FIRE HAZARDS OF PACKAGED FLAMMABLE DUSTS — FOLLOW UP OF HSE's INVESTIGATION AND FIRE TRIALS

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A programme of large-scale trials has been carried out to investigate the hazards of packaged flammable dusts. The dusts studied included rubber, coal, wood, epoxy, polyester, polythene and corn flour. Trial samples ranged from 250–1000 kg. To reflect storage arrangements in warehouses, some trials were carried out on palletised bags of flammable dust stored at elevation on racks.

The main conclusion is that most flammable dusts at 20 mesh or finer are likely to present severe fire risks if stored in pallet stacks or on racks. This includes a huge range of natural products, plastics and fine chemicals including pharmaceuticals. Many significantly coarser dusts are also likely to pose a high risk in the event of fire.

This paper presents a summary of the trial data as well as images showing important aspects of the behaviour of the dusts under test. A video compilation of the test work is available and will be shown at the symposium. Some of this material graphically illustrates the high level of fire risk posed by flammable dusts.

INTRODUCTION

In November 1999 there was a serious fire at the Stockport Rubber Company (SRC) in which a man was killed and two others narrowly escaped. The fire took hold in pallet loads of paper sacks filled with 50 mesh rubber crumb and spread with a speed and ferocity that surprised the men involved as well as HSE and fire service investigators.

A series of medium and large scale fire trials were carried out to investigate the behaviour of this type of rubber crumb [Ref.1]. Large scale trials on a full pallet load of rubber crumb showed that the fire spread rapidly and then sustained a high rate of heat release for a long period. The rapid burning was caused by dispersal and burning of the flammable dust as it ran out of bags in the upper parts of the pallet.

In the UK the Health and Safety Executive (HSE) has responsibility for enforcing standards of process fire safety, including the storage of highly flammable solids. The SRC fire, raised questions about the adequacy of fundamental understanding underpinning fire safety guidance given to industries storing flammable dusts. It became clear that little was known about what chemical types and grades of dust could present a fire risk and how serious the risk could be. There have also been a number of serious chemical warehouse fires in which fires were reported to spread extremely (and unexpectedly) quickly in stocks of solid materials; the Allied Colloids fire (1992) is an example. One explanation for the high rate of fire spread was that low melting point solids formed spreading pools and consequently behaved like flammable liquids. The test work following the SRC fire suggested that the fire risk from flammable dusts might be more general and more serious.

A programme of research work at the Health and Safety Laboratory was organised to answer some of the general questions about flammable dusts raised by the tragic fire at SRC and other incidents.

OBJECTIVES OF THE RESEARCH

The main objective of the work was to improve fundamental understanding of how the fire hazard of flammable dusts depends on:

1. Type of dust
2. Fineness of dust
3. Rheology i.e. the flow characteristics of the dust in shear
4. The storage layout — especially the height of storage
5. Location of point of ignition

An important secondary objective was to accumulate a stock of good quality video footage of dust fires that could be used in training and other future efforts to improve standards of fire safety.

METHODS AND EQUIPMENT

The trials were carried out in a cubical enclosure (size 7.5 m) shielded with polythene to provide shelter in the early stages of fire development. When the fire size exceeded about 20 MW the polythene melted; preventing a transition to heavily smoke-logged and ventilation controlled conditions. The larger trials on stacks with an overall height of around 5 m were carried out with polythene shielding only on the upstream side raised. This provided effective shelter in the early stages of fire development whilst allowing good quality video recordings throughout.

Smaller trials were carried out with the sample stack in a 2×2 metre steel tray to retain unburned dust that flowed down from the stack. This tray was mounted on load cells to allow the measurement of burning rate i.e. the rate of combustion rather than the rate of flow of material from the stack.

The roof of the test enclosure (at a height of 7.5 metres) was fitted with an array of thermocouples. These measurements provide another indication of the rate of growth of the fire.

Load measurements were not made for the larger 5 metre stack trials since it was not practicable to retain and weigh all of the fallen dust to allow an estimate to be made of burn rate. In these larger experiments assessment of the rate of growth of the fire was based solely on temperature measurements. Layout of bags in larger trials is shown in Figure 1.

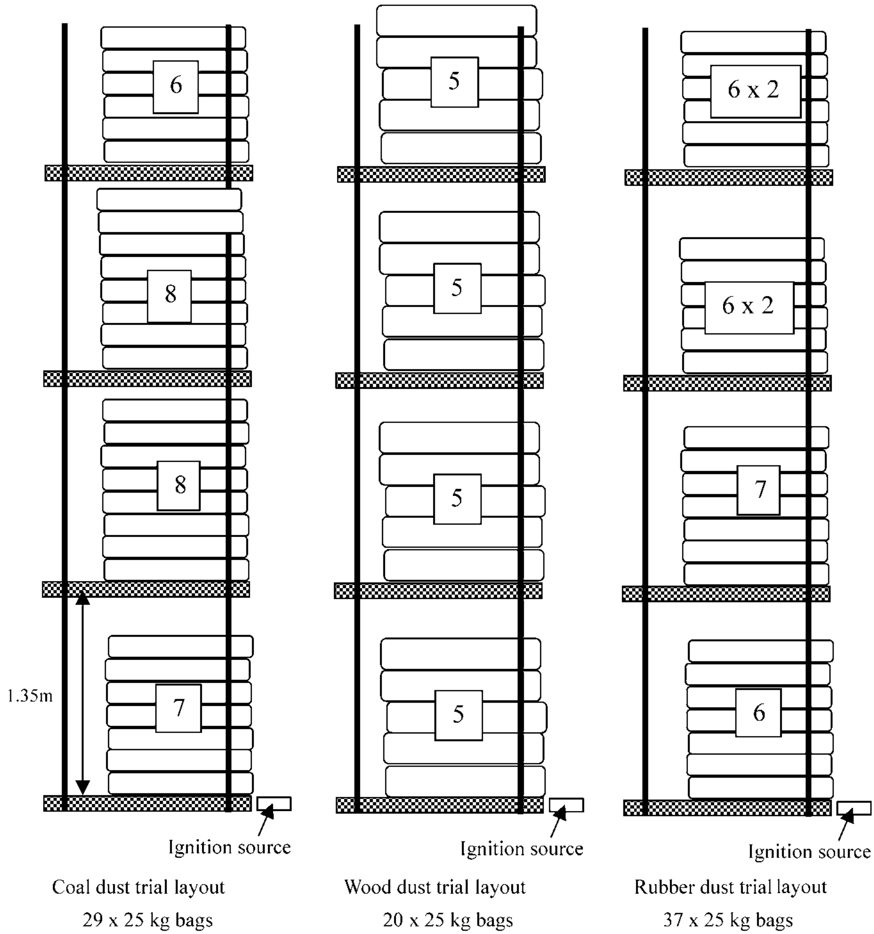

Figure 1. Arrangement of bags of dust in rack fire trials

Most trials were started with a small (125 g) wooden crib. This is the Source Number 7 described in BS 5852. Some small trials used a tray containing 0.5 litres of heptane. Large scale trials on wood and coal dust were started using a tray containing 2.5 litres of heptane. All of the trials were started with an ignition source at the bottom of the stack except the 4 pallet high stack trial on rubber crumb — which was started with a Number 7 Crib on top of the stack.

None of the sacks were shrink or stretch wrapped apart from the 4 pallet stack trial on rubber crumb referred to above. In this case all of the pallets were stretch wrapped.

TRIAL PROGRAMME

The trials carried out in the programme are listed in Table 1.

RESULTS

Details of the measurements made are given in an HSL report (Ref 3). A summary of the maximum rate of fire growth in each of the trials is shown in Table 2.

A compilation of video records of the test work has been prepared and this is available from HSE.

DISCUSSION

MASS LOSS AND TEMPERATURE RISE AS INDICATORS OF THE RATE OF FIRE GROWTH

Figure 2 shows a clear correspondence between measured maximum rate of temperature increase at ceiling level and the rate of increase in the mass burning loss rate – for the trials

Table 1. Summary of trial conditions

Material	Approximate fineness	Number of trials	Height of stack (m)	Ignition source
	Small scale trials (overall stack height <2 m)			
Rubber crumb	40# (finest)	3	10 × 25 kg bags	Wood crib
Rubber crumb	20#	2	10 × 25 kg bags	Wood crib
Rubber shred	10# (approx)	3	10 × 25 kg bags	Wood crib
Coal dust	100 μm (fine) median (mass) size	2	10 × 25 kg bags	Wood crib (1) Heptane tray (1)
Coal dust	145 μm (medium) median (mass) size	2	10 × 25 kg bags	Wood crib (1) Heptane tray (1)
Wood dust	180#	1	10 × 25 kg bags	Wood crib
Wood dust	25#	2	10 × 25 kg bags	Wood crib (1) Heptane tray (1)
Epoxy powder	Fine <100#	1	10 × 25 kg boxes	Heptane tray
Polyester powder	Fine <100#	1	10 × 25 kg boxes	Heptane tray
Polyethylene powder	Approx 20#	2	10 × 25 kg bags	Wood crib (1) Heptane tray (1)
Maize starch	<38 μm	3	10 × 25 kg bags	Wood crib
	Large scale trials (overall stack height >5 m)			
Rubber crumb	40#	1	37 × 25 kg bags	Wood crib (at top of stack)
Coal dust	145 μm	1	29 × 25 kg bags	Heptane tray
Wood dust	25#	1	20 × 25 kg bags	Heptane tray

Table 2. Summary of results from trials

Material	Approximate fineness	Maximum temp rise rate (°C/min)	Maximum mass loss rate (g/s)	Ignition source
		Small scale trials (overall stack height <2 m)		
Rubber crumb	40#	220	140	Wood crib
		210	110	Wood crib
		70	30	Wood crib
Rubber crumb	20#	330	180	Wood crib
		160	70	Wood crib
Rubber shred	10#	80	45	Wood crib
	(approx)	50	20	Wood crib
		70	40	Wood crib
Coal dust	100 μm (fine)	140	–	Heptane tray
	median (mass) size	<10	–	Wood crib
Coal dust	145 μm (medium)	100	–	Heptane tray
	median (mass) size	<10	–	Wood crib
Wood dust	180#	8	–	Wood crib
Wood dust	25#	100	–	Wood crib
		70	–	Wood crib
Epoxy powder	Fine <100#	120	–	Heptane tray
Polyester powder	Fine <100#	110	–	Heptane tray
Polyethylene	Approx 20#	<10	–	Wood crib
powder		<10		Heptane tray
Maize starch	<38 μm	<10	–	Wood crib
		<10		Wood crib
		<10		Wood crib
		Large scale trials (overall stack height >5 m)		
Rubber crumb	40#	3600	–	Wood crib (at top of stack)
Coal dust	145 μm	4200	–	Heptane tray
Wood dust	25#	5100	–	Heptane tray

Notes:
1. Where several figures are given these corresponds to the results of separate trials, listed in the order of testing.
2. The figure for the first 25# wood dust corresponds to fire growth to a sustained period of burning. There was another more rapid period of temperature increase but this was not sustained.

in which mass loss was measured. The mass loss rate is most directly related to burning rate but the rate of increase in ceiling temperature is an appropriate alternative indicator of fire growth rate and potential fire hazard.

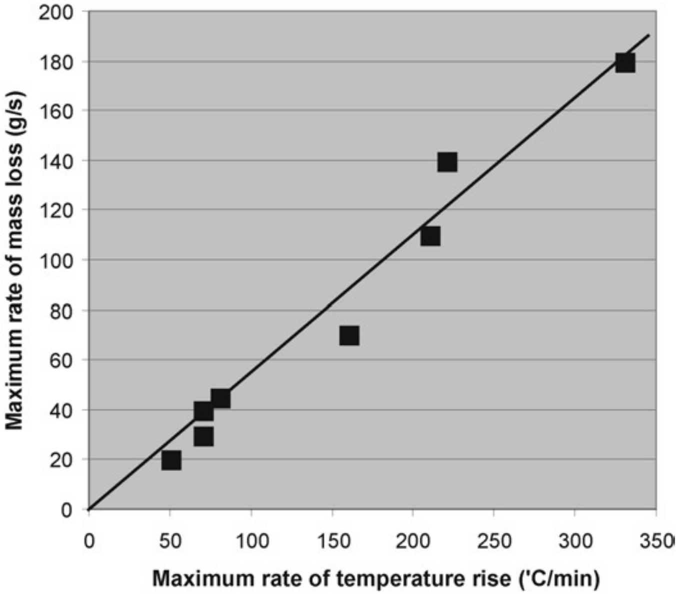

Figure 2. Correlation between maximum mass loss rate and maximum rate of temperature rise

REPRODUCIBILITY

For materials where the properties of the dust remained constant there was a reasonable degree of reproducibility. In the particular case of the finest grade of rubber crumb there was a clear change in the rheology of the samples with time. The last trial on the 40# sample was done on bags that had been stored for several months at an ambient temperature of 30°C at the bottom of a 2 metre high stack. The combination of somewhat elevated temperature, pressure and time led to a significant increasing the strength of binding forces between particles. This compaction of the dust increased the tendency of the material to "clump" in a fire i.e. not to fall out of the bags or to be lost in large lumps that fall without efficient dispersal. The trials consequently showed lower rates of fire growth.

This illustrates the potential importance of changes in rheology that may occur over time. Samples for any experimental testing should be chosen carefully to represent the full range of behaviour that a stored material may show.

EFFECTS OF PARTICLE SIZE

Results from single pallet trials on three grades of rubber crumb 40#, 20# and shred (10#) are shown in Table 3. These results and video records of the trials clearly show that fire growth is more rapid in the finer grades for ground level storage.

Table 3. Effect of particle size in single pallet trials

Grade of rubber crumb	Average max temp rise (°C/min)
40# (fine)	215*
20#	245
Shred	66

*The final trial on compacted 40# material has been excluded

A number of factors reduce the rate of burning of very coarse dusts.

i. Dispersal of the dust stream for a leaking bag is less efficient.
ii. Heating of the surface particles to the ignition point takes longer so that many may not be ignited.

No high level multi-pallet trial on rubber shred was carried out. Both of the factors that restrict burning of shred for a single pallet at ground level are significantly changed in the case of a rack storage fire. The increased distance of fall and violent fire-driven upflow in a pallet stack fire will increase the efficiency of dispersal of particles. The increased time of exposure and higher rates of heat transfer from flames in a stack fire will also increase the efficiency of ignition and the burning rate. It is likely that the clear difference in hazard between shred and finer grades for ground level storage would substantially disappear in high rack storage.

The table of results for three grades of rubber crumb gives some indication that the worst case may be dusts at around 20 mesh. The trials on wood dust also showed a reduced hazard for very fine dust compared to 25 mesh material. Possibly inter-particle forces are more effective at restricting dispersal of very fine grades.

EFFECTS OF DUST TYPE

The results of all the trials on different types of dust are summarized in Table 4. The reasons why a few of the materials tested did not show high rates of fire growth are varied.

Table 4. List of dusts shown to be high hazard

Materials giving a clear indication of high fire hazard	Materials not showing high fire hazard behaviour in low level trials
Rubber crumb (all grades)	Cornflour
Coal dust	Polyethylene
Wood dust (25#)	Fine wood dust (180#)
Epoxy powder	
Polyester powder	

In the case of polythene the low softening and melting temperature led to a layer of mobile material under the surface of bags exposed to flame. This softened material inhibited the flow of dust from the stack. In conditions of relatively low heat transfer (i.e. at the start of a fire with any small ignition source) a period of a minute or two is required to heat the bag to the ignition point. There is time for a relatively thick layer of softened/molten plastic to form under the paper. It is possible that the polythene dust tested would burn rapidly in conditions where burn through of the containment was more rapid and flow of powder was significant e.g. in a stack fire.

Cornflour formed a hard, stable, charred layer under the surface of exposed bags. This layer burned slowly even when exposed to flame from the crib and prevented any escape and dispersal of dust. Again the thickness and stability of the charred layer of flour under the surface of bags would have been less had the bags been burned away rapidly in conditions of higher heat flux. It is therefore likely that cornflour would burn more rapidly in conditions where burn through of the containment was more rapid e.g. in a stack fire.

The very fine wood dust tested showed a strong tendency to clump i.e. not to flow in response to gravity but to remain stable or break off in lumps. In a single pallet test with a small ignition source it has to be gravity that provides the force to displace material from the surface. In a stack fire this is not the case – dust can be displaced from exposed surfaces by the erosive action of the fire driven upward flow across the surface. It is likely that this fine wood dust would burn more rapidly if involved in a stack fire.

Neither grade of coal dust were ignited by a wooden crib, although they did ignite and burn rapidly following ignition by a tray of heptane. The area of paper affected by the burning crib directly is small and in this case the fire did not spread on the surface of the bags. This may be because coal dust has a relatively high thermal conductivity compared, for example, with wood dust. This means that heat leaks away from the paper surface to the bag contents efficiently enough to prevent significant areas reaching the firepoint. The type of bag is also important — if there are air gaps between the paper layers, and therefore a poor thermal contact between layers, fire spread over the surface of the bags is more likely.

Most of the dusts types tested behaved in a way that suggests that they could fuel very high rates of fire growth if stacked more than one pallet high or stored on high racks.

EFFECTS OF HEIGHT OF STORAGE

Overall stack height is the most important factor in assessing the hazard of a stock of flammable dust. Fires in dusts stored at elevation are very severe (high burning rate) and develop extremely rapidly. An impression of the high rate of spread of fire in dusts stored on racks can be gained from the views of wood dust stack fire in Figure 3.

Table 5 compares the initial rate of rise of ceiling temperature for 38 bags of rubber crumb stored on one pallet at ground level and 37 bags on four pallets to height of around 5 m. Rates of spread and fully developed burning rates are at least an order of magnitude greater if a flammable dust is stored at elevation in a pallet stack or a rack system.

Figure 3. Rapid fire growth in wood dust Times from ignition: Top left: 11 min 30 s Top right 11:45 Lower left 11:50 Lower right 11:55

There are two main reasons for this difference:

1. The dispersal of dust is more efficient both as it falls and as it hits the ground if the height of storage is greater.

Table 5. Comparison of fire development rates in low level and high rack storage (rubber crumb)

Storage configuration	Rate of temperature increase (°C/min)
Single pallet (38 bags)	200
4 pallet stack (37 bags)	3600

2. The strong fire-driven flow in a stack fire dislodges further dust increasing the rate of heat generation.

This latter factor is responsible for the extremely high rates of fire growth in the stack fires. Particularly rapid fire growth was observed in the case of the wood dust because in this case fire initially spread (slowly) over a number of bags in the lower pallet layers exposing the dust within. With no forces other than gravity operating most of this dust remained in place, but the stack gradually entered a dangerous state where it became unstable to exponential fire growth triggered by a small disturbance. A small release of dust can generate heat sufficient drive a flow up the stack that releases more dust. This produces more heat, a stronger flow, more dust and so on.

Figure 4 shows the rate of fire growth in the three stack fires.

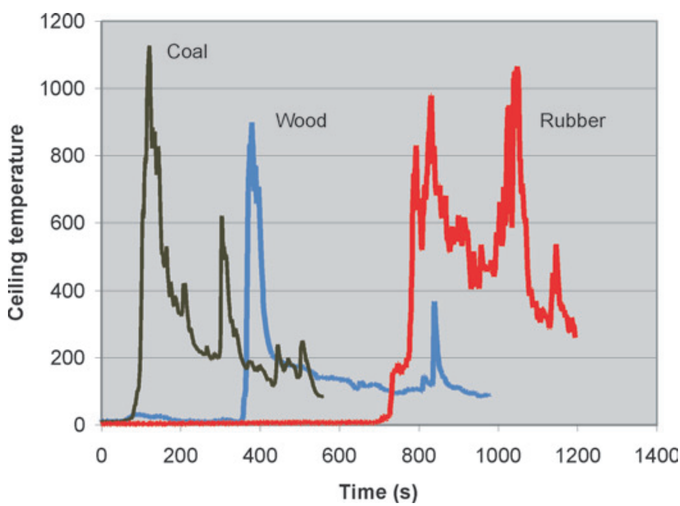

Figure 4. Temperatures at ceiling level for wood, coal and rubber dust stack fires nb. The rubber crumb fire is ignited at the top

Extremely intense external flaming could occur during a fire in large stocks of flammable dusts in high rack storage — potentially much more severe than for a flammable liquid store. This is because in the case of flammable liquid fires the process of fuel vaporisation requires heat. A ventilation controlled evaporation/burning regime is typically established, where the rate of vaporization is limited to (roughly) the amount that can be burned by the available air supply. For flammable dusts stored at elevation this limit on the rate of fuel loading does not apply.

The rate of lateral spread of fire in high buildings is likely to be greatly enhanced by low level spreading of a burning dust clouds formed as streams of dust impact on the ground. The speed of travel and extent of these burning clouds spreading across the floor may lead to higher rates of sideways fire spread than would occur with a spreading pool of flammable liquid.

It is worth recording that the entrainment and burning process in the well-developed phase of the large experimental stack fires was violent but relatively inefficient. Surfaces (e.g. plants, roads, vehicles etc.) were thickly coated with unburned dust for a distance of several hundred metres downstream. Flammable toxic dusts and mixtures of flammable dusts and inert but dispersible toxic powders are likely to cause particularly severe problems.

EFFECTS OF LOCATION OF POINT OF IGNITION

There have been a number of serious warehouse fires in which ignition occurred because of the failure of light fittings. Hot fragments can be produced which may ignite plastic or paper packaging materials if they fall on pallets in the upper levels.

The rubber crumb stack trial was started with a small wooden crib on top of the pallet to reproduce this type of ignition. The aim was to investigate whether fire would spread downwards and if so at what rate.

For the first 12 minutes the fire spread slowly on stretch-wrapping covering the bags. Eventually the bags were breached and a rubber crumb fire developed in the top pallet. There were periodic flows of dust from this upper pallet fire, which produced intense but relatively short-lived burning streams around the lower pallets.

After around 40 seconds this intermittent fire exposure of the lower pallets led to ignition at low level and rapid spread to all of all the remaining surfaces of the stack.

EFFECTS OF CONTAINER TYPE

Only a limited amount of work was done on this. Trials on polyester and epoxy powders in polythene bags and cardboard boxes showed that dispersal of dust and high rates of fire growth are possible for boxed as well as bagged material.

CONCLUSIONS

i. Most flammable dusts at 20 mesh or finer are likely to present severe fire risks if stored at elevation in pallet stack or on racks. This includes a huge range of natural products, plastics and fine chemicals. Many significantly coarser dusts are also likely to behave dangerously.

ii. The authors are not aware of any small scale test currently available that will unambiguously identify a dust as "flammable" in the sense referred to above. It is likely that there will be a rough correspondence with dusts classified as explosible in the Hartmann tube or similar test. But some finely divided combustible organic or metallic materials that are not explosible may well present a fire risk.

iii. Some free flowing, readily ignitable dusts represent a significant fire hazard even in ground level storage. Rubber crumb is one example.

iv. In high rack storage the rate of fire growth and final burning rate may exceed levels for flammable liquid stores.

v. Fire spread over the surface of a number of bags is necessary before the dust fire accelerates. This spread is promoted by: dusts with low thermal conductivity; air gaps between paper layers, shrink or stretch wrapping and larger ignition sources.

vi. The hazards of flammable dusts in both paper bags and cardboard boxes have been demonstrated. Plastic sacks are relatively rare for this type of product because of the risk of static discharge and dust explosions. It is very likely that most flammable dusts would pose high fire risk if packed in plastic sacks, in any case.

vii. High rack dust fires will spread sideways through the normal mechanisms of fire exposure of upper pallets to flames under the roof and direct fire exposure of neighboring pallets. Rapid low level fire spread may also occur as streams of dust hit the floor and produce rapidly spreading burning clouds.

viii. Downward fire spread may be rapid when driven by burning streams of falling dust.

ix. Care must be exercised in attempting to fight high rack dust fires. The fire may enter a state where a disturbance e.g. application of fire extinguisher or water jet, will trigger ultra-rapid fire growth.

x. Dispersal of unburned toxic powders during a major chemical storage fire could have serious safety and environmental consequences.

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