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EXPLOSIONS OF marginally EXPLOSIBLE
DUST MIXTURES DISPERSED IN A LARGE-SCALE
VERTICAL TUBE

by

K. N. PALMER and P. S. TONKIN

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SUMMARY

The extent to which dusts that are marginally explosible according to small-scale tests are able to propagate explosion in large-scale equipment has been investigated. Mixtures of an explosible and an inert dust were made up in various proportions to give a range of explosibilities, and were dispersed in air in a vertical explosion tube. The range of concentration in air over which the mixtures were explosible was measured, and the proportion of inert dust required in the mixture to prevent explosion was determined. The dust mixtures were also tested in the small-scale apparatus.

Most marginally explosible dusts from the small-scale tests (i.e. marginally Class I) would propagate explosion on the larger scale. Dusts that required a large source of ignition in small-scale tests did not propagate explosion on the larger scale.

Good agreement was obtained between the calculated and the experimental values of the minimum amount of inert dust required to prevent propagation, when mixed with the explosible dust. The calculated values of the explosible limits of dust mixtures were lower than those determined experimentally, after allowing for the velocity of fall of the dust particles, but evidence was obtained that a substantial proportion of the dust suspension remained unburnt.

This report has not been published and should be considered as confidential advance information. No reference should be made to it in any publication without the written consent of the Director of Fire Research.

August, 1965

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

EXPLOSIONS OF marginally EXPLOSIBLE DUST MIXTURES DISPERSED IN A LARGE-SCALE VERTICAL TUBE

by

K. N. Palmer and P. S. Tonkin

Introduction

Many combustible dusts can cause dust explosions if they are dispersed in air and ignited, and they can cause severe damage to industrial plant and loss of life. When dusts are handled in industry, particularly on a large scale, it is important to know whether or not they are explosible. A wide range of dusts has been tested for explosibility, and a list of these dusts is published periodically⁽¹⁾. However, further dusts are continually being produced or are involved in incidents, and the testing of these materials for explosibility is carried out at the Fire Research Station on samples submitted by H.M. Factory Inspectorate or by industry direct.

The dusts are classified according to explosibility by means of routine small-scale tests. The principle of each of the tests is the dispersion of a small quantity of the dust in the presence of a source of ignition, and any production of flame is observed. The test apparatus is as follows, further details are given elsewhere⁽²⁾.

- (a) Horizontal tube: a glass tube, open at each end, with an electrically heated wire coil igniter, part way along the tube. The dust is dispersed from a heap in the tube by a puff of air.
- (b) Inflamator: a vertical glass tube, open at the top end, usually with a coil igniter near the bottom. The dust is blown in through a side-arm in the upper part of the tube.
- (c) Hartmann apparatus: a vertical perspex tube, open at the top end, with an electric spark igniter near the bottom. The dust is dispersed upwards from the bottom of the tube by a puff of air.
- (d) Modified Hartmann apparatus: as (c) above, but with electric coil igniter.
- (e) Furnace apparatus: a vertical silica tube, open at the bottom, heated externally by an electrical winding. The dust is blown through the tube from the top.

In apparatus (a) to (d) the source of ignition is regarded as small, in apparatus (e) it is larger.

From their performance in the tests, the dusts are classified as follows⁽¹⁾:

Class I : dusts which ignite and propagate flame readily, the source of heat required for ignition being small;

Class II : dusts which ignite readily with flame but require a larger source of ignition;

Class III : dusts which do not ignite in the tests.

Hence Class I dusts have the greatest dust explosion hazard.

For convenience the test apparatus is small-scale, but it does not give information on the following points, which are of considerable practical importance in relation to the installation of safety measures:

- (a) the propagation of dust explosions in large-scale plant, and particularly whether dusts that are marginally Class I in the tests would cause vigorous explosions on a larger scale;
- (b) whether Class II dusts can propagate explosion away from the influence of the ignition source in large-scale plant.

Experiments have therefore been carried out to examine these points with apparatus of larger scale than that of the tests. The apparatus consisted of a vertical tube, closed at one end, in which dust was dispersed at the top and allowed to fall freely. There was no flow of air through the tube. The vertical tube method was described by Jones and White⁽³⁾, who used a 27.3 cm diameter tube to measure the lower flammability limits of woodmeal, charcoal and sulphur. Essenhigh and Woodhead⁽⁴⁾ used tubes up to 7.6 cm diameter in their measurement of the lower and upper flammability limits and the flame speeds of cork dust.

A tube of 7 cm diameter was used by Powell⁽⁵⁾ who investigated the flammability limits of lycopodium dust mixed with limestone. Mixtures containing up to 78 per cent by weight of limestone had well-defined limits. At slightly higher percentage of limestone small changes in the composition produced large changes in the probability of propagation, and detailed analysis was not possible. Maguire, Slack and Williams⁽⁶⁾ used a 14 cm diameter tube to measure the flammability limits of a coal dust. None of the above work was directly concerned with the explosibility of the dusts, or the effects of increased scale.

In the present work the tube was about 25 cm in diameter and 5.2 m long, which provided an apparatus approaching in scale to that of industrial plant. The dusts used were mixtures of a Class I and a Class III dust, which enabled the whole range of explosibility to be covered. The behaviour of dust mixtures which were Class II or marginally in Class I in the small-scale tests could then be determined in the large scale vertical tube apparatus. An assessment could then be made of the likelihood of flame propagation in Class II dusts in industrial plant.

As a preliminary to the present work, some exploratory experiments were carried out by personnel at the Safety in Mines Research Establishment, Buxton. The apparatus was a vertical tube, of diameter 7.6 cm and length 3.1 m, and dust mixtures were tested with various ignition sources. A summary of the work is given in Appendix 1.

Experimental

Materials

The phenol formaldehyde dust (Class I) was an industrial grade moulding powder stated to be of mean particle diameter 15 microns. The moisture content was determined by heating to constant weight in an oven at 105°C and was 4.1 per cent. The ash content was determined by heating in a muffle furnace at 800°C and was 3.2 per cent. The magnesium oxide dust (Class III) was an industrial grade powder stated to be of mean particle diameter 11 microns. The moisture content was found to be 2.2 per cent.

Mixtures of the two dusts were made in a rotating drum mixer with off-centre mountings to ensure end to end tumbling of the charge in addition to the movement caused by the rotation of the drum. The minimum time for satisfactory mixing of a charge was 2 hrs. The extent of mixing was determined by taking samples from a batch at intervals during mixing, and ashing in a muffle furnace. The mean compositions of samples taken after 1 and 2 hours did not vary by more than 1 per cent.

Apparatus

Explosion tube

The vertical explosion tube consisted of flanged sections of ducting bolted together. 4.3m (14 ft) of its length was of 16 gauge steel and a further 0.92m (3 ft) consisted of three equal lengths of clear perspex, positioned at convenient points in the tube for observation of the dust flames. The internal diameter of the tube was 25.4 cm (10 in). Fig.1 is a diagram of the explosion tube.

Manually operated sliding trays were situated at positions 1.8m (6 ft) and 3.5m (11.5 ft) from the top of the tube. These trays were used to collect dust in determinations of dust concentrations and particle velocities. In addition, at the top of the tube and at 4.6m (15 ft) from the top, cut-off slides were situated which were used for closing off the tube. The trays, slides and their housings were all made of aluminium.

A dust collecting bin was fitted to the bottom of the tube. The bin was protected from hazardous explosion pressures by relief vents closed with covers held by magnets. The explosion tube, dust feed, and collecting bin, with supporting structure, are shown in Plates 1 and 2.

A dust and fume extraction unit consisted of a centrifugal fan and dust filter assembly which was sited outside the laboratory and was connected to the apparatus by a flexible metal ducting. The ducting could be fixed either to the dust collecting bin or to an extraction hood at the top of the tube, and a crimped ribbon flame arrester was installed to prevent flame from entering the ducting. The capacity of the fan was 25 m³/min and dust was separated from the effluent gases by a commercial fabric and wire gauze filter.

Igniting source

The igniting source was a propane flame which was injected horizontally into the explosion tube and covered the cross section of the tube. The ignition unit consisted of a 0.31m (1 ft) length of explosion tube to which an external side tube was attached and through which propane and air were released from reservoirs by solenoid valves. In most experiments about 190 ml of propane measured at N.T.P. were used to form the igniting source.

In a few experiments, where the effect of the size of the igniting source on the extent of partial propagation of flame was being investigated, the volume of propane was increased to 355 ml. Ignition of the gas was effected by a continuous induction spark in the side tube. No part of the ignition unit protruded into the explosion tube. The unit was situated either near the top or near the bottom of the tube.

Dust feed

The dust was fed at a uniform rate from a hopper by a screw conveyor on to a perforated metal plate at the bottom of a dispersing cylinder, which was 20 cm diameter and 15 cm high. The dispersing cylinder was vibrated at 100 c/s and delivered the dust into the explosion tube (Fig.1). Two screw conveyors were used in the experiments: one with helix 11.5 cm diameter and 92 cm long and the other 3.8 cm diameter and 30 cm long. The screw conveyor was rotated by a friction wheel which was in contact with a rubber surfaced disc, 48 cm in diameter, fitted to one end of the shaft of the screw. The unit was powered by a $\frac{1}{4}$ horse power motor through a pulley and gearing system which enabled the speed of the friction wheel to be varied. The speed of rotation of the screw was varied by moving the friction wheel along its shafting which coincided with a radius of the disc.

For experiments with the top of the explosion tube closed the outlet from the screw conveyor was connected to the dispersing cylinder by means of flexible rubber hose; when the top of the explosion tube was open the flexible hose and the lid of the dispersing cylinder were removed.

Cine camera

Flame velocities were determined from films obtained with a cine camera whose speed could be varied up to about 250 frames/s. The film was fast panchromatic and its speed through the camera was indicated by marks made by a small neon lamp incorporated in the camera.

Dust and gas sampling

The apparatus used for obtaining dust and gas samples from flames is shown diagrammatically in Fig.2. It consisted of a 0.6 cm internal diameter probe extending into the centre of the explosion tube at a point 1.8 m above the igniting source, and it connected to a cylinder of 7.6 cm diameter made from two B.S.P. 3 in to 1 in reducing female sockets. The dust was collected on a filter paper held in a butt joint between the two sockets; the joint was made gas tight with adhesive tape. A 4l reservoir and a gas sampling bottle, 250 ml capacity, were connected in parallel to the side of the filter paper holder remote from the explosion tube. Gas flow into the reservoir and the gas sampling bottle was controlled by magnetic valves, and a vacuum pump completed the system. By operating the magnetic valve on the reservoir first, the system on the upstream side of the magnetic valves was purged of air and the gas sampling bottle could then be filled with undiluted gases from the explosion tube.

Procedure

The procedure adopted for determining the explosibility of dust at a given concentration was firstly to measure the concentration in the explosion tube and then to carry out a series of three explosion tests. The dust concentration was checked during the series and if the two determinations differed from the mean value by more than 5 per cent the

series was rejected and the experiments were repeated.

The hopper was filled with dust and the screw conveyor was operated until the whole of its helix was filled. The friction driving wheel was set at a known position and the conveyor and dispersing cylinder were operated continuously to deliver dust into the explosion tube. When dust was falling steadily in the tube the cut-off slide at the top of the apparatus and a sliding tray either at 1.8m or 3.5m from the top of the tube were closed simultaneously. The delivery of dust was then switched off. The dust trapped in the tube between the slide and the tray was allowed to settle into the tray and was then weighed. The weight of the dust divided by the volume of the tube in which it was trapped gave the mean dust concentration in the explosion tube. Next, the dust feed was again started and when steady conditions were obtained the igniting flame was injected into the dust cloud. Observation was then made as to whether or not flame propagated in the dust cloud and if so the distance and direction of propagation were also recorded. Two more explosions were attempted and the concentration determination was then repeated. The position of the friction driving wheel on its shafting was changed and the above procedure was repeated for other dust concentrations until the lower and upper flammability limits were established for each dust mixture.

For experiments with the top of the explosion tube closed and the bottom open, and with the igniting source either near the top of the tube or near the bottom, the procedure was as described above. For experiments in which the top of the tube was open and the igniting source was near the bottom the procedure was similar except that the lowest slide was closed immediately before the igniting flame was applied.

The radial distribution of dust in the explosion tube was determined by firstly measuring the mean dust concentration as described above. The dust collecting tray was then replaced by a holder containing 13 aluminium containers, each 2.5 cm diameter and 4.8 cm high, which was in the form of a right-angle cross intersecting at the centre of the tube. The cross and the containers were inserted in the falling dust cloud for a given time and then withdrawn. The dust concentration determination was repeated. From the weights of dust in the containers and their positions the dust distribution along two diameters of the explosion tube could be obtained at a known mean concentration.

The mean velocity of fall of the dust in the explosion tube was calculated from the mean concentration of dust in the tube and the dust collected in a measured time in a sliding tray (Eq 1)

$$v = \frac{10^3 m}{wa} \quad (1)$$

where v = mean velocity of the falling dust - cm/s
 m = mass of dust collected in unit time - g/s
 w = mean concentration of dust in the tube - g/l
 a = area of cross section of the tube - cm²

To obtain information on the consumption of resin and oxygen in the flames samples were taken of the dust and the gas immediately behind the flame front. When the flame had just passed the sampling point (1.8m above the ignition source) two solenoid valves were operated manually on the sampling apparatus and caused

dust and gas to be abstracted from the flame. The dust samples were ashed in a muffle furnace at 500°C and the proportion of phenolformaldehyde resin burnt in the explosion was calculated from the weight of the residue obtained. The gases were analysed for oxygen and carbon dioxide only, in an Orsat apparatus.

Some experiments were also carried out in which samples of dust were collected at the bottom of the explosion tube, in the absence of flame, and were ashed to determine whether the composition of the mixture had altered as it fell down the tube. No change in composition was detected. No attempt was made to measure whether the dust fell as individual particles, or in clusters, but from visual observation some aggregation of the dust was apparent. This point is considered further in the discussion.

Results

Measurement of flammability limits

The effect of magnesium oxide on the flammability limits of phenol formaldehyde resin was measured with the following three explosion tube arrangements, and the results are shown in Fig.3, 4 and 5.

- (i) Top of tube closed, bottom open; ignition near bottom
- (ii) Top of tube closed, bottom open; ignition near top
- (iii) Top of tube open, bottom closed; ignition near bottom

The graphs indicate, for each resin/magnesium oxide mixture, the ranges of concentrations over which there was no flame propagation, propagation for the whole length of the tube, and partial propagation i.e. the flame travelled at least 0.6m but did not traverse the full length of the tube.

Each point on the graphs represented three tests; if the extent of flame propagation varied within a group of tests the result shown is that for the most extensive propagation.

The tube arrangement in which propagation was most likely to occur was (iii), above. Under these conditions partial propagation was obtained with the mixture containing 75 per cent magnesium oxide, which did not occur with the other two tube arrangements. Propagation for the whole length of the tube, with arrangement (iii), was obtained with all dust mixtures up to that containing 70 per cent magnesium oxide. This again did not occur with the other tube arrangements.

The appearance of the explosion flames varied with the concentration of the dust mixtures and their composition. With concentrations near the flammability limits, and with either partial or slow-moving full-length propagation, the flames were short and tended to be fragmented, particularly with high concentration of dust. With more vigorous explosions, at concentrations away from the flammability limits, the flames became longer and eventually filled the whole length of the explosion tube. The amount of solid carbon formed in the explosions was negligible and combustion appeared to be in the vapour phase.

Results of small-scale tests

The phenol formaldehyde/magnesium oxide mixtures were classified for explosibility in the usual small-scale tests listed in the Introduction. Further measurements were made of the explosion properties of the dusts, by the usual procedures⁽²⁾. A summary of the results is given in Table 1.

Table 1

Results of explosibility tests in small-scale apparatus

Mixture composition resin/magnesium oxide	Explosibility Class	Test apparatus in which ignition occurred	Minimum ignition temperature °C		Minimum explosible concentration g/l	Maximum explosion pressure* lb/in ²	Maximum rate of pressure rise lb/in ² /s
			Apparatus (a)	Apparatus (e)			
100/0	I	a-e	1000	450	0.015	107	6500
50/50	I	a-e	1150	450	0.07	78	1100
45/55	I	a-e	1200	450	0.09	69	450
40/60	I	b-e	-	450	0.09	66	400
35/65	I	b-e	-	450	0.14	12	100
30/70	I	b-e	-	460	0.16	5	50
25/75	I	c-e	-	480	0.18	2	20
20/80	I	d-e	-	510	-	2	10
15/85	II	e	-	510	-	-	-
10/90	II	e	-	520	-	-	-
5/95	III	-	-	-	-	-	-

*Calculated in usual manner⁽²⁾, in which pressure rise due to dispersion air (6.5 lb/in²) was subtracted from peak pressure measured.

Apparatus: a : Horizontal tube
b : Inflamator
c : Hartmann
d : Modified Hartmann
e : Furnace

Dust distribution

Fig. 6 illustrates the dust distribution obtained in the explosion tube along diameters at right angles. This was typical for all the dust mixtures tested with the top of the tube closed and the bottom open. Fig. 7 is a typical distribution curve showing the dust distribution along one diameter when the top of the tube was open and the bottom closed.

Falling dust velocities

Fig. 8 shows the variation of mean velocity of fall of the dust with concentration. A similar curve was obtained for each dust mixture.

The mean velocity of fall of pure phenol formaldehyde resin was measured at a concentration of 0.03 g/l, which was near the lower flammability limit, and was 50 cm/s.

Air circulation in the explosion tube

Air movement in the tube caused by falling dust was observed by introducing white smoke. The smoke rose vertically in the tube, over a central region approximately 17 cm in diameter, and was carried downwards near the wall. The cycle of movement was continuous.

Dust and gas analyses

The flames which propagated to the top of the explosion tube in high dust concentrations were fragmented, indicating that probably only a proportion of the phenol formaldehyde resin was burnt in the flame. Analyses were made of the samples of dust taken from behind the flame front, as described above. The results are shown in Fig. 9 which confirms that only a proportion of the dust was burnt at any concentration.

Fig. 10 shows the amount of oxygen consumed immediately behind the flame in explosions with various dust concentrations. In both Fig. 9 and 10 the calculated best line through the experimental points is shown.

Flame velocities

Velocities of flames which propagated in the dust clouds are given in Table 2 together with other relevant information. The values shown were the minimum and maximum flame velocities obtained in different experiments within the concentration ranges indicated.

Table 2

Velocities of flames in dust clouds

Tube arrangement	Position of igniter	Dust Mixture Phenolformaldehyde Resin/Magnesium Oxide	Concentration Range g/l	Flame Velocities obtained in the experiments	
				Minimum cm/s	Maximum cm/s
Top closed bottom open	Near the bottom of the tube	100/0	0.07	100	120
"	"	50/50	0.23 - 0.47	110	400
"	"	45/55	0.17 - 0.72	280	770
"	"	40/60	0.29 - 0.46	400	420
"	Near the top of the tube	50/50	0.15 - 0.24	530	1,100
"	"	45/55	0.28 - 0.37	740	920
"	"	40/60	0.31 - 0.70	370	1,250
"	"	35/65	0.42 - 1.07	150	410
Top open bottom closed	Near the bottom of the tube	100/0	0.03 - 0.08	100	1,450
"	"	75/25	0.06 - 0.10	370	1,050
"	"	45/55	0.13 - 0.29	400	1,150
"	"	40/60	0.23 - 0.39	260	690
"	"	35/65	0.31 - 0.95	280	670

Discussion

Flammability limit determinations

Lower and upper flammability limits were obtained with most of the phenol formaldehyde resin/magnesium oxide mixtures that were explosible. The concentrations of dust mixture suspensions at which the limits occurred were clearly defined; this was the case with each of the three arrangements of the tube and igniter (Fig. 3-5). Three types of flame behaviour occurred: the flame either propagated the whole length of the tube, or partial propagation occurred over a fraction of the length, or the flame did not propagate away from the igniting source. The extent of partial propagation was not affected when the volume of propane used for ignition was increased by 87 per cent, and so it is unlikely that the extent of partial propagation was governed by energy derived from the igniting source. A more likely explanation of the existence of partial propagation is that as the flame was propagating relatively slowly, and its composition was near the flammability limit, it was readily affected by random variations of concentration in the dust suspension. Dust mixtures that were only able to sustain partial propagation have therefore been regarded as explosible for practical purposes.

Each of the curves in Fig. 3-5 was characterised by a flat-topped region, flanked by steeply sloping gradients as the proportion of magnesium oxide was reduced. A similar shape of curve was obtained with lycopodium - limestone dust mixtures⁽⁵⁾, and a flat-topped peak occurred with mixtures containing between 75 and 80 per cent limestone. In the present experiments the upper flammability limits increased markedly as the proportion of phenol formaldehyde resin in the mixtures was increased. However, as stated previously, the flames occurring at these limits did not fill the whole cross-section of the tube, but propagated as narrow streaks. The concentration of dust in the flames may therefore have been less than the mean concentration measured.

The dust concentrations at the flammability limits shown in Fig. 3-5 were measured by the procedure described above. Because the dust was falling through the air in the tube, the quantity entering the flame was different than if the dust had been stationary. For instance, in Fig. 3, the lower flammability limit of pure phenol formaldehyde resin is shown as 0.030 g/l. At these low concentrations the flame velocity was about 100 cm/s (Table 2), whereas the mean velocity of fall was 50 cm/s. Hence the actual amount of dust entering the flame was greater than that measured by a factor $(100 + 50)/100$. The true lower flammability limit was thus 0.045 g/l. The actual quantity of dust entering the flame was greater than the mean concentration when the flame propagated upwards and less for downward propagation.

Mechanism of flame inhibition

Alternative approaches

Two possible mechanisms for the inhibition of dust flames by an inert solid diluent were considered. The first mechanism was that the addition of the inert material caused the flame speed of the dust explosion to decrease until it was ultimately less than the velocity of fall of the dust particles. Depending upon whether propagation was upwards or downwards, the flame would then either be carried downwards into combustion products or would be unable to overtake the

falling dust particles. Upon examination, the experimental results did not support this proposed mechanism. Minimum values of the flame velocities measured relative to the explosion tube, listed in Table 2, were appreciably greater than zero. In addition, visual observation of the explosion flames propagating upwards did not show a pronounced retardation as would be expected if the flame were swept downwards by falling dust. The proposed mechanism was therefore discarded.

The second mechanism was that the presence of the inert material in the flame acted as a thermal sink, and that when a certain amount of the heat generated by the flame was absorbed by the inert dust propagation of the flame would cease. The assumption was that if the flame temperature were reduced by cooling with inert dust to a value less than that of a flame at the lower flammability limit of the pure fuel, then the flame would be quenched. A similar process has been shown to hold approximately (e.g. by Penner and Mullins⁽⁷⁾) for the extinction of premixed gas-air flames with inert gases, although in these cases the fuel-oxidant-inert mixtures were homogeneous and hence the structure of the flames would be different from that in resin dust explosions. Attempts have been made to apply a similar assumption to the quenching of coal dust explosions by stone dust, but in a recent review Essenhigh⁽⁸⁾ concluded that the amount of stone dust required was less than 20 per cent of that predicted. However, the combustion mechanism of coal particles may well be complicated by the presence of both volatile and non-volatile constituents of the coal. In the present work the combustion appeared to be principally in the vapour phase.

Derivation of equations.

The physical processes involved in the propagation of dust flames have not yet been clarified, but in the present case the following overall process was envisaged and is discussed in more detail later. The phenol formaldehyde and magnesium oxide dust particles entered the front of the flame zone together. The flame zone consisted of the luminous burning region and the free oxygen with which it is in close proximity (Fig. 10). The combustible dust vaporised and burned with diffusion flames, leaving the inert dust in suspension in the flame zone acting as a thermal sink. It was not immediately apparent whether the inert dust dispersed as the resin vapours burned and expanded, or remained at the same concentration as before entering the flame zone. An assessment of the probable behaviour was made by comparing the acceleration to be expected from the drag force of the expanding gas on the particles with the acceleration required if the particles were to disperse as the gas expanded.

Neglecting, for the moment, interacting forces between the particles:

$$\text{drag force on inert dust particle} = \frac{1}{2} C A \rho_1 u^2.$$

where C is drag coefficient (function of Reynold's Number)

A is projected area of particle

ρ_1 is density of gas

u is relative velocity between gas and particle.

If the dust particle attained the gas velocity, u would then have decreased to zero.

$$\text{Mean acceleration of particle} = f_1 = \frac{1}{2} C A \rho_1 \frac{u^2}{3} \frac{6}{\pi d^3 \rho_2}$$

where d is diameter of particle (assumed spherical and uniform)

ρ_2 is density of particle

$$\text{Hence } f_1 = \frac{C}{4} \frac{\rho_1}{\rho_2} \frac{u^2}{d}$$

If the particles dispersed as the gas expanded, the approximate acceleration required $= f_2 = \frac{u^2}{2s}$

where s is distance over which the acceleration occurred.

$$\text{Hence } \frac{f_1}{f_2} = \frac{C}{2} \frac{\rho_1}{\rho_2} \frac{s}{d} \quad \dots\dots (2)$$

To obtain an assessment of the ratio f_1/f_2 only approximate values of the quantities in equation (2) were required. For a flame velocity of 100 cm/s (Table 2) and an expansion ratio of about 5 (see below) the value of u would be 400 cm/s. The kinematic viscosity of the gas was taken as 2 cm²/s and its density (ρ_1) as one fifth of that of air at N.T.P. The relation between C and Reynolds Number was obtained from Perry⁽⁹⁾, as was $\rho_2 = 3.7 \text{ g/cm}^3$. To be effective in quenching flame the inert dust must act very near to the flame front, and hence s is likely to be of order 1 cm or less. Here, $s = 1 \text{ cm}$ was taken.

Table 3 shows values of f_1/f_2 and C for various values of d .

Table 3
Values of f_1/f_2 from equation (2)

d (cm)	C	f_1/f_2
10^{-3}	130	5
2×10^{-3}	60	1
4×10^{-3}	35	0.3
6×10^{-3}	25	0.1
10^{-2}	15	0.05

The values of f_1/f_2 in Table 3 were calculated on the assumption that there were no interacting forces between the particles i.e. that Stokes Law applied. This assumption is not strictly correct. Another uncertainty was the extent to which the dust was dispersed by the feed mechanism at the top of the tube; the particles could descend in clusters rather than as individuals. Both these effects would have increased the velocity of fall of the particles which were assumed to behave kinematically as if of increased diameter. From Fig. 8 the mean velocity of fall of the dust particles in air was in the range 60-150 cm/s

and would have corresponded to diameters of 10^{-2} to 2×10^{-2} cm for individual particles of density 3 g/cm^3 falling in still air⁽⁹⁾, according to Stokes Law. The value of f_1/f_2 for an effective particle diameter of 10^{-2} cm is small (Table 3), i.e. the acceleration due to drag is small compared with that required to disperse the inert dust. The conclusion was therefore drawn that the inert dust particles were not dispersed as the resin particles vaporised, burned, and expanded. The concentration of inert dust in the flame front was taken as equal to that ahead of the flame.

Supporting evidence has been reported for cork dust flames⁽⁴⁾. From photographs of the flames, in which the movement of individual incandescent particles was measured, it was concluded that dust particles in the "nose" of the flame were nearly stationary whereas those more deeply within the flame were rapidly accelerated. There was in fact evidence that particles were decelerated as they entered the flame, before being rapidly accelerated towards the rear of the flame. The thickness of the zone within which the particles were moving slowly appeared to be about 2 cm in a tube of diameter 7.6 cm. In this zone the particles were incandescent but their concentration had not been diminished by expansion of the gas.

The proposed mechanism of flame propagation in the dust suspension can now be enlarged upon as follows. The fuel on vaporisation become ignited and burned with a diffusion flame, i.e. it mixed with air and burned simultaneously. Considering firstly a stoichiometric resin-air mixture with inert dust, each particle of fuel was associated with a volume of cold air just sufficient for complete combustion of the fuel. During combustion hot products would be generated of greater volume than the oxygen that was consumed and, as the system was at constant pressure, gases would move to the rear of the flame. As it is unlikely that the exhausted gases would be combustion products only, some air would probably also be involved. To maintain the oxygen balance, either fuel would need to accompany the air or there would need to be some unburnt fuel behind the flame front remaining from a previous removal of air. The presence of free oxygen and unburnt fuel within the flame was shown in the experiments (Fig. 9 and 10). On completion of combustion the volume originally occupied by cold air would be filled with hot combustion products. For a stoichiometric mixture the diameter of this volume of products is of the same order as the original distance between the fuel particles, which is proportional to the particle diameter. Hence the transfer of heat to neighbouring fuel, which is necessary for flame propagation, would be able to occur. As the inert dust is believed not to accompany movement of fuel vapour and combustion products, at least in the front of the flame zone, it follows that to prevent flame propagation the heat to be absorbed by the inert dust at its initial concentration would be obtained from a volume of hot products equal to that of the air initially associated with the fuel. The conditions in the front of the flame zone, particularly with concentration of inert dust, would determine whether flame would propagate further or would be extinguished.

For dust concentrations between stoichiometric and the lower explosible limit a similar mechanism would apply, but the distance between fuel particles would be greater. Ultimately, the ignition of neighbouring particles would be unable to occur. Between stoichiometric and the upper limit excess fuel vapour would be present, and would restrict the temperature rise on combustion, but otherwise the situation would be similar to that for stoichiometric mixtures.

If the inert dust acted solely as a thermal sink, two cases have to be considered. Firstly, when the fuel concentration was between the lower flammable limit and stoichiometric, only the inert dust acted as a thermal sink. Secondly, when the fuel concentration was between stoichiometric and the upper flammable limit, the surplus fuel also acted as a thermal sink. The increase in gas volume on volatilisation of the resin was neglected.

$$(i) \quad x_2 > x > x_1$$

where x is resin concentration (mass/unit volume)

x_1 is concentration at lower flammability limit

x_2 is stoichiometric concentration

Heat absorbed by inert dust in attaining limit flame temperature = $y c_2 (T_1 - T_0)$

where y is concentration of inert dust (mass/unit volume)

c_2 is mean specific heat of inert dust

T_1 is flame temperature at lower (or upper) flammability limit

T_0 is ambient temperature

Heat to be absorbed in attaining limiting temperature = $\frac{H}{r} (x - x_1)$

where H is heat of combustion/unit mass of resin dust

r is mean expansion ratio on combustion

For flame quenching $yc_2 (T_1 - T_0) = \frac{H}{r} (x - x_1)$

$$y = \frac{H (x - x_1)}{rc_2 (T_1 - T_0)} \quad \dots\dots (3)$$

At the peak value

$$y = \frac{H (x_2 - x_1)}{rc_2 (T_1 - T_0)} \quad \dots\dots (4)$$

$$(ii) \quad x_3 > x > x_2$$

where x_3 is resin concentration at upper flammability limit.

Heat to be absorbed = $\frac{H}{r} (x_2 - x_1)$

Heat absorbed by inert dust = $yc_2 (T_1 - T_0)$

Heat absorbed by fuel vapour = $\frac{c_1}{r} (x - x_2) (T_1 - T_0)$

where c_1 is mean specific heat of resin vapour, and neglecting heat of vaporisation.

For flame quenching,

$$yc_2 (T_1 - T_0) + \frac{c_1}{r} (x - x_2) (T_1 - T_0) = \frac{H}{r} (x_2 - x_1)$$

$$y = \frac{H (x_2 - x_1)}{rc_2 (T_1 - T_0)} - \frac{c_1}{rc_2} (x - x_2) \quad \dots\dots (5)$$

When $x = x_2$, Equation (5) reduces to Equation (4).

Application of equations

Numerical values for the quantities in Equation (3) - (5) have been calculated as follows.

The chemical composition of the phenol formaldehyde resin was not known precisely, but was assumed to be akin to that of phenol (C_6H_6O) or cresol (C_7H_8O). For either of these compounds the stoichiometric mixture in air (x_2) is 0.12 g/l. The heats of combustion were 7790 and 8150 cal/g respectively⁽¹⁰⁾; a mean value for H of 8000 cal/g was taken.

The lower flammability limit (x_1) had been determined experimentally and was 0.045 g/l. Hence by enthalpy calculation⁽¹¹⁾

$$T_1 = 1370^\circ K \text{ when } T_0 = 300^\circ K.$$

The mean specific heats of phenol formaldehyde resin and magnesium oxide, C_1 and C_2 , were taken as 0.35 and 0.28 cal/g/°K respectively⁽¹²⁾.

The mean expansion ratio (r) was calculated from $T_1/T_0 (= 4.6)$ and from experimental determinations of the maximum explosion pressure. The maximum pressure occurred with a resin-air mixture considerably richer than stoichiometric and the effect of the surplus resin on the maximum pressure could not be estimated readily by theoretical means. From Table 1, the maximum absolute pressure measured was 128 lb/in² (= 107 + 6.5 + 14.7). The air used for the dispersion of the dust entered the pressure vessel before the explosion occurred. Hence the initial absolute pressure within the vessel was 21 lb/in² (= 14.7 + 6.5), and the expansion was 128/21 or 6.1. The mean expansion ratio was therefore (6.1 + 4.6)/2.

$$\text{i.e. } r = 5.4$$

With the above numerical values, Equations (3) and (5) for the lean and rich side of stoichiometric respectively become:

$$y = 4.9 (x - 0.045) \quad \dots\dots (6)$$

$$y = 0.37 - 0.23 (x - 0.12) \quad \dots\dots (7)$$

The minimum amount of inert dust required to make a non-explosible dust mixture is given by Equation (4):

$$y = 0.37 \text{ g/l}$$

The percentage of inert in the mixture = $\frac{0.37 \times 100}{(0.37 + 0.12)} = 76 \text{ per cent}$, at a total dust concentration of 0.49 g/l.

The results represented in Fig. 3-5 were plotted with $100y/(x + y)$ as ordinate and $(x + y)$ as abscissa for experimental convenience. Lines derived from Equations (6) and (7) are included in Fig. 3-5.

Comparison of equations with results

The tube arrangement in which explosions most readily occurred was that in which flame propagated upwards from the closed end (Fig. 5). Comparison of the equations derived above has been made with Fig. 5, which represented the worst conditions.

The results in Fig. 5 were not corrected for the increase in concentration at the flame front due to the downward movement of the dust particles. Consequently the experimental points and lines should be shifted to the right to obtain a true comparison with the lines calculated from Equations (6) and (7). The increase in the dust concentration can be gauged from Table 2 and Fig. 8, and was about 50 per cent. Equations (6) and (7) thus underestimated the lower and upper flammability limits of resin/magnesium oxide mixtures, particularly at higher dust concentrations (Fig. 5). However, the resin in the dust suspensions was not completely burnt (Fig. 9), and the percentage that was burnt decreased as the dust concentration increased. At high concentrations less than 50 per cent of the resin was burnt. This factor reduces the extent to which Equations (6) and (7) underestimated the flammability limits.

The proportion of magnesium oxide needed in the dust mixture to prevent explosion was calculated as 76 per cent, and was in excellent agreement with the experimental results (75 - 80 per cent). As it is this proportion of magnesium oxide which determined whether or not the mixture would propagate flame in the apparatus, it is of considerable importance in relation to the Classification procedure (see below). The composition of the dust mixtures could be accurately controlled in advance, whereas the concentration of a suspension was subject to wider variations, so the good agreement with experiment gave increased support to the theory. Additional experiments are in hand with dusts of different thermal characteristics to test the theory further. A corollary of the theory is that if an inert gas were used instead of an inert dust, the gas would disperse as the resin burned, and hence for materials of the same mean specific heat a greater mass of inert gas than of inert solid would be required.

The importance of the type of ignition source would not be expected on theoretical grounds to be great, provided that enough energy was released to produce localised burning. This expectation agrees with the results given in the Appendix, where both thermal and electrical igniters were investigated. Insufficient results had been obtained for a clear and consistent picture of the flammability limits in a narrow tube (Fig. 11 and 12) but there were indications that the lower flammability limits were greater than in the larger scale tube. A detailed comparison could not be made.

Comparison between results and Classification

Explosions with flame propagation over at least a fraction of the tube length were obtained with dust mixtures containing 75 per cent or less of magnesium oxide. Mixtures containing 80 per cent, or more, did not propagate flame. Tests in the small-scale apparatus, the results of which were given in Table 1, showed that the Hartmann apparatus with spark ignition also yielded

flames with mixtures containing up to 75 per cent magnesium oxide. The Modified Hartmann apparatus yielded flames with the 80 per cent mixture, whereas the Horizontal tube and the Inflamator only yielded flames with mixtures containing up to 55 and 70 per cent magnesium oxide respectively. On the basis of these results, dusts that were marginally Class I, in the sense that flame was obtained in only some of the small-scale tests, should be regarded as explosible. Possible exceptions are dusts that give flame only in the Modified Hartmann apparatus, but the extent to which this apparatus overestimated the explosion hazard cannot be found exactly from the present results.

Marginally explosible dust mixtures had a narrower range of flammable concentrations than more vigorous mixtures (Fig. 3-5), and the maximum explosion pressures and rates of pressure rise were also lower (Table 1). Thus the likelihood of a severe explosion occurring with a marginal dust would be considerably less than with a dust which exploded in each of the small-scale tests. The present system of Classification does not permit sub-division of Class I dusts according to their explosibility.

No explosions were obtained in the large-scale apparatus with Class II mixtures. These mixtures contained more than 80 per cent of magnesium oxide (Table 1), and were well separated from the explosible composition regions in Fig. 3-5. In addition the magnesium oxide content was above the theoretical maximum for flame propagation in air (76 per cent). In this scale of ducting Class II dusts would not be expected to propagate explosion away from the influence of the ignition source in air at atmospheric temperature.

Further indication of the behaviour of Class II dusts may be obtained from Equation (4). The dust is dispersed into heated air in the Furnace apparatus, but the quantities H , c_2 , and T_1 would be approximately independent of the air temperature (T_0). As T_0 is increased, both $(x_2 - x_1)$ and r will decrease, approximately proportionately. The quantity $(T_1 - T_0)$ will decrease substantially as T_0 is increased over the range used in practice, and hence y will also increase substantially. The proportion of magnesium oxide required to prevent explosion will be noticeably greater with elevated air temperatures, and there will thus be a range of dust mixtures in Class II. These mixtures would not be able to sustain flame propagation in air at atmospheric temperature. The Furnace apparatus may be operated at temperatures up to 1000°C, but the air which carries the dust into the Furnace is cold. The air temperature in the Furnace apparatus during a test would therefore depend upon the initial pressure in the reservoir, the rate of release, the effectiveness of mixing, and the dimensions of the Furnace. As a result the performance of the dust in the Furnace depends substantially upon the design and operation of the apparatus. Hence the division between Class II and Class III dusts is arbitrary, whereas that between Class I and Class II is fundamental.

Conclusions

1. Most marginally explosible dust mixtures that could be ignited by a small source of ignition in the small-scale test apparatus would propagate explosion on a larger scale.
2. Dust mixtures that required a relatively large source of ignition in small-scale tests did not propagate explosion on a larger scale.

3. Marginally explosible dusts have a comparatively narrow range of flammable concentrations, and generate only moderate explosion pressures. Marginal dusts are thus relatively unlikely to cause severe explosions.
4. The calculated minimum amount of inert dust required to prevent explosible mixtures agreed well with experiment on a large scale.
5. The explosible limits of dust mixtures were higher than the calculated values, after allowing for the velocity of fall of the dust particles, but an appreciable amount of the dust suspension remained unburnt.

Acknowledgments

Assistance in the experiments was received from T. M. Davies, C. A. Wright, Mrs. S. A. Morris, D. K. Freeman, A. J. Kelly, J. F. Card, and in the design of the apparatus from P. G. Quinton.

The results in Table 1 were obtained by Miss M. M. Raftery and Mrs. J. S. Harris.

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APPENDIX I

At the beginning of the investigation into the behaviour of dust mixtures in apparatus of dimensions greater than bench size some experiments were carried out by personnel at the Ministry of Power, Safety in Mines Research Establishment, Harpur Hill, Buxton, Derbyshire.

The vertical explosion tube was 3.4 m long and 7.6 cm internal diameter, and the dust clouds were formed with various mixtures of phenolformaldehyde resin and magnesium oxide.

Dust delivery into the top of the explosion tube was effected by a commercial type feeder working in conjunction with a vibrating sieve. Various aids to dust dispersion into the tube from the sieve were used and the dust was allowed to fall through the air in the explosion tube, under gravity.

Four types of igniting source were used in the experiments as follows:-

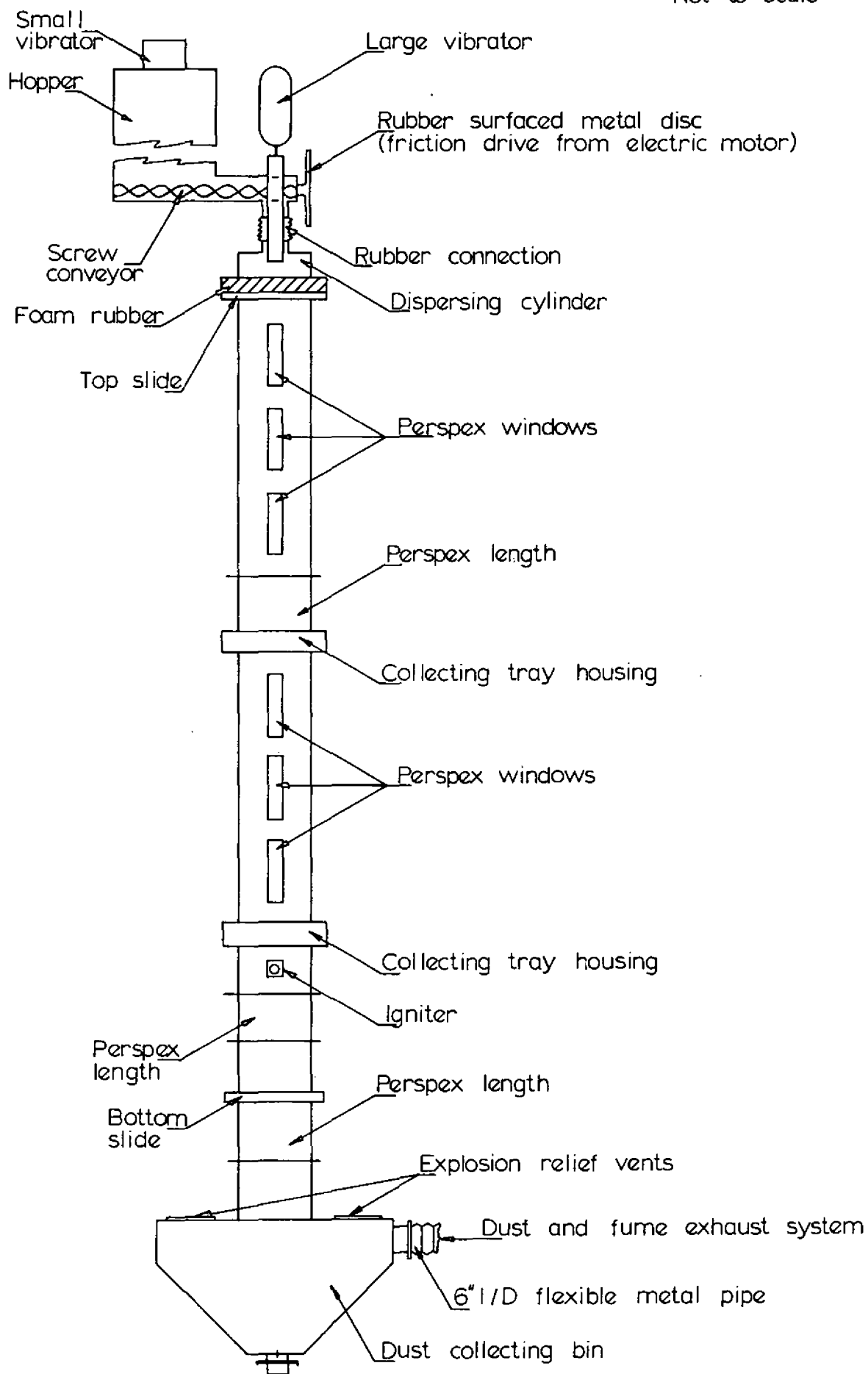
- (1) methane flame
- (2) carbon arc
- (3) furnace which ignited small quantity of dust as the latter was blown through it into the falling dust cloud in the explosion tube.
- (4) electrically heated coil of chromium, aluminium and iron alloy wire (20 s.w.g.).

Ignition took place near the bottom of the explosion tube which was either closed or open thus allowing flame propagation either from a closed end to an open end of the tube or from an open end to a closed end of the tube.

Five mixtures of phenolformaldehyde resin and magnesium oxide were used; they contained the following percentages of resin by weight: 30, 32.5, 50, 60 and 75. In some experiments the dust clouds were of resin only.

The results are shown in Figs. 11 and 12 and are plotted irrespective of the igniter used. None of the igniters was noticeably more effective than others in causing ignitions.

Not to scale



1/6298 F.R. 605

FIG. 1. VERTICAL EXPLOSION TUBE APPARATUS

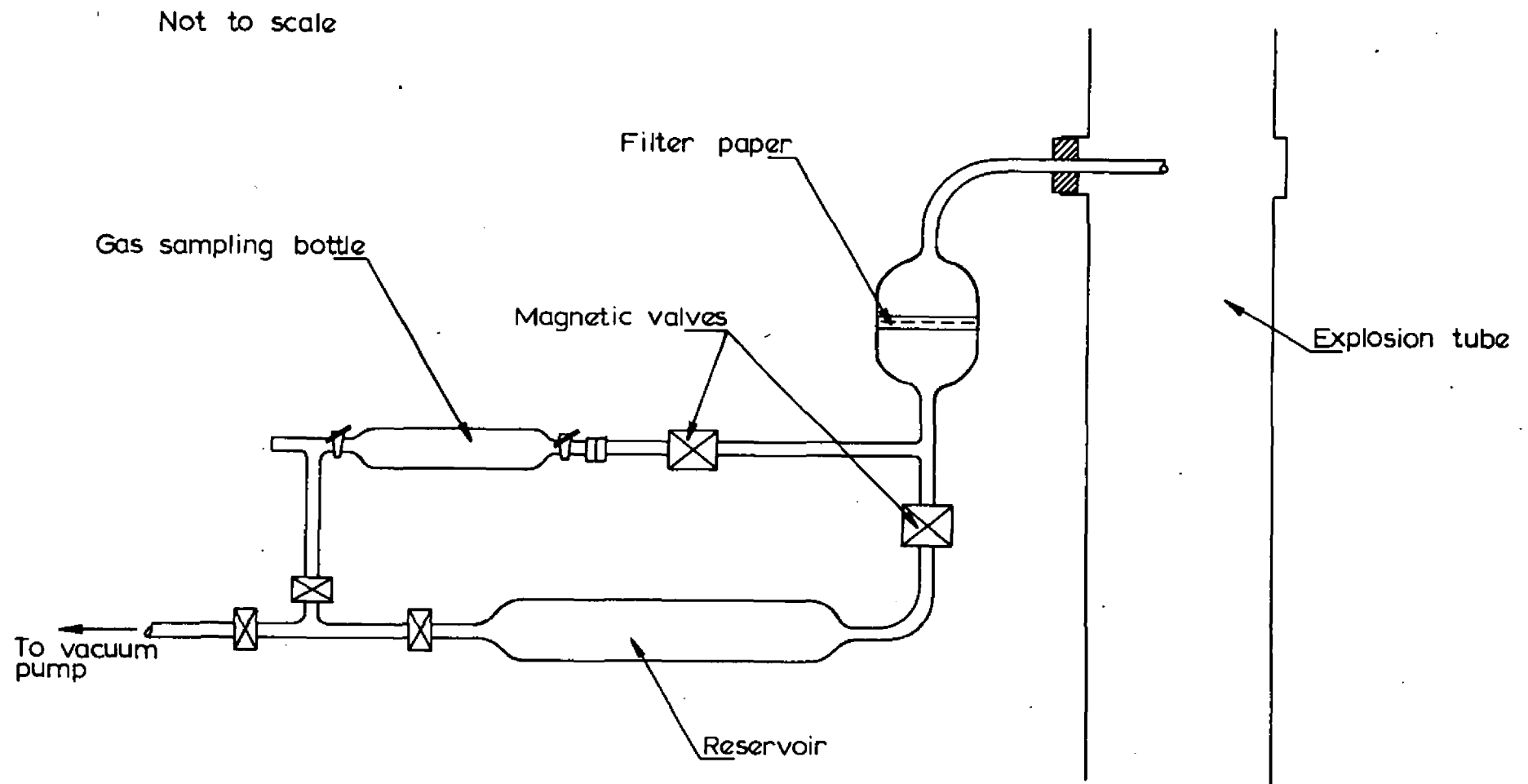


FIG. 2. DUST AND GAS SAMPLING APPARATUS

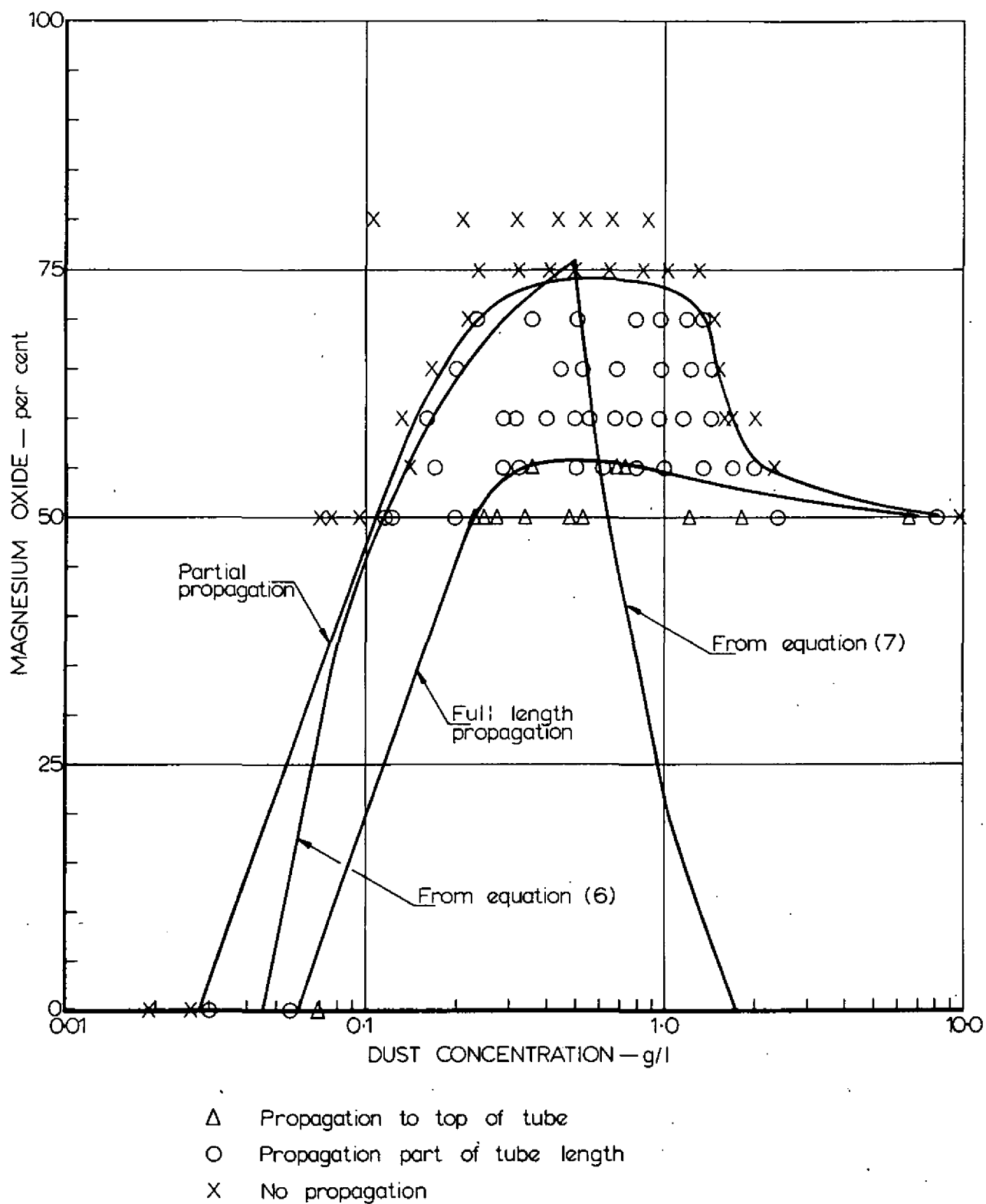
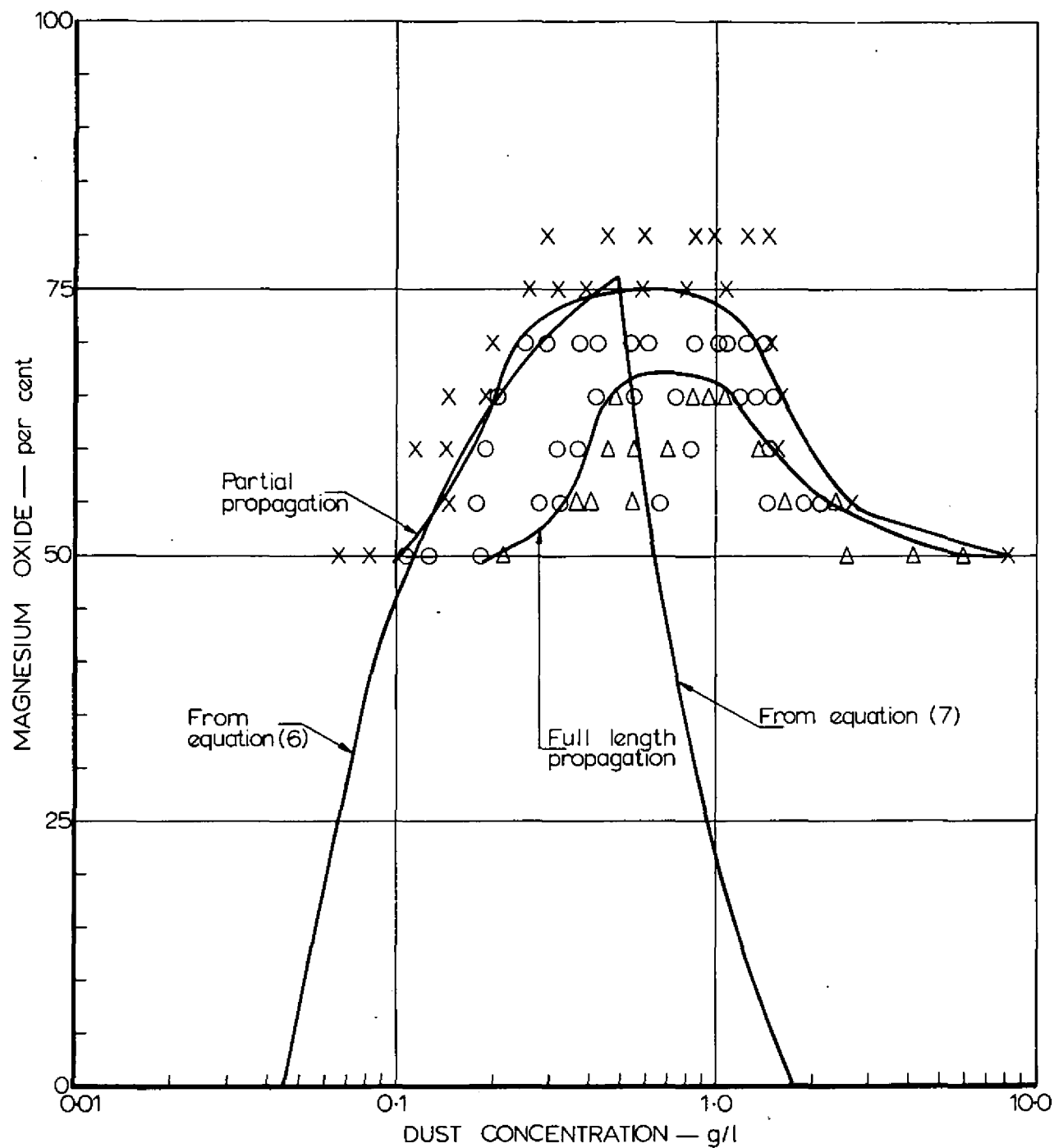
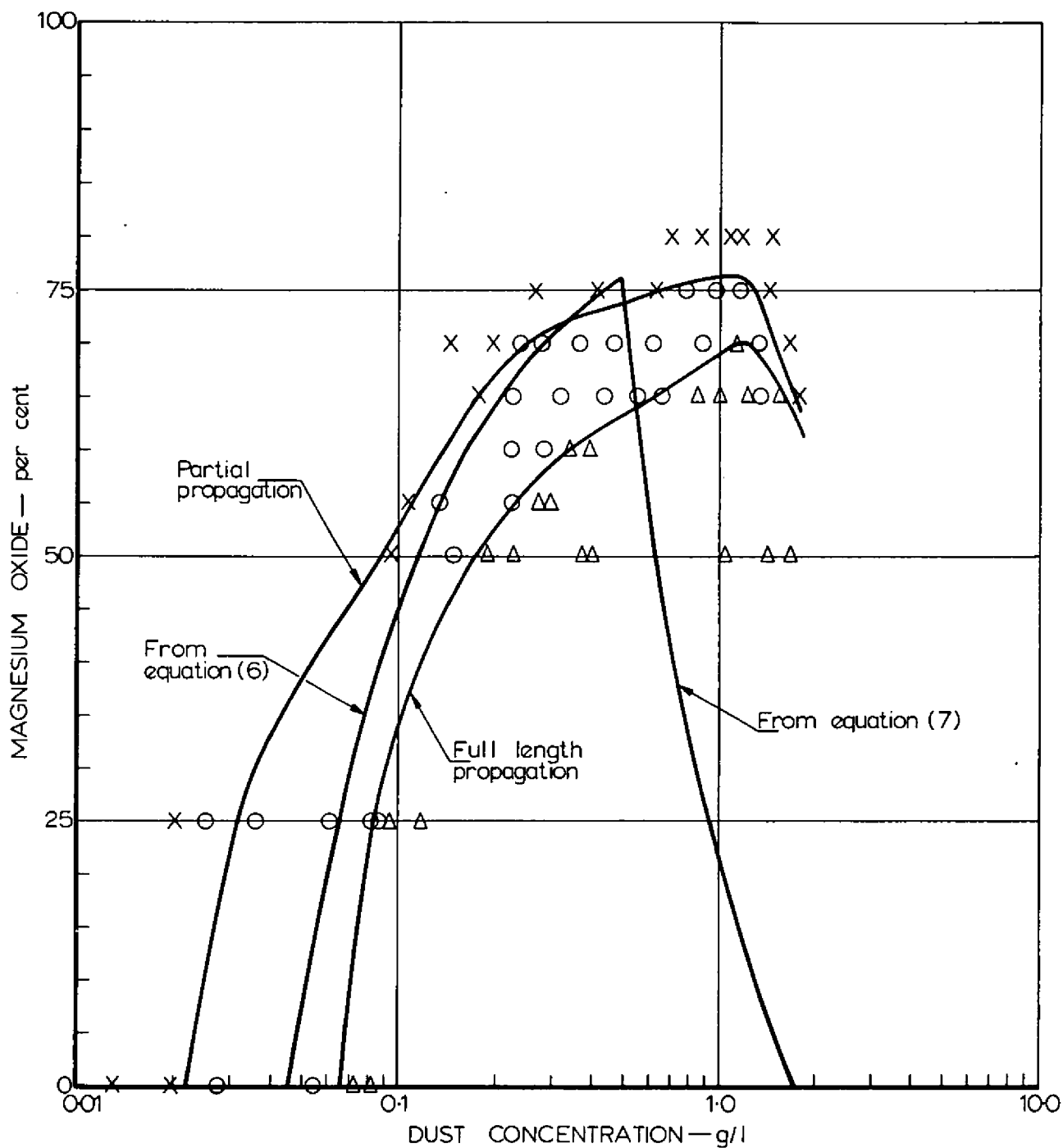


FIG. 3. FLAMMABILITY LIMITS OF RESIN-MAGNESIUM OXIDE MIXTURES (TOP OF TUBE CLOSED, BOTTOM OPEN, IGNITER 3.7m FROM THE TOP OF THE TUBE)



- Δ Propagation to bottom of tube
- O Propagation part of tube length
- X No propagation

FIG. 4. FLAMMABILITY LIMITS OF RESIN-MAGNESIUM OXIDE MIXTURES (TOP OF TUBE CLOSED, BOTTOM OPEN, IGNITER 1.7m FROM THE TOP OF THE TUBE)



- Δ Propagation to top of tube
- O Propagation part of tube length
- X No propagation

FIG. 5. FLAMMABILITY LIMITS OF RESIN-MAGNESIUM OXIDE MIXTURES (TOP OF TUBE OPEN, BOTTOM CLOSED, IGNITER 3.7 m FROM THE TOP OF THE TUBE)

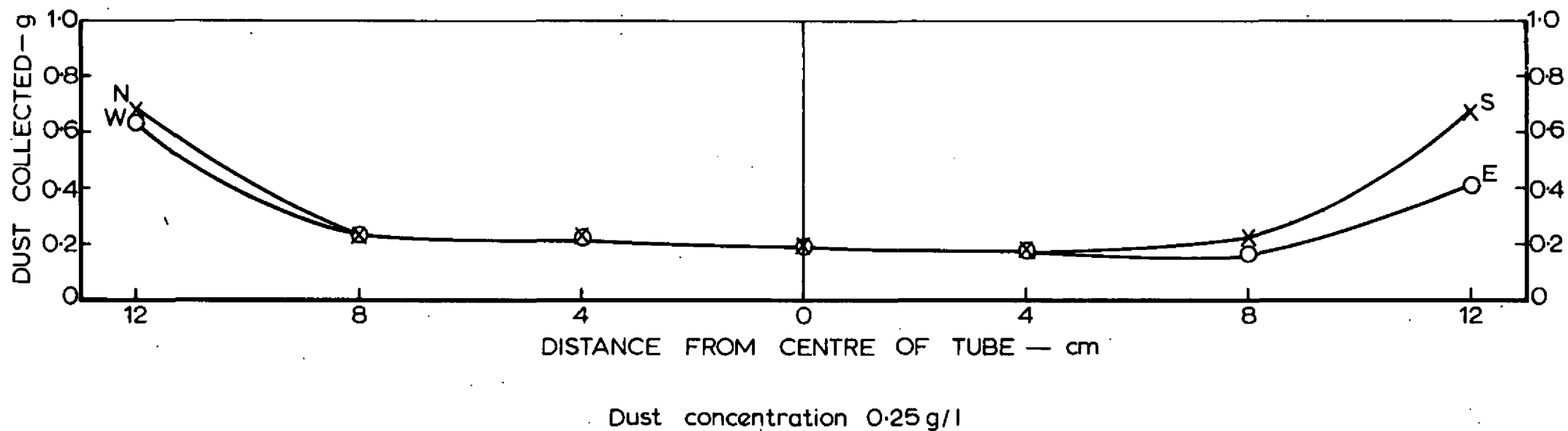


FIG. 6. DUST DISTRIBUTION IN EXPLOSION TUBE ALONG TWO DIAMETERS AT RIGHT ANGLES—TUBE CLOSED AT TOP, OPEN AT BOTTOM

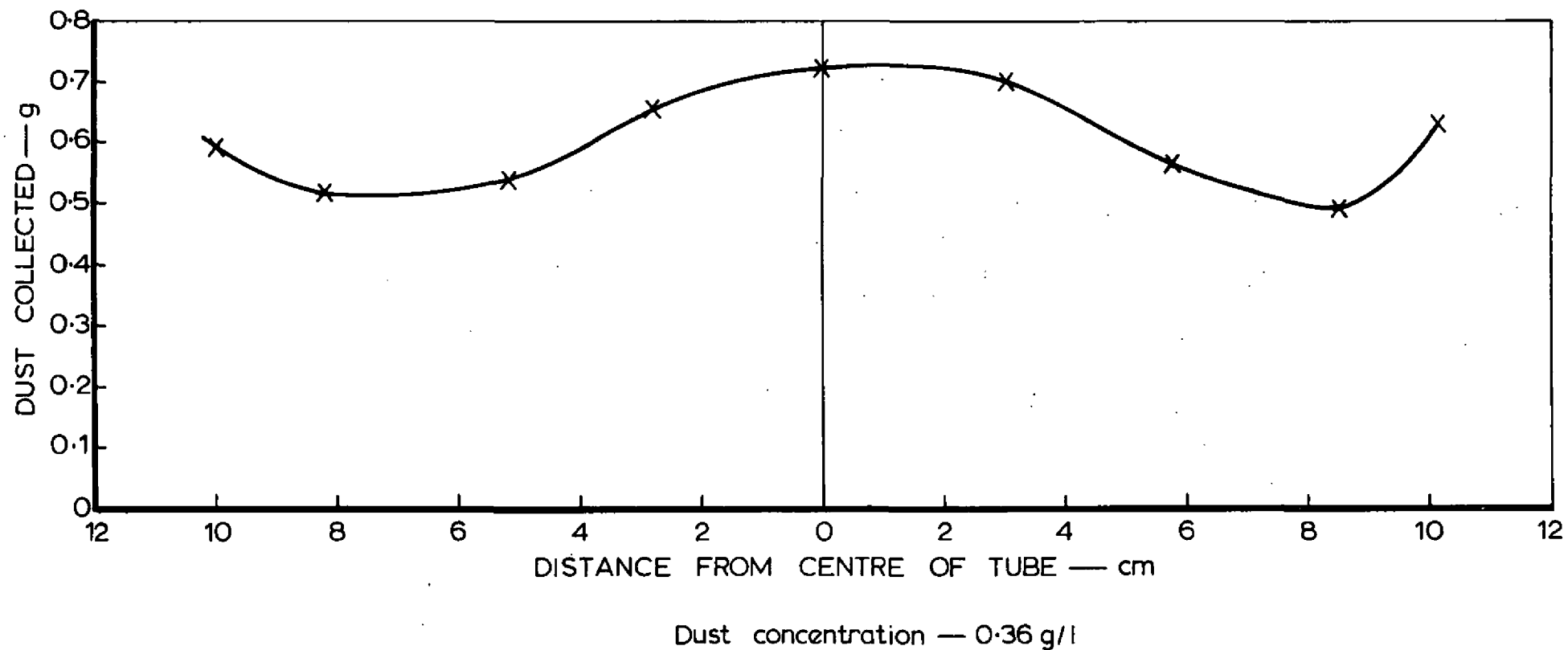


FIG. 7. DUST DISTRIBUTION IN EXPLOSION TUBE ALONG A DIAMETER —
TUBE OPEN AT TOP, CLOSED AT BOTTOM

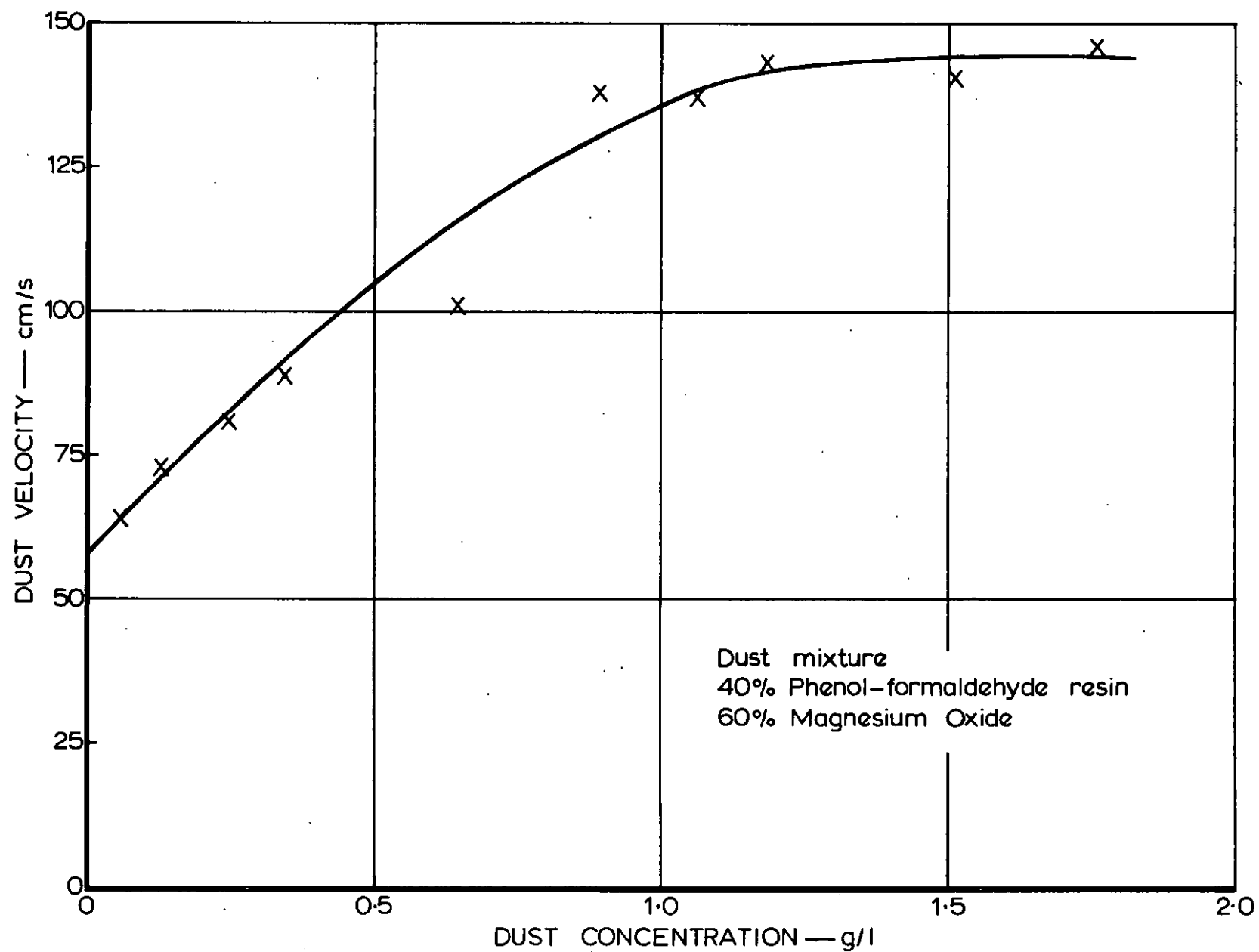


FIG. 8. VARIATION OF MEAN VELOCITY OF FALL OF DUST WITH CONCENTRATION

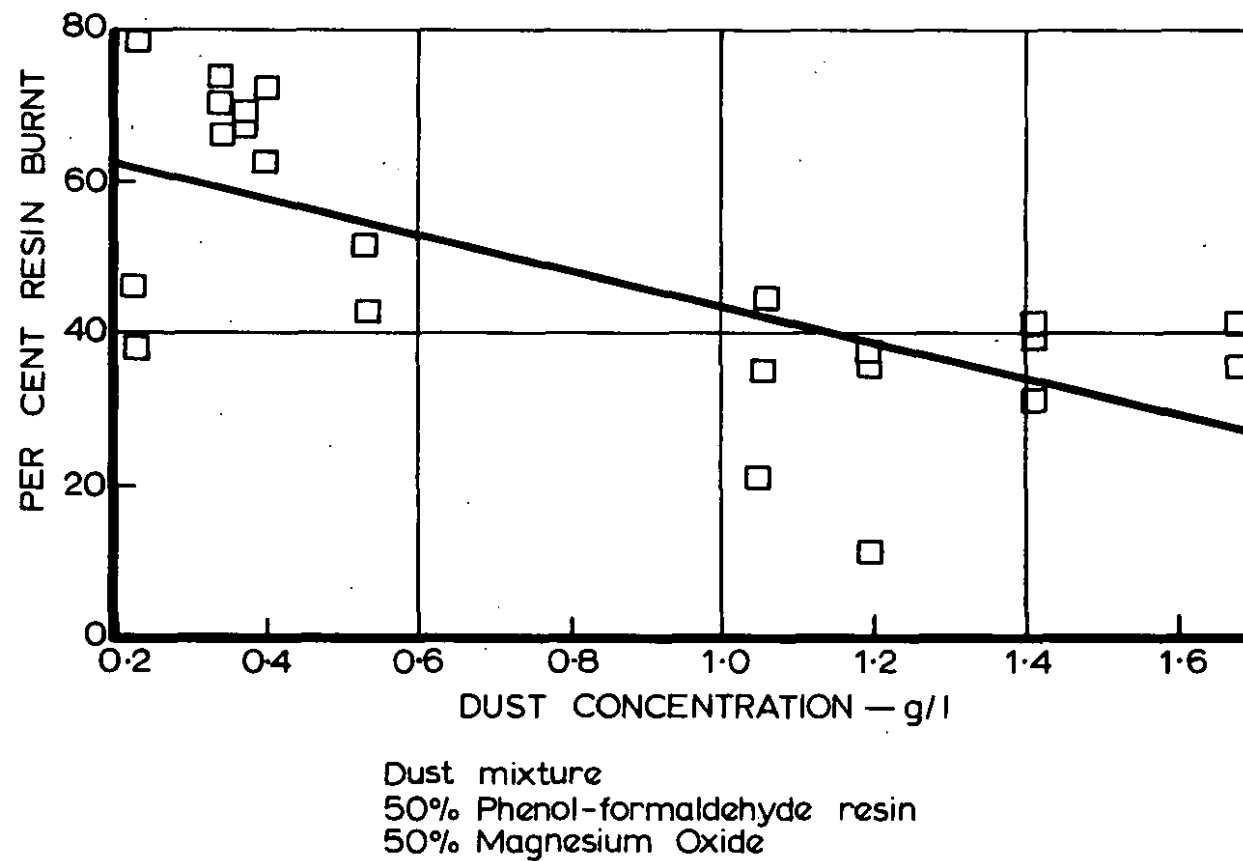
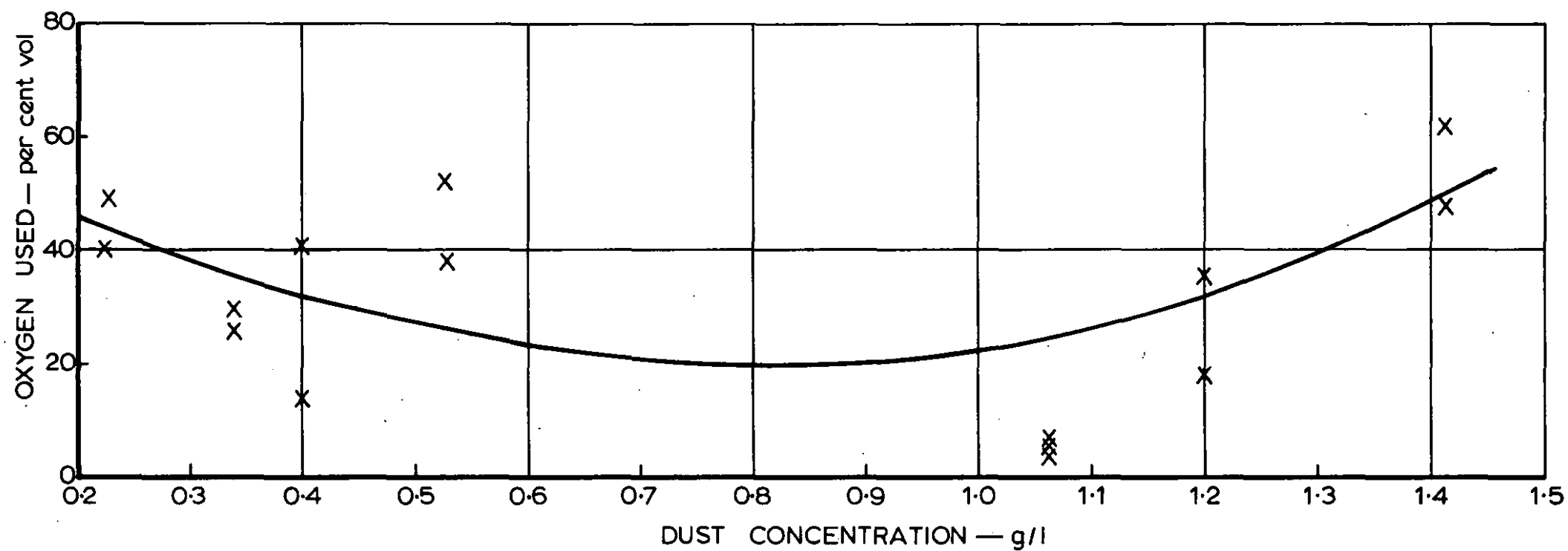
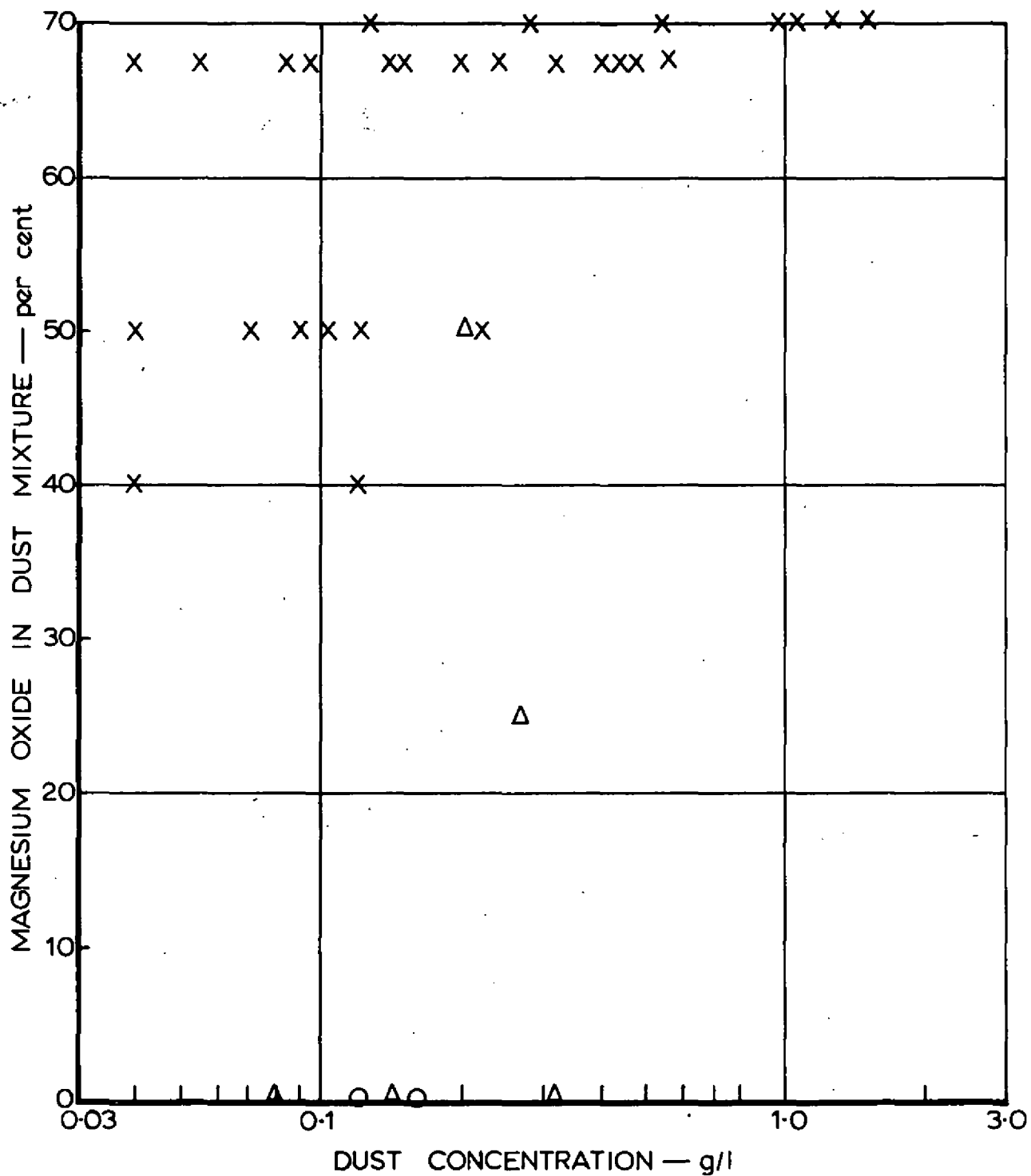


FIG. 9. PHENOL-FORMALDEHYDE RESIN BURNT WITH CHANGE IN DUST CONCENTRATION IN THE EXPLOSION TUBE



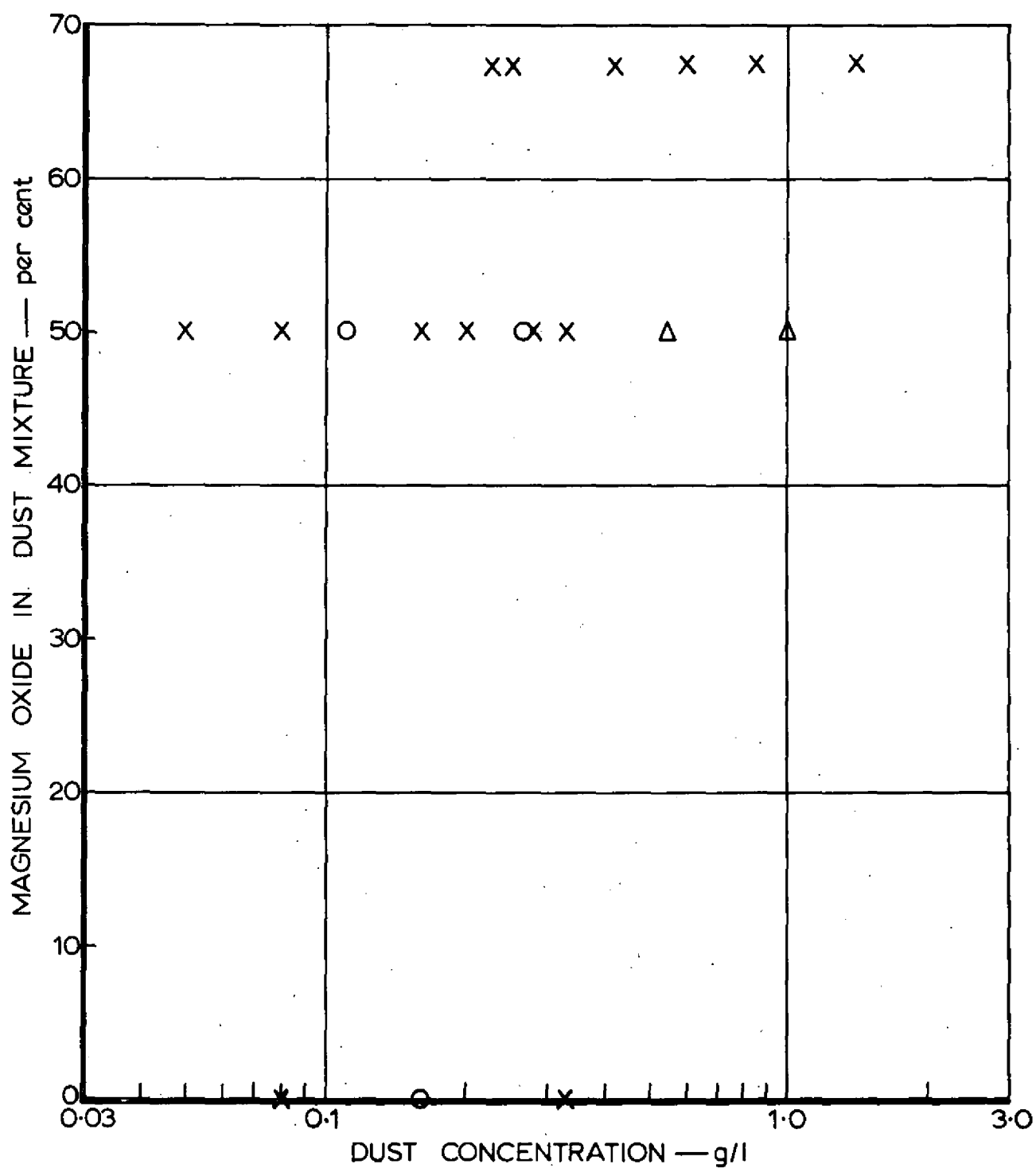
Dust mixture : 50% Phenol-formaldehyde resin 50% Magnesium Oxide

FIG. 10. OXYGEN USED BY FLAMES PROPAGATING IN VARIOUS DUST CONCENTRATIONS



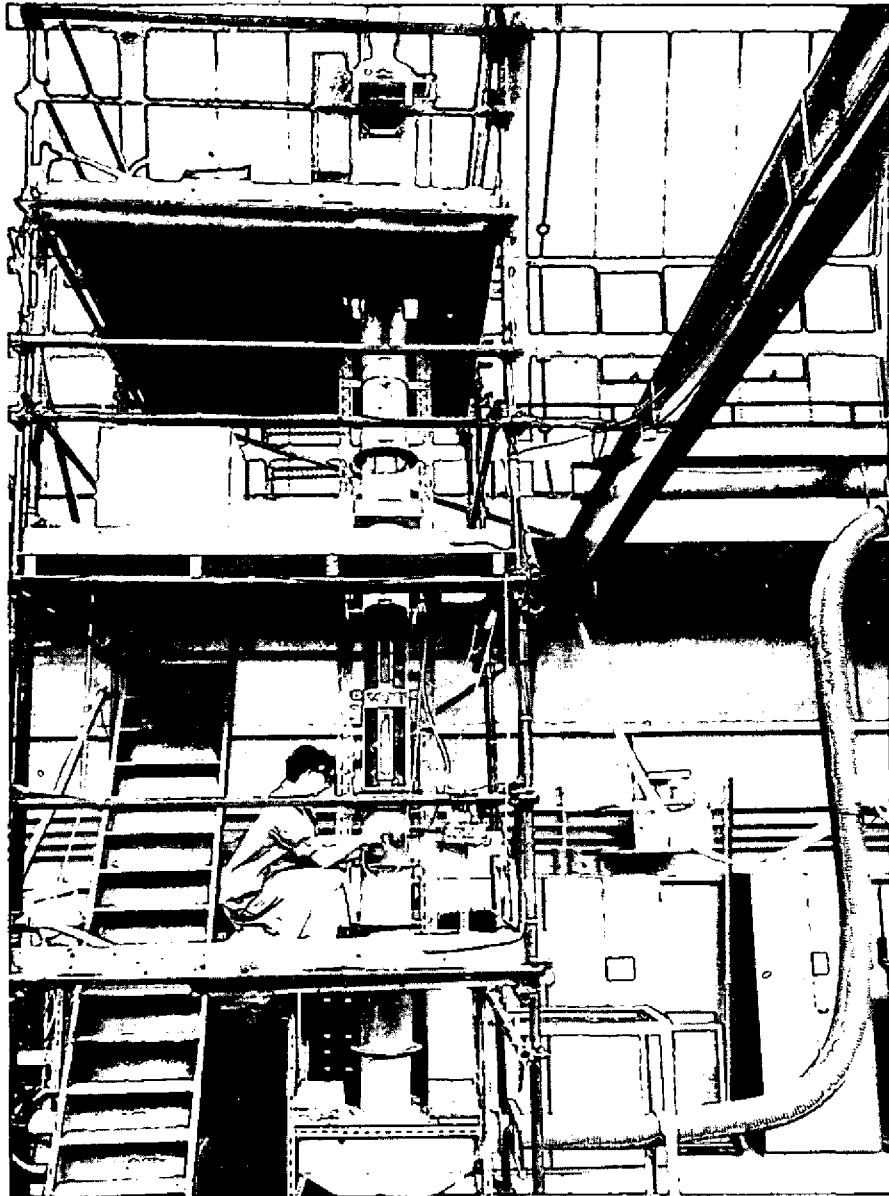
- Δ Propagation full tube length
- O Propagation part tube length
- X No propagation

FIG. 11. RESULTS FROM S.M.R.E. BUXTON (APPENDIX I)
IGNITION NEAR CLOSED END OF THE TUBE



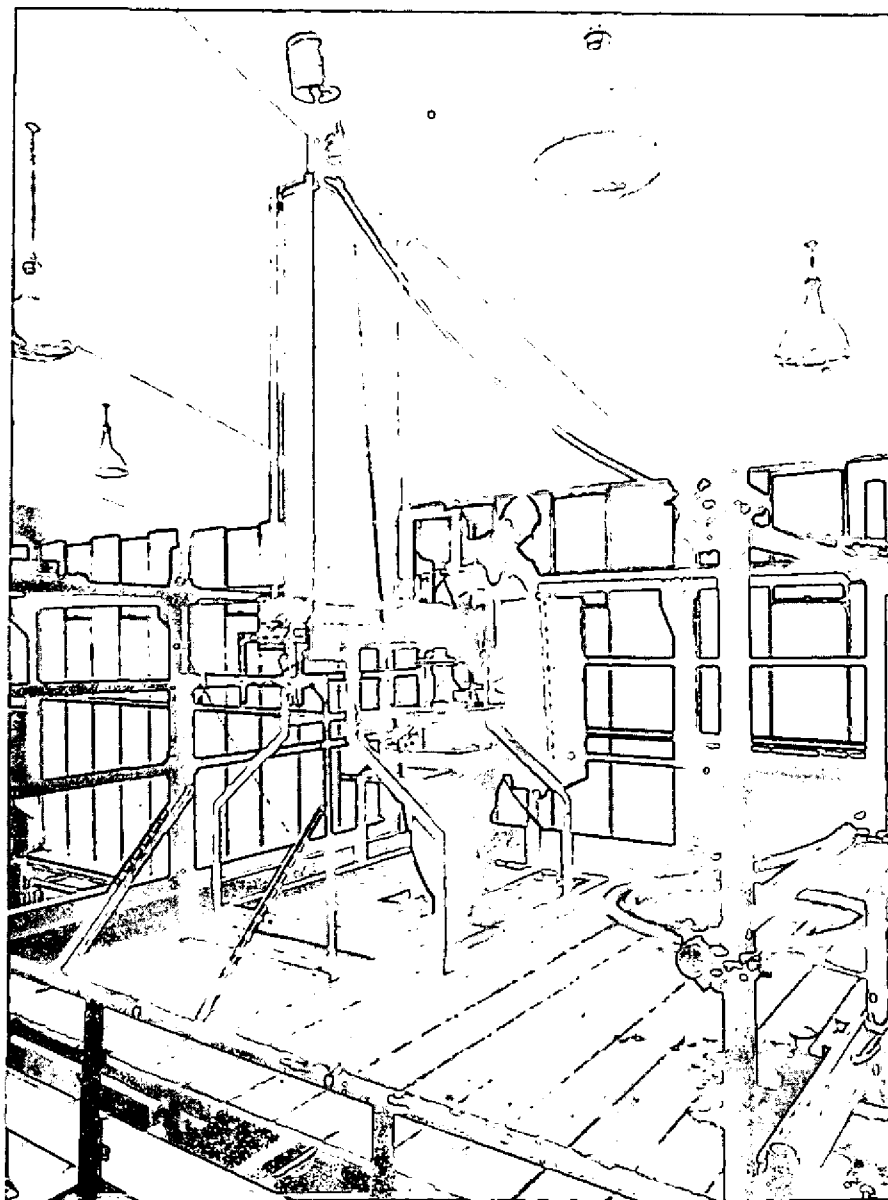
- Δ Propagation full tube length
- O Propagation part tube length
- X No propagation

FIG.12. RESULTS FROM S.M.R.E. BUXTON (APPENDIX I)
IGNITION NEAR OPEN END OF THE TUBE



GENERAL VIEW OF VERTICAL TUBE
APPARATUS

PLATE 1



DUST FEED TO VERTICAL TUBE
APPARATUS

PLATE 2

