A plausible mechanism for initiation of dust explosions by electrostatic spark discharges in industrial practice

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Abstract

A study of ignition of dust clouds by electrostatic spark discharges triggered by the explosive dust cloud itself has been performed. This trigger mechanism probably operates when dust explosions are initiated accidentally by electrostatic sparks in real industrial situations. In conventional methods for determining the minimum ignition energy (MIE) of dust clouds in the laboratory, the delay between dust cloud generation and spark discharge can be chosen at liberty to create the most favourable conditions for ignition. However, this degree of freedom does not exist in an accidental industrial situation. The present investigation nevertheless indicates that for some dusts MIE values produced by the inherent dust cloud trigger method are only modestly higher than values for the same dusts obtained by standard laboratory methods. For other dusts, however, the discrepancies were considerable, and a possible main reason for this is suggested.

As opposed to the spark triggering methods used in current standard MIE testing of dusts, the inherent dust triggering method also works for spark energies < 1 mJ. It is suggested, therefore, that a new standard MIE test for dust clouds for the MIE range < 1 mJ may be developed based on this method of spark triggering. In addition to resembling an electrostatic spark ignition mechanism likely to operate in practice, this triggering method also simplifies the test apparatus. If required, an additional series inductance can easily be incorporated in the discharge circuit. However, before apparatus and test method can be specified it is necessary to resolve some remaining puzzles.

Keywords: Dust explosion; Minimum ignition energy; Spark triggering; Test method

1 Introduction

The possibility of initiation of accidental dust explosions by electrostatic sparks is a central safety concern in many industries handling combustible powders/dusts. In any hazard evaluation, the minimum ignition energy (MIE) is a central parameter (Eckhoff, 2003).

In current standard MIE testing (IEC, 1994; CEN 2002), two separate electric discharge circuits are used, one being related to electrostatic discharges, the other to intrinsic safety of electrical apparatus. The latter application, discussed by Eckhoff (2002), requires a more conservative experimental determination of MIE than the former, which implies the inclusion of a series inductance in the discharge circuit to prolong the spark discharge times. Further details are given by Randeberg and Eckhoff (2004).

Tests for determining the MIE are usually performed in a vessel of about 1 litre volume, into which a transient dust cloud is generated by exposing a given mass of dust to an air blast. The spark is delivered between two metal electrodes some pre-determined time after onset of dust dispersion, using an electronic delay system. This delay, together with the quantity of dust dispersed and the intensity of the dispersing air blast, are tuned for each type of dust to obtain the most favourable conditions for spark ignition.

The spark energy is normally taken as $\frac{1}{2}CU^2$, where C is the discharge capacitance and U the voltage to which it has been charged. Alternatively the 'net' spark energy can be determined by measuring spark current and voltage across the spark gap as functions of time during the discharge, and integrating the power versus time curve. If the total circuit resistance is significantly larger than the average spark resistance, the measured 'net' energy will be correspondingly lower than $\frac{1}{2}CU^2$.

In current standard MIE tests, optimal synchronization of onset of dust dispersion and onset of spark discharge is crucial for establishing the most favourable conditions for ignition. However, this kind of synchronization is highly unlikely in accidental initiation of dust explosions by electrostatic sparks in an industrial environment. In stead the interaction of the dust cloud itself with the spark gap most probably constitute a central element in the spark triggering process. For this reason this triggering method and the resulting MIEs were made the subject of the present investigation. Some preliminary results were presented by Randeberg and Eckhoff (2004). Further results of ongoing research will be published elsewhere in due course. The two main objectives of the present paper are:

i) To suggest that dust-cloud-initiated breakdown of high-voltage spark gaps is a plausible mechanism for initiation of dust explosions by electrostatic spark discharges in industrial practice.

ii) To suggest that this method of triggering may be used to develop a test method for determining MIE of dust clouds in the MIE range < 1 mJ.

2 The dust cloud acting as a spark trigger

Due to tribo-electric charging, non-grounded metal objects in industrial plants may obtain voltages of several kV (Cross, 1987; Lüttgens and Glor, 1989; Lüttgens and Wilson, 1997). This charging will not result in any electrical discharges as long as the field strength is within the limits of breakdown of the dielectric medium (in the present context air) between the objects acting as electrodes. However, disturbance of the electric field can initiate breakdown and subsequent spark-over.

Particle contamination of the electrode surface or in the space between the electrodes can disturb the field between the electrodes and cause the electrode gap to break down at significantly lower voltages than for a non-contaminated gap. Eckhoff (1970) described some practical experiences with this type of breakdown. When embarking on his very first experiments with electric spark ignition of clouds in air of lycopodium clavatum, he was advised to use an optical method to obtain synchronization of dust dispersion and breakdown of the spark gap. However, when dust was introduced into the system, it appeared that the spark gap broke down even if the optical synchronization system failed. It was concluded that the breakdown action could then only be due to the appearance of the dust itself at the spark gap. Further experiments showed that the spark gap, having a distance corresponding to a breakdown voltage of 10.0 kV, was readily broken down by a dust cloud even at a preset voltage of only 8.0 kV. The breakdown efficiency appeared to be dependent upon the dust concentration, so that higher concentrations were more efficient than lower, but this point was not studied in detail.

Research has revealed that breakdown by dust particles can be initiated by micro discharges produced by the particles when they approach the electrodes, and the dielectric strength of the gas may be reduced to as low as ten percent of the uncontaminated value (Laghari and Qureshi, 1981). It is shown that breakdown is initiated at a lower voltage when particles are moving freely in the space between the electrodes than when affixed to the electrode face, resulting in a sort of “trigatron” breakdown initiation (Dakin and Hughes, 1969). Both experimental and numerical analyses have confirmed that mobile objects are able to trigger breakdown at lower voltages than fixed ones (Samuila *et al.*, 1995). Large conductive particles are shown to affect the breakdown in a more pronounced way than smaller ones. Formation of particle chains is also an important factor reducing the dielectric strength of gases (Dascalescu *et al.*, 1997). Charged particles are found to decrease the dielectric strength further (Dascalescu *et al.*, 1996). For further discussion of plausible breakdown mechanisms reference is made to Randeberg and Eckhoff (2004).

The conclusion is that the dust cloud itself may be a plausible trigger of electrostatic sparks giving rise to accidental dust explosions in industrial plants.

3 Apparatus

3.1 Ignition test apparatus

The basic mechanical structure of the test apparatus is illustrated in Figure 1.The basic mechanical parts of the apparatus were identical to those of Kühner's MIKE apparatus, which is often used for determining MIEs of dust clouds according to current international (IEC, 1994) and European (CEN, 2002) standards. However, significant modifications were made both on the dust dispersion system. The system for spark triggering was entirely different. In a standard MIE apparatus, dust dispersion and spark triggering are timed independently using an electronic delay circuit or synchronized electrode displacement, whereas in the present method the experimental dust cloud itself triggers the spark.

Also the design of the dust dispersion system used in the present experiments differs substantially from most of those used in standard MIE tests. The dust is dispersed by an air blast caused by opening a valve and emptying a 50 cm^3 pressurised air reservoir, as shown in Figure 1. A closed dust reservoir is placed downstream of the air outlet valve, and the particles are forced further downstream by the air blast through a pipe and into a mushroom shaped nozzle at the bottom of the explosion chamber, from which a transient explosive dust cloud is generated in the main explosion vessel. This vessel is a 1.2 litre glass tube, identical to the one used in the MIKE apparatus. The steel bottom of the explosion vessel is also identical to that of the MIKE apparatus.

By forcing the dust particles through a nozzle, particle agglomerates are torn apart and the effective particle size reduced, as described by Yamamoto and Suganuma (1984). This method differs from the conventional dispersion method, in which the dust sample is first placed at the bottom of the explosion vessel as a heap and subsequently just blown into a cloud by a blast of air impinging on the heap. In the present method, the dust heap is forced through the dispersion system and exposed to strong shear forces, which, together with impacts of particle agglomerates against the nozzle walls contribute to reduced agglomeration in the resulting dust cloud.

The electrodes are 2 mm diameter tungsten rods. The tips are slightly rounded off in order to reduce charge leakage by corona discharge. The electrode gap distance was set at 8 mm throughout the tests reported in the present paper.

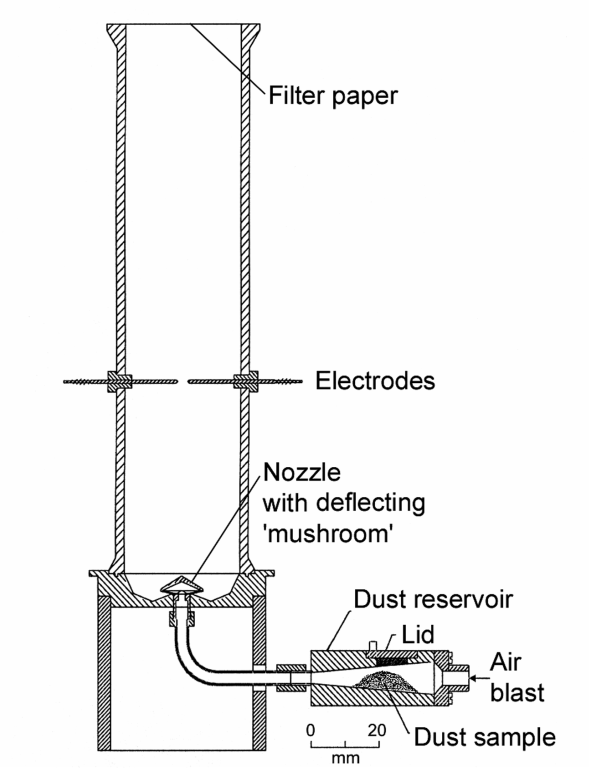


Figure 1. Cross-section of the explosion vessel and the dust dispersion system. The air blast is generated by emptying a 50 cm^3 pressurised air reservoir, fitted with a solenoid valve, upstream of the dust reservoir.

3.2 *Spark generator*

A schematic outline of the electric circuit is given in Figure 2. In order to produce a spark of a given energy ($\frac{1}{2} CU^2$) a single or several capacitors in parallel were first charged through a charging resistor R to the desired static DC high voltage. The value of R was sufficiently large to render the time constant RC long enough to ensure that only a single spark could occur during the lifetime of the transient explosive dust cloud.

The voltage between the electrodes was set at the selected value U prior to the dispersion, and the dust particles triggered the electrical breakdown. The energy delivered in the spark was assumed equal the stored capacitor energy prior to breakdown, $\frac{1}{2} CU^2$. The final value of U prior to spark discharge was assumed to equal the voltage measured by the voltmeter of the high voltage source (virtually no current was flowing through R when C was fully charged). Further details of the circuit are given by Randeberg and Eckhoff (2004)

Ignition tests were performed both with and without a significant series inductance in the discharge circuit, i.e. both with pure capacitive and protracted sparks. The series inductance

L used was a simple wire-wound coil with plastic core with an inductance of 0.7 mH, which is of the same order as the standard value of 1-2 mH (IEC, 1994).

4 Initial experiments and test procedure

4.1 Reliability of spark triggering by dust particles

A series of tests was performed to investigate the lowest voltage at which various dusts were able to initiate breakdown at a given electrode gap distance. The mass of dust dispersed, and the dispersion air pressure of the 50 cm^3 reservoir remained constant throughout these tests. Also the same discharge capacitance C of 3 nF was used in all the tests. There was no added series inductance in the discharge circuit. Further details concerning apparatus and procedures are given by Randeberg and Eckhoff (2004). The results of the spark triggering tests, presented in Table 1, indicate that coarse particles trigger the spark discharge at somewhat lower voltages than finer ones of the same material.

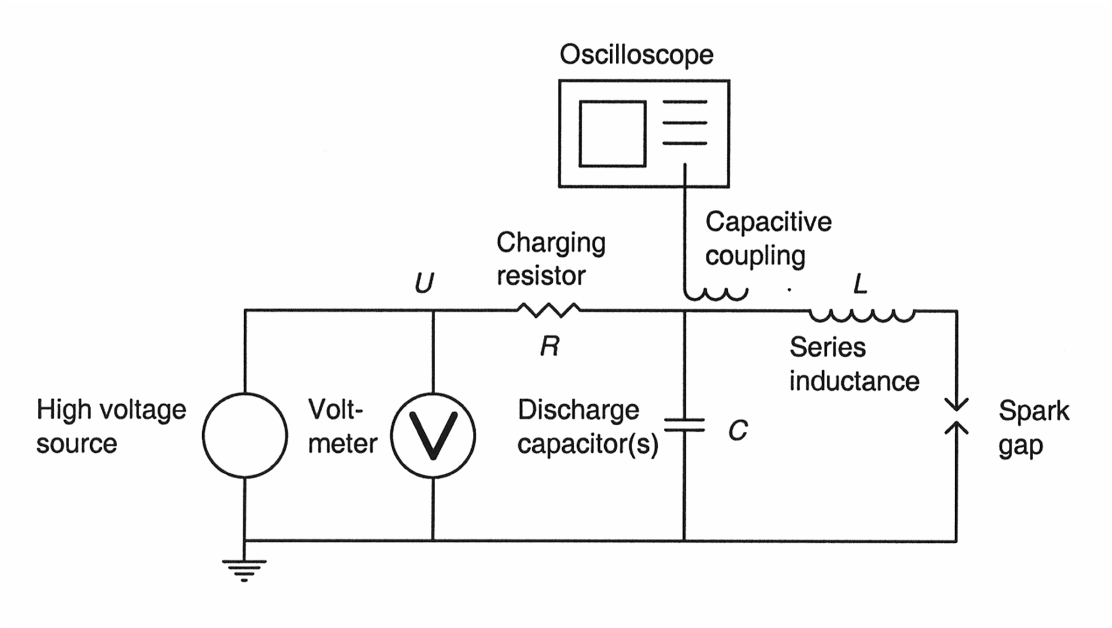
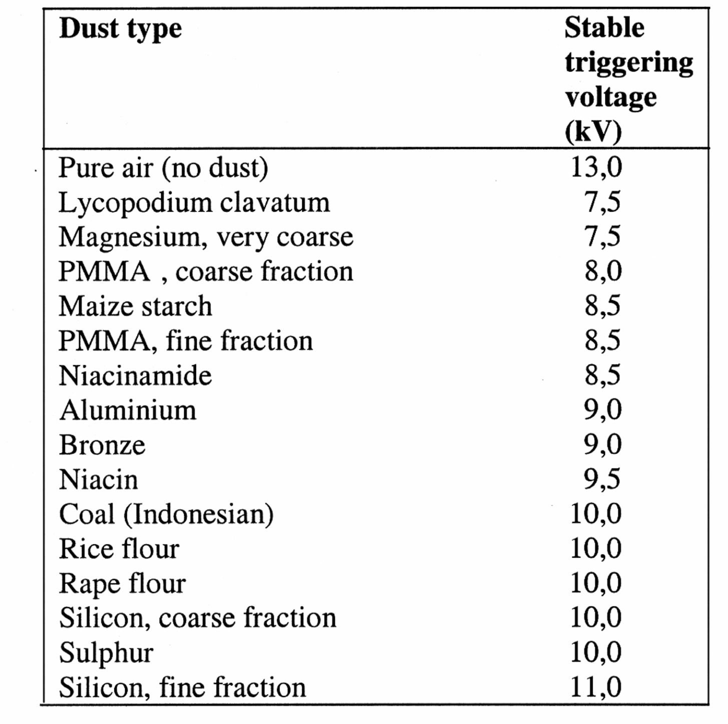


Figure 2. Schematic layout of the electric discharge circuit. The voltmeter is integrated in the high voltage source, measuring the output voltage U. The series inductance L was not included in tests with pure capacitive sparks.

Table 1. Minimum gap voltages for various dusts (in steps of 0,5 kV) at which dispersion of 0.9 g dust produces a spark in three consecutive tests.



Dust type	**Stable triggering voltage (kV)**
Pure air (no dust)	13,0
Lycopodium clavatum	7,5
Magnesium, very coarse	7,5
PMMA , coarse fraction	8,0
Maize starch	8,5
PMMA, fine fraction	8,5
Niacinamide	8,5
Aluminium	9,0
Bronze	9,0
Niacin	9,5
Coal (Indonesian)	10,0
Rice flour	10,0
Rape flour	10,0
Silicon, coarse fraction	10,0
Sulphur	10,0
Silicon, fine fraction	11,0

This behaviour is in agreement with the findings of Dascalescu *et al.* (1997). On the other hand, the results do not indicate any obvious difference between conductive and dielectric particles. As pointed out by Randeberg and Eckhoff (2004) the present study has so far not identified the specific chemical and physical properties of the dust particles, apart from the particle size, that promote their ability to initiate spark discharge. The permittivity of dielectric particles and the particle shape may be two such properties. Further investigations needs to be carried out to identify particle properties that influence the mechanisms of breakdown.

4.2 Ignition delay

When the dust cloud itself is used as the spark trigger, the delay between onset of dust dispersion and sparking will vary from trial to trial, depending on a number of experimental details beyond control. This was found to be particularly true with the gap voltage quite low compared with the breakdown voltage in quiescent air. On the other hand the delay between dust dispersion and spark breakdown tended to increase somewhat systematically with decreasing pre-set gap voltage. With a longer delay the turbulence of the dust cloud is likely to be lower than if the delay is short, which would be expected to favour ignition.

4.3 Test procedure for MIE determination

Ignition tests were performed in series of ten trials at each spark energy ($\frac{1}{2}CU^2$). In the first part of the tests the mass of dust dispersed and the dispersion air pressure were maintained constant at selected values considered favourable for ignition, based on experience. If spark-over did not occur in a trial, the trial was discarded and a fresh trial was made. This was continued until ten trials with successful spark triggering had been obtained. The frequency of ignition was then taken as the fraction of these ten trials that resulted in ignition of the dust cloud. When $\frac{1}{2}CU^2$ had been reduced to a level giving low ignition probabilities, the mass of dust dispersed and the dust dispersion pressure were varied and new tests were done to see if higher ignition probabilities could be obtained at that value of $\frac{1}{2}CU^2$.

5 MIE results for lycopodium clavatum

The ignition frequency as a function of spark energy was determined for lycopodium clavatum, both with and without an added series inductance of 0.7 mH. The lycopodium was tested with its natural moisture content of about 3 % by mass. The results are given in Figure 3 together with the results obtained by Eckhoff (1975) for the same type of dust, using the electronic CMI-circuit to obtain the most favourable delay between onset of dust dispersion and spark discharge for ignition.

If MIE is defined as the spark energy at which the extrapolated frequency-of-ignition-versus-capacitor-energy curve crosses the zero-frequency line, Figure 3 shows that the minimum stored capacitor energy that produced ignition in the present tests, using a 0.7 mH series inductance, only exceeds the value obtained by Eckhoff (1975), who used a series inductance of about 1 mH, by a factor of about 2. On the other hand the average slope of the frequency-of-ignition-versus-energy curve from the present experiments is considerably smaller than that of the data of Eckhoff (1975). This is assumed to be due to a greater scatter in the experimental conditions from trial to trial in each series of ten formally identical trials in the present investigation, mainly because of lack of control of the ignition delay. It seems reasonable to assume that the poorer the control of the experimental conditions, the smaller the slope of the frequency-of-ignition-versus-capacitor-energy curve will be. Likewise, the more careful the control of the experimental conditions, down to minute details, the steeper the curve will be. However, the ultimate question is not the slope of the frequency-of-ignition-versus-capacitor-energy curve, but at which spark energy this curve crosses the zero-frequency line.

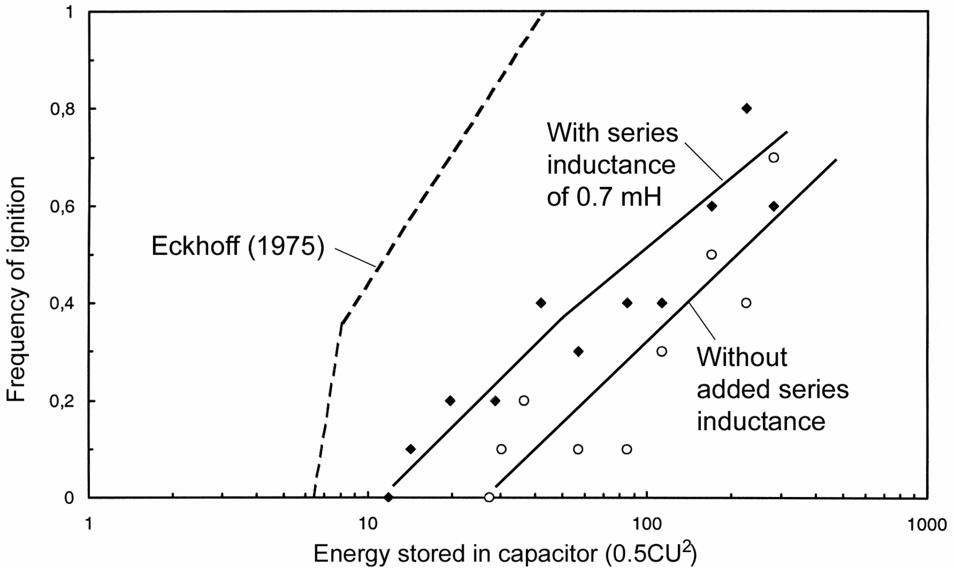


Figure 3. Frequency of ignition for transient clouds of lycopodium clavatum in air as a function of stored capacitor energy for pure capacitive and protracted sparks (added series inductance). The spark discharges were triggered by the transient dust cloud itself. Each data point represents ten ignition trials. Comparison with data from Eckhoff (1975) obtained by using a conventional MIE test with electronically synchronized sparks.

6 Ignition trials with two dusts used in Round Robin calibration of standard MIE tests.

Ignition experiments were also attempted using a niacinamide dust (CaRo00/01) and a niacin dust (CaRo 03) adopted for Round-Robin calibration of standard MIE test methods (Cesana, 2001 and 2004). However, for reasons not yet resolved, both dusts turned out to be difficult to ignite using the dust cloud spark trigger method, even at quite high spark energies. It was thought that one possible reason for this could be the strong tendency of the two dusts to trigger the spark at quite short delay times, and thus causing the spark to appear in the early phase of dust dispersion and hence at relatively high turbulence levels and low dust concentrations. It was attempted to solve this problem by increasing the difference between the breakdown voltage of the gap in air, and the actual lower voltage right to the limit where spark triggering was hardly possible. However, this did not cause any significant increase of the increase the ignition delay. Further work is required to resolve this puzzle.

7 The need for differentiating between MIEs of dust clouds < 1 mJ

Because current standard methods for determination of MIEs of dust clouds do not enable measurements below a few mJ, it is common practice to stop differentiation between MIEs at this point by just saying e.g. MIE < 3 mJ, no matter whether the real value is 1 or 0.1 mJ, or even smaller.

This is not satisfactory, because logically differentiation is just as important in the range below 1mJ as in the range above this quite arbitrary value. The energy range of accidental electrostatic sparks in industry most probably extends far below 1 mJ, and it is obviously important to know at which spark energy a given dust could get ignited also in the low-energy range.

It is reasonable to assume that most low-energy sparks occur at comparatively low gap voltages, and hence at correspondingly short gap lengths, and the question arises whether this will create quenched conditions for ignition The answer to this is that the quenching distance for dust clouds will be expected to decrease with MIE, in accordance with what has been confirmed for explosive gas mixtures. Figure 4 gives some data for gases indicating that the quenching distance is approximately proportional to the square root of MIE. Hence, assuming that this correlation also applies to dusts, and the quenching distance for a dust of MIE = 100 mJ is 10 mm, the value for a dust of MIE = 1 mJ would be 1 mm. For a dust of MIE = 0.1 mJ the quenching distance would be 0.3 mm.

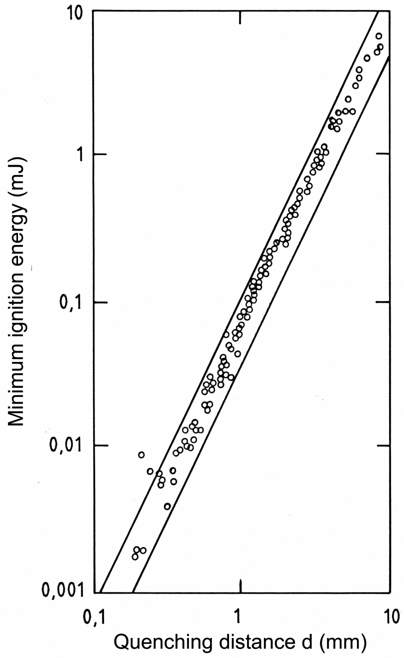


Figure 4. Correlation of MIE for unquenched ignition of explosive mixtures of combustible gas and air, and corresponding quenching distances. From Kuchta (1985)

8 Conclusions

1. It has been re-confirmed that the gap between two electrically conducting electrodes carrying a high-voltage difference somewhat lower than the natural breakdown voltage in air, can be effectively broken down, and a spark discharge initiated, by blowing dust particles into the gap.
2. It has also been re-confirmed that dust explosions can be initiated in this way if the dust cloud breaking the gap down is explosive. It is suggested, therefore, that such spark triggering, by the explosive dust cloud itself, is a plausible mechanism of electrostatic spark initiation of accidental dust explosions in the process industries.
3. The dust cloud's ability to trigger the spark, in this way, measured as the lowest voltage at which breakdown occurred, depends strongly on the dust properties. Hence, coarse particles seem to be able to produce breakdown of a given gap at lower preset gap voltages, than fine particles. On the other hand, conductive particles did not initiate breakdown at lower preset gap voltages than dielectric ones. Further research is needed to clarify the various particle and electrode properties that influence gap breakdown by

dust particles. The influence of the intensity of the dust dispersion process also requires further investigation.

4. A preliminary MIE value for clouds in air of lycopodium clavatum was obtained by extrapolating the experimental frequency-of-ignition-versus-spark-energy curve to zero ignition frequency. The resulting MIE was only moderately higher, by a factor of about 2, than typical values for lycopodium clavatum found using conventional MIE test methods.
5. The lower spark energy limits of current standard MIE methods for dust clouds are in the range 1-5 mJ. It is suggested, therefore, that the method of direct dust cloud triggering may be used to develop a new standard method for determining MIEs of dust clouds in the MIE range < 1 mJ. Besides being realistic in relation to the ignition mechanism encountered in industrial situations, this trigger method works at spark energies far below 1 mJ, and also considerably simplifies the experimental apparatus.

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