

IGNITION AND COMBUSTION OF DUST CLOUDS IN HOT ENVIRONMENTS -  
AN EXPLORATORY STUDY

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Standard tests for the flammability and explosibility classification of dust clouds are carried out at ambient temperatures. However, many industrial operations (e.g. drying) operate at elevated temperatures. The effect of this on the explosibility classification, ignition sensitivity and pressure/time characteristics has been studied. The relevance of the results obtained is discussed with respect to the statutory and design requirements for protection against dust explosions.

INTRODUCTION

Section 31 of the Factories Act (1961) states that where a dust, which is liable to explode on ignition, is used in any plant or process then all practicable steps shall be taken to restrict the spread and effects of such an explosion. More recently, the Health and Safety at Work, etc., Act (1974) places the onus on the manufacturer of a chemical to ensure the safety of his proposed operations with that chemical. A manufacturer has to ascertain, therefore, whether his materials and the operations in which they are used present an explosion hazard. An essential part of this is the explosibility (flammability) classification of any dust clouds produced from his materials.

In the United Kingdom, dust explosibility classification is based on the results of a set of three standard tests, shown in Table (1), which are described in detail by Raftery (1).

TABLE 1 - Standard Explosibility Classification Tests

Apparatus	Direction of Dispersion of Dust	Ignition Source
Vertical tube	Vertically upwards	Electric spark or electrically heated wire coil
Horizontal tube	Horizontally	Electrically heated wire coil at 1300°C
Inflamator	Vertically downwards	Electric spark or electrically heated wire coil

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In each test, the dust is dispersed by a blast of air into a glass tube at ambient temperature and a source of ignition is applied. Dusts are classified as Group (a) if they ignite and propagate flame in any of the three tests with a small source of ignition. Such dusts are regarded as explosible, liable to give rise to a dust explosion hazard and as coming within the scope of Section 31 of the Factories Act (1961). Dusts which do not propagate flame in any of the tests are designated Group (b) and are classified as non-explosible though they may present a fire risk.

Previously dust samples were tested with a wider range of conditions and were classified as follows:

- Class I : Dusts which ignite and propagate flame readily with a small ignition source in an ambient temperature environment (No.1 Wheeler Test).
- Class II : Dusts which do not ignite in the Wheeler Test but which ignite readily with flame when dispersed in a heated atmosphere (Godbert-Greenwald Furnace Test).
- Class III : Dusts which do not ignite in either test.

Palmer (2) states that as a general guide, dusts which previously were Class I may now be taken as Group (a) whereas those previously Class II and III are now regarded as Group (b).

If a dust is shown to be explosible, further information on the extent of the explosion hazard may be required when considering suitable precautions for the safe handling of the dust. Two parameters which can be used are the ignition sensitivity of the dust cloud and its maximum explosion pressure and rate of pressure rise.

The tests used to classify the explosibility of a dust cloud as Group (a) or Group (b) and those used to determine its explosion parameters are all performed at ambient temperatures. Since chemical reaction rates increase with temperature, the ignition and propagation of a flame through a dust suspension would be expected to occur more readily if the temperature of the dust and its surroundings were above atmospheric. Above ambient temperatures often arise in industrial plant such as dryers and furnaces.

Up to the present little consideration has been given to the effect of temperature on the explosibility classification of powders and its significance to statutory requirements. The effect of a heated environment on the parameters which define the ignition sensitivity and violence of an explosion that are used to prescribe safety precautions have seldom been studied. This paper reports the results of a preliminary investigation into these factors and discusses the implication of the results obtained vis-a-vis statutory requirements and explosion protection.

#### EXPLOSIBILITY CLASSIFICATION

The I.Chem.E. User Guide for Dryers (3) recognises that the classification of dusts into Group (a) and (b) is not valid in heated air and that some Group (b) dusts, e.g. those which were originally Class II, may be explosible at higher temperatures. The Guide suggests that in the absence of any test involving localised ignition sources in hot environments, a classification of explosibility could be based on whether the dust propagates flame in a Godbert-Greenwald Furnace held at 1000°C, the apparatus being the same as for the determination of the minimum ignition temperature (1).

This proposal would result in all Class II dusts being regarded as capable of forming explosible dust clouds and coming within the scope of Section 31 of the Factories Act when used at temperatures above 110°C. It is recognised that using this criterion some materials that would not be capable of sustaining or propagating flame in a plant situation may be classified as explosible. This is because (i) the proposed temperature (1000°C) is greater than that employed in the majority of industrial operations; (ii) the test does not simulate the more common occurrence of a localised ignition source in a heated environment. The latter, more realistic, situation has been examined to determine its effect on classification.

#### Effect of Temperature on Classification

Test Equipment and Procedures. Nagy and Surincik (4) have shown that when a dust is dispersed through a standard Godbert-Greenwald furnace most of the dust cloud passes through unheated. In order to ensure that a heated dust cloud was produced, a Godbert-Greenwald furnace was modified so that both the dust and dispersing air could be preheated to the furnace temperature. A localised ignition source, provided by an electrically heated platinum wire coil similar to that used in the horizontal tube test (1), was situated at the bottom of the furnace tube (Figure 1). The ignition coil was maintained at 1300°C as in the Group (a)/(b) classification tests. The temperature of the furnace, sample holder and dispersion air reservoir was maintained at 200°C. Although dryers operate at higher temperatures (e.g. up to 500°C for Spray Dryers) the evaporative load normally reduces the temperature of the dry powder and any dust cloud to 130-200°C.

In order to test a sample, the dispersion air reservoir was filled to between 15 and 35 kNm<sup>-2</sup> and a small quantity of the dust was placed in the sample holder. The apparatus was left for several minutes to allow the air and dust to reach 200°C before the dust was dispersed through the furnace and past the ignition coil. Each dust was tested a minimum of five times with differing air dispersion pressures and sample quantities. It was considered that an ignition had occurred if flame propagated away from the ignition source and out of the bottom of the furnace tube.

Samples. Ten organic materials representative of Class II dusts used in the Chemical Industry (i.e. pigments, dyes) were tested. To ensure good dust dispersion the particle size of the samples was less than 75 micron. Powders which had a thermal decomposition temperature of greater than 200°C were chosen so that an ignition could not be attributed to the decomposition of the powder or evolution of flammable volatiles. The samples represented materials that are normally dried at temperatures exceeding 110°C.

Results. It was found that three of the ten Class II dusts ignited in the test. This indicates that although the test involving the furnace at 1000°C is too critical, there are a significant number of dusts, classified as Group (b) that can be ignited by a localised heat source in a hot environment. Such materials could propagate flame and therefore give rise to dust explosions. However, none of the dusts ignited if the sample and dispersion air were not heated.

#### IGNITION SENSITIVITY

The effect of increasing temperature on the ignition sensitivity of a dust cloud has been assessed:

- (a) by measuring the temperature of a heated wire coil required to produce ignition and

(b) by determining the minimum spark ignition energy.

Samples. Lycopodium powder and hydroxy propyl methyl cellulose powder with a particle size of less than 75 micron were used. Gravimetric analysis of the powders showed that there was a 3% weight loss when a sample of lycopodium powder was heated to constant weight at 150°C, while hydroxy propyl methyl cellulose showed a 2% weight loss when heated to constant weight at 100°C. Mass spectrometric analysis showed that with both powders only water vapour was being evolved. The ignition sensitivity tests, described below, were carried out with the undried samples and repeated with samples that had been heated to constant weight in order to differentiate between the effect of temperature and of water loss.

#### Ignition with Heated Coil

The apparatus and procedure was similar to that described above. The temperature of the sample holder, dispersion air reservoir and furnace was held at ambient, 50°C and 100°C while the temperature of the ignition coil was altered in 10° increments until ignition occurred. Five tests were performed with differing dispersion air pressures and sample quantities at each ignition coil temperature. The results are shown in Table (2).

TABLE 2 - Effect of Dust Cloud Temperature on the Coil Temperature Required for Ignition

Temperature of Dust Cloud (°C)	Coil Temperature Required for Ignition (°C)			
	Lycopodium		Hydroxy propyl methyl cellulose	
	Undried	Dried	Undried	Dried
Ambient	920	930	950	950
50	910	920	940	920
100	890	900	860	870

Increasing the temperature of the dust cloud decreases the ignition coil temperature required to produce ignition. Since both the dried and undried samples showed a similar variation, this change is not primarily due to loss of water before ignition.

#### Minimum Spark Ignition Energy

The sensitivity of a dust cloud to ignition by electric discharges is defined by its minimum spark ignition energy and is measured at ambient temperatures using a modified version of the Vertical Tube Apparatus (1). A previous study, by Carpenter and Davies (5), of the minimum ignition energy of heated dust clouds was confined to experiments using coal dust with differing degrees of volatiles. The results showed that the minimum ignition energy decreased with increasing temperature but that a minimum value was obtained, and at higher temperatures the minimum ignition energy rose sharply. This increase was attributed to reaction of the dust with the oxygen of the air before dispersion. However, the results obtained may be considered specific to dusts which contain a flammable volatile component. In some ways the mixture they

produce when heated can be considered analogous to a hybrid mixture for which Bartknecht (8) has shown that the vapour component can increase the sensitivity of the mixture to ignition even though it is below its lower flammable limit. The effect of temperature on the minimum ignition energy has therefore been measured for two samples that do not give off flammable vapours over the temperature range studied.

Test Equipment and Procedures. The apparatus used in the present study to determine the effect of temperature on the minimum ignition energy is shown in Figure 2. The ignition tube, air reservoir, and dust dispersion cup could be heated to 150°C. 4 mm brass electrodes with hemispherical tips were used and the electrode gap was set so that breakdown occurred at 10 kV. Capacitative discharge sparks, the energy of which was calculated by  $\frac{1}{2} CV^2$  Joules, were produced by the circuit shown in Figure 3. Although there is considerable debate as to the most appropriate means of measuring the minimum ignition energy of a dust cloud (7), a capacitative discharge has been used in this investigation as it is considered to simulate an electrostatic discharge from insulated metal plant.

A range of dust cloud concentrations was obtained by varying both the quantity of the dust and the pressure of the dispersion air. Observations were made until the lowest spark energy at which flame propagation away from the electrodes through the dust cloud was obtained. The criterion for "no-ignition" was based on 50 tests.

Results. The effect of temperature on the minimum ignition energies of lycopodium powder and hydroxy propyl methyl cellulose are shown in Figure 4. It can be seen that the minimum ignition energy for both powders decreased markedly as the temperature increased. The minimum ignition energy of lycopodium powder was reduced from 90 mJ at room temperature to 12.5 mJ at 150°C while that of hydroxy propyl methyl cellulose was decreased from 160 mJ at ambient to 40 mJ at 100°C.

The minimum ignition energy of lycopodium powder measured in this study is higher than has previously been reported by Eckhoff (7). This is in part due to differences in the spark discharge circuit. The minimum ignition energies reported here are intended to demonstrate the effect of temperature and should not be regarded as absolute values for either material.

#### EXPLOSION VIOLENCE

A measure of the violence of a dust explosion is given by the maximum explosion pressure and maximum rate of pressure rise developed in a closed container. In the U.K. these parameters are measured in the Hartmann Bomb which is a strengthened version of the Vertical Tube Apparatus (1) and has a volume of 1.2 l. Values of the maximum explosion pressure are required if a plant is to be sufficiently strong to contain the full explosion pressure. Alternatively the maximum rate of pressure rise is required if explosion venting or suppression is to be used to protect against the effects of an explosion.

Equipment and Procedure. In order to determine the effect of temperature on these two explosion parameters, a Hartmann Bomb was fitted with heaters such that the bomb, dust dispersion cup and air reservoir could be heated to 100°C. The test procedure differed from the standard in two respects: (i) ignition of the dust cloud was produced by a cerium/magnesium fuse head which gives multi-point ignition and therefore reduces the cooling effect of the test vessel walls, (ii) during the test the optimum delay between dust dispersion and ignition using different dust concentrations was first determined. Gibson (8)

has reported that these conditions minimise the imperfect dust dispersion of the Hartmann bomb and increase data reproducibility.

Dust concentrations were selected to span the stoichiometric mixture and ten experiments were obtained for each concentration tested.

Samples. Lycopodium powder, terephthalic acid and giberilic acid with a particle size of less than 75 micron were used in the tests. The lycopodium powder was used undried; gravimetric analysis of terephthalic and giberilic acid showed no weight loss at 150°C.

Results. Table 3 shows the maximum explosion pressure and maximum rate of pressure rise at ambient temperature and 100°C for the three dusts. A series of experiments showed that the results obtained varied by less than 5%.

TABLE 3 - Effect of Temperature on Maximum Explosion Pressure Rise and Maximum Rate of Pressure Rise

	Max Explosion Pressure Rise (kNm <sup>-2</sup> ) P max			Max Rate of Pressure Rise (kNm <sup>-2</sup> ms <sup>-1</sup> ) (dP/dt) max	
	Measured		Calculated 100°C	20°C	100°C
	20°C	100°C			
Terephthalic acid	653	506	491	37.9	53.1
Giberilic acid	623	496	468	66.2	77.2
Lycopodium powder	707	534	533	59.3	69.6

The effect of temperature on the maximum pressure developed in a constant volume system can be predicted from a simple model if it is assumed that the maximum temperature, T<sub>m</sub>, reached by the combustion products is independent of the initial temperature, T<sub>0</sub>.

$$P_m = P_0 \frac{\bar{M}_u}{\bar{M}_b} \frac{T_m}{T_0} \dots \dots \dots (1)$$

Nagy (9) states that  $\frac{\bar{M}_u}{\bar{M}_b}$  may be regarded as constant hence the maximum pressure is inversely proportional to the initial temperature and the value at the elevated temperature may be calculated from that measured at ambient. Comparison in Table 3 shows reasonable agreement considering the simplicity of the model. The decrease in maximum pressure that can be expected in heated industrial environments can therefore be calculated from data obtained at ambient temperatures.

No previous data on the effect of temperature on the maximum rate of pressure rise of dust clouds are known. This exploratory study indicates that (dP/dt) max increases with increasing temperature.

An analytical treatment (9) indicates that the variation of (dP/dt) max includes a quadratic function of initial temperature but the measured increase for methane-air does not have this magnitude. Furthermore, data in N.F.P.A.

(10) shows  $(dP/dt)$  max increasing and decreasing with temperature for different gases and vapours. A more detailed study of this topic is required, however, the present data indicates that the change in  $(dP/dt)$  max caused by increases in temperature that can occur in industrial processes are not insignificant and may well have to be incorporated into the design of explosion vents and suppression equipment.

#### IMPLICATIONS FOR EXPLOSION PROTECTION

While the results presented are only a preliminary study of the problems arising with heated dust clouds, they clearly show that a moderate increase in temperature can alter the explosibility classification of the materials, increase its ignition sensitivity, and change its pressure-time characteristics. The most disturbing effect is the substantial increase in the sensitivity to electrostatic spark ignition.

A Group (b) classification does not, therefore, exclude the possibility of an explosion and the need to provide explosion protection if the dust cloud is dispersed in heated air. The Godbert-Greenwald Furnace Test at 1000°C provides a too stringent and unrealistic definition of explosibility. A more accurate simulation of industrial situations is required and a classification based on a test using a localised ignition source in a heated environment needs to be developed. The detailed specification of a test cannot be made from the limited evidence available and it is unlikely that one set of conditions will be uniquely superior to all others. The present work indicates that preheating of the sample and dispersing air is essential; experience also suggests that the heated environment might be better based on the Vertical Tube Apparatus rather than the short Godbert-Greenwald Furnace.

In powder processes safety can rarely be based on the control of ignition sources and has to be achieved by explosion protection. The most common exceptions to this are processes in which electrostatic discharges are the only source of ignition (e.g. pneumatic transfer lines). The reduction in minimum ignition energy with increasing temperature is therefore of potential practical significance. If this effect is confirmed for other dusts then, in heated environments, the type of protection needed against static electricity could change from the minimum (i.e. earthing of plant) to a level at which the control of insulated conductors, plastics and discharges from the powder itself may have to be considered - a much more complex situation.

The significance of the Temperature/Pressure-Time relationship is complex and detailed evaluation requires further work. If protection is based on containment then the reduction in maximum pressure rise with increasing temperature will enhance safety.

The value of the maximum rate of pressure rise is crucial to the design of explosion vents and suppression systems. The measured changes in this parameter (17-40%) are significant and if the same dependence continues at higher temperature levels then it is a factor which must be incorporated into explosion protection design. The limited nature of this investigation and the conflicting data on vapours shows that more work is required before definite conclusions can be made.

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SYMBOLS USED

$\bar{M}_u$	= average molecular weight of unburnt fraction
$\bar{M}_b$	= average molecular weight of burnt fraction
$P_o$	= initial pressure ( $\text{kNm}^{-2}$ )
$P_m$	= final pressure ( $\text{kNm}^{-2}$ )
$P \text{ max}$	= maximum explosion pressure rise ( $\text{kNm}^{-2}$ )
$(\frac{dP}{dt})_{\text{max}}$	= maximum rate of pressure rise ( $\text{kNm}^{-2} \text{ms}^{-1}$ )
$T_o$	= initial temperature ( $^{\circ}\text{K}$ )
$T_m$	= final temperature ( $^{\circ}\text{K}$ )

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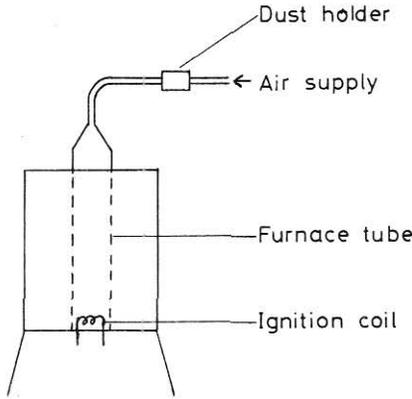


Figure 1 Furnace apparatus

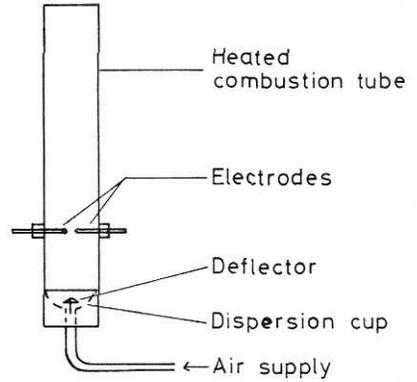


Figure 2 Minimum ignition energy apparatus

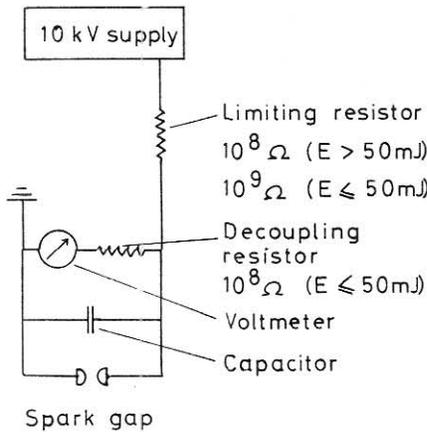


Figure 4 Capacitive spark generator

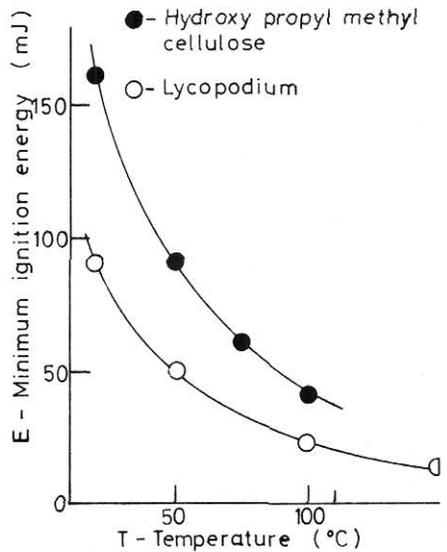


Figure 4 Variation of minimum ignition energy with temperature