

THE EXPLOSIBILITY OF DUSTS IN SMALL-SCALE TESTS AND LARGE-SCALE INDUSTRIAL PLANT

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SYNOPSIS

The established small-scale tests for determining the explosibility of combustible dust clouds in air are briefly described. The extent to which dusts that are marginally explosible in the tests are able to propagate explosion in large-scale equipment has been investigated with dust mixtures of graded explosibility and with individual industrial dusts. From the behaviour of the dusts in large-scale equipment a reappraisal has been made of the existing Classification of dusts for explosibility.

The dust mixtures used were composed of a readily explosible and an inert material. Calculation of the minimum percentage of inert dust required to prevent propagation of flame in the explosible dust was in good agreement with the experimental findings.

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 as well as 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.

Up to the present the dusts have been classified according to explosibility by means of routine small-scale tests which have increased in number over the years. A considerable store of results and experience has accumulated and to obtain continuity the test apparatus and procedures have changed relatively little once they became established. 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 apparatus² is as follows:

(a). HORIZONTAL TUBE: in which the dust is dispersed over a wire coil igniter situated part way along the tube.

(b). INFLAMMATOR: a vertical tube down which the dust falls over a coil igniter near the bottom.

(c). VERTICAL TUBE: (Hartmann apparatus), in which the dust is dispersed upwards from the bottom of the tube over an electric spark igniter.

(d). MODIFIED VERTICAL TUBE: as (c) above but with electric coil igniter.

(e). FURNACE APPARATUS: an electrically-heated tube through which dust is blown from the top.

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

From their performance in the tests the dusts have been classified¹ as follows:

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 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 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.

At the request of H.M. Factory Inspectorate experiments have 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. The tube was about 25 cm in diameter and 5.2 m long, being an apparatus on the scale of industrial plant. There was no flow of air through the tube. The vertical tube method has been used previously,³⁻⁶ but the work was not concerned directly with examining the explosibility of the dusts or with the effects of increased scale.

In the present work the dusts used were either mixtures of a Class I and a Class III dust, which gave controlled variation of explosibility, or were a number of single industrial dusts. The behaviour of dusts which were in Class II or marginally in Class I could then be studied in the large-scale apparatus and compared with the behaviour in small-scale tests.

Experimental

Materials

The dust mixtures were made from phenol-formaldehyde resin (Class I) and from magnesium oxide (Class III). The resin was an industrial moulding powder of mean particle diameter 15 μ and its moisture content was 4.1%. The ash

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TABLE I.—Sizing Analyses and Moisture Content of the Industrial Dusts

Dust	Moisture content (%)	Per cent weight			
		—60+72 mesh	—72+120 mesh	—120+240 mesh	—240 mesh
Methyl cellulose	7.5	8.0	20.8	21.8	49.4
Manioc	14.1	29.0	43.6	25.4	2.0
Sodium carboxy methyl cellulose	11.2	18.1	22.2	12.9	46.8
Processed starch*	11.3	11.3	27.2	23.7	37.8
Polyvinylidene chloride	4.5	24.6	28.6	27.4	19.4
Calcium citrate	11.2	15.4	46.8	24.8	13.0

* A product derived from the processing of the normal carbohydrate.

content was determined in a muffle furnace at 800°C and was 3.2%. The magnesium oxide was an industrial powder of mean particle diameter 11 μ and its moisture content was 2.2%. The two dusts were mixed in a rotating drum and the mixing was checked by sampling and ashing in a muffle furnace.

The industrial dusts were commercial grades as marketed by manufacturers, and were sieved through a B.S.60 mesh before use. The usual procedure of drying and sieving during classification of the dusts² was not used. Further details of the dusts are given in Table I.

Apparatus

The explosion tube consisted of flanged sections of ducting bolted together: 4.3 m of its length was of steel and a further 0.92 m consisted of three equal lengths of clear Perspex placed at convenient points in the tube for observation of the dust flames. The internal diameter of the tube was 25.4 cm. The general arrangement is shown in Fig. 1. The sliding trays

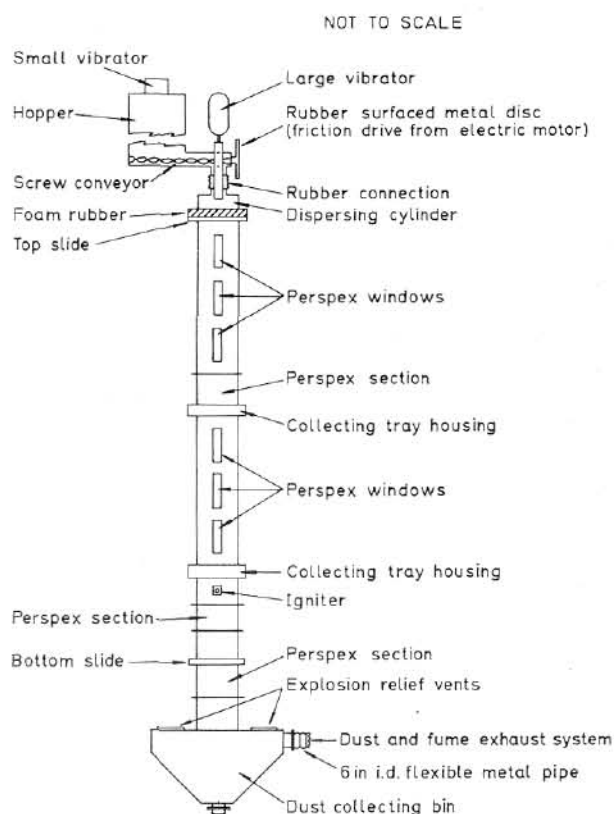


Fig. 1.—Vertical explosion tube apparatus

used to collect dust in determinations of concentrations and particle velocities were situated 1.8 m and 3.5 m from the top of the tube. Further slides were near the top and bottom of the tube.

The dust was fed uniformly from a hopper by a screw conveyor onto a perforated metal plate at the bottom of the dispersing cylinder (Fig. 1). The dispersing cylinder was vibrated and delivered the dust into the explosion tube. A general view of the dust feed apparatus is given in Fig. 2. For experiments with the top of the explosion tube closed the outlet from the screw conveyor was connected to the dispersing cylinder with flexible rubber hose; when the top of the tube was open and the bottom closed the flexible hose and the lid of the dispersing cylinder were removed and the dust and fume exhaust system was brought to the top of the tube.

The igniting source was a propane flame injected horizontally right across the explosion tube at a height 1.5 m from the bottom of the tube. Propane and air were released from reservoirs by solenoid valves and the gas mixture was ignited by an electric spark. No part of the ignition unit protruded into the explosion tube. In most experiments about 200 ml of propane, measured at N.T.P., were used; in a few experiments where the effect of the size of the igniting source was being investigated the volume of propane was increased to 350 ml.

Flame velocities were determined from films obtained with a cine camera whose speed could be varied up to 250 frames per second. The apparatus used for obtaining dust and gas samples from flames is shown in Fig. 3. By operating the magnetic valve on the reservoir first the system on the upstream side of the valve was purged of air and the gas sampling bottle could then be filled with undiluted gases from the explosion tube.

Procedure

The general procedure adopted was firstly to measure the dust concentration in the explosion tube and then carry out a series of three explosion tests. This was repeated at various dust concentrations until either a flammable range was obtained or it was established that the dust would not propagate flame in the large-scale tube. Dust concentrations were determined by collecting and weighing dust trapped in a known volume of the explosion tube and calculating the mass per unit volume. The concentration was checked during each series of tests and if the variation exceeded $\pm 5\%$ the series was rejected. After the initial measurement of dust concentration and when steady conditions were resumed the igniting flame was injected into the dust cloud. We then looked to see whether flame propagated in the cloud and if so the distance and direction of propagation were also recorded. For experiments in which the top of the tube was open and the bottom closed the procedure was similar except that the lowest slide was closed immediately before the igniting flame was applied.

The dust distribution along two diameters of the explosion tube was obtained by inserting small cylinders arranged in a right-angled cross in the dust suspension and weighing the contents of each cylinder. The dust concentration was also determined. The mean velocity of fall of the dusts in the explosion tube was calculated from the mean concentration and the weight of dust collected in a tray over a measured time.

To obtain information on the consumption of dust and oxygen in the flames some samples were taken immediately behind the flame front using the apparatus already described. The dust samples were ashed in a furnace at 500°C and the proportion of phenol-formaldehyde resin burnt in the explosion was calculated from the weight of the residue. The oxygen

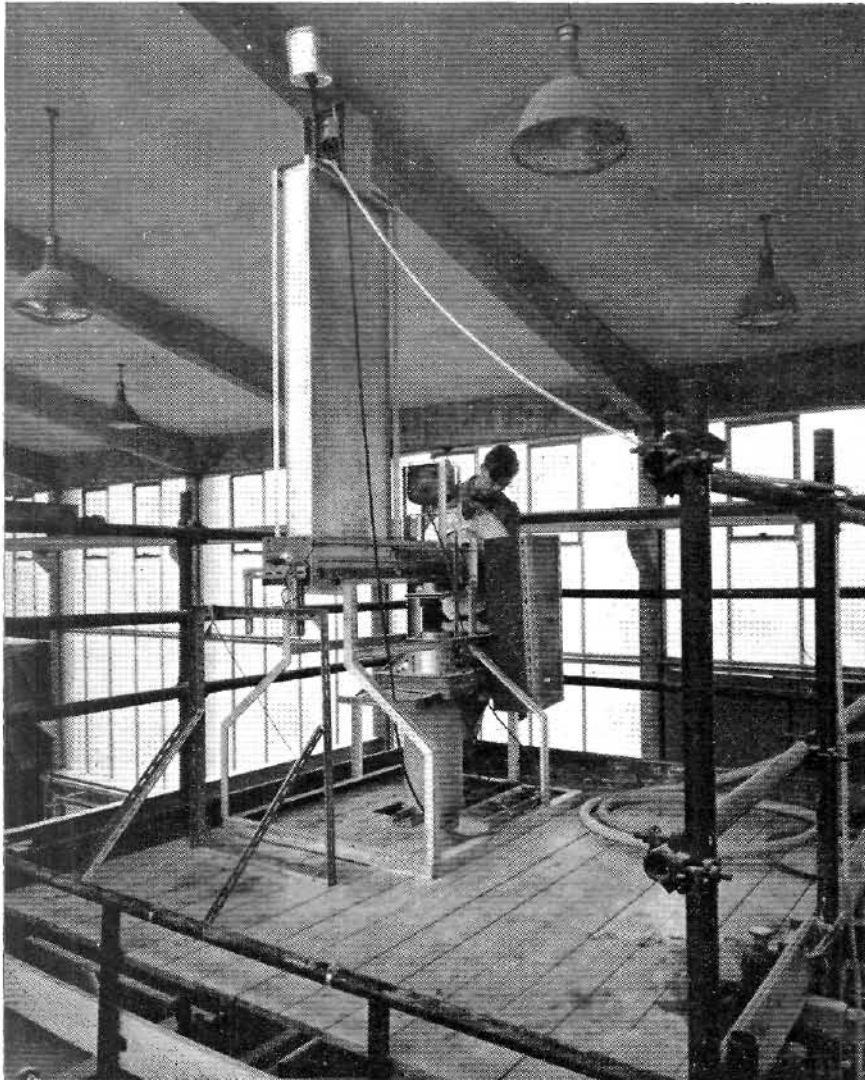


Fig. 2.—Dust feed to vertical tube apparatus

contents of the gas samples were determined with an Orsat apparatus.

Some experiments were also carried out in which samples of dust mixture 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 it looked as if there was some aggregation of the dust.

Results

The range of flammable concentrations was investigated for each dust and dust mixture. Experience showed that the most favourable arrangement of tube for flame propagation was the bottom of the tube closed and the top open with the igniting source near to the bottom. The results for this arrangement are shown in Figs 4 and 5. Further tests with the phenol-formaldehyde resin/magnesium oxide mixtures were carried out with the top of the tube closed and the

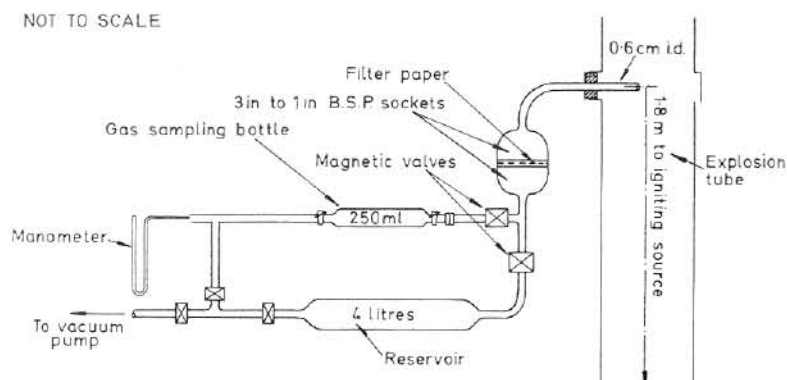


Fig. 3.—Dust and gas sampling apparatus

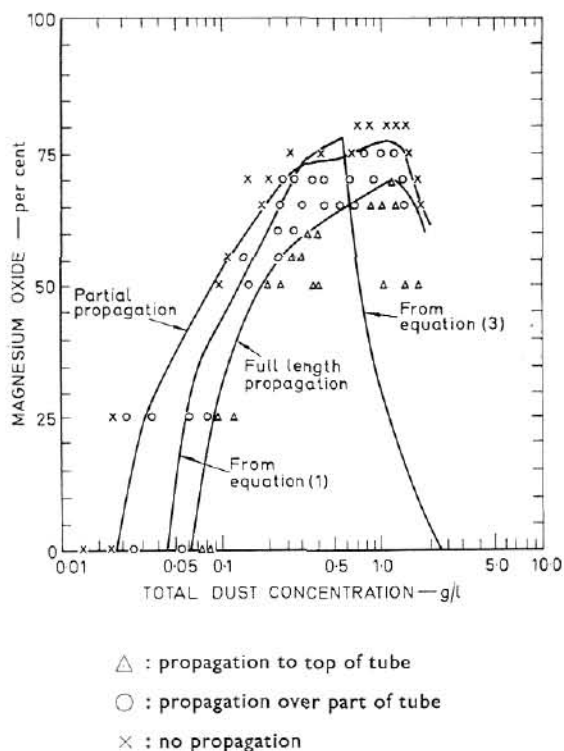


Fig. 4.—Flammability limits of mixtures of resin/magnesium oxide (top of tube open, bottom closed)

bottom open and with the ignition source in the same position; the results are shown in Fig. 6. In Figs 4 to 6 distinction is made between no flame propagation, propagation for the whole length of the tube, and partial propagation, *i.e.* the flame travelled at least 0.6 m but did not traverse the full length of the tube. Each point represented three tests; if the extent of flame propagation varied within a group of tests the results shown is that for the most extensive propagation.

The appearance of the explosion flames varied with the concentration of the dust. Near the flammability limits the flames were short and tended to be fragmented, particularly with high concentrations of dust. With more vigorous explosions the flames were longer and eventually filled the whole length of the explosion tube. The amount of solid carbon formed in the explosions was negligible.

Each of the dusts was classified for explosibility in the small-scale tests listed in the Introduction. Further measurements were made of explosion properties of the dusts by the usual methods.² A summary of the results is given in Table II.

The dust distribution along two diameters of the explosion tube is shown in Fig. 7 for methyl cellulose. Similar results were obtained with other dusts. The variation of mean velocity of fall of dust with concentration is shown in Fig. 8 for methyl cellulose and a mixture of resin/magnesium oxide. Similar curves were obtained for other mixtures and industrial dusts. The mean velocity of fall for 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 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

TABLE II.—Results of Explosibility Tests in Small-scale Apparatus

Dust	Explosibility class	Test apparatus in which ignition occurred	Minimum ignition temperature (°C)		Minimum explosible concentration (g/l)	Maximum explosion pressure* (lbf/in ²)	Maximum rate of pressure rise (lbf/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	—	—	—	—	—	—
Methyl cellulose	I	a-e	960	350	—	—	—
Manioc	I	b-e	—	450	—	—	—
Sodium carboxy methyl cellulose	I	b, d and e	—	320	—	—	—
Processed starch	I	d and e	—	460	—	—	—
Polyvinylidene chloride	II	e	—	620	—	—	—
Calcium citrate	II	e	—	520	—	—	—

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

† Represents 100% resin, 0% magnesium oxide.

APPARATUS: a: Horizontal tube
 b: Inflamator
 c: Vertical tube (Hartmann apparatus)
 d: Modified vertical tube
 e: Furnace apparatus

TABLE III.—*Velocities of Flames in Dust Clouds*

Tube arrangement	Dust mixture Phenol-formaldehyde resin/magnesium oxide	Concentration range (g/l)	Flame velocities	
			Minimum (cm/s)	Maximum (cm/s)
Top open/bottom closed	100/0	0.03-0.08	100	1450
Top open/bottom closed	45/55	0.13-0.29	400	1150
Top open/bottom closed	40/60	0.23-0.39	260	690
Top open/bottom closed	35/65	0.13-0.95	280	670
Top closed/bottom open	100/0	0.07	100	120
Top closed/bottom open	50/50	0.23-0.47	110	400
Top closed/bottom open	45/55	0.17-0.72	280	770
Top closed/bottom open	40/60	0.29-0.46	400	420

and was carried downwards near the wall. The cycle of movement was continuous.

At concentrations near the flammability limits the flames were fragmented, indicating that probably only a proportion of the dust was burnt. A short investigation with one dust mixture, involving the withdrawal of samples of dust and gas, was carried out and the results of this are given in Figs 9 and 10. In both figures the calculated best line through the experimental points is shown.

Flame velocities for a range of phenol-formaldehyde resin/magnesium oxide mixtures are shown in Table III. The velocities were the minimum and maximum obtained in different experiments within the concentration ranges indicated.

Discussion

Determination of flammability limits

Lower and upper flammability limits were obtained with most of the mixtures of phenol-formaldehyde resin/magnesium oxide and with manioc and processed starch. Lower

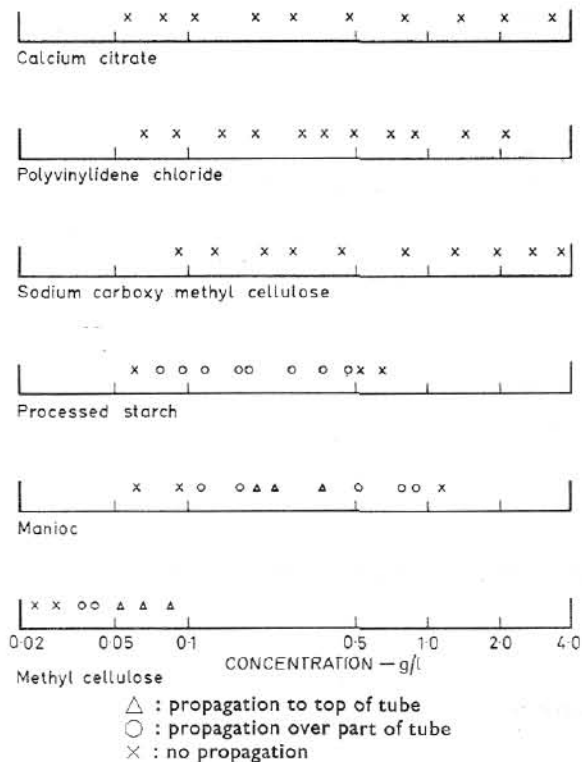


Fig. 5.—*Flammability limits of some industrial dusts (top of tube open, bottom closed)*

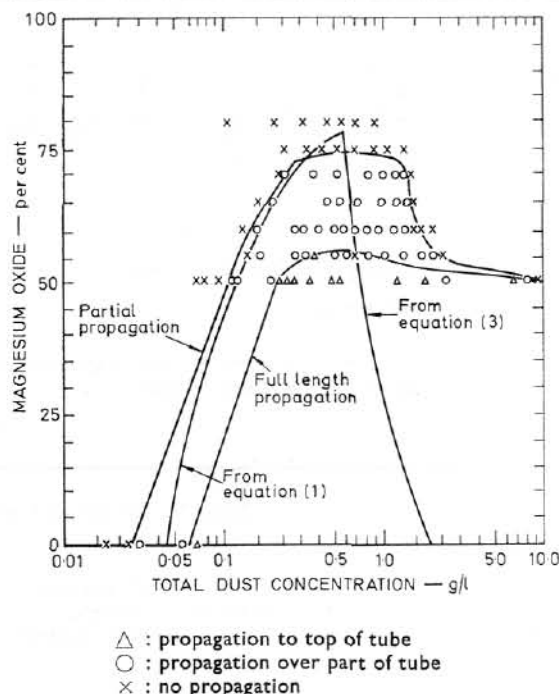


Fig. 6.—*Flammability limits of mixtures of resin/magnesium oxide (top of tube closed, bottom open)*

limits were also obtained for the resin alone and for methyl cellulose dust; to avoid damage to the apparatus the full flammability range was not explored. The dust concentrations at which the limits occurred were clearly defined with all the dusts. Three types of flame behaviour occurred (Figs 4 to 6); the extent of partial propagation was not affected when the volume of propane used for ignition was increased by 75% and so it is unlikely that the extent was governed by energy derived from the igniting source. A likely explanation 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 Figs 4 and 6 was characterized by a flat-topped region flanked by steeply sloping gradients as the proportion of magnesium oxide was reduced. The upper flammability limits increased markedly as the proportion of resin in the mixtures was increased although the flames occurring at these limits did not fill the whole cross section of the tube but propagated as narrow streaks. The concentration

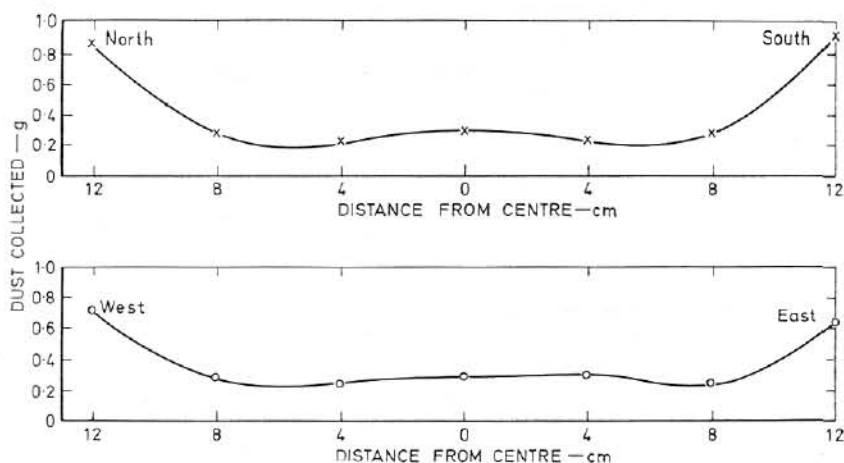


Fig. 7.—Dust distributed along two diameters of the explosion tube containing 0.26 g/l of methyl cellulose (top of tube open, bottom closed)

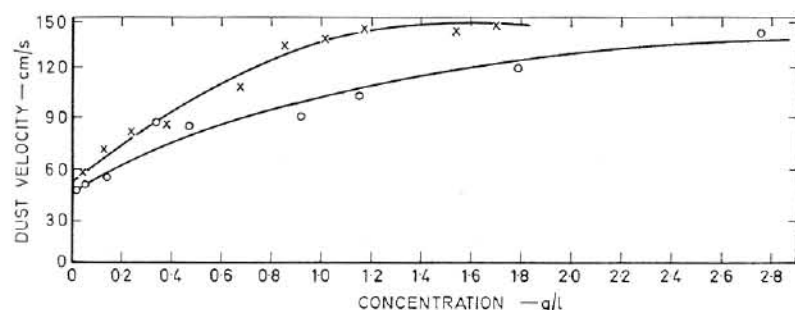
of dust in the flames may therefore have been less than the mean concentration measured.

Because the dust was falling through the air in the tube the quantity entering the flame was greater than if the dust had been stationary. For instance, in Fig. 6 the lower flammability limit of resin alone as measured by the procedure described above is 0.030 g/l. At these low concentrations the flame velocity was about 100 cm/s (Table III) and the mean velocity of fall was 50 cm/s. Hence the amount of dust entering the flame was greater than that measured by a factor $(100+50)/100$, and the true lower flammability limit was 0.045 g/l.

Comparison between large-scale results and the classification system

Explosions with flame propagation over at least part of the tube length were obtained with resin mixtures containing 75% or less of magnesium oxide. Mixtures containing 80% or more did not propagate flame. Flame propagation was also obtained with methyl cellulose, manioc, and processed starch. There was no flame propagation in the dust clouds of sodium carboxy methyl cellulose, polyvinylidene chloride, and calcium citrate in the large-scale explosion tube.

Tests in the small-scale apparatus the results of which are given in Table II, showed that the vertical tube test apparatus with spark ignition also yielded flames with resin mixtures containing up to 75% magnesium oxide and with methyl cellulose, manioc, and processed starch. The modified vertical tube test apparatus yielded flames with mixtures containing up to 80% magnesium oxide and with sodium carboxy methyl cellulose as well as with the methyl cellulose, manioc, and processed starch. The inflammator yielded flames with mixtures containing up to 70% of magnesium oxide and with three of the industrial dusts (Table II). The horizontal tube gave flames with mixtures containing up to 55% magnesium oxide and with only one industrial dust, *viz.* methyl cellulose.



○ : methyl cellulose
 × : 40% phenol-formaldehyde resin and 60% magnesium oxide

Fig. 8.—Velocity of falling dust at various concentrations

To summarise, none of the dusts or dust mixtures which were Class III or Class II in the small-scale tests propagated explosion in the large-scale tube. These materials were thus not explosible under the conditions investigated. No evidence was obtained that Class II dusts would be capable of propagating explosion away from the influence of the ignition source in large-scale plant provided that the working temperature of dust and plant were not greater than the ambient. Further theoretical consideration of Class II dusts is given below.

Several of the dusts and dust mixtures were marginally Class I, *i.e.* flame was obtained in only some of the small-scale tests with a small ignition source. Most of these marginally Class I dusts propagated flame in the large-scale tube. For practical purposes marginally Class I dusts should be regarded as explosible.

Marginally explosible dusts and dust mixtures had a narrower range of flammable concentrations than more vigorous materials (Figs 4 to 6) and the maximum explosion pressures and rates of pressure rise were also lower (Table II). 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. In industry the explosion risk also depends on other factors such as the ease of ignition of the dust, the quantity handled, and the nature of the processing.

The mechanism of flame quenching

An explanation was sought for the mechanism whereby a material such as magnesium oxide was able to prevent flame propagation in suspensions of a combustible dust such as phenol-formaldehyde resin. The simplest mechanism would be that the magnesium oxide acted as a heat sink and was chemically inert; this was taken as a working hypothesis.

Two possible processes for the flame quenching were

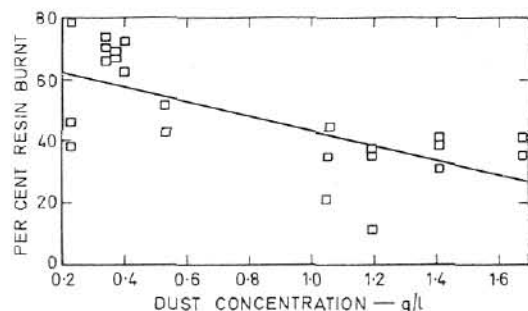


Fig. 9.—Dust mixture of 50% phenol-formaldehyde resin and 50% magnesium oxide. The effect of dust concentration on the amount burnt

considered. The first process was that addition of the inert material caused the flame speed of the explosion to decrease until it was ultimately less than the velocity of fall of the dust particles. With upward propagation the flame would then be carried downwards into combustion products and would be extinguished. The experimental results did not support this process. Minimum values of the flame velocities measured relative to the explosion tube, listed in Table III, were appreciably greater than zero. In addition, visual and photographic observations of the flames did not show a pronounced retardation as would be expected if they were swept downwards by falling dust. The process was therefore not considered further.

The second possible process was that the presence of the magnesium oxide in the flame acted as a thermal sink and that when a certain proportion of the heat generated by the flame was abstracted propagation would cease. The assumption was that if the flame temperature were reduced by cooling to a value less than that of the flame at the lower flammability limit of fuel then the flame would be quenched. A similar process has been shown to hold approximately for the extinction of pre-mixed gas-air flames⁷ 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. Unsuccessful attempts have been made to apply a similar assumption to the quenching of coal dust explosions by stone dust.⁸ However, the combustion mechanism of coal particles is 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.

The physical mechanism involved in the propagation of dust flames has not yet been clarified but in the present case the following overall process was envisaged. 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 was in close proximity (Figs 9 and 10). The combustible dust vaporized and burned with diffusion flames leaving the

inert dust in suspension in the flame zone acting as a thermal sink. A more detailed picture of the mechanism may be obtained by considering a stoichiometric dust-air mixture in the explosion tube open at its lower end. During combustion hot products would be generated of a greater volume than the oxygen consumed and, as the system was at constant pressure, gases would move to the rear of the flame. On completion of combustion the volume originally occupied by a fuel particle surrounded 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. Hence the transfer of heat to neighbouring fuel, which is necessary for flame propagation, would be able to occur.

It was not immediately apparent whether the inert dust would disperse as the resin vapours burnt and expanded, or would remain 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 on the particles due to expanding gas with the acceleration required if the particles were to disperse as the gas expanded. It was found that the acceleration due to the drag was 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 vaporized, burned, and expanded. This conclusion may only be applicable near the front of the flame zone where combustion is relatively rapid because of the high oxygen concentration. However, it is near the front of the flame zone where the heat balance would be critical in deciding whether further propagation could be sustained. Away from the front of the flame zone different considerations may apply but these would not be expected to govern the thermal conditions at the flame front.

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 particles in the "nose" of the flame were nearly stationary whereas those more deeply within the flame were rapidly accelerated. There was evidence that particles were decelerated as they entered the flame and 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 relative positions had not been affected by expansion of the gas.

The heat balance equations

Two cases have to be considered with the inert dust acting as a thermal sink. Firstly, when the fuel concentration was leaner than stoichiometric only the inert dust would act as a thermal sink. Secondly, when the fuel concentration was richer than stoichiometric surplus fuel would also act as a sink. The increase in gas volume on volatilisation of the resin was neglected.

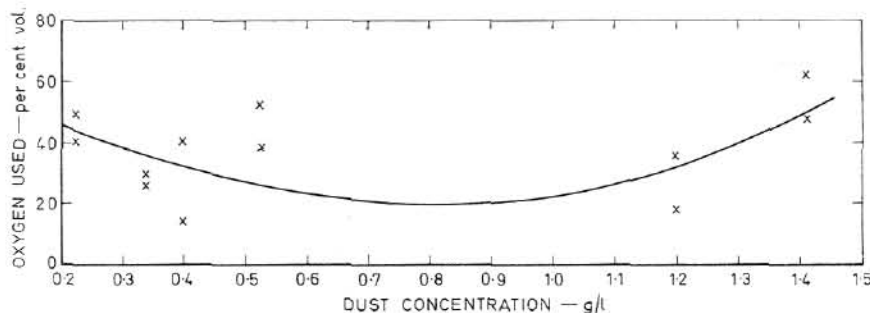


Fig. 10.—The oxygen used by flames propagating in various concentrations of a dust of 50% phenol-formaldehyde resin and 50% magnesium oxide

For concentrations on the lean side of stoichiometric:

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

where:

- c_2 = mean specific heat of inert dust.
- H = heat of combustion per unit mass of resin.
- r = expansion ratio on combustion.
- T_0 = ambient temperature.
- T_1 = flame temperature at flammability limits.
- x = resin concentration (mass per unit volume).
- x_1 = resin concentration at lower flammability limit.
- y = concentration of inert dust (mass per unit volume).

Hence:

$$y = \frac{H(x - x_1)}{rc_2(T_1 - T_0)} \quad (1)$$

At the peak value:

$$y = \frac{H(x_2 - x_1)}{rc_2(T_1 - T_0)} \quad (2)$$

where x_2 is stoichiometric concentration.

For concentrations richer than stoichiometric:

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

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

Hence:

$$y = \frac{H(x_2 - x_1)}{rc_2(T_1 - T_0)} - \frac{c_1}{rc_2}(x - x_2) \quad (3)$$

when $x = x_2$, equation (3) reduces to equation (2).

Numerical values for the quantities in equations (1) to (3) have been calculated as follows.

The chemical composition of the phenol-formaldehyde resin was not known precisely but was assumed to be similar to that of phenol or cresol. 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,⁹ a mean value for H of 8000 cal/g was taken. The lower flammability limit (x_1) was determined experimentally and was 0.045 g/l. Hence by enthalpy calculation¹⁰ $T_1 = 1370^\circ\text{K}$ when $T_0 = 300^\circ\text{K}$, and hence $r = T_1/T_0 = 4.6$.

The mean specific heats of resin and magnesium oxide, c_1 and c_2 , were taken as 0.35 and 0.28 respectively.¹¹

The results represented in Figs 4 and 6 were plotted with $100y/(x+y)$ as ordinate and $(x+y)$ as abscissa for experimental convenience. Lines derived from equations (1) and (3) are included in Figs 4 and 6.

The minimum amount of inert dust required to quench a stoichiometric resin flame, *i.e.* the peak value, is given by equation (2): $y = 0.44$ g/l.

The percentage of inert dust in the mixture = $(0.44 \times 100)/(0.44 + 0.12) = 78\%$, at a total dust concentration of 0.56 g/l.

Comparison of the equations with the experimental results

The tube arrangement in which explosions most readily occurred was that in which flame propagated from the closed end (Fig. 4) and comparison of the equations derived above has been made with these results which represented the worst conditions.

The dust concentrations in Fig. 4 were not corrected for the falling 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 the

equations. The increase in the dust concentration can be gauged from Table III and Fig. 8 and was about 50%. Equations (1) and (3) thus underestimated the lower and upper flammability limits of resin/magnesium oxide mixtures, particularly at higher dust concentrations (Fig. 4). However, the resin in the dust suspensions was not completely burnt (Fig. 9) and the proportion that was burnt decreased as the dust concentration increased. At high concentrations less than half the resin was burnt. This factor reduces the extent to which the equations underestimated the flammability limits.

The proportion of magnesium oxide needed in the dust mixture to prevent explosion was calculated as 78%, and was in excellent agreement with the experimental results (75–80%). The composition of the dust mixtures could be accurately controlled in advance, whereas the concentration of a suspension was subjected to wider variations, so the good agreement with experiment gave increased support for the theory. Additional experiments are in hand with dusts of different thermal characteristics to test the theory further.

The theory gives further evidence of the explosibility of Class II dusts, which only ignite in the furnace apparatus.² In this apparatus the dust is dispersed into the heated air, but the qualities H , c_2 , and T_1 in equation (2) 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. Because the air temperature in the furnace apparatus during the test depends upon the initial pressure in the reservoir, the rate of release, the effectiveness of mixing, and the dimensions of the furnace, the performance of the dust clearly depends substantially upon the design and operation of the apparatus. Hence the division between Class II and Class III dusts is somewhat arbitrary, whereas that between Class I and Class II is more fundamental.

Conclusions

1. Dusts and dust mixtures that required a relatively large source of ignition in small-scale tests (Class II dusts) did not propagate explosions on a larger scale.
2. Most marginally explosible dusts and dust mixtures that could be ignited by a small source of ignition in the small-scale test apparatus (marginally explosible Class I) would propagate explosion on a larger scale.
3. Marginally explosible dusts have comparatively narrow ranges 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 propagation of flame in an explosible dust agreed well with experiment on a large scale.

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Davies, C. A. Wright, Mrs. S. A. Morris, D. K. Freeman, and the results in Table II were obtained by Miss M. M. Raftery and Mrs. J. S. Harris.

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DISCUSSION

Dr. N. GIBSON said that in the conclusions to the paper it was stated that "Marginally explosible dusts . . . generate only moderate explosion pressures". As "marginally explosible" is defined in terms of ignition temperatures of standard heat sources or the spread of flame in the large tube, does this mean there is a direct correlation between either ignition temperature or spread of flame in the tube and rate of pressure rise in an explosion or maximum pressure?

Mr. TONKIN said that the term "marginally explosible" was not defined in terms of ignition temperature or the spread of flame in the large tube. There were other factors contributing to the explosibility of a dust. While dusts which were considered as marginally Class I in the small-scale tests usually had lower pressure rise values, comparatively narrow ranges of flammable concentrations and slower flame speeds than those obtained with more vigorous Class I dusts the work did not establish a correlation between either ignition temperature or spread of flame in the tube, and rate of pressure rise.

Dr. H. S. EISNER said that this very interesting paper gave a rather new angle on the whole question of testing of dusts. Historically, the reason why one went from these small-scale tests to the larger scale was that one expected that dusts which might not be so explosible on the small-scale tests would prove rather more so on the large scale. The work of Palmer and Tonkin, in general, appeared to show that, on the larger scale most of the dusts tested were in fact less explosible. He wondered whether it might not be dangerous to generalise from these experiments because it might be possible that the conditions that existed in this particular apparatus, both for

ignition and for propagation of the flame, might not be as stringent as could arise in actual industrial application.

Thus, sodium carboxy methyl cellulose, which it had been possible to explode in three of the small-scale apparatuses, failed to explode in the larger-scale tube. To conclude from such experiments that sodium carboxy methyl cellulose was safe from the point of view of dust explosion in a large-scale plant could turn out to be wrong.

Mr. TONKIN said that he wished to make the point that dust testing was carried out for the benefit of H.M. Factory Inspectorate and for industry.

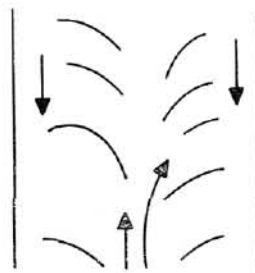
The sodium carboxy methyl cellulose did not explode in all the Class I tests. It was a marginal Class I, and while he would agree with Dr. Eisner that one should not be too hasty in relaxing precautions, what the work showed particularly was that the Class II dusts would not propagate in this sort of system and on this scale. While it was not right for him to anticipate any decisions by the Factory Inspectorate—a body that had been fully informed of the work and with which there had been liaison throughout—he did not think that, at the present time, it would be possible to differentiate between marginal Class I dusts that would propagate flame and those that would not in a large-scale tube. If it was a Class I dust, then some precautions would be considered. It was the Class II dusts about which people were thinking anew and which were the main concern of the reappraisal.

Dr. EISNER said that he had really hoped that Mr. Tonkin might advance some reason why sodium carboxy methyl cellulose did not perform on the large scale as it did on the small scale.

Mr. TONKIN replied that in the small-scale tests the extent of flame propagation was sufficient to call it an explosion, although the flame might still have been under the influence of the igniting source. In the large-scale tube with the source of ignition being injected for a short time the dust flame near the igniter was being constantly fed with cold dust. That would minimise the influence of the igniting source on subsequent flame propagation.

Dr. W. E. MASON referred to tests described on page 69 of the paper in which it was discovered that there was a recirculation flow within the tube, with air flowing up the middle and down the sides. He wondered if that affected the results of the explosibility tests in any way.

Mr. TONKIN replied that there had been no intention of controlling the movement of the dust inside the tube once it was introduced at the top. A qualitative test carried out to study the air movement showed that it was cascading over a considerable length of the tube as shown in the figure:



There were dust distribution curves in the paper and the concentrations were higher at the edges of the tube than in the centre. He thought that it might affect the large-scale results as regards flammability limits but not in terms of whether the dust should be regarded as explosible.

Mr. P. L. KLAASSEN said that petroleum products were classified in Classes A, B and C, and D, with flashpoint determinations. He asked if Palmer and Tonkin forecast any standards in the future for the classification of dusts. As far as he could see it seemed to be beginning. Was there an international set of standards contemplated for dusts or was there no connection between the work which Palmer and Tonkin and their co-workers were doing and what was happening in the United States of America and Germany?

Mr. TONKIN replied that there was not as much connection internationally between dust testing bodies as there was between bodies testing petroleum products. The Bureau of Mines in America had done a very great deal of dust explosibility testing and work done in this country tended to be similar.

Indeed they had one apparatus of American design and found that results obtained in the two laboratories were similar. Obviously, other countries had their local codes of practice and the British classification system did not apply in other countries. At present no international set of standards was contemplated.

Mr. H. G. RIDDLESTONE said that in the International Electrotechnical Commission, a committee had been set up to look into the question of dust explosion hazards with electrical equipment. The committee was trying to collect all the information available from different countries on methods of classifying dusts, dust explosion risks and methods of protecting electrical equipment so as to avoid dust explosions.

Mr. N. B. SIBLEY asked if cork dust had to be classed as Class I marginal.

Mr. TONKIN emphasised that the term marginal Class I that he had mentioned was not an official classification. He merely used that term for a definition in the work to differentiate between the dusts that did not explode in all the Class I test apparatus and those that did.

Cork dust exploded in all the test apparatus, including the horizontal tube, and could not be considered a marginally explosive dust.