

FIRE AND EXPLOSION HAZARDS OF MEAT & BONE MEAL: STORAGE, TRANSPORT AND PROCESSING

Steven J Manchester

Fire and Risk Sciences (FRS) Division, BRE Ltd, Garston, Watford, WD25 9XX

In order to restore consumer confidence in eating beef following the BSE outbreak, the UK Government instigated the Over Thirty Month Scheme (OTMS). This is a voluntary scheme whereby cattle over thirty months, showing no clinical signs of BSE are slaughtered and their carcasses incinerated or rendered into Meat & Bone Meal (MBM). As a result of this scheme producing huge quantities of MBM, extensive storage areas were required. A number of these stores have experienced fires. BRE was asked to investigate these fire incidents to determine the cause, and to undertake a research programme to assess the fire and explosion hazards in storing, processing and transport. This paper describes the research, testing and consultancy work undertaken by BRE on MBM, which has produced specific guidance to mitigate the hazards.

KEYWORDS: Meat & Bone Meal, spontaneous combustion, dust explosion, calorimetry, fire.

BACKGROUND

As a result of the BSE crisis that afflicted the UK in 1996, the Government instigated the Over Thirty Month Scheme (OTMS) to restore consumer confidence in eating beef. This involved the culling of cattle showing no clinical signs of BSE, once they had reached an age of thirty months. The carcasses were either incinerated or rendered into Meat & Bone Meal (MBM) and tallow. Huge quantities of MBM were produced, which had reached over 470,000 tonnes as of March 2000, prior to the commencement of an incineration programme to destroy the MBM. However, at this time only one incinerator was capable of incinerating the MBM being produced. Large in-door storage areas, mainly old factory and farm buildings, were used to hold the MBM while awaiting incineration, with some stores holding material for over four years before being emptied.

INTRODUCTION

Following a number of fires involving MBM in storage, the Intervention Board (now the Rural Payments Agency) commissioned BRE to undertake research with the following objectives:

- Investigate the potential causes of fire in MBM during bulk transport and storage;
- Assess the hazards and risks associated with fires and dust explosions in the material; and
- Provide guidance on prevention and mitigation of fires and dust explosions with MBM during storage, transportation and processing.

A research programme was devised which focussed on the following areas:

- Site visits to six MBM stores, two of which had experienced fires in the MBM material, and an incinerator process plant handling MBM.

- Investigation into the cause of the fires in the two stores.
- Self-heating investigation on a number of MBM samples from stores around the UK and Northern Ireland.
- Dust explosibility assessments and guidance on preventative and protective measures.
- Toxic analysis of the combustion gases produced from smouldering and flaming combustion of MBM.
- Bomb and cone calorimetry studies on the fire behaviour of MBM.
- CFD modelling studies on the fire plume to predict the deposition of combustion products from a fire in a store and on a vehicle.
- Guidance on fire prevention, fire-fighting and the environmental effects of a MBM fire in a store or on a vehicle.
- Clean-up methodology to be followed after a fire.

In addition a site visit to an incinerator was also undertaken to assess the dust fire and explosion hazards from handling and processing MBM.

MBM IN STORAGE

SITE VISITS AND FIRE INVESTIGATION

The first part of the project was to visit a selection of the MBM stores, including the stores which had experienced fires, to get a first hand knowledge of the conditions within the stores and the potential fire/explosion hazards. This exercise was an essential part of the fire investigation into the two incidents. Discussions with the site operators also provided an invaluable source of information on the fire incidents themselves and the general loading/unloading and storing procedures that were followed at each of the stores.

From the site visits the general conditions of storage were as follows:

- MBM was stored in stockpiles of typically greater than 10,000 tonnes inside old/disused factory or farm buildings.
- The stores contained no temperature controls, although temperature monitoring of the pile was carried out on a regular basis.
- The buildings were generally in good enough condition to keep the MBM dry, some had electricity supplies still functioning.
- Some stores contained piles of MBM which were not compacted, but were piled loosely into the building.

It was also apparent from discussions with the Intervention Board and the store operators that the nature of the MBM varied from store to store. The main reason for this seemed to be due to the different rendering companies employed, which meant that the MBM supplied for storage was not identical in all cases. Variations included the MBM being ground into a fine dust rather than being a mixture of fines and large lumps of bone, larger proportions of blood meal, and different fat contents. All of these variations in the content of the MBM, in conjunction with the different storage volumes and conditions,

meant that visiting the stores was essential to ensure a representative experimental programme and hence be able to offer guidance on fire/explosion safety.

From the visits to the two stores which had reported fires it was concluded that both fires almost certainly started from self-heating of the MBM leading to spontaneous combustion. The evidence for this was:

- Ideal conditions for self-heating, i.e. large volumes of MBM stored without compartmentation for very long (3–4 years) periods of time.
- No compaction of the MBM pile in these particular stores, allowing air into the pile.
- The MBM was piled around the building roof supports, allowing air ingress.
- No identifiable external sources of ignition.
- Good security of the sites and the buildings reducing the probability of arson.
- Temperature records from monitoring at these sites and also other stores, showing self-heating of the MBM.
- Experimental evidence of the propensity of MBM to undergo self-heating leading to ignition.

EXPERIMENTAL PROGRAMME

Following the site visits to the stores a detailed experimental programme was discussed and agreed with the Intervention Board in order to fully characterise the fire and explosion properties of MBM and use this data to perform a risk assessment on the storage, transport and processing conditions. Further studies were also undertaken using Computational Fluid Dynamics (CFD) modelling to estimate the environmental consequences of a MBM fire in a store and while being transported.

Isothermal Self-Heating Tests

Self-heating^[1,2] is the occurrence of a rise in temperature within a body of material in which heat is being generated by some process taking place within the material at a greater rate than heat is lost to the surroundings. In certain circumstances the temperature rise may increase both in magnitude and rate sufficiently to culminate in combustion; that is, there may be a 'self-ignition' or 'spontaneous ignition'. External heat sources may sometimes be necessary for the occurrence of such ignition but, by definition, these will be less than sufficient in the absence of heat generation within the material itself.

MBM from three stores were chosen for an in-depth investigation into the self-heating properties. The purpose of this part of the project was to provide advice on safe storage temperatures and volumes, and the times required for self-heating to occur. The test method is described in detail by Beaver^[3].

The materials under test were placed in cubical wire mesh baskets of different side length: 75 mm, 100 mm, 150 mm, and 200 mm. The baskets were filled with the sample and levelled with a straight edge. The material was not compacted into the cube. The filled cube was then suspended in a pre-heated oven and thereafter maintained at a known temperature to within $\pm 1^\circ\text{C}$. The centre and surface temperatures of the sample were monitored using 1.0 mm, stainless steel sheathed, chromel/alumel thermocouples. These

were connected to a chart recorder and a personal computer, so that the self-heating process could be observed and recorded.

The results from the ignition tests are summarised in Tables 1–3.

Table 1. Summary of test results for Preston store

Test sample	Cube size (mm)	Critical temperature (°C)	Time to ignition (hr)
Preston	75	162	4.5
	100	154	8.1
	150	142	16.1
	200	134	30.3

Table 2. Summary of test results for Alleena store

Test sample	Cube size (mm)	Critical temperature (°C)	Time to ignition (hr)
Alleena	75	171	3.8
	100	162	7.0
	150	150	15.1
	200	144	26.0

Table 3. Summary of test results for Newtownstewart store 2

Test sample	Cube size (mm)	Critical temperature (°C)	Time to ignition (hr)
Newtown-stewart	75	176	3.8
	100	167	6.8
	150	154	15.0
	200	143	28.1

Two types of behaviour were observed;

1. the central sample temperature rising by a relatively small amount ($< 20^{\circ}\text{C}$) above the pre-set oven temperature and then gradually falling back to the oven temperature (sub-critical behaviour, Figure 1), or
2. the central sample temperature rising to a high value of about 300°C , and then gradually falling back to the oven temperature (super-critical behaviour, Figure 2).

The results, when applied to the full-scale MBM storage conditions, showed that the ambient temperature at which self-heating can occur in the samples tested was 46–49°C, with times to ignition varying from 4.9 years to 21.5 years. At the time of the investigation, some of the stores containing the MBM had been storing the material for over four years. It was found that MBM at a temperature of between 67–73°C could lead to an ignition within as short a time-scale as 157 days.

From the experimental results, and the subsequent calculations using Thermal Ignition Theory for the ignition timescale of warm MBM, it is most probable that the fires were due to the MBM being warm when it arrived at the stores from the rendering plants. This, coupled with the non-compaction of the MBM as it was loaded into the stores and the huge volumes resulted in an eventual self-heating leading to a flaming ignition.

Dust Explosion Tests

During the unloading and loading operations at the stores dust clouds were formed by the fine material in the MBM. If ignition sources were present, this could lead to an ignition of the dust cloud creating an unconfined explosion. A series of tests were undertaken on the fine dust component of MBM samples from eleven different stores to ascertain its susceptibility to ignite and the severity of the explosion once ignited. The tests undertaken were:

- Classification
- 5mm layer
- Minimum ignition temperature
- Minimum ignition energy
- Explosion indices (Maximum pressure and Kst)

Details on these tests can be found in reference 4.

The results of the testing showed that MBM can be ignited from hot surfaces at temperature above 280°C when present as a dust layer; and temperatures above 450°C when present as a dust cloud. MBM was not sensitive to ignition from low energy (<500 mJ) electrostatic sparks, but could be easily ignited with higher energy sparks (8–10J). The explosion indices tests showed that pressures as high as 7.6 bar g could be reached in a confined explosion, with Kst values as high as 62 bar ms⁻¹.

These results were then used to determine the risks from identifiable ignition hazards present in a typical store, particularly during the dust creation stages of loading and unloading from transport. Once these had been determined, suitable explosion prevention and protection methods were highlighted.

Toxicity Studies

One of the main concerns of the study was the potential life threat from the combustion products from a fire involving MBM in a store. The aims of this part of the study were to characterise the combustion atmospheres with a view to assessing the toxic hazard. Three MBM samples from three different stores were decomposed in the BRE tube furnace. Two decomposition conditions were studied, a non-flaming thermal oxidative condition at

375°C, representing a slow smouldering combustion (such as may be found during self-heating), and a slightly ventilated flaming condition at 650°C, which may result from an external ignition source or from the development of a self-heating reaction.

The major toxic fire gases were monitored: carbon dioxide, carbon monoxide, oxides of nitrogen, oxygen and smoke optical density. Samples were also taken for the analysis of cyanide, chloride, phosphate/phosphite, sulphide and sulphate anions and for significant volatile organic compounds.

It was found that the yields of major toxic gases were greater under flaming than non-flaming conditions. Under both flaming and non-flaming conditions, the greatest contribution to the lethal toxic potency of the fire effluents was attributable to hydrogen cyanide and organic nitriles (58–78%), with less being attributable to carbon monoxide (4–11%). See Table 4.

Table 4. Contributions to the toxic potency

Material	Test run	LC ₅₀ Concentration (g/m ³)	Relative contribution to lethal toxic potency (%)			
			from CO	from HCN + nitriles	from organic irritants	from inorganic irritants
Non-flaming @ 375°C						
Preston	T143	7.4	8.5	58.1	23.9	9.7
Alleena	T144	8.9	4.2	55.9	30.2	8.8
Chorley	T146	8.3	3.9	61.2	26.2	7.7
No 2						
Flaming @ 650°C						
Preston	T142	8.1	10.7	64.9	6.3	11.7
Alleena	T145	9.5	9.2	69.5	7.2	6.9
Chorley	T147	10.0	9.0	77.6	3.0	8.4
No 2						

The results of the study showed that fires involving MBM are capable of causing dangerously toxic atmospheres in enclosed spaces, such as stores which are filled to capacity, with relatively low masses decomposed.

Cone Calorimetry

One of the identified potential fire hazards of the storage of MBM was the threat of an external ignition source causing a fire. To ascertain the likelihood and consequences of MBM being ignited by an external fire source, a study of the combustion of three MBM samples were undertaken using the Cone Calorimeter. The cone calorimeter is an internationally recognised bench-scale method for assessing the reaction to fire performance of materials^[5]. A heat flux of 50kW m⁻² was used to simulate a large external fire. The test

provided data on a wide range of parameters including, ignitability, rate of heat release, smoke production, carbon dioxide and carbon monoxide production.

It was found that MBM is readily ignitable from a large fire source. It ignites within a few seconds exhibiting a rapid burning combustion on ignition, which soon subsides into a slow but steady burning rate. Peak rate of heat release rates were within the range 87–136 kW/m² (see Figure 3). The data obtained from the cone calorimetry was also used to assist in the computer modelling work of a fire plume.

Bomb Calorimetry

In order to gain an understanding of the fire hazard posed by charred and burnt MBM material, resulting from a self-heating ignition, its calorific value was determined. The bomb calorimeter apparatus was used for this test and the sample was taken from a charred sample found at one of the stores, after heat measuring probes had identified a hot-spot in the stockpile.

It was found that the material had a gross calorific value of 18.4 MJ/kg, indicating that even though it had already been subjected to self-heating, it still contained a significant quantity of combustible material. As such, burnt MBM should still be regarded as a combustible material and not as "inert waste".

Computational Fluid Dynamic Modelling of the Fire Plume

Studies were undertaken on the behaviour of a fire plume and the potential for the plume to disperse products away from a fire occurring in a store.

Two different scenarios, chosen in discussion with the client, were considered for this study. The first scenario simulated the movement of combustion products of a potential fire inside a typical warehouse building containing MBM. The warehouse chosen for the study was on an urban site, with dimensions of 70m by 80m in plan, 6m up to the eaves and 10m up to the ridge of the building (Figure 4). The second scenario simulated the dispersion of a fire plume, and dry and wet deposition of its combustion products in the surrounding environment from a vent opening of 1.5m by 3.0m in area. The vent opening represents a burned through roof-light as a consequence of a possible localised breach of the roof.

For the first scenario, simulating the movement of combustion products inside the warehouse, a transient simulation with a growing fire was carried out. Assuming that the fire loses approximately 35% of the total heat release rate by radiation, the fire source was modelled as a convective source of heat with peak convective heat release rate of approximately 1.6MW. Initially, apart from a leak around the access point to the building (i.e. the door), the building envelope was considered completely closed. As the fire grew, the combustion products started to accumulate under the roof. When the gas temperatures reached approximately 100°C (which is pessimistic estimate of the softening temperature for plastic roof-light panel) at the roof level, it was assumed that a building breach occurred of 1.5m by 3m in area, simulating a burned through roof light, on the upwind side of the building. At that time, the access door (1.5m wide by 4m high) was opened at the ground level. The model provided predictions of the transient development of the hot layer of combustion products inside the warehouse and characteristics of the fire plume emerging from the breach of the roof.

For the second scenario, the source discharge conditions of the fire effluents at the point of breach from the warehouse fire (convective heat release rate of 1.6 MW) were then used for simulating the dispersion of the fire plume and particle deposition into the surroundings. The fire plume emerging from a single opening resulting from the breach produced an average discharge velocity of 2.5 m/s and gas temperature of 200°C at the vent opening in the roof, thus giving the total discharge mass flow rate of 8.4 kg/s.

In general, a wide variety of local meteorological wind conditions will prevail, which depend upon the local topology and weather conditions. The weather conditions could involve high and low wind speeds, neutral, stable and unstable atmospheric conditions. This study was limited to one meteorological condition corresponding to high wind speed of 9.8m/s under neutral stable condition, which was considered to represent a typical weather condition in the UK.

The predicted results suggest the highest concentrations of the fire effluents to be close to the building, then falling steadily with increasing distance. For an assumed rate of dry deposition of 0.1m/s, the wet deposition generally represents only a relatively small component of the total, around 10%. For a lower assumed rate of dry deposition of 0.01m/s, the wet deposition is comparable to the dry deposition.

GUIDANCE ON FIRE PREVENTION

To reduce the probability of self-heating:

- Keep the storage volumes as small as possible by using a number of small store rather than one large store.
- If a large storage building is used consider splitting the area into smaller compartments.
- Material being placed into the store should be at ambient temperature.
- Material being stored should be kept cool and dry.
- Compact the MBM as it is placed into the store to remove air voids and reduce the quantity of oxygen available for self-heating.
- Monitor the temperature of the MBM pile, ideally at the centre, to enable early detection of the onset of any self-heating.

Buildings and any services such as electricity points must be maintained in good order to reduce the risks of an ignition from an external source. Ideally, buildings should be constructed of non-combustible materials. A high level of security is desirable to minimise the risk of arson. If mechanical equipment is used within the building it must be maintained in good working order. Hot-working procedures, such as welding and cutting should be fully and carefully monitored.

An automatic fire detection system should be installed in each store building to complement the existing practice of manual temperature monitoring of the MBM pile.

FIRE-FIGHTING STRATEGY

Sprinkler systems may be installed if desired, but it is expected, in the absence of any experimental data suggesting otherwise, that they may be of little benefit. They may

extinguish surface fires, but will not be able to penetrate into the MBM pile to extinguish the deeply seated fires created by self-heating.

Due to the risk of production of hazardous gases, smoke and particulates during MBM fires within an enclosed space, and the further risk of subsidence of the MBM pile, it is not advised that store personnel tackle any fires that occur. Personnel should immediately retire from the building and the fire service be called when a fire is detected or suspected. Breathing apparatus must be worn by fire-fighters inside the building.

If the fire is at the surface of the pile water spray may be used to douse the flames at the surface. The hot and burnt material should then be removed and allowed to cool before disposal. If the fire is deep seated within the pile then pumping large quantities of water onto the MBM will not be effective, as penetration will be minimal. Alternative options that may be used include: smothering the fire by limiting the oxygen ingress into the building and using compaction to limit the oxygen ingress within the MBM, directly injecting extinguishant into the pile via probes, digging out and removing all of the hot and burning material, and leaving the smouldering fire to burn.

CLEAN-UP METHODOLOGY

Water used to extinguish the fire will be contaminated and should not be allowed to enter the water table if at all possible. All run-off water should be contained and collected for safe disposal. Removal of burnt MBM within the store should be undertaken, but with care, as digging into the pile may cause re-ignition. Burnt MBM should also be disposed of safely as it will almost certainly contain combustible material. Decontamination using appropriate disinfectants should be undertaken on equipment and apparatus coming into contact with the MBM material, burnt or non-burnt. Some clean up of the surrounding area may also be required if the fire plume resulted in deposits of soot and ash particles on the ground and nearby buildings.

MBM DURING TRANSPORT

MBM is transported at two different stages of the MBM storage/incineration process. It is transported from the rendering plant to the store and then, possibly four years or more later, it is taken from the store to the incineration plant. The results of the experimental tests on MBM, described in the storage section, were also used to assist the fire/explosion hazard identification and risk assessment on transporting MBM.

FIRE HAZARDS

It has been shown that MBM is a combustible material that has the potential to self-heat and can easily be ignited from external fire sources. From the self-heating experimental studies it was found that the risk from self-heating during transport is extremely low. This is due to the short length of time the MBM would be in transit (typically 2–3 hours) and the relatively small volume being transported. This is however for MBM material at ambient temperature. If material were to be transported that was already warm or hot, possibly from the rendering process or from self-heating during storage, then the risk increases significantly. External

fires occurring on the vehicle, possibly as a result of a road traffic accident or vehicle ignition sources, could also ignite the MBM.

Fire prevention methods should include checking the MBM before loading to ensure it does not contain warm or hot material, and ensuring good maintenance of the vehicle to reduce the risk of a fire starting on the vehicle igniting the MBM. All vehicles transporting MBM should carry portable fire extinguishers and have the drivers trained in their use. As a minimum extinguishers should be of the type to fight Class A (solid combustibles) and Class C (electrical). However, if a fire is suspected inside the truck body, i.e. within the MBM load, then the doors should be kept shut and the fire service called. Opening the doors may cause the fire to flare-up due to the ingress of air.

The hazards from burning MBM and the clean-up methodology are generally as described earlier.

DUST EXPLOSION HAZARDS

During transportation of MBM there will be little possibility of a dust cloud being present and hence there is minimal risk from an explosion. However, during loading and unloading of the MBM a dust cloud will be created and care should be taken to minimise the risk of an ignition. Potential ignition sources will need to be identified and measures taken to eliminate or reduce the likelihood of their presence. Methods that reduce or limit the formation of dust clouds during loading and unloading should be explored.

MBM INCINERATION PROCESS

PROCESS OVERVIEW

MBM held in storage is eventually moved to an incineration plant for destruction. On arrival at the plant it is unloaded into a receiver area building of the plant where the MBM is tipped through a metal grid, to break-up any large lumps, and onto a conveyor. The receiver area building above the chutes leading to the conveyor is fitted with local air extraction and dust filter units, as during unloading dust clouds are created within this building.

The MBM is taken by conveyor to a silo before being taken away by screw conveyor feeding another conveyor belt. This conveys the material to the incinerator, which is fed by a screw conveyor. The incinerator operates at temperatures of 1100–1200°C where the MBM is destroyed.

POTENTIAL IGNITION SOURCES

A risk assessment of the process was undertaken and identified a number of potential ignition sources:

- Electrical equipment, particularly within the MBM receiver building, which will need to be rated for use in an explosive atmosphere.
- Burning material. The operator of the site mentioned that on occasions the MBM arrives in a heated condition showing evidence of charring. If glowing embers are

discharged into the process, these may act as a source of ignition, particularly if sucked into the dust filter unit.

- Hot surfaces. All equipment, such as motor surfaces, light fittings, that have hot surfaces which may come into contact with dust clouds or have dust layers formed on them, should be appropriately rated. This rating is based on the results of the 5mm layer ignition and the minimum ignition temperature tests as described briefly earlier.
- Friction heating and impact sparks. Moving parts such as conveyor bearings should be inspected regularly to ensure they do not overheat and any debris particularly metal objects should be removed from the MBM prior to being processed.
- Electrostatic discharge. Although the experimental studies showed that the MBM dust is not sensitive to ignition from electrostatic discharges (minimum ignition energy test), as a minimum precaution the plant should be well earthed.
- Welding or cutting operations. Maintenance or repair work may produce localised heat and sparks that could ignite dust deposits. Work should only be permitted in areas cleared of dust.

EXPLOSION PREVENTION METHODS

To prevent the possibility of an explosion a number of measures can be taken:

- Eliminate as far as possible all potential ignition sources. This should entail ensuring all electrical and mechanical equipment operated in explosive atmospheres is corrected rated, monitoring the condition of the MBM on arrival (i.e. there is no hot or burning material present) and good maintenance of equipment involving moving parts.
- Avoid the formation of dust clouds by local exhaust ventilation and by good housekeeping.
- Correct temperature rating of equipment with hot surfaces.
- Permits to work in areas where flammable materials are present.
- Good quality control of the MBM to eliminate debris, particularly metal objects.
- Keep the storage time of the MBM material in the silos to as short a time as possible to reduce the risk from self-heating, particularly if the temperature inside the silos is above ambient.

EXPLOSION PROTECTION METHODS

A number of techniques may be used to protect against the consequences of an explosion or fire involving MBM.

- Installation of explosion protection systems in plant items where dust clouds are present, for example the dust filter units and silos. The particular type of system chosen will mainly depend on its location and volume. Common methods used are, relief venting, suppression and containment.
- Isolation systems to prevent an explosion from an ignition in one plant item propagating through the process and affecting other equipment.
- Continuous temperature or carbon monoxide monitoring within the silos to detect signs of self-heating and linked to an alarm/fire extinguishing system.

CONCLUSIONS

1. Long-term storage of MBM in large volumes can lead to self-heating and eventual ignition. Care should be taken within the stores as fine dust that forms part of the MBM material is flammable and will ignite if it comes into contact with a source of ignition. Burning MBM produces toxic combustion products that can quickly reach dangerous concentrations, particularly within the store buildings filled close to capacity. Calorimeter studies have shown that MBM is readily ignitable from external heat sources and still contains a high level of combustible material in the charred residues from self-heating. Hence, measures need to be in place to reduce the risk of external fires or other heat sources igniting the MBM.
2. Transportation of MBM also presents a potential fire hazard, though as the quantities being transported are considerably less than in storage, the risk from self-heating is much lower provided the material is not already burning when loaded. There is also a risk of a fire starting elsewhere on the vehicle igniting the MBM, and all practical measures need to be employed to reduce this risk. Loading and unloading vehicles will create dust clouds and care should be taken to ensure no ignition sources are present during these operations.
3. Processing MBM can lead to a number of ignition hazards from the dust clouds generated and from layers of dust on hot surfaces. A formal risk assessment and hazardous area classification will be required in accordance with European Union ATEX Directives^[6,7] and UK DSEAR legislation^[8].

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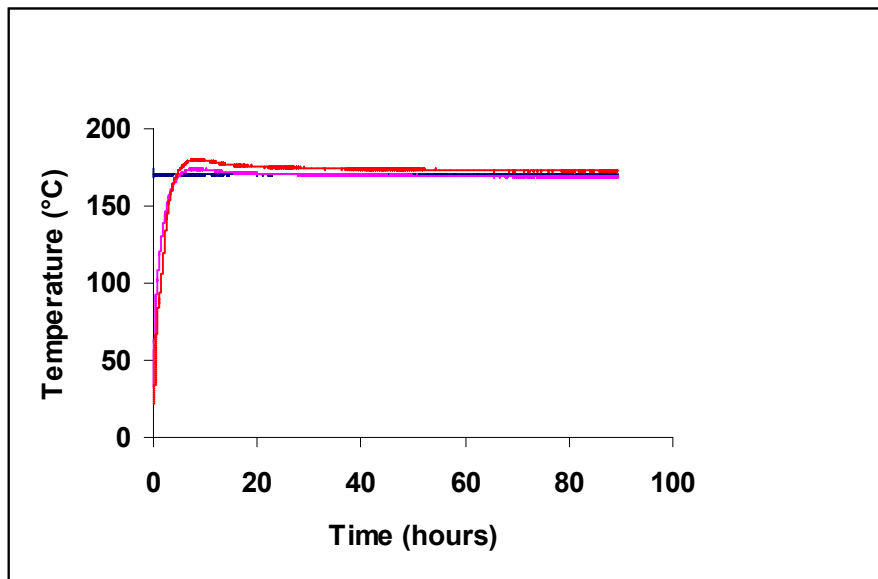


Figure 1. Temperature - time profile at sub-critical temperature of 170°C

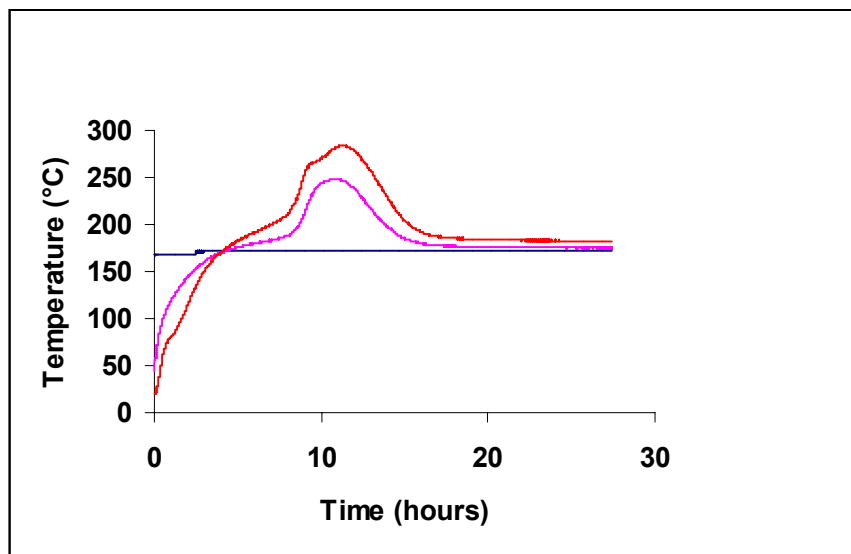


Figure 2. Temperature - time profile at super-critical temperature of 172°C

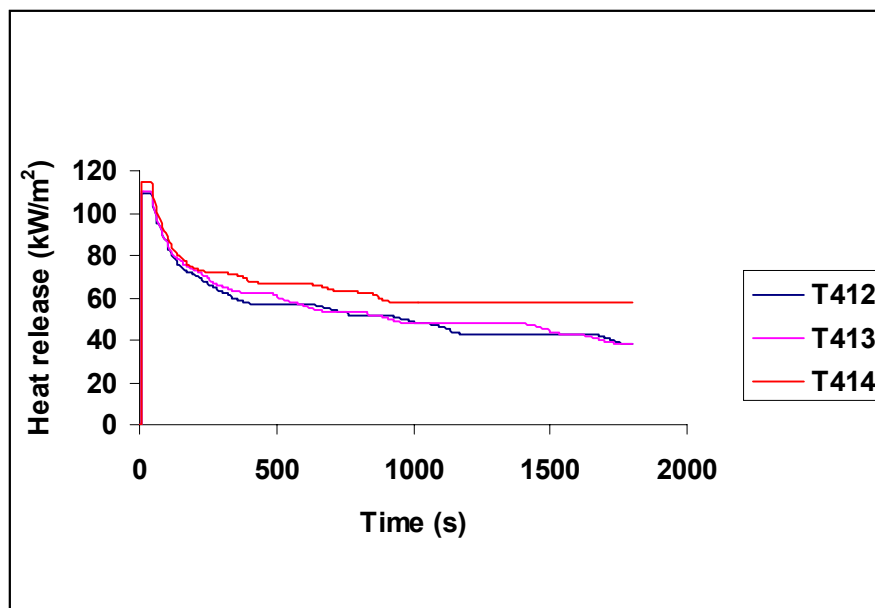


Figure 3. Cone calorimeter test: heat release vs time

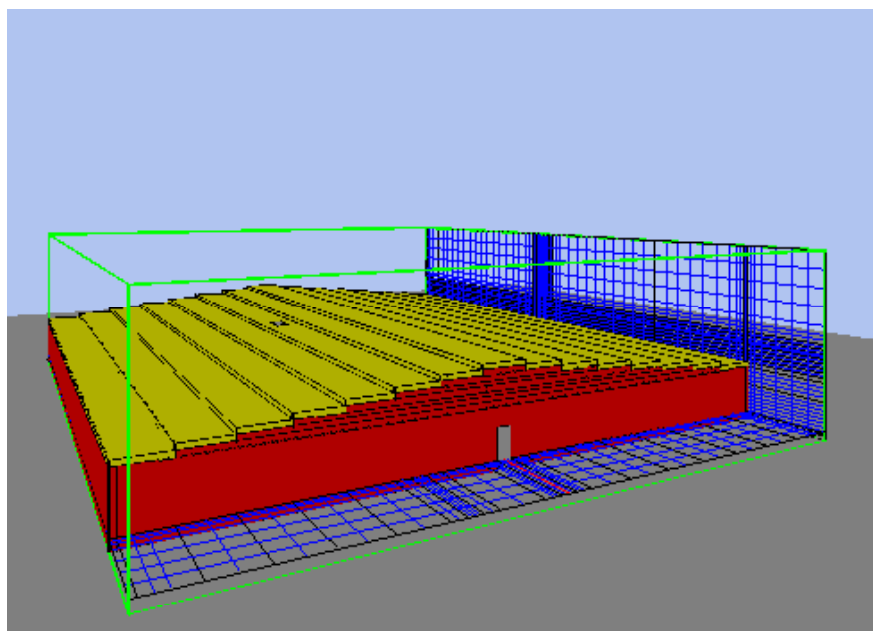


Figure 4. Typical warehouse used for CFD studies