Safe storage of wood pellet and wood chip fuel

Prepared by the Health and Safety Executive

Wood pellet and wood chip boilers are used in homes, community buildings, and businesses as a renewable energy alternative to oil or gas fired boilers. They are also increasingly being considered for use in large scale power generation.

Outside the UK, there have been at least nine fatalities since 2002 in Europe caused by carbon monoxide poisoning following entry into wood pellet storage areas.   This report describes a study, involving seven site visits, to develop evidence to inform HSE engagement with the industry on the prevention of carbon monoxide poisonings.

The study confirmed that potentially dangerous atmospheres may be generated in both wood pellet and wood chip storage. The study found that: knowledge of the hazards associated with these fuels, including confined space entry, was limited at sites operating small boiler systems; there had been limited communication of the health and safety issues between companies supplying and maintaining boilers, those manufacturing and supplying fuel, and users; and that while an HSE Safety Notice had raised awareness generally, not all the recommendations had been taken up at individual sites.

HSE Books

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KEY MESSAGES

Wood pellets and wood chip biofuel can produce dangerous (toxic) atmospheres in unventilated, enclosed spaces producing carbon monoxide and carbon dioxide, and depleting oxygen concentrations.

Appropriate controls to control the potential risk are ventilation and restriction of access to unauthorised persons. The stores and their adjacent areas should be assessed to determine if they should be classed as confined spaces. Training and safe working procedures are required.

An HSE Safety Notice has increased awareness of the hazard, particularly amongst operators of small wood pellet or wood chip boiler systems, but the application of controls recommended by HSE is not comprehensive.

Users of stores frequently do not have written risk assessments or safe working procedures in place. There may therefore be a need for further guidance to be produced in this area.

EXECUTIVE SUMMARY

RESEARCH AIMS AND OBJECTIVES

The aim of the work was to carry out the following:

- obtain information on how wood pellets and wood chips are stored before use,
- to ascertain how the build-up of carbon monoxide in storage is controlled,
- to find out what health and safety information suppliers and users have with regard to the storage and use of wood pellets/chip,
- to obtain data with regard to the levels of carbon monoxide and other relevant gases in wood pellet/chip storage areas, and
- to produce a report that includes an initial view on best control practices and procedures for use within the industry.

METHODOLOGY

The following activities were conducted:

- six site visits to locations using small scale wood pellet / chip fuelled boiler systems and one visit to a large scale pellet store, to assess storage practice, risk management systems and controls, including ventilation rate measurements,
- real time measurement of gases and vapours in the stores, and the microbiological content of the fuel, and
- laboratory research into carbon monoxide and carbon dioxide emissions and oxygen depletion from wood pellets and chip.

MAIN FINDINGS

Site visits and laboratory tests found that:

- potentially dangerous atmospheres may be generated in both wood pellet and wood chip stores,
- wood pellets produce carbon monoxide and carbon dioxide, and deplete oxygen,
- wood chips produce carbon dioxide and some carbon monoxide, and deplete oxygen,
- dangerous atmospheres in fuel stores may also arise from poorly vented boiler combustion gases,
- knowledge of the hazards associated with wood pellets and wood chips was limited at sites operating small boiler systems, but greater at the large pellet store,
- there has been limited communication of the health and safety issues between companies supplying and maintaining boilers, those manufacturing and supplying fuel, and users,
- an HSE Safety Notice has raised awareness generally, but not all the recommendations have been taken up at individual sites,
- the potential risk is controlled by restricting access to the stores with locked entries; some stores have warning signs and carbon monoxide alarms,
- unplanned ventilation within store rooms may reduce the build-up of dangerous (toxic) atmospheres, and
- the industry is wary of employing increased ventilation due to the potential for ingress of moisture and deterioration of the fuel.

CONCLUSIONS

The findings of this work suggest that:

- Minimum ventilation standards should be determined to prevent significant build-up of toxic gases (i.e. off-gassing) during wood pellet and wood chip fuel storage.
- Wood pellet and wood chip fuel suppliers and distributors should produce and distribute comprehensive and consistent guidance (including material safety datasheets) on storage to end users.
- Ambient temperature and relative humidity are also factors effecting off-gassing. Consideration may therefore need to be given to control of the internal storage environment.

CONTENTS PAGE

1. INTRODUCTION

1.1 CONTEXT

Domestic, commercial and industrial use of wood pellet boilers in the UK is increasing, but this is still a comparatively new activity. There are concerns that the risks associated with wood pellets, particularly the release of carbon monoxide and absorption of oxygen during storage, are not understood, and that the health and safety information provided by manufacturers and suppliers to control the potential risks, is inadequate. This prompted an HSE Safety Notice to be issued (HSE 2012).

Wood pellet boilers are used in homes and businesses as a renewable energy alternative to oil or gas fired boilers. They are also being installed to replace coal-fired boilers in community buildings, e.g. schools, community halls and leisure centres. This technology is already becoming established in Europe.

Since 2002 there have been at least nine fatalities caused by carbon monoxide poisoning following entry into wood pellet storage areas reported in the literature (Gauthier et al, 2012). To date there have not been any deaths in the UK that have been linked to release of carbon monoxide from wood pellets during storage. At present these boiler systems tend to be smaller scale than those used in Europe, particularly for domestic installations; however, wood pellets are also increasingly being considered for use in large scale power generation. There are potential risks associated with each.

It is hoped that the HSE Safety Notice will help reduce the likelihood of any fatalities occurring in the UK, but further knowledge and evidence is still needed to enable better guidance and information to be produced for duty holders in the wood pellet industry, in particular those that manufacture and supply wood pellets, and install and service wood pellet boilers.

Since the issue of the safety notice there have been a number of enquiries, mostly from local authorities, asking if a similar risk of carbon monoxide release exists when wood chip is stored. Again, this was an area that was not understood, so an assessment of the potential risk of carbon monoxide release from wood chip was also included.

1.2 WOOD PELLET AND WOOD CHIP FUEL

Most wood pellets are produced by milling wood chips, shavings, or saw dust into a fine powder which is then dried and compressed under high pressure and extruded through a die (Svedberg et al 2008). The high pressure causes heating of the wood, and the natural lignin present in the wood acts like a glue holding the pellet together. Typically pellets are 6 or 8 mm in diameter and contain less than 10% moisture with no additives or binders. Pellets up to 12 mm are known, and starch may be used as a binder (biomassenergycentre.org.uk). Briquettes are similar to wood pellets, but are physically larger, e.g. 50 to 100 mm in diameter and 60 to 150 mm in length.

Wood chips are produced by processing timber though a wood chipper. They are typically 20-50 mm long, but need to be compatible with heating system feed mechanisms e.g. augers. Larger sized chips flow less easily and are more prone to bridging during storage (particles locking together to form an arch). The composition of the wood chips depends upon the feedstock e.g. virgin or recycled wood. Freshly harvested wood can have a moisture content of >60%. Seasoning (natural drying) can achieve a moisture content of 25 to 30%. Kiln drying

may further reduce the moisture content. Waste wood generally has a lower moisture content (18-25%).

Wood pellets and chips need to be kept dry not only to maintain their calorific value and ease of ignition, but also to prevent microbiological growth. Additionally pellets may swell and breakdown causing transportation problems.

1.3   ASSOCIATED HAZARDS

There are a number of health and safety hazards associated with the transportation and storage of wood pellets and wood chip fuels, including airborne dust, gaseous toxic emissions, spontaneous combustion and asphyxiating and explosive atmospheres. In the context of fuel storage, the often limited access, the free flowing nature of the fuel and the fuel transportation machinery also present a hazard. There is also a problem when fuel does not flow freely and bridges and voids are created. As they are enclosed and there is a reasonably foreseeable risk of serious injury or death these storage areas should be considered to be confined spaces, as defined by the Confined Space Regulations 1997 (HSE 1997).

Under suitable conditions of temperature and moisture, wood fuel can provide the nutrients for micro-organisms to grow and proliferate. The heat from microbiological proliferation may raise the temperature sufficiently to start thermal oxidation, generating further heat and eventually leading to increased off-gassing and combustion.

There are also a number of fuel store hazards associated with any connected boiler system. The mechanism for feeding fuel to the boiler may also provide a route for exhaust fumes (e.g. carbon monoxide) to permeate back to the fuel store if the flue system is not working adequately, or a continuous path of fuel for 'burn back'.

Air composition

In a study of wood pellets stored in industrial warehouses and domestic store rooms, Svedberg et al (2004) found high levels of carbon monoxide and hexanal. In another study of wood pellets in ships holds, storage of pellets was shown to deplete oxygen and produce carbon monoxide, carbon dioxide, methane and a range of volatile organic compounds (VOCs) (Svedberg et al 2008). Logs and wood chips in ships holds have been shown to deplete atmospheric oxygen and produce dangerous (toxic) levels of carbon dioxide (Svedberg et al, 2009). In this case microbial activity was thought to be the primary cause of decomposition of the wood chips, whereas oxidative decomposition was thought to be the probable cause of the pellet decomposition. The atmosphere within a confined space however may also be affected by other mechanisms e.g. continued respiration of living wood cells, combustion, gas leaks, rusting iron or steel etc. A triple fatality occurred on a German registered ship in Goole Docks, UK in May 2014, investigated by the UK Department for Transport's Marine Accident Investigation Branch. The cause of death was determined as reduced oxygen levels in the ship's cargo hold and access compartments (between 5% and 6% oxygen content at the bottom of the ladder into the compartment). It is likely that the sawn timber cargo caused the deprivation of oxygen (MAIB 2014).

Carbon monoxide and carbon dioxide are both asphyxiants. The US National Institute for Occupational Safety and Health (NIOSH) has defined IDLH (Immediately Dangerous to Life or Health) values of 1200 ppm for carbon monoxide and 40,000 ppm (4 %) for carbon dioxide (NIOSH 1995). These values do not take into account a possible simultaneous exposure to an oxygen deficient atmosphere, which would increase the effect. In the UK, carbon monoxide has workplace exposure limits (WELs) of 30 ppm and 200 ppm (8 h time weighted average (TWA)

and 15 minute reference periods respectively) (HSE 2005). Carbon dioxide has corresponding WELs of 5000 and 15,000 ppm.

The Approved Code of Practice (ACOP) to the Confined Space Regulations 1997, states that there are substantial risks if the concentration of oxygen in the atmosphere varies significantly from normal (i.e. 20.8%); and very low oxygen concentrations (i.e. below 16%) can lead to unconsciousness and death (HSE 1997). The US Occupational Safety and Health Administration (OSHA) defines as oxygen deficient, any atmosphere that contains less than 19.5% oxygen (OSHA 2011).

Methane and carbon monoxide are both explosive. The lower explosive limit (LEL) for methane is 5 % by volume, and 12 % by volume for carbon monoxide.

Airborne dust

Dust can become airborne during delivery or if moved during maintenance or repair. Ignition of a confined wood dust cloud could result in an explosion. The LEL for wood dust varies with composition, particle size and moisture content, but an airborne concentration of 40 g/m³ is often quoted as the LEL for wood dust. The worst-case situation given in a BIA database, is a lower explosion limit of 15 g/m³ (BIA 1997). BIA (Berufsgenossenschaftliches Institut für Arbeitssicherheit) is the Professional Associations' Occupational Safety Institute in Germany.

Disturbance of fuel by workers, especially in a confined space can lead to exposure to inhalable or respirable dust particles. Hardwood and softwood dust are occupational asthmagens, and hardwood dust is a carcinogen. Wood dust has a WEL of 5 mg/m³ as an 8 h TWA.

If fungal spores or bacteria become airborne during handling of fuel it can result in respiratory exposure sufficient to trigger the immune system and potentially lead to occupational asthma or extrinsic allergic alveolitis such as Farmer's Lung Disease (Swan et al, 2007). Inhalation of endotoxin (material released from the cell walls of some bacteria) can cause short-term flu like symptoms. The Dutch expert committee on occupational standards (DECOS), a committee of the health council of the Netherlands, has proposed a health based 8 h TWA occupational exposure limit (which has yet to be implemented) for airborne endotoxin of 90 endotoxin units (EU)/m³.

1.4   INCIDENCES OF CARBON MONOXIDE POISONINGS IN STORE ROOMS

Gauthier et al (2012) have recently reported two cases of lethal carbon monoxide poisoning in wood pellet store rooms and reviewed the literature. This report identified 14 fatalities from 12 incidents involving storage of wood products between 2002 and 2011. Eight of the incidents (nine fatalities) involved wood pellets, the remainder involved timber, wood chip and pulp wood. Seven of the incidents occurred in ship's cargo holds, including three involving pellets. The remaining five incidents all involved pellet storage: two at pellet silos and three described as at 'private households'. The last three were in 2010-2011, and two were further described in detail in the paper. Oxygen depletion as well as carbon monoxide poisoning may have contributed to the deaths.

In the first incident in Germany, an engineer died after opening a pellet bunker door to work on a faulty filling level gauge. The pellet bunker had a capacity of 155 tons and supplied fuel for a heating system serving 700 households. Chemico-toxicological investigation of the peripheral blood carried out as part of the post-mortem examination showed a lethal carbon monoxide concentration of 60% carboxyhaemoglobin (COHb). Air measurements immediately after the incident detected carbon monoxide concentrations of more than 500 ppm. One year before,

values of 1000 ppm had been measured during a test procedure. Measurements made during research in connection with the accident demonstrated a maximum carbon monoxide concentration of 53,700 ppm in the airtight storeroom. Combustion or a defect in the heating system was ruled out as the source of the carbon monoxide.

In the second case in Switzerland, a caretaker's wife died after going to inspect a problem with a wood pellet conveyor. The pellet store room was 82 m³ and was around a third full. It supplied a heating system to 60 households. The woman's body was found wedged beneath the circular cover above the opening of the screw conveyor. Postmortem examination and chemico-toxicological analysis of blood taken from the heart showed a carbon monoxide concentration of 75% COHb. Measurements made at the scene a few days after her death showed a room temperature of 26°C, relative humidity of 48%, and a carbon monoxide concentration of 7500 ppm. The concentration was still 2000 ppm after ventilating the room, 'according to the regulations', for 2 h. This reading appears to indicate that there was little ventilation prior to the incident.

The third case in Ireland was not reported in detail in the paper, but a copy of the Coroner's report was obtained (Coroner, Co. Laois, Ireland, 2011). A householder entered a 7 tonne capacity pellet store whilst investigating a poorly performing boiler system and collapsed. The store was a rigid walled silo and roughly half full of pellets. There appeared to be no ventilation and access was via a ladder to a small high level hatch. Carbon monoxide in blood was measured at 54.4% saturation on admission to the hospital emergency department, and 46% at the post mortem. The Irish Health and Safety Authority investigated the death. Although it was noted that wood pellet generation of carbon monoxide was a possibility, there was evidence that the gas in the store had originated from the boiler. The system had a history of unsatisfactory operation (smoke escaping into the garage where it was located), and an extraction fan was retrospectively fitted to the top of the 3 m tall flue. After the fatality, the boiler was tested and it was found that the flue was still not working properly, and there was evidence (tar deposits) that flue gases had contaminated the screw feeder back to the silo.

The Gauthier paper also references field measurements made in customer wood pellet stores by Emhofer and Pointner as part of the Bioenergie2020+ study, showing that raised carbon monoxide concentrations were particularly found in airtight pellet storerooms. The concentrations were greater than 30 ppm in 68% of the measurements, and more than 1000 ppm in 9%. All three fatalities reported above also occurred in seemingly unventilated store rooms: the store in Germany was described as 'airtight'; that in Switzerland still contained 2000 ppm carbon monoxide after ventilating the room 'according to the regulations' for 2 h; and the store in Ireland judged from its appearance and description in the coroner's report. Wood pellet stores are generally watertight to prevent deterioration of the fuel. Contact with water can cause the pellets to swell, increase microbial activity and subsequent self-heating and increase off-gassing (Pinnacle Pellet inc, 2009). This apparently includes the possibility of humid air condensing, and so therefore there is a potential conflict with ventilating the store to remove dangerous (toxic) atmospheres (Österreichisches Normungsinstitut, 2003).

2. METHODOLOGY

2.1   SITE VISITS

Seven sites were identified for investigation. Six sites had small to medium sized boiler systems (≤ 250 kW) with associated storage (≤ 15 tonnes), and included store rooms and silos, purpose built and converted stores. The sites included five pellet stores and one wood chip store. The sites were identified via the HSE manufacturing sector and were chosen primarily for the variety of storage types they represented.

The seventh site represented large scale wood pellet storage (8000 tonnes), used for storing fuel off site by a power generation company.

Details of the sites are summarised below.

2.1.1   Site 1 – external reinforced plastic wood pellet silo

This site was a school which has a wood pellet fuelled heating system operating from September to April. The heating system was three to four years old and consisted of a 150 kW boiler and a large external glass reinforced plastic silo, 6-7 m high with a capacity of 15 tonnes of pellets (Photograph 1). The silo had two visible hatches, one in the side at a height of 3 m, and the other located on the top of the silo. There was no ready access to either hatch. The silo appeared weatherproof but poorly ventilated. The pellets were delivered to the silo by pneumatic delivery from a lorry (10 tonnes delivered roughly every three months). The boiler was fed with pellets via an auger.

Photograph 1 Site 1 pellet storage silo

2.1.2 Site 2 – purpose built wood pellet store room

This site was a school which has two wood pellet fuelled boilers for heating and hot water. During the summer one of the boilers is shut down. The purpose built boiler room and adjacent pellet store are sited within the school building and were 4-5 years old (Photographs 2 and 3). The store room was approximately 5 m by 2 m with a 3 m high ceiling constructed from cement blocks lined with medium density fibreboard. There is an access door and a viewing window (which could be opened), and a light located inside. The access door opens to seven horizontal boards positioned across the doorway to prevent egress of pellets, therefore further access depends upon how full the store is. The store appears to be water tight but poorly ventilated. The pellets are delivered pneumatically to the store (7 tonnes delivered every six weeks in winter). There are two separate augers each feeding a boiler.

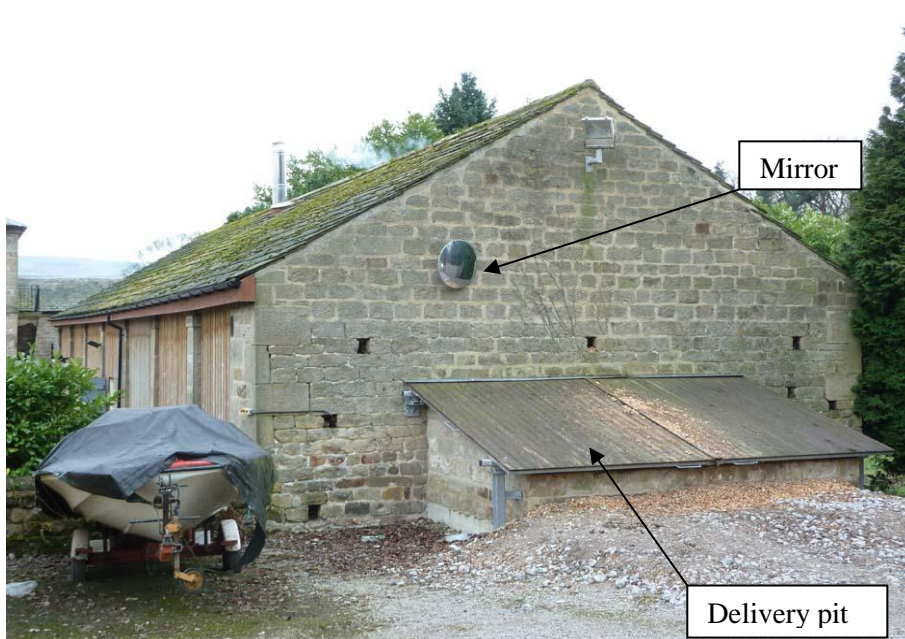**Photograph 2** Site 2 wood pellet store

Photograph 3 Site 2 open access door to the pellet store

2.1.3   Site 3 – converted barn wood chip store

This site was a company headquarters on a country estate. Heating was provided all year round by a relatively new 250 kW boiler fuelled by wood chips. The boiler and adjacent store room were situated within a converted slate roofed stone barn (Photographs 4 and 5). The store room was 6 m square with a 3 m high ceiling, and had a capacity of around 8 tonnes. The floor and sides were constructed of plywood. Above the store was a bat loft, accessed via the store. The store itself was accessed via a 48 cm by 58 cm hatch. A fluorescent light was situated above a viewing window. The store appears to be relatively weather-proof and well ventilated. Wood chip is produced on site and delivered to the store by tractor and trailer (weekly 4 tonne deliveries), tipping the chips into a 3 m by 2.5 m screened pit and removed into the store via two auger screws. The furnace is fed by another auger screw. A circular sweeping arm guides wood chips from the wider areas of the floor towards the auger screw. The corners of the store have been boxed out to form triangular voids to prevent pockets of ageing fuel developing.

Photograph 4 Site 3 boiler house and wood chip delivery pit

Photograph 5 Site 3 wood chip store access hatch in the boiler room

2.1.4 Site 4 – fabric wood pellet silo inside former coal store

Site 4 was a school. A 250 kW boiler wood pellet fuelled boiler provides heating in winter. The wood pellets are stored in a former coal store within the school building (Photograph 6). The original system (store room with auger) was installed 2.5 years before the visit. This has since been replaced by a fabric silo six months before the visit because of feed problems. The silo (capacity 5.9 tonnes) appears to be made of woven nylon hung on a steel framework, and almost fully occupies a 3.9 m by 2.3 m room with 2.8 m high ceiling. There is no access into the silo. The room had brick walls and a sealed plywood ceiling. The store room appeared to be quite weather-proof and well ventilated. Deliveries (4.5 tonnes) to the store are made pneumatically every three to four weeks in winter. The furnace is fed via two auger screws in series.
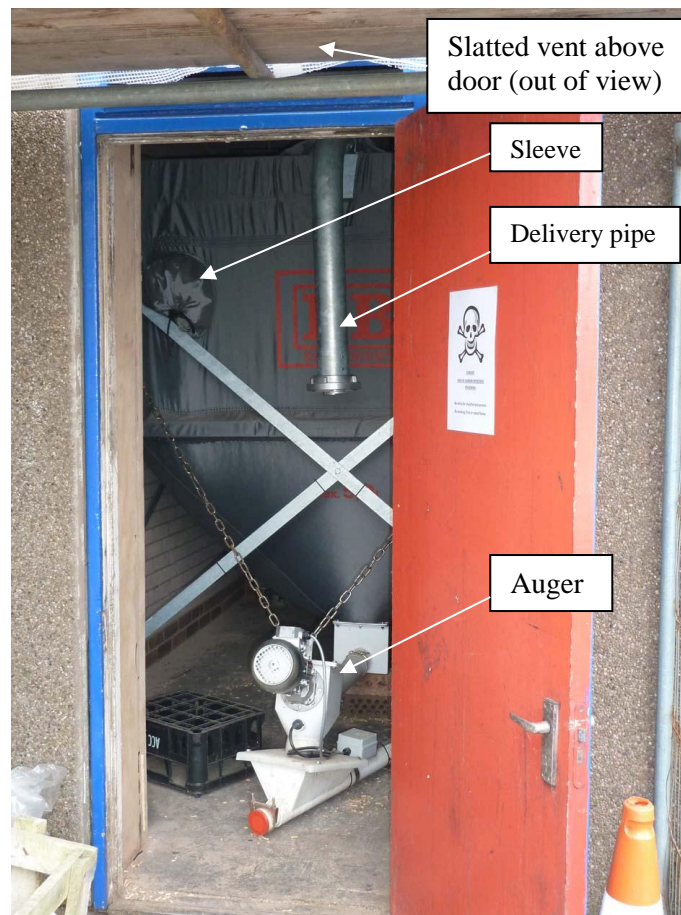
Photograph 6 Site 4 fabric silo in the wood pellet store room

2.1.5 Site 5 – wood pellet store room inside converted coal store

Site 5 was a small school. During winter, heating and hot water is provided by a nine year old 150 kW wood pellet fuelled boiler system. The boiler room and store was situated within the school building. The pellet store room was a converted coal store (Photographs 7 and 8), and was almost completely filled by an internal store constructed of wood and metal, approximately 1 m wide, 3.5 m deep and 2.8 m high, with a capacity of 4 tonnes. The store had a raised access hatch (approximately 1 m from the floor), only practicable for access when the store contents are depleted. The store appeared weatherproof but poorly ventilated. Deliveries of 3-4 tonnes are made pneumatically, approximately every four weeks. The furnace is fed via an auger screw.

Photograph 7 Site 5 wood pellet store
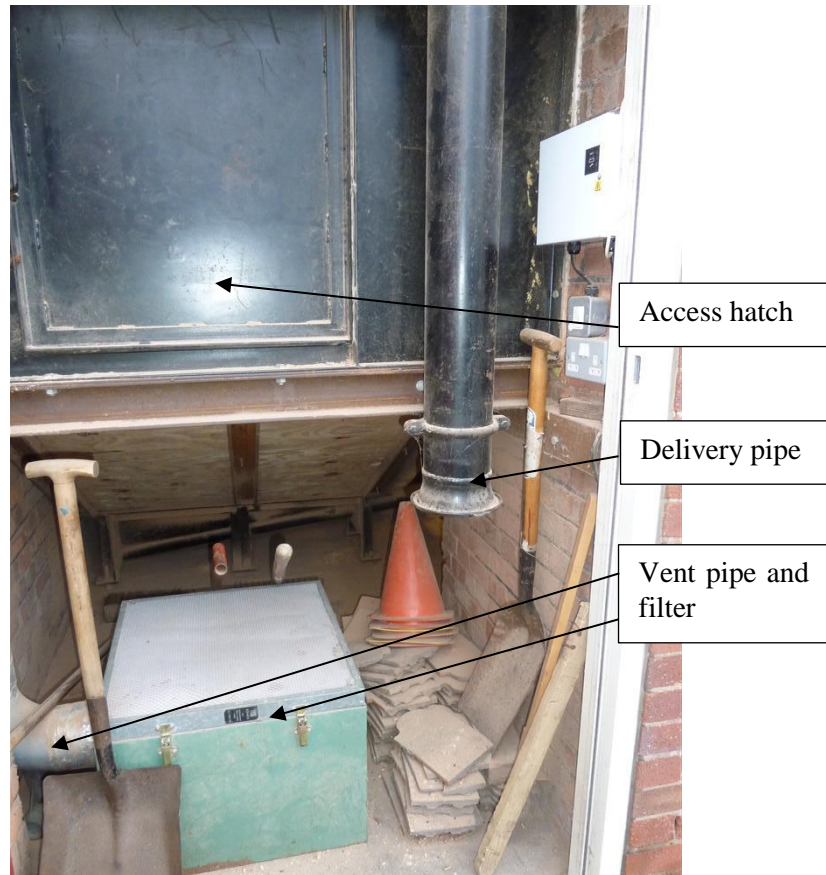
Photograph 8 Site 5 pellet store entrance

2.1.6 Site 6 – fabric wood pellet silo in boiler room

Site 6 was a youth club, open 13:00 to 21:00 daily. The heating and hot water is provided all year by a wood pellet fuelled boiler system. A 15 kW boiler and a fabric pellet silo occupy a single room within the building (3.5 m by 3.3 m wide and 4.3 m high), which is also used by the cleaners for storage (Photograph 9). The silo is 1.6 m square, 1.8 m high and has the capacity for 2.8 tonnes of pellets. It consists of a galvanised steel frame and a main body made of anti-static woven plastic fabric. The room was water tight with little ventilation. There was no access into the silo. Deliveries of around 2.5 tonnes are made pneumatically four times a year. Pellets are fed to the boiler via an auger system.

Photograph 9 Site 6 wood pellet storage silo in the boiler room

2.1.7 Site 7 – large scale wood pellet storage in a former grain store

Site 7 was a large pellet store used for off-site storage by a power generation company (Photographs 10 and 11). It has been used for storing wood pellets since 2011 and has been filled and emptied twice. It is a former grain store manufactured from corrugated steel, and contains three sections each 55 m by 18 m, and 10.5 m high. Each can be accessed via a roller shutter door. The store appeared weatherproof and was ventilated. During the visit, two of the sections were each holding 4000 tonnes of pellets. The third section held peanuts. Deliveries from a nearby port are made by tipper lorries, which deposit the pellets directly into the storage shed, and a mechanical shovel and pusher is then used to stack the pellets. When the pellets are required they are loaded onto a lorry by a mechanical shovel.

Photograph 10 Site 7 wood pellet storage facility

Photograph 11 Inside Site 7 wood pellet storage facility

2.2 ASSESSMENT OF CONTROLS AND EXPOSURE

During the visits, site representatives were interviewed to identify their knowledge of the hazard and risk associated with the storage of wood pellets or chips. Information was collected on delivery and storage of the fuel, operation and maintenance of the heating system, and the risk management strategy in place. The accommodation and equipment were examined to establish and assess the controls present.

At four of the small sites, and at the large site, further measurements were made as follows:-

- air monitors were set up to assess real time changes in store room air composition,

- diffusive samplers were left to sample volatile organic compounds (VOCs) present,

- the air change rate in the four small stores was determined, and

- bulk samples of fuel were taken for investigation of potential microbial activity and laboratory based monitoring of air composition changes.

Staff at these sites were also asked to keep a log of activities undertaken which involved the wood stores during the monitoring period.

Before entering the wood stores, air quality measurements were made using a Neotronics Impact and sampling probe. When entering the store a personal gas alarm was worn (MSA Altair 4X). Any mechanical operations deemed hazardous were disabled and one person remained outside (either HSE or site staff). These were precautions determined by HSE staff.

No measurements were made inside the silo at Site 1 because it was outdoors, impermeable and relatively inaccessible. No measurements were made at Site 5 as the pellet store room was not suitable for access for the planned work.

At two sites (Sites 4 and 6), access to the fuel area was not possible because the fuel was in a silo with no access hatch; therefore air measurements were made in the store room in which the silo was situated. These silos were both made from fabric and expected to be permeable to gases, and the rooms were readily accessible.

2.2.1 On site real time measurement of air composition

An Ion Science GasClam real time air monitor was left in the wood stores to collect data on changes in air composition and air temperature over a four week period, at one measurement per hour. The GasClam was chosen because it was able to monitor all the gases of interest; primarily carbon monoxide and oxygen, but also methane, carbon dioxide and 'total' VOCs. It was also battery operated and intrinsically safe (ATEX certified for Groups IIA and IIB gases).

2.2.2 Diffusive sampling of volatile organic compounds

Diffusive sorbent tubes (Tenax TA and Chromosorb 106) were left alongside the GasClam monitor to sample VOCs. The diffusive tubes were analysed by HSE's Buxton laboratory by thermal desorption – gas chromatography with flame ionisation detection. Recollected fractions of each sample were further analysed by mass selective detection to confirm identification of the reported analytes.

2.2.3 Air change rate measurement

The ventilation rate or air change rate of the wood pellet and chip stores, or rooms containing silos, were measured using a modified version of the step-down method (Etheridge and Sandberg, 1996). This involved injecting a tracer gas (10 % SF_6, balance N_2) into the room, mixing it with the room air using a desk top fan to obtain a uniform concentration and then monitoring the concentration as it was diluted by incoming clean air. The concentration of SF_6 was monitored using an infrared spectrometer (Miran 1a, S/N 407051R); the data were logged on a Grant 2020 Squirrel Data Logger.

For instantaneous and perfect mixing the concentration of tracer gas decreases at an exponential rate following the equation:

$$C_t = C_0 . e^{-nt}$$

Where C_t is the concentration of SF_6 at time t, C_0 is the concentration of SF_6 at time t = 0 and n is the air change rate in air changes per unit time. This equation was used to calculate the air change rate. A plot of natural log of C against t should produce a straight line with a negative slope, the gradient of which is n.

2.2.4 Microbiological activity

The bulk pellet and chip samples were analysed for potential microbiological activity by HSE's Buxton laboratory. A 20 g sample of each fuel was suspended in 100 ml of ¼ strength Ringers solution. Ten-fold dilutions of this suspension were prepared in ¼ strength Ringers solution. These dilutions were used to inoculate nutrient agar plates for incubation at 25°C and 37°C, and Malt agar plates for incubation at 25 and 40°C. Following incubation for seven days, any emerging colonies were counted and the results used to calculate the level of contamination per gram of fuel.

2.2.5 Laboratory based monitoring of air composition

Bulk samples of fresh wood pellets from the company supplying Sites 1, 4 and 5 ('Source B') and wood chips from Site 3, were subsequently obtained for laboratory based tests measuring oxygen, carbon monoxide, carbon dioxide, flammable gases and VOCs in the headspace of sealed containers packed with the fuel. Other researchers have previously used this approach to investigate wood pellets (Kuang et al, 2008), but HSE were unaware of any similar data for wood chips. This test also acted as a control and reference for the site measurements.

Tests were performed shortly after collection, in 60 litre high density air tight polyethylene drums. Logging MultiRae gas monitors and Gemini Tiny Tag+2 temperature and humidity meters were placed inside the drums which were then sealed with rubber gaskets and steel closure bands. These were left for a period of time in an air conditioned laboratory. Pressure was not monitored because previous studies have shown there to be minimal change at room temperature (Kuang et al, 2008).

A second set of tests was performed with freshly chipped wood chips and dried wood chips. The wood had already been seasoned to some extent before chipping. A portion of the chips were dried further in the laboratory by heating to 30°C in a climatic chamber for 20 hours whilst being flushed with dry air (<5 % relative humidity - RH) at 4 litre/min. The average moisture content of ten randomly selected wood chips was measured using a GE Protimeter Surveymaster.

The second set of tests was prompted by the relative humidity of the air inside the wood chip drum reaching 100%, which is above the manufacturer's specifications for the carbon monoxide and VOC sensors. In the second test the quantity of chips was reduced, and the drum was also monitored using a Gasmet Fourier Transform Infrared (FTIR) Spectrometer. The Gasmet was connected to one of the drums with PTFE tubing and could be isolated by valves to limit leakage. As the Gasmet is not designed to recirculate a sample for continuous measurement, potential leakage was monitored by injecting 100 ml of 1% sulphur hexafluoride in nitrogen to act as a marker (it was considered that an insignificant leak over a period of minutes could become significant over a period of days).

3. RESULTS

3.1 ACTIVITIES

3.1.1 Delivery

At the smaller sites visited, workers were relatively remote from the delivery process, positioned either outdoors or just inside an open external door.

At the five small pellet sites (Sites 1, 2, 4, 5 and 6), delivery was done pneumatically from a tanker via a flexible hose connected to an inlet pipe, and these are therefore enclosed systems. One company supplied Sites 1, 4 and 5, and another supplied Sites 2 and 6. Attempts are made in the system design to minimise damage to the pellets during delivery (thus reducing production of wood dust), for example, by minimising the length and turns within the pipework and using impact protection mats within the stores. The air used to propel the pellets into the silo must escape somewhere, and will contain dilute gaseous emissions and airborne wood dust. At Sites 2 and 5 the outlet pipe was directed through a particle filter. At Site 5 this was then vented at ground level within the store room. At Site 2 the filter had been removed due to continual blocking, and so the dusty air was emitted directly through a high level external vent. At Sites 1 and 6 air was directed via an outlet pipe back to the inlet pipe area, with no visible filter attached. At Site 4 the incoming air reportedly escapes though the fabric of the silo.

At Site 7, workers were more exposed to the pellets as they were handled in the open; however, drivers remain in their vehicle cabs during delivery. This may reduce workers' wood dust exposure if windows remain shut and the cab ventilation filtered. However, it would not be as effective at preventing ingress of carbon monoxide if present, or against oxygen deficiency.

At Site 3, wood chips were also handled in the open when being tipped into a delivery pit. The process is performed outdoors, and a mirror allows a view of the pit from the tractor cab.

No examples of bulk bag delivery were encountered during this work.

3.1.2 Store and feed mechanism management

At Site 1 there has never been any requirement to enter the silo/store to perform maintenance or repair tasks. Such access would be severely restricted by the height of the access hatch. A weighing mechanism determines the quantity of remaining pellets in the silo.

The site manager at Site 2 reported that there was no requirement at present for entry into the pellet store; however, in the past the store had occasionally been entered to check the transfer screws. An internal light and viewing window allows the pellets to be monitored.

There is reportedly little reason for Site 3 staff to enter the wood chip store, but they do look in sometimes when there has been a breakdown, to check fuel levels or the sweeping arm, and to break up steep piles of chips at the edge of the store with a pole as stocks are used up. An internal light and viewing window also allows the chips to be monitored.

There is reportedly little reason for the site manager at Site 4 to enter the store containing the fabric silo. The previous system at Site 4 (a store room with auger) required occasional entry as the pellets did not slide properly to the auger because the sloping floor was not steep enough. Since the new fabric silo system was installed there has only been one similar incident whereby a cavity was created after the pellets formed an arch. This was remedied by the site manager crawling under the silo and hitting the wall with his hand. The silo sits on four load cells

designed to estimate the quantity of remaining fuel; however, these were not working at the time of the visit. Once the level of pellets has fallen sufficiently, the inside of the silo can be inspected through a sleeve on the front wall; however the actual purpose of the sleeve is to allow removal of pellets should this be required e.g. to access the auger for repair.

As the level of pellets in the Site 5 store decreases it is necessary to periodically open the hatch at the front of the store in order to lean in and level the pellets with a garden rake to ensure they cover the auger screws.

There was no access to the fabric silo at Site 6; however, the room in which it was situated was regularly accessed by cleaners. The level of wood pellets in the silo can be estimated by touch.

At Site 7, the pellets are only stored. Carbon monoxide and air temperature are monitored twice per week using a personal monitor, once by the store owner and once by a representative of the power company. This task involves walking along the top of the wood pellets and taking measurements at predetermined points along the store. When there is evidence of degradation of the pellets (as indicated by an increase in temperature or carbon monoxide) the store is monitored more frequently until the wood pellets are removed or the levels drop. Inspection lasts for less than an hour.

3.1.3 Boiler maintenance

The boilers at Sites 1 to 6 require little day to day management. A thermostat generally controls delivery of fuel to the boiler. In kindle mode a slow rate of delivery is maintained to keep the fire lit and levels up to prevent burn back.

The only routine maintenance tasks reported involve emptying ash from the boiler and occasionally cleaning the boiler flues. At Site 5 this was performed weekly. The ashes in the Site 4 furnace need cleaning out every one to two weeks: each tube is brushed out and then the furnace is shovelled out and vacuumed. The process takes about half an hour. At Site 3, ash-collecting bins located beneath the flue and burn chamber are emptied weekly. The Site 6 boiler has self-cleaning heating surfaces and automatic ash removal from the burning tray, giving long intervals between cleaning.

3.1.4 Annual service and repair

The boilers are generally serviced twice a year by specialist companies who are also called out for repairs. The four schools and the youth club all used the same company. The boilers generally have an annual service in the summer and a combustion check in the winter. The service at Sites 1, 3, 4 and 5 also included the feed mechanism. At Sites 2 and 6 it was not thought to include the auger screw feed.

At Site 3 the service engineer is required to enter the wood chip store to check the sweeping arm. Auger motors are positioned outside the store. Access to the augers themselves would be hindered by the presence of pellets in the store.

Residual wood dust in the store is not generally required to be removed. Much of the dust present is said to be ultimately transferred to the furnace via the auger. It was reported that the maintenance company had requested access to the Site 2 store to clear away excess dust; however because of the levels of pellets in the store at the time this task was not carried out.

Once established, repairs to the systems generally relate to operation of the furnace and not the fuel storage or delivery systems; however, the service company for the schools have reported

that problems have been encountered with foreign objects (e.g. nuts and bolts) jamming augers. Site 2 initially had problems with the auger screws which appear to be resolved now.

At Site 2 there have also been problems with the burners getting clogged up, and Site 5 had experienced some problems with the flue gases and burning efficiency in the past that lead to the fitting of a fan in the boiler flue.

3.1.5 Activity log

The activity log data (Table 1, Appendix A) reveals that the stores were accessed by workers at four of the five sites monitored (periods of between 19 to 42 days). Actual entry to the store only occurred at two sites: twice in 29 days at Site 3 to redistribute chips (10 min each time), and twice weekly at Site 7 to take measurements (30 min each time). At Sites 4 and 6 there was activity in the room containing the silo.

Deliveries of wood chip via the tipping pit at Site 3 were weekly, and generally took 20 to 30 minutes. A single pneumatic delivery of pellets took place at Sites 4 and 6, lasting 15 to 20 minutes.

Site 6 had a boiler service during the sampling period lasting around 90 minutes.

3.2 RISK MANAGEMENT

3.2.1 Information, Instruction and Training

Generally, information, instruction and training at the smaller wood pellet storage sites was minimal. Training was often restricted to the operation and basic maintenance of the boiler system when it was first installed, and did not include the risks associated with confined spaces, or the potential for carbon monoxide poisoning.

There was a general lack of awareness at the smaller sites, of the potential risk presented by the storage of wood pellets or chips in a confined space. Silos are generally inaccessible; however, rooms containing fabric silos and/or boilers are arguably confined spaces.

The 2012 HSE Safety Notice and subsequent provision of information from Local Educational Authorities had resulted in action at Sites 3, 4 and 6, and raised some awareness at Sites 2 and 5.

The Site 3 maintenance engineer had been employed for 16 years and had looked after the wood chip boiler for two years. He had been shown how to operate the boiler and delivery augers. He was aware of the hazard from moving machinery whilst in the store, and of composting producing spores. However, he was unaware of issues regarding air quality (oxygen and carbon monoxide) before the recent HSE Safety Notice was issued, and did not understand the implications of the store being classed as a confined space. The instruction manual supplied with the system gives health and safety information on cleaning the boiler and warns to use low voltage bulbs in the storage room.

The Site 4 site manager had worked at the school for 24 years, and had looked after the wood pellet store for 2.5 years. He has received basic training on operating the furnace; but, no training with respect to the pellet store. His knowledge of the hazards associated with storing wood pellets is based on the recent HSE Safety Notice. There are four laminated instruction cards on lighting the boiler, turning off the boiler, cleaning the boiler and cleaning the flues.

With respect to health and safety, the instructions address emptying the conveyor tube of fuel on shut down and maintaining flue-fan operation during cleaning.

At Site 6 it was speculated that the installation company would have initially trained someone at the centre to clean up general dust and empty the ash bin; this was likely to have been the head cleaner, but this could not be confirmed. The system is controlled automatically with little input except for maintenance. The youth workers at the centre have no training on the use of the system and any problems are reported to the council office which arranges for a service engineer to visit. The recent HSE Safety Notice had raised some awareness and resulted in a warning sign being put on the door of the boiler/wood pellet room and the installation of a carbon monoxide alarm.

Training on wood pellet storage with respect to health and safety was good at Site 7, with the external storage company being linked into the power generation company's safety regime.

3.2.1.1   Manufacturer's Safety Data Sheet (MSDS)

None of the smaller sites (Sites 1 to 6) had a Manufacturer's Safety Data Sheet (MSDS) for the wood fuel. The wood chips burnt at Site 3 are produced on the estate, but are also supplied to other users. The other smaller sites visited were supplied by just two companies.

The MSDS for the imported Site 7 fuel was quite comprehensive (Pinnacle Pellet inc, 2009). It included chemical, fire and explosion hazards from wood dust, carbon monoxide, carbon dioxide, methane and oxygen depletion. Advice on handling, storage, ventilation and entering 'enclosed' spaces was also given. Hydrocarbons emitted are identified as 'primarily aldehydes, acetone, methanol, formic acid'. Wood pellets in containment are recommended to be ventilated at 'one air exchange per 24 hours at 20°C and a minimum of two air exchanges per 24 hours at 30°C and above', and that pellets in 'long period storage in large bulk containment' should be 'as air tight as possible'.

3.2.2   Management Controls

No risk assessments were available for inspection covering the risk of carbon monoxide poisoning posed by the storage of wood pellets at the smaller sites.

Warning notices on the storage area doors at Sites 4 and 6 give some instructions on the procedure for entry (ie; checking the carbon monoxide alarm, keeping the door open whilst inside).

The power generation company and Site 7's employees have a safe working procedure and risk assessment of the dangers of working at the site. This includes information on personal protective equipment (PPE), the use of personal alarms for monitoring carbon monoxide, the dangers of combustible dust and oxygen, and lone working.

3.2.2.1   Access to a Confined Space

Access to the boiler rooms and fuel stores was generally restricted at all sites via lockable doors, with keys being held by a responsible person (although they were not always aware of confined space hazards). At Site 6 the boiler room door was unlocked on the initial visit but locked on the subsequent visit. This room is accessed regularly by cleaners to store equipment.

The Site 1 pellet silo is further restricted by the inaccessibility of the two access hatches without a ladder.

The Site 3 tipping pit cover is locked and a steel mesh prevents access to the augers.

The Site 7 store doors are kept locked unless the doors are opened for inspection or ventilation purposes in dry conditions. Then they may be left open for long periods. The site personnel are aware of confined space entry controls: workers wear personal gas monitors, a buddy system was used when monitoring of the store was taking place, and personal radio communication is maintained with a person on the outside during entry.

3.2.2.2 Warning Signs

There were warning signs on the storage room doors at Sites 3, 4, 6 and 7 (Photographs 12 to 14).

At Site 3 there were commercially produced warning signs on the outside of the store room hatch door and above the tipping pit warning that the store is considered a confined space, authorised personnel only are permitted, and that there is a potential hazard from moving machinery. There was no warning of possible carbon monoxide or depleted oxygen hazards, and when the hatch door is open the sign is not visible. Although the warning sign said that the wood store was a confined space, this was not reflected in company procedures or training.

At Site 4 there are warning signs on the inside and outside of the pellet store door warning that there is a risk of carbon monoxide poisoning, authorised personnel only are permitted, and that smoking or naked flames are prohibited. The sign was identified and sourced by searching the internet.

The door to the Site 6 boiler room had a notice on both sides and used the information recommended on the HSE Safety Notice. This covered: the risk of carbon monoxide poisoning and lack of oxygen; no entry for unauthorised persons; no smoking, fires or naked flames; ventilating the room adequately before entering; keeping the door open whilst inside; and danger from moving parts.
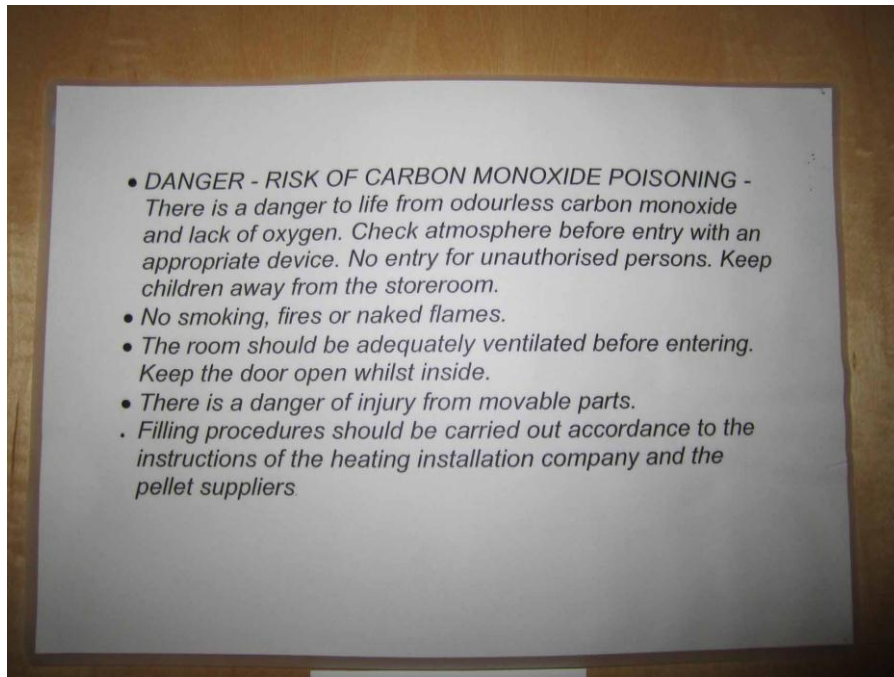
The Site 7 storage areas have carbon monoxide warning signs close to the roller doors and no smoking signs.

Photograph 12 Site 3 warning notice by tipping pit – identical to notice on internal hatch door

Photograph 13 Warning sign present on both sides of Site 4 store room door

Photograph 14 Site 6 warning notice present on both sides of the store room door
(text taken from the HSE Safety Notice)

3.2.2.3   Air Quality Checks

Air quality checks or forced ventilation were not generally made before entry to the smaller store rooms or rooms containing silos; however, Sites 4 and 6 had carbon monoxide alarms by the room entrance, and at Site 6, a warning notice on the door specifically mentions checks and ventilation.

Air quality checks are made with a hand held monitor before entry at Site 7.

3.2.3   Engineering Controls

3.2.3.1   Ventilation

The Site 1 silo was located outside therefore there was no opportunity for gases and vapours generated by the wood pellets to build up anywhere other than inside the silo itself. No forced ventilation system had been applied to the pellet silo. The boiler room was fitted with a slatted (vented) door to ensure adequate air was available for the boiler.

At Site 2, the store room had no forced mechanical or natural ventilation. The room through which the store is accessed had a small slatted external vent allowing some natural ventilation. The boiler room was fitted with a slatted (vented) door to ensure adequate air was available for the boilers. It is unlikely that this would have significant influence on the air movement on the floor above where the pellet store was situated.

The Site 3 tipping pit allows natural ventilation of the store, even when the covers are closed. There were two vents on the wall in the adjoining boiler room, primarily to supply air for combustion.

31

The room containing the Site 4 pellet silo had natural ventilation via a louvre window (80 cm by 30 cm) above the door. There was a large gap in the wall (60 cm by 80 cm) between the pellet store and the boiler room. The boiler room was well ventilated via two louvred doors (200 cm by 170 cm).

At Site 5, the room accessing the pellet store was ventilated via a slatted vent installed above the door. The store room itself had no planned ventilation. The boiler room was fitted with double slatted (vented) doors to ensure adequate air was available for the boiler. Although there was a gap in the wall between the two rooms (boiler room and pellet store entrance), it is unlikely that this would have significant influence on the air movement within the vicinity of the pellet store.

There was no forced ventilation in the boiler/pellet storage room at Site 6. There was a small vent (approximately 0.25 m x 0.25 m) in an external wall providing natural ventilation. There was also a non-return valve located in the boiler flue which could draw air from the plant room into the flue to balance pressures. This will also contribute to the ventilation of the room.

The Site 7 store had a high level wall vent at either end of the each of the stores. During dry conditions the doors to the stores are opened to increase ventilation. The stores are not completely isolated from each other: a space above the internal wall allows air movement between each of the three bays.

3.2.3.2 Alarm systems

There were carbon monoxide alarm systems identified at Sites 4, 6 and 7.

A BRK 'CO4000' carbon monoxide alarm had been newly fitted high up just inside the Site 4 wood pellet store door, just below the louvre window and beside the fabric silo.

A Fire Angel CO alarm had been installed in the Site 6 boiler room. It sat on a surface at waist height just inside the door. The alarm is checked on a weekly basis by the head cleaner. These are domestic carbon monoxide alarms and not really intended for industrial/commercial premises.

There were no carbon monoxide alarms or monitors installed in the Site 7 storage area, however the workers entering the store monitor carbon monoxide and temperature using a personal monitor / alarm. Oxygen is not measured. Staff are instructed to limit exposure to carbon monoxide to no more than 15 minutes at 200 ppm.

It should be noted that carbon monoxide detectors detect raised levels of this gas, but not depleted oxygen levels. None of the sites measured oxygen levels.

It was also reported that the boiler service company for the school sites were planning to issue their engineers with personal carbon monoxide monitors.

3.2.3.3 Outlet pipe filter

It was reported that a bag was placed over the outlet pipe during the filling operations at Site 1 to prevent the spread of any wood dust generated.

Due to continual blocking, the in-line particle filter (Dura Pak 80 bag filter) at Site 2 had been removed from the exhaust duct. The unfiltered air was vented outside through a first floor louvred window.

As noted earlier, there was no exhaust pipe on the Site 4 silo, resulting in the incoming air escaping through the fabric of the silo. The fabric presumably filters out much of the coarse airborne dust.

At Site 5, displaced air was vented through a particulate filter at ground level inside the pellet store building.

There was no filter fixed on the Site 6 return air pipe.

3.2.3.4 Exhaust gases

All of the boilers were fitted with flues. Induction fans to aid removal of flue gases were identified on the boiler flues at Sites 1, 3, 4 and 5. Although not identified, they may have been present at Sites 2 and 6.

The Site 5 boiler is fitted with forced and induction draught fans. The induction fan was fitted retrospectively due to problems encountered.

Use of the induction fan during cleaning operations to remove dust is recommended by the Site 1 boiler manufacturers, in effect providing some degree of local exhaust ventilation. This procedure was also practiced at Site 4.

The flue at Site 6 was fitted with a non-return valve (as described earlier).

3.2.4 Personal Protective Equipment

None of the sites provided PPE specifically for protection against exposure to gases and vapours generated by the fuel; however, PPE was available for other hazards.

At Site 1, instructions provided by the boiler manufacturer recommended gloves, goggles and a dust mask when cleaning and de-ashing the boiler.

At Site 3, the boiler maintenance manual requires the use of a dust mask and gloves when overhauling the combustion chamber, ash chamber and flue (i.e. service company staff) and when emptying the ash store (i.e. site staff).

At Site 4, when pellets were previously stored in a store room, a North 7700-30m half mask respirator fitted with P3 filters was worn when entering the store (if worn properly and face fitted, this would have provided protection against wood dust, but would provide no protection against carbon monoxide or an oxygen deficient atmosphere). This is no longer required as it is not possible to access inside the new fabric silo. The site manager wears a filtered face piece (FFP) dust mask (Arco IA8100 FFP1 disposable respirator) when cleaning out the boiler. Other PPE worn includes goggles and welder's gauntlets. The site manager was not face fit tested for either type of mask. Both types of mask were kept in the store room.

The wood pellet delivery driver at Site 6 wears a high visibility vest and safety boots.

Staff working with wood pellets at Site 7 are supplied with disposable dust respirators (FFP3) and are face fit tested. These provide protection from dust only. Staff checking the temperature in the wood store wore reusable boiler suits, safety helmets and safety boots.

3.3 MEASUREMENTS

Notes on the circumstances relating to the real time measurements were made, and the results obtained on site and in the laboratory are summarised in Tables 2 to 14 and Figures 1 to 10 in Appendices A and B respectively.

3.3.1 GasClam on site real time monitor results

3.3.1.1 *Carbon monoxide, carbon dioxide and methane*

The GasClam monitors did not identify any significant build-up of carbon monoxide, carbon dioxide or methane at any of the four small stores (Table 4). At two of the sites the GasClam monitors were positioned outside fabric silos. The GasClam at the larger Site 7 store recorded a peak carbon monoxide concentration of 27 ppm, with a mean of 5 ppm (Figure 1). Information supplied by the company indicated that, at times, these levels had been higher with levels as high as 106 ppm; and, at a different store, levels had been measured at greater than 200 ppm. Emhofer and Pointner report that carbon monoxide production peaks during the first six weeks (i.e. 42 days) after production of wood pellets (reported in Gauthier et al, 2012). It is anticipated that pellets delivered in the winter will be freshly produced, in which case it is likely that monitoring at all the small sites would have included pellets within this period. However, the imported pellets at Site 7 were at least 120 days old, but, nevertheless still producing carbon monoxide.

For comparison, Svedberg et al (2004) found mean carbon monoxide concentrations of 56 mg/m³ (~49 ppm) in an industrial production plant warehouse and 123 mg/m³ (~107 ppm) from a domestic storage room. In three months of continuous monitoring in one 'passively ventilated storage bin', the peak concentration (estimated as ~60 mg/m³ (~52 ppm) carbon monoxide) was recorded two months after delivery.

3.3.1.2 *Oxygen*

The GasClam monitor oxygen results presented some problems in interpretation. The oxygen levels at Sites 2, 6 and 7 were similar to those in ambient air, but those at Sites 3 and 4 were more varied (Figures 2 and 3).

At Site 3, a number of peak concentrations were registered (four at 27%, the upper limit of the sensor), which are symptomatic of the valves seizing and preventing the GasClam from sampling properly, and are believed by the manufacturer, Ion Science, to be unreliable. Elsewhere the concentration varied between 15.4 and 21.0% in a number of depressions which did not correspond with any known events over the sampling period. Ion Science believe that these could be genuine results; however, considering the high level of general, albeit natural ventilation, oxygen concentrations as low as 15.4% seem unlikely.

The GasClam data for Site 4 also showed variable oxygen concentrations; the concentration started at an initial peak of ~27% and fell below 20.9% over two periods in a series of depressions, with a minimum reading of 16.0%. The changes did not correspond with any known events over the sampling period. Ion Science also believe that these could be genuine results; however, these also were taken at a location with a high level of general ventilation.

The summary oxygen data for Sites 3 and 4 in Table 4 are therefore presented without the peak concentrations, but including the depressions.

3.3.1.3   Total VOCs

The GasClam at Site 3 detected peak VOC concentrations in the wood store on dates coincident with wood store activity (20/2/13, 26/2/13, 7/3/13, 13/3/13 and 19/3/13, from Table 1, Appendix A) (Figure 4). There was no corresponding peak on 15/3/13. Peak concentrations of up to 29 ppm total VOC were detected; however, these were relatively short lived peaks, typically lasting less than one day.

The VOC data from Site 7 are also presented graphically in Figure 5; however no contextual evidence was recorded e.g. on days when the store was ventilated. Peak concentrations up to 11 ppm total VOC were detected and these were similarly short lived.

3.3.1.4   Temperature

The temperatures recorded reflected the cold outside air temperature at Sites 3, 4 and 7 (means of 6, 8 and 13°C respectively). At Sites 2 and 6 where the stores were situated inside better insulated larger buildings the temperatures were higher (18 and 24°C respectively). At Site 7, historical records show that temperatures can rise to 51°C. The air temperatures measured at Sites 4 and 6 would have been affected by the GasClam being outside the silo and at Site 6 being in the same room as the boiler. Carbon monoxide production would be expected to increase with temperature (Kuang et al, 2008). Svedberg et al (2004) found that carbon monoxide varied with ambient temperature.

3.3.2   Diffusive Tube VOC analytical results

The VOCs identified at all sites where measurements were taken were present at extremely low levels (Tables 5 to 9, Appendix A). The concentrations quoted are averages for the whole exposure period. Peak exposures may have occurred within this period, but they were unlikely to have presented a risk to the health of anyone exposed because of the low concentrations measured.

With measurements such as these, it can be difficult to identify which compounds arose from the wood pellets or chips, and what was already present in the background environment. For instance, the Site 4 pellet store was situated next to a car park and hence some of the compounds detected (e.g. toluene, alkanes and alkylated benzenes) may have arisen from vehicle engine exhaust and not the pellets. The results at higher concentrations indicate that the wood chips emitted terpenes, and wood pellets emitted predominantly aldehydes, but also some terpenes. This is consistent with previous findings by other researchers (Svedberg et al 2004, Svedberg et al 2009).

The samples with the highest levels of VOCs were from the wood chip store at Site 3 (Table 6). The VOCs identified were all terpenes (principally 340 ppb alpha-pinene and 151 ppb limonene), which are compounds associated with plant material and are major components in tree resin. The chips had been freshly produced and had not gone through any processing other than 18 months seasoning.

The Site 7 samples from the large scale pellet store also had higher levels of VOCs (Table 9) and had the greatest variety of components (over 30 compounds). The range of compounds identified included aldehydes (C_4 to C_9), ketones (C_3 to C_{10}), terpenes (camphor, alpha-pinene, limonene), as well as some alcohols, alkanes and aromatics. The individual major components were n-hexanal (119 ppb), a 4-C substituted benzene (93 ppb), n-pentanal, n-heptanal, n-octanal, acetone, 2-heptanone and pentyl-furan (13-21 ppb). However diesel powered vehicles were being used in the store during the last day of monitoring.

Samples taken at the other three smaller pellet stores (Sites 2, 4 and 6: Tables 5, 7 and 8) had fewer compounds at lower concentrations. The principal compounds found at Site 2 were n-hexanal (38.5 ppb) and hexanoic acid (10 ppb), and at Site 6 were hexanol (18 ppb), alpha-pinene (7.5 ppb) and hexanoic acid (5 ppb). The Site 4 detected compounds were very low (<1 to 5 ppb), perhaps reflecting the fact that the samples were collected outside of a fabric silo in a well-ventilated room. The Site 6 samples were also collected outside a fabric silo, but in a room with a lower level of ventilation. Nevertheless compounds associated with pellets (n-pentanal, n-hexanal, hexanol, hexanoic acid and alpha-pinene) were detected at both these sites, perhaps reflecting slow permeation through the fabric. It should be remembered that some may have originated from the natural environment (albeit it being winter) or from cleaning fluids stored nearby (Site 6).

3.3.3 Ventilation test results

The air change test results are presented in Table 10. The measurements from Sites 2, 3, 4 and 6 were all made in rooms (store rooms or rooms containing silos) which were naturally ventilated.

The Site 2 store had limited ventilation and had the lowest mean air change rate (1.7 air changes per hour - ach). Nevertheless it is considered by the HSE specialist to be at the high end of what could be expected for such a space.

The air change rate determined at Site 6 (mean 2.8 ach) was also from a room with little obvious planned ventilation, and again would be at the high end of the expected range. It is likely that the ventilation is partially driven by air extraction from other areas of the building and by air extracted via the boiler flue. The boiler was reportedly operating in slumber/kindle mode during the visit. An increase in the ventilation rate part way though the test may have been caused by an increase in the combustion rate of the boiler and thus the volume flow rate of exhaust gases in the flue. The Technical guide for the boiler suggests that it is incompatible with a balanced flue, therefore all air for combustion may have been drawn from the room and been expelled through the flue.

Site 4 had more visible ventilation in the form a ventilation grille above the door. The mean air change rate here was 8.8 ach, which the HSE specialist considered high for this type of space. This measurement was for a room containing a fabric silo and which also had a gap in the partition wall between the pellet store and the boiler room.

The Site 3 store room air change rate test had the highest measurement (mean 20.2 ach) but with large variation between three tests. The ventilation rate of naturally ventilated spaces is strongly dependent upon prevailing weather conditions, namely wind speed and direction and temperature differences between the inside and outside air. It is suspected that this was the cause of much of the variability in the ventilation rates measured here.

At all four of these sites the ventilation rate was higher than expected (based on the experience of the HSE specialist), and it is suspected that air could have been drawn for combustion by the boiler via the delivery auger, thus driving ventilation of the store. During the Site 2 test the boilers were observed to increase and decrease their output consistent with variations in the ventilation rate.

Measuring the ventilation rate at Site 7 using the tracer gas method would have been problematic due to the large volume of the space and the dividing walls between storage bays. This made it difficult to mix the tracer gas and maintain a uniform concentration. Typically, from HSE specialist experience, similar naturally ventilated spaces have air exchange rates in the range 0.5 - 2 ach, dependent upon prevailing weather conditions. With the main doors open, the air change rate will be higher than with the door closed. The ventilation will be driven by

pressure differences across the building envelope with air passing through the vents in the walls and through any adventitious gaps in the building fabric such as open doors and gaps between the roof and walls, and the walls and the floor. The air change rate will be dependent upon the volume of wood pellets in the store as they reduce the effective volume of the room, whilst the volume flow rate of air entering and leaving will remain essentially constant.

3.3.4   Microbiological analytical results

The results of the microbiological analysis are shown in Table 11.

It was clear from the results that there is a difference in microbiological content in wood pellets (Sites 2, 4 and 7) compared to wood chips (Site 3). No micro-organisms were detected in two samples of wood pellets from two facilities (Sites 2 and 4), and tests on the third sample (Site 7) only found low levels of *Aspergillus fumigatus* fungi, and mesophilic fungi (25°C) in concentrations of 125 colony forming units (cfu) per gram of fuel. However, there were 33,000 cfu/g mesophilic fungi and up to 18.1 million cfu/g bacteria in the sample of wood chips from Site 3. These results suggested that the prevailing conditions prevented microbial activity in the wood pellets. This could be a combination of reduced water availability, and the compression of material to create the pellets from the raw material, creating a hard impervious outer surface which discouraged microbial colonisation.

Previous work published by Madsen et al (2004) helps to put the microbiological data into context. In a study of the dustiness and microbiological content of biofuels, they measured the microbial content of straw, wood chips, wood pellets and wood briquettes used in commercial biomass incinerators. It was found that wood chips and straw contained between 80,000 and 3.1 million cfu/mg bacteria (3100 million cfu/g) and 4.15 million cfu/mg fungi (4150 million cfu/g), while in wood pellets and briquettes they ranged from 20 to 60 cfu/mg bacteria (20,000 to 60,000 cfu/g) and fungi were below the detection level.

Svedberg et al (2009) found <9 cfu/g bacteria and <9 cfu/g fungi in dry wood pellets, and 940,000 cfu/g bacteria and 710,000 cfu/g fungi in wood chips.

If the conditions, such as temperature and humidity become favourable there is the potential for degradation of organic materials by any bacteria or fungi present. Although the Site 3 wood chips looked relatively moist, air temperature in the store varied between 0 and 10°C over the period monitored. There is also a high turnover of wood chips in the store, and efforts had been made to prevent pockets of ageing fuel developing. Any resultant bacteria or endotoxin produced would only become a problem if people were exposed to any airborne inhalable dust generated.

3.3.5   Laboratory Based Monitoring of Air Composition

3.3.5.1   *Results*

Details of the tests are presented in Table 12, Appendix A. Selected monitoring results are shown in Figures 6 to 10 in Appendix B. The measurements were used to estimate gaseous emission factors (see Appendix C).

In all tests, the air temperature inside the drums was stable throughout the tests (around 20 to 22°C). The wood pellet drum had a relative humidity (RH) of ~42%, but the initial wood chip drum test increased to and subsequently remained at 100% RH after only 3 hours and 20 minutes. In the follow up tests the humidity settled to ~90% RH.

The gaseous emissions from the wood pellets (Figure 6) showed the oxygen concentration falling to a minimum of 0.1% and the VOC concentration increasing to a maximum of 47 ppm after 26 days. The carbon dioxide concentration increased and reached 1,500 ppm by the end of the test. The carbon monoxide concentration steadily increased to 1042 ppm after 5 days when it appeared to reach the sensor's maximum range even though this is specified as 1500 ppm by the manufacturer. The flammable sensor did not show any response.

The gaseous emissions in the initial wood chip test were more complicated (Figure 7). The oxygen concentration fell to zero after 13 days. The carbon dioxide concentration quickly increased beyond the sensor's maximum value of 50,000 ppm after 3 days and the flammable sensor did not show any response. However, the carbon monoxide concentration rapidly increased to 96 ppm after 20 hours before falling to less than 10 ppm after 13 days. The VOC concentration increased to 80 ppm in 1.5 hours before similarly falling to less than 1 ppm again after 13 days. After 19 days it was noticed that the MultiRae monitor pump had failed and was operating in diffusion mode i.e. with a slower response time.

Subsequent testing of the monitors revealed that both carbon monoxide sensors were faulty and were indicating negative concentrations even when exposed to high concentrations of carbon monoxide. All sensors worked correctly after the monitors were left to stabilise for two days. Additional tests were conducted on the carbon monoxide sensor, exposing it to gas mixtures of carbon monoxide with high carbon dioxide or reduced oxygen, and it behaved as expected. The monitor was placed back into the wood chip drum 20 days after the original test was completed for a further five days: the carbon dioxide and oxygen concentrations behaved in a similar manner as before, the VOC and flammable concentrations showed no response, and the carbon monoxide concentration steadily increased to around 35 ppm (see Figure 8).

In the second series of tests, the undried wood chips (Figure 9) show carbon monoxide, carbon dioxide and oxygen concentrations following a similar trend as the initial test (Figure 7) except the concentrations were not as extreme. However, the VOC concentration peaked at 2450 ppm after about 12 hours which was approximately two orders of magnitude greater than measured on the initial test. The measurements of carbon monoxide, carbon dioxide and VOC concentration taken by the Gasmet FTIR confirmed the measurements made with the MultiRae.

The dried wood chip emissions (Figure 10) followed a different pattern from the undried wood chip. The carbon dioxide steadily increased from 620 ppm to 1500 ppm, VOCs increased to around 70 ppm, and the oxygen concentration remained at 20.9%. The carbon monoxide concentration did not start to increase until the second day when it increased rapidly to about 380 ppm, followed by a less rapid rise to approximately 530 ppm.

3.3.5.2   Evaluation

The emissions of gases from wood pellets followed the expected pattern as shown previously by Kuang et al (2008), and Fan and Bi (2012), but the pattern for wood chips was more complicated.

The oxygen depletion and carbon dioxide emission from wood chips developed as expected, up to the point that the carbon dioxide sensor was saturated (~1000 ppm). However, the emission patterns for carbon monoxide and VOCs were unexpected with an initial rapid increase and then fall in their concentrations during the first day of exposure. Tests on cross-sensitivity of the carbon monoxide sensor to carbon dioxide and oxygen indicated no effect, however, for most of the test, the gas sensors were exposed to very high humidity. Resumption of the test again still showed very high carbon dioxide and humidity, but this time the carbon monoxide concentration continued to climb through the five days of the test, following the pattern expected from Fan and Bi (2012) and levelled out at about a third of the original peak

concentration. This suggests that the high relative humidity and carbon dioxide concentration did not act as interferents with respect to the carbon monoxide sensor during the initial part of the original test. The lower concentrations measured in the second period are presumably a result of the opening of the drum and the wood chips aging.

The undried wood chip emissions in the second series of tests, as measured by the MultiRae and confirmed by the Gasmet FTIR, followed a similar trend as the first test. The carbon monoxide and VOC concentrations increased to a maximum within two days of the start of the test and then fell. The carbon dioxide concentration steadily increased and the oxygen concentration steadily fell during the test. However, the concentrations attained (relative to the quantities of wood chip used) were different to those obtained in the first wood chip test (see Table 13). This second wood chip test can be considered more reliable since the humidity remained within the specification of all the sensors. An additional contribution to the variation seen was that the wood chips were from different batches, made from different proportions of wood types. The wood chips for the first test were mainly larch and spruce, but the wood chips for the second series of tests were mainly spruce.

The dried wood chips produced emission concentration trends that were closer to those from wood pellets than from undried wood chips, since the concentrations of carbon monoxide, carbon dioxide and VOCs all steadily increased without any obvious maxima. However, there were some significant differences; the oxygen concentration did not change, the carbon monoxide concentration only started to increase during the second day, and the concentrations produced relative to the mass of wood were different. The differences between these results and the undried wood chip and wood pellets results is unclear, but drying wood chip prior to storage will not prevent emissions.

It can be concluded that the decomposition of wood chip is much more complicated than that of wood pellets. Carbon monoxide and carbon dioxide were produced from both fuels, but wood pellets produced more carbon monoxide than wood chips, whilst these produced more carbon dioxide than wood pellets.

Kuang et al (2008) suggested that chemical decomposition of wood pellets was the dominant mechanism for off-gassing as the emission rates followed a simple first-order kinetic model and was highly temperature dependent.

It is believed that emissions from wood chips are predominantly from microbiological processes (Svedberg et al, 2009). It is clear that this is a much more complex process, with concentrations rising and falling. Some of the processes may be affected by the presence or absence of the other gases, and moisture also has an effect.

4. SUMMARY DISCUSSION

4.1 POTENTIAL FOR EXPOSURE

This research has shown that there is the potential for people to access wood pellet or wood chip stores, either for inspection, to redistribute fuel for the transfer mechanism, or to investigate other problems. This may be the case particularly with newly commissioned and/or poorly designed fuel stores for boilers. On breakdown of the heating system, it is initially the site operator who inspects the problem, and where there is pressure to resume operation, workers may be tempted to investigate inside the store. If not easily resolved, then specialist maintenance staff will be required. For major repairs to the fuel transfer system, the pellets/chips would need to be removed to give access to the transport system. During servicing, access inside the store was not generally required for augers transferring wood pellets; however, it was required for the sweeping arm used in the wood chip store. There were conflicting reports on whether stores and silos require cleaning out of residual dust.

Access to boiler rooms and fuel stores is generally restricted to key holders. Some designs such as the tower silo at Site 1 have very restricted access. The two fabric silos encountered could not be entered, but any gases produced will be capable of diffusing out of the silo through the walls and might accumulate in the room. Very small concentrations of carbon monoxide were detected at these two sites, as well as some low concentrations of VOCs. Other designs of store room cannot be accessed until the level of fuel has decreased sufficiently. Regular access to the large Site 7 store was required to make measurements using hand held monitors.

4.2 CONTROLS

There are a number of preventative measures available to inhibit changes to the air in the fuel store, such as keeping the fuel dry and cool, but ideally to ensure good air quality the store should have some degree of continuous ventilation. This however, would increase the risk of spontaneous combustion. Where continuous ventilation is impossible, an air quality check and ventilation will be required before entry. Personal alarm monitors would also be appropriate. If there is still a residual risk of harm then suitable and sufficient arrangements for rescue in the event of an emergency including injury unconnected with confined space entry would need to be made. Staff should be trained to understand the potential hazards and controls present, including confined space issues. There should be written information available including a risk assessment, safe working procedures and MSDSs. Access should be restricted, and there should be adequate warning signs in place. Key holders especially should understand the risks. When the store is opened e.g. for ventilation, access should still be controlled. Air quality checks should include oxygen measurement as well as carbon monoxide.

Ventilation

The small stores did not have any planned mechanical or natural ventilation, although two stores tested had higher than expected air change rates. It is speculated that there is some ventilation via the delivery tubes and the boiler, which would presumably apply to other similar systems, but, this has not been confirmed. If this is correct, then when the boiler is turned off, e.g. in the summer, the ventilation rate could be much lower. Boiler rooms containing silos are likely to have a high air change rate during operation; however combustion in boilers may also be a source of carbon monoxide. The large store had natural ventilation via louvered windows; however, it was still necessary to open the doors periodically.

Access

Initial access was restricted at all the sites. Staff at the large store checked the air quality (carbon monoxide only) before entry. Fixed alarms at two of the small sites with silos located inside rooms also provided warning of carbon monoxide. None of the sites checked oxygen levels. One site required ventilation of the room before entry (indicated on a warning sign), but the building design made this impracticable and this instruction was therefore unlikely to be followed. There were warning signs at the large site and three of the small sites. However at one site, once access had been obtained, a sign could no longer be seen because it was only on the outside of the door. None of the sites had any form of temporary barrier e.g. rope or mesh door. The large site had a buddy system during entry, and the outside worker would act as a sentry, but a barrier would be of value if the large roller door was to be left open for long periods unattended.

Information, instruction and training

Other than the perception of a possible hazard from carbon monoxide, there was limited knowledge amongst the workers at small stores of appropriate risk management procedures or controls. This was not the case at the larger store, where there was a much higher level of training and control procedures. Warning signs and carbon monoxide detectors have recently been fitted at some of the smaller sites as a result of information in the HSE Safety Notice, passed on via intermediaries.

There was little understanding of confined space entry controls. Rooms containing silos with pedestrian access doors may not be perceived to be a confined space or to be very low risk. Under the Confined Space Regulations 1997, a 'confined space' has two defining features. Firstly, it is a place which is substantially (though not always entirely) enclosed and, secondly, there will be a reasonably foreseeable risk of serious injury from hazardous substances or conditions within the space or nearby. Such areas are also often in close proximity to the boiler. In one case a small gap underneath a silo had been accessed. This would be classed as a confined space. Other factors such as ventilation etc. would need to be considered when assessing the risk presented.

There was virtually no written information concerning off-gassing of wood pellets from local suppliers of fuel or from companies installing and maintaining boiler systems. Until now this issue does not appear to have been considered sufficiently by this emerging sector.

4.3   AIR COMPOSITION IN WOOD PELLET STORES

During this work, the limited number of measurements taken did not reveal any significant changes to carbon monoxide, carbon dioxide and oxygen in store rooms or in rooms containing fabric silos. Air change rates measured were all greater than 1.7 air changes per hour, although it is suspected that the operation of the boiler could also have influenced ventilation. This value is still significantly higher than the one air change per 24 hours at 20°C stated in the MSDS obtained for the pellets used at Site 7.

Temperature and age of the pellets also has an effect on the oxidation process. The measurements at the small sites took place in the winter where the turnover of wood pellets was likely to be high caused by increased boiler use, and therefore the pellets fresher; however, the external air temperatures may have had a cooling effect on some of the wood pellets. At the largest store (Site 7), with aged pellets and a relatively low estimated ventilation rate, there were low, but measurable concentrations of carbon monoxide. Other than Site 7 (4000 tonnes), the

quantities involved in this study (2.5 to 7 tonnes) were also somewhat smaller than those in the confirmed fatal off-gassing incidents discussed in the literature (155 tonnes and an estimated 19 tonnes).

The limited measurements in this study were not planned as a representative survey. In contrast, Emhofer and Pointner report 9% of air tight wood pellet stores may have carbon monoxide concentrations of over 1000 ppm (reported in Gauthier et al, 2012). In Svedberg's study (2004), carbon monoxide at 56 mg/m³ (~49 ppm) was found in a warehouse, and at 123 mg/m³ (~107 ppm) in a domestic store room containing 5 tons of wood pellets in Sweden.

The laboratory tests confirmed that the wood pellets encountered during this work were capable of producing large gaseous emissions of carbon monoxide and carbon dioxide, and depleting oxygen. The results produced are indicative of possible behaviour, but are not definitive concentrations that would be found in the workplace. As such, values are dependent on a number of factors including wood type, temperature, age, surface area and the ratio of wood to headspace (Gauthier et al, 2012). Ventilation will reduce these effects. Moisture is also an issue for wood chips. The risk may vary with the season: in the winter pellets are likely to be fresher, but in the summer the pellets may be warmer, and ventilation of stores may decrease if boilers used for heating are not used.

Dangerous levels of both carbon monoxide and oxygen can be produced, and it should be remembered that when present in the same atmosphere there will be a combined effect. Carbon monoxide is of greater concern than carbon dioxide, but carbon dioxide may also contribute to the combined hazard.

4.4   AIR COMPOSITION IN WOOD CHIP STORES

Fresh wood chips can produce carbon monoxide, but not in the same quantities as wood pellets; however, there is still a hazard from carbon dioxide emissions and depleted oxygen. Artificially drying the chips decreases the rate of carbon dioxide production but increases the rate of carbon monoxide production.

Like the wood pellets, wood chip also emits VOCs such as terpenes, but here did not emit organic compounds such as aldehydes, and other oxygenated VOCs.

The issue of composting is much greater for wood chip because of the much higher levels of moisture and microbiological contamination present.

Wood chips are not as regularly shaped as pellets and are therefore more likely to present fuel transfer problems such as bridging in stores, requiring intervention by staff, and therefore access into the stores.

5. CONCLUSION

Both wood pellet and wood chip biofuel can produce dangerous atmospheres when stored in an unventilated enclosed space. Both fuels can produce carbon monoxide and carbon dioxide. Wood pellets in particular produce carbon monoxide, and wood chip carbon dioxide. Both fuels can deplete air of oxygen.

Fuel suppliers are in frequent contact with wood pellets or wood chips, and boiler maintenance companies can be expected to have access to fuel stores intermittently; however, contact for operators of small boiler systems is varied. Some may have little or no requirement for access until a fault occurs, whereas those with badly designed fuel transfer systems may require more frequent access.

Knowledge of the hazards of dangerous atmospheres is limited amongst the operators of small boiler systems. Awareness of the hazard has been raised following the publicity produced by the HSE Safety Notice (HSE-2012). This has led to some action to address the issues of control at some sites (e.g. posting of warning signs and fitting of domestic carbon monoxide alarms). Boiler rooms and fuel stores are usually kept locked, but there is little in the way of written risk assessments and prescribed safe working procedures. Site managers can be inexpert in matters of health and safety such as confined space entry. The industry (companies supplying and maintaining boilers and storage equipment, and the fuel suppliers) are themselves only just becoming aware of the issues involved and as yet have not provided comprehensive authorative guidance.

Staff at the large wood pellet store were more knowledgeable about health and safety requirements for storage of wood pellets, but they too are still developing expertise in this new technology.

The fundamental controls for preventing exposure to dangerous atmospheres and depletion of oxygen are:

- prevention of dangerous gas levels accumulating (including low oxygen) by ventilation;

- the recognition of these fuel stores as a confined space, i.e. restricting access except to authorised workers with the necessary training;

- having a safe system of work, including supervision, air quality checks, etc. as required by the Confined Space regulations, 1997; and

- giving consideration to areas where escaped gases may accumulate.

During examination of a range of differing types of small wood pellet and wood chip store, no significant concentrations of carbon monoxide were detected. Each measurement location had a reasonably high ventilation rate (>1.7 air changes per hour) which was assumed to have controlled build-up of carbon monoxide. Ventilation was generally unplanned and may have been reliant on operation of the boiler. Ventilation therefore may be reduced for long periods during the summer if the boiler is unused. The design and location of the store can affect ease of access or accumulation of gaseous emissions in the vicinity.

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APPENDIX A. RESULTS FROM MONITORING

Table 1 Activity log entries

Site	Comment
Site 2	No activities involving the pellet store during the sampling period (19 days).
Site 3	26/2/13 Delivery of wood chips (30 min) 6/3/13 Delivery door (60 min) 6/3/13 Inspection and redistribution (10 min) – via inner door 7/3/13 Delivery door (20 min) 13/3/13 Inspection and redistribution (10 min) – via inner door 15/3/13 Delivery door (20 min) 19/3/13 Delivery door (20 min) (Note personal access to the store is not possible through the delivery door)
Site 4	5/4/13 Fuel level and feed check (10 min) 8/4/13 Wood pellet delivery (15 min)
Site 6	14/3/13 Regular boiler service (90 min) 21/3/13 Wood pellet delivery (20 min) (Regular access to the boiler room by cleaners was not recorded)
Site 7	Site failed to provide a log for access and ventilation; however, they reported that half hour inspections are made twice weekly.
nb Sites 1 and 5 not included in monitoring.	

Table 2 Summary of site visits and measurements

Site	Sampling dates	Bulk Fuel Sample	Air Measurements	GasClam monitor	Diffusive tubes	Microbiological Analysis
Site 2 Purpose built pellet store room.	28/2/13-19/3/13 Monitoring started 24 days after last delivery.	6 mm diameter wood pellets (Source A - UK)	Air sampling and ventilation rate determined inside the pellet store.	19 days (452 readings)	19 days (27105 min)	Yes
Site 3 Converted barn wood chip store.	20/2/13-21/3/13 Monitoring started 1 day after last delivery (1 day after chipping) & further weekly deliveries made.	Wood chips, up to 2 cm x 10 cm (produced on site)	Air sampling and ventilation rate determined inside the wood chip store.	28 days (664 readings)	29 days (41715 min)	Yes
Site 4 Fabric pellet silo inside a former coal store.	5/3/13-8/4/13 Monitoring started 6 days after last delivery. (~14 days after production*) Second delivery 8/4/13.	6 mm diameter wood pellets (Source B - UK)	Air sampling and ventilation rate determined in the room containing the pellet silo.	27 days (634 readings)	34 days (48675 min)	Yes
Site 6 Fabric pellet silo in a boiler room.	11/3/13-11/4/13 Monitoring started 33 days after last delivery. Second delivery 21/3/13.	Wood pellets (Source A - UK) No sample	Air sampling and ventilation rate determined in the room containing the pellet silo.	31 days (726 readings)	31 days (44500 min)	No Sample
Site 7 Large scale pellet storage in a former grain store.	11/9/13-23/10/13 Monitoring started ~68 days after delivery* (120 days after export).	6 mm diameter wood pellets (Source C - Canada)	Air sampling (only) inside the pellet store.	29 days (708 readings)	42 days (60285 min)	Yes
* Estimated values Sites 1 and 5 not included in air monitoring because of access problems. Similarly, no bulk samples were taken from the Sites 1, 5 and 6 because the pellets were inaccessible.						

Notes on wood fuels present during monitoring

The day of production of the pellets from Site 4 was estimated from the date of acquisition from the supplier.

The company supplying pellets to Sites 1, 4 and 5 (Source B) claim that their pellets are Grade A and conform to the European standard CEN/TS 14961. The pellets were reported to be made from unseasoned virgin pine wood dust. Recycled wood reportedly has too high an ash content for use with these systems.

The wood chips at Site 3 were produced and delivered to the store the day before the first visit. The wood had been seasoned for 18 months before chipping and was said to contain <35% water. The chips varied in size up to roughly 10 cm by 2 cm and felt relatively moist with little fine dust. The chips were reported to be softwood (mainly spruce and larch but also containing some pine).

The wood pellets used by the power generation company usually come from abroad. The batch stored at Site 7 originated from Canada and was transported to the UK by ship. The date of export was identified from the Certificate of Origin which gave the vessel departure date. The MSDS supplied with the Site 7 wood pellets states that wood pellets are manufactured from lingo-cellulosic saw dust, planer shavings or bark, following one or any of a combination of drying, size reduction, densification, cooling and dust removal operations. The wood pellets are typically manufactured from a blend of feedstock with the composition shown in Table 3.

Table 3 Typical feedstock used to manufacture the wood pellets at Site 7
(taken from the wood pellet MSDS)

Feedstock	Oxygenated compounds (indicative composition in % weight)		
		Cellulose	30-40
		Hemi-cellulose	25-30
		Lignin	30-45
		Extractive (terpene, fatty acids, phenols)	3-5
Additives	None except as stated in Wood Pellets Production Specification		
Binders	None except as stated in Wood Pellets Production Specification		

GasClam Monitors

GasClam sampling at Sites 3, 4 and 7 ended before the return visit to pick up the sampler when the batteries ran out.

Table 4 GasClam real time monitor results: mean (range)

Site	Temperature (°C)	CO (ppm)	CO_2 (%)	O_2 (%)	CH_4 (%)	VOC (ppm)
Site 2	18.1 (15.8 - 20.6)	1.2 (0 - 2)	0.0	20.6 (20.5 - 21.4)	0	0.01 (0 – 1)
Site 3	5.6 (0.0 – 10.2)	1 (0 – 3)	0.1 (0.0 – 0.1)	19.5* (15.4 - 21.0)	0	2 (0 – 29)
Site 4	8.2 (5.6 – 10.8)	0.02 (0 – 1)	0.001 (0.0 – 0.1)	19.1* (16.0 - 26.8)	0	0.005 (0 – 1)
Site 6	23.9 (10.3 - 26.9)	0.3 (0 – 3)	0.01 (0.0 – 0.1)	20.9 (20.0 - 21.0)	0	0.2 (0 – 1)
Site 7	12.9 (5.8 – 22.1)	5 (0 – 27)	0.03 (0.0 – 0.1)	20.2 (19.5 - 20.8)	0	0.9 (0 – 11)
Quoted Accuracy		$<\pm$ 3 ppm	$\pm$ 2 % FSD ($\pm$ 0.1 %)	$\pm$ 5 % of reading $\pm$ 1 digit	$\pm$ 2 % FSD ($\pm$ 0.1%)	$\pm$ 5% of reading $\pm$ 1 digit
CO – carbon monoxide; CO_2 – carbon dioxide; O_2 – oxygen; CH_4 – methane; VOC – volatile organic compounds *the reliability of these data is discussed in the text.						

Analysis of sorbent tubes

The diffusive tube VOC analytical results quoted below are the mean of two results from the tube type collecting most analyte. The individual results are subject to 15% expanded uncertainty and are not blank corrected. It was deduced that the sample and blank tubes at Site 2 were misidentified, however the results are unaffected.

Table 5 Site 2 VOC mean analytical results

Analyte	Concentration (ppb)
Propanoic Acid	1.5
Hexanoic Acid	10
Pentanal	1.5
Hexanal	38.5
Toluene	0.5
n Alkanes C12 to C13	5

Table 6 Site 3 VOC mean analytical results

Analyte	Concentration (ppb)
Alpha-Pinene	340
Beta-Pinene	88
Limonene	151
Carene	56
Other Terpenes	77

Table 7 Site 4 VOC mean analytical results

Analyte	Concentration (ppb)
Hexanal	2
Toluene	5
Total Xylene	3
Alpha-Pinene	3
Limonene	<1
nC7 to nC10 alkanes	2
1,2,4-Trimethyl benzene	1
Other alkylated benzenes	2

Table 8 Site 6 VOC mean analytical results

Analyte	Concentration (ppb)
Pentanal	2
Hexanol	18
n Alkanes nC7, nC8 & C10	2
Ethylebenzene & xylene polymers	1
Pentanoic Acid	1
Hexanoic acid	5
Alpha-Pinene	7.5
Carene	4
Other Terpenes	4.5

Table 9 Site 7 VOC mean analytical results

Analyte	Concentration (ppb)	Analyte	Concentration (ppb)
Acetic Acid	0.8	n-Pentanone	2.0
n-Butanol	0.9	4 methyl-2- pentanone	1.0
n-Hexanol	15	2-Heptanone	15.6
iso Butanal	0.6	2-Octanone	3.7
n-Butanal	1.1	2-Nonanone	5.9
iso Pentanal	0.9	2-Decanone	3.6
n-Pentanal	20.7	Ketone species	1.5
n-Hexanal	119	Camphor	7.9
n-Heptanal	13	Alpha-Pinene	3.8
n-Octanal	16.3	Terpene species	2.1
n-Octenal	5.1	Limonene	2.7
n-Nonanal	9.6	n-Pentane	0.9
Benzaldehyde	6.1	n-Heptane	4.2
Methylethylbenzaldehyde	2.9	n-Octane	6.5
Acetone	15	Toluene	1.2
Methylvinylketone	0.3	iso Propylbenzene	1.25
n-Butanone	1.0	4C substituted Benzene	92.5
iso Pentanone	0.9	Pentylfuran	13.5

Measurement of air change rate

Due to the size and layout of the Site 7 store it was not possible to mix the trace gas to a uniform concentration to enable a ventilation rate to be determined. The store consisted of three sections, two of which were in use to store pellets, and openings above the internal walls allowed air exchange between the neighbouring sections. Therefore a visual assessment was made of the store and an estimated air change rate given.

Table 10 Air change rate test results

Site	Ventilation rate (air changes per hour)
Site 2 (determined in pellet store)	1.7 (varying 1.5 to 2.1 over 100 minutes)
Site 3 (determined in wood chip store)	20.2 (mean of 25.9, 21.9 and 12.8)
Site 4 (determined in room containing pellet silo)	8.8 (mean of 9.1, 8.6 and 8.7)
Site 6 (determined in room containing pellet silo)	2.8 (varying 2.0 to 3.5 over 60 minutes)
Site 7* (visual assessment only of pellet store)	Estimated 0.5 to 2* (from similar naturally ventilated spaces, and dependent upon prevailing weather)
*Due to the size and layout of the store (openings to adjoining stores) it was not possible to mix the trace gas to a uniform concentration	

Bulk sample analysis

Table 11 Microbiological analytical results

Site	Sample Description	Bacteria NA 25°C (cfu/g)	Bacteria NA 37°C (cfu/g)	Mesophilic Fungi 25°C (cfu/g)	Aspergillus fumigatus Malt 40°C (cfu/g)
Site 2 (Source A)	6 mm diam. pellets	ND	ND	ND	ND
Site 3 (on site source)	Wood chips (up to 10 cm)	1.81×10^7	2.61×10^6	3.30×10^4	ND
Site 4 (Source B)	6 mm diam. pellets	ND	ND	ND	ND
Site 7 (Source C)	6 mm diam. pellets	ND	ND	125	Low levels
cfu/g – colony forming units per gram ND – not detected					

Laboratory trials

Table 12 Laboratory air composition test sample details

Test	Sample	Wood Type	Prepared	Test Started	Estimated Mass (kg)
Series 1	Wood chips from Site 3	90% larch and spruce, some Scots pine and very small amount of silver birch. Felled in 2012.	Chipped on 15/8/13	16/8/13 and 10/10/13	8.9[1]
	Wood pellets from Source B	Pure pressed sawdust.	Pelletised on 19/8/13	20/8/13	28.2
Series 2	Wood chips from Site 3	Almost entirely spruce.	Chipped on 12/3/14	13/3/14	3.6[2]
				18/3/14	3.0[3]
1 – Reportedly contains <35% moisture.					
2 – Undried wood chip. Mean moisture content = 26.1%					
3 – Dried wood chip. Mean moisture content = 12.6%					

Table 13 Emission concentrations produced in laboratory headspace air composition tests

Test	Mass (kg)	Period (days)	Carbon monoxide (ppm)	Carbon dioxide (%)	VOCs (ppm)
Wood pellets	28.2	34	>1042	0.2*	47
Wood chips (undried)	8.9	35	96	>5	80
Wood chips (undried)	3.6	15	60*	3.5	2481
Wood chips (dried)	3.0	11	543*	0.1*	73
* - maximum not reached during the period of the test.					

Table 14 Indicative emission and consumption factors

Test	ρ_w (kg/m³)	M_w (kg)	V_g (l)	Carbon monoxide		Carbon dioxide		Oxygen depletion	
				C_g (ppm)	f (mg/kg)	C_g (ppm)	f (mg/kg)	C_g (%)	f (mg/kg)
Wood pellets	1049[1]	28.2	33.1	>1042	>1.6	15,470	21.8	20.9	295
Undried wood chips	700[2]	8.9	47.3	~96	~0.6	>50,000	>319	20.8	1328
Undried wood chips	700[3]	3.6	54.9	60	1.1	35,570	650	5.7	1042
Dried wood chips	400[4]	3.0	52.5	543	11.4	1500	31.5	0.0	-

ρ_w – Density of wood
M_w – Mass of wood
V_g – Volume of gas
C_g – Maximum gas concentration measured
f – Emission factor calculated

1 – Mean wood pellet density taken from measurements on ten pellets.
2 - Based on the maximum density of either dry larch (500 – 550 kg/m³), spruce (400-700 kg/m³) and Scots pine (510 kg/m³) (The Engineering Toolbox, 2012),
3 - Based on the maximum density of spruce (400-700 kg/m³).
4 - Based on the minimum density of spruce (400-700 kg/m³).

APPENDIX B. SELECTED AIR MONITORING GRAPHS

Figure 1 Site 7 wood pellet store carbon monoxide concentrations
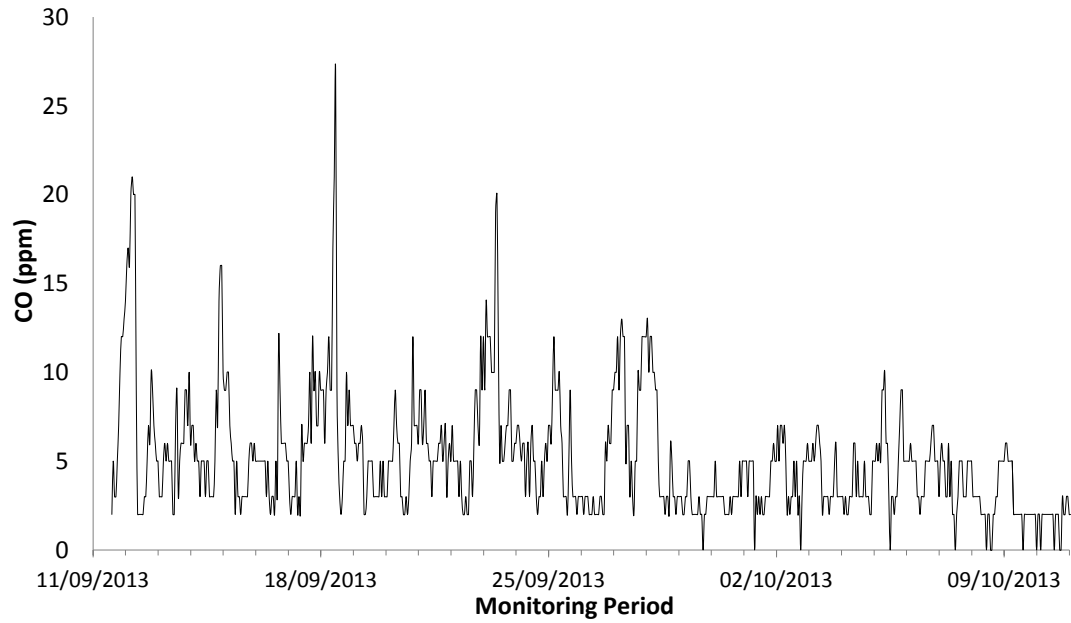
Figure 2 Site 3 wood chip store oxygen concentrations
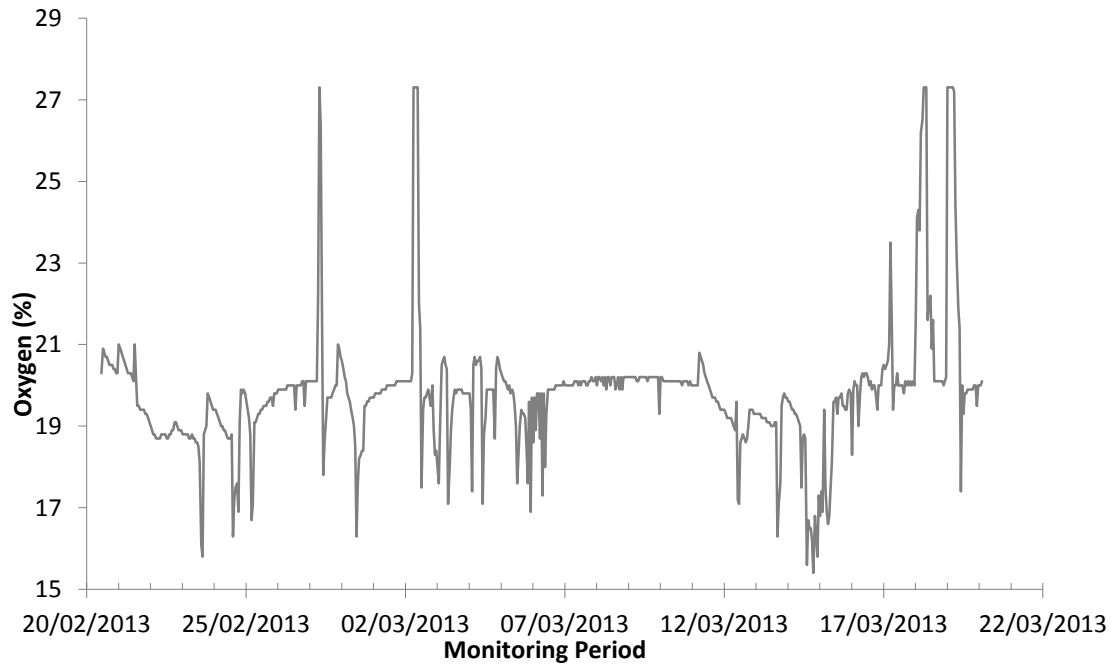
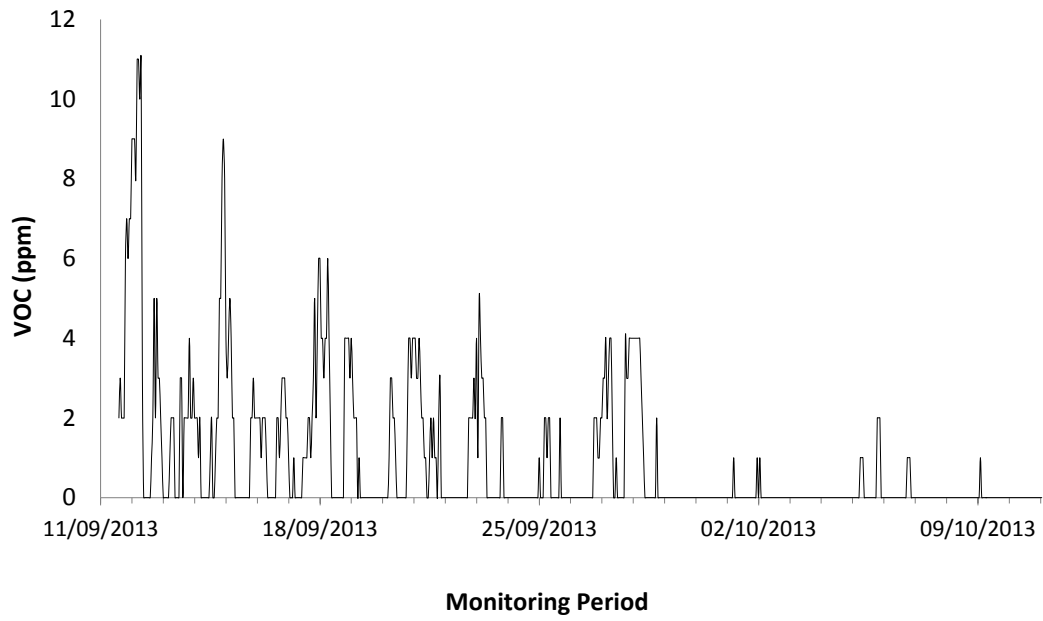**Figure 3** Site 4 - adjacent to fabric wood pellet silo - oxygen concentrations
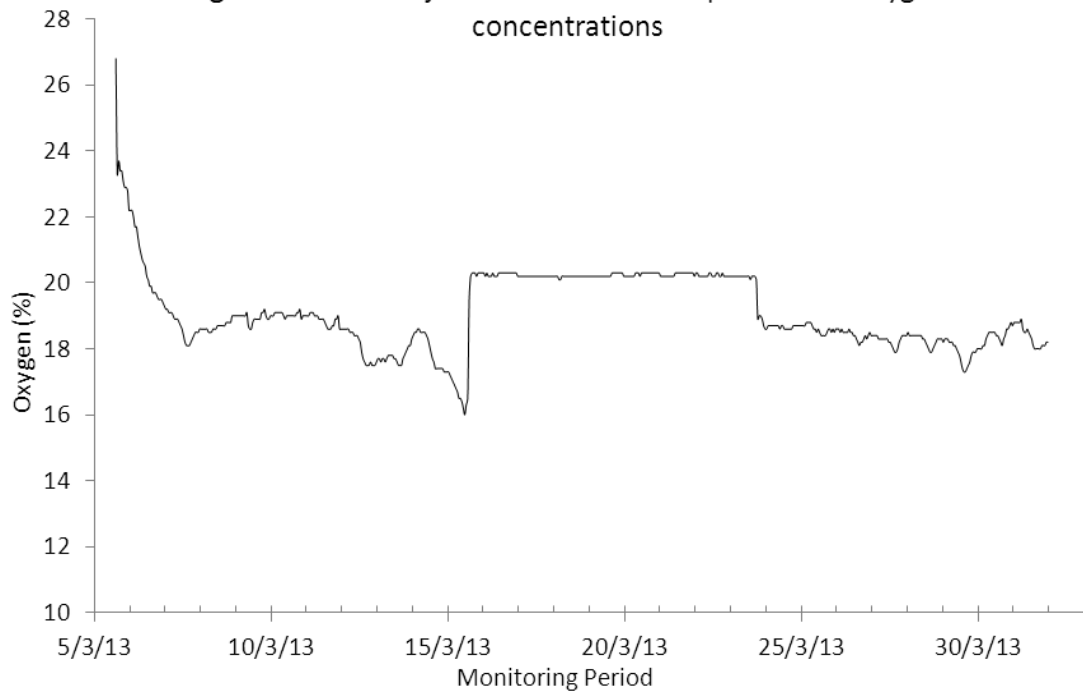
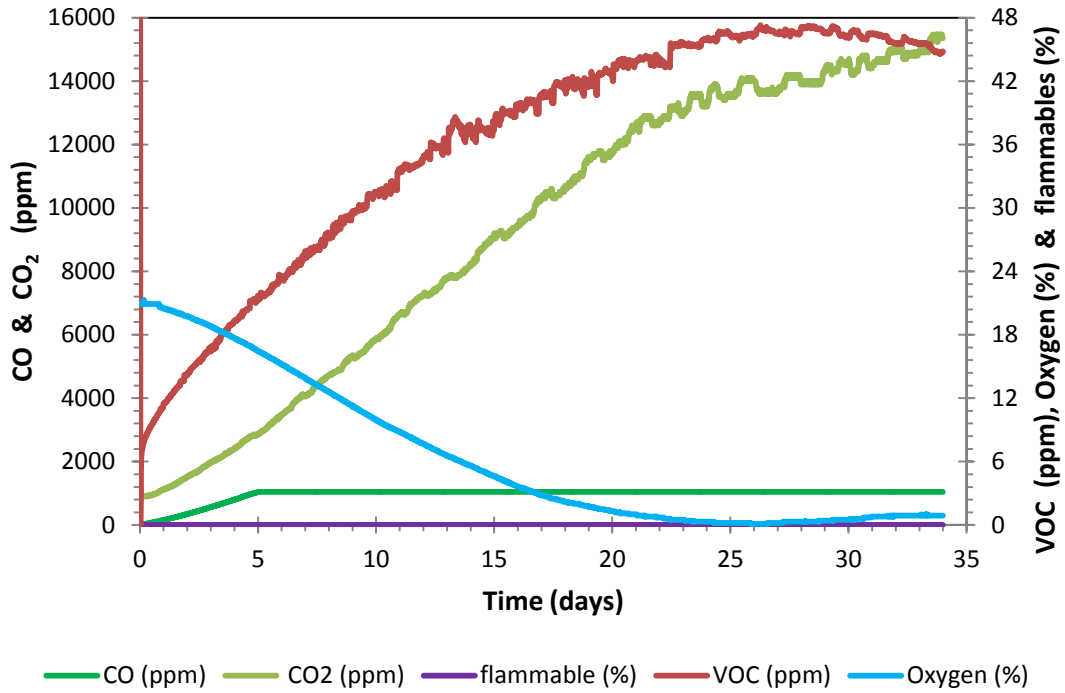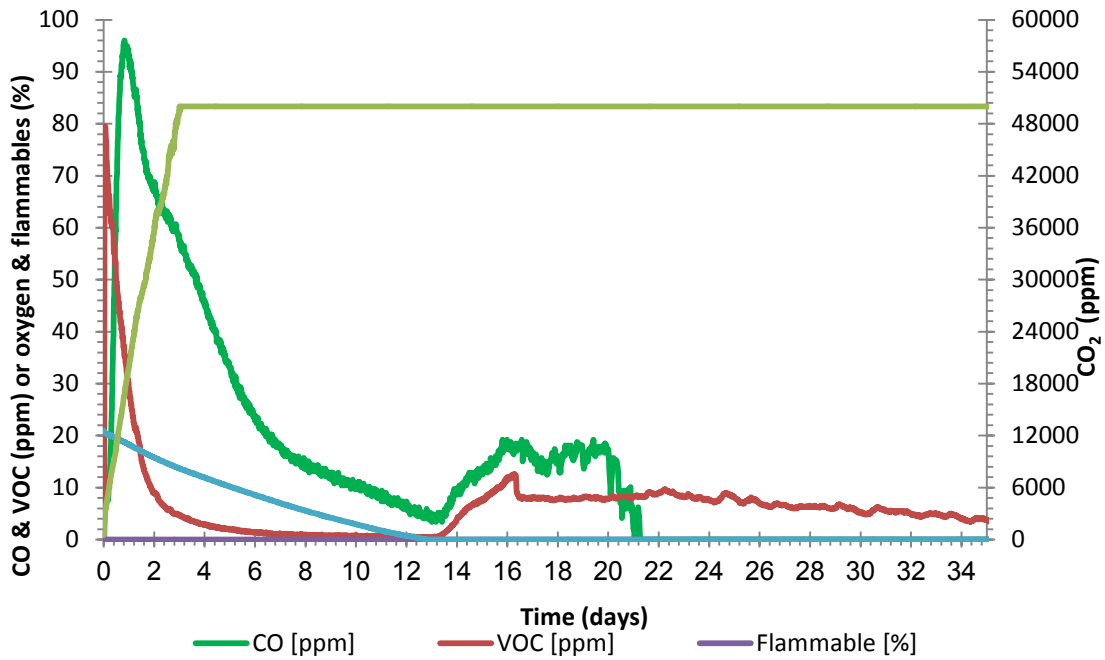**Figure 4** Site 3 wood chip store total VOC concentrations
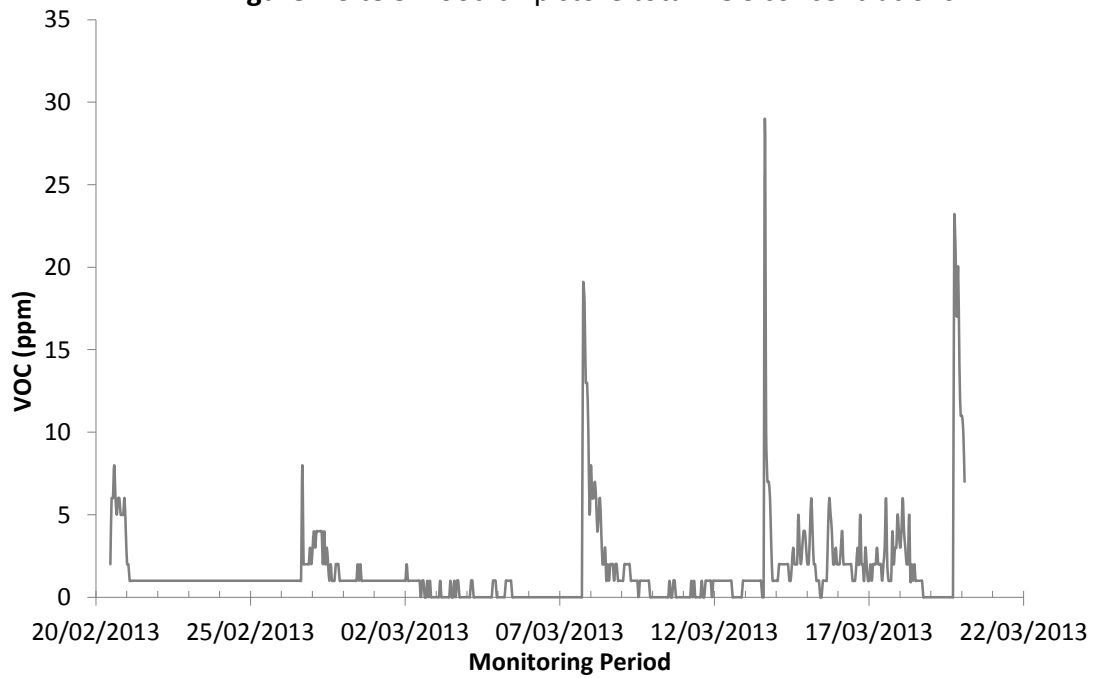
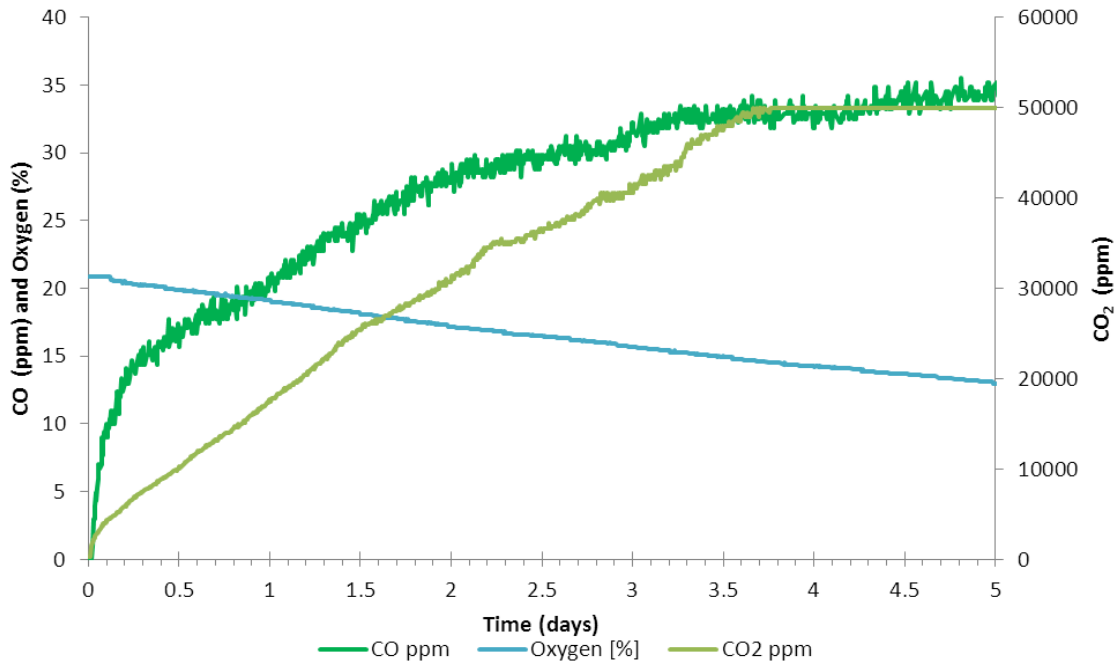**Figure 5** Site 7 wood pellet store total VOC concentrations

Figure 6 Laboratory monitoring of air composition above wood pellets

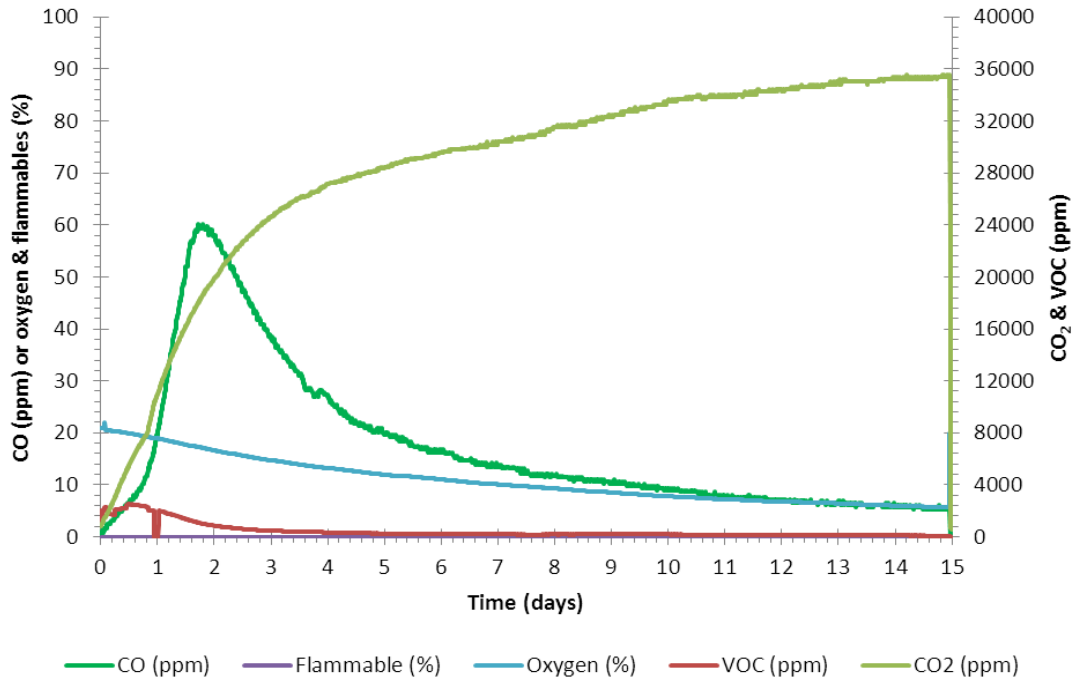CO (ppm) —— CO2 (ppm) —— flammable (%) —— VOC (ppm) —— Oxygen (%)

Figure 7 Laboratory monitoring of air composition above wood chip
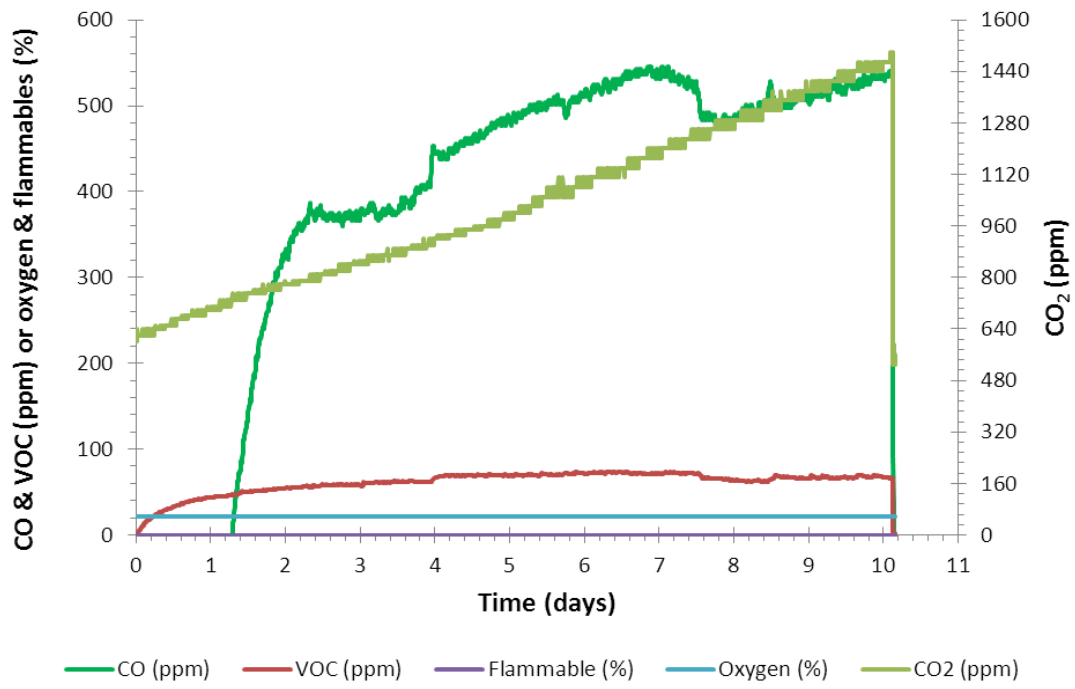

CO [ppm] —— VOC [ppm] —— Flammable [%]

Figure 8 Resumption of monitoring of air composition above wood chip

Figure 9 Laboratory monitoring of air composition above undried wood chip

Figure 10 Laboratory monitoring of air composition above dried wood chip

APPENDIX C. GASEOUS EMISSION FACTORS

The laboratory based measurements can be used to estimate the concentrations of emitted gases from similar wood pellets or chips that could occur in storage areas with comparable conditions, by calculating a gaseous emission factor, f (dimensions of milligram gas per kilogram wood material), and estimating the mass of wood stored, and the air volume in the storage area, then allowing for either still air, or taking in to account the air exchange rate of the storage area.

The gaseous emission factor can be calculated by:

$$f = 10^6 \times \frac{C_g V_g \rho_g}{M_w}$$

Where:
C_g is the maximum gas concentration (ppm) ideally measured when steady-state occurs,
V_g is the total gas volume in the container (m^3),
ρ_g is the density of gas assumed to be the same as air density, 1.2 kg/m^3, and
M_w is the mass of wood material (kg).

V_g is equal to the container volume (60 litre) less the total volume of wood material. The volume of wood can be calculated from its weight and density. For wood pellets, the density was calculated as the average value of the measured weight of single wood pellets divided by their measured volume. For the mixed species and irregularly shaped wood chips, the density was estimated from literature values. However, only densities for dry wood could be found, therefore the maximum was chosen as this is more likely to match that of the average density of the non-seasoned wood chips.

However, in a number of tests, reliable measurements of steady state emissions were not made, either because the gas concentration exceeded the sensor concentration range or because of the uncertainty caused by the high humidity. Nevertheless, an indication of the lower limit for f for those measurements that exceeded the sensor ranges and an indication of the maximum carbon monoxide emission factor for wood pellets can be calculated. Additionally, it is possible to make an estimate of the oxygen consumption from the minimum oxygen concentrations and assuming that these were achieved from an initial concentration of 20.9%. The results are shown in Table 14.

The carbon monoxide emission factor for wood pellets was found to be >1.6 mg/kg compared to that of 12.4 mg/kg found by Kuang et al (2008). The carbon monoxide emission factor for undried wood chips (1.1 mg/kg) was smaller than that for wood pellets, but dried wood chips had a larger emission factor (11.4 mg/kg).

The carbon dioxide emission factor (21.8 mg/kg) for wood pellets was similar to that of 20 mg/kg found by Kuang et al (2008) for wood pellets at 20°C, but considerably smaller than the figure for wood chip (650 mg/kg).

The oxygen consumption factor was significantly larger for undried wood chip (1042 mg/kg) than for wood pellets (295 mg/kg).

Safe storage of wood pellet and wood chip fuel

Wood pellet and wood chip boilers are used in homes, community buildings, and businesses as a renewable energy alternative to oil or gas fired boilers. They are also increasingly being considered for use in large scale power generation.

Outside the UK, there have been at least nine fatalities since 2002 in Europe caused by carbon monoxide poisoning following entry into wood pellet storage areas.   This report describes a study, involving seven site visits, to develop evidence to inform HSE engagement with the industry on the prevention of carbon monoxide poisonings.

The study confirmed that potentially dangerous atmospheres may be generated in both wood pellet and wood chip storage. The study found that: knowledge of the hazards associated with these fuels, including confined space entry, was limited at sites operating small boiler systems; there had been limited communication of the health and safety issues between companies supplying and maintaining boilers, those manufacturing and supplying fuel, and users; and that while an HSE Safety Notice had raised awareness generally, not all the recommendations had been taken up at individual sites.