metric Units)

Effect of two obstacles on maximum explosion pressure

28 l explosion vessel

Two arresters (Type a) 11 cm diameter (K = 4.9)

Maximum explosion pressure kg/cm^2

(means of two tests)

Type of obstacle and area obstructed per cent	Obstacle position	Ignition position	Pressure above obstacles	Pressure below obstacles
Orifice 25 Shelf 50	Remote Near	Remote	0.09	0.11
Orifice 75 Shelf 75	Remote Centre	Remote	0.18	0.20
Orifice 75 Shelf 75	Centre Remote	Remote	0.30	0.30
Orifice 75 Shelf 75	Near Centre	Remote	0.47	0.48
Orifice 75 Shelf 75	Centre Near	Remote	0.25	0.27

Table 21 (British Units)

Effect of perforated metal obstacle on the maximum explosion pressure

1 ft^3 explosion vessel

Two (Type a) arresters 4.3 in diameter (K = 4.9)

Maximum explosion pressure lb/in^2

Ignition position	Shelf position	Pressure above shelf	Pressure below shelf
Remote	Remote	1.2	1.2
Remote	Centre	1.2	1.2
Remote	Near	0.7	0.7

Table 22 (British Units)

Effect of perforated metal shelf obstacle of area 90 per cent of cross-sectional area of the vessel

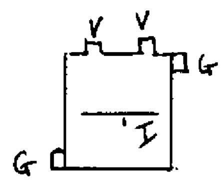
1 ft^3 Explosion vessel

Two (Type a) arresters 4.3 in diameter (K = 4.9)

Obstacle arrangement A

Maximum explosion pressure lb/in^2

(means of two tests)



V Vent

G Gauge

I Ignition

Ignition position	No obstacle	Position of obstacle		
		Remote	Centre	Near
Remote	0.6	1.2	1.1	0.9
Centre	0.5	0.6	0.6	0.5
Near	0.4	0.5	0.5	0.4

Table 21 (Metric Units)

Effect of perforated metal obstacle on the maximum explosion pressure

28 l explosion vessel

Two (Type a) arresters 11 cm diameter (K = 4.9)

Maximum explosion pressure kg/cm^2

Ignition position	Shelf position	Pressure above shelf	Pressure below shelf
Remote	Remote	0.08	0.08
Remote	Centre	0.08	0.08
Remote	Near	0.05	0.05

Table 22 (Metric Units)

Effect of perforated metal shelf obstacle of area 90 per cent of cross-sectional area of the vessel

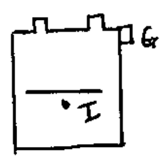
28 l explosion vessel

Two (Type a) arresters 11 cm diameter (K = 4.9)

Obstacle arrangement A

Maximum explosion pressure kg/cm^2

(means of two tests)



V Vent

G Gauge

I Ignition

		Position of obstacle		
Ignition position	No obstacle	Remote	Centre	Near
Remote	0.04	0.08	0.08	0.06
Centre	0.04	0.04	0.04	0.04
Near	0.03	0.04	0.04	0.03

Table 23 (British Units)

Effect of 6 mesh gauze obstacle on the maximum explosion pressure

1 ft^3 explosion vessel

Two (Type a) arresters 4.3 in diameter (K = 4.9)

Ignition position	Gauze position	Pressure above gauze	Pressure below gauze
Remote	Remote	0.7	0.7
Remote	Centre	0.8	0.8
Remote	Near	0.6	0.6

Table 24 (British Units)

Maximum explosion pressures with three dimensional obstacles

1 ft^3 explosion vessel

Two (Type a) arresters 4.3 in diameter (K = 4.9)

Type of obstacle	Maximum pressure lb/in^2
6 in cube	1.1
6 x 6 x 12 in bar	0.6

Table 23 (Metric Units)

Effect of 6 mesh gauze obstacle on the maximum explosion pressure

28 l explosion vessel

Two (Type a) arresters 11 cm diameter (K = 4.9)

Maximum pressure kg/cm^2

Ignition position	Gauze position	Pressure above gauze	Pressure below gauze
Remote	Remote	0.05	0.05
Remote	Centre	0.06	0.06
Remote	Near	0.04	0.04

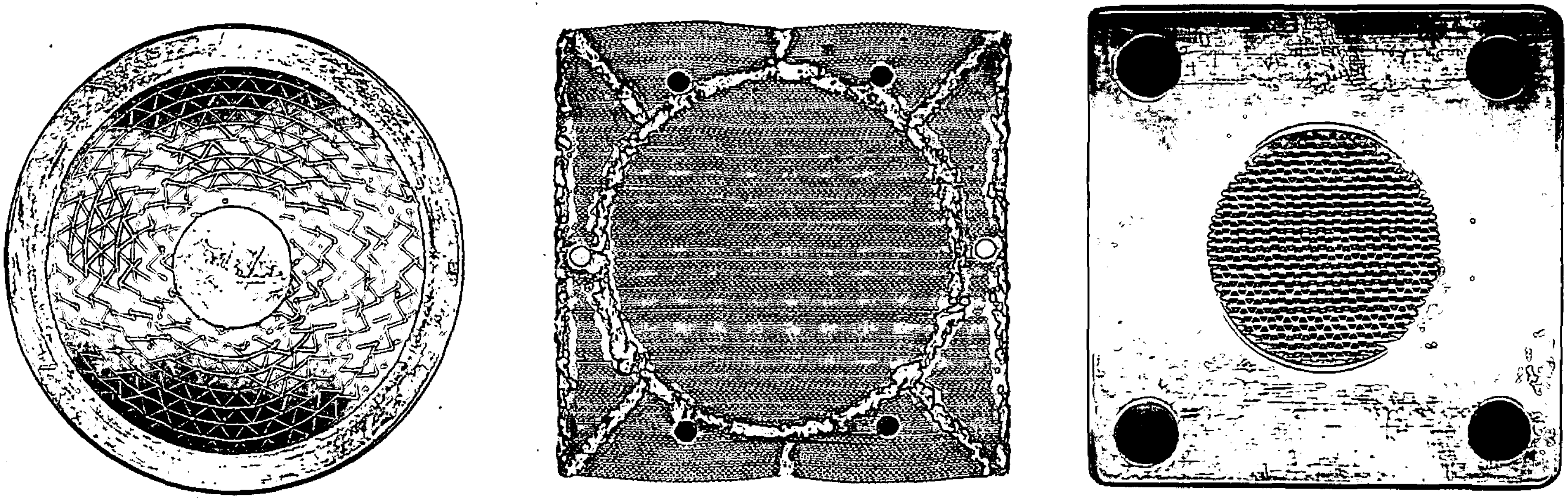
Table 24 (Metric Units)

Maximum explosion pressures with three dimensional obstacles

28 l explosion vessel

Two (Type a) arresters 11 cm diameter (K = 4.9)

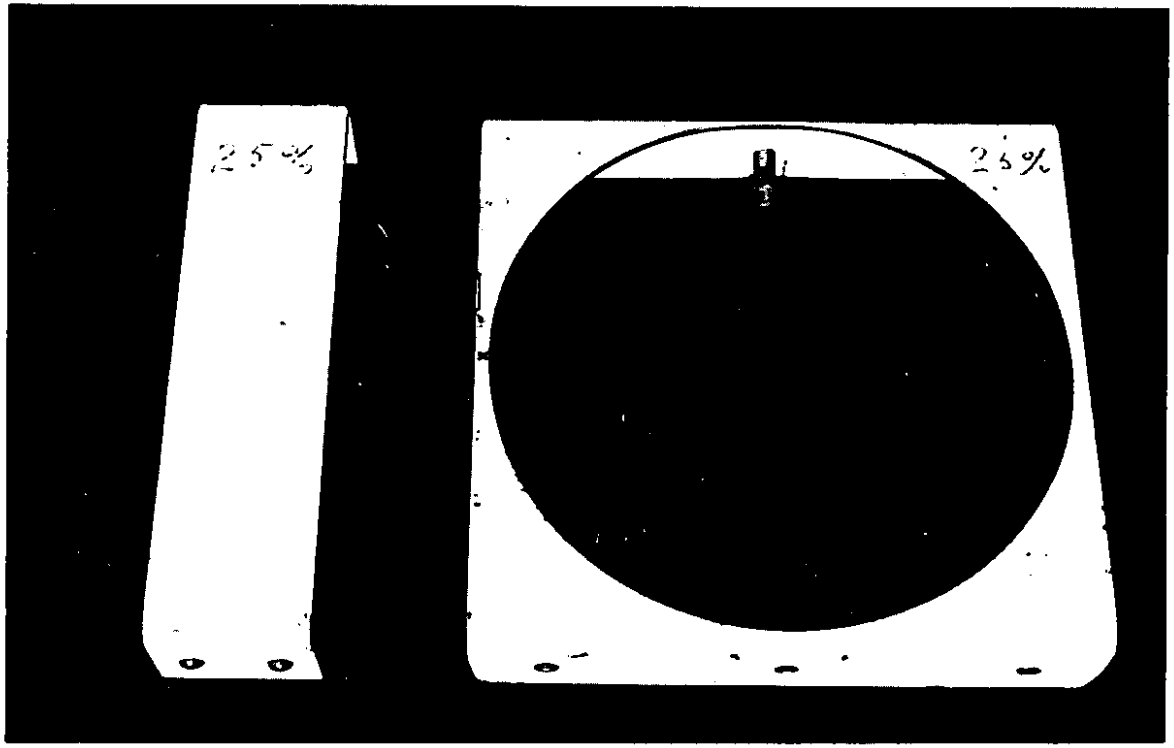
Type of obstacle	Maximum pressure kg/cm^2
15 cm cube	0.08
15 cm x 15 cm x 30 cm bar	0.04



TYPE A TYPE B TYPE C

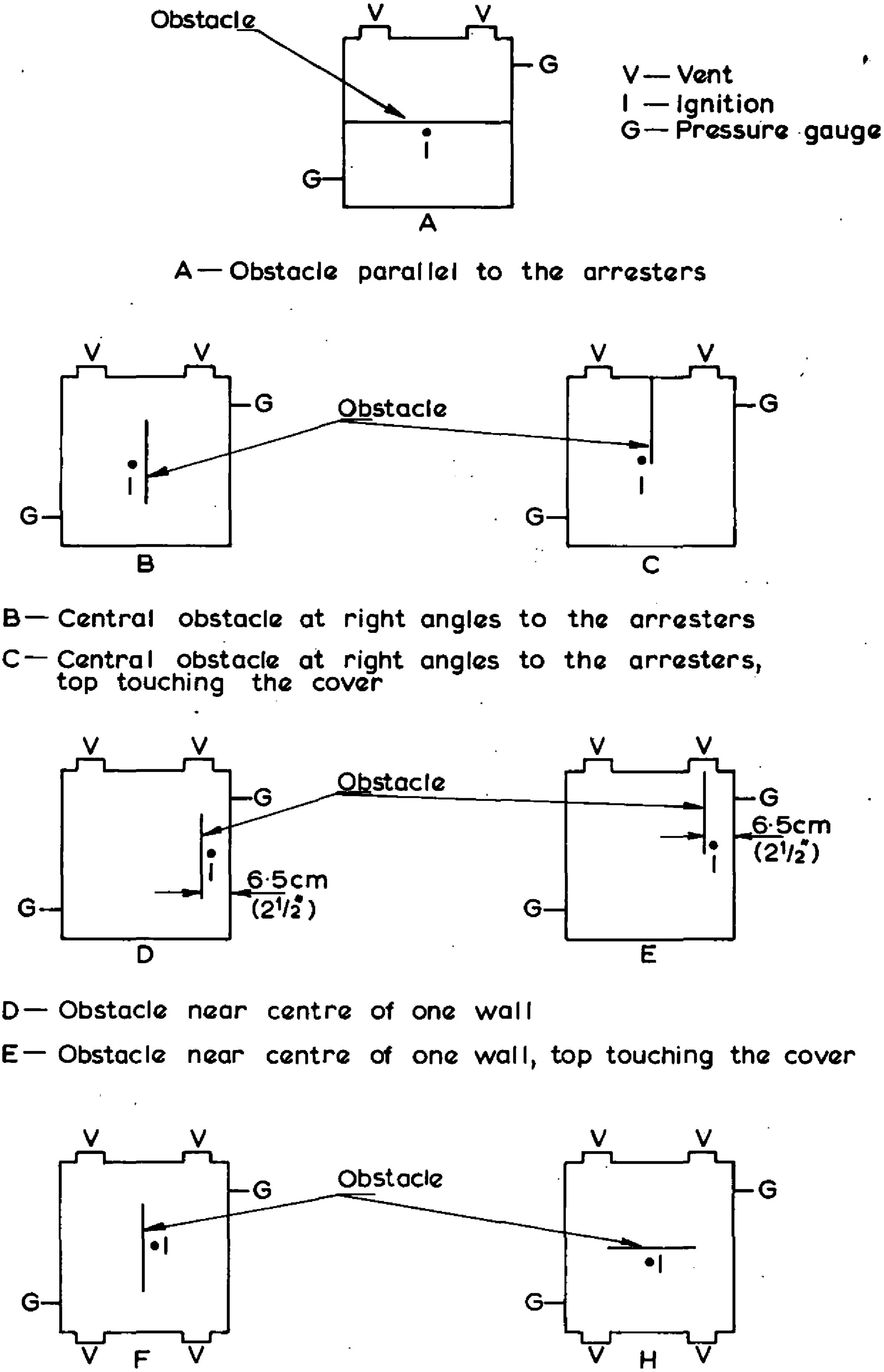
VARIOUS TYPES OF ARRESTERS

FIG. 1



ORIFICE AND SHELF OBSTACLES BLOCKING
25 PER CENT OF THE CROSS-SECTIONAL
AREA OF THE VESSEL

FIG. 2



A — Obstacle parallel to the arresters

B — Central obstacle at right angles to the arresters

C — Central obstacle at right angles to the arresters, top touching the cover

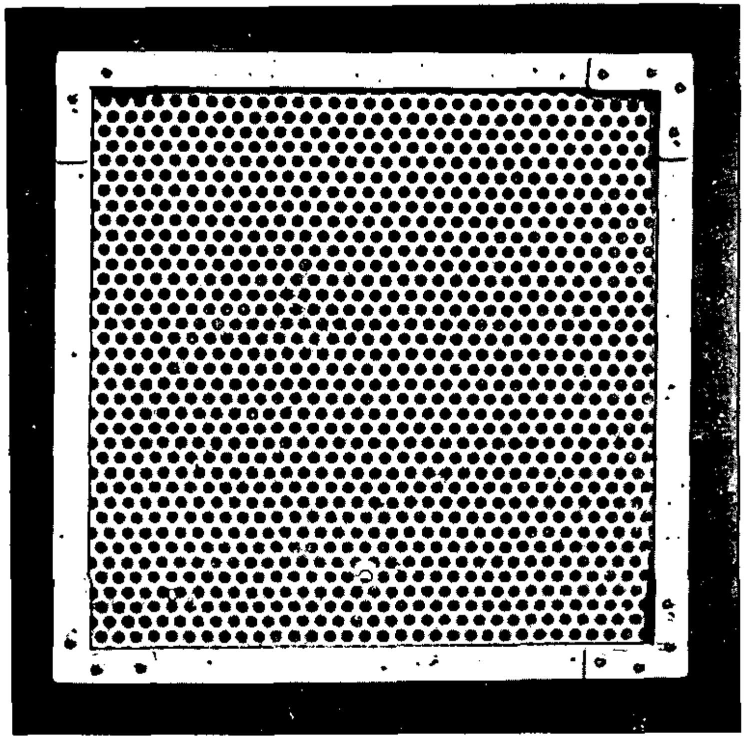
D — Obstacle near centre of one wall

E — Obstacle near centre of one wall, top touching the cover

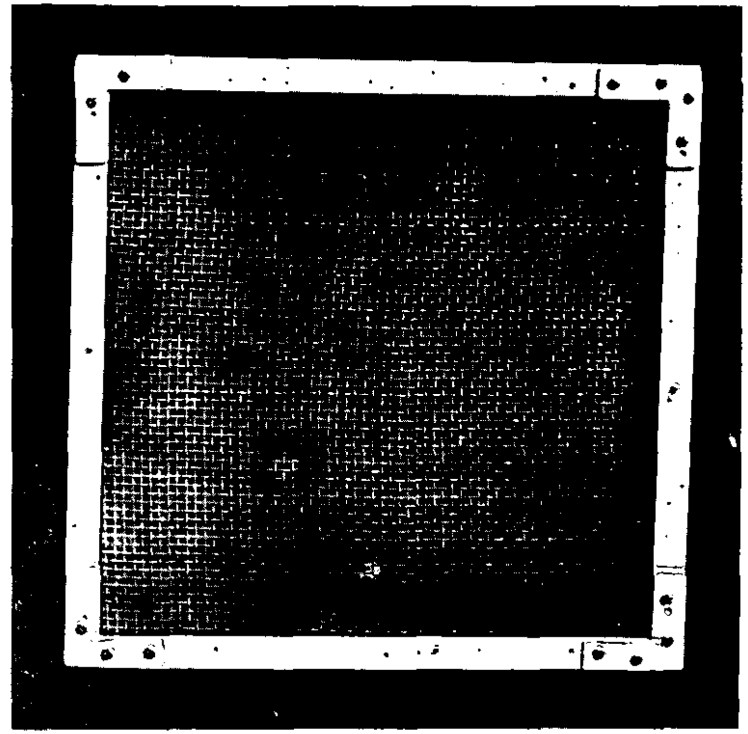
F — Vertical central obstacle with distributed vents

H — Horizontal central obstacle with distributed vents

FIG. 3. VARIOUS ARRANGEMENTS OF VENTS AND OBSTACLES



PERFORATED METAL OBSTACLE



WIRE GAUZE OBSTACLE

FIG. 4

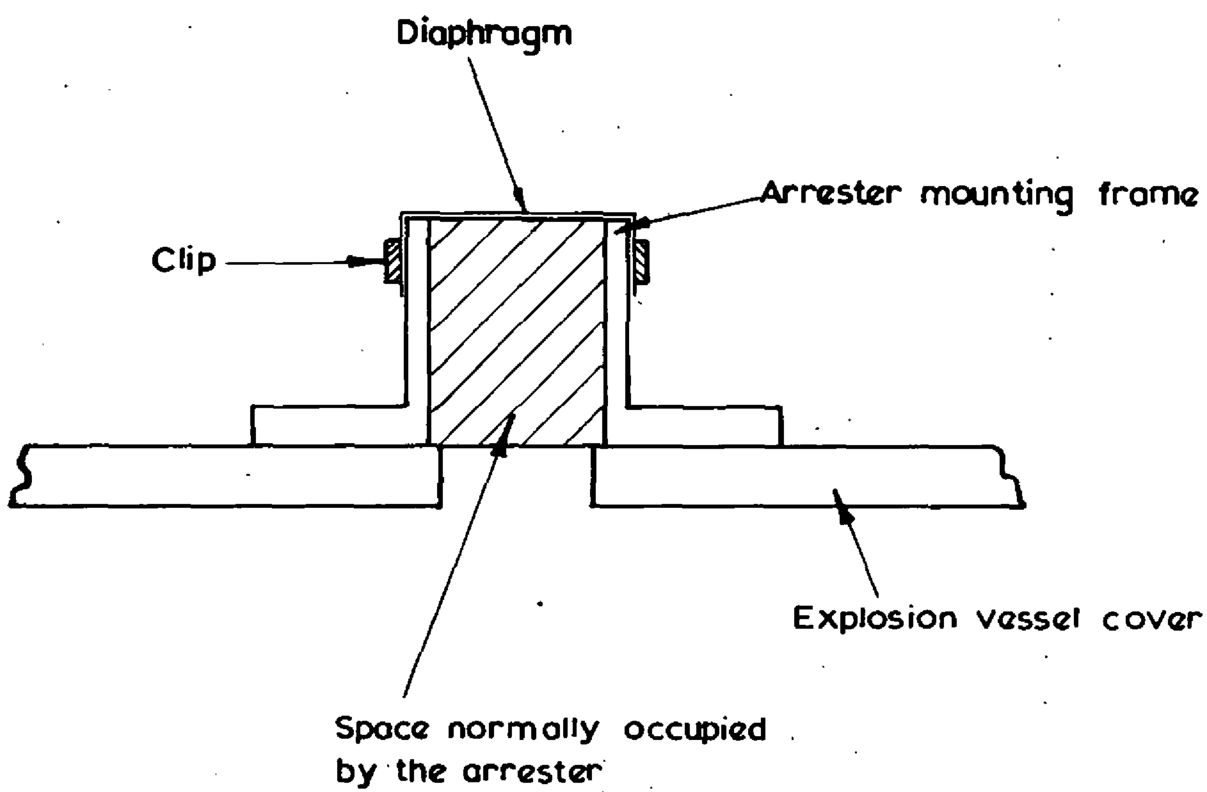
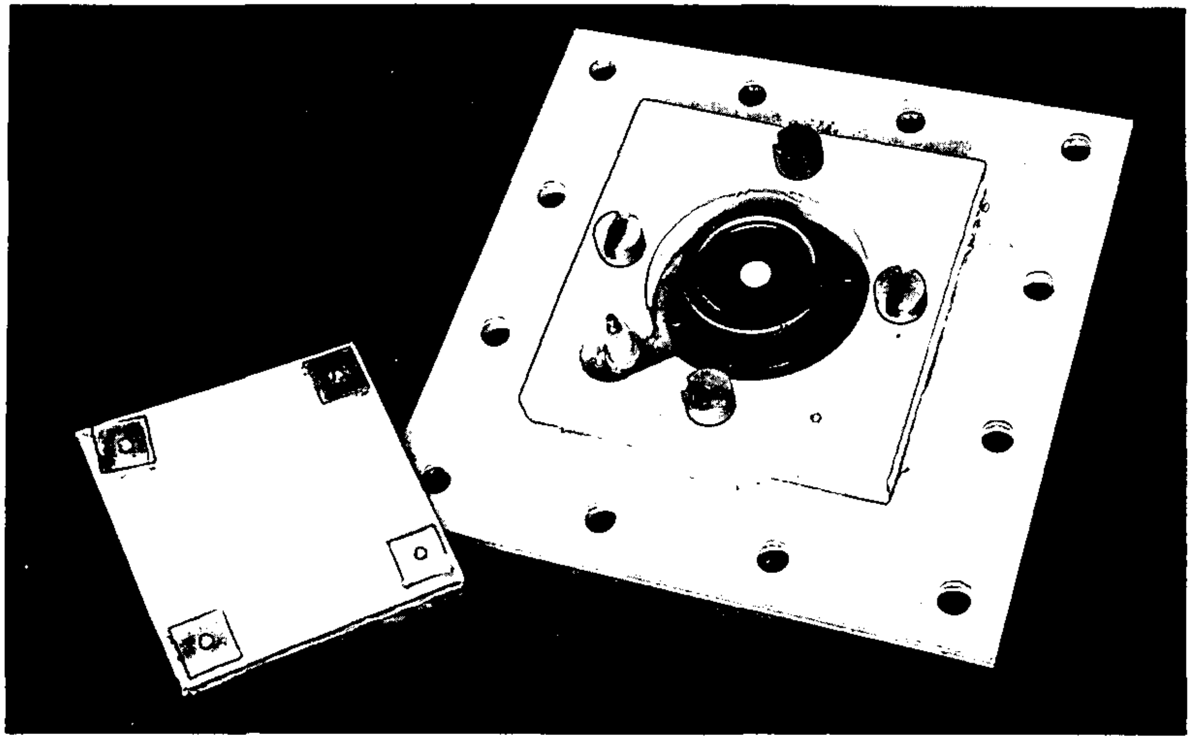


FIG.5. METHOD OF CLIPPING THE DIAPHRAGM TO THE ARRESTER HOLDER



MAGNETIC COVER ASSEMBLY WITH THE
ARRESTER COVER REMOVED

FIG. 6

F.R. 658 1/75V2

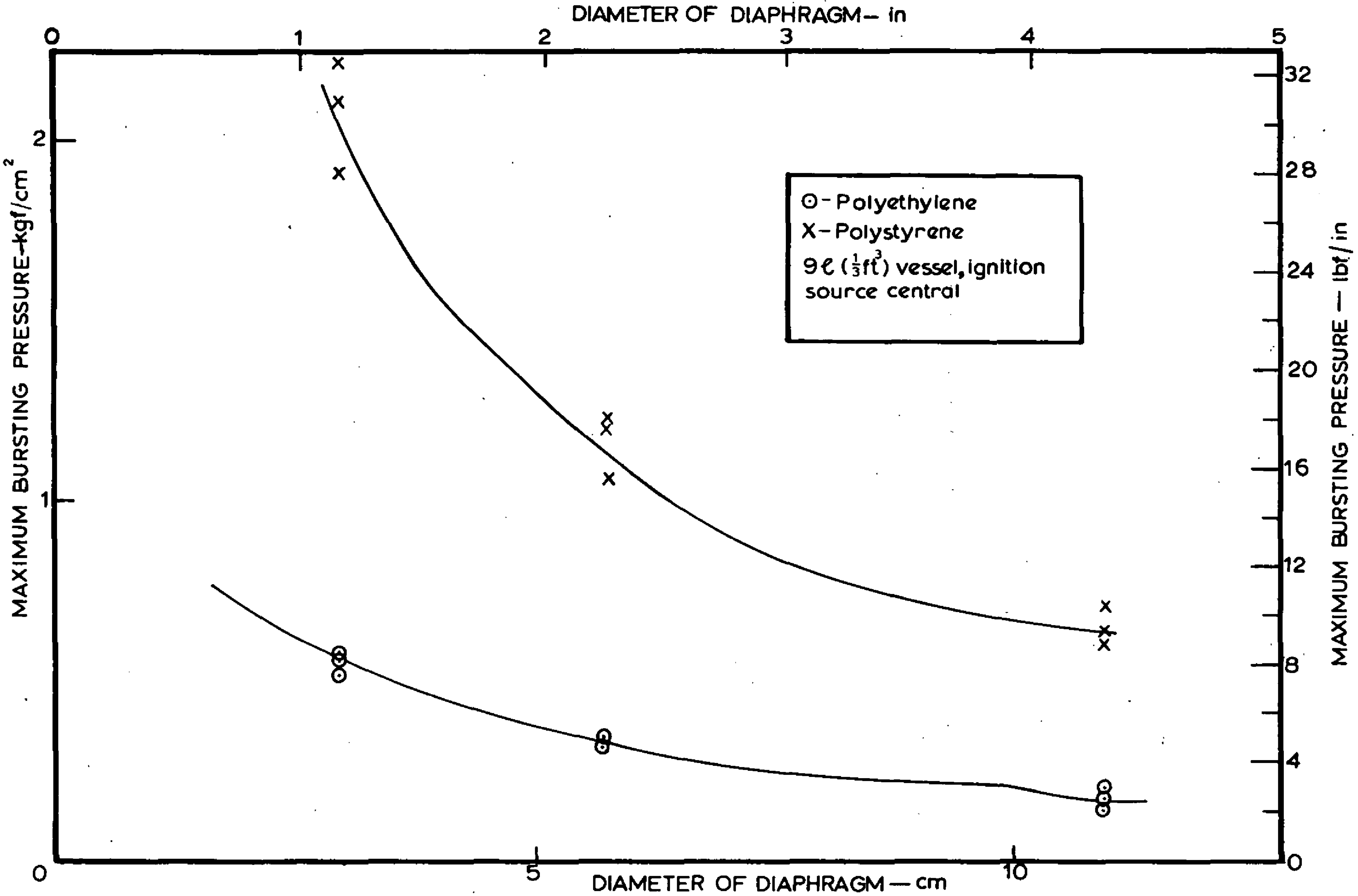


FIG.7. RELATION BETWEEN BURSTING PRESSURE AND DIAPHRAGM DIAMETER

FR. 658. 1/75/3

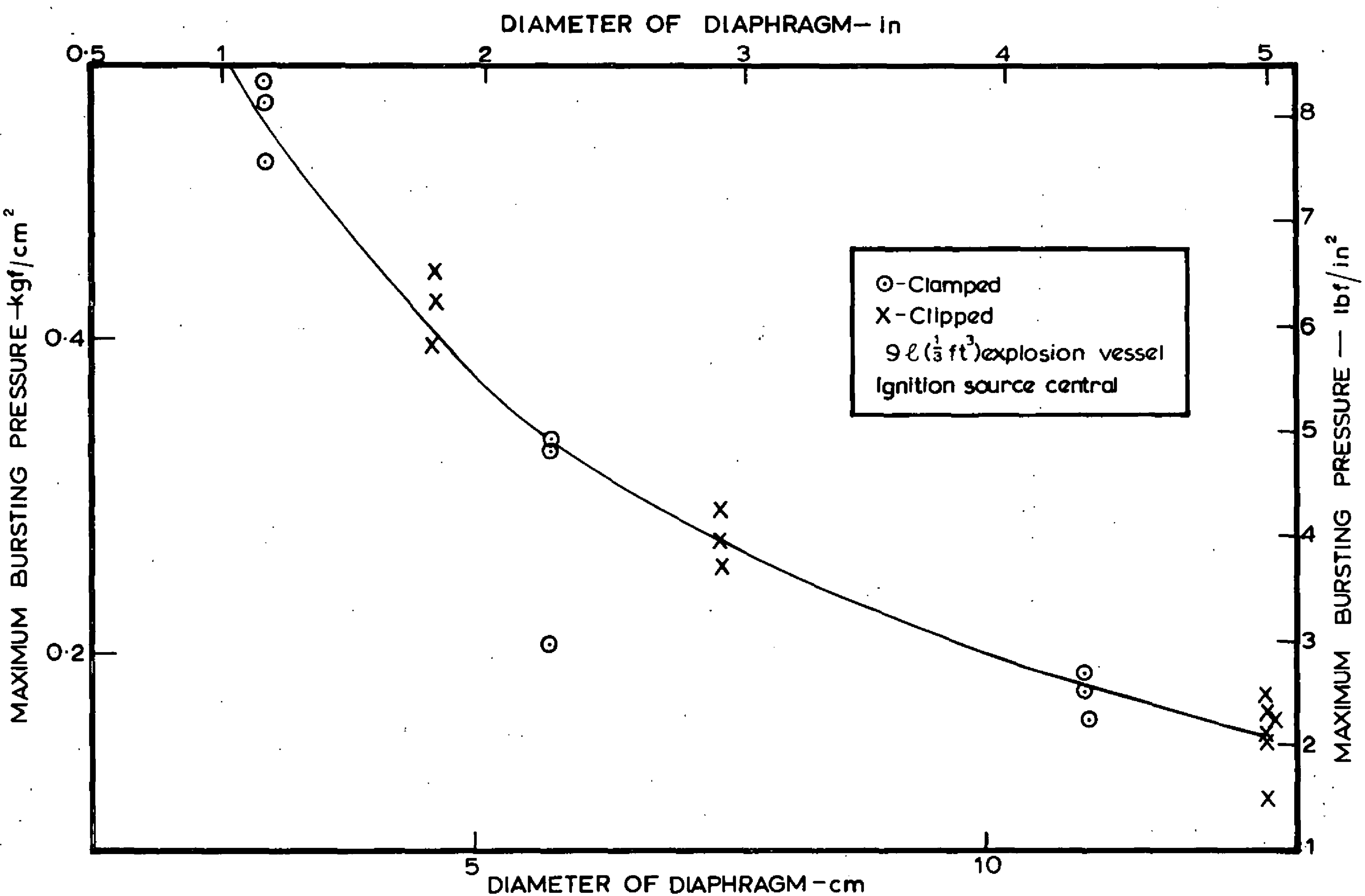


FIG.8. EFFECT OF THE METHOD OF MOUNTING OF POLYETHYLENE DIAPHRAGMS ON THE MAXIMUM BURSTING PRESSURE

FR 658. 1/7514

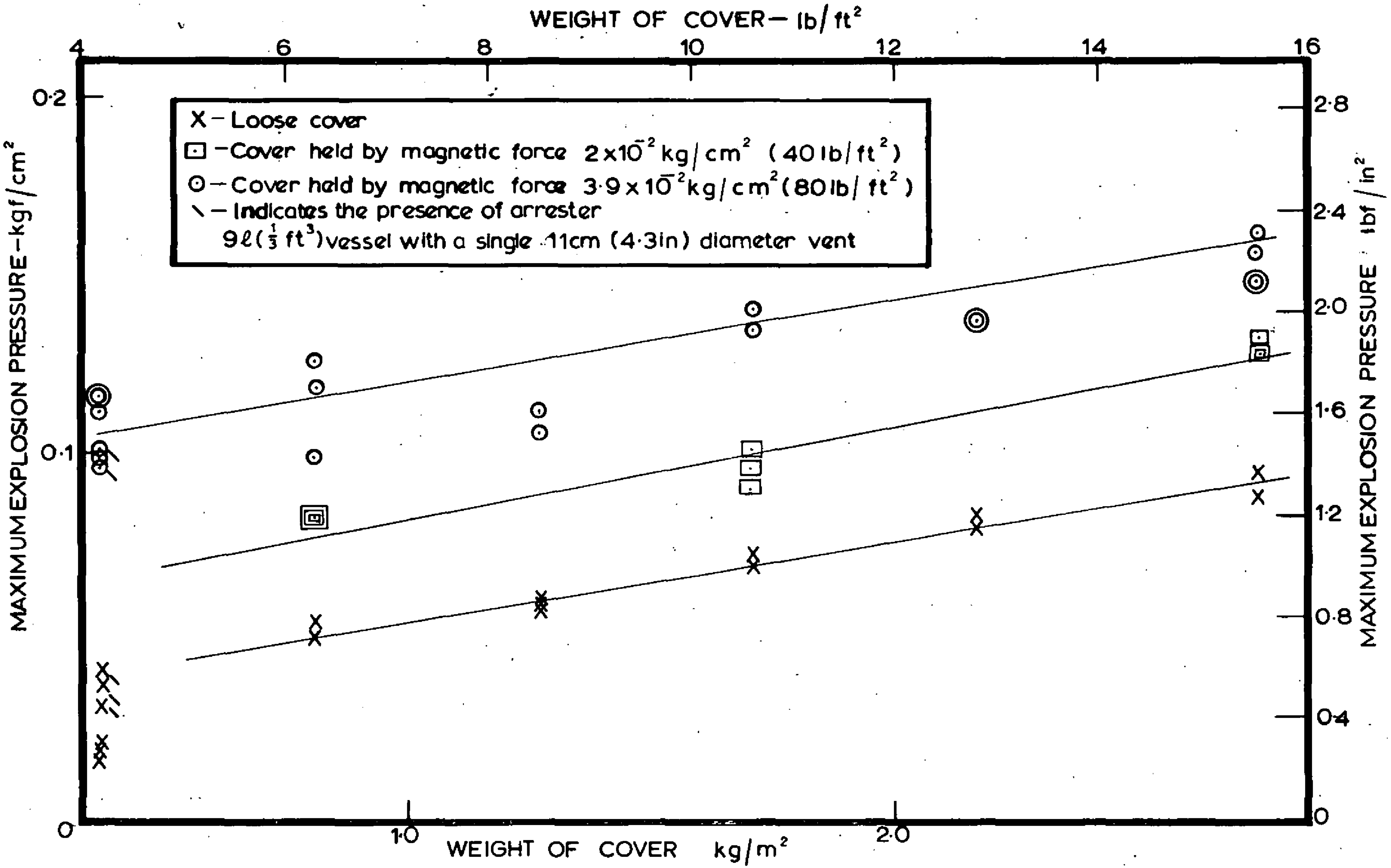


FIG.9. RELATION BETWEEN MAXIMUM PRESSURE AND THE WEIGHT OF VENT COVER OR THE WEIGHT OF THE VENT COVER PLUS FORCE OF THE MAGNETS

FR 658 1/7515

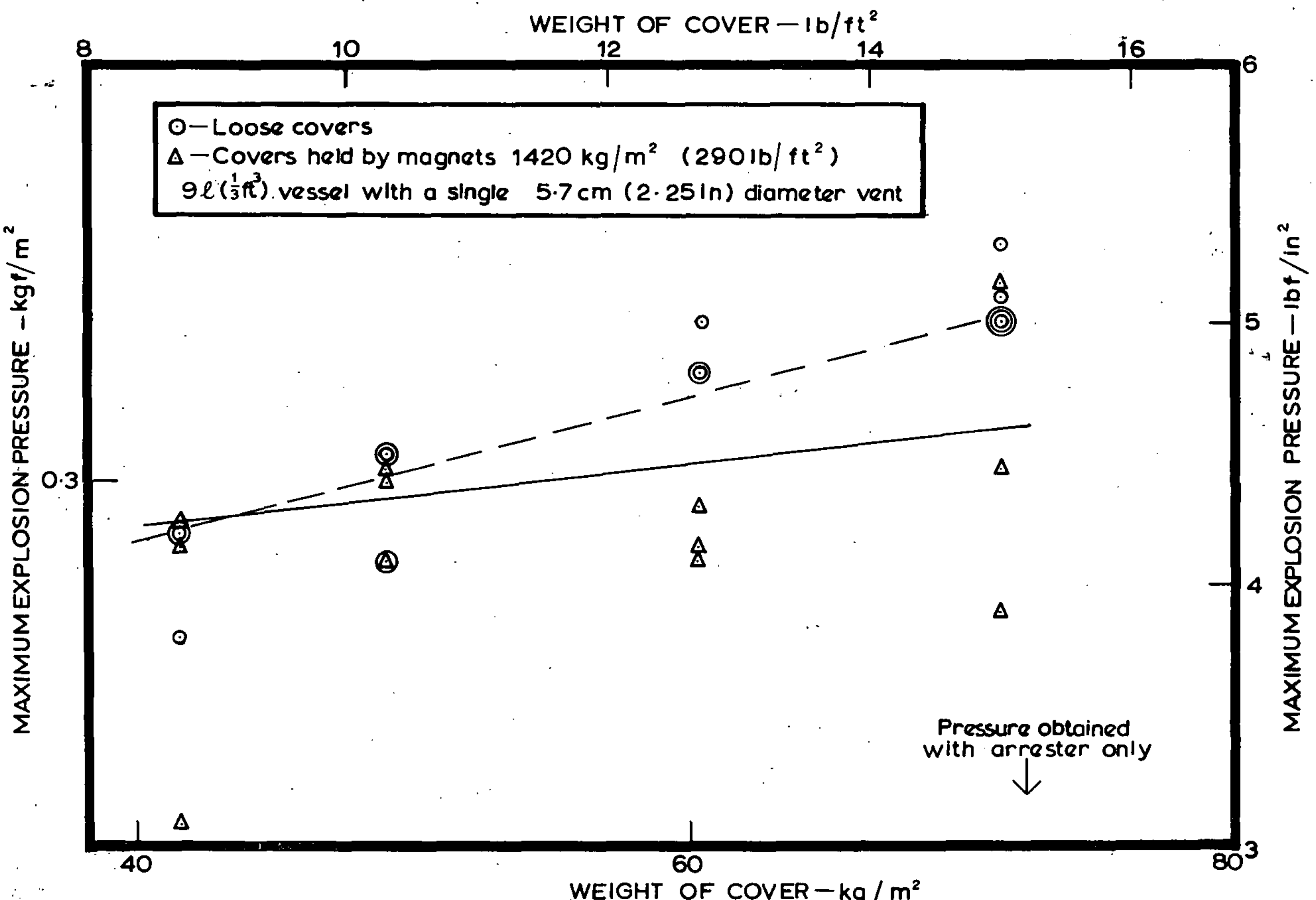
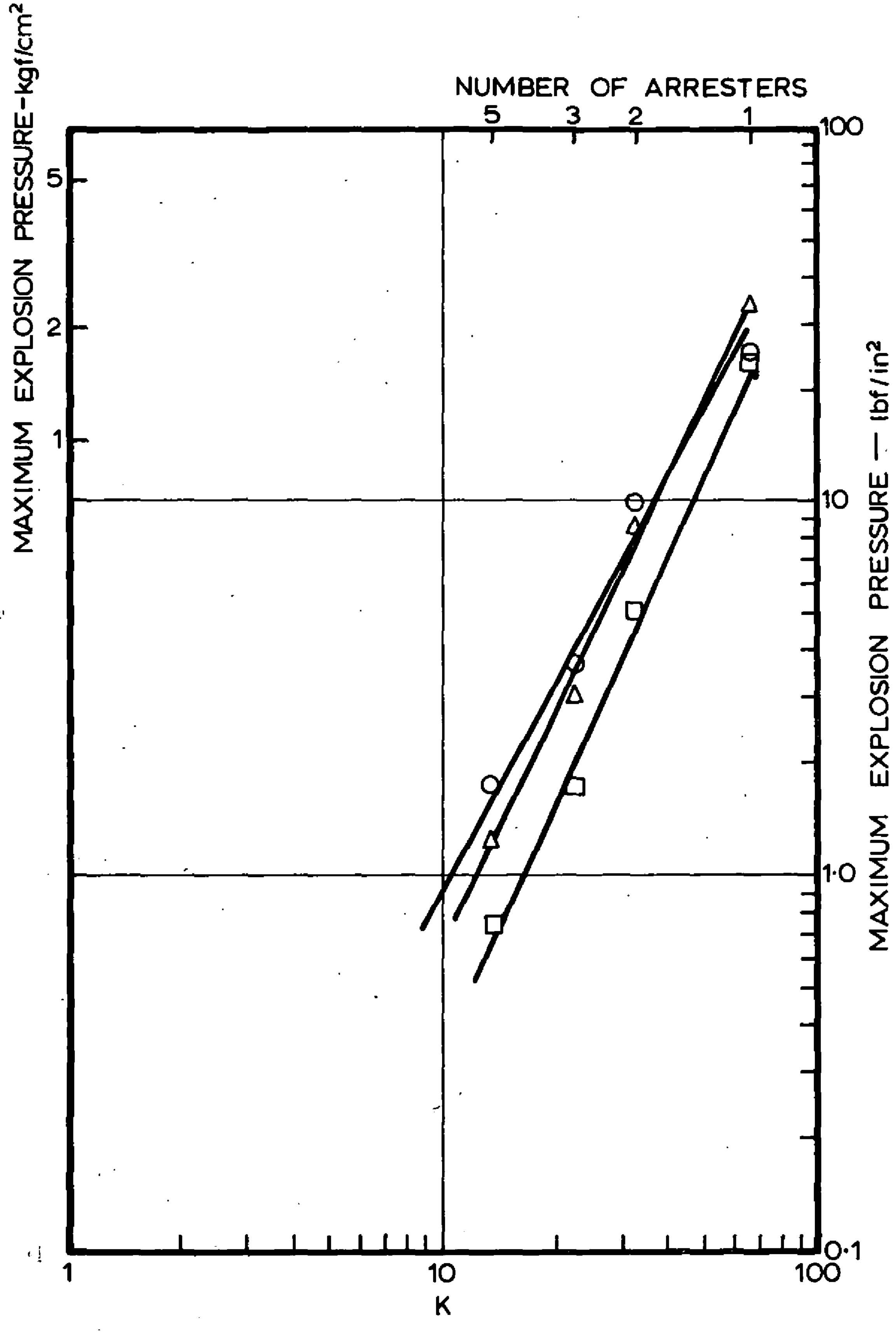


FIG.10. RELATION BETWEEN MAXIMUM PRESSURE AND THE WEIGHT OF THE VENT COVER OR THE WEIGHT OF THE COVER PLUS FORCE OF MAGNETS

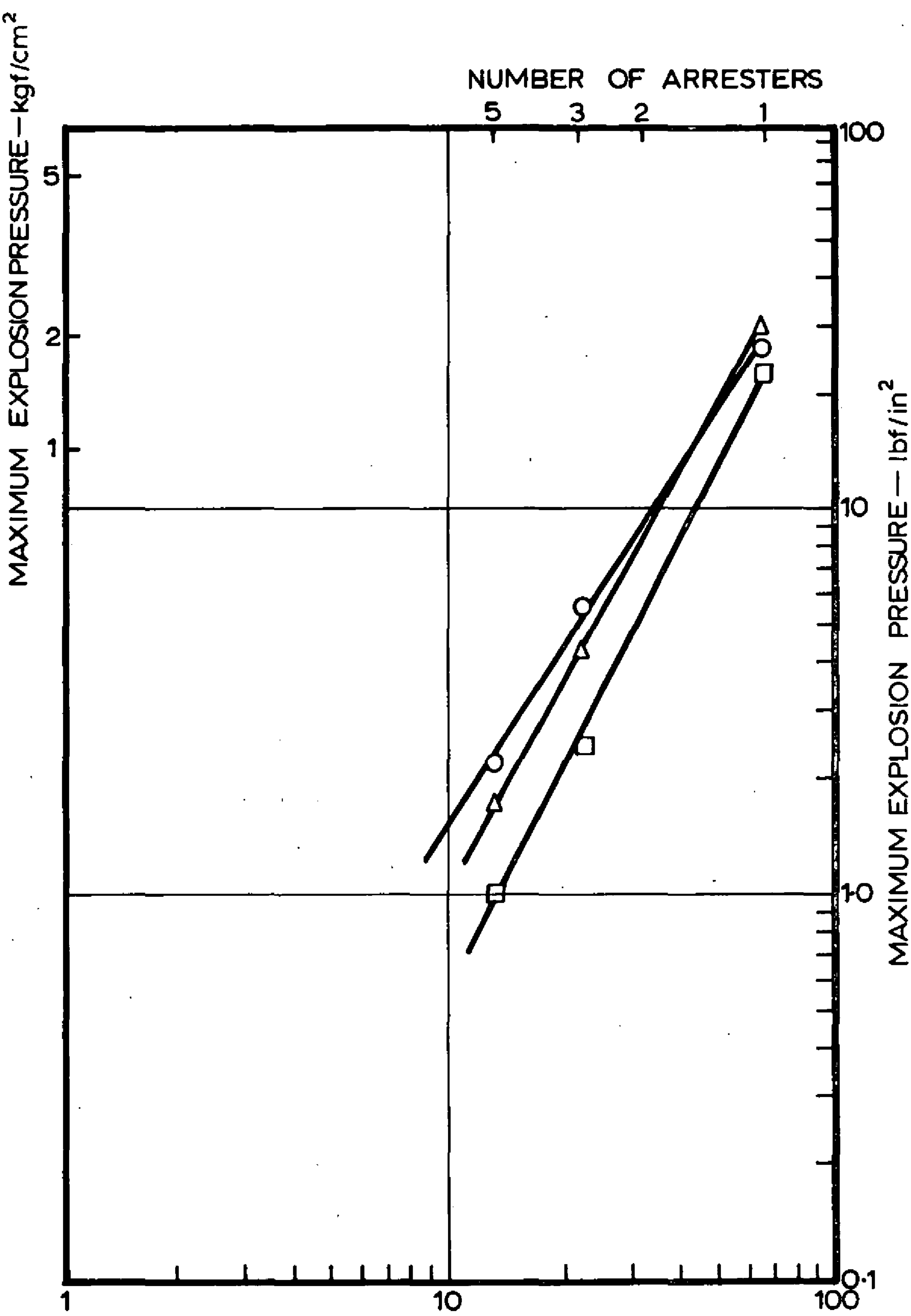


Position of the igniting source
□ — Near
Δ — Centre
○ — Remote

Nickel arresters (type b)
Ribbon thickness 0·008 cm (0·003 in)
9 ℓ (1/3 ft³) explosion vessel

FIG. 11. RELATION BETWEEN THE VENT AREA AND THE MAXIMUM EXPLOSION PRESSURE

FR. 658 1/7516



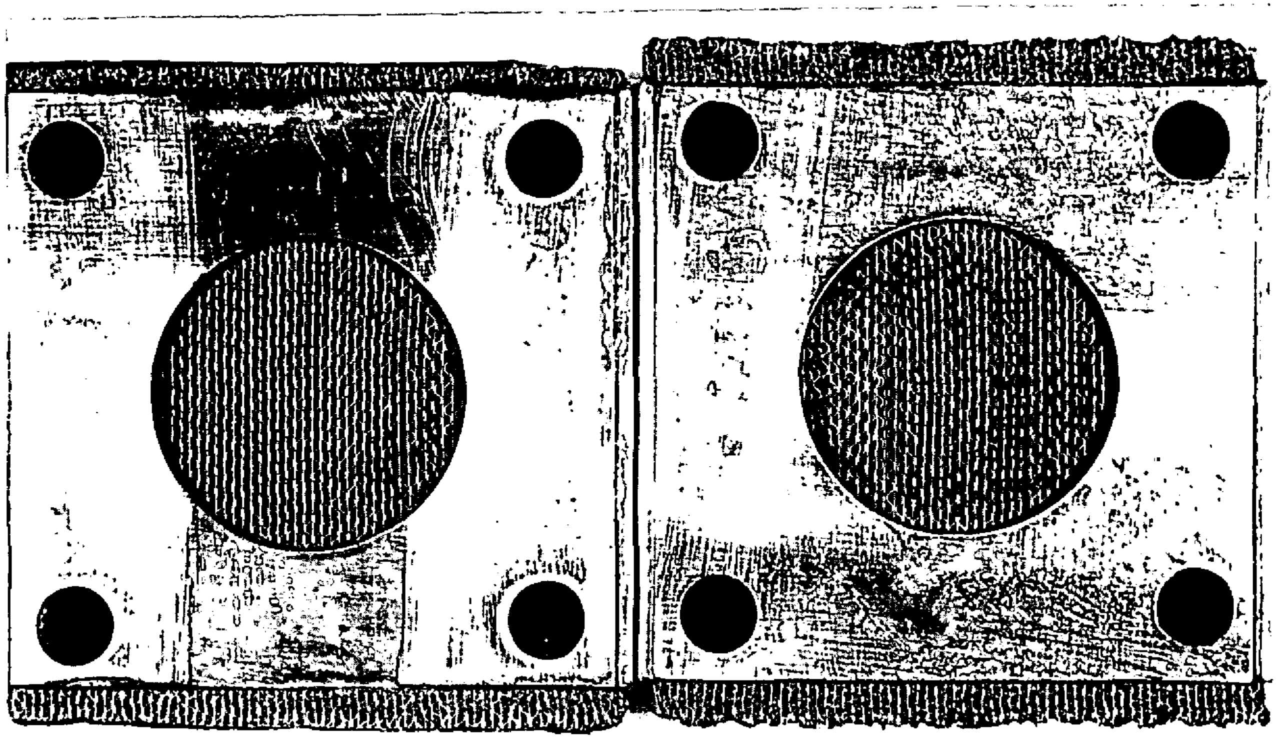
Position of the igniting source

□ — Near
Δ — Centre
O — Remote

Nickel arresters (type b)
Ribbon thickness 0·018 cm (0·007 in)
9ℓ ($^1/_3 ft^3$) explosion vessel

FIG. 12. RELATION BETWEEN THE VENT AREA AND THE MAXIMUM EXPLOSION PRESSURE

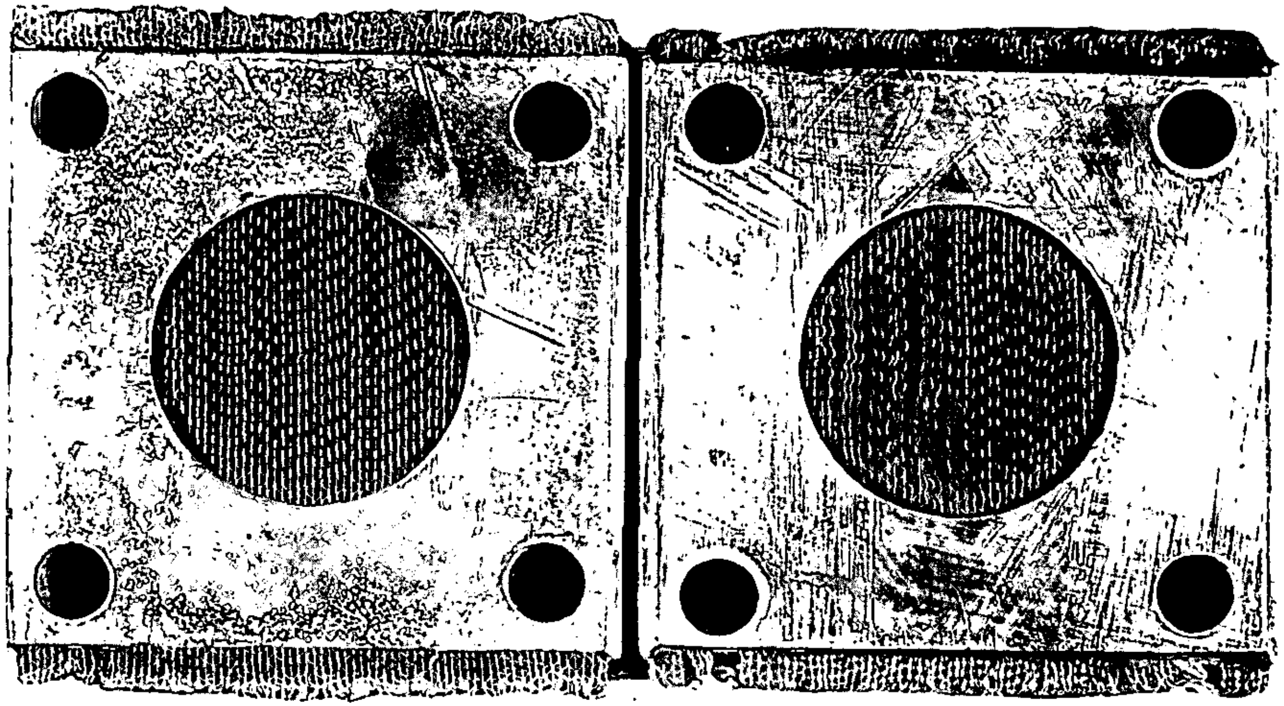
FR 658. 1/7517



Undamaged Damaged

NICKEL ARRESTERS TYPE B
RIBBON THICKNESS 0. 005 in (0. 013 cm)

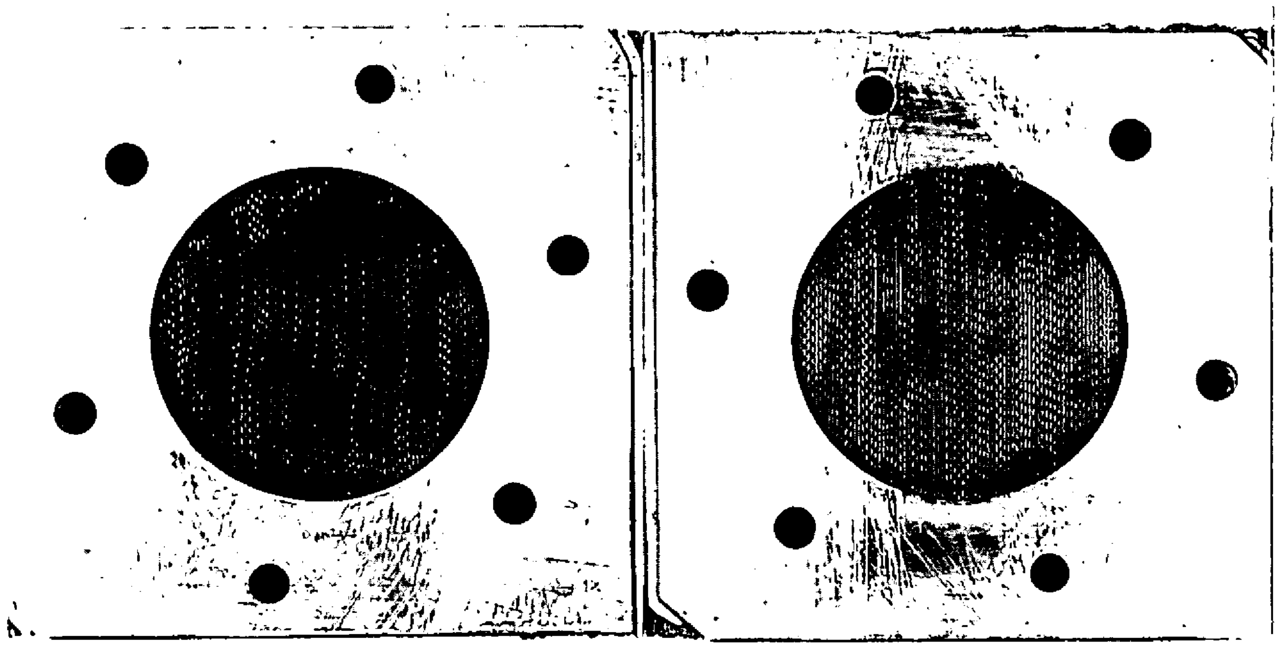
FIG. 13



Undamaged Damaged

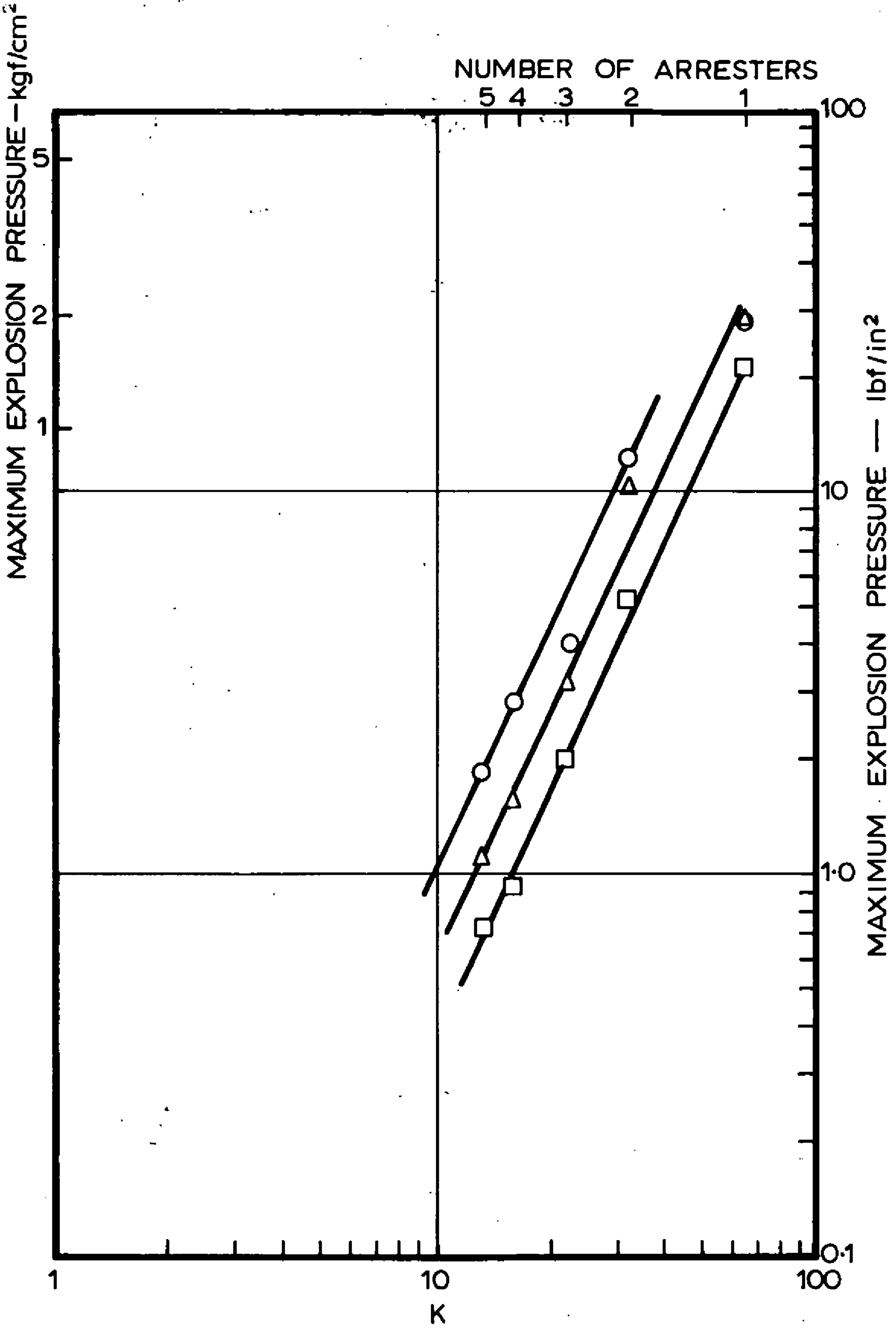
NICKEL ARRESTERS TYPE B
RIBBON THICKNESS 0.003 in (0.008 cm)

FIG. 14



DAMAGED AND UNDAMAGED NICKEL ARRESTERS
TYPE B RIBBON THICKNESS 0.003 in (0.008 cm)

FIG. 15



Position of the igniting source

□ — Near
Δ — Centre
O — Remote

Incoloy arresters (type c)
Ribbon thickness 0·019 cm (0·0076 in)
9 ℓ ($^1/_3 ft^3$) explosion vessel

FIG. 16. RELATION BETWEEN THE VENT AREA AND THE MAXIMUM EXPLOSION PRESSURE