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THE PROTECTION OF EQUIPMENT WITH FLAME ARRESTERS, EFFECT OF VARIATION OF GAS COMPOSITION AND

by

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SUMMARY

Further evaluation has been made of performance data for the use of flame arresters for protection of electrical equipment. A correlation is presented between the fundamental burning velocity of the flammable mixture and the maximum explosion pressure for both propane-air or ethylene-air mixtures.

The effect of contents of various vessels on the maximum explosion pressures developed was studied.

KEY WORDS: Flame arresters, electrical equipment, gas composition.

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INTRODUCTION

Often 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 vapour could be present. If the flammable material penetrated into the equipment it could ignite and propagate flame outside the equipment, thus causing an external explosion or fire. The internal explosion is usually accompanied by an increase in the 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 the flame, but permitting relief of the explosion pressure. The method has several advantages including cheapness, relatively light construction of the casing, and minimising increased weight.

The first part of an investigation of the method has already been reported[1], and some of the findings described in this note have been described in detail elsewhere[2, 3]. This note summarises further information on the performance of the flame arresters in various conditions envisaged in use. The factors reported here are:

1. The relationship between the fundamental burning velocity of the flammable mixture and the maximum explosion pressure.
2. The effect on the maximum explosion pressure of contents within the enclosures such as shelf, baffles, and three dimensional obstacles.
3. The effect of ignition by several simultaneous sources.

The choice of these three particular factors was determined by the effect they may have on the maximum explosion pressure. It is recognized that the explosion pressure in a vertical vessel can be greatly affected by changing the rate of combustion. This rate is known to be dependent on turbulence and the fundamental burning velocity of the gaseous mixture. It also depends to some extent on the mode of ignition because large or multiple sources of ignition provide initially large combustion rates.

The flammable gases used were propane and ethylene in air.

The results given in this note together with those reported previously enable the venting requirements for Groups II and III gases and vapours (B.S. 229) to be assessed for industrial equipment of volume up to 3 ft^3 (85 l).

APPARATUS AND MATERIALS

Explosion vessels

Three sizes of cubical vessels 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		Volume of explosion vessel		
in	cm	$\frac{1}{3}$ ft^3 (9 l)	1 ft^3 (28 l)	3 ft^3 (85 l)
1.15	2.9	3-5	-	-
2.25	5.7	-	4	-
4.30	11.0	1	1,2	2-4

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. When obstacles were present, in propane-air flammable mixtures the pressure was measured on both sides of obstacle. 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 all other tests one gauge was used and this was situated 2 in (5 cm) from the top cover or in the centre of one wall. 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 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 a brass tube. 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. Alloy A 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. Alloy A 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		Ribbon metal	Ribbon thickness		Crimp height		Thickness of arrester	
in	cm		in	cm	in	cm	in	cm
1.15	2.9	Cupro-nickel	0.0025	0.0063	0.045	0.11	1.5	3.8
		Nickel	0.003 0.005 0.007	0.008 0.013 0.018	0.020	0.05	1.0	2.5
		Alloy A	0.0076	0.019	0.020	0.05	1.0	2.5
2.25	5.7	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	Cupro-nickel	0.0025	0.0063	0.045	0.11	1.5	3.8
		Nickel	0.003 0.007	0.008 0.018	0.020	0.05	1.0	2.5
		Alloy A	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 whenever quoted using ionisation gaps.

Flammable gas

A 4.0 per cent by volume propane-air mixture and 6.5 per cent ethylene-air mixture were 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 cent 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 obstacle the igniting source was in the centre of the vessel. 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. Some tests were also carried out with vents distributed between the two covers of the explosion vessel and central obstacles parallel to the arresters as in arrangement H (Fig. 3).

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 200gauge 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 l) explosion vessel

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

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.

PROCEDURE

Except in the majority of tests with the obstacles, the explosion vessel rested inside the larger 15.6 ft^3 (440 l) enclosure. The propane-air or ethylene-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. The flammable gas after each test was disposed 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 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

Explosion within unobstructed vessels

The results obtained with propane-air flammable mixtures have already been reported[1]. There were many similarities between the explosions with propane-air and ethylene-air gaseous mixtures, and the main distinguishing characteristics with the ethylene-air were the greater maximum explosion pressures, rates of pressure rise and flame velocities.

All pressure records were smooth during the period of time while the flame front moved to the vent. After this usually various vibrations developed, many of an acoustic nature. Explosions with the ignition near the vent gave pressure records of longer duration and these often showed absence of peaks. With multiple vents ignition remote from the vent always resulted in the highest maximum pressure, but with single vents there was little difference between the maximum pressures with the ignition remote or at the centre. Peak pressures with ignition remote or at centre with propane air mixtures occurred when the flame front arrived at the vent or the arrester[1], with ethylene-air peak pressures could in some tests occur a few milliseconds after the flame arrived at the vent.

Fig. 5 shows the maximum explosion pressures plotted against the vent area, for ethylene-air flammable mixtures the line for propane-air is included for comparison[1]. Figure 6 shows the maximum explosion pressures for the same vents covered with the flame arresters, these evidently are twice as high as the pressures obtained with open vents. Measurements obtained with the 3 ft (85 l) vessel indicate that for a given K value the maximum pressure in this vessel was about twice the value of the pressures obtained in smaller explosion vessels, both for open vents and vents covered with flame arresters.

Table 5 shows the maximum and minimum of flame speeds measured with open vents. Table 6 shows similar results with vents covered with flame arresters. The results indicated that for a given gaseous mixture the largest variations in the flame speeds were caused by changing the position of the igniting source. The highest flame speeds occurred when the igniting source was remote from the vents, the speeds measured while the igniting source was near the vent or at the centre of the vessel were always lower. The flame speeds recorded between the igniting source and the wall opposite the vents were lowest.

The speed with ethylene-air were approximately double the propane-air values. The presence of the arresters had little effect on the flame speed with both mixtures.

Table 5

Maximum and minimum flame speeds with open vents for propane and ethylene mixtures (ethylene in brackets)

Volume of explosion vessel		Minimum flame speed		Maximum flame speed	
ft^3	l	$ft\ s^{-1}$	$m\ s^{-1}$	$ft\ s^{-1}$	$m\ s^{-1}$
⅓	9	3.7 (8.0)	1.3 (2.4)	19 (38)	5.8 (12)
1	28	1.7	0.5	19	5.8
3	85	4.4	1.3	19	5.8

Table 6

Maximum and minimum flame speeds with vents fitted with arresters for propane and ethylene mixtures (ethylene in brackets)

Volume of explosion vessel		Minimum flame speed		Maximum flame speed	
ft^3	l	$ft\ s^{-1}$	$m\ s^{-1}$	$ft\ s^{-1}$	$m\ s^{-1}$
⅓	9	3.7 (8.0)	1.2 (2.4)	18 (40)	5.5 (12.1)
1	28	2.8 (9)	0.8 (2.7)	18 (30)	5.5 (9.2)
3	85	(6)	(1.8)	(60)	(18.3)

Table 7

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		Mixture
				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	4.0 per cent propane-air
	90	A	4.8	$\frac{1}{3}$	9	2.3*	0.16	4.7*	0.33	
	90	H	–	$\frac{1}{3}$	9	2.3	0.16	10.1	0.70	
Orifice plate	75	A	4.9	1	28	0.6	0.04	2.6	0.18	
	75	H	–	$\frac{1}{3}$	9	2.3	0.16	2.1	0.15	
Shelf and orifice plate	75	–	4.9	1	28	0.6	0.04	6.8	0.48	
Perforated metal	56	A	4.9	1	28	0.6	0.04	1.2	0.08	
Wire gauze	38	A	4.9	1	28	0.6	0.04	0.8	0.06	
Cube	25	–	4.9	1	28	0.6	0.04	1.1	0.08	
Bar	50	–	4.9	1	28	0.6	0.04	0.6	0.04	
Shelf	50	A	4.9	1	28	2.1	0.14	5.1	0.24	6.5 per cent ethylene-air
	25	A	4.9	1	28	2.1	0.14	3.5	0.36	
	50	A	10	1	28	6.0	0.42	18.0	1.27	
	75	A	13	$\frac{1}{3}$	9	10.0	0.70	25.0	0.86	
	25	A	13	$\frac{1}{3}$	9	10.0	0.70	12.3	1.76	
Orifice	75	A	13	$\frac{1}{3}$	9	10.0	0.70	22.0	1.55	
	25	A	13	$\frac{1}{3}$	9	10.0	0.70	16.0	1.15	
Perforated metal	56	A	4.9	1	28	2.1	0.14	5.9	0.41	

*Acoustic motion.

Explosion in vessels fitted with obstructions

The results with obstacles and propane-air were reported in detail elsewhere[2]. Table 7 shows selected results. These indicate that obstacles of various forms occupying a substantial fraction of the vessel cross-sectional area, may cause large increases in the maximum explosion pressure. The results are given for the most adverse conditions; the explosions in other cases were lower. However, it is evident that ethylene-air mixtures gave very much higher maximum pressures, and also higher rates of pressure rise were recorded.

There were a number of characteristics common to all experiments. The maximum explosion pressure increased greatly with the increased area of the obstacle. The position of the obstacle had small effect on the maximum pressure, but the positioning of the igniting source was of prime importance and the highest pressures always occurred with igniting source remote from the vents.

With propane-air and ethylene-air mixtures a perforated metal obstacle gave lower explosion pressures than an unperforated shelf of the same span. Three dimensional obstacles had less effect on the maximum pressure than the two dimensional obstacles occupying the same area.

The maximum explosion pressures obtained after simultaneous ignition with three large sources, may be compared with the values for ignition with a single inductive spark, in Table 8. 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.

Table 8

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	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

DISCUSSION

Vessels without obstacles

In all vented explosions two different processes may be distinguished. One is the combustion of the flammable gas, this produces a greatly increased volume of products. The other process is the ejection of the expanded or cold gases through a vent provided for the purpose. The maximum explosion pressure in a vessel results from the action of these two opposing processes. The combustion rate governs the rate of expansion of the gases and the size of the vent governs the volume of gases expelled. By equating the rate of generation of combustion products with the rate of venting, the maximum explosion pressures can be calculated[1].

Good agreement was obtained between measured and calculated maximum explosion pressures for propane-air mixtures. This theory predicts that the maximum explosion pressure for a given K will increase with the square of the measured flame speed between the igniting source and the vent. The range of measured relevant flame speeds for ethylene-air flammable mixture is 30-40 ft/sec (9.2-12.2 m/sec) for ⅓ ft^3 (9 l) and 1 ft^3 (28 l) vessels and this compares with 18-20 ft/sec (5.5-6.2 m/sec) obtained with propane-air mixture for the same vessels Tables 5 and 6. The square of the ratio of the flame speeds for the two gases varies between 2.5-4. The ratio of the maximum explosion pressures with ethylene-air and propane-air is close to the maximum value of this range Fig. 5. The maximum explosion pressures recorded in 3 ft^3 (85 l) explosion both for propane-air and ethylene-air flammable mixtures were about twice the corresponding pressures obtained with the smaller vessels Fig. 7. The relevant maximum flame speeds measured with ethylene-air flammable mixture are approximately 1.5 - 2 times those measured with the other explosion vessels Table 6, and they are consistent with the recorded increase in the explosion pressure. No corresponding maximum flame speeds with propane-air mixture while using arresters are available for comparison.

The higher maximum explosion pressures obtained with the larger vessels are not entirely surprising, as work elsewhere with larger containers produced higher values[4], and higher maximum pressures were expected with larger vessels.

It would be desirable to correlate the maximum explosion pressure with the fundamental burning velocity, as this could enable predictions to be made for a variety of gas mixtures. Such correlation however could only be valid if the rates of burning remained constant for a variety of experimental conditions. Present results indicate however that the rates of burning may be subject to variation caused by the size of explosion vessels thus making such extrapolation difficult for larger vessels.

Explosion vessels with obstacles

The effect various obstacles had on the maximum explosion pressures in a propane-air flammable mixture is summarised in this Note and reported in more detail elsewhere[2]. Although a great deal of experimental work was carried out no simple relationship was found between the shape and the area of obstacle and the corresponding maximum explosion pressure.

Obstacles interfere with the development of the explosion by generating additional turbulence, thus increasing the rate of burning, this subsequently resulting in higher maximum explosion pressures. The principal factors operating were the area of the obstacle and the position of the igniting source. Ignition in the position remote from the vent always gave highest maximum pressures and this suggested that the free volume was an important factor in the maximum explosion pressure development.

Only small pressure gradients across the obstacle were recorded with the propane-air mixture and these never exceeded 1 lb/in^2 (0.07 kg/cm^2). Certain geometrics of obstacles, ignition and vent tended to produce lower pressures, and it seemed that the operative principles in pressure reduction were early venting facilitating slow movement of gases and avoidance of disturbance to the flammable mixture moving ahead of the flame front. The turbulent burning however is a very complex and still largely unpredictable process, making even small extrapolation difficult. One object of the present work was to establish the effect on the maximum explosion pressure of the gases having greater fundamental burning velocities, and ethylene was used as being convenient representative of group III. Direct comparison may be made between the highest maximum pressures with propane-air and ethylene-air flammable mixtures. Table 9 shows this comparison for both 1 ft^3 (28 l) and $\frac{1}{3}$ ft^3 (9 l) explosion vessels with various obstacles.

Table 9

Ratio of the maximum explosion pressures

$\frac{\text{Ethylene-air}}{\text{Propane-air}}$ obtained with various obstacles

	Per cent of cross-sectional area blocked by obstacle		
	25 per cent	50 per cent	75 per cent
1 ft^3 (28 l) vessel shelf obstacle K = 5	3.9	4.6	N.d.
½ ft^3 (9 l) vessel shelf obstacle K = 13	1.4	2.9	3.0
1 ft^3 (28 l) vessel perforated metal K = 10	N.d.	5.0	N.d.

N.d. Not determined.

Although the results with obstacles show some definite trends, they are only valid for very similar conditions, and they may be greatly affected by the dimensional variations of obstacles and vessels.

APPLICATION OF THE RESULTS

The results described widen the scope of the existing design data. They indicate the maximum explosion pressures that will be produced by explosions of some of group III gases. They also indicate that the maximum explosion pressures in vessels with no obstruction will be predictable with some measure of accuracy. The effect of contents is not easily predictable and only some measure of guidance is available from the data obtained with simple obstacles. As the industrial casings requiring protection will have great variety of obstacles, the assessment of the maximum explosion pressures in such casings may be subject to tests.

ACKNOWLEDGEMENT

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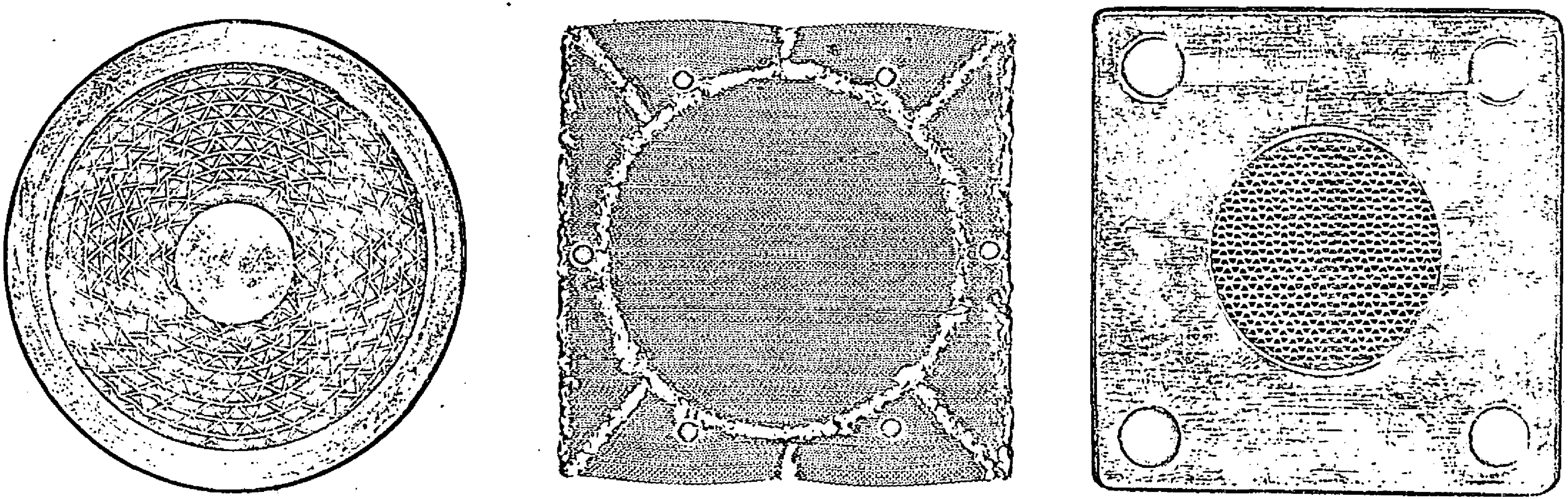
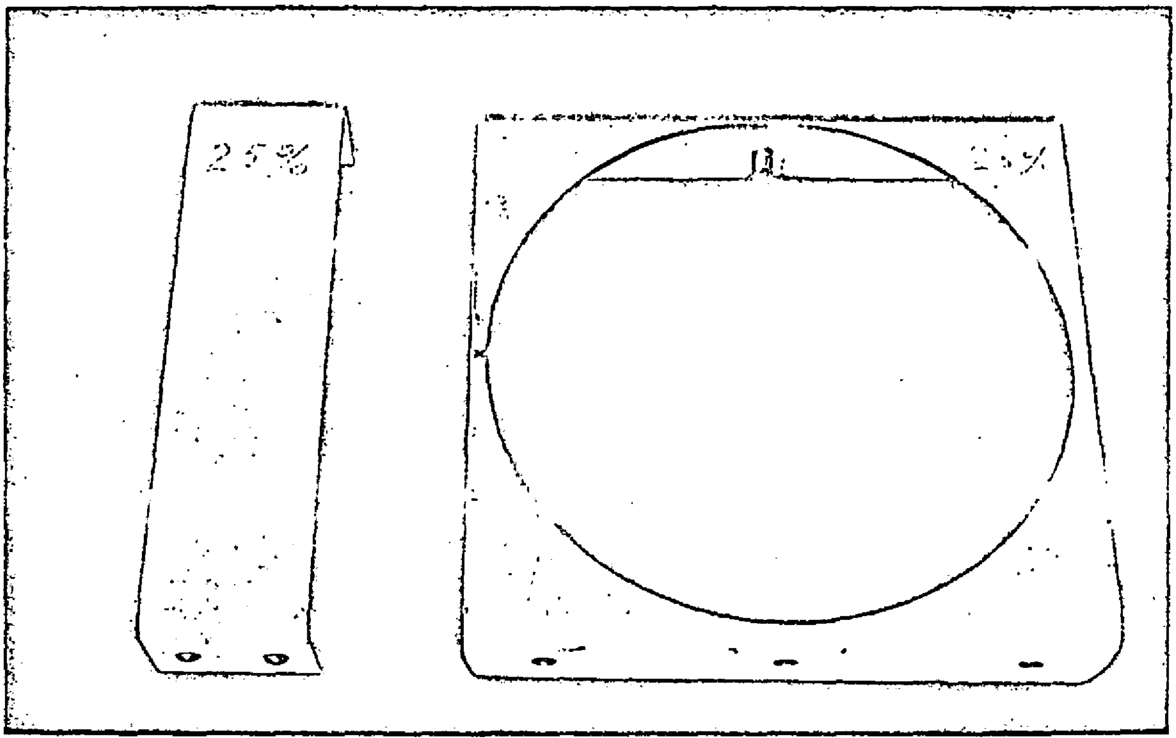


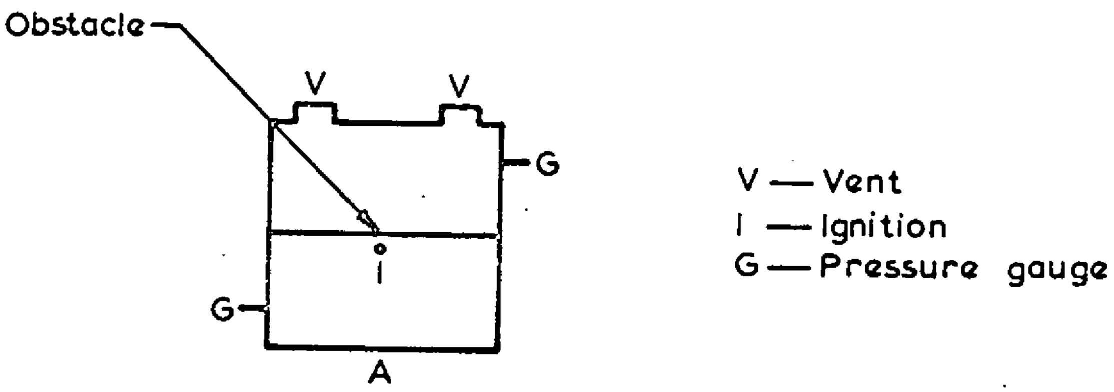
CUPRO NICKEL ALLOY A NICKEL

FIG. 1

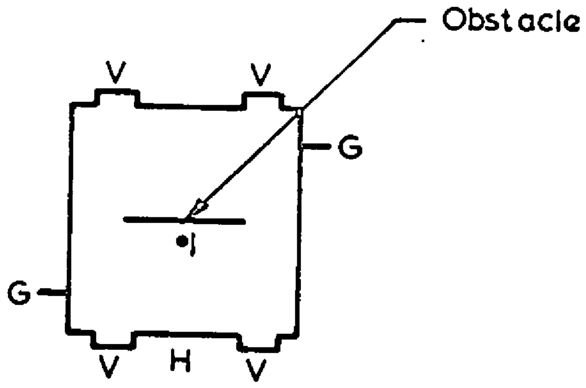


ORIFICE AND SHELF OBSTACLES BLOCKING 25 PER CENT OF THE CROSS-SECTIONAL AREA OF THE VESSEL

FIG. 2



A — Obstacle parallel to the arresters



H — Horizontal central obstacle with distributed vents

FIG. 3. ARRANGEMENTS OF VENTS AND OBSTACLES

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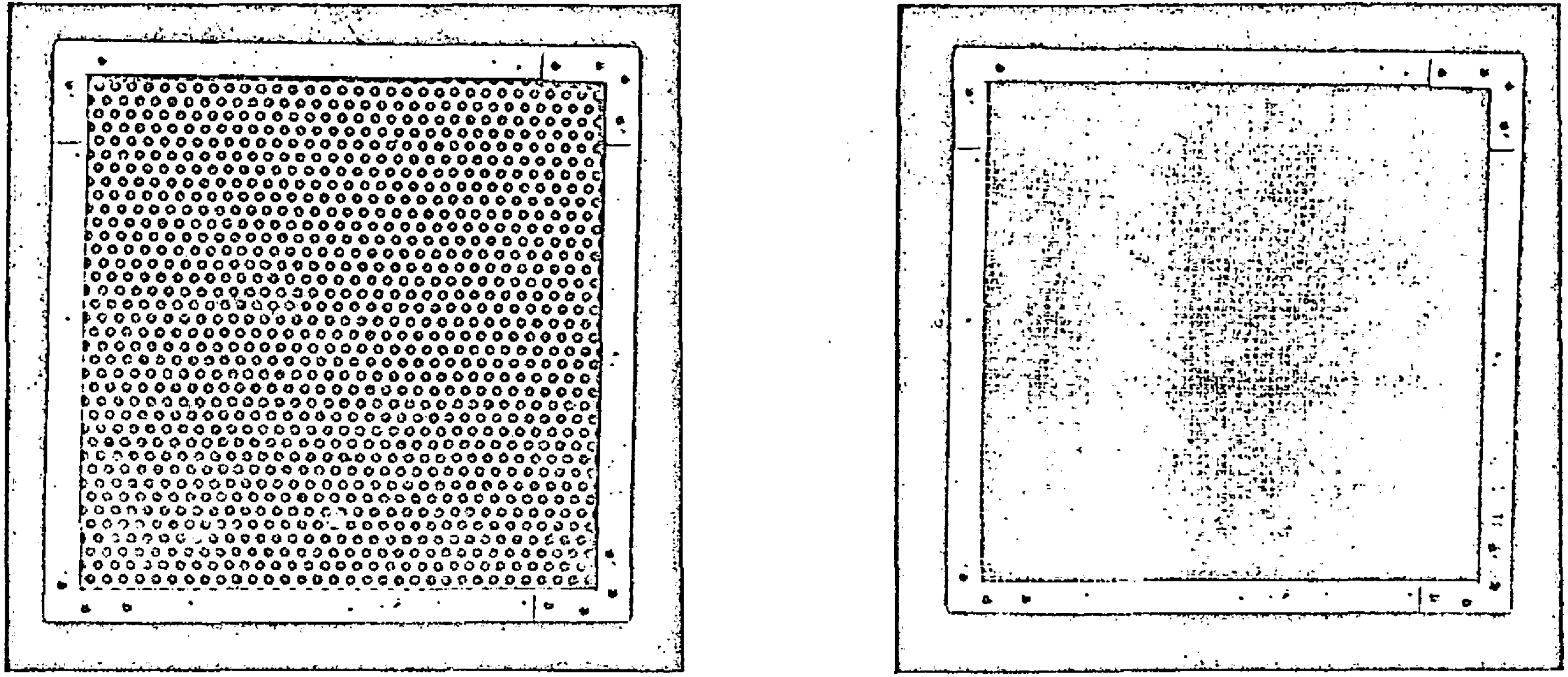


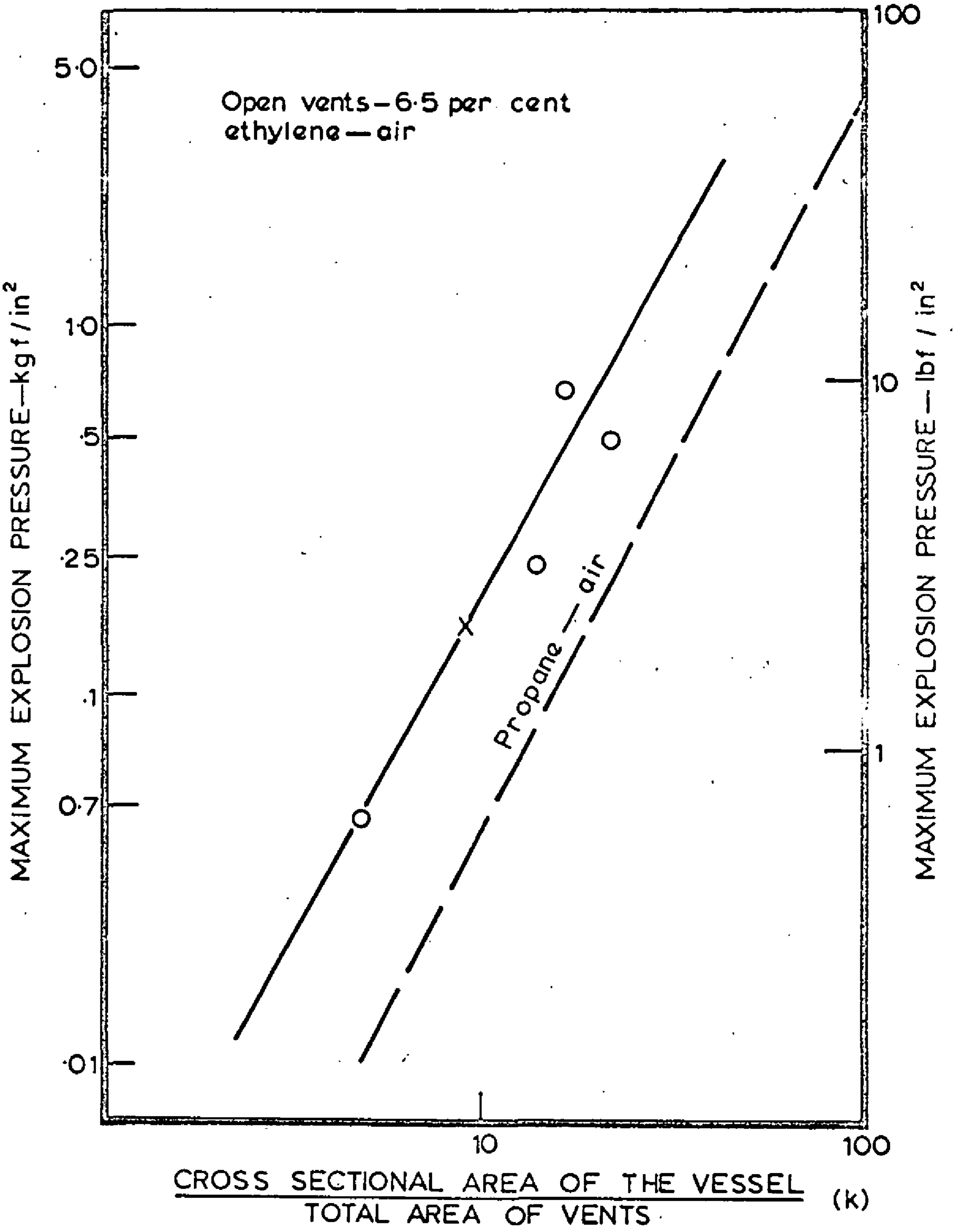
A

PERFORATED METAL OBSTACLE

B

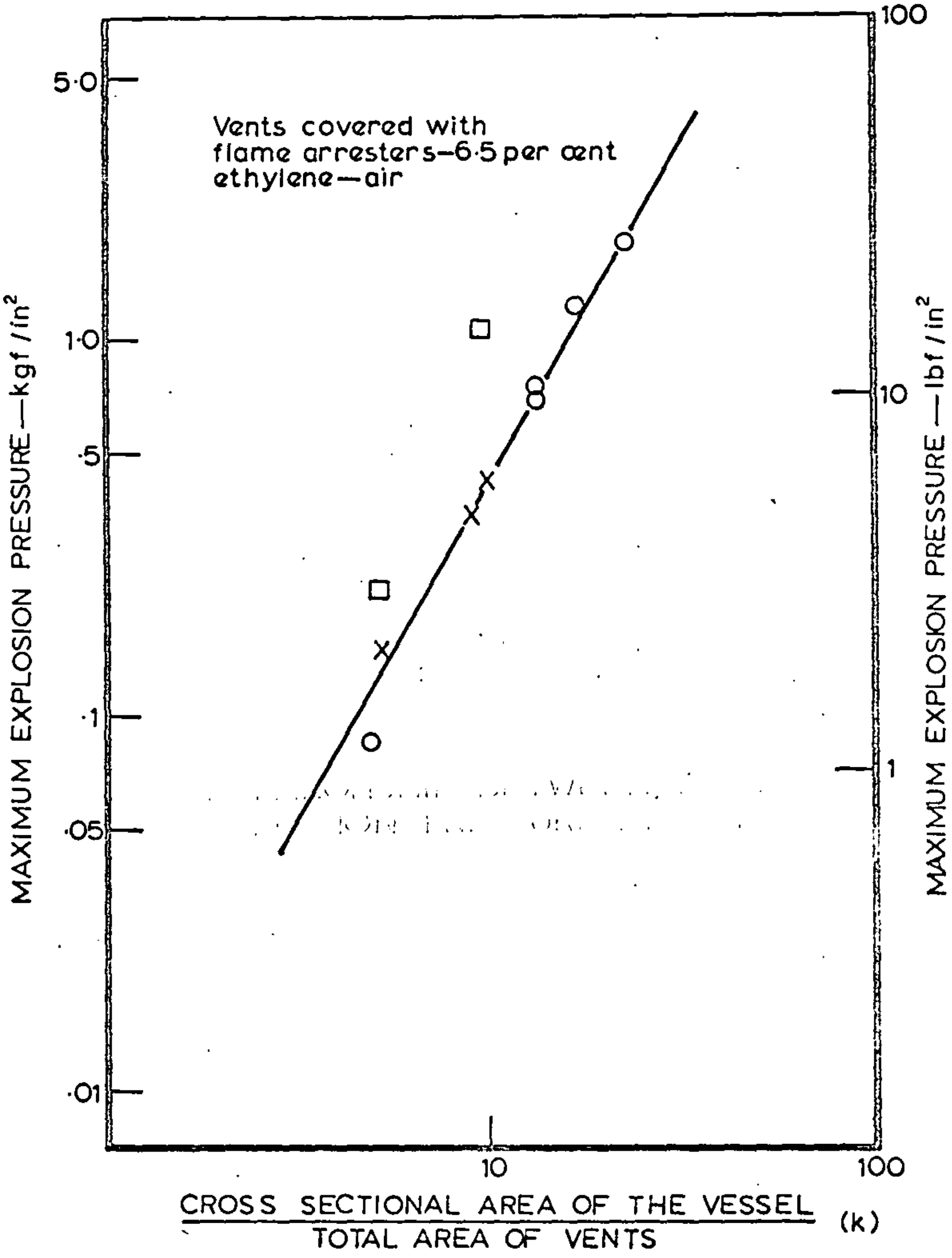
WIRE GAUZE OBSTACLE

FIG. 4



SYMBOL	VOLUME OF VESSEL	
	l	ft^2
O	9	$\frac{1}{3}$
X	28	1

FIG. 5. RELATIONSHIP BETWEEN MAXIMUM EXPLOSION PRESSURE AND THE VENT AREA



SYMBOL	VOLUME OF VESSEL	
	l	ft^3
○	9	$\frac{1}{3}$
X	28	1
□	85	3

FIG. 6. RELATIONSHIP BETWEEN MAXIMUM EXPLOSION PRESSURE AND THE VENT AREA

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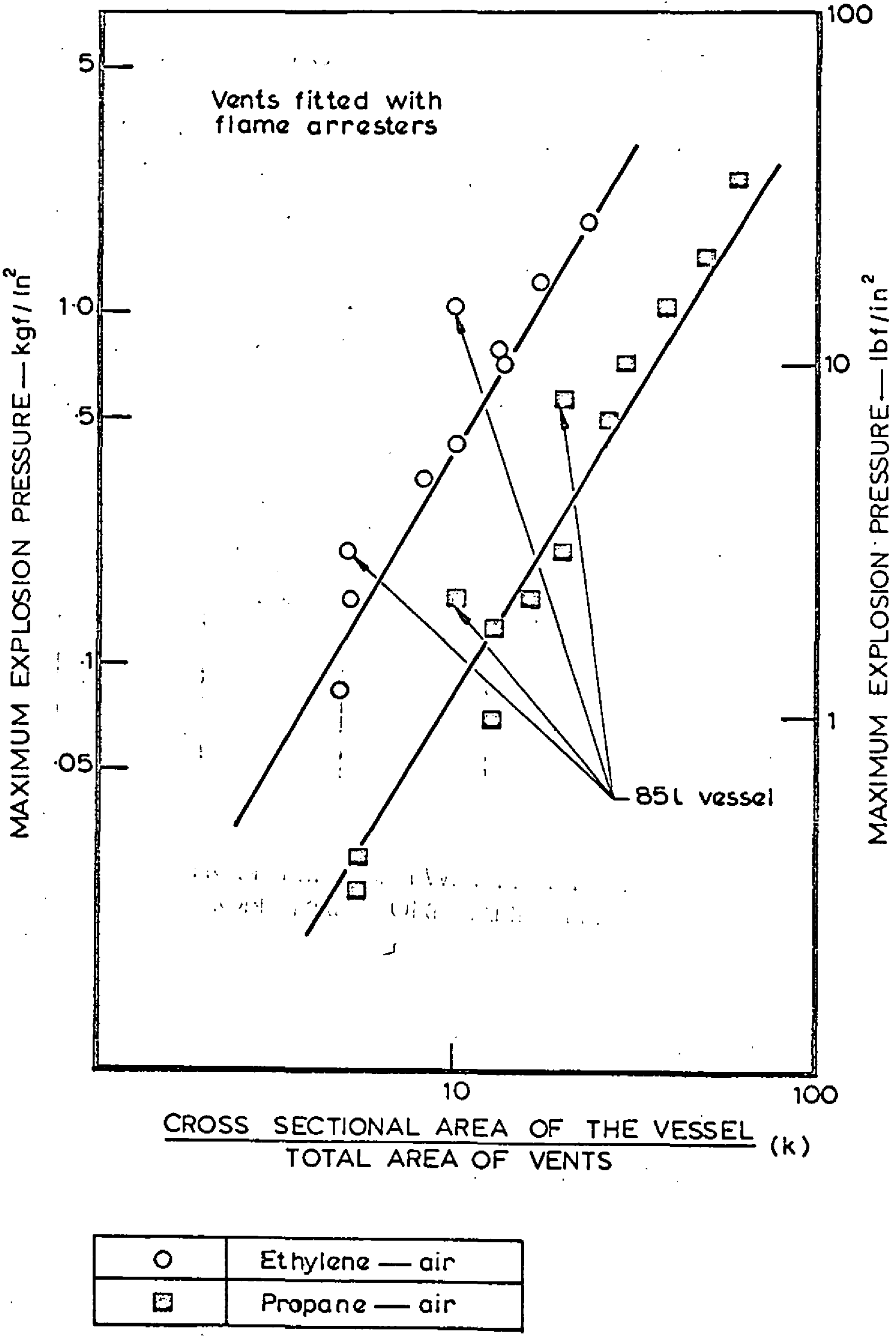

FIG. 7. RELATIONSHIP BETWEEN MAXIMUM EXPLOSION PRESSURE AND THE VENT AREA FOR PROPANE AND ETHYLENE—AIR FLAMABLE MIXTURE

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