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DUST EXPLOSIONS IN A LARGE SCALE CYCLONE PLANT

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P. S. TONKIN and C. F. J. BERLEMONT

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SUMMARY

Explosions in a cyclone plant have been investigated to obtain information on their behaviour in a full scale dust handling plant. The dusts used were cork, phenol-formaldehyde resin, wheat flour and polypropylene.

The effects of vent position and vent shape on explosion pressures in a cyclone have been studied and vent sizes necessary to relieve the explosion pressures to low values have been determined.

The effect on explosion pressures in a cyclone of venting through lengths of ducting has been studied. A relationship between the weight of the vent cover and explosion pressure has also been established.

The work has shown the extent to which rotary valves limit the propagation of dust explosions.

KEY WORDS: Cyclone, dust explosion.

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INTRODUCTION

The fire and explosion hazards connected with cyclone separators and associated plant are well known in industry. One hundred and thirty-six fires in such plant were reported in the United Kingdom during 1968[1].

Previous work[2] established a relationship between explosibility class and the explosibility of dusts in the turbulent conditions of a cyclone unit, but it was necessary to study further the means of reducing the explosion hazard. Information was sought regarding the following matters:-

(i) Venting areas necessary to reduce explosion pressures to safe values.

(ii) The effect of vent shape and vent position on explosion pressure in a cyclone.

(iii) The safe venting of the products of explosions away from the plant through ducting to prevent damage and loss of life.

(iv) The extent to which rotary valves act as explosion checks.

(v) Pressure values at points in the plant other than in the cyclone itself.

Dusts with different explosion parameters were used in the work but they were all classified group (a) for explosibility.

EXPERIMENTAL

Materials

All the dusts were commercial grades as marketed by the manufacturers and as used in industry. The phenol-formaldehyde resin was a moulding powder of mean particle diameter 15 microns, moisture content 4.1 per cent and density 1.4 g cm^{-3}. Sizing analyses of the other dusts used are given in Table 1.

The properties of the flour were typical of flour used in the baking industries of this country.

Table 1

Sizing analyses and moisture contents of the dusts

Dust	Moisture content (per cent)	Density g cm^{-3}	Per cent weight				
			+60 mesh	-60+72 mesh	-72+120 mesh	-120+240 mesh	-240 mesh
Cork	10.6	0.25	12.4	7.4	17.4	16.9	45.9
English Flour	14.6	1.5	0.1	0.3	1.7	23.7	74.2
Polypropylene	0.5	0.9	7.8	76.0	12.4	0.8	3.0

APPARATUS AND EXPERIMENTAL PROCEDURE

Cyclone Plant

The plant consisted of a number of units all connected to form closed circuits for both the air stream and the conveyance of dust. Fig.1 is a diagram of the plant.

The cyclone was constructed of 3 mm (0.125 in) thick mild steel plate, was 1.9 m (6.25 ft) in height, 1.22 m (4 ft) diameter at the top and had an outlet at the bottom 193 mm (7.6 in) in diameter. The upper part of the cyclone was cylindrical in shape of height 0.62 m (2 ft) and of volume 0.71 m^3 (25.2 ft^3). This was joined to a conical section of volume 0.5 m^3 (17.8 ft^3).

The inlet of the cyclone was connected to a fan of approximately 0.9 m (3 ft) diameter, by means of steel flanged ducting 1.8 m (6 ft) of which was horizontal and 230 mm (9 in) internal diameter, the remaining 3.5 m (11.5 ft) of which was 300 mm (11.75 in) internal diameter and vertical. The outlet at the bottom of the cyclone was connected to a six bladed rotary valve which returned the dust, extracted by the cyclone, to the dust hopper of volume 0.15 m^3 (5 ft^3). The air outlet at the top of the cyclone was a pipe, 300 mm (11.75 in) internal diameter, situated in the centre of a 610 mm (24 in) outside diameter annulus of 6.4 mm (0.25 in) thick mild steel plate. The air outlet pipe extended into the cyclone 460 mm (18 in) and was joined to an outlet scroll outside. The scroll was connected to the intake side of the fan by ducting of internal diameter 300 mm (11.75 in), a 0.9 m (3 ft) length of which was horizontal and the remaining 4 m (13 ft) length was vertical. In the top of the scroll there was a 390 mm (15.4 in) diameter hole which could either be covered with a steel plate or used as a vent (V1 Fig.2). Another six bladed rotary valve at the bottom of the hopper delivered dust into the return air stream for re-circulation. A deflector was fitted at the

bottom of the return air duct to direct the air stream beneath the outlet from the rotary valve to ensure good mixing of dust and air. The ducting connecting with the fan inlet constituted a mixing chamber for the dust and air and was fitted with an access door of area 0.18 m^2 (1.9 ft^2) which also acted as an emergency vent. A sliding air intake regulator was fitted in the ducting on the inlet side of the fan (Z Fig.1).

The top of the cyclone was divided into six sector shaped vents (Fig.2) each of area 0.12 m^2 (1.3 ft^2) which could be covered with metal plates and bursting materials. Metal plates were used to either completely close a vent or reduce its area. Plates 4 and 5 show the two types of vent cover used in order to reduce the vent area. One type when fitted gave an open area designated a 'circumferential' vent and the other type formed a 'radial' vent. Plate 6 shows the reduction of a circumferential vent to two thirds of its original area.

The cyclone and lengths of ducting were fitted with inlet bosses for accommodating flame detectors and pressure measuring devices.

A 7 h.p. 3 phase electric motor powered the fan through a 'vee' belt drive. The fan speed, measured by a fitted tachometer, was 1300 rpm and air was circulated at 32 $\pm$ 0.9 m^3 (1130 $\pm$ 30 ft^3) per minute.

The rotary valves were operated by 0.5 h.p. electric motors through variable and fixed ratio gearing systems. Both valves could be operated at speeds from 16 rpm to 180 rpm as measured by tachometers fitted to the valves.

To allow access to all parts of the plant staging was erected around it at two levels, 1.8 m (6 ft) and 4.3 m (14 ft) from the ground. The whole plant was situated in a steel framed galvanised iron cladded building, part of the roof of which could be opened during experiments. Sliding doors on one side of the building permitted the photographing of the explosions.

The igniting source for the dust cloud was a propane/air flame which was injected into the explosion ducting through two inlet pipes 19 mm (0.75 in) diameter (at D Fig 1) 1.37 m (4.5 ft) from the cyclone inlet. Two igniting units, each as shown in Fig.3, were used at 90° to each other in each experiment. About 0.7 l (0.025 ft^3) of propane gas, measured at N.T.P was used for each experiment.

Dust concentration

The concentration of the dust cloud in the inlet duct to the cyclone was measured by isokinetic sampling[3] at position Y Fig 1. The apparatus is shown diagrammatically in Fig.4. It consisted of a probe 19 mm (0.75 in) diameter with its open end in the explosion duct, the other end being connected to the inlet of a small, high efficiency cyclone of top diameter 38 mm (1.5 in)

and height 133 mm (5.25 in) the air outlet of which connected with a high speed fan by way of a solenoid valve. On the outlet side of the fan the air passed through a control valve and flow meter to atmosphere. The dust, separated in the small cyclone, was collected in a bottle attached to the bottom outlet of the cyclone. The system was operated by remote control. The dust concentration was calculated from the weight of dust collected and the volume of air withdrawn at the same velocity as that of dust suspension.

Air velocity

The air velocity in the plant was measured with a pitot tube and manometer[4], at position Y Fig.1, which was 2.44 m (8 ft) from the fan outlet and was the furthest distance possible along straight ducting from the fan. An orifice plate was situated in the return air duct (X Fig 1) and the pressure differential between points H and L (Fig 1) was used as an operating indicator of steady conditions within the plant during experiments[5].

Stopping of rotary valves

In order to investigate the ability of rotary valves to isolate an explosion the power circuit to the valve at the bottom of the cyclone was modified to facilitate automatic stopping of the valve by the explosion in the cyclone. Fig.5 shows the circuit breaking system. The modification consisted of incorporating in the circuit a micro switch, which was operated by a hinged vent cover immediately the latter was lifted by the explosion. Also in the circuit was a relay fitted with a mechanical variable delay mechanism which could be set to give up to 5 seconds delay, if needed, between the operation of the micro switch and breaking the electrical circuit to the valve. In this way the power to the valve was switched off and the valve stopped. No mechanism was used to stop the rotary valve other than the power cut off and the shortest period possible between an explosion and the valve stopping was 0.5 s. This period was independent of the working speed of the valve before power cut off.

The weight of the hinged vent cover was varied in order to obtain various explosion pressures in the cyclone and to study the effect of pressure on the ability of the valve to stop flame passing through it.

Time periods between events were measured from photographic records of oscilloscope traces.

In the experiments in which the valve was not stopped the vent covering was brown paper.

Cork dust was used in all the experiments.

A photo transistor situated at J1 (Fig 1) detected flame in the dust hopper.

Cine photography

Cine films of most of the experiments were taken on 16 mm colour reversal film at 24 frames per second.

Pressure measurements

The explosion pressure in the cyclone was measured with capacity and inductance pressure cells at position E (Fig 1) and at other positions in the plant as required. The outputs from the cells were amplified and fed into a cathode ray oscilloscope. Drum camera records of the oscilloscope traces were obtained.

Flame detection

The flame detectors used were photo transistors housed in window nuts. Their outputs were fed into the oscilloscope. Throughout the work the detectors were sited at positions in the plant selected from D,W,P,P1,N, J1 and A (Fig.1). The glass windows in the nuts were kept free from adhering dust particles by fine jets of high velocity air passing across them. The outputs of the photo-transistors were checked before each experiment.

Vent covers

In most of the experiments the vent covering used was brown paper of thickness 0.05 mm (0.002 in). Its bursting pressure was measured under static conditions in a separate apparatus which consisted of a metal vessel 0.9 m x 0.6 m x 0.15 m deep (3 ft x 2 ft x 6 in) with a vent in the lid the same shape and size as those on the cyclone. The pressure was measured using a capacity pressure gauge as in the cyclone experiments, in which the paper vent covering was of constant size even when the vent area was varied.

The experimental hinged vent cover used in the experiments is shown in Plate 1. The area of the vent was 0.12 m^2 (1.3 ft^2) and the weight of the cover could be varied by bolting steel plates of known weight to its underside. The maximum cover weight used in the experiments was 27.3 kg (60 lb).

Ducting used in the venting experiments

Experiments to investigate the increase in explosion pressure caused by ducting attached to cyclone vents were carried out using an adapter fitted to a sector shaped vent on the cyclone and 400 mm (16 in) internal diameter flanged ducting of various lengths fitted to the top of the adapter. The various ducting arrangements used in the experiments are shown in Fig.6. The vent closure in the experiments was brown paper as described above. The ducting was manufactured in 18G steel with flanges 32 mm (1.25 in) wide.

In each section of ducting provision was made for fitting pressure gauges and phototransistors. A 45 degree elbow of throat diameter one radius, and of the same internal diameter and gauge steel as the ducting, was used in conjunction with the straight ducting. The elbow was designed so that it would cause the same frictional loss under steady flow conditions as a length of ducting of the same diameter 6.1 m (20 ft) long when incorporated in a position other than at an end of a conveying system[6]. Plate 2 shows arrangement 'A' (Fig 6), namely the adaptor and 45 degree elbow in position on the cyclone.

Test method

The general procedure for carrying out an experiment in the cyclone was, firstly to fit covers on vents of the required area, then the fan was started, and when normal working conditions had been attained, as indicated by the pressure differential across the orifice plate, the air velocity in the ducting was measured with a pitot tube. After starting the rotary valves the dust concentration was measured and this was followed by the injection of the igniting source. The resulting explosion was observed and filmed until flame no longer propagated through the open vents.

RESULTS

Mean air velocity in the plant

Measurements with no dust in suspension gave a mean air velocity in the vertical explosion duct of 460 $\pm$ 12 m min^{-1} (1500 $\pm$ 40 ft min^{-1}). All measurements were carried out with the air intake regulator (Z Fig 1) fully open.

Small scale standard tests

Explosibility data relating to the dusts used in the experiments as determined in the small scale standard tests[7] are given in Table 2.

Table 2

Explosibility of the dusts

Dust	Explosibility classification	Maximum Pressure		Maximum rate of pressure rise	
		kN m^{-2}	lbf in^{-2}	kN $m^{-2}s^{-1}$	lbf $in^{-2}s^{-1}$
Cork	(a)	600	87	20,000	2,900
Phenol-formaldehyde resin	(a)	740	107	44,800	6,500
English flour	(a)	680	98	12,400	1,800
Polypropylene	(a)	430	62	2,420	350

Initial operating pressure in the cyclone

In all the experiments there was an initial positive pressure of 1.0 kN m^{-2} (0.15 lbf in^{-2} gauge) in the cyclone. The pressure was measured at point E (Fig.1) and was that at which the fan circulated the air.

The pressure values given below were in excess of this initial pressure.

Hinged vent covers

Fig.7 is a plot of the maximum explosion pressures obtained in the cyclone with cork dust explosions against the weight of a hinged vent cover.

Bursting pressure of vent covering material

Fig.8. shows the bursting pressures of the brown paper vent covers used in all the experiments unless stated otherwise. They were obtained by using compressed air at various rates of pressure rise. The vent shape and area was the same as for one sector vent on the cyclone. The calculated best line through the points is shown.

Venting explosions through ducting

The results of the series of experiments in which the cyclone explosions were vented through lengths of ducting are given in Table 3. The vent used was V2 (Fig 2) with a vent area of 0.12 m^2 (1.3 ft^2) and the cork dust concentration was 0.30 $\pm$ 0.01 g/l (0.30 $\pm$ 0.01 oz/ft^3). Pressures in the cyclone were measured at position E (Fig.1) and those in the ducting were measured at positions marked 'Pr' (Fig.6). Distances of positions marked 'Pr' from the end of the ducting and the elbow in which the latter was used, are given in Table 8.

Table 3
Pressure in cork dust explosions vented through ducting fitted to the cyclone vent

Ducting arrangement	Maximum Explosion Pressure			
	IN CYCLONE		IN DUCTING	
	kN m^{-2}	lbf in^{-2}	kN m^{-2}	lbf in^{-2}
A	6.2	0.9	3.4	0.5
B	7.6	1.1	5.5	0.8
C	11.0	1.6	6.9	1.0
D	13.8	2.0	9.7	1.4
E	25.5	3.7	19.3	2.8
F	13.8	2.0	6.2	0.9
NO DUCTING	4.1	0.6	-	-

Experiments using polypropylene

Experiments were carried out using polypropylene but the particular grade of dust did not ignite when the fan was working at its normal speed of 1300 rpm. It was found, however, that at reduced fan speeds the polypropylene dust could be ignited. Thus some experiments were carried out in which the power to the fan was cut off and the igniting flame was injected into the system at various speeds of the fan as it slowed from its maximum powered speed. The results are given in Table 4.

It was not possible to run the fan continuously at speeds other than maximum and thus results could not be obtained from a series of tests using polypropylene, for direct comparison with those obtained using other dusts.

Table 4

Results of polypropylene experiments

Expt.	Pressure in cyclone		Rate of Pressure Rise		Nominal Dust concentration	Vent Area		Fan Speed
	kN m^{-2}	lbf in^{-2}	kN $m^{-2}s^{-1}$	lbf $in^{-2}s^{-1}$	g/l	m^2	ft^2	rpm
1	7.6	1.1	16.5	2.4	0.42	0.08	0.87	600
2	3.8	0.55	7.6	1.1	0.42	0.08	0.87	600
3	8.3	1.2	31.7	4.6	0.25	0.08	0.87	600
4	5.9	0.85	23.4	3.4	0.15	0.08	0.87	600
5	9.7	1.4	23.4	3.4	0.36	0.08	0.87	600
6	10.3	1.5	14.5	2.1	0.36	0.08	0.87	700
7	3.8	0.55	14.5	2.1	0.36	0.08	0.87	500
8	5.2	0.75	9.7	1.4	0.36	0.08	0.87	500
9	3.1	0.45	8.3	1.2	0.31	0.08	0.87	500
10	8.3	1.2	15.9	2.3	0.36	0.08	0.87	700
11	7.6	1.1	17.9	2.6	0.36	0.08	0.87	700

Selection of dust concentrations used in the experiments

For each of the dusts used in the experiments it was necessary to find the concentration in the ducting between the fan and the cyclone which gave the highest explosion pressures in the cyclone plant. Thus for each dust, experiments were carried out and pressures measured for a range of dust concentrations giving the corresponding range of explosion pressures. The curves obtained are shown in Fig.9. In each case weaker explosions occurred at both ends of the concentration range. In the case of cork dust some of the pressures were below the bursting pressure of the vent covering.

The effect on explosion pressure of varying vent area, vent shape and vent position

Fig.10 shows the variation of explosion pressures obtained in the cyclone with various vent areas for the dusts used. In these experiments radial shaped vents were used in the number four vent position (Fig.2). Figs 11, 12 and 13

show the effect of vent shape on explosion pressures in the cyclone using vent position two (Fig 2) and Figs. 14, 15 and 16 show the effect of vent position on explosion pressure. For the latter experiments radial vents were used on vent positions numbers two and four (Fig.2).

In Figs 10 and 15 the highest pressure shown with the smallest vent for phenol-formaldehyde resin was that obtained in an experiment in which the maximum pressure was unexpectedly high and the full deflection of the pressure trace was off the measuring scale. The figure given was the highest obtainable from the pressure record. Maximum pressure was a value in excess of that figure as indicated on the graph.

Venting through the cyclone axial air outlet

The results in Table 5 show the effect on cyclone pressure of venting explosions through the axial air outlet of the cyclone (K Fig 1). Comparison is made between pressures obtained by venting through the air outlet pipe and those obtained by using a vent of smaller area on top of the cyclone. Cork dust was used in the experiments. The circular vent covering was brown paper.

Table 5

The effect on cyclone pressure of venting through the axial air outlet

Vent area		Position of vent	Cyclone pressure	
m^2	ft^2		$kN\ m^{-2}$	$lbf\ in^{-2}$
0.06	0.65	Top of cyclone	13.8	2.0
		Top of cyclone	11.0	1.6
		Top of cyclone	17.2	2.5
0.07	0.75	Axial air outlet	25.5	3.7
		Axial air outlet	22.8	3.3
		Axial air outlet	24.1	3.5

Rotary valves as explosion checks

Results of experiments, in which the ability of rotary valves to stop explosion propagation was observed, are given in Table 6.

Table 6

Rotary valves as explosion checks

(cork dust)

Expt. No.	Time between explosion and rotary valve stopped - seconds	Pressure in cyclone		Time between explosion and flame in dust hopper - seconds	Rotary valve speed rpm
		kN m^{-2}	lbf in^{-2}		
1	Valve not stopped	3.5	0.5	1.4	46
2	Valve not stopped	2.8	0.4	1.2	46
3	0.5	14.5	2.1	No flame	152
4	0.5	15.9	2.3	No flame	152
5	0.5	17.9	2.6	0.2	152
6	0.5	25.5	3.7	0.4	152
7	0.5	13.8	2.0	No flame	42
8	0.5	13.1	1.9	No flame	42
9	0.5	17.2	2.5	0.3	42
10	0.5	20.0	2.9	0.2	42

Pressure measurements at various points in the plant

In some experiments the pressure was measured in the cyclone itself and at another point in the plant simultaneously. The results of these experiments are given in Table 7.

Table 7

Pressures in the cyclone plant

DUST	Cyclone pressure at position E		Pressure at position N		Pressure at position A		Rate of pressure rise in cyclone	
	kN m^{-2}	lbf in^{-2}	kN m^{-2}	lbf in^{-2}	kN m^{-2}	lbf in^{-2}	kN $m^{-2}s^{-1}$	lbf $in^{-2}s^{-1}$
CORK	13.8	2.0	-	-	12.1	1.75	355	51.4
	12.1	1.75	-	-	7.3	1.05	250	36.2
	15.2	2.2	-	-	16.6	2.4	405	58.5
	5.2	0.75	2.4	0.35	-	-	90	13.1
	5.9	0.85	3.1	0.45	-	-	140	20.3
	16.6	2.4	17.2	2.5	-	-	420	60.7
	12.1	1.75	7.3	1.05	-	-	285	41.3
ENGLISH FLOUR	3.8	0.55	0.4	0.05	-	-	51	7.4
	4.5	0.65	0.4	0.05	-	-	53	7.7
	9.3	1.35	8.0	1.15	-	-	91	13.2
	10.8	1.55	10.0	1.45	-	-	140	20.3
	15.2	2.2	12.8	1.85	-	-	170	24.7
	17.9	2.6	18.6	2.7	-	-	195	28.2
	15.9	2.3	15.9	2.3	-	-	170	24.7

DISCUSSION

Dusts

There were significant differences in the explosibility properties of the dusts, notably in the values of maximum pressure and rates of pressure rise as determined in the small scale test apparatus[7], and shown in Table 2. In the cyclone these differences were reflected in the maximum pressures obtained as shown in Fig.10.

Venting through steel ducting

The effect on cyclone pressure of venting through lengths of steel ducting, of cross sectional area 0.14 m^2 (1.4 ft^2) (approximately the same as that for one sector shaped vent) was investigated using cork dust. The results given in Table 3 show that duct arrangement A gave a pressure value about 1.5 that for the vent alone (Fig 10). The single 1.8 m (6 ft) length of ducting gave a value about twice that for the vent alone, while for arrangement C the corresponding factor was about three. As the addition of ducting became more complex so the effect on the pressure in the cyclone became more pronounced and with the arrangement E (Fig 6) the pressure value obtained in the cyclone was approximately seven times that of the vent alone. With arrangement F (Fig 6) the pressure in the cyclone was raised by a factor of four as compared with that for the vent alone. In arrangement E (Fig 6) the elbow was imposing the same frictional impedance on the effluent gases as ducting equal in length to 15 duct diameters[6]. From the results obtained with arrangements B and D

it may be predicted that straight ducting of the same length as arrangements E and F (Fig 6) would give pressures in the cyclone of 15.9 kN m^{-2} (2.3 lbf in^{-2}) and 9.7 kN m^{-2} (1.4 lbf in^{-2}) respectively. Thus the elbow had the effect of increasing the pressure by about 50 per cent over that which would be expected with the same length of straight ducting.

In all the experiments the pressures in the ducting were lower than those in the cyclone itself.

In general the trends indicated by the results of this series of experiments were in accordance with those of previous work[8] in which explosions in cubical galleries were vented through ducting, but there were differences in magnitude. Comparing a gallery with a cyclone both with vents such that pressures of about the same value were obtained when venting without ducting, venting through ducting increased the pressure in the gallery by values up to eleven and in the cyclone by seven times. The differences in pressure magnitude between the two types of plant was probably due to the basic operation of the cyclone in forming dust clouds with different characteristics from those obtained in other types of plant.

This short series of experiments has shown that venting cyclone explosions safely through ducting is possible providing vent area, vent position and vent shape on the cyclone are correctly designed, the cross sectional area of the ducting is at least as large as the vent area and short lengths of ducting are used. The work has also shown that if an elbow or bend has to be used in any duct system its position in the design is a major consideration. If possible such fittings should not be used. Bends and elbows with angles greater than 45 degrees would be expected to impose an even greater impedance on the effluent gases from such a vent.

Venting with hinged cover

Figure 7 shows the effect of varying the weight of a hinged vent cover on explosion pressure. A vent area of 0.12 m^2 (1.3 ft^2) and cork dust were used throughout this series of experiments.

The results show the marked inertia effect of the cover on the explosion pressure at the various weights used and may be compared with those obtained using the same dust and vent area but with a vent covering of low bursting pressure (Figs 10 and 11).

Pressure at different points in the plant

The measurement of pressure in the cyclone and at points in the plant away from the cyclone simultaneously showed that, in general, pressures were different but of the same order. Generally the results in Table 7 show that the pressure differences were less when there were higher rates of pressure rise in which case

the pressure at points away from the cyclone were slightly greater than those in the cyclone. This effect results from the fact that higher rates of pressure rise give shorter time for the dissipation of the energy released and parts of the plant become restrictive and give rise to conditions which have adverse effects on the flow of gases. The results show that for design purposes it must be borne in mind that the whole plant can be subjected to the maximum pressure developed in any one part of that plant.

Rotary valves as explosion checks

The results given in Table 6 show that flame was observed and detected on the delivery side of the rotary valve which was situated at the bottom of the cyclone and returned the dust into the dust hopper.

From the results it may be seen that explosion pressure had an effect upon the speed with which flame appeared on the delivery side of the valve and with higher pressures obtained in these experiments flame appeared on the delivery side of the valve even when the latter was stopped 0.5 s after the beginning of the explosion. In other cases, in which explosion pressures were lower and the valve was stopped in 0.5 s no flame was detected or observed in the dust hopper. In experiments in which the rotary valve was not stopped flaming occurred on its delivery side even with a vent covering which ensured the low pressure of 3.5 kN m^{-2} (0.5 lbf in^{-2}) or less. This can be expected since burning dust from the cyclone is likely to be conveyed to the hopper by the rotating valve regardless of explosion pressure.

The shortest time recorded by the photo-transistor at position J1 and confirmed by cine film for appearance of flame on the delivery side of the valve was 0.2 s. The valve was turning during this time and from the dimensions of the valve (Fig 18) it may be shown that burning dust could have been delivered into the dust hopper. While the results show that very quick stopping of the rotary valve, coincident with relatively low explosion pressures, can stop the propagation of the explosion, reliability to prevent the propagation of explosions should not be placed solely on rotary valves.

Experiments using polypropylene dust

Polypropylene was a difficult dust to ignite in the conditions of the cyclone plant, and it was not possible to initiate an explosion in its dust cloud with the fan working at its full speed of 1300 rpm. Explosions were not possible above 700 rpm. The results in Table 4 were obtained with a vent area of 0.08 m^2 (0.87 ft^2). As seen from the figures in Table 1 the polypropylene was a relatively coarse dust and this caused quick migration of the bulk of the dust cloud to the

wall of the cyclone and consequently made ignition of the cloud in the cyclone difficult. High turbulence at normal working speed probably prevented ignition of the dust cloud in the duct but polypropylene in a more finely divided form might have ignited in these conditions. Plate 3 is a photograph, taken through a polyethylene vent cover, of the polypropylene dust entering the cyclone and shows the early migration of the bulk of the dust to the walls of the cyclone. Polypropylene is classified in group (a) for explosibility and would constitute an explosion hazard during starting up and closing down in a cyclone plant, and in addition is a fire hazard in most circumstances.

Dust concentrations for use in the experiments

For investigating the effect of vent area on explosion pressure it was necessary to find for each dust the concentration which would create the most severe explosible conditions in the cyclone. Experiments were therefore carried out with one vent size in which the dust concentration was varied and the resulting explosion pressures measured. The curves (Fig 9) are similar in shape to those obtained in laboratory scale tests used to measure the maximum explosion pressure for a dust[9], in that maximum pressure values were obtained within a range of dust concentrations giving pressure plateaux rather than peak values. The magnitudes of the pressure values obtained are different in the two types of apparatus, as might be expected in results obtained in vented and totally closed apparatus (Table 2)

Explosion pressure and vent area

Fig 10 shows the effect of vent area on pressure in a cyclone for cork dust, English flour and phenol-formaldehyde resin. The repeatability was characteristic of large scale dust explosion experiments[8].

The pressures were obtained with radial vents fitted to vent position number 4 (Fig 2). The curves show that below a certain vent area explosion pressures increased greatly. In the case of phenol-formaldehyde resin the pressure was unexpectedly high and increased by a factor of at least 6 causing severe damage to the plant. In order to avoid further damage experiments with flour using vent areas less than 0.04 m^2 (0.43 ft^2) were not carried out.

In industry the recommended safe venting area[10] would be 0.09 m^2 (1 ft^2) for 0.6 m^3 (20 ft^3) of cyclone for cork dust and flour and 0.09 m^2 (1 ft^2) for 0.42 m^3 (15 ft^3) for phenol-formaldehyde resin. For the cyclone used in the experiments this would mean about 0.28 m^2 (3 ft^2) of venting for the resin and about 0.18 m^2 (2 ft^2) of venting for the other dusts. Fig 10 shows that these vent areas would be adequate to reduce explosion pressure to below 6.9 $kN\ m^{-2}$ (1.0 $lbf\ in^{-2}$) for all three dusts.

Explosion pressure and vent shape

Comparison between pressures obtained with two vent shapes is shown in Figs 11-13 inclusive. For English flour and phenol-formaldehyde resin the 'radial' vents were shown to give lower explosion pressures whereas with cork dust the values obtained with both types of vent were similar.

This result may be considered with reference to the method by which solid particles are separated from the gas within cyclones. It has been shown[11] that particles entering the cyclone are subjected to two opposing forces in the radial direction, one due to centrifugal force which tends to move them to the wall of the cyclone and the other the drag of the carrier gas which tends to move them towards the centre of the cyclone as it leaves through the axial outlet after 'spiralling' from the inlet to near the apex. The cyclone radius at which the equilibrium orbit for a given particle forms and in which the particle is separated depends, in general, upon the physical properties of the dust and carrier gas and particularly upon the diameter and density pf the dust particles. It may also be shown[11] that the greater the free falling velocity of a particle the greater is the radius in a cyclone at which it will separate.

The free falling velocity for a particle may be expressed in terms of the physical properties of the dusts and the air as follows[11]:-

$$u = \frac{d^2 g \rho_s}{18 \eta} \qquad \ldots\ldots\ldots(1)$$

where u = free falling velocity

d = particle diameter

ρ_s = density of the solid particles

η = viscosity of the air

g = gravitational acceleration

Taking the viscosity of air at 20°C as 181×10^{-6} poise[12] and the mean particle diameters and densities from Table 1, the free falling velocities for cork, phenol-formaldehyde resin and flour are 9.1×10^{-4} cm s^{-1} 9.5×10^{-5} cm s^{-1} and 2.7×10^{-3} cm s^{-1} respectively. From this it is seen that cork dust and flour would separate at relatively larger cyclone radii than the resin. The large proportion of flour of particle size less than 66 microns (240 mesh) would rotate at a relatively short radius, higher in the cyclone than cork dust of the same particle size but nearer to the cyclone centre than the larger particles of flour. In the latter conditions more dust would be likely to be involved in an explosion.

In these conditions a 'radial' type vent with part of its area towards the centre of the cyclone would be likely to be more effective as shown by both phenol-formaldehyde resin and flour. The stratification of cork in the cyclone would be such that a large proportion of the dust would be near the periphery of the cyclone so that in an explosion the circumferential type vent would be expected to be effective but the 'radial' type vent would not be expected to give lower explosion pressures. Figure 11 shows this to be the case and for the smallest vent area pressures tended to be higher with the radial vent indicating that the vent area near the periphery of the cyclone was not so efficient as was the corresponding circumferential vent.

Vent position

It has been shown that in no case was the venting through the number four position (Fig.2) better than that through the number two position. The latter position was immediately above the path of the incoming burning dust and could vent the explosion early in its propagation. With venting in the number four position the dust would be circulating lower in the cyclone and more dust would be involved in the explosion and thus the latter would be well established before venting, resulting in higher pressures in the cyclone than those obtained with venting in the number two position for cork and phenol-formaldehyde resin as fuels. For flour, with a relatively low rate of pressure rise (Table 2), the slight delay in venting the explosions by using the number four position did not make the resulting explosion pressures significantly different from those obtained when venting through the number two position.

Vent Area

The relationship between maximum explosion pressure and vent area will be considered in more detail in a subsequent F.R.Note.

The pressures obtained in the large scale work were those measured in the cyclone itself and thus these results apply specifically to cyclones. The mechanism of separating solids from gases, characteristic of cyclones, controlled the pattern of dust clouds in the cyclone itself. The phenomenon of multiple 'peaks' on some pressure records, brought about by the effect of the initial explosion on the normal pattern of the dust cloud in a working cyclone, indicates that in other types of plant, where the dust cloud taking part in an explosion would have different characteristics from those in a cyclone, larger vent areas would probably be necessary to ensure explosion pressures comparable with those obtained in the cyclone.

Venting through the cyclone axial air outlet

The results obtained by venting cork dust explosions through the axial air outlet from the cyclone (Vent 1 Fig 2) and given in Table 5 indicate that as a vent the outlet permitted higher explosion pressures than a vent of smaller area situated on top of the cyclone. The curve for cork dust explosions shown in Fig 10 shows that a vent of the same area as the air outlet pipe but situated on top of the cyclone could be expected to permit explosion pressures in the cyclone of about 9.7 $kN\ m^{-2}$ (1.4 $lbf\ in^{-2}$) which is less than half the values obtained with the axial air outlet vent.

In cyclones the dimensions of the air outlet pipe are dictated by the size of the cyclone and the separating efficiency of the latter depends partly upon the critical dimensions of the pipe. Since the pipe dimensions, position and function are not governed by safety requirements it is not likely to be capable of ensuring explosion pressures as low as those obtained by venting in the body of the cyclone itself.

CONCLUSIONS

1. The effect of venting cyclone explosions through ducting systems on explosion pressures in a cyclone has been investigated. Results show variation of pressure with ducting length and with inclusion of an elbow in the venting system.
2. During cyclone explosions pressure has been measured in the cyclone itself and in other parts of the plant simultaneously. The pressure differences are, in general, marginal and appear to depend upon rates of pressure rise.
3. The role of rotary valves as explosion checks has been investigated and such valves cannot be relied upon to fulfil this function in all circumstances.
4. A linear relationship has been established between explosion pressure in the cyclone and the weight of a hinged explosion relief cover.
5. Vent sizes, on top of the cyclone, which ensured relatively low explosion pressures were established for all three dusts used. For two of the dusts vent sizes at which values of maximum explosion pressures increased rapidly were also established.
6. It has been shown that vent shape has a significant effect on explosion pressure in a cyclone.
7. Lower explosion pressures were obtained when the vent position, on top of the cyclone, was near the entrance to the cyclone than when the vent position was remote from it.

8. Venting through the axial air outlet from the cyclone resulted in cyclone pressures about 2.5 times greater than the pressures which would result when using a vent of the same area in the body of the cyclone itself.

ACKNOWLEDGMENTS

Mrs S A Morris and Mr R C Rowley assisted with some of the experiments. The small scale classification tests were carried out by Miss M M Raftery and Mrs W Evans.

REFERENCES

1. United Kingdom Fire and Loss Statistics 1968 - Ministry of Technology and Fire Offices' Committee, Joint Fire Research Organization. HMSO.
2. PALMER, K.N., and TONKIN, P.S. Fire Research Note No. 639, 1966.
3. HAWKSLEY, P.G.W., BADZIOCH, S and BLACKETT, J.H. Measurement of solids in flue gases B.C.U.R.A. 1961.
4. British Standards Institution: Methods of testing fans for general purposes. B.S. 848 : Part 1 : 1963.
5. British Standards Institution: Methods for the measurement of fluid flow in pipes B.S. 1042 : Part 1 : 1964.
6. PERRY, J.H. Chemical Engineering Handbook. 4th Edition, McGraw Hill Book Company, 1963.
7. RAFTERY, M.M. Explosibility tests for industrial dusts. Fire Research Technical Paper No.21 1968 HMSO.
8. HARTMAN, I., and NAGY, J. Venting dust explosions. Industrial and Engineering Chemistry Vol 49 No.10, October 1957.
9. NAGY, J., COOPER, A.R. and STUPAR, J.M. Pressure development in laboratory dust explosions. U.S. Department of the Interior, Bureau of Mines Report of Investigations No. 6561 - 1964.
10. DEPARTMENT OF EMPLOYMENT. Dust explosions in factories. Health and Safety at Work. New Series No.22 HMSO 1970.
11. COULSON, J.M., and RICHARDSON, J.F. Chemical Engineering Volume two Pergamon Press London 1955 pp 550-551.
12 KAYE, G.W.C., and LABY, T.H. Tables of Physical and Chemical Constants. Longmans Green and Co.Ltd. June 1957.

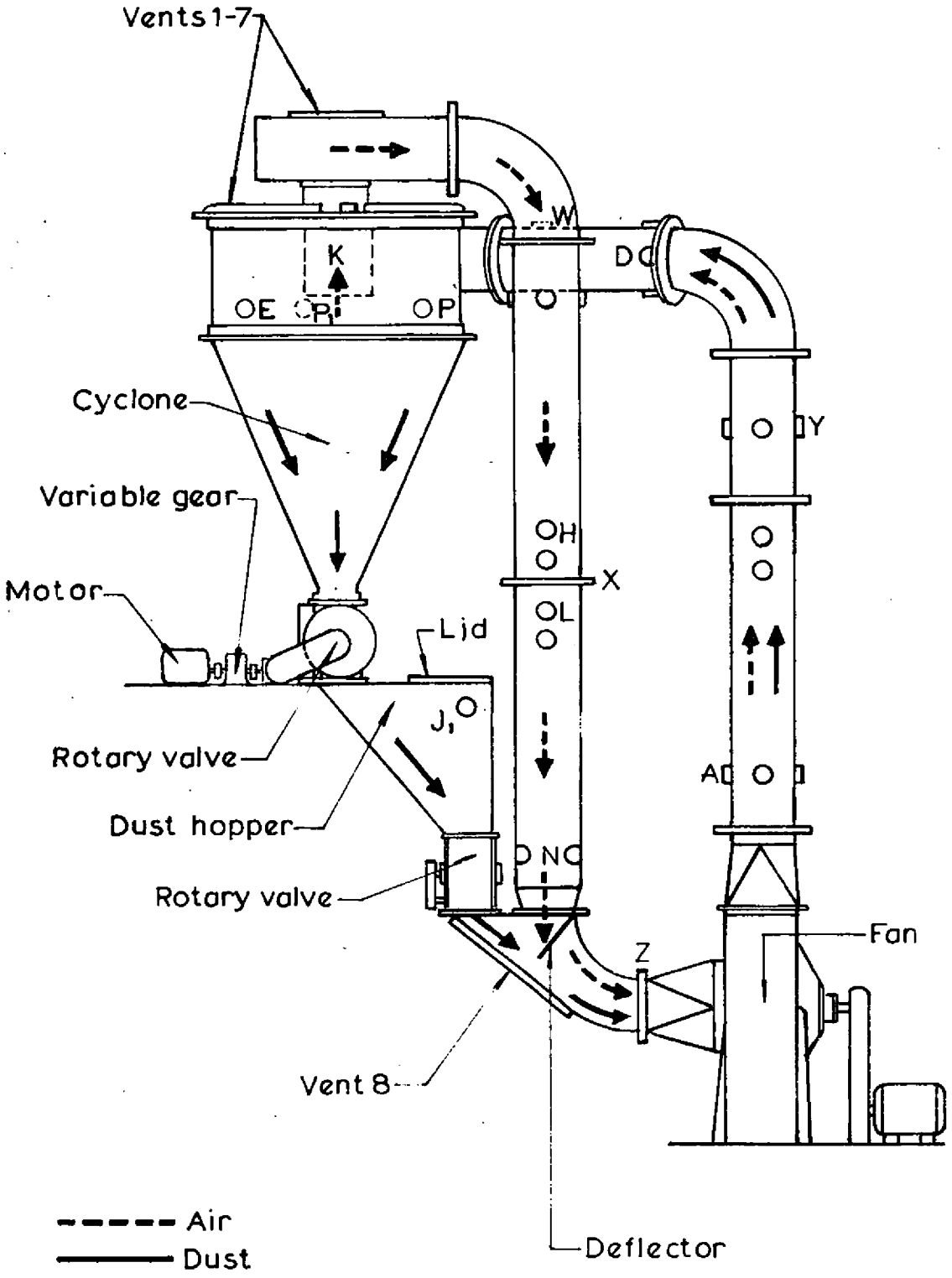


FIG.1 THE CYCLONE PLANT

1170) FR. NOTE 942

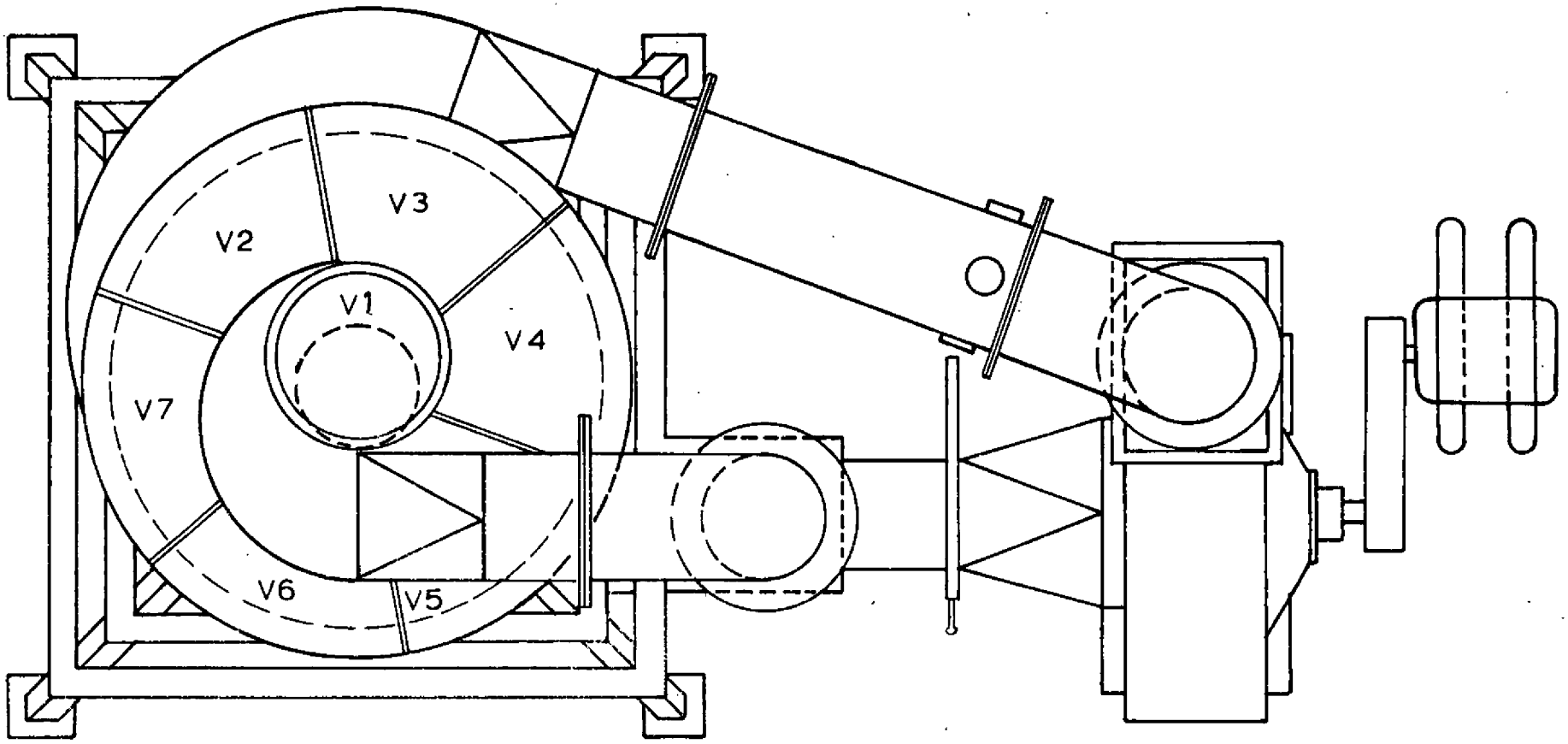


FIG. 2 VENTS AT THE TOP OF THE CYCLONE

1/7065 F.R. 639 ALSO USED ON FR NOTE 942

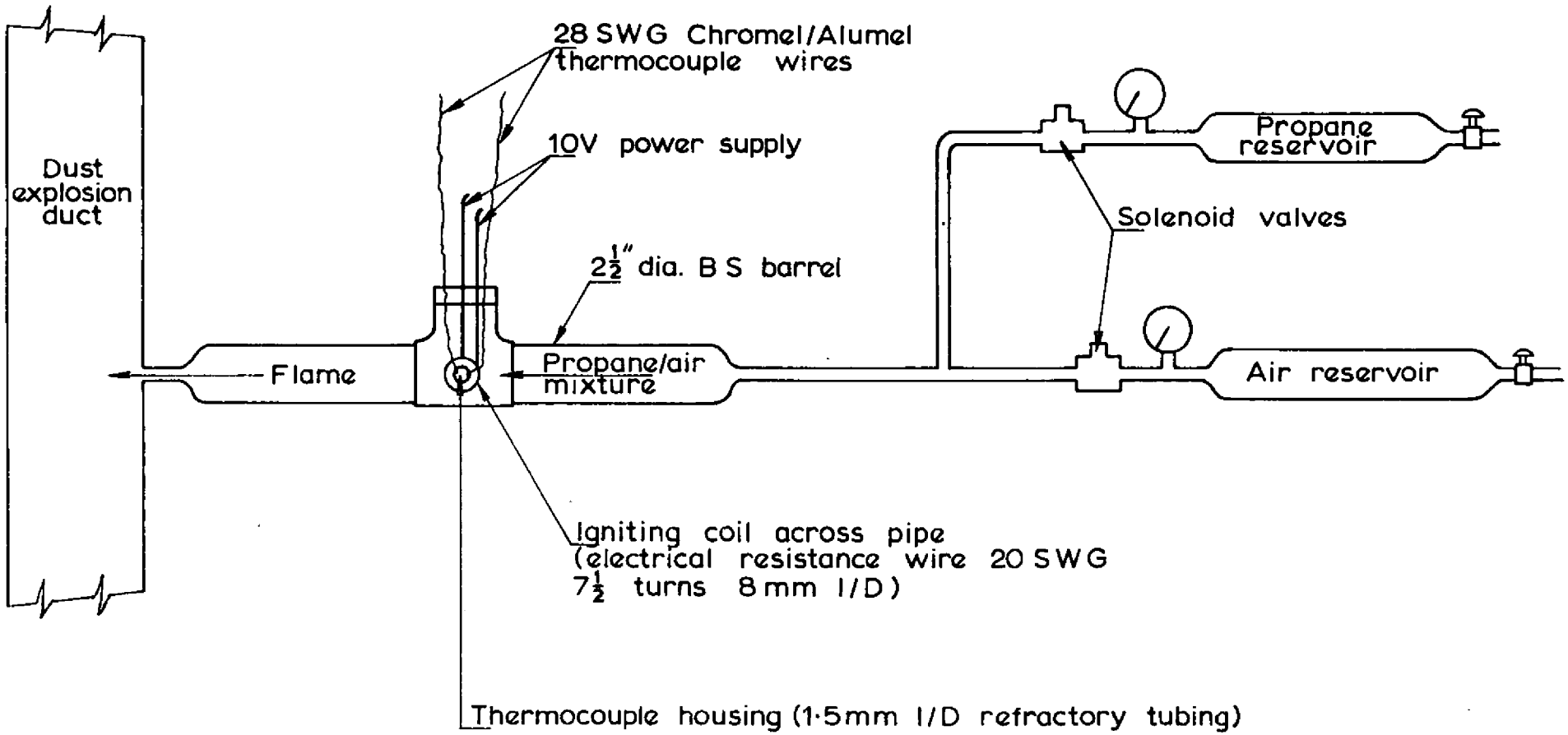


FIG. 3. DIAGRAM OF AN IGNITING UNIT

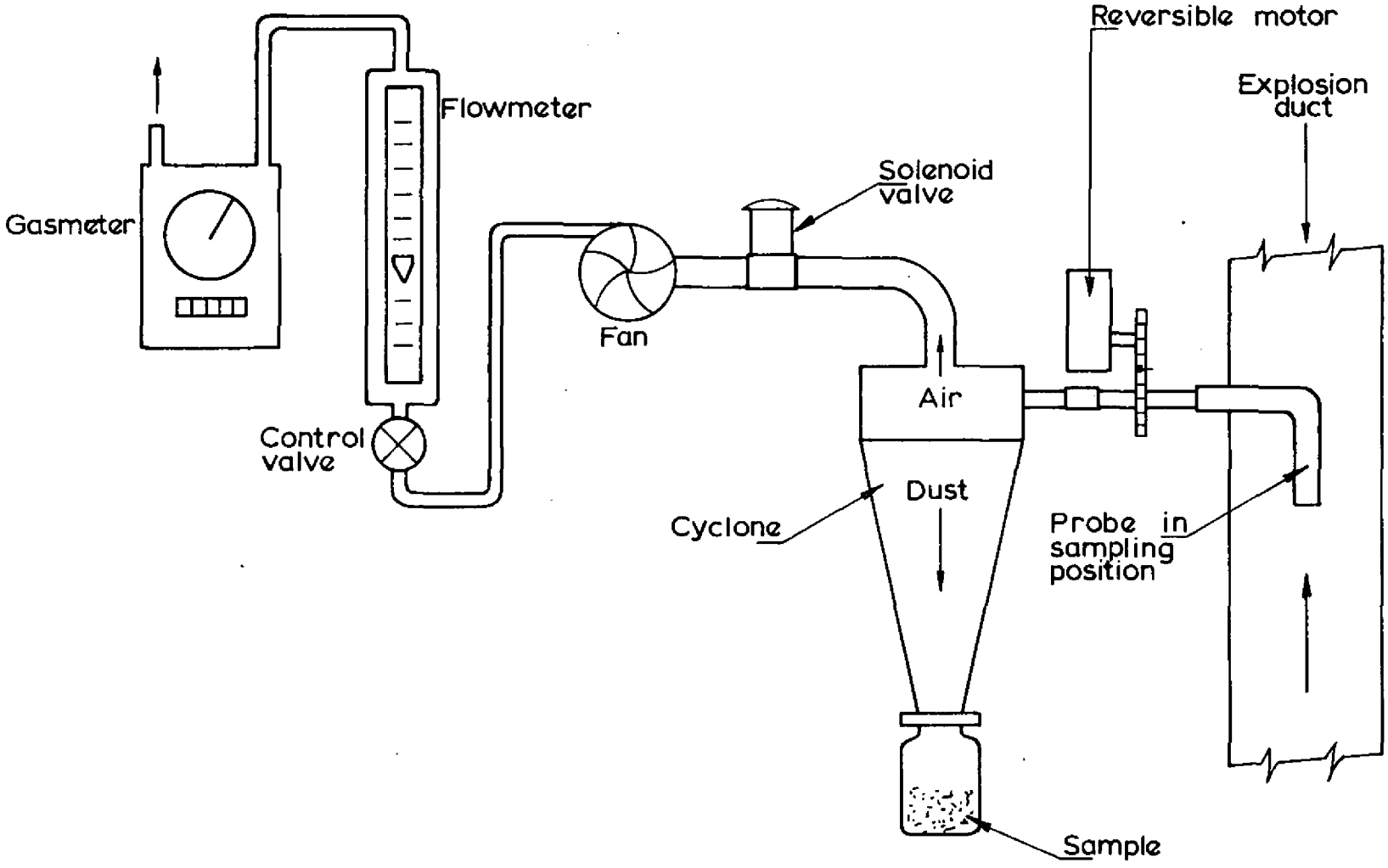


FIG. 4. DUST SAMPLING SYSTEM

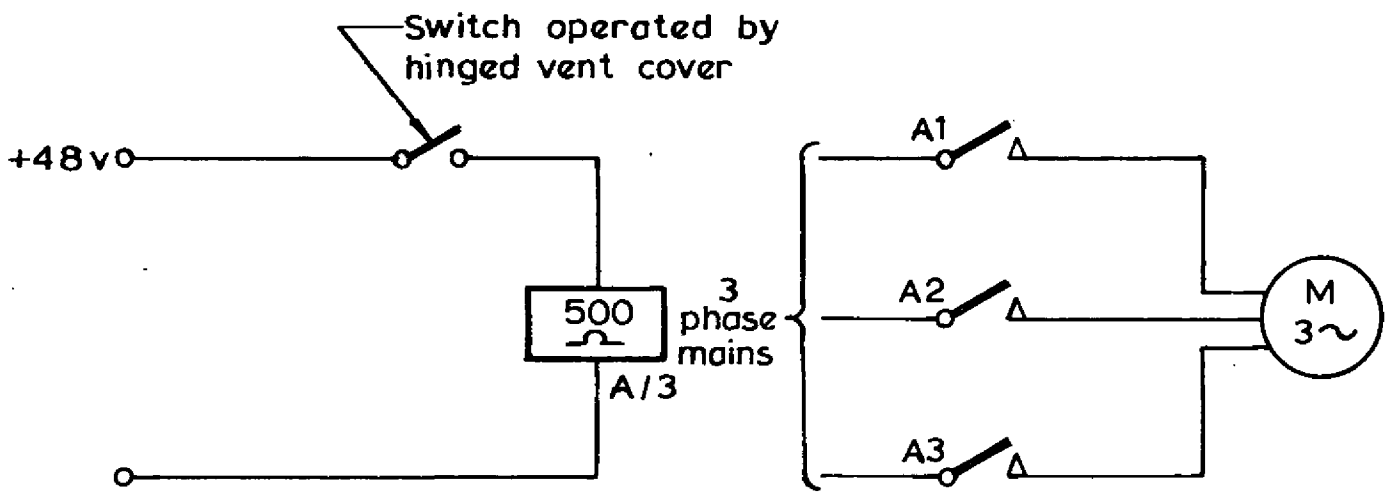


FIG.5 CIRCUIT FOR AUTOMATIC STOPPING OF ROTARY VALVE

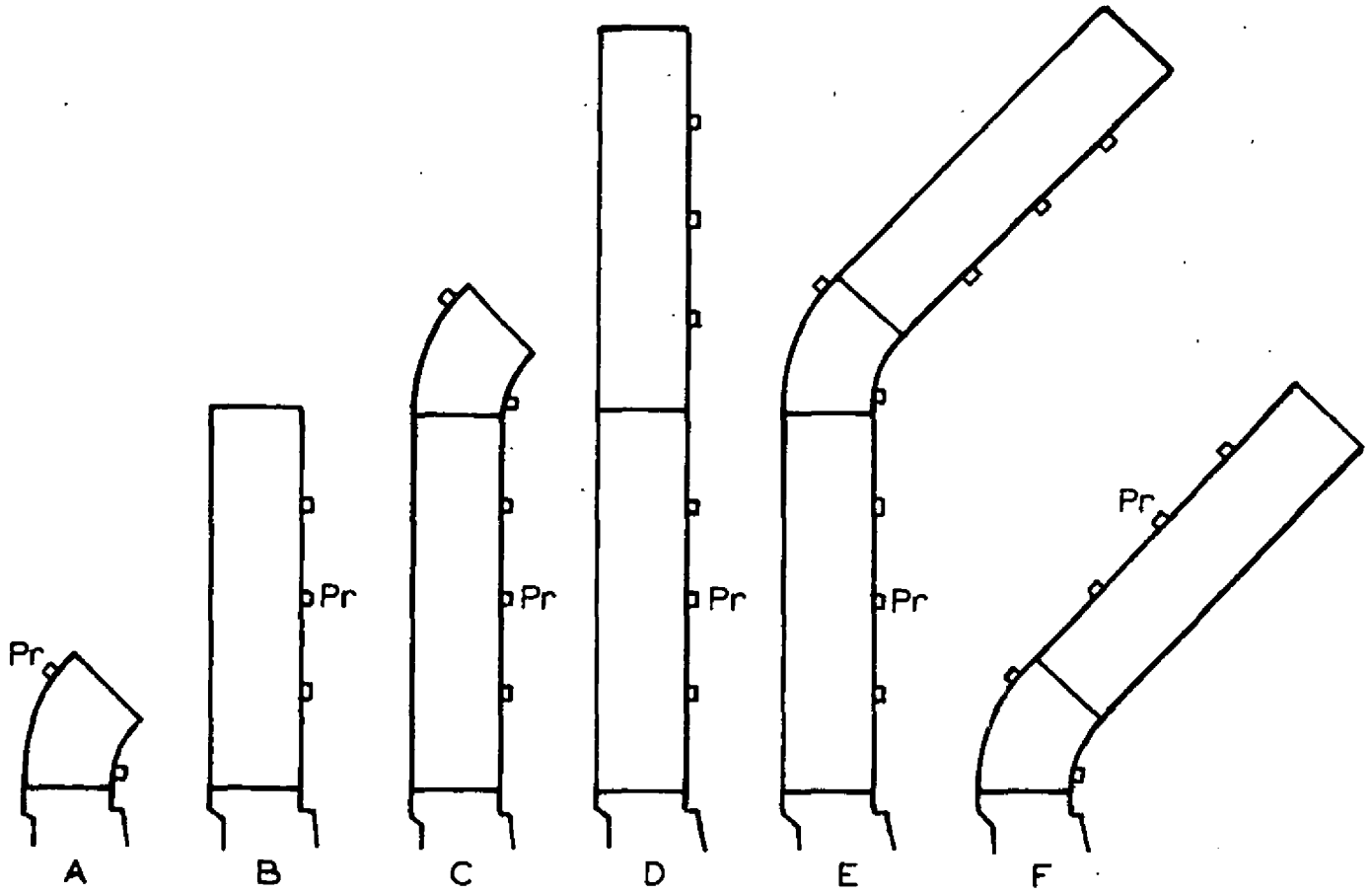


TABLE 8 Dimensions of ducting

Arrangement	Description	Length of ducting above vent or equivalent length when elbow was used		Where pressure measured			
				Distance from elbow		Distance from end of duct	
		m	ft	m	ft	m	ft
A	Adaptor plus elbow	0.86	2.83	In the elbow		0.15	0.5
B	Adaptor plus one duct length	2.08	6.83	-	-	0.91	3.0
C	Adaptor plus one duct length plus elbow	2.7	8.83	0.91	3.0	1.5	5.0
D	Adaptor plus two duct lengths	3.9	12.83	-	-	2.7	9.0
E	Adaptor plus one duct length plus elbow plus one duct length	10.0*	32.83*	0.91	3.0	3.4	11.0
F	Adaptor plus elbow plus one duct length	2.7	8.83	0.91	3.0	0.91	3.0

* Equivalent duct length as defined above

FIG.6 DETAILS OF DUCTING USED IN VENTING EXPERIMENTS

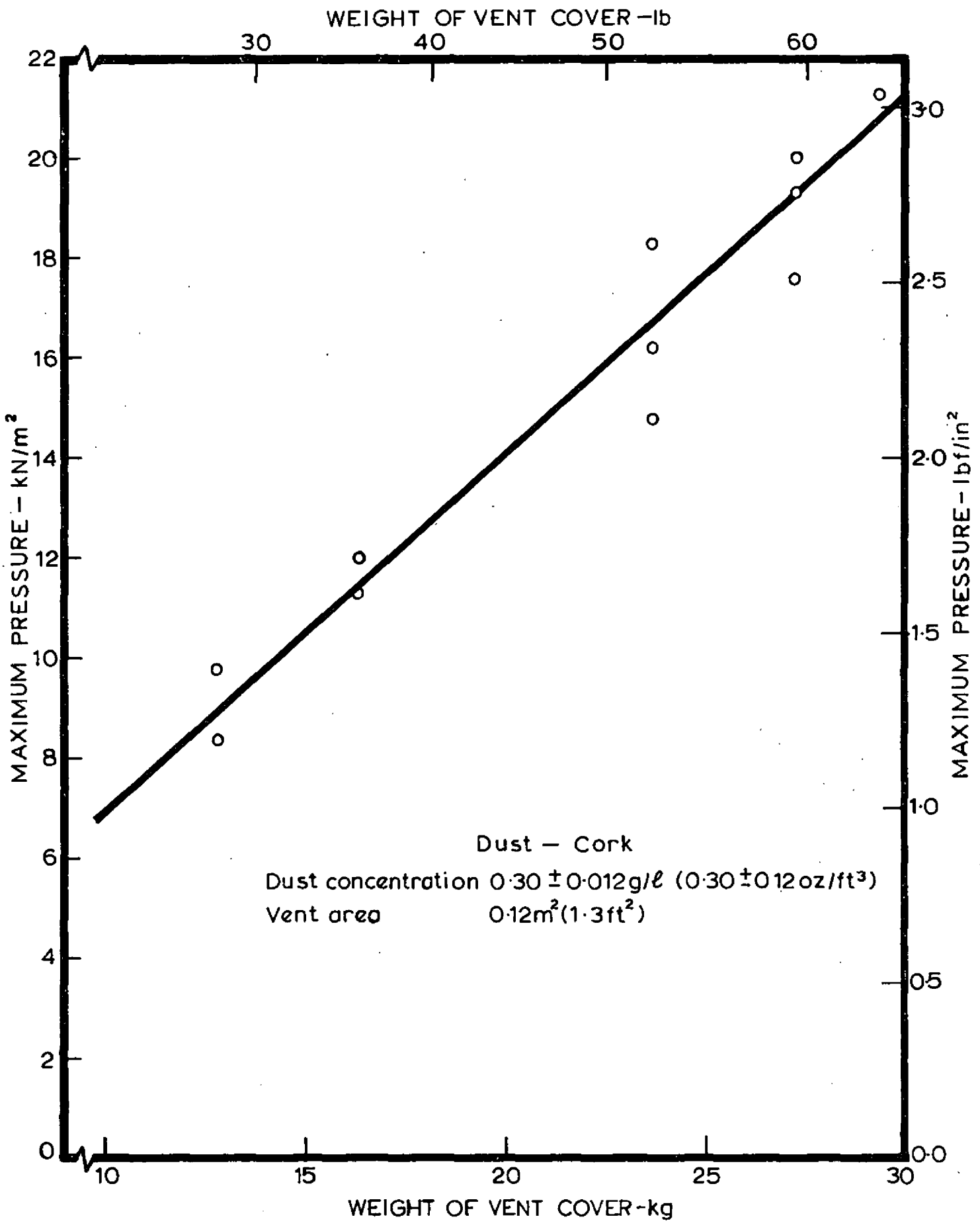


FIG. 7 EXPLOSION PRESSURES WITH VARIOUS HINGED VENT COVER WEIGHTS

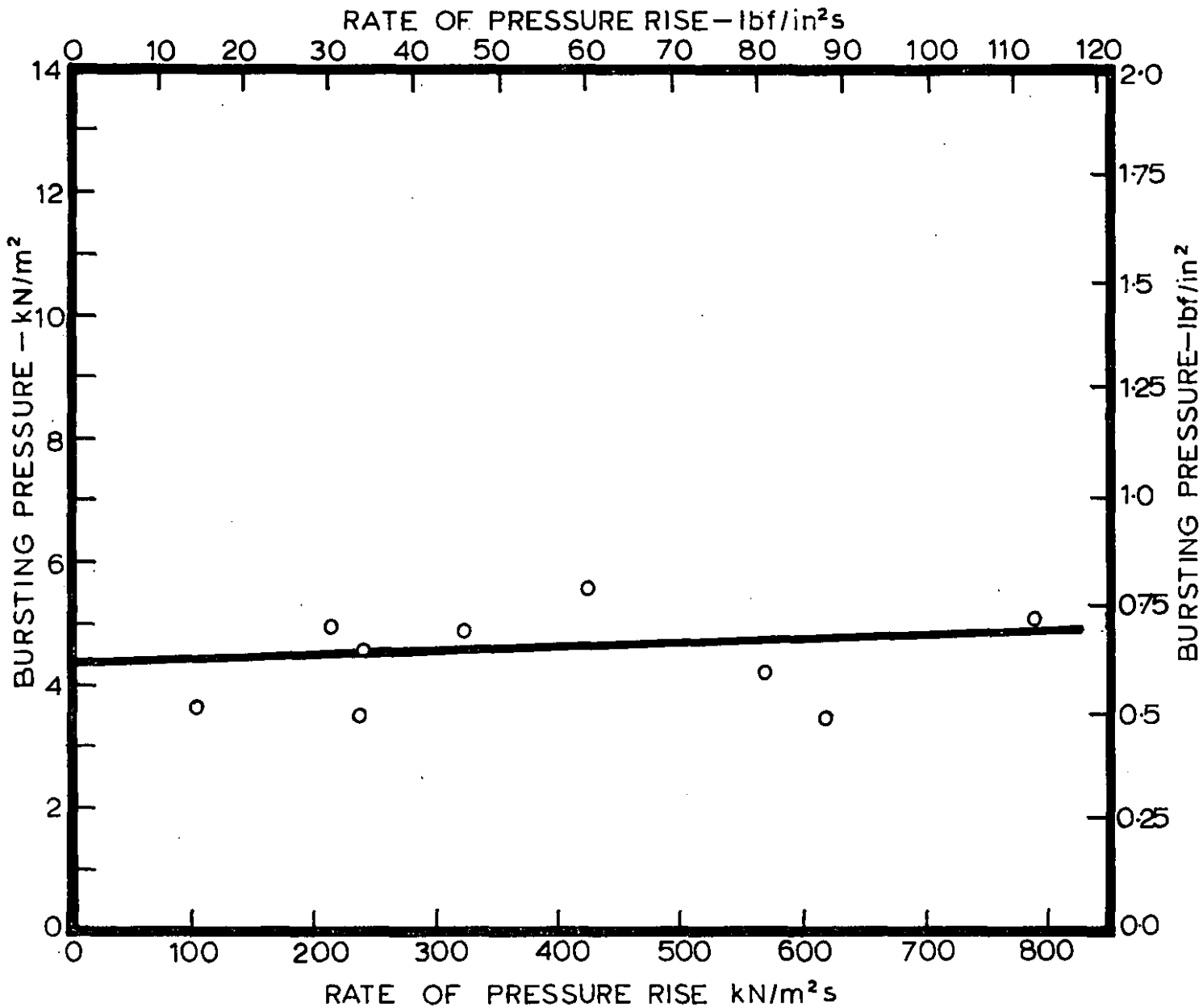


FIG.8 BURSTING PRESSURE OF BROWN PAPER VENT COVERS

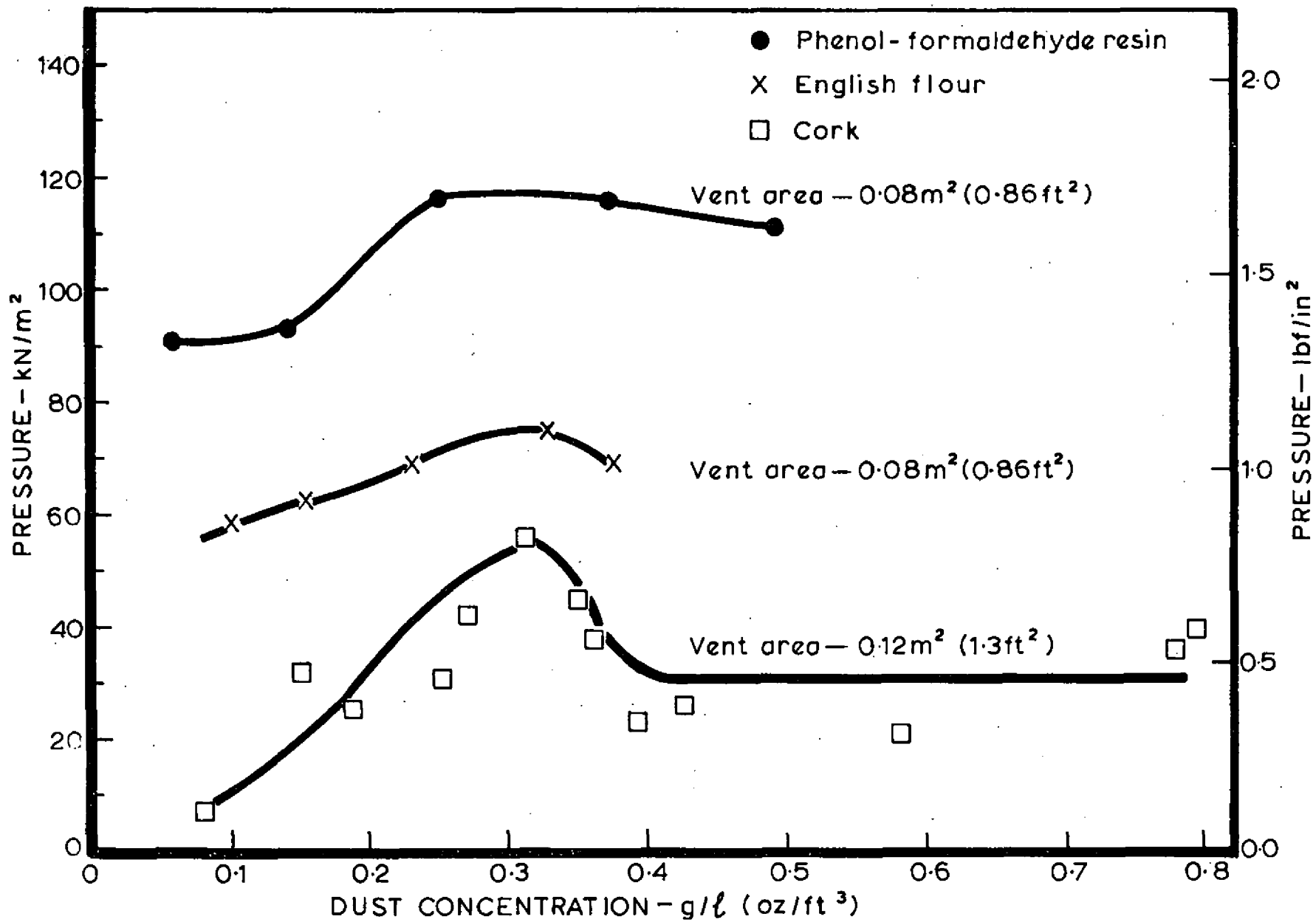


FIG.9 PRESSURE IN THE CYCLONE WITH VARIOUS DUST CONCENTRATIONS

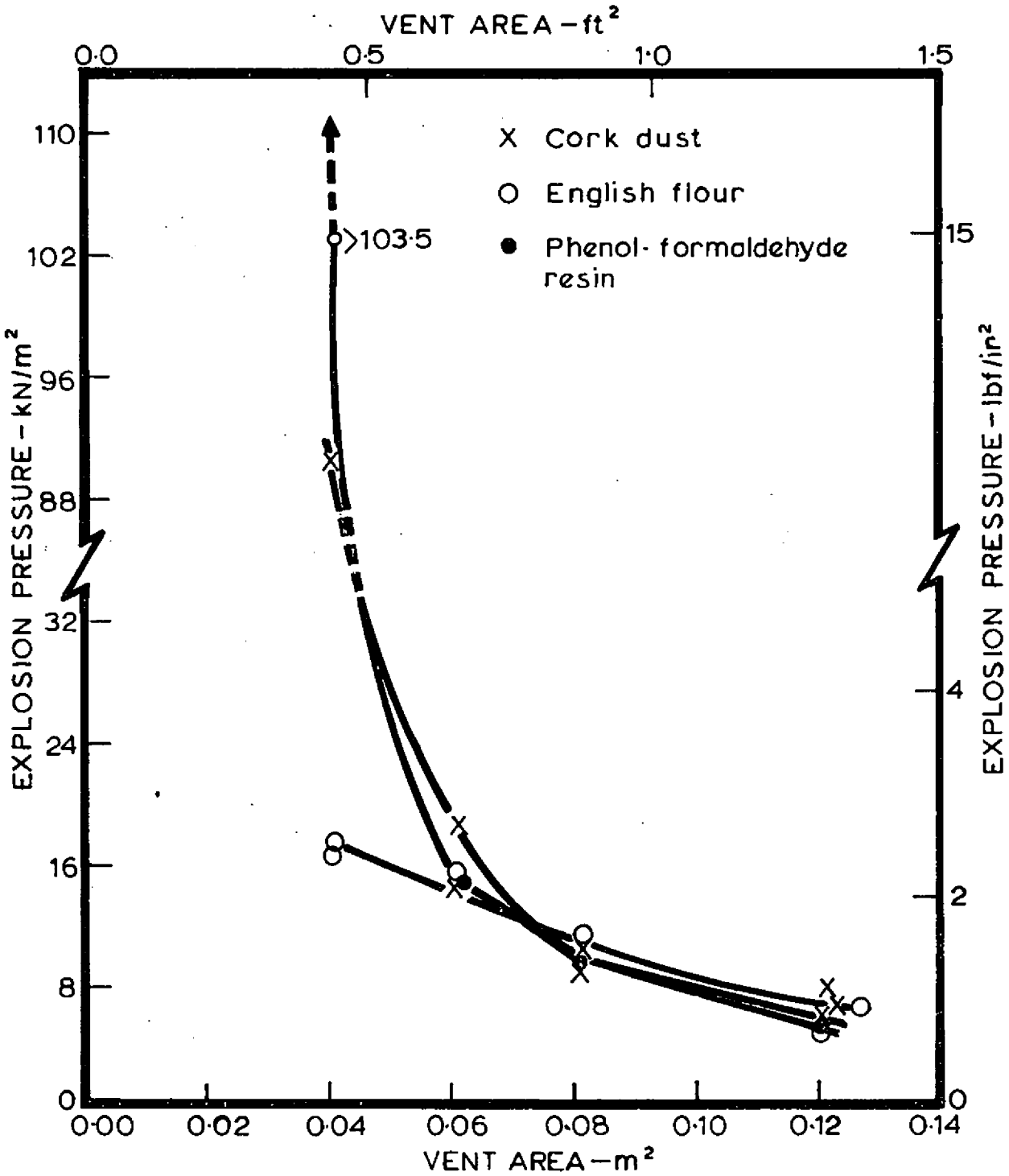


FIG.10 THE EFFECT OF VENT AREA ON EXPLOSION PRESSURE IN A CYCLONE

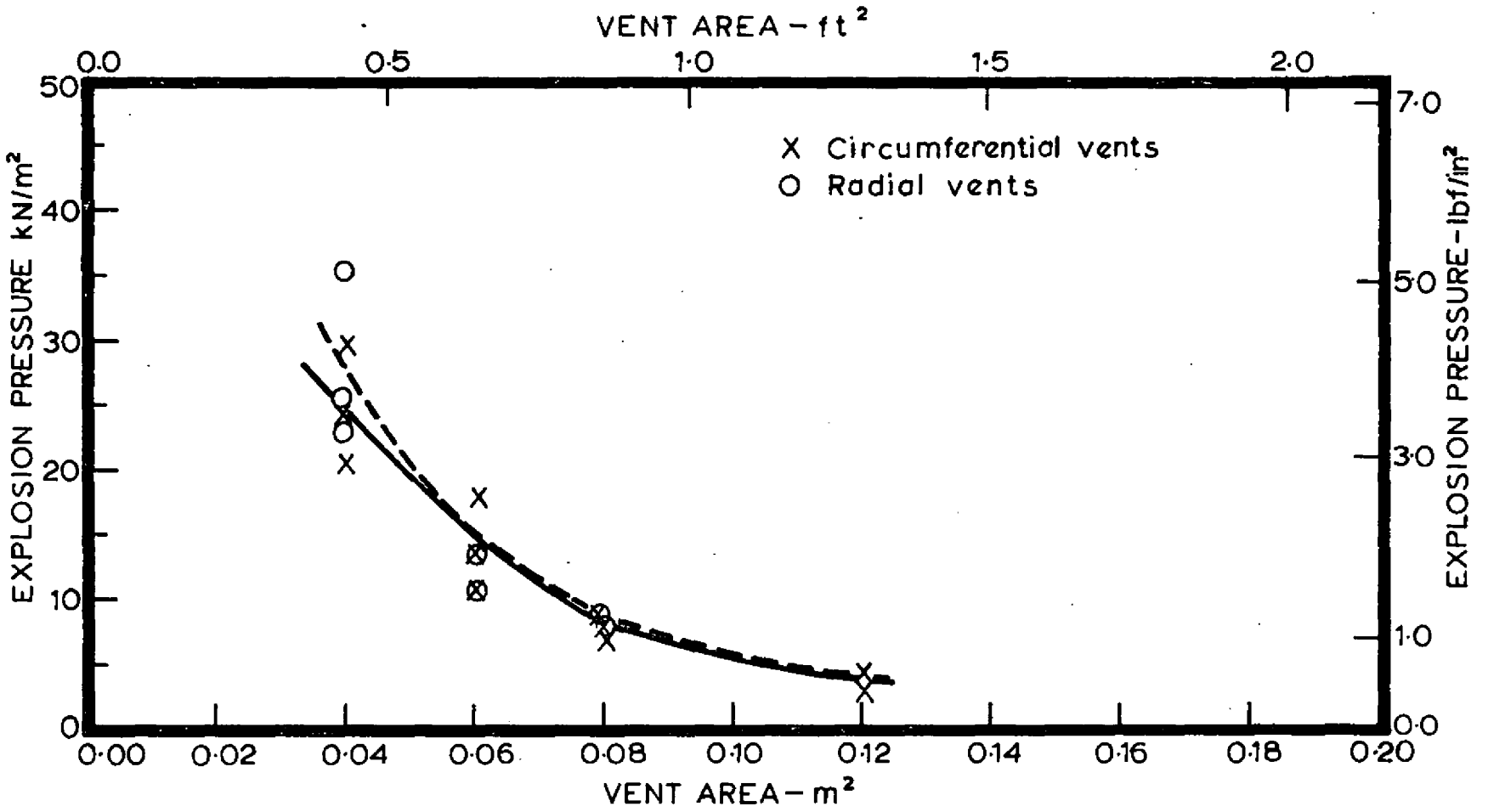


FIG.11 THE EFFECT OF VENT SHAPE ON CORK DUST EXPLOSION PRESSURE

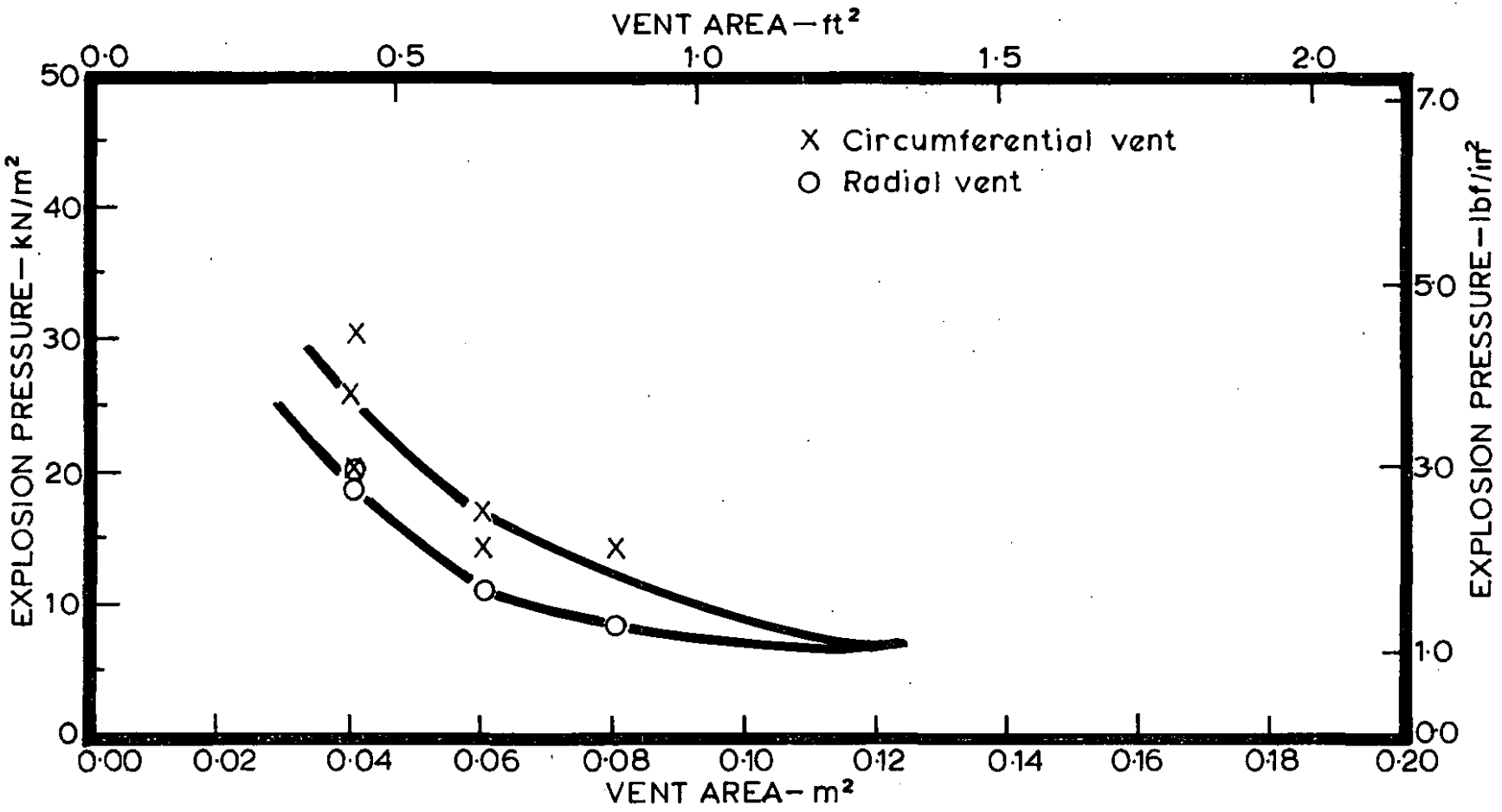


FIG.12 THE EFFECT OF VENT SHAPE ON PHENOL-FORMALDEHYDE RESIN EXPLOSION PRESSURE

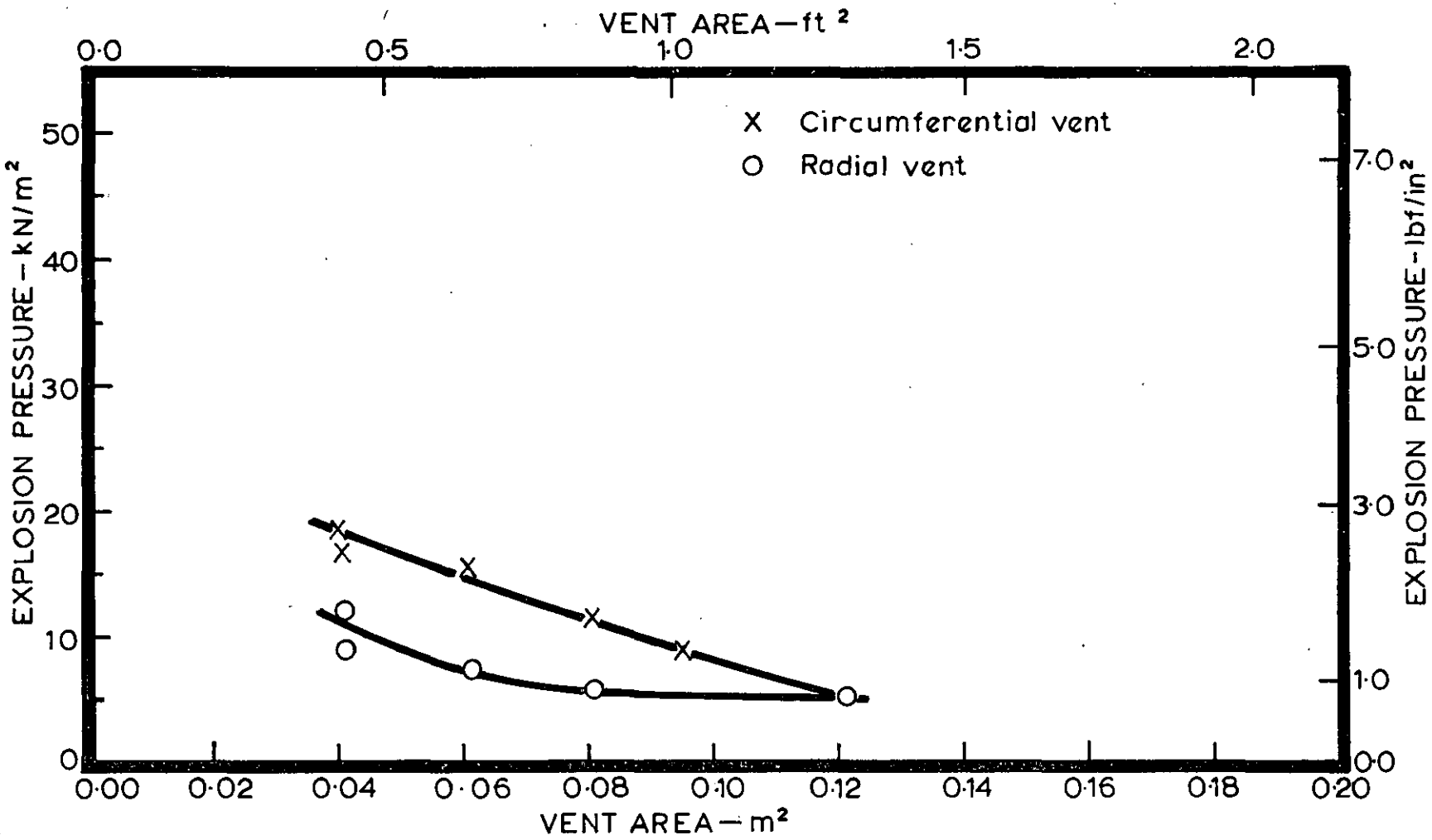


FIG. 13 THE EFFECT OF VENT SHAPE ON ENGLISH FLOUR EXPLOSION PRESSURE

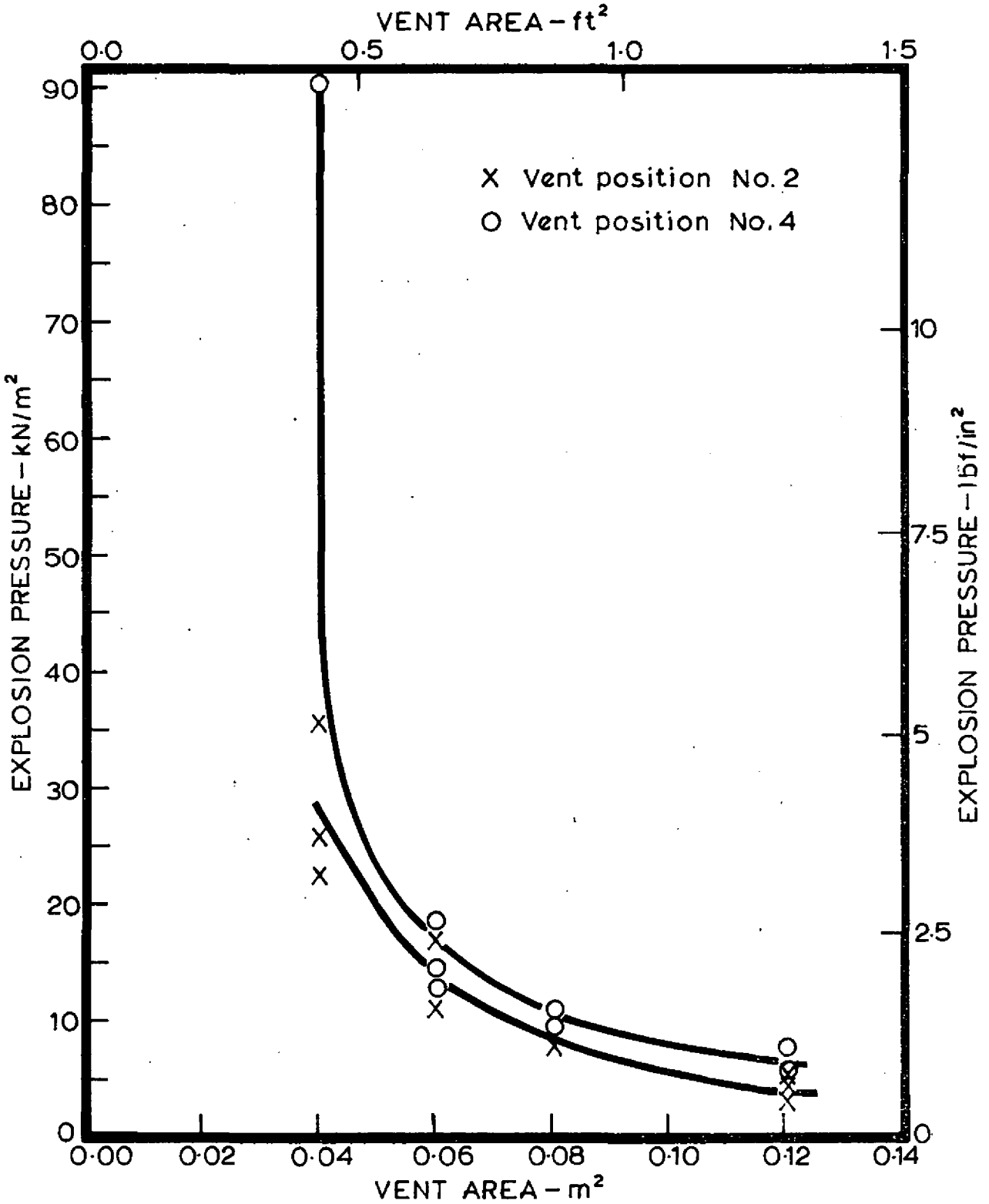


FIG.14 THE EFFECT OF VENT POSITION ON CORK DUST EXPLOSION PRESSURE

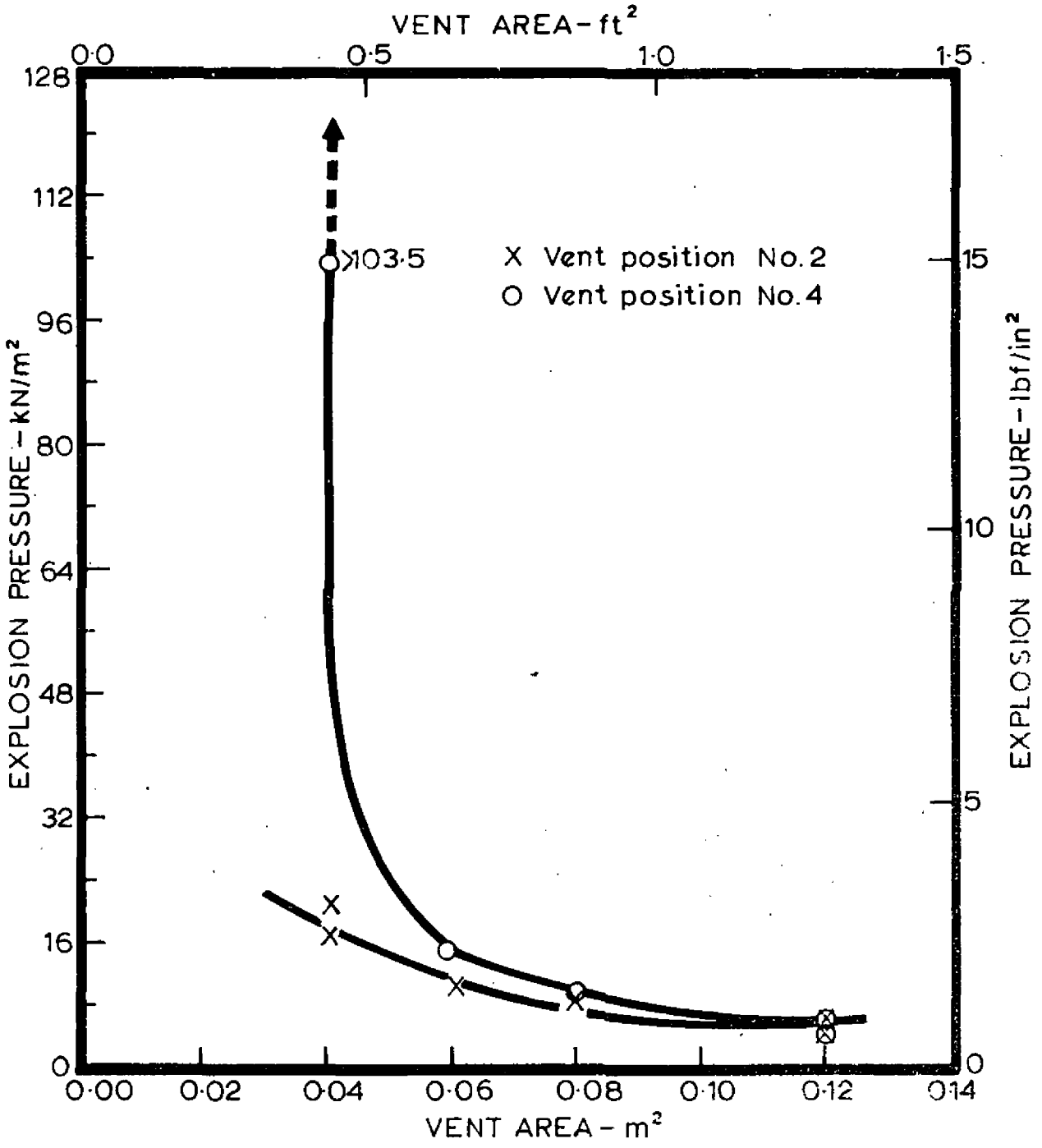


FIG.15 THE EFFECT OF VENT POSITION ON PHENOL-FORMALDEHYDE RESIN EXPLOSION PRESSURE

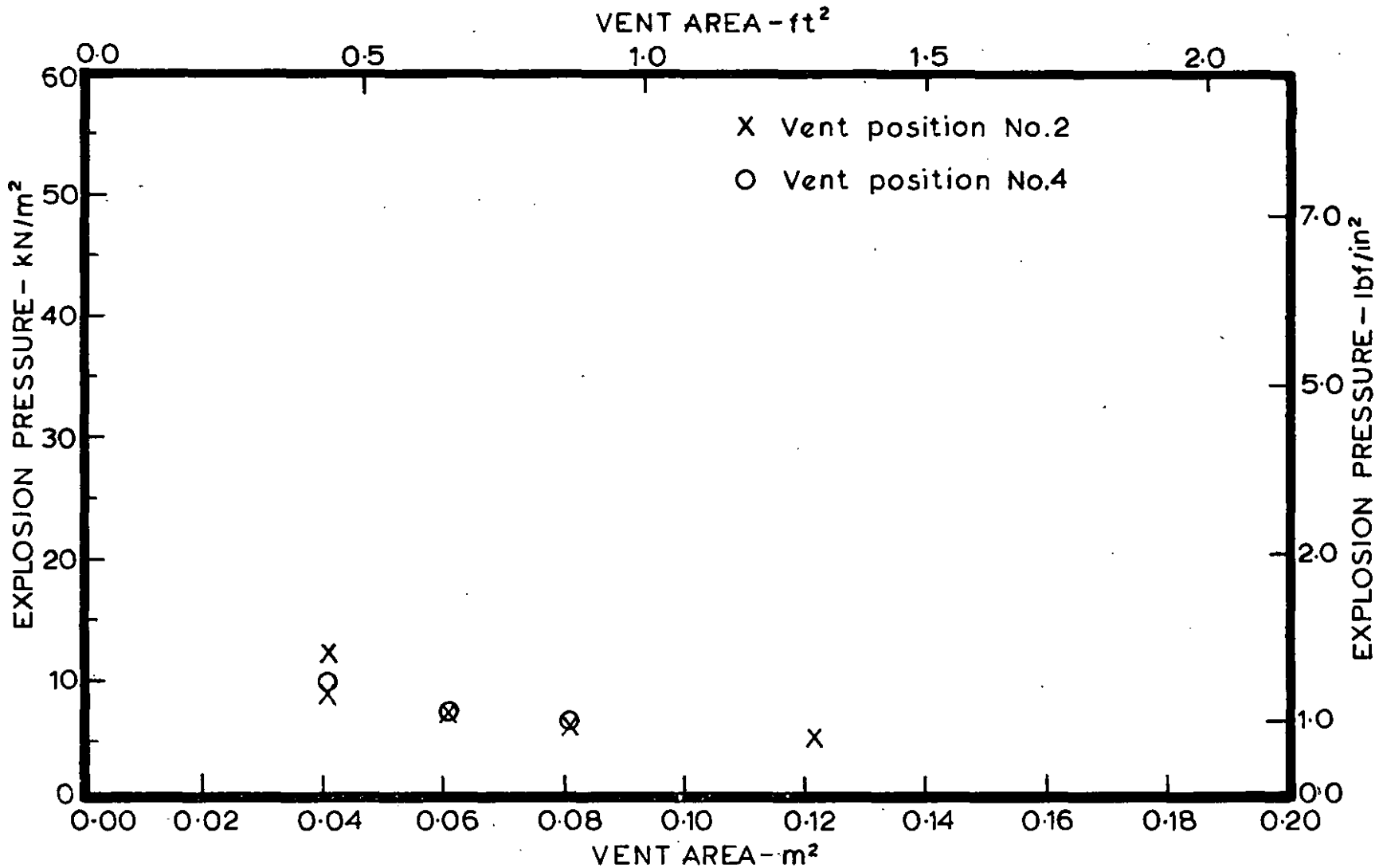


FIG. 16 THE EFFECT OF VENT POSITION ON ENGLISH FLOUR EXPLOSION PRESSURE

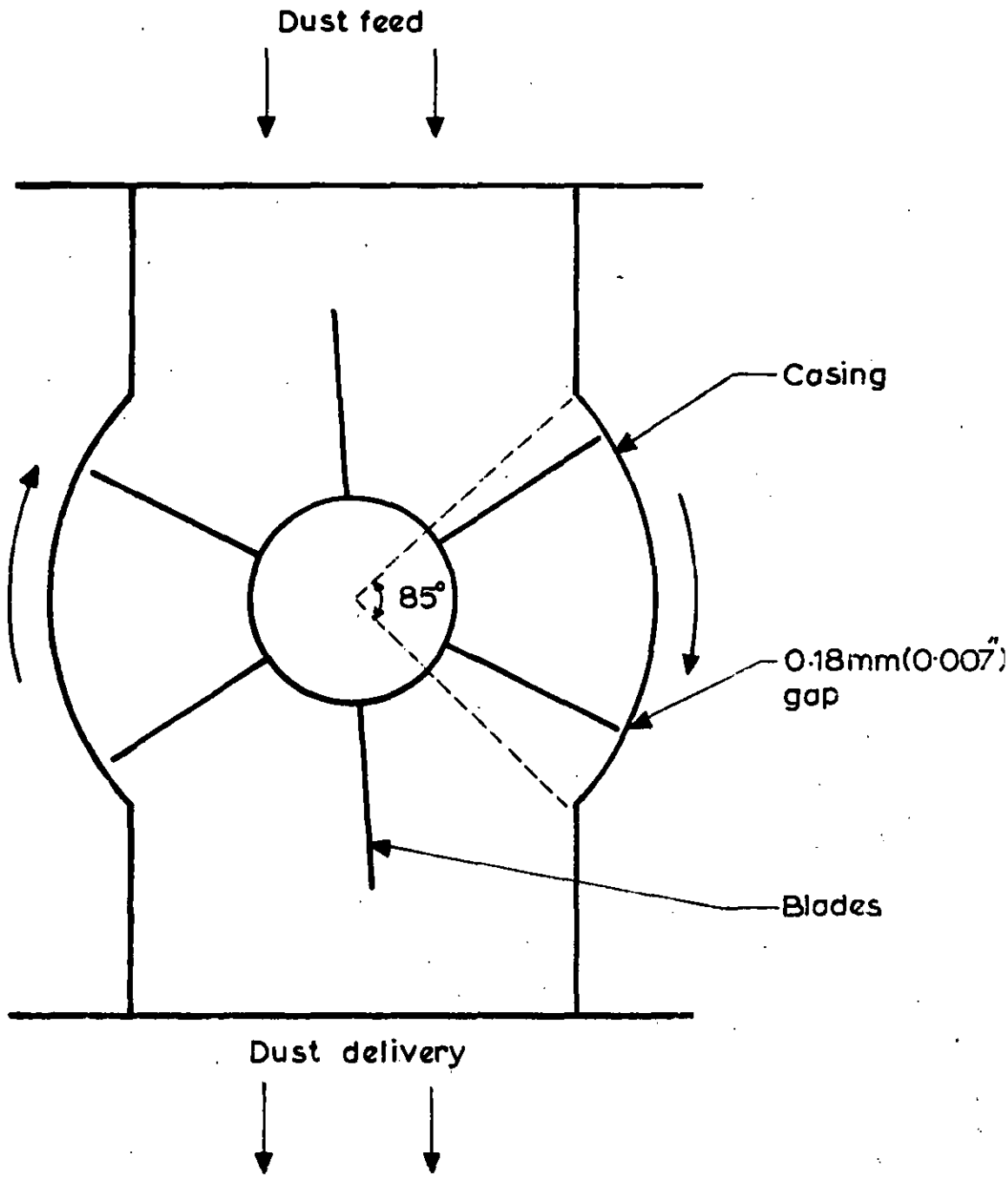


FIG. 17 DIAGRAM OF A ROTARY VALVE (END VIEW)

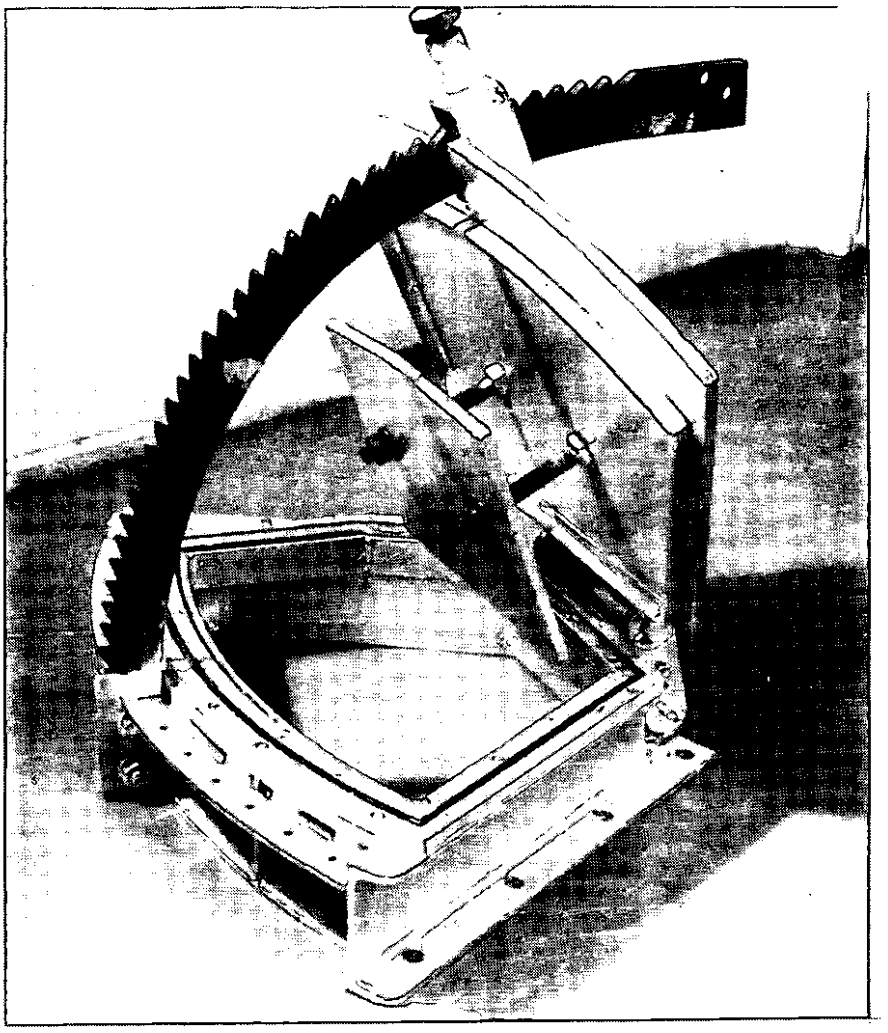


PLATE 1. EXPERIMENTAL HINGED VENT COVER

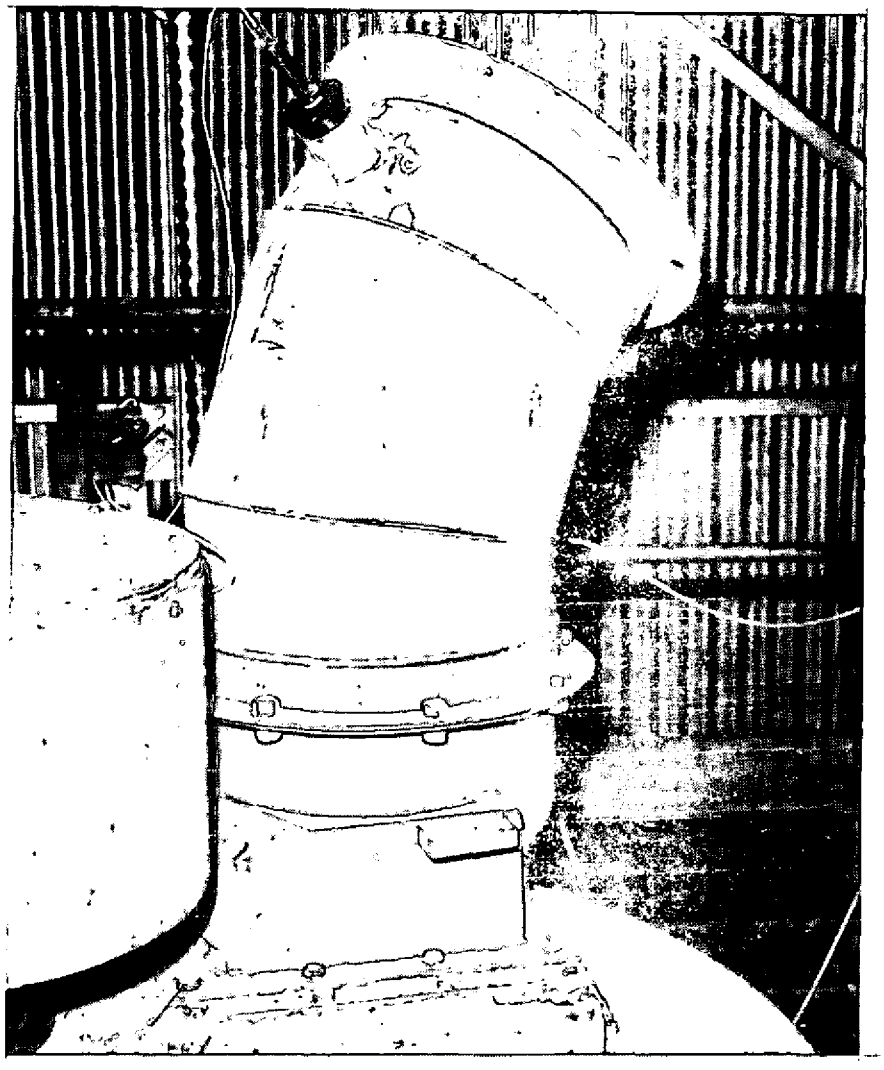
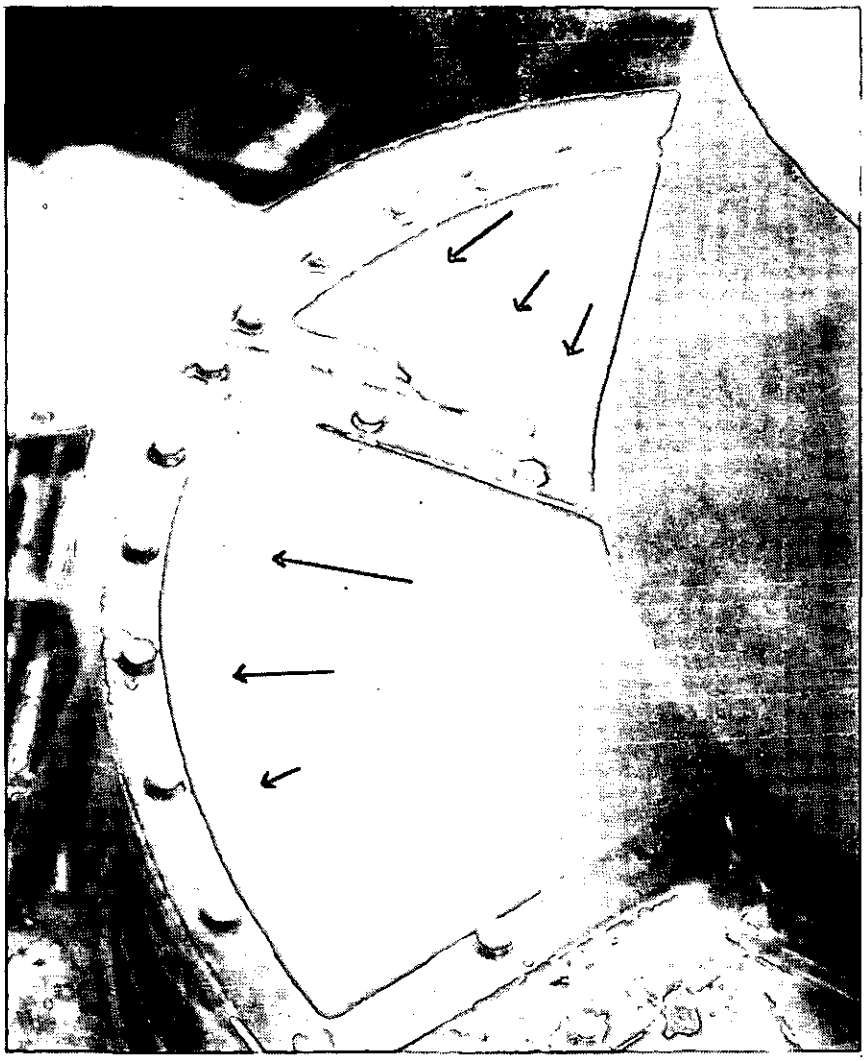


PLATE 2. ADAPTOR AND ELBOW USED IN CYCLONE VENTING EXPERIMENTS



Arrows indicate dust

PLATE 3. POLYPROPYLENE DUST ENTERING AND SEPARATING IN THE CYCLONE

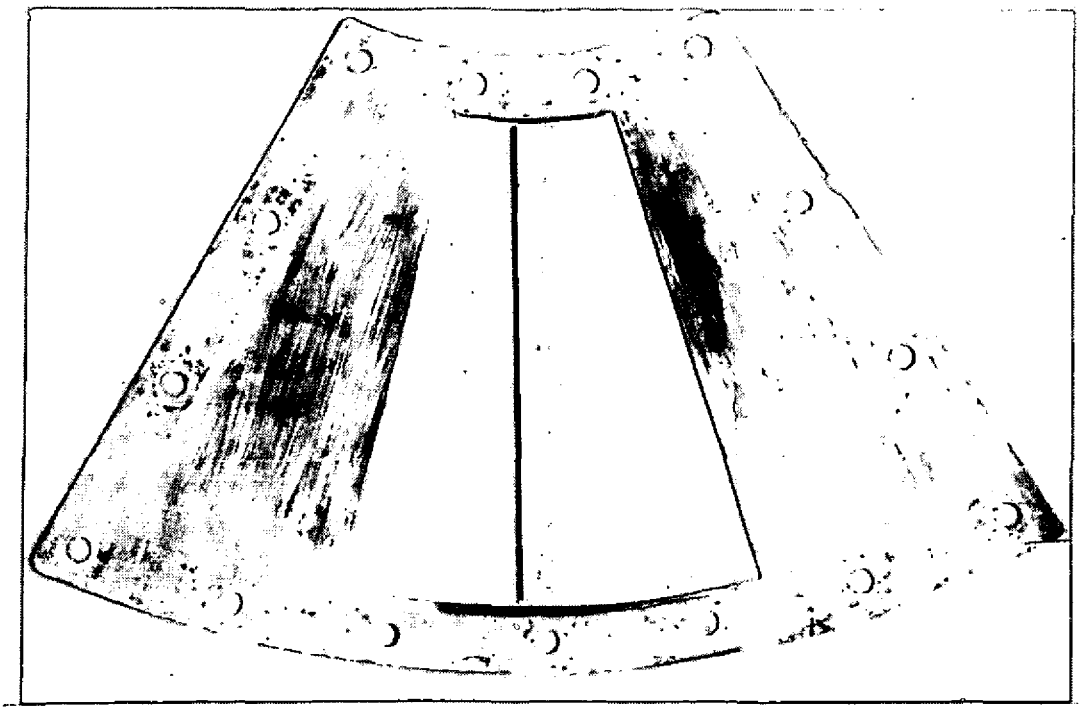


PLATE 4. RADIAL TYPE VENT AS USED ON THE CYCLONE

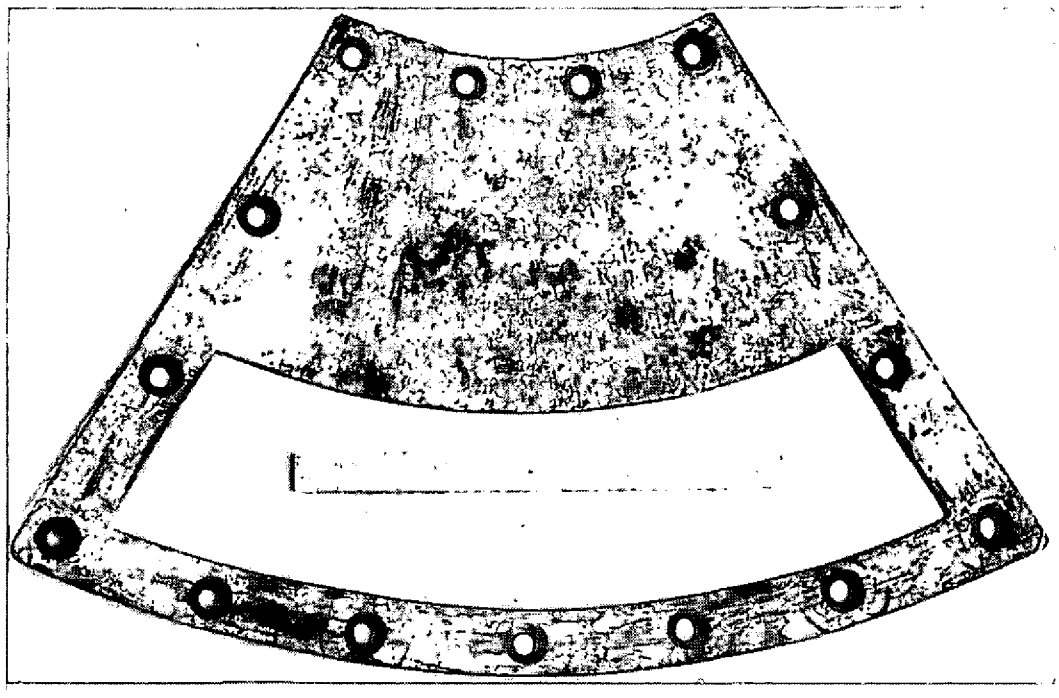


PLATE 5. CIRCUMFERENTIAL TYPE VENT
AS USED ON THE CYCLONE

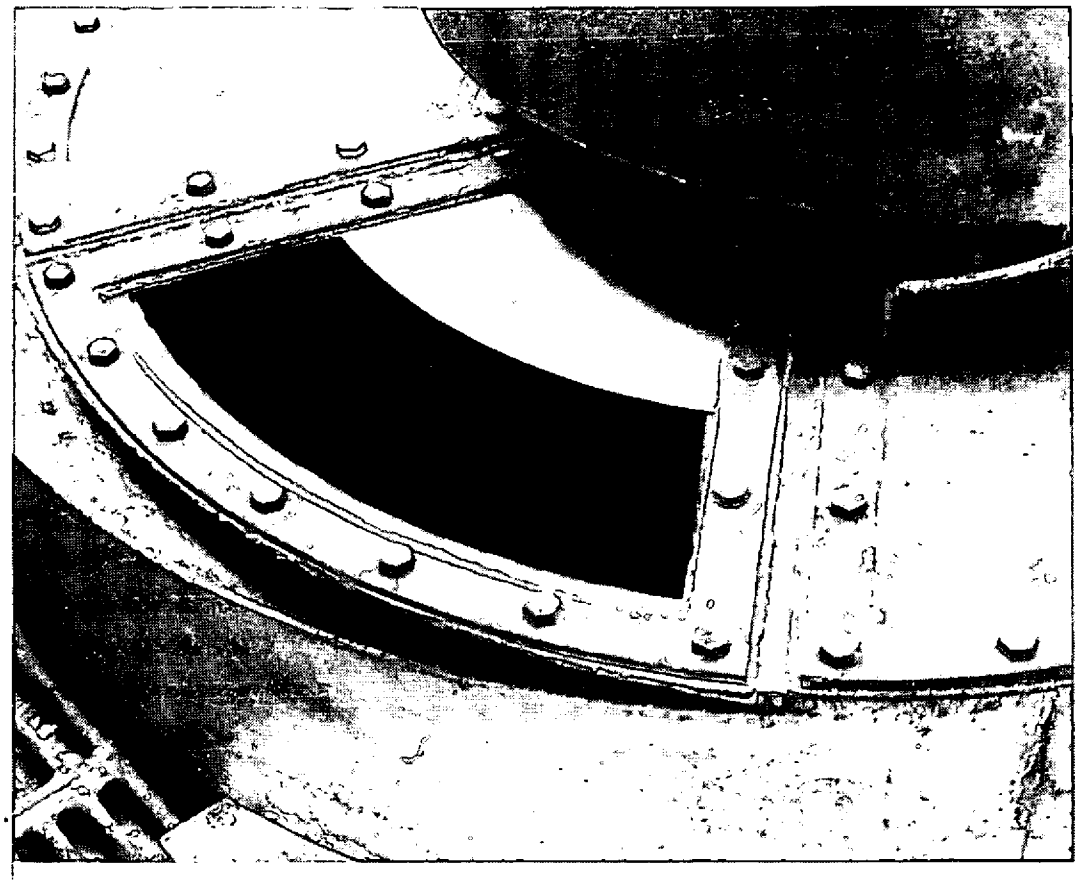


PLATE 6. REDUCTION OF CYCLONE VENT AREA TO TWO THIRDS