MECHANICAL IGNITION OF DUST ACCUMULATIONS AND THE IGNITION CAPABILITIES OF SMOULDERING NESTS

G.A. Lunn and J. Gummer

Health and Safety Laboratory, Harpur Hill, Buxton, Derbyshire, UK, SK17 9JN

This paper is a report of a research project into ignition of dust accumulations by rotating, contacting surfaces submerged in the dust and the ability of burning accumulations to ignite dust clouds. A relationship has been developed between the temperature of the hot surface and the power expended by friction at the wheel contact point. Considering the complicated nature of both the tests and the various combustion behaviours and physical properties of the dusts studied the overall trend shown by the results is a relatively clear one and a reasonable indication of the maximum temperatures likely to be developed by a given friction power loss for this apparatus can be obtained. The present results show that the onset temperatures for smouldering combustion are similar to the temperatures that lead to combustion when dust deposits are in contact with relatively large surfaces heated electrically. Smouldering nests of dusts prove to be poor ignition sources for explosive dust clouds, but flaming nests were able to ignite clouds of all the dusts used up to the maximum MIT used - 600°C to 675°C. Smouldering nests with temperatures above approximately 700-800°C were, however, able to ignite sulphur clouds.

INTRODUCTION

Hazardous mechanical friction in dust handling plant is usually accidental but surveys of industrial dust explosion incidents show that, in a substantial percentage, friction and mechanical failure and flames and flaming material are known ignition sources[1,2,3]. Research has been done on the potential for ignition by mechanical sparks and frictional heating but there is no generally accepted method of estimating the likelihood of ignition by mechanical sources of dusty environments. The information available in the literature is not sufficiently wide to give a guidance framework with the potential for general use.

This paper is a report of a research project on the ignition of dust deposits due to mechanical friction by rotating, contacting surfaces submerged in the dust and the ability of burning accumulations to ignite dust clouds. Burning nests with different characteristics have been introduced into clouds of dusts covering a range of Minimum Ignition Temperatures (MITs). Various dusts have been subjected to a submerged source of frictional heating and burning dusts with different Train Firing properties have been used as the nest material and the dust clouds have MIT values of approximately 400°C, 500°C and 600°C.

EXPERIMENTAL DETAILS

FRICTION APPARATUS

An apparatus was designed that would produce frictional effects between two rotating metal disks of 150 mm diameter (see Figure 1). The disks are driven independently by two 5.5 kW motors, both capable of a maximum speed of 1450 rpm (giving a speed of 11.38 m/s at the periphery of the disks). The speed can be increased, however, by changing the pulley ratios from 1:1 to 1:2, so enabling a maximum speed of 2900 rpm (peripheral speed 22.76 m/s). Analogue outputs from the controllers allow constant monitoring of the power and torque levels throughout testing.

One of the two disks is fixed in position and the other disk is mounted on a lay (secondary) shaft, driven by a chain drive. This is connected to a sleeve that pivots about the drive shaft, thus allowing radial movement. A loading arm is connected to the sleeve at the pivot point, allowing various loads to be applied.

Figure 1 Friction apparatus.

The power and torque levels of each disk were monitored continuously during each test. The surface temperature of the disks was checked using a UKAS calibrated thermocouple and indicator. Mild steel disks were used on all the tests. All had a diameter of 150mm and thickness of 25mm. To ensure repeatability during the tests, the disks were either skimmed (using a lathe) or changed at regular intervals for new disks. This ensured the disks had a smooth surface before each test.

Initial testing showed that an enclosure was required to keep the dust around the contact area of the two disks. A steel enclosure (approx 3.6 litres) was produced that straddled the disks. This enabled the dust to be contained around the contact point of the two disks. Due to the fine nature of certain dusts, however, material was found to be escaping from the enclosure around the disks. To solve this problem, a second enclosure - volume 7.2 litres - was constructed that completely enclosed the two disks.

Various combinations of load, speed and duration of test were tried for each dust in order to find conditions that would produce burning in the dust deposit.

FINDING SUITABLE SMOULDERING DUSTS

The burning behaviour of a range of dusts was tested by subjecting a line of each dust to a flame ignition source. From the results a number of dusts was selected with characteristics covering a range of cloud Minimum Ignition Temperatures and Layer Ignition values. The values for the dusts selected for the friction apparatus tests are shown in Table 1.

Table 1:Ignitability Characteristics

Dust type	Dust Layer Glow temp (deg C)	Minimum Ignition Temperature (MIT) (deg C)
Sulphur	250-270	280-370
Lycopodium	280	410*
Woodflour	310-320	480-500**
Tea (Earl Grey)	300	510*
Cornflour (st2)	440-450	450-500**
Calcium Stearate	>450	450-500**
Anthraquinone	>450	600-675**

* Measured in BAM oven at HSL.

** Measured in Godbert Greenwald furnace at Syngenta.

Other results were taken from reference 4.

LARGE SCALE VERTICAL TUBE TESTING

A large scale vertical tube apparatus was designed and produced to test the ability of burning nests to ignite dust clouds. The final design consisted of a 2m long perspex tube with an internal diameter of 0.3m. A vibrating hopper and screw feed arrangement was chosen. In this apparatus dust was fed into an air flow in a pipe connected to the top of the 2m long perspex tube. The rate of feed and air flow were both variable to so that a wide range of dust concentrations could be produced (see Figure 2).

Figure 2 Vertical tube apparatus

PRODUCING THE BURNING NEST

For the main series of tests, coherent smouldering or burning nests were to be used as the ignition source in the vertical tube arrangement. In order to obtain sustained combustion some form of airflow either through or over the smouldering dust sample is usually necessary. Several different methods for producing sustained combustion were tried and the best was a bank of dust over which was passed warm air at 50°C. This method allowed sustainable smouldering nests to be created with most dusts. Land Cyclops Ti35+ infrared Thermal Imaging (TI) camera was used to measure the burning temperature of various dusts.

EXPERIMENTAL RESULTS

FRICTION APPARATUS

Discussion of Frictional Heating Results

The results from the friction apparatus tests are discussed in this section in terms of the surface temperature developed by the power expended in the frictional process during the turning of the two wheels against each other. The power expended is calculated from the power-time traces measured during the tests. These traces reveal the total power measured throughout the test and the power expended in the friction process is obtained by subtracting the background power:

Power = Power levels during the test (disk1 + disk2) - Background power (disk 1 + disk2)

Ignition and combustion of the dust has been equated with the onset of smouldering at red heat. Figure 3 shows an example when burning inside the friction apparatus did not occur.

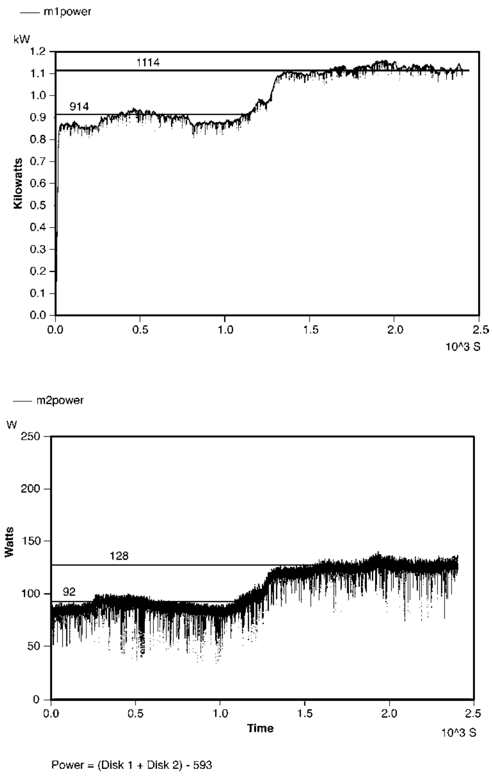

Figure 3 Power traces from a test with wood dust: non-ignition

At approximately 20 minutes into the experiment, there is an increase in the power necessary to rotate the discs. An example for wood dust of a power-time trace in which ignition did occur is shown in Figure 4. At approximately 8 minutes from the end of the test i.e 32 minutes from the start, there is a second increase in the power level. In this example, a smouldering combustion began.

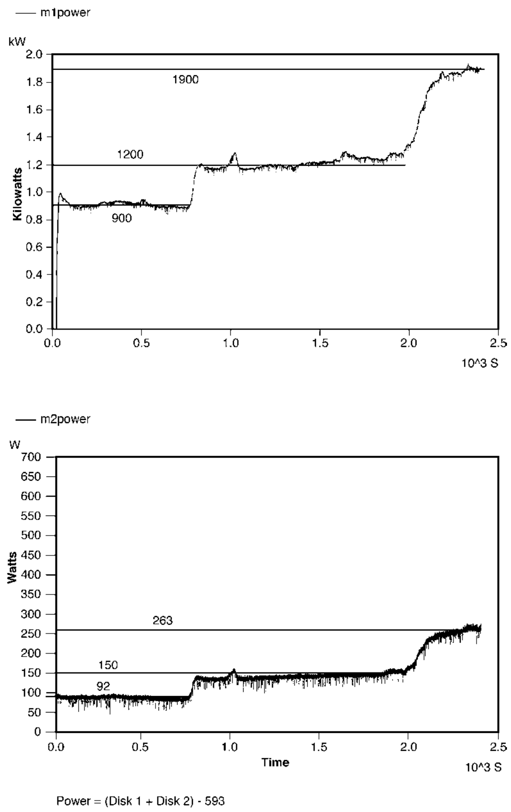

Figure 4 Power traces from a test with wood dust: ignition

The factor determining whether the dust accumulation will ignite is the generation of a critical temperature somewhere in the dust. In this apparatus the highest temperatures measured at the end of the test were always on the disks. Although the bulk dust did experience a rise in temperature over the course of a test, this did not approach the temperature of the disk surface.

The apparatus generates a localised heat source, essentially, although it is an extended one. Rather than a hot spot at the contact point, the heated surface extends round the circumferences of the disks, with generally little variation in temperature. In most tests, however, the disks had different temperatures. Ignition of the dust deposits occurred at a disk surface, but not necessarily at the contact point.

The temperature at the disks arises because of power expended in the friction process. Three variables can affect the power expended - the relative velocity of the disks, the load applied and, to some extent, the dust surrounding the disks. An analysis of the data and considering the power expended at the start of each run indicates that, generally, at a constant relative velocity the power expended increases with load and at a constant load power expended increases with an increase in relative velocity. This is a very general conclusion, however, and there are exceptions in the experimental data. Likewise, the power expended at given conditions of load and relative velocity varies with the dust, but no consistent pattern emerges from the results. The most accessible measurements from the tests are the power expended during the friction process and the temperature generated at the disks.

The temperature at the disks is measured at the close of the tests, and on deriving a relationship between the power expended and the temperature at the rubbing point, it needs to be recognised that the temperatures are a result, not of the average power over the test duration, but of the power expended during the final stages of the test. So in obtaining the data points for Figure 5, which shows the relationship between power expended and the surface temperatures measured, higher or lower power levels occurring earlier in the test have been ignored - only power levels in action at the end of the test have been used. Figures 3 and 4 show how the power levels have been extracted from the traces.

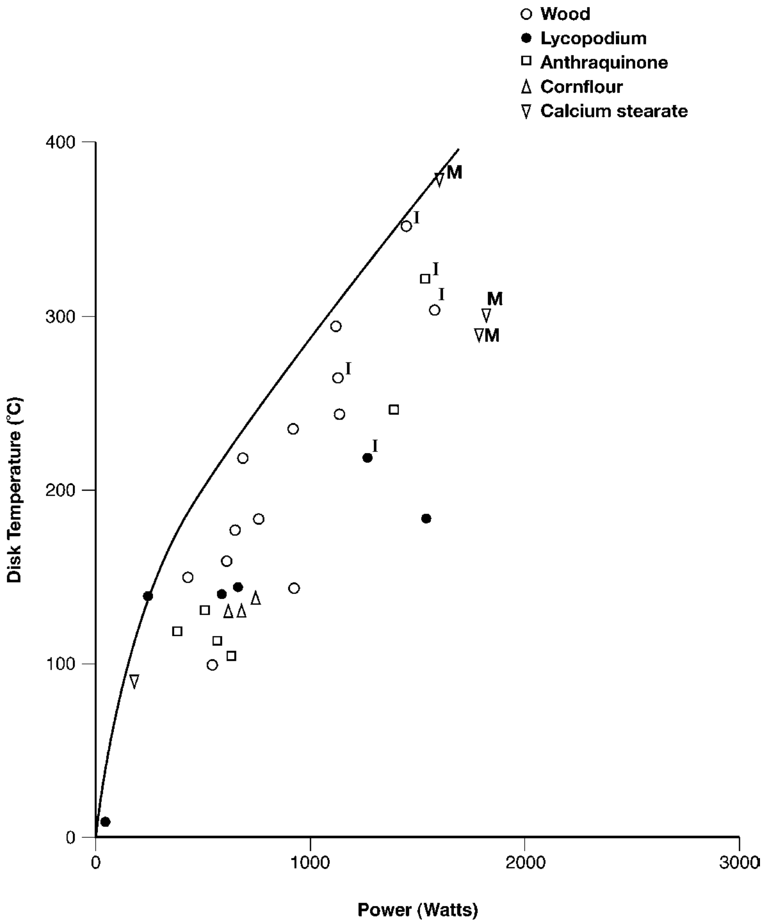

Figure 5 Surface temperature against power expended by friction

Considering the complicated nature of both the tests and the various combustion behaviours and physical properties of the dusts studied the overall trend shown by the results is a relatively clear one and Figure 5 gives a reasonable indication of the temperature developed by a given friction energy loss for this apparatus. If a line is drawn to envelope the experimental points a value can be given to the maximum temperature likely to be produced by a given energy loss.

The conditions that lead to ignition are not, however, typified by the final minutes of the test. Only an analysis of the trace as it develops throughout the test can show what distinguishes an ignition condition from a non-ignition. The example in Figure 3, which is the trace for a wood-dust test that did not lead to ignition, shows that for the first half of the test, 20 minutes approximately, the energy expended amounted to 470 watts. This value is fairly typical of the wood dust tests in the early stages. On the basis of the graph in Figure 5, this energy expenditure would lead to temperatures of approximately 170°C maximum.

Temperatures at this level produce some change in the dust - perhaps charring - which after a time produces an increase in the energy expended in turning the disks. The temperature produced by this higher energy - 649 watts - is measured at 210°C maximum (on the basis of Figure 5) but does not produce an ignition. In Figure 4, burning occurs after a period of approximately five minutes during which the energy expended is 757 watts, producing a maximum temperature of approximately 230°C , on the basis of the graph in Figure 5. From this analysis, then, in this apparatus, if the energy expended is in the region of 700 watts, maximum temperatures of approximately 210°C - 230°C are generated and these are capable of producing smouldering combustion in wood dust. These temperatures compare to 310 - 320 for the 5 mm thick layer test, and 210- 230°C for cones of wood-dust over a small box heated with a constant electrical power[5].

For lycopodium ignition probably occurs in the region of 190°C. A cone of lycopodium over an electrically heated box ignited at temperatures between 175°C and 200°C.

For an St2 Cornflour, the highest rate of energy dissipation was 746 W, which would give a maximum temperature of 230°C, insufficient to cause ignition. The ignition temperature of a 5 mm layer is > 450°C and a cone over an electrically heated box did not ignite at a temperature of 280°C.

Comparisons of some of the wood dust tests where the duration of the tests was curtailed suggest that 20 minutes is required for the disks to reach their maximum temperature. Some tests with wood dust were carried out over a range of test durations with power expended of about 1000 W. The tests suggest that approximately 20 minutes is necessary for extensive smouldering of the dusts to occur.

The results from the mechanical apparatus reveal that a power expended of approaching 1 KW is necessary to generate disk temperatures in the region of 200-240°C in a time of under 40 minutes and probably in the region of 20 minutes. An electrical heating device, at a power of 106 watts requires three to four hours to reach this temperature when covered with a cone of dust. As the power input increases the time to reach a given temperature decreases, but in the end it is the surface temperature generated that is the critical factor in determining the likelihood of ignition.

As the temperature necessary to produce combustion varies with the dust, then it follows from Figure 5, that, generally, the necessary power expended in friction varies also. It is thus difficult to suggest, on the basis of the present results, that there is a limiting relative velocity below which combustion will not occur. For wood dust, no ignitions occurred at a relative velocity below 9.8 m s^{-1}, at the highest loads used. At lower loads, higher relative velocities were required to produce ignition. Dusts which are more difficult to ignite than wood dust generally require a higher relative velocity if ignition is to occur at a given load.

The question arises as to the practical relevance of these measurements and whether more simple tests could provide data for estimating the risk of frictional ignition of a powder deposit. The present results show that the onset temperatures for smouldering combustion are similar to the temperatures that lead to combustion when dust deposits are in contact with relatively large surfaces heated electrically. A hot surface test, using electrical heating, may be a more realistic way of testing for the likelihood that frictional heating will lead to burning of a dust deposit.

SMOULDERING NESTS AND THE IGNITION OF DUST CLOUDS

Once the risk of combustion in a dust accumulation has been assessed, the danger that a burning dust pocket might ignite an explosive dust atmosphere needs to be estimated.

DETERMINING THE BURNING TEMPERATURE

A review of the literature on the behaviour of smouldering nests indicates that the size and temperature of the nest are important in producing an ignition of dust clouds. The first step in this set of tests was to produce a series of burning nests with dust banked-up as shown in Figures 6 and 7 and ignited using a blow torch. The burning temperature was measured using

Figure 6 Smouldering nest - lycopodium

Figure 7 Burning nest - lycopodium

a thermal imaging camera for a range of conditions - burning with smoulder, burning with flame and burning with warm air applied. The results are given in Table 2

TABLE 2:Burning Temperature of Dust Deposits

Dust tested	Type of burning	Air applied at 50C?	Temperature range (C)
Wood	smouldering	No	690
Wood	with flame	No	730
Wood	smouldering	Yes	850-900
Earl Grey fines	smouldering	Yes	800-940
Lycopodium	with flame	No	650
Lycopodium	with flame	Yes	1056-1173
Lycopodium	with flame	After air removed	820-850
Lycopodium	smouldering	Yes	1,050
Baby milk powder	smouldering	Yes	950-1000
Baby milk powder	smouldering	No	700
Baby milk powder	with flame	Yes	960
Cornflour (st2)	smouldering	No	800
Cornflour (st2)	small pockets of flame	Yes	830
Cornflour (st2)	with flame	Yes	900
Coal dust	smouldering	Yes	>1170
Calcium stearate	with flame	Yes	700
Calcium stearate	with flame	No	900
Anthraquinone	with flame	No	860
Hot coil (used on setup tests)			670-680

A burning nest of dust was positioned inside the vertical tube close to the bottom and its burning mode noted. A dust cloud was then created within the tube using the screw feed arrangement.

In some of the tests the burning nest was dispersed by an air blast from a conical nozzle buried in the dust, to see if the action of breaking-up the smouldering deposit would result in ignition of the dust cloud.

An analysis of the results is shown in Table 3, where the temperature of the nest is divided into three bands - approximately 700°C; 800°C to 900°C;and approximately 1000°C and above. The type of burning is listed, along with the Minimum Ignition Temperature of the dust cloud and whether or not ignition occurred. In the majority of tests where smouldering was the mode of combustion, ignitions did not take place even when high smouldering temperatures were evident and the temperature difference between this temperature and the cloud MIT was high. Only when the nest was dispersed and the temperature difference was high did ignition occur. Sulphur dust clouds were the only ones which would ignite on smouldering nests, but even then the temperature difference between the nest and the cloud MIT was greater than 500°C. By contrast, if flaming combustion took place ignition of a dust cloud was practically guaranteed, even when the flames were small.

A short series of experiments was conducted in which air was supplied to a smouldering nest of dust. The pressure and temperature of the air were varied to see if the burning mode of the sample could be altered.

Tests, involving wood dusts, confirmed that nests burning with a flame could be created from smouldering deposits of dusts by the addition of a suitable air supply.

Table 3:Ignition Conditions.

Temperature of Nest (^oC)	Mode of Combustion	MIT of Dust Cloud (^oC)	Ignition Y/N
Wood 690	Smoulder	280-370	N
Wood 690	Smoulder	480 - 500	N
Wood 690	Smoulder	410	N
Wood 690	Smoulder	600-675	N
Wood 730	Flames	410	Y
Wood 730	Flames	450 - 500	Y
Wood 730	Flames	600 - 675	Y
St2 Cornflour 830	Flame	450 - 500	Y
Anthraquinone 860	Flame	600 - 675	Y
Tea 800 - 940	Smoulder	510	N
Wood 850-900	Smoulder	280-370	Y
Wood 850 - 900	Smoulder	410	N
Wood 850 - 900	Smoulder	450 - 500	N
Wood 850 - 900	Smoulder	480 - 500	N
Calcium Stearate 900	Flame	450 - 500	Y
Tea 800-940	Smoulder	600 - 675	N
Milk 950 - 1000	Smoulder	410	N
Milk 950 - 1000	Smouldering then	410	Y
Milk 960	dispersed	410	Y
Lycopodium 1050	Flame	410	N
Coal > 1170	Smoulder	410	N
Coal > 1170	Smoulder	410	Y
Coal > 1170	Flame	600 - 675	N
Coal > 1170	Smoulder	600 - 675	Y
	Flame		

DISCUSSION OF THE BURNING NEST RESULTS

The tests on ignition of clouds by burning nests show that smouldering nests are very poor ignition sources, but once flaming combustion occurs ignition of the dusts used is practically a certainty even when the flames are very small. Work at Syngenta[6] on the ignition of dust clouds has shown that clouds can be ignited by various burning or smouldering ignition sources. Three ignition sources - paraformaldehyde, which burns with a flame, $Fe^{3+}(H_2)$, which smoulders, and incandescent particles of saw dust - were used. Sulphur and lycopodium dust clouds of various concentrations were blown over the first two of the ignition sources, and both dusts ignited. The incandescent particles were introduced into the dust clouds soon after the clouds had been produced. The sulphur clouds ignited, but the lycopodium did not.

These tests were repeated with dusts of various MIT values, from 270^{o}C to above 1000^{o}C, as measured in the Godbert Greenwald furnace. With the burning layer, dusts with MITs above 600^o to 800^{o}C did not ignite; with the smouldering layer, dusts with MITs above 340^{o}C, approximately, did not ignite; with the incandescent particles, dusts with MITs above about 330^{o}C did not ignite. Some tests using layer ignition sources of various areas and temperatures showed that as the area decreased, for a given temperature, the dust MIT above which a dust cloud did not ignite increased.

The results from the current project are in agreement with those of Syngenta. Smouldering nests did not ignite dust clouds with MIT values above 400^{o}C, but flaming nests were able to ignite clouds of all the dusts used up to the maximum MIT used - 600°C to 675°C. Sulphur clouds were ignited by smouldering nests with temperatures above approximately 700-800°C.

A review of the wider literature also shows that burning nests are poor sources of ignition[7,8,9,10]. The likelihood of ignition of a dust cloud by a hot nest is low if the nest burns only by smouldering Ignition depends crucially on the production of either flame or incandescent particles and if flaming does take place then the risk of an ignition is very high.

The question then arises as to how likely the production of burning nests is in practice. Despite all the reports of ignition incidents in industrial plant, experimental studies have in the main indicated that transport of nests through industrial plant is not easy. Clearly, the Train Firing Test is the primary method for determining whether a dust deposit will either propagate smouldering or inflame. In practical situations, however, both the temperature and air flow inside dust-handling plant can have an effect on the burning behaviour. If the air above the dust deposit is at a temperature higher than normal room temperature, the requirements for ignition may fall. Layer ignition temperature typically decrease by 40°C-60°C at an air temperature of 100°C.

Various tests have been developed to measure the ignition behaviour of dust deposits in streams of hot air. Similar tests could tell whether smouldering dusts were in danger of flaming. The IChemE Guide, *Prevention of fires and explosions in dryers* described tests developed to simulate various conditions and obtain measurements of the temperature at which exothermic reaction begins[11]. If the dust deposits and surrounding conditions properly simulate practical situations, the temperature at which deposit burning progressed to flaming combustion could be used as a basis for safe procedures with an adequate safety margin incorporated.

CONCLUSIONS

The results of these experiments show that hot surfaces produced by friction are able to initiate smouldering combustion in dust deposits at temperatures similar to those obtained using electrical heating. The power required to produce these temperatures is much higher than when an electrical ignition source is used but ignition occurs at a shorter time. Whereas ignition requires several hours when heated electrically, ignition by mechanical means occurs in less than an hour at a similar surface temperature. A relation between the energy lost by friction and the temperatures developed has been demonstrated.

Clearly, potential ignitions in practice have to be anticipated by determining the type of frictional event likely to occur and applying data and information from a test that is close as practicable to the expected event. In practice, only a limited set of tests to determine the risk of ignition will be available; they will be chosen not only on technical grounds but on cost and time considerations also and they will not cover all likely situations in detail. The effects of scale need to be considered - small areas require less power to produce smouldering than large ones - but the present results are perhaps typical of the frictional heating likely to occur in practical mechanicl equipment.

A practical way forward may be to take a two-track approach. Firstly to develop an electrical heating test to characterise the combustion behaviour of the dust deposit and secondly to generate a set of data on the temperatures likely to be generated in different frictional environments either without the presence of dusts or with an inert dust typical physically of industrial powders. By merging the results of both these series of tests, a practical scheme of assessing ignition risks of dust deposits could be developed.

Burning nests of dust have been shown to be poor sources for ignition of dust clouds if smouldering combustion alone takes place. When flaming combustion occurs, however, ignitions of dust clouds are, to all intents and purposes, guaranteed. Clearly, the Train Firing

Test is the primary method for determining whether a dust deposit will either propagate smouldering or inflame. In practical situations, however, both the temperature and air flow inside dust-handling plant can have an effect on the burning behaviour. If the air above the dust deposit is at a temperature higher than normal room temperature, the requirements for ignition may fall. Layer ignition temperatures typically decrease by 40°C-60°C at an air temperature of 100°C.

Various tests have been developed to measure the ignition behaviour of dust deposits in streams of hot air. Similar tests could tell whether smouldering dusts were in danger of flaming. If the dust deposits and surrounding conditions properly simulate practical situations, the temperature at which deposit burning progressed to flaming combustion could be used as a basis for safe procedures with an adequate safety margin incorporated.

REFERENCES

1. Abbott, J.A. BMHB Survey of dust fire and explosions in the UK 1979-84 (British Materials Handling Board, ISBN 0 85624 4554).

2. Porter, B. Industrial Incidents. Paper presented at Dust Explosions: Assessment, Prevention and Protection, 24th November, London (1989).

3. Jeske, A and Beck, H. Evaluation of dust explosions in the Federal Republic of Germany, EUROPEX Newsletter No 9 p2 (July, 1989).

4. Eckhoff, R. K. Dust explosions in the process industries. 2nd edition. Butterworth Heinemann (1997).

5. Torrent, J. Private Communication. LOM, Madrid, Spain.

6. Bailey, M. and Walker,N. Private Communication. Syngenta, Manchester, UK.

7. Pinkwasser, Th. On the ignition capacity of free-falling smouldering fires. Euromech Colloquium 208, Explosions in Industry. (1986).

8. Zockoll, C. Ignition effect of smouldering pockets in dust-air mixtures. VDI-Berichte. 701, p295. VDI-Verlag GmbH, Dusseldorf (1989).

9. Alfert, F. et al. The ignition capability of nests of smouldering material and hot objects in industrial plants. VDI-Berichte No 701. pp 303-319 (1988).

10. Jaeger, N. Zundwirksamkeit von glimmnestern in staub/luft-gemischem. VDI-Berichte 701, p263. VDI-Verlag, GmbH, Dusseldorf, (1989).

11. Abbot, J. Prevention of fires and explosions in dryers – A User Guide. The Institution of Chemical Engineers. 2nd Edition. Rugby, UK. (1990).