# FIRE RISKS FROM PACKAGED FLAMMABLE DUSTS – HSE FIRE INVESTIGATION AND TEST WORK AT HSL

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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. Many industrial premises hold solid materials that are flammable. These materials could include natural and synthetic substances such as plastics, rubber, paper and textiles in the form of blocks, sheets, fibres, granules and powders. If these materials are not suitably stored or used they could lead to serious fire hazards. The risk is of heavy losses to the company involved and a threat to the lives of people both on and off site.

This paper discusses an HSE investigation involving a major fire at a rubber crumb processing plant that resulted in a fatality of an employee. The serious nature of the rubber crumb fire and its rapid escalation (which destroyed the company's approximately 70 tonnes of packaged product within minutes) prompted an in depth study at the Health and Safety Laboratory in Buxton. This paper also discusses some intermediary observations made.

## INTRODUCTION

In many cases people within industry are not fully aware of the fire characteristics of the materials they use, handle or store within their premises. This is probably largely due to them not fully understanding its properties and the requirements necessary for adequate storage arrangements and additional safeguards that might be needed against a fire.

It is not always easy to predict how a solid flammable material may burn when heated and the resulting fire develops. This is because the behaviour of a burning material largely depends on several factors. These include, the quantity of flammable material involved, how it is packaged and stored in the workplace.

The fire that HSE investigated at a rubber crumb processing factory in Stockport in 1999 established that the packaged rubber crumb fire did indeed occur because of poor understanding about fire hazards associated with the material and because of inappropriate packaging practices.

## THE INCIDENT

The fire occurred during the night shift at 00.31 on 25th Nov 1999. There were only 3 people were working the night shift on the site at the time of the incident. Sadly one of them died in the fire.

The fire started in an area where freshly processed rubber crumb was being loaded into 25kg three-ply paper sacks. These sacks were stacked on a pallet accommodating 46 sacks in total to make up an 1150 kg load. The sacks were shrink-wrapped to improve load stability in storage and transportation. A hand held propane gun was used for the shrink-wrapping operation. It was reported that immediately after completion of shrink-wrapping the employee decided to move the pallet into the storage area located at the front of the factory. It was whilst he was moving the load using a fork lift truck that he noticed smoke coming out of the freshly shrink-wrapped load of rubber crumb. He called out to alert his colleagues to the developing fire and raced up to the office, situated on the mezzanine floor, to ring the fire brigade. The fire spread quickly to the neighbouring stock of packaged rubber crumb product. The rate of fire spread and high smoke production hampered attempts to fight the fire with extinguishers and the other two employees were forced to make their escape. Unfortunately, the employee who went to raise the alarm became trapped by smoke and flames.

It was reported that the local fire brigade responded immediately and were at the company's site within 4 minutes of the alarm being raised but by the time they arrived the fire was already raging fiercely.

## THE PREMISES

The factory was a single floor corrugated cement sheet building with a pitched roof. The walls were in filled with breeze blocks to a height of around 2.7m and from above about 3.4m from the ground level there were glazed panels. These were protected on the outside by steel mesh. The roof was supported by steel trusses and clad with profiled cement panels.

Small offices were constructed in one front corner of the building with access to a changing room and an office located on the mezzanine floor. The roof of the middle section of the building was at a higher level to accommodate the bucket elevators required for moving the products from the milling and sieving processes. With the exception of the offices, the whole structure was completely open. This openness offered the possibility of free flow of smoke under the roof from one part to another.

## THE PROCESS

The main process undertaken at the premises is the grinding of tyre re-tread waste to make different grades of rubber crumb. A range of product grade is produced that vary in the size distribution of the crumb. The mean particle size varies from the finest grades at around 150 micron diameter to over 1mm diameter for the coarsest grades. The processed rubber crumb is used in the manufacture of such products as children's play surfaces.

Raw material is processed via a storage hopper, a loading conveyor and bucket elevator, a box magnet on the conveyor and a rotary drum magnet at the inlet of the bucket elevator remove fragments of wire.

From the storage hopper the material is introduced into one of two independent grinding loops via screw feeders. A second bucket elevator lifts material in the grinding loop on to a sieve. The oversize fraction re-enters the mill whilst product is moved into a conveying duct where a large volume of cooling air is introduced. The product is separated from the cooling air in a cyclone separator and accumulates in a finished product hopper. finer grades are then bagged directly into paper sacks. Coarser grades are sieved again to remove finer fractions before bagging. There are additional magnetic separators to remove any remaining metal fragments in the grinding loop and the product line.

Temperature sensors are fitted under the grinding mill and in the associated elevator feed screws. These sensors are set to trigger an alarm and shut down the plant if the temperature of material in the grinding loop rises above a set temperature. The fire point of vulcanised rubber is around 200°C, so the sensors should prevent overheating leading to a fire.

Tests carried out at HSL following previous HSE visits in 1992 established that the material was explosible. HSE advised the company to afford adequate explosion relief to bucket elevators, hoppers and cyclones.

**BAGGING PROCESS**

The most significant secondary process undertaken in terms of the fire investigation were bagging of product, stacking of bags on pallets, shrink wrapping of complete pallets load of material and moving of the complete wrapped pallets to a storage area.

Both polythene and 2 and 3-ply paper sacks were used to hold the finished rubber crumb in 25 kg lots. One of the employee stated that 3-ply paper sacks were used in the pallet in which the fire started. The empty sacks used are reinforced with paper tape pre-stitched with natural fibre thread at one end. After filling the sacks are closed with the aid of a hand held stitcher using synthetic fibre thread.

After filling the bags of crumb are flattened by being gentle trampling to assist stacking and stability. The bags are then stacked on to a pallet. Two dabs of a water-based paste are applied between layers of bags to improve the stability of the pallet load.

Some pallets, including the one in which the fire apparently started, were shrink wrapped immediately after being stacked. A 450 gauge polythene cover was put over the load. If the bags had been properly flattened, this cover would reach down to the bottom of the load. A propane fuelled heat gun was used to shrink and tighten the cover around the stack of bags. The shrink-wrapping process depended on the gun being held the correct distance from the polythene cover. If the gun was brought too close to the cover or was left in the same place for too long the cover would melt, creating holes in the cover. The Fire Service inspected several pallets that had escaped fire damage after the fire; holing of the plastic cover caused by close contact with the heat gun was fairly common. The total height of a pallet load containing 46 bags is something over 2 metres in height. This means that it is difficult to monitor and control the heat gun as it is applied to the top surface of the pallet. Finally the completed pallets were moved by a fork lift truck to a storage area to await despatch.

**OTHER ISSUES**

This investigation also revealed that the standard of housekeeping within the factory was poor. This is in spite of the company's claim that they vacuum cleaned the process area regularly. Accumulations of dust to a depth of 150mm were observed on support beams and electrical apparatus, such as strip lighting. This gave cause for serious concern. The foreseeable secondary explosion hazards of this dust were explained to the company. Appropriate advice to keep such areas free from dust was given.

 

The level of dust accumulation in and around the electrical motors and their housings was considered a potential fire hazard. Overheating of the motors as a consequence of dust accumulation was explained to the company. Appropriate advice to keep motors and their housing free of dust was thus afforded.

In spite of the earlier advice in 1992 given by HSE on the provision of explosion relief, the dust collection unit and its explosion relief was very poorly positioned within 1m of a desk used by operators. The potential dangerous consequences were stressed to the company. An alterative much safer location for resiting the dust collection unit and the explosion relief was advised. The company agreed to move the dust collection unit well away from the process area into the yard outside.

## FIRE DAMAGE

The fire damage was most severe in the front part of the building. Approximately 70 tonnes of fine rubber crumb was destroyed by the fire in this area, together with some other plastic and packaging materials. Above the palletised storage area the cement panels covering the roof in the front part of the building were also completely destroyed. Structural steel in roof trusses at the front part of the building was also badly distorted by the heat from the fire. A wooden staircase leading to the Quality Manager's office and an adjacent toilet on the first floor were also completely burned away.

Heat and fire damage was observed at roof level above the machinery in the middle section of the building. This was consistent with strong flames extending upwards from under the roof on the front section.

## IGNITION MECHANISMS

A number of possible causes for the initial ignition were considered but discounted. These included electrical faults, self-heating, malicious ignition, FLT malfunction and process overheating are all considered to be unlikely sources of ignition in this instance.

The propane powered heat gun is however considered an obvious possibility, since the pallet that caught fire had been shrink-wrapped a minute or two before the fire was discovered.

Some basic tests carried out by the Fire Service on empty sacks showed that to ignite the paper sacks required a relatively long exposure to the heat gun. When the heat source was removed the paper sacks generally self-extinguished. Only if the frayed paper end of the sack was ignited did the fire persist when the heat source was removed.

The Fire Service tests also showed that the paper reinforced stitching at the pre-stitched end could also be ignited by a short application of the heat gun. This continued to burn, igniting the end of the sack and the hessian stitching. Eventually the sack was breached and the flammable contents would have started to leak out.

It was concluded that the propane gun could have ignited the edges of the sacks at the top of the pallet during the shrink-wrapping operation. This ignition would have led to a very small but growing fire that might well have been overlooked for a minute or two during the transportation of the rubber crumb loaded pallet.

 

## UNUSUAL FEATURES OF THE FIRE

There were two features of this fire that might have important implications for the safe storage of rubber crumb and possibly other finely divided combustible products.

i) *The fire grew extremely rapidly*. Generally very rapid fire growth is associated with high stacks of expanded plastic foam or baled textiles. In this case the storage was only one pallet high and the product had a high density and was packaged.
ii) *The premises became smoke logged very rapidly*. This is clearly closely related to the rapid spread of flame. Nevertheless, it is significant that smoke began to seriously impede escape within a couple of minutes despite the open character of the building and the fact that the roof extended to a height of over 13 metres in places.

Following the fire the Health and Safety Laboratory carried out a number of tests to investigate the rate and mechanism of fire growth in palletised rubber crumb. The results of these tests have also been used as inputs in an analysis of smoke logging of the factory. It is hoped that the results of these investigation will improve understanding of the fire hazard associated with this kind of product and provide data suitable to undertake realistic risk assessments in other premises.

## FULL SCALE TESTS – FIRE GROWTH IN PALLETISED RUBBER CRUMB

Two full scale tests of fire growth in a pallet load of 40 mesh rubber crumb were carried out in the high rack test rig at HSL in Buxton. This rig is essentially a cubical enclosure of height 7.5m that can be conveniently clad with polythene on two sides so that the early stages of fire growth take place in relatively sheltered conditions. If a fire grows to a size greater than around 5 MW the polythene softens and fails, preventing the fire from becoming ventilation controlled.

## TEST 1

An array of thermocouples was used to monitor the temperature under the roof deck. In this first test a pallet load of 38 x 25kgs bags was burned on an open steel tray 1.8m x 2.3m x 0.3m (high). This tray was supported on 4 load cells. This arrangement allowed the measurement of the rate of mass loss in the early stages of the fire. After around 5 minutes some material fell from the pallet over the edge of the tray and thereafter effective monitoring of the rate of heat release through measurement of the rate of mass loss was not possible.

The fire was started with a British Standard Number 7 pine wood crib. This has a mass of 125g and produces a peak heat output equivalent to four crumpled sheets of broadsheet newsprint.

When the paper sacks were breached the rate of fire development was extremely rapid. The fine rubber powder ran down from the edges of the sacks igniting and burning immediately. As the rate of heat release increased the updraft of air around the pallet became more vigorous. This flow increased the rate of ablation of the surfaces of the pallet and drove a proportion of the material released upwards, so that it burned as a dust cloud rather than a solid pile. The observed rate of fire development was consistent with the eyewitness accounts of a major conflagration occurring within a couple of minutes of the first signs of fire.

Results of some of the measurements of temperature at ceiling level (7.5 m elevation) in the area just above the pallet are shown in the graph below.

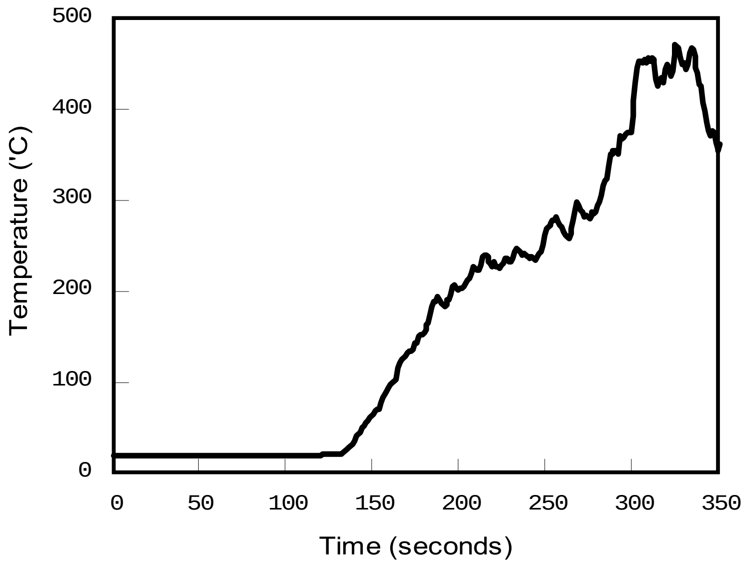


**Figure 1.** Ceiling temperatures 7.5m above base of pallet 38 x 25 kgs rubber crumb (40#)

The first signs of raised temperatures at roof level occurred after around 140 seconds. The temperature rises steadily to around 500°C in the next 160-170 seconds. Thereafter there is a fall in the recorded temperature in this area of the ceiling. This is mainly caused by progressive failure of the plastic shielding around the rig and consequently increased plume deflection.

Results of measurements of mass and mass loss rate together with the average temperature are shown in figure 2.

The shifting of load as material pours down from burning bags produces some variations in apparent mass loss but it is clear that the rate of mass loss becomes significant at around 140 seconds after ignition. It rises to a level of around 250g/s after about 250 seconds. The rate of total heat production (both radiant and convective) from styrene-butadiene rubber is around 27 kJ/g so a mass loss rate of 250 g/s corresponds to a rate of heat release of 6.7MW .The proportion of heat production radiated by the highly emissive flames depends on the size of the fire but for a fully burning pallet would probably be slightly over 50%.

In order to compare the rate of fire growth with other types of commodity the rate of mass loss and heat release have been fitted to quadratic "t-squared" curves. If this fit is carried out over the first 210 seconds of the fire a value of 0.28 is obtained for the "a" parameter in the t-squared fire growth expression i.e.

**Heat release (kW) = $a.t^2 = 0.28.\ t^2$ (t in seconds)**

If the fit is carried out over the first 300 seconds a value of 0.18 is obtained for "a".

 

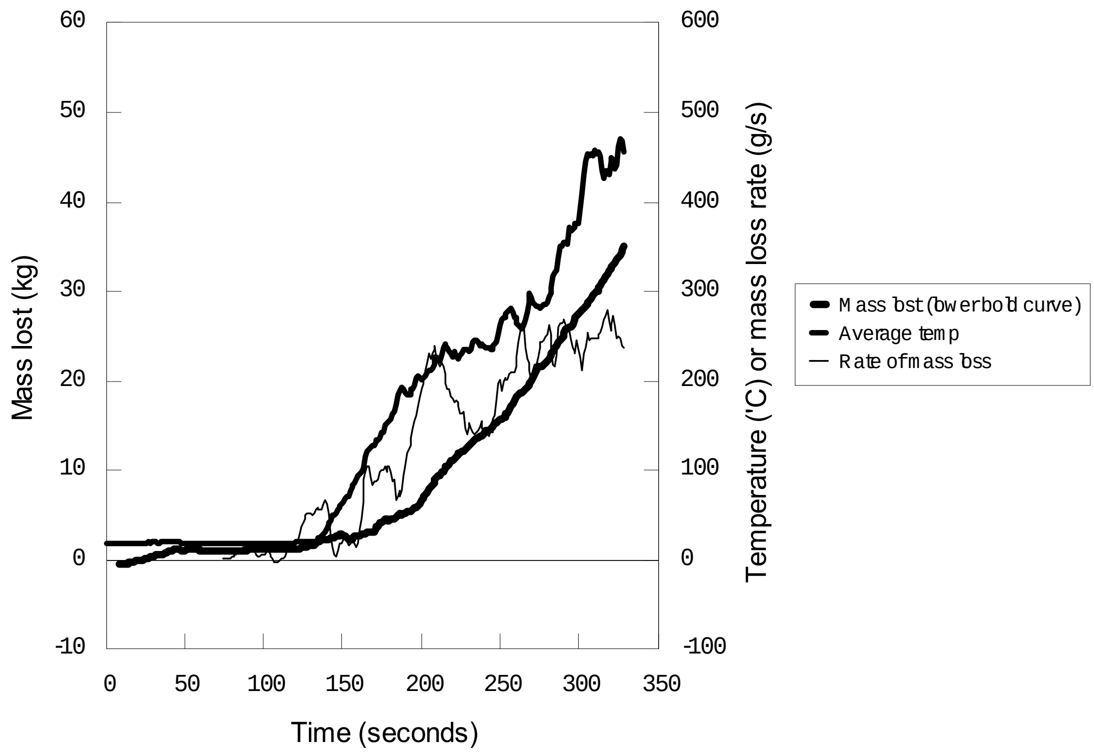


**Figure 2.** Mass loss, mass loss rate and temperature for 38 x 25 kgs sacks rubber crumb (40 #)

**Heat release (kW) = a.t² = 0.18. t² (t in seconds)**

The most hazardous category in the American National Fire Prevention Association (NFPA) system of t-squared fires for use in risk assessment is ***ultra-fast***, which is taken to correspond to a value of (a) of 0.18. This means that the rubber crumb fire grew as quickly or more quickly than the most severe case considered in this system of fire risk assessment. Other materials that may fall into this category include, for example, high stacks of polyurethane or polystyrene foam, flammable liquids in plastic bottle and long rolls of paper stored on their ends.

At the site where this fire investigation was carried out, the ignited pallet load of rubber crumb was in close proximity to a number of other such loads. After the initial growth of fire to a few megawatts there would have been very rapid fire growth over exposed surfaces of nearby pallets, driven by the high radiative heat transfer.

TEST 2:

The second test carried out HSL was less successful than the first. In order to improve visibility the plastic shielding (destroyed in the first test) was not replaced. A breeze on the day of the test led to flames being blown away from the ignited face and under the pallet. The fire developed on the sheltered side of the pallet opposite to the point of ignition. The flames were blown away from the top of the pallet reducing the rate of fire spread and thus the rate of burning. However, after a period of 7-8 minutes a large fire developed.

 

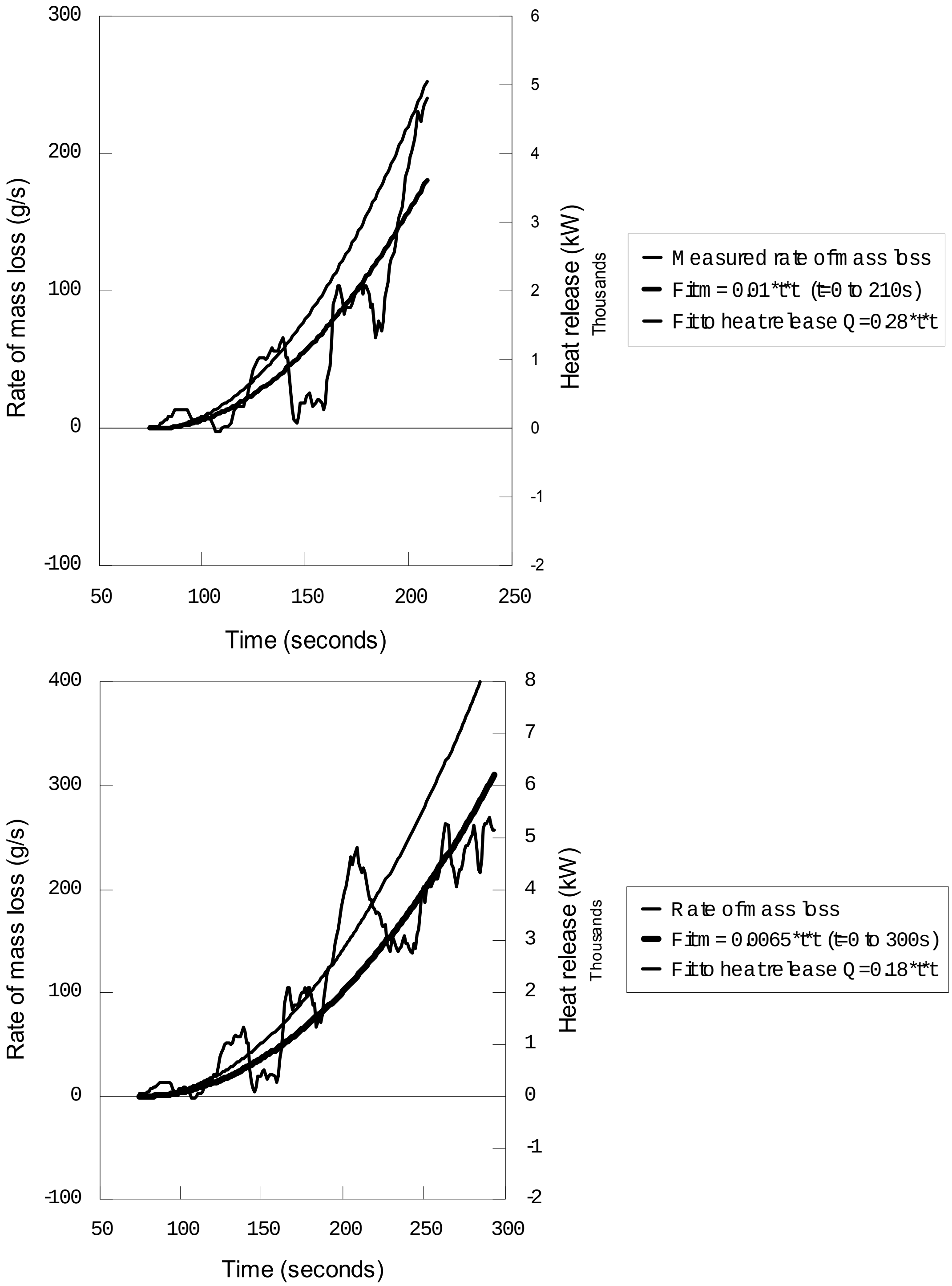


**Figure 3.** Measured mass loss rate and fits to mass loss and heat release

 

## MEDIUM SCALE TESTS OF FIRE HAZARDS

HSE use a medium scale test to assess the fire hazard of solids stored in bulk. This test classifies materials as HIGH or NORMAL hazard according to two aspects of their fire performance: the rate of development of fire and the potential to generate smoke. The test is general applied to cellular plastics and lightweight textiles in block, roll or baled form.

The medium scale test is essentially a compromise between the full scale testing, which produces immediately applicable results, but is expensive; and bench scale testing that is cheap but produces results that have to be extrapolated to be of use. The hazards of rubber crumb were effectively demonstrated by the large scale tests described above, but it is of interest to see how the materials classified by the medium scale screening test. The test also allows the measurement of smoke yield which is significant in the context of understanding the circumstances that led to the fatality at the incident site in Stockport.

The test is not regularly applied to powdered, high density materials. There is therefore no established method for choosing the sample geometry. The general principle followed for other types of material is to try to reproduce in the test, as precisely as possible, a small section of a storage being assessed. In the case of blocks of foam or rolls of textiles this is generally possible to do satisfactorily. The case of a powder in 25 kg sacks is more problematic. It was observed that the mechanism of burning involved material being dislodged from the surface of breached bags then dispersing and burning as it fell. These processes are difficult to reproduce realistically in a small scale test.

Two sample geometries were chosen in which 5 kgs of rubber crumb was packed in 10 x A4 manila envelopes. These were stacked in different ways in the two tests.

Results from the two tests were broadly similar. The potential of rubber crumb to fuel a very rapidly growing fire did ***not*** show up in either test. The smoke yield was also low over the period of the test, because only a small proportion of the sample burned in this period. The measurements of smoke and heat production suggest that, if all of the 5 kg sample had in fact burned, the smoke production would have been 900 $m^3$ ODm1. This is in excess of the limit defining a high hazard material of 400 $m^3$ ODm1.

The conclusion is that the causes of high rates of fire growth in palletised rubber crumb are probably very difficult to assess effectively in a test of the sort currently used by HSE. A better understanding of the fire hazard of palletised fine combustible powders is required. It may be possible to devise a special smaller scale test to determine whether another material of this sort represents as high a level of hazard as fine rubber crumb.

## ANALYSIS OF SMOKE LOGGING

The rapid filling of the building with dense black smoke was probably a key factor in the tragic consequences of the fire at Stockport. The details of the process of smoke logging are quite complex because of the variable roof height, growing fire, uncertain heat transfer, venting of roof panels etc. Nevertheless, it is possible to calculate approximately how long it took for the smoke layer to descend to head height level and what the visibility was at this stage.

 

**BASIC ANALYSIS**

The floor to ceiling height in the section of the building where the fire started was 8.64 m. The most commonly used expression for the mass flow of air into a hot layer above a typical fire is based on Thomas, P. et al, Fire Research Technical Paper No.7 -1963)

$$\text{Mass flow} = 0.096P_{fire}\ \rho_o \,.\, Y^{3/2} \,.\, (gT_o/T_f)^{1/2} \qquad \text{(Equation 1)}$$

Where:
- $P_{fire}$ is the perimeter of fire plume near the source (m)
- $\rho_o$ is the density of air at ambient temperature (1.2 kg/m$^3$)
- $y$ is the height of the base of the hot layer above the fire base (m)
- g is gravitational acceleration i.e. 9.81 m/s$^2$
- $T_o$ is the ambient temperature (K)
- $T_f$ is the temperature of the gases entering the hot layer.

The perimeter of the rubber crumb pallet fire increases somewhat as the fire progresses and material spills from the pallet; a figure of $P_{fire} \sim 8$m is appropriate. The initial height of the base of the hot layer is approximately 8.6m. Results from the large scale test undertaken suggest that after the first 60 seconds the parameter $(gT_o/T_f)^{1/2}$ is in the range 1.9 to 2.2, so a value of 2 will be assumed.

With these assumptions Equation 1 gives a mass flow of air into the hot layer of 46 kg/s. Before the raised section of roof is filled there will be further rapid entrainment as hot smoke flows towards and then up into the middle roof space. Such extra entrainment is ignored in this basic calculation and it is assumed that the fire plume is the only source of entrainment into the hot layer. There will also be cooling of the smoke through both radiant and convective contact with the walls and roof of the building. We assume that rapid high temperature radiant cooling lowers the average temperature in the hot layer to around 200°C. In this case the initial rate of increase in volume in the hot layer is approximately 66 m$^3$/s.

A first estimate of the time taken to smoke log the building to a height of 2.7m (floor level in the upper storey) can be obtained by dividing the volume of the building above this level by the initial volume flow rate.

$$T = 6882\text{m}^3 / 66\ \text{m}^3/\text{s} = 104 \text{ seconds}$$

If it is assumed:

a. The smoke is well mixed.
b. The yield of smoke is 900 m$^3$ ODml / 5kg as in the medium scale tests.
c. The average rate of mass loss during smoke logging is 250 g/s.

The optical density of the smoke (at 200°C) is 0.64. In these conditions a non-luminous object would be completely invisible if it were further than 2 metres distant.

In fact the time to smoke logging would be greater than the result above because as the hot layer deepens the fire plume increasingly re-entrains smoke, so the effective value of y in Equation I falls. For example, if the average effective height were to be midway between the roof height and final layer height, the time for smoke logging would be increased to 190 seconds. Where smoke re-entrainment was significant the smoke density would be increased. If the smoke logging time increased to around 200 seconds the visibility would reduce to around 1 metre.

Apart from the neglect of smoke re-entrainment many of the assumptions on which this analysis are based are very crude. The lower surface of the hot layer would not necessarily be horizontal. There might be a number of significant effects that would hasten the contamination of air near the ground; for example, air cooled by contact with the walls flows downward through the hot layer, developing a momentum that takes it below the lower surface of the hot layer. It is also possible that large scale vertical structures driven by the strong flow into the middle part of the ceiling could disturb the lower surface of the hot layer. It would be possible to investigate the smoke logging process in detail but this would require Computational Fluid Dynamics.

## CONCLUSIONS FROM ANALYSIS OF SMOKE LOGGING

The conclusion from the basic analysis of smoke logging of the building is that the smoke layer will deepen rapidly, reaching the level of the floor of the first storey after around 200 seconds. This roughly corresponds with the time taken for the burning of a single pallet to reach its maximum severity. This means that anyone attempting to fight the growing fire would begin to perceive smoke close to head height at about the same time as the fire reached a stage when it was clearly uncontrollable. This appears to broadly correspond to the account given by the company.

## GENERAL CONCLUSIONS & RECOMMENDATIONS FOR ACTION

1. Storage of palletised rubber crumb represents a high hazard in terms of the potential to fuel a very rapidly developing fire that produces a large amount of dense smoke. It is considered that a lack of awareness of the fire risks associated with this product at the factory may well have been a contributory factor in the death of its employee at Stockport.
2. Steps are necessary to improve awareness of the risks of palletised rubber crumb through advisory and regulatory work by HSE and the Fire Service, and by providing clear warnings when the material is supplied e.g. hazard warning sheets and markings on packaging.
3. The use of a hand-held LPG fired naked flame gun is considered to be totally inappropriate for shrink-wrapping rubber crumb. This is because rubber crumb is a high fire hazard material and as such would fuel a fire producing large quantities of dense smoke very rapidly. To reduce risks alternative cold methods should be used.
4. There is a strong possibility that other finely divided combustible materials may behave in a similar manner to the rubber crumb tested at HSL. This is currently under investigation and the findings will be published at the conclusion of the study being carried out at HSL.
5. If a fire grows rapidly, the time for smoke logging of even large open structures may be very short. Emergency procedures that involve employees contacting the Fire Service before exiting are potentially dangerous. This is especially true when making an emergency call causes someone to lose track of the progress of the fire.
6. Necessary precautions against fire and explosion as set out in HSE's Guidance Note HS(G) 103, entitled “Safe handling of Combustible Dusts”, ISBN 0-7176-0725-9. This guidance note can be obtained from good booksellers.

 

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