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# Fire Research Note

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THE SUPPRESSION OF COAL DUST EXPLOSIONS WITH  
LIMESTONE AND SODIUM CHLORIDE DUSTS

by

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SUMMARY

The efficiencies of limestone and sodium chloride dusts in suppressing coal dust explosions have been measured in a large scale vertical explosion tube. The explosibility of the dust mixtures in small scale test apparatus has been compared with their explosibility in the large scale tube.

The results obtained with the coal dust/stone dust mixtures were in good agreement with those obtained from experiments elsewhere in a large scale gallery. The agreement indicated that the results obtained with other industrial dusts in the vertical tube would apply to larger scale industrial plant.

The minimum percentages of the diluents required to prevent explosions in the vertical tube have been compared with those calculated from heat balance equations derived from a theory based on the thermal properties of the dusts. Reasonable agreement was obtained for limestone dust.

Sodium chloride was a better explosion suppressor than stone dust and its efficiency was much greater than predicted by calculations based on its thermal properties.

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# THE SUPPRESSION OF COAL DUST EXPLOSIONS WITH LIMESTONE AND SODIUM CHLORIDE DUSTS

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## INTRODUCTION

The inerting properties of many substances, when present in dust clouds containing explosible dusts, have been investigated and reviewed<sup>1,2,3</sup>. Attempts had been made to propose mechanisms by which these substances quench dust explosions<sup>3</sup>.

In the present work two series of experiments were undertaken with limestone and sodium chloride dusts as respective diluents. The work was carried out in a large scale vertical explosion tube so that a comparison could be made between the explosion suppressing properties of the two diluents used, and in the case of stone dust, to compare the experimental results with values calculated from equations based on the thermal properties of the dusts<sup>4</sup>. Comparison could also be made with previous large scale work<sup>3</sup>. The comparison would give some indication as to whether the vertical tube apparatus, which was 25 cm (10 in) in diameter, gave results representative of full industrial scale of more than 1 m diameter.

All the dust mixtures used were classified for explosibility in the small scale test apparatus<sup>5</sup> so that further information could be obtained on the relationship between explosibility class and the explosibility of dusts in large scale plant.

## EXPERIMENTAL

### MATERIALS

The fuel was a bituminous gas coal dust with a volatile matter content of 36.4 per cent determined on a dry ashless basis. The National Coal Board Rank Code Number was 501. The moisture content of the fuel was 1.9 per cent and the ash content was 2.2 per cent. A sizing analysis is given in Table 1.

The limestone dust was a commercial colliery grade and its moisture content was 0.1 per cent. A sizing analysis of the stone dust is also given in Table 1.

The sodium chloride was a general purpose reagent and had a mean particle size of 50 microns, 92 per cent being between 65 and 25 microns.

Table 1.  
Sizing analysis of coal dust and stone dust

Upper size of sieve fractions (microns)	Per cent by weight	
	Coal	Stone dust
251	100	100
211	100	93
124	100	73
64	89	53

Mixtures of the dusts were made in a rotating drum mixer. In order to ensure adequate mixing, samples were taken for analysis at time intervals during mixing until the mean compositions of two consecutive samples did not vary by more than one per cent.

#### APPARATUS

The vertical explosion tube apparatus used in the experiments was the same as that described in detail previously<sup>4</sup> and is shown in Fig.1. The tube was 25.4 cm (10 in) internal diameter and its overall length was 5.2 m (17 ft). Three 0.31 m (1 ft) long sections of perspex, and windows in the steel lengths of the tube, permitted observation and photography of flames propagating in the dust clouds.

Manually operated sliding trays were used to collect dust falling in the explosion tube. From the amount of dust collected, properties of the dust clouds such as distribution, concentration and velocities of the falling particles were measured.

The igniting source was a propane flame injected into the explosion tube horizontally to cover the cross section of the tube<sup>4</sup> and it was situated 1.5 m (5 ft) from the bottom of the tube.

The apparatus used to feed the dust into the top of the explosion tube was the same as that used previously<sup>4</sup>.

For experiments in which the tube arrangement was top closed, bottom open, a lid was installed on the dispersing cylinder, and the flexible pipeline for dust and fume extraction was moved to the dust collecting bin at the bottom of the tube.

Flames were filmed using the cine camera and photographic materials as in previous work<sup>4</sup>.

## PROCEDURE

The general procedure adopted for determining the explosibility of a dust mixture was firstly to measure the total dust concentration in the explosion tube, then carry out a series of three explosion tests. The dust concentration was checked during the series. This procedure was repeated at various dust concentrations until either a flammable range was obtained for the dust mixture or it was established that the mixture would not propagate flame. In the experiments with the tube arrangement top open bottom closed, the bottom slide was closed before the igniting flame was applied.

The procedures for determining dust concentration and dust distribution in the explosion tube and velocities of falling dust were as used in previous work, and are described in detail elsewhere<sup>4</sup>.

## RESULTS

The effect of stone dust and sodium chloride on the flammability limits of coal dust were measured using a tube arrangement of top open and bottom closed. This arrangement had been shown previously to be the most favourable for flame propagation in dust clouds<sup>4</sup>. The results are given in Fig.2 and Fig.3.

The graphs show for each dust mixture the concentration ranges over which there was no flame propagation, partial propagation, and propagation over the whole tube length. The dust concentrations shown in Fig.2 and 3 were 'static mass concentrations' as measured in the experiments. Each point on the graphs represented three tests and where distance travelled by the flames varied within a group of tests, the point signifies the most extensive propagation.

From visual observations, the course of the explosions represented in Fig.2 and 3 was similar to that obtained previously with phenol formaldehyde resin dust and magnesium oxide diluent<sup>4</sup>. The same criterion for partial propagation was therefore applied, namely the flame travelled a distance greater than 0.6 m (2 ft) but not over the full tube length.

In further experiments with coal dust alone, the lower flammability limit was measured with the tube arrangement top closed and bottom open; the results are given in Table 2. In these experiments a new type of flame behaviour was

observed: a dust flame propagated downwards from the igniting source, even at concentrations below that at which upward propagation occurred. The extent of downward propagation is given in Table 2. A suggested explanation of the downward propagation was that only part of the coal volatilized and flamed in the hot gases of the igniting source, and that the solid residue continued to fall, accompanied by burning volatiles around each particle, toward the bottom of the tube. In contrast, with plastics dusts, complete volatilization of burning particles was believed to occur<sup>4</sup>; on volatilization the fall of the particles would be expected to cease rapidly because of their reduced density, and this could cause the observed enlargement of the igniting source. With the coal dust, where downward propagation occurred, the moving particles would not enlarge the igniting source upwards; any upward movement of a flame was regarded as evidence of propagation.

Table 2

Flammability of coal dust in large scale vertical tube  
(top of tube closed, bottom open)

Dust concentration g/l	Extent of flame propagation m	
	upwards	downwards
0.05	nil	1.0
0.07	nil	1.0
0.11	0.5	1.0
0.13	1.0	> 1.0
0.16	0.5	> 1.0
0.22	2.0	> 1.0
0.26	top of tube	bottom of tube

Results of the small scale standard explosibility tests are given in Table 3. The 84/16 coal/sodium chloride and the 35/65 coal/stone dust mixtures were marginally Class I dusts, because they gave ignitions in only some of the small scale tests.

Table 3

## Results of explosibility tests in small-scale apparatus

Dust mixture	Explosibility Class	Test apparatus in which ignition occurred	Minimum ignition temperature °C apparatus (e)
100 coal	I	a - e	490
99 coal/1 sodium chloride	I	a - e	490
98/2	I	a - e	490
96/4	I	a - e	490
94/6	I	a - e	500
92/8	I	a - e	500
90/10	I	a - d*	nd
88/12	I	a - e	510
86/14	I	a - d*	nd
84/16	I	a, c, d, e	510
45 coal/55 stone dust	I	a - e	520
40/60	I	a - e	520
35/65	I	c, d, e	520

nd = not determined \*e - nd

Apparatus: a : Horizontal tube

b : Inflammator

c : Hartmann

d : Modified Hartmann

e : Furnace.

Figure 4 shows dust distribution curves for coal dust along two diameters of the explosion tube.

Figure 5 shows the variation in falling dust velocity with change in concentration for the 40/60 coal/stone dust mixture.

Velocities of flames propagating in the dust clouds are given in Table 4. The values are the minimum and maximum obtained for the dust concentration ranges shown.



Table 4

## Velocity of flames in dust clouds

Tube arrangement	Dust mixture	Concentration range g/l	Flame velocities obtained in the experiments	
			Minimum cm/s	Maximum cm/s
Top open bottom closed	100 coal/0 sodium chloride	0.06 - 0.23	240	1190
"	99/1	0.05 - 0.19	300	1120
"	98/2	0.03 - 0.25	280	980
"	96/4	0.08 - 0.21	120	960
"	94/6	0.10 - 0.45	75	870
"	92/8	0.19 - 1.51	180	400
"	86/14	0.29 - 0.35	170	660
"	40 coal/60 stone dust	0.33	300	490
"	45/55	0.12 - 1.1	270	830
Top closed bottom open	100 coal/0 stone dust	0.13 - 0.26	200	270

## DISCUSSION

## FLAMMABILITY LIMIT DETERMINATIONS

Lower and upper flammability limits were obtained with all the coal dust/stone dust and with most of the coal dust/sodium chloride mixtures used in the experiments (Fig.2 and 3); the tube arrangement was top open, bottom closed. The lower flammability limit of coal dust alone was measured with this tube arrangement (Fig.2 and 3). The lower limit of the coal dust was also obtained with tube arrangement top closed, bottom open and the value under these conditions was greater than that obtained with the other tube arrangement (Table 2). In addition, downward propagation of flame was observed even at low dust concentration; this did not occur when the bottom of the tube was closed (Fig.2 and 3) but under these conditions there would be upward movement of the dust suspension due to expansion effects near the closed end of the tube. The results in Table 2 may be compared with those reported for the same coal dust in a tube 14.2 cm (5.5 in) in diameter. For a probability of at least 0.3

for some flame propagation (i.e. at least one propagation in three tests), the criterion used in the present work, a coal dust concentration of about 0.16 g/l (0.16 oz/ft<sup>3</sup>) was necessary<sup>7</sup> as compared with between 0.07 and 0.11 g/l (0.07 and 0.11 oz/ft<sup>3</sup>) (Table 2). In addition, it was reported that no propagation could be obtained in a tube of 7 cm (2.75 in) diameter<sup>7</sup>. There is thus strong evidence that in tubes up to 25 cm (10 in) diameter, the lower flammability limit decreased as the diameter increased.

The curves obtained with stone dust and sodium chloride exhibited different characteristics. The stone dust curve had a flat topped region as exhibited in previous work with diluent dusts<sup>4,6</sup> while the curve obtained with sodium chloride exhibited a sharp peak. A partial explanation of the differences in shape is given by the greatly increased effectiveness of the sodium chloride in preventing explosion. As it is the minor constituent of the mixture with coal dust, the total dust concentration plotted as abscissa varied relatively little as the percentage of sodium chloride increased. With limestone dust, the stone was the major component of the mixture and the total dust concentration increased markedly as the percentage of stone dust was increased. This gave the appearance of a flat topped curve. The effectiveness of the sodium chloride in quenching explosion is considered in more detail below.

#### COMPARISON WITH EXPLOSIBILITY CLASSIFICATION

All the dust mixtures were tested in the standard apparatus and classified for explosibility as shown in Table 3.

In the coal dust/stone dust series of experiments no propagation of flame was obtained in the large scale tube with the mixture containing 65 per cent stone dust. This mixture was a marginal Class I dust giving only weak explosions in the Hartmann apparatus and no explosions in the other apparatus with small sources of ignition. The division between dust mixtures which exploded in the large scale tube, and those that did not, lay between the 60 and 65 per cent stone dust mixtures. The small scale tests thus slightly over-estimated the explosibility; similar behaviour was found previously<sup>4</sup>.

In the coal dust/sodium chloride experiments no flame propagation was obtained in the large scale vertical tube with the mixture containing 16 per cent sodium chloride. This mixture was regarded as a marginal Class I dust since it did not explode in the Inflammator but it did propagate flame in all the other

apparatus with small sources of ignition (Table 3). The 84/16 coal dust/sodium chloride mixture was therefore not as marginal Class I as the 35/65 coal dust/stone dust mixture. The proportions of stone dust and sodium chloride required to suppress explosion showed clearly that the sodium chloride was relatively far more efficient.

#### COMPARISON WITH RESULTS FROM COAL MINE RESEARCH

The minimum amount of limestone required to prevent coal dust explosions (60-65 per cent) as determined in the large scale vertical tube apparatus may be compared with the value of 65 per cent limestone required with the same coal dust in a mine gallery 1.22 m (4 ft) diameter and 100 m (330 ft) long<sup>8</sup>. The good agreement between the two sets of values indicates that results for the large scale vertical tube may be applied to industrial plant of considerably larger diameter; direct experimentation with which would be difficult and expensive. Evidence of a scale effect, as observed with the lower flammability limit of pure coal dust in narrower tubes, was not obtained in comparison of the present work with the gallery results.

In the experimental gallery, which was horizontal, the coal dust/stone dust mixtures were deposited on the floor and the dust cloud was raised by the explosion itself, following ignition at the closed end of the gallery. In the vertical tube, the dust cloud was raised separately before explosion was attempted. The agreement between the results for the two experimental techniques indicate that the suppressant action of the stone dust was not due to the increased mass of dust required to be raised in suspension. This mechanism had been proposed as a possible explanation for the gallery results<sup>3</sup>.

#### THEORETICAL CONSIDERATIONS - HEAT BALANCE EQUATIONS

In previous reports<sup>4,9</sup> concerned with the explosibility of combustible plastics dusts mixed with various non-combustible diluents, consideration was given to the mechanism whereby the diluents suppressed the explosion. With one exception, sodium iodide, it appeared that the effect of the diluent material was to act as a heat sink, and that when sufficient diluent was present the amount of heat absorbed prevented further propagation of flame. The limited amount of heat required for propagation to continue was assumed to be that released by the flame of the combustible dust, alone, at the lower flammability limit concentration.

The physical processes involved in the propagation of the plastics dust flames have not yet been clarified, but the overall process was believed to be

as follows; the combustible and diluent dust particles entered the flame front together, the combustible particles rapidly vaporized completely and burnt with diffusion flames, leaving the diluent in suspension in the flame acting as a thermal sink. Further discussion is given elsewhere<sup>4</sup>. Calculations based on this model gave results which, in general, were in good agreement with experiment<sup>4,9</sup>.

With coal dust as combustible, however, some modification of the previous assumptions would be necessary. The main reason would be that not all the fuel particle is likely to vaporize on entering the flame; and some carbonaceous residue would be expected. The solid residue would be surrounded by vaporized fuel initially, which would be burning with a diffusion flame, hence direct access of oxygen to the residual solid would not be expected whilst there was still volatile material burning. After the volatiles had been burned, oxygen could then clearly react with the solid surface. However, it is likely that the propagation of the flame is governed principally by conditions at the front of the flame, where combustion of the volatiles would still be in progress. The solid material formed on the devolatilization of the coal would thus, at least initially, act as a heat sink rather than a source of fuel; if a coal/stone dust suspension were entering the flame then two solid heat sinks would be present. For coal and diluent dusts the heat balance equations derived previously<sup>4</sup> would become:

for concentrations on the lean side of stoichiometric

$$(y_1 c_2 + y_2 c_3) (T_1 - T_0) = \frac{H}{r} (x - x_1) \quad (1)$$

at the stoichiometric concentration

$$(y_1 c_2 + y_2 c_3) (T_1 - T_0) = \frac{H}{r} (x_2 - x_1) \quad (2)$$

for concentrations on the rich side of stoichiometric

$$(y_1 c_2 + y_2 c_3) (T_1 - T_0) + \frac{c_1}{r} (x - x_2) (T_1 - T_0) = \frac{H}{r} (x_2 - x_1) \quad (3)$$

where  $x$  is volatiles concentration (mass per unit volume)

$x_1$  is volatiles concentration at lower flammability limit

$x_2$  is stoichiometric concentration of volatiles

$y_1$  is concentration of diluent dust (mass per unit volume)

$y_2$  is concentration of non-volatile residue from fuel (mass per unit volume)

$c_1$  is mean specific heat of volatiles, neglecting heat of volatilization

$c_2$  is mean specific heat of diluent dust

$c_3$  is mean specific heat of non-volatile residue from coal

$T_1$  is flame temperature at flammability limits

$T_0$  is ambient temperature

H is heat of combustion per unit mass of volatiles

r is expansion ratio on combustion

In the general case the total dust concentration is given by  $(x + y_1 + y_2)$ , and by  $(x_2 + y_1 + y_2)$  at the stoichiometric concentration.

For equations (1)-(3) to be applied, information was required on the amount of volatiles produced from the coal under flame conditions and on the lower flammability limit of the volatiles in the absence of non-volatile residue. These aspects are considered in Appendix 1 and 2 respectively.

#### APPLICATION OF EQUATIONS

In applying equations (1), (2) and (3) to the results in Fig.2 and 3 the following values were taken for the properties of the coal.

$$x_1 = 0.050 \text{ g/l} \quad (\text{Appendix 2})$$

$$x_2 = 0.11 \text{ g/l}$$

$$y_2 = \frac{0.38}{0.62} x = 0.61 x \quad (\text{Appendix 2})$$

$$c_1 = 0.35, \text{ the value for phenol formaldehyde resin vapour}^4 \text{ being used as no direct value for coal volatiles was available. An approximate value for } c_1 \text{ was adequate for equation (3).}$$

$$c_3 = 0.23$$

$$T_0 = 300^\circ\text{K}$$

$$H = 8300 \text{ cal/g}$$

$$r = 5.0 \quad (\text{Appendix 2})$$

The specific heats of the diluent dusts were taken as 0.29 and 0.25 respectively for stone dust and sodium chloride<sup>14</sup>. The stone dust was assumed to be calcium carbonate, and the mean specific heats were calculated for a temperature of  $900^\circ\text{K} = \frac{1500 + 300}{2}$ .

The calculated lines obtained by inserting the above values in equations (1) and (3) are shown in Fig.2 and 3 for the coal dust/stone dust and the coal dust/sodium chloride systems respectively. The horizontal axis was calculated as  $(x + y_1 + y_2)$  and the vertical axis was  $\frac{100 y_1}{x + y_1 + y_2}$

For the coal dust/stone dust mixtures (Fig.2) the observed flammability limits were wider than those calculated from equations (1) and (3) particularly

with the upper limits. The minimum proportion of stone dust required to prevent propagation at any concentration of the coal dust/stone mixtures, calculated from equation (2), was 57 per cent at a total dust concentration of 0.40 g/l (0.40 oz/ft<sup>3</sup>). The former value may be compared with 60-65 per cent obtained in the experiments (Fig.2), with more than 65 per cent obtained in the small scale explosibility tests (Table 3), and with 65 per cent obtained with the stone dust in a full scale mine gallery<sup>8</sup>. As explained previously<sup>4</sup>, the peak value (57 per cent) is a more severe check on the validity of the theory than are the flammability limits which are subject to chance variations in concentration of the suspension. The limits would also be affected by the fact that the explosions were initiated at a closed end of the tube, thus probably altering the dust concentration during the experiment because of movement of suspension ahead of the flame caused by expansion due to the combustion. No correction for this expansion effect was made to the calculated lines. In addition, evidence was obtained previously<sup>4</sup> that considerable quantities of both dust and air could pass through the flame front unburnt, particularly at the higher concentrations. Non-uniformity in the flame would tend to increase the upper flammability limits, the experimental values of which were much higher than the calculated values.

Exact agreement between the calculated peak value and that obtained by experiment would be unlikely. Inspection of equation (2) shows that the quantities  $T_1$ ,  $x_1$ , and  $r$  all depend directly upon the value taken for the lower flammability limit of the volatiles. In solving the equation for  $y_1$  an error in the lower flammability limit would affect numerator and denominator in opposite senses, thus leading to a relatively large variation. It may be seen from Table 2 that the value of 0.09 g/l (0.09 oz/ft<sup>3</sup>) taken for the lower flammability limit of the coal dust alone may be in error by at least 10 per cent. This would lead to a corresponding variation in the calculated peak value and should be considered when comparison is made with the various experimental results.

The application of equations (1) and (3) to the results for coal dust/sodium chloride (Fig.3) showed clearly that the theory had broken down. The peak value obtained in the experiments was about 15 per cent sodium chloride in the mixture, whereas the calculated value was 60 per cent. Clearly the sodium chloride is far more effective in preventing explosion than would be expected on the basis of its thermal properties alone and some further explanation must be sought. Sodium iodide, in conjunction with phenol

formaldehyde resin dust<sup>9</sup>, also showed greatly improved effectiveness over that which would be expected on the grounds of thermal properties alone. However, sodium bicarbonate did not show this increased effectiveness<sup>9</sup>. The indication is that the halide portion of the diluent molecule is particularly effective in suppressing explosion but the mode of action has not been established. One conclusion would be that the halogen interfered with the flame processes and thereby exerted a chemical inhibition effect on the flame reactions. Alternatively, but probably less likely, the halogen may interfere with the production of volatiles from the dust particles, possibly changing the decomposition pattern so that fewer combustible volatiles are evolved and more solid non-volatile residue is produced. There is insufficient evidence available at present to reach any firm conclusion.

On comparing the effects of the limestone and the sodium chloride on the explosibility of the coal dust, it is clear that the sodium chloride could not have been regarded as acting solely as a thermal sink, but that the limestone might well have. In any event the chemical inhibition properties of the limestone if they existed, were relatively small and the major part of the explosion suppression properties of the limestone could be accounted for on a straightforward thermal sink theory. There is a need for further information on the structure of the dust flames, and also for a more precise measurement of the lower flammability limit of both the coal dust itself and also the volatiles evolved from it. If this information were obtained, equation (2) could be used more effectively to predict the effect of other diluents providing their thermal properties, particularly specific heat, and their variation with temperature were known. The equation could also be used to select diluents which acted by thermal means from those which showed some form of chemical effect.

#### VOLATILE CONTENT AND STONE DUST REQUIREMENT

The minimum proportion of stone dust required to prevent explosion in coal dust has been calculated from equation (2), and this treatment may be extended to enable the stone dust requirement for coals of other volatile contents to be estimated. The extrapolation necessarily involves some further assumptions, but it is of interest to make because the relationship between stone dust requirement and volatiles content has been extensively studied in large scale mine tests. Typical results are those reported for a mine gallery 1.22 m (4 ft) in diameter<sup>15</sup> using Fullers earth as the diluent dust.

The assumptions required in using equation (2) for various coals are that the stoichiometry and the heat of combustion of the coals and their volatiles remain constant, as does the mean specific heat of the non-volatile residue from the coals. As already stated the proportion of volatile yielded by a coal particle depends upon whether the coal is of the swelling type or not, as well as upon the proximate analysis<sup>11</sup>. For swelling and non-swelling coals the loss in volatiles was 1.7 and 1.3 times the respective amounts determined by the standard method<sup>10</sup>. From the data available<sup>11</sup> it appears that the factors 1.7 and 1.3 remain fairly constant for swelling and non-swelling coal, irrespective of the rank of the coal.

Lines calculated from equation (2) for both swelling and non-swelling coals, are shown in Fig.6, together with the line representing gallery tests with coal dust/Fullers earth mixtures. The diluent dust was assumed to have a mean specific heat of 0.29, i.e. that of limestone, and the lines show the proportion of diluent calculated to be required to prevent propagation of explosion in coals of various volatile contents as determined by the standard method<sup>10</sup>.

The calculated total dust concentrations varied only slightly, from 0.40 g/l for high volatile content coals to 0.47 g/l (0.47 oz/ft<sup>3</sup>) for low volatile coal just capable of sustaining explosions. The experimental values, using Fullers earth, varied irregularly between 0.25 and 0.60 g/l (0.25 and 0.60 oz/ft<sup>3</sup>) with a mean of 0.47 g/l (0.47 oz/ft<sup>3</sup>) for eleven coals covering a wide range of volatile contents<sup>15</sup>. Both calculated lines (Fig.6) underestimated the proportion of diluent required, but exact comparisons could not be made because of uncertainty regarding the thermal properties of Fullers earth. In particular, the specific heat was not reported<sup>15</sup>. The general shapes of the curves were, however, similar and each of them indicated that no diluent would be required if the volatiles content of the coals were below certain critical values. These values were 14 per cent for swelling coals and 18 per cent for non-swelling coals, they may be compared with a value of 12.5 per cent obtained by extrapolation from the gallery experiments. The total dust concentrations were in good agreement. In addition, if the constants in equation (2) were adjusted so that the calculated lines in Fig.6 covered on 12.5 per cent volatiles, the percentage of limestone required for the swelling coal of volatiles content 36.4 per cent would be 60 per cent. The experimental values were 60-65 per cent (see above).

Judged on the basis of calorific value alone, there would be no clear reason why coals containing less than 12.5 per cent volatiles should not



propagate dust explosions. Nevertheless, both experimental tests and practical experience have confirmed that coals having low volatile contents do not present a dust explosion hazard. The coals can be burned in a pulverised fuel furnace, but under these conditions the particles are in a heated enclosure. If, however, it is accepted that the non-volatile residue formed when the coal dust particle enters a flame can act as a heat sink, as is proposed in the present work, then a physical reason for the observed behaviour in gallery and furnace is apparent. Although the agreement between the calculated and observed values was only moderate, the general trends were correct and would justify further measurements of the thermal properties of the dusts under explosion conditions.

In addition, a review would be timely of all the available evidence on the relationship between diluent dust requirement and volatiles content of coals. Information has been published in a number of countries, based on experiments often on very large scale, but the general picture is at present rather confused. In particular the dependence of the results on the type and size of ignition source needs to be assessed to ensure that comparisons are made only between explosions that have propagated away from the influence of the source of ignition. The work reported here should give some guidance towards clarifying the position, and it is also capable of simple extension, e.g. to the calculation of the lower flammability limits of coals of various volatile contents.

#### CONCLUSIONS

1. The minimum amount of limestone dust required to prevent explosion in coal dust dispersed as a cloud in air in a 25 cm diameter vertical tube was in good agreement with the value reported elsewhere for a mine gallery of 1.2 metres diameter.
2. The results with limestone dust were in general agreement with calculated values based on the thermal properties of the dusts. The calculations could be satisfactorily extended to cover coals of different volatile content.
3. The relationship between the explosibility of coal dust/limestone mixtures in the large scale vertical tube apparatus and in the small scale tests are similar to that established previously with other fuels and diluents.
4. The agreement between the results for the vertical tube and the mine gallery indicated that conclusions reached for other industrial dusts in the vertical tube would apply to larger-scale industrial plant.
5. Sodium chloride was much more effective than limestone in preventing explosion in coal dust clouds. The effectiveness was much greater than indicated by calculations based on its thermal properties alone.

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The results in Table 3 were obtained by Miss M. M. Raftery and Mrs. J. S. Harris.

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## APPENDIX 1

### VOLATILES PRODUCTION UNDER FLAME CONDITIONS

As the flame temperature is of the order of  $10^3$ °C and the flame velocity is of order  $10^2$  cm/s (Table 4) the rate of temperature rise of small particles entering the flame will be of order  $10^4$  or  $10^5$ °C/s. Under these conditions of rapid heating the amount of volatiles produced from coal differs from that obtained when the volatiles content of coal is measured by the standard procedure<sup>10</sup>. A greater amount of volatiles is released on rapid heating, the increase depending upon whether the coal is of the swelling or non-swelling type<sup>11</sup>. In the present work a swelling coal was used<sup>12</sup>.

On heating coals rapidly in an inert atmosphere, the maximum weight loss  $W$  is given by<sup>11</sup>.

$$W = Q VM_0 (1 - C)$$

where  $Q$  is a factor representing the increase in volatiles production.

$VM_0$  is the volatile matter content expressed on a dry ash-free basis and determined by standard procedure<sup>10</sup>

$C$  is a constant.

For swelling coals  $C$  is small compared with unity, at temperatures about 1200°C (see below), and  $Q$  is approximately 1.7. The loss in volatiles was thus 1.7 times that determined by the standard method<sup>10</sup>. For non-swelling coals,  $C = 0.14$ , and  $Q$  is approximately 1.5. Thus the total loss of volatiles would be greater by a factor of 1.3 than for slow rates of heating.

## APPENDIX 2

### LOWER FLAMMABILITY LIMIT OF VOLATILES ONLY

For the purposes of calculation it is necessary to know the lower flammability limit of the volatiles from coal, in the absence of the non-volatile component, and with negligible air movement ahead of the flame. The lower limit of the volatiles cannot be measured directly from the experiments, and the results in Table 2 have been used as a basis for an estimate as follows.

The lower flammability limit of coal dust was taken as 0.09 g/l (0.09 oz/ft<sup>3</sup>) (Table 2) and because of the continued downward movement of burning particles, after ignition, the dust concentration as measured was taken as the relevant concentration. The flame was envisaged to propagate from particle to particle, and as the relative separation of particles would remain constant, the concentration would not be affected by the downward movement of the dust cloud.

The fraction of volatiles, produced by the coal at rapid rates of heating, is  $0.364 \times 1.7 = 0.62$  (see Appendix 1).

Hence, the concentration of volatiles in the observed lower limit flame was  $0.09 \times 0.62 = 0.056$  g/l (0.056 oz/ft<sup>3</sup>). This value is not the true lower limit concentration of the volatiles because of the heat sink effect of the non-volatile fraction of the coal. An estimate of this effect has been made by comparing, for the lower limit flame, the sink effects of the surplus air with that of surplus air plus non-volatile fraction. Considering firstly the heat sink effect due to surplus air, the quantity of surplus air per litre of dust suspension is given by

$$\frac{0.11 - 0.056}{0.11} \text{ litres}$$

of air measured at room temperature, where the stoichiometric mixture contains 0.11 g/l (0.11 oz/ft<sup>3</sup>) of volatiles in air. This value for the stoichiometric mixture of the volatiles was taken because it is the same for various coals and cokes<sup>12</sup>.

The load of non-volatiles is  $0.034 \times 5$  g, where an expansion ratio of 5 has been taken (see below). The expansion ratio factor was applied because the volatile constituents expand on heating whereas the non-volatiles were assumed to effectively change their concentration<sup>4</sup>.

The heat load arising from 0.17 g of non-volatiles is equivalent to the load caused by

$$0.17 \times \frac{0.23}{0.27} \times \frac{22.4}{28.8} \text{ litres}$$

of air at atmospheric temperature and pressure. The specific heat of air was taken as 0.27, and the mean specific heat of the non-volatiles was derived as 0.23; this latter value was obtained from a heat content of 261 cal/g, for a temperature rise of 1160°C<sup>13</sup>. The heat content was obtained by extrapolation from an observed temperature range up to 756°C of a char from a high volatile bituminous coal previously carbonized at 927°C.

The additional heat load due to the non-volatiles was therefore equivalent to that of 0.11 litres of air.

Thus the lower limit of the volatiles, in the absence of non-volatiles, would be given by

$$\frac{0.056}{1.11} = 0.050 \text{ g/l}$$

This value may be compared with 0.045 g/l obtained with phenol formaldehyde resin<sup>4</sup>, and with the values in the range 0.045-0.050 g/l for many gas and liquid hydrocarbons. The calculated lower limit of the volatiles was in reasonable agreement with these values.

With a lower flammability limit concentration of 0.050 g/l, and taking the heat of combustion of coal and coal products as 8,300 cal/g<sup>12</sup>, the mean flame temperature at the lower flammability limit was calculated to be 1510°K.

Hence

$$r = \frac{1510}{300} = 5.0$$

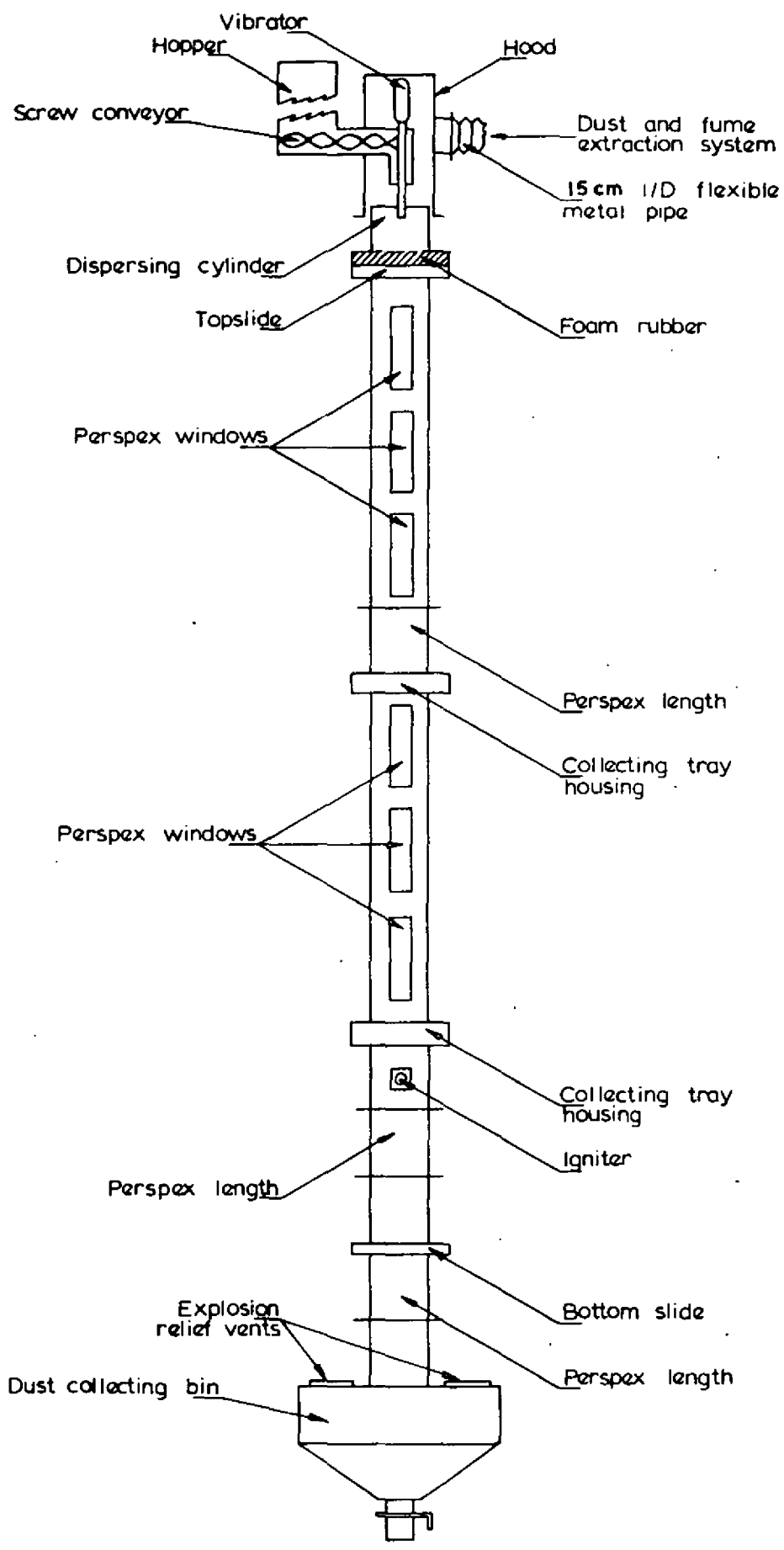


FIG.1. VERTICAL 25 CM I/D DUST EXPLOSION TUBE

13505-4-8-47 17993-1-10-87  
 FER 078 + 1087  
 17993-1-10-87  
 13505-4-8-47

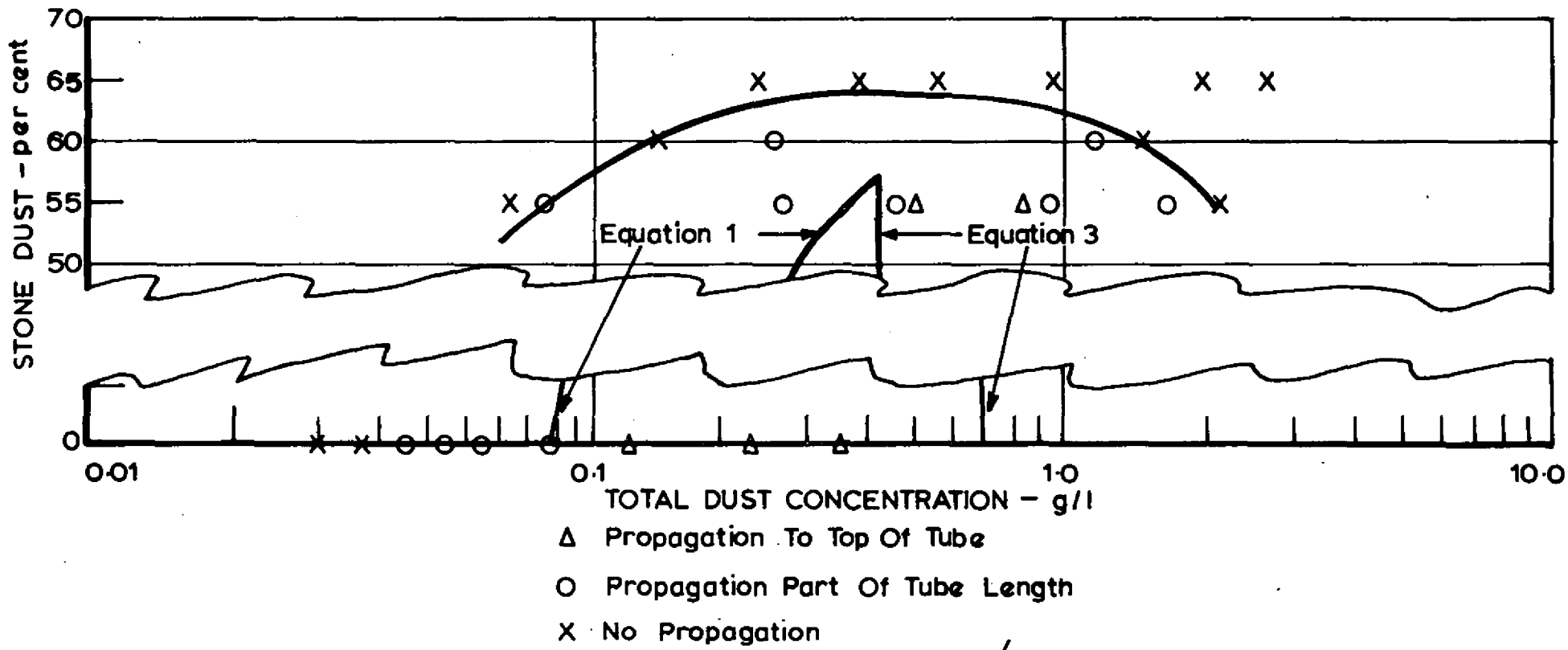


FIG.2.FLAMMABILITY LIMITS OF COALDUST/STONE DUST MIXTURES  
(TOP OF TUBE OPEN, BOTTOM CLOSED)

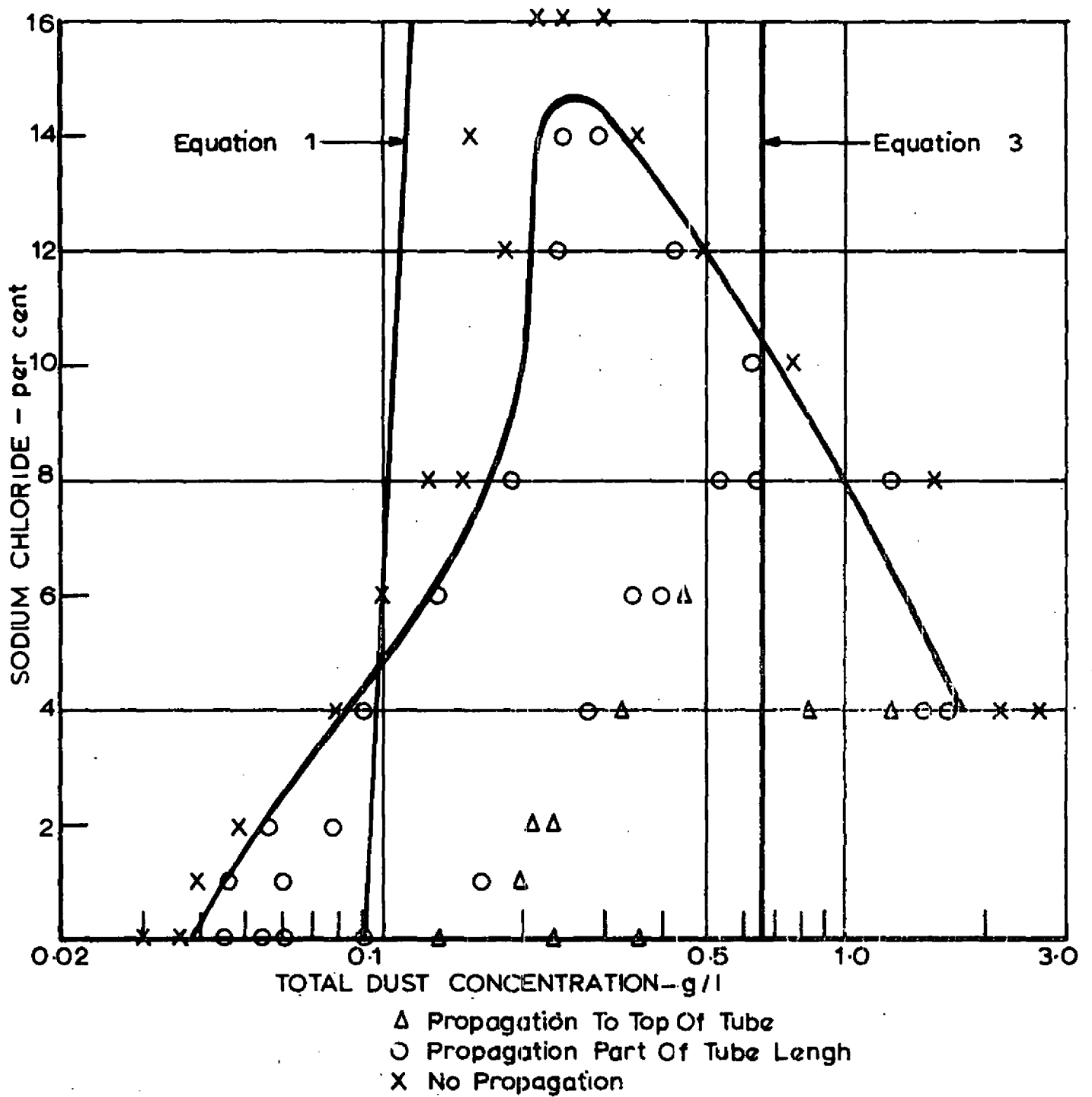


FIG.3. FLAMMABILITY LIMITS OF COAL DUST/SODIUM CHLORIDE MIXTURES (TOP OF TUBE OPEN, BOTTOM CLOSED)

1/7905 FR 607



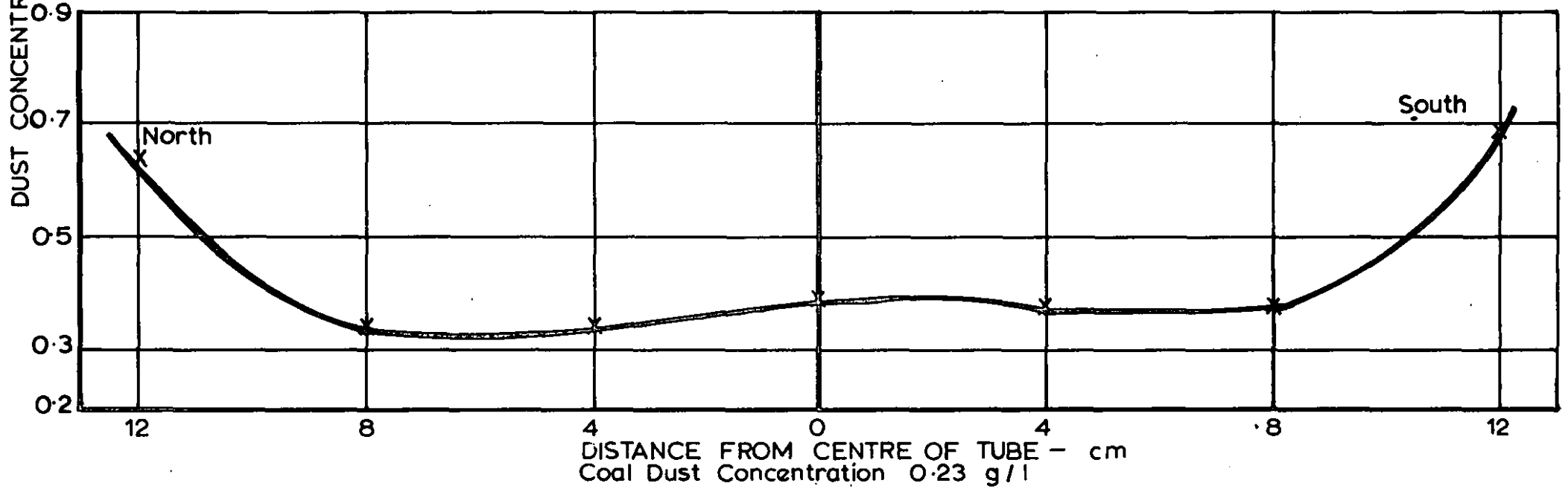
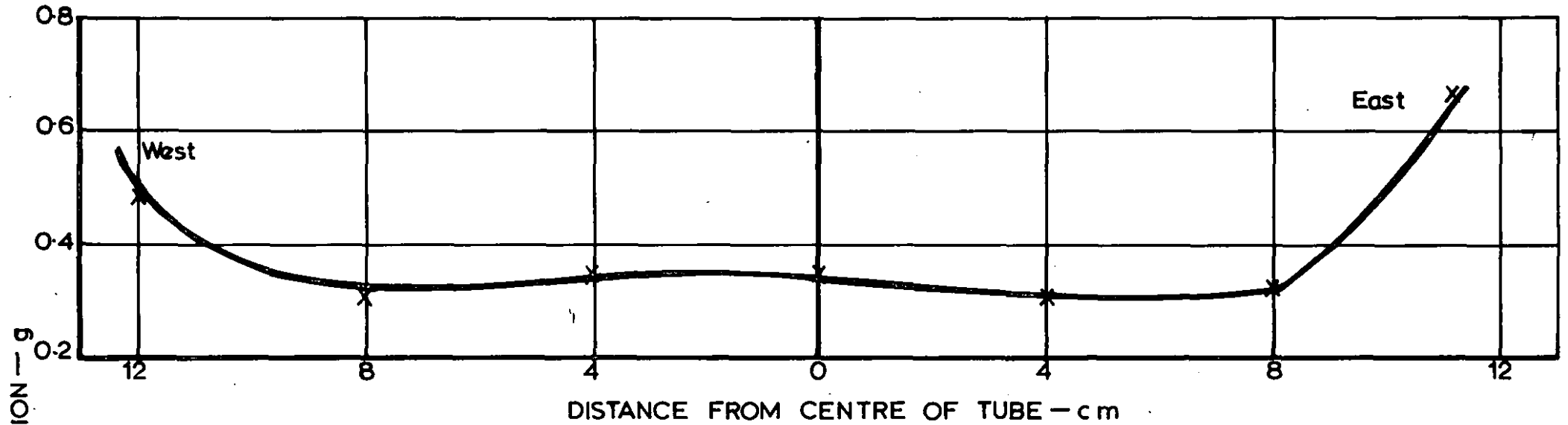


FIG. 4. DUST DISTRIBUTION ALONG TWO DIAMETERS OF THE EXPLOSION TUBE

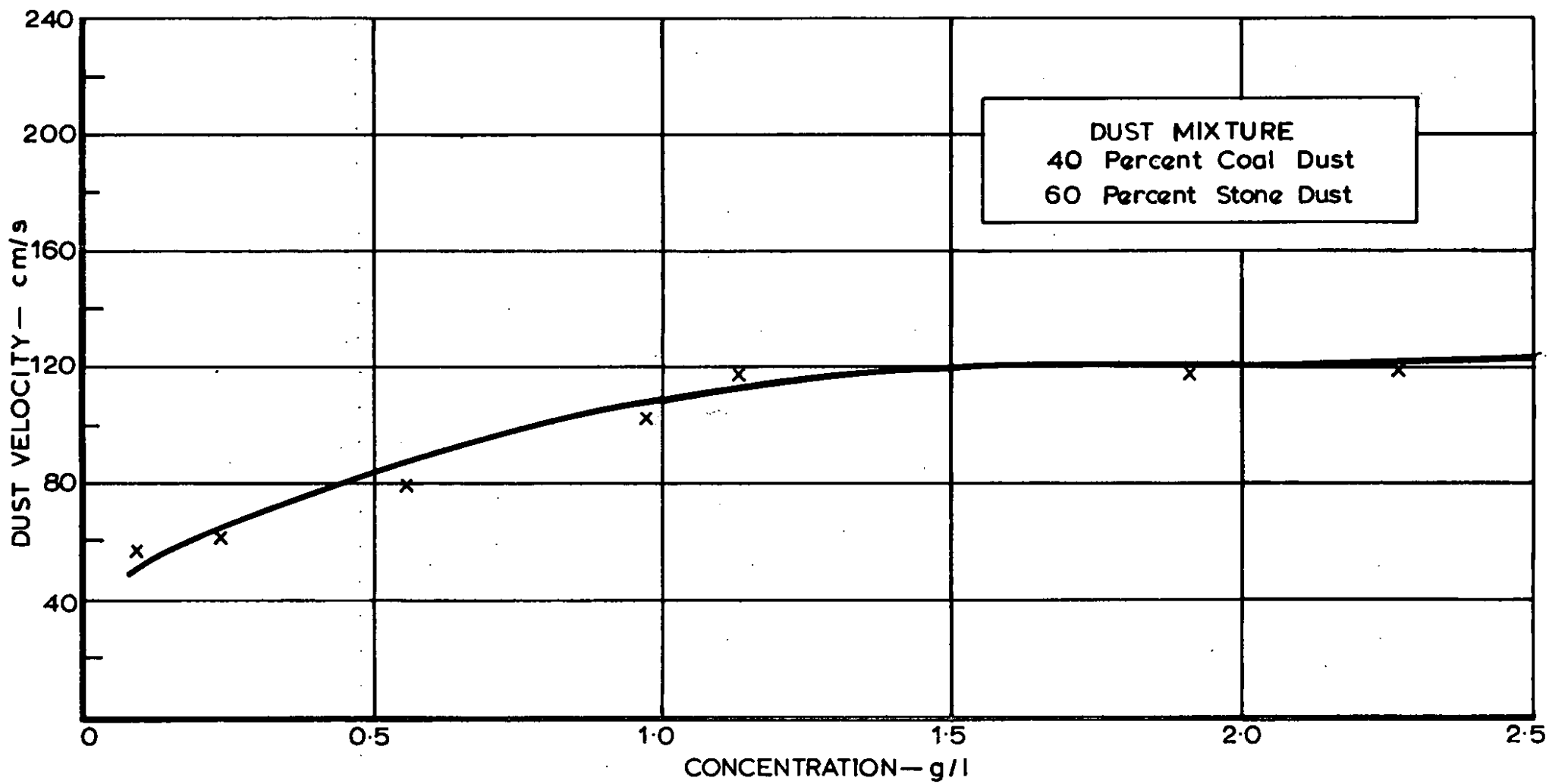


FIG.5. FALLING DUST VELOCITIES AT VARIOUS DUST CONCENTRATIONS

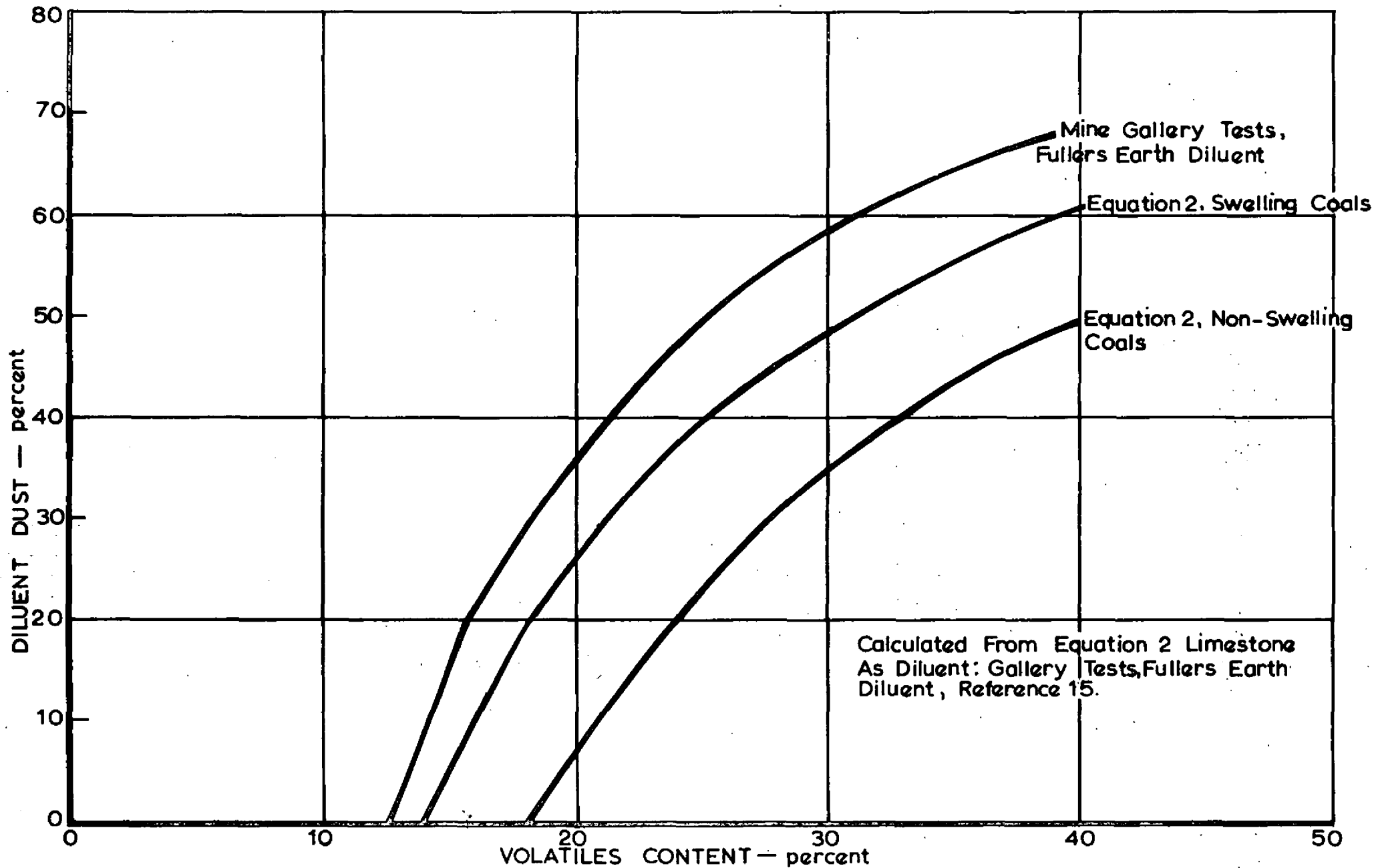
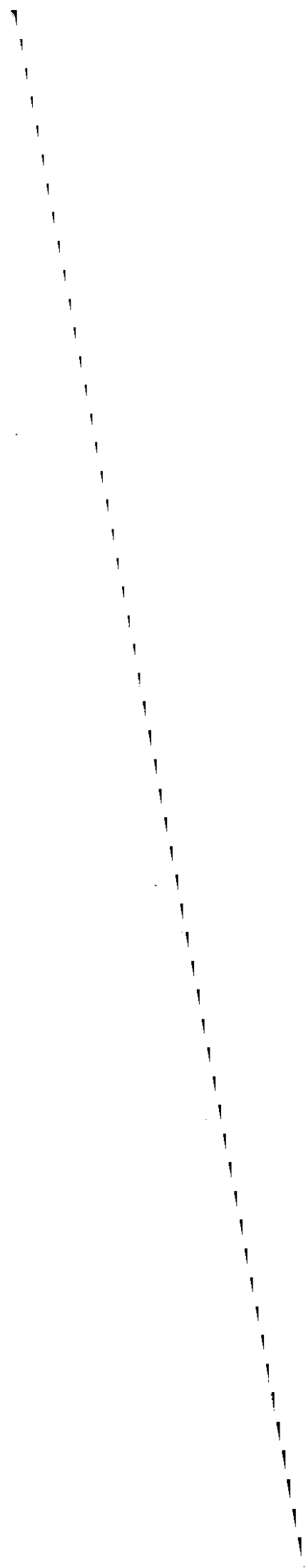


FIG. 6. VARIATION OF MINIMUM PERCENTAGE OF DILUENT TO PREVENT EXPLOSIONS WITH VOLATILES CONTENT OF COALS



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