

This publication focuses on the health and safety issues of the supply chain of solid biofuels with the objective to highlight commonly used mitigation methodologies to promote a better working environment when dealing with solid biofuels. It has been compiled as a joint effort by experts active in Tasks 32, 36, 37 and 40 of the IEA Bioenergy Agreement, with their own specific fields of expertise. Only through this cooperation, it was possible to touch upon the full range of issues in one publication that one may come across when developing projects in which solid biomass fuels are produced, traded or used.

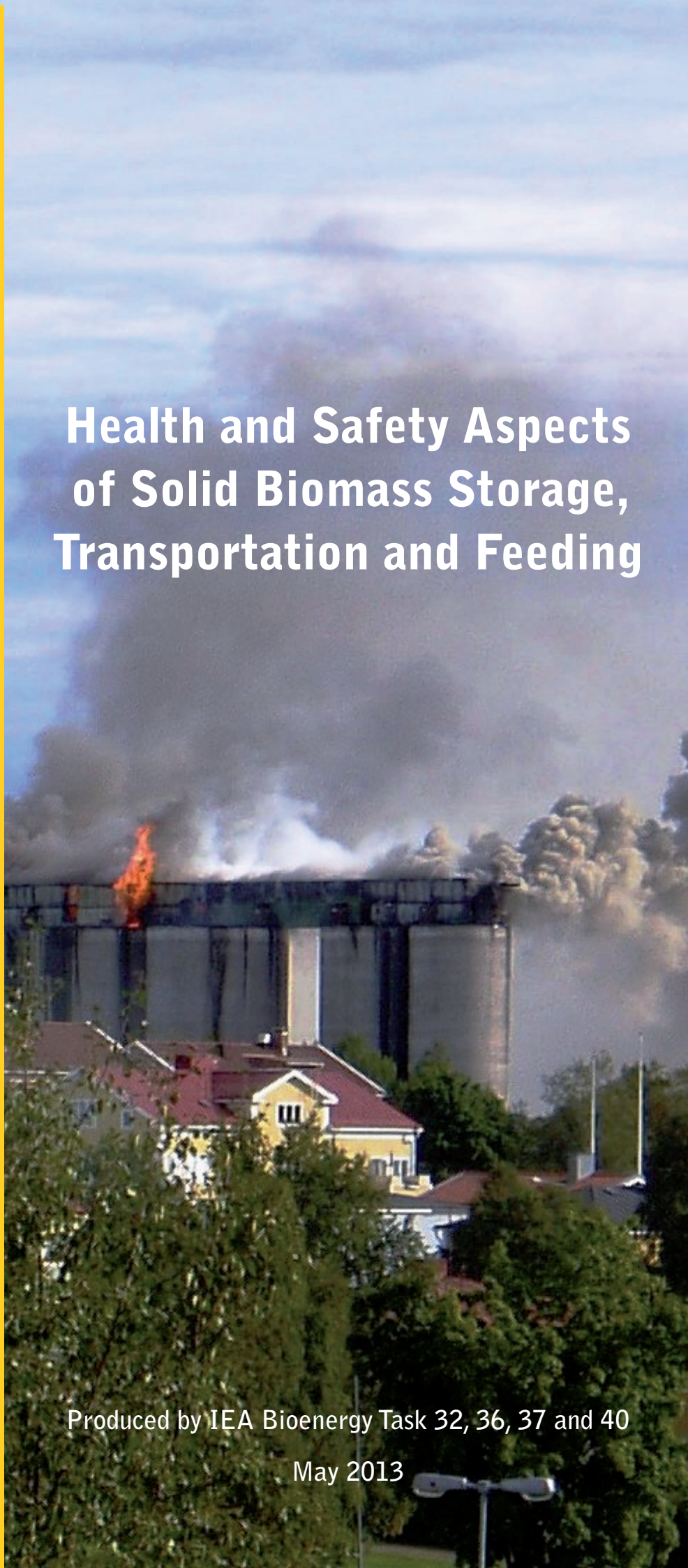
The properties of a biomass material and the intended use determine how the material should be safely transported and stored. Self-heating, off-gassing and dust explosions are significant challenges for the industry that have already resulted in significant losses of capital investments and even tragic loss of life. Likewise, exposure to biologically active material, such as moulds and spores may form a serious hazard for the health of workers involved. With the growth of the bioenergy sector, it is important not only that opportunities for bioenergy are implemented in an efficient and economic manner, but also safely.

Health and Safety Aspects of Solid Biomass Storage, Transportation and Feeding

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HEALTH AND SAFETY ASPECTS OF SOLID BIOMASS STORAGE, TRANSPORTATION AND FEEDING

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PREFACE

The rapid increase in the production and use of various types of biomass as energy carrier also leads to an increase in handling and storage activities throughout the supply chain. Biomass is a broad description of many materials with different chemical composition, moisture content and physical characteristics, each requiring special attention in order to comply with safety and health regulations. Some types of biomass used today such as wood pellets) are commercialized as biofuel commodities traded around the globe, while others are under-going intense research to explore the potential for commercial use.

The properties of a biomass material and the intended use determine how the material should be safely transported and stored. Self-heating, off-gassing and dust explosions are significant challenges for the industry that have already resulted in significant losses of capital investments and even tragic loss of life. Likewise, exposure to biologically active material, such as moulds and spores may form a serious hazard for the health of workers involved. With the growth of the bioenergy sector, it is important not only that opportunities for bioenergy are implemented in an efficient and economic manner, but also safely.

IEA Bioenergy recognises the importance of safe production, trade and utilisation of a growing amount of biomass fuels. This publication focuses on the health and safety issues of the supply chain of solid biofuels with the objective to highlight commonly used mitigation methodologies to promote a better working environment when dealing with solid biofuels. It has been compiled as a joint effort by experts active in four different Tasks within the IEA Bioenergy Agreement, with their own specific fields of expertise. Only through this cooperation, it was possible to touch upon the full range of issues in one publication that one may come across when developing projects in which solid biomass fuels are produced, traded or used.

Although this publication does provide the reader with significant understanding of the relevant safety issue as well as several guidelines for handling, storage and transportation, it is important to realize that differences in material also lead to differences in risks and needs for safety measures, and every individual situation needs to be carefully assessed. The topic also remains important as new biofuels enter the market.

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EXECUTIVE SUMMARY

With the continuous growth in production and utilisation of solid biofuels, an increasing number of incidents have taken place related to the handling of the biofuels, resulting in affected personnel due to injuries, infections, intoxications etc. resulting in illness or tragic loss of life, or severe material damage due to dust explosions, fires etc. This report has been written by various experts that are active in the IEA Bioenergy agreement, to provide the reader with an understanding of the causes, effects and mitigation measures overview of the issues.

The properties of a biomass material and the intended use determine how the material should be safely produced, transported, stored and used. While woody biofuels such as pellets and chips from fresh or recycled wood dominate the market in terms of volumes, other solid biofuels such as straw, biodegradable fuels used for anaerobic digestion and municipal solid waste pose specific health and safety challenges that need to be addressed.

Self-heating processes may be due to biological metabolic reactions (microbiological growth), exothermic chemical reactions (chemical oxidation) and heat-producing physical processes (e.g. moisture absorption), and it may occur both for dry and wet biofuels. It may become problematic if a pile or silo is so large that the heat generated cannot be easily dissipated to the surroundings. While this is not the case for relatively small scale installations as e.g. used by households, it needs attention for larger industrial storages. Several test methods are available for determining self-heating potential and self-ignition of materials on small scale, which can then be extrapolated to predict self-heating potential at larger scale. Apart from self-heating, biomass stock may be set on fire through various external sources such as hot bearings, overheated electric motors, back-fire, etc.

Several conclusions can be drawn from the full scale silo fires that have already taken place. The most important prevention measure to take is temperature monitoring of

the storage at several different locations in the fuel bulk. For detection of any activity of the bulk, CO concentration should be measured in the air above the pellet surface. The first sign of an on-going self-heating process is often a sticky and irritating smell (probably from aldehydes and low molecular carboxylic acids). If this is sensed, there is already pyrolysis taking place somewhere in the fuel bulk and a fire fighting operation has to be initiated. Such fire fighting strategy needs to be determined case by case and requires specialised fire fighting equipment and trained staff. Water should not be used in case of wood pellets, due to rapid expansion of the pellets (hindering the extinguishing operation and subsequent unloading of the silo) and the formation of explosive H₂ through water gas shift reactions. A silo fire is usually extinguished by inerting the closed silo from the bottom, after which fuel is discharged from an opening in the silo wall.

Off-gassing is the process where volatile organic compounds are released in the logistical chain. One mechanism is the initial release of lipophilic compounds, yielding carbonyl compounds (aldehydes and ketones) and also complex terpenes. CO, CO₂ and CH₄ may also be released. The concentrations of aldehydes found in domestic sites and warehouses constitute a health hazard and require attention and preventative measures to be taken. Hexanal may enter the body by contact with skin or by inhalation and cause skin irritation, headaches, and discomfort on the eyes and nose. Other aldehydes such as methanal and ethanal are suspected to be carcinogenic in high doses and may also have some short time effect on human health. There are several guidelines issued by government official institutes that describe the effect these aldehydes have on human health depending on exposure time and level. Monoterpenes (particularly present in fresh raw material) cause eyes and respiratory system irritation. CO may be released from the auto oxidation of lipophilic compounds. Related hazards are predominantly poisoning, but it may also contribute to self heating or ignition processes. A combination of proper

ventilation, gas meters and the use of self-contained breathing devices is needed in areas where the levels of CO might increase to poisonous concentrations.

Dust clouds are a major cause of damage in the bioenergy sector. The combination of relatively small particle sizes and low minimum ignition energy results in a high ignition sensitivity. Significant amounts of factory dust may stay suspended in the air, so that the Minimum Explosible Concentration is easily reached under practical conditions if cleaning and ventilation are not done sufficiently. It is therefore important to minimize the risk of dust explosions, by minimizing the risk of sparks (e.g. due to electrostatic discharge through proper grounding) and good dust housekeeping through dust prevention and dust collection. Once an explosion takes place, it needs to be properly contained, suppressed or vented. Compliance with ATEX Directives and NFPA guidelines is essential in this respect.

The health risks posed by biomass fuels in the form of dusts and bioaerosols come from both the physical particle and size effects. As particles become smaller they pose a greater hazard. As a result limits on PM₁₀ and PM_{2.5} (particles less than 10 µm or 2.5 µm respectively) are becoming more prevalent in national regulations. In addition the organic nature of biomass fuels may result in additional impacts through either allergenic or pathogenic routes. The most prevalent feature will be the allergenic responses and the majority of the effects will be minor and short lived; but increasing severity of impact will also be linked to falling incidence of response. In the same way pathogenic responses will be a rare occurrence, but potentially result in severe hazards.

The biological materials released from biofuels are similar to the naturally occurring background levels and the human population are equipped with bodily responses to deal with this natural environmental exposure. This

natural bodily response and the degree of variation in individual sensitivity makes the determination of dose response relationships particularly difficult. Without this level of understanding it is difficult to ascribe definite limits and regulations that are "safe" for the population at large whilst also protecting the population from hazards that derived from the alternatives to biofuel use (e.g. climate change, fossil fuel emissions, fuel poverty). Thus this area is generally governed by guideline values and recommendations to minimise exposure rather than definitive limits that are derived from hard scientific data.

The potential health impact of bioaerosols from waste management processes is relatively low for waste collection, transfer and sorting. Whilst it can be moderate for open microbial processes such as composting (particularly during movement and unloading of material) due to pathogenic microorganisms and microbial constituents or metabolic products, such as organic dust and endo-toxins, the risk is relatively low in the case of anaerobic digestion where processes are contained and the product is often hygienised. The risks are generally airborne, and therefore likely to occur through inhalation of bioaerosols, but there are also ingestion risks, often through hand-mouth contact or from infection of wounds.

Trauma and sharps injuries are the most common recorded cause of accidents and injury in the forestry and waste management sectors and we have assumed that these also affect workers in the bioenergy and energy from waste parts of these sectors. The serious nature of some injuries and the number of injuries means that there has been a lot of work to reduce injuries and in most countries there are established obligations and guidance. Rather than comprehensively reviewing this legislation we have provided an introduction with references, providing an insight into the risk evaluation and mitigation methodologies available at international and national level.

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TERMINOLOGY USED

Absorbancy

measure of the amount of water absorbed by the wetted material expressed as percent of the original weight of the material (dry basis)

Adsorption

phenomenon whereby atoms, ions, or molecules from a gas, liquid, or dissolved solid adheres to a surface. The process creates a film of the adsorbate on the surface of the adsorbent

Angle (critical angle) of repose

steepest angle of descent measured in degrees of the slope of material relative to the horizontal plane when granular material on the slope face is on the verge of sliding. The slope may be the convex perimeter of a conical pile or a flat slope depending on the shape of the pile

Angle (critical angle) of drain

Steepest angle of descent measured in degrees of the slope of material relative to the horizontal plane when granular material on the slope face is on the verge of sliding. When biomass is held in a silo or hopper and drained through a gate at the bottom the material is usually forming a cone within which the material, especially material with high particle aspect ratio such as pellets, partially becomes interlocked before released by the forces of gravity. The angle of drain is normally a few degrees higher than the angle of repose

Condensable gas

gas which is going through transition from gaseous to liquid or solid state at a certain temperature. The process is reversible but not necessarily at the same temperature such as most of the hydro-carbons from biomass

Non-condensable gas

gas which does not go through transition from gaseous to liquid or solid state at normal temperature ranges such as carbon monoxide, carbon dioxide, methane from biomass

Explosibility

propensity by gaseous, liquid or solid material to ignite and violently transform to high pressure gas while emitting sound and light and normally followed by fire

Explosion (primary and secondary)

violent event emitting sound and light immediately followed by fire. An initial explosion followed by fire may dislodge dust deposited on beams, floor, machinery etc. and igniting this material resulting in a secondary explosion, usually a few seconds after the first explosion. Thermal energy is transferred from the first to the second explosion through deflagration

Detonation

violent event generated by sudden expansion of gas into a supersonic shock wave (molecular speed higher than the speed of sound) not followed by fire

Deflagration

violent event describing subsonic combustion propagating through thermal conductivity by means of hot burning material (usually dust) heating the next layer of cold material and igniting it in consecutive sequence. The process can be characterized as an exploding fire whereby the burning material partly deposits on surfaces in its path and causing significant damage and injuries

Deflagration index

a measure in bar meter per second and a product of the pressure rate and propagation of an explosion as established by testing standards

Desorption

phenomenon whereby a substance is released from or through a surface. The process is the opposite of sorption

Dust

fragmented material of small size caused by a non-voluntary process as opposed to powder or meal which is normally manufactured to size. There is no official definition of what constitutes dust in terms of physical size. Dust from some material smaller 430 micron is considered explosive by OSHA in USA (see also Fines)

Flammability

propensity by gaseous, liquid or solid material to catch fire upon exposure to ignitable external source. For solids like dust from biomass the flammability is determined by testing method establishing the speed of burning in mm per time unit

Flash point

propensity by vapour of a material to ignite under atmospheric conditions in the presence of a thermal source at a temperature and as determined by testing method. A lower flash point temperature indicates higher flammability. Material with flash points below 100 °F (38 °C) are regulated in the United States by OSHA as potential workplace hazard

Heat Rate

measure of the number of heating units expressed in kJ required to generate output energy expressed in MWh (a ratio kJ/MWh). Used to express thermal efficiency of thermal conversion facilities such as power plants

Hygroscopicity

propensity of material for moisture sorption (relative humidity in the air) from the surrounding atmosphere through a combination of adsorption, absorption and desorption

Hygroscopic

characteristic of material with propensity to adsorb or absorb moisture from the air

Hydrophobicity

propensity to repel water when in contact

Hydrophobic

characteristic of material with propensity to repel water

Hydrophilicity

propensity to attract water when in contact

Hydrophilic

characteristic of material with propensity to attract water

Off-gassing

spontaneous emission of condensable and non-condensable gases such as carbon monoxide, carbon dioxide, methane, hydrocarbons from biomass

Permeability (bulk permeability) in storage

ability of gas such as air to pass through the void in biomass during storage. Permeability is measured in $\text{m}^3/\text{s}/\text{m}^2$ and depends for example on the viscosity of the gas (including moisture content and temperature) and the bulk porosity of biomass

Sorption

phenomenon whereby a substance is absorbed or adsorbed through a surface or adsorbed on a surface. The process is the opposite of desorption

Wettability

ability of a liquid to maintain contact with a solid surface, resulting from intermolecular interactions when the two are brought together. The degree of wetting (wettability) is determined by a force balance between adhesive and cohesive forces

ABBREVIATIONS USED

ACGIH	American Conference of Governmental Industrial Hygienists
AD	Anaerobic Digestion
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
ATEX	ATmospheriques EXplosives, used for two European Directives related to protection of workers from explosion risk in areas with an explosive atmosphere
BSFSC	British Columbia Forest Safety Council
CAFS	Compressed Air Foam System
CEC	Canadian Electrical Code
CENELEC	The European Committee for Electrotechnical Standardization (CENELEC)
CFR	US Code of Federal Regulations
CO	Carbon Monoxide
COHb	carboxyhemoglobin
DC	Direct Current
DNPH	dinitrophenylhydrazine
DSEAR	Dangerous Substances and Explosive Atmospheres Regulations. The implementation of the ATEX code in UK
EL	Exposure Limit
EMC	Equilibrium Moisture Concentration
EN	Norme European (French), or European Standard
ES	Explosion Severity
FID	Flame Ionization Detector, for measurement of organic species in a gas stream
FTIR	Fourier transform infrared spectroscopy
GS-MS	Gas Chromatography – Mass Spectroscopy
HPLC	High Pressure Liquid Chromatography
HSE	UK Health and Safety Executive
IARC	International Agency for Research on Cancer
IEC	International Electrotechnical Commission
IMO	International Maritime Organization
IR	Infrared
IS	Ignition Sensitivity
ISO	International Organization for Standardization
Kst	Deflagration Index [Bar m/s]. Constant expressing the maximum pressure increase per time unit dP/dt_{max} if an explosion were to take place in a fixed volume of 1 m^3 .
LEL	Lowest Explosion Limit
LOC	Limiting Oxygen Concentration [%]
MBT	Mechanical Biological Treatment
MEC	Minimum Explosible Concentration [g/m^3]
MHB	Materials Hazardous in Bulk
MHT	Mechanical Heat Treatment
MIE	Minimum Ignition Energy [mJ]
MSB	the Swedish Civil Contingency Agency
MSDS	Material Safety Data Sheet

NEC	National Electrical Code. Standard issued by NFPA
NFPA	US National Fire Prevention Association
NIOSH	National Institute for Occupational Safety and Health
NMAB	US National Materials Advisory Board
OSHA	US Occupational Safety and Health Administration
PEFC	Programme for the Endorsement of Forest Certification
PEL	Permissible Exposure Limit
PPE	personal protective equipment
ppm	parts per million
REL	Recommended Exposure Limit
SCBA	self-contained breathing apparatus
SHS-GC	Static Head Space Gas Chromatography
SOP	standard operating procedures
SPME	Solid Phase Microextraction
STEL	Short Term Exposure Limit (usually during 15 minutes)
SYP	Southern Yellow Pine
TLV	Threshold Limit Value
TWA	Time Weighted Average
USBM	US Bureau of Mines
USEPA	U.S. Environmental Protection Agency
UNMTC	UN Manual of Tests and Criteria
VOC	Volatile Organic Compound
WPAC	Wood Pellet Association of Canada
wt% (w.b.)	mass percentage on wet basis

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1 INTRODUCTION

With the increasing amounts of biomass being produced, traded and used for energy, it is becoming increasingly important to implement the supply chains in a safe manner. This publication covers the health and safety aspects of various solid biofuels that are commonly traded for various thermochemical and biological applications, varying from small scale combustion devices to large scale power plants, as well as anaerobic digestion plants.

The types of biomass used today vary broadly in chemical composition, moisture content and physical characteristics. The properties of a biomass material and the intended use determine how the material should be safely transported and stored. Some of the key risks are associated with self-heating, off-gassing, dust explosions and exposure to biologically active materials. Regretfully various incidents have already happened that have resulted in loss of production, capital investments and even loss of life.

This publication focuses on the health and safety issues of the supply chain of solid biofuels with the objective to highlight commonly used mitigation methodologies to promote a better working environment when dealing with solid biofuels. Although it touches upon the full range of health and safety related issues in the production, trading and utilisation of solid biofuels, it is impossible to cover every individual aspect in great detail for every circumstance; therefore the reader is sometimes referred to other literature, standards etc. for more information.

After this introduction and a definition of the biomass types covered in report (chapter 1), this report describes the cause and mitigation measures for various hazards in individual chapters as follows:

- Hazards from self-heating and fire (chapter 3)
- Off-gassing from lignocellulosic biomass (chapter 4)
- Dust and gas explosions (chapter 5)
- Biological health risks (chapter 6)
- Hazards from sharps and trauma (chapter 7)

Finally, chapter 8 describes the occupational hazards in transporting solid biofuels.

2 DEFINITION OF BIOMASS AND SOLID BIOFUELS

The coverage of this report is solid biofuels, which implies directly that gaseous and liquid biofuels are excluded. In accordance with a collaborative agreement made October 15, 2010 between CEN/TC 335 and ISO/TC 238 new standards will be developed under ISO in order to increase the applicability of standards internationally but will be published as ISO-EN Standards. ISO/TC 238 is also in the process of incorporating standards specifically for safety and health when handling and storing solid biofuels. Biomass in accordance with ISO/TC 238 is "material of biological origin excluding material embedded in geological formations and/or transformed to fossil". Solid Biofuels in accordance with ISO/TC 238 is "solid fuels produced directly or indirectly from biomass".

Biomass used for production of solid biofuels in accordance with ISO/TC 238 is categorized in accordance with Table 1 in Appendix A (excerpt from ISO 17225-1 [90]). Biomass types such as food waste, manure, household garbage, municipal sewage waste are not included in the ISO/TC 238 classification standards, but as there are important unique safety and health measures, they are dealt with in this report.

Peat is not included in the ISO/TC 238 Standards at this time. Peat belongs to a separate class of fuel and is used extensively in Finland and to some extent in Sweden and Ireland for energy production and can be densified, handled and stored in a similar fashion as woody biofuels.

The ISO Standards do not restrict the use of biomass for use as solid biofuels. It is up to local authorities to regulate fuel selection and emission standards for conversion to energy. The performance of the equipment used for conversion to energy is to a large extent determining which solid biofuels can be used in a particular application and location. Issues such as sustainability, forest management and agriculture policies may also impact the selection of biomass.

The ISO Standards also include a broad specification of torrefied (mildly heat treated) biomass, which is expected to become a major commercial solid biofuel within the next few years. The process is of interest particularly for power production at large scale, since the torrefied material is similar to regular coal. The torrefaction treatment may also increase the quality of solid biofuels based on non-woody biomass, which may add extremely large volumes of fibre for production of solid biofuels.

2.1 Woody biomass

ISO Category 1 – Woody biomass includes forest, plantation and other virgin wood as well as by-products

and residue from the wood processing industry. There are also subcategories for chemically treated woody materials as well as blends and mixtures.

2.1.1 Refined wood fuels

Typical refined wood fuels are pellets and briquettes with low moisture content, high energy density and homogenous size and shape. These refined wood fuels started to be manufactured in large scale primarily in the 1980s in Sweden and USA and the quantity produced has increased every year since in Europe, North America and Asia to become an internationally traded commodity in a similar way to grain and other agriculture products produced in large bulk volumes. The oil price and the energy politics with environmental penalties for fossil fuels have affected this development towards larger production [104].

The development of refined wood fuels also means less handling for consumers compared to non-compressed biofuels. Other benefits of refined wood are a more constant quality and a more uniform geometry of the product. This has led to the development of automated systems, for example pellet burners in domestic homes. In addition problems with the fuel freezing together, substance losses, moulds etc. are minimal due to the low moisture content [104].

Large power stations are burning biofuels as a replacement for coal or in combination with coal using so called co-firing technologies.

The majority of wood pellets are produced by milling wood chips, bark, planer shavings or sawdust into a fine powder, which, after drying, is compressed into pellets. Typically wood pellets have a diameter of 6-8 mm and a length not exceeding 40 mm. The moisture content is usually between 6-10% and a gross calorific value around 20 MJ/kg (or net calorific value at constant pressure above 16.5 MJ/kg). The ISO 17225-1 Standard defines criteria such as diameter, length, density, moisture content and ash content for wood pellets [25, 98, 138, 173].

ISO 17225-3 defines the criteria for wood briquettes [25, 138].

2.1.2 Recycled wood

Recycled wood may consist of packaging wood, demolition wood and waste wood from building and construction activity. As this material comes from different origins it can sometimes be hard to maintain quality control of the product. High ash content and high concentrations of creosotes, arsenic, copper or other heavy metals can be a problem with some treated wood waste streams. On the other hand untreated recycled wood can be of good quality and low contamination. Therefore, the description of the recycled wood is important [104].

2.1.3 Purpose grown woody biomass

The use of purpose grown woody biomass (such as willow and poplar) for the production of solid biofuel is under development and it is possible this material will be used for production of pellets and briquettes. This could become a viable fuel complementing forest biomass in regions with low yield agriculture.

2.2 Non-woody biomass

ISO Categories 2/3/4 – Non-woody biomass is a group of materials that can be used as solid biofuels for production of heat and power.

Solid biofuels are also made from herbaceous, fruit and aquatic material. These biofuels are not yet common, but advanced research is currently being conducted with the objective of developing pre-treatment that allows compression to pellets and briquettes and facilitates effective handling, storage and combustion for energy conversion.

2.2.1 Kernels, seeds and shells

Of this source of biomass one of the most common fuels currently used are olive kernels, produced as a bi-product from olive oil manufacturing. The kernels, whole or crushed into smaller fractions, are usually mixed with other fuels before burning. The reason for only mixing a small amount of olive kernels (5-10%) with other fuels is the high alkali and ash content. Olive kernel fuel can both be dry (kernels only) or moist (kernels, residues of the fruit pulp, shell and even olive oil). Storage and handling of the dry fuel increases the risk for dust explosions, while storage of the moist fuel increases the risk for self-heating, mostly due to biological activity in the fuel.

Other examples of this group that have been used as fuels include cacao beans, citrus waste, shea nuts etc. These fuels are not so common, at least in northern Europe. The fuels are normally used in small amounts in combination with other wood fuels or coal. The risks with storage and handling of these fuels are the same as described for olive kernels above; dry fuels increase the risk for dust explosions, while storage of the moist fuel increase the risk for self-heating [73, 166].

2.2.2 Grain and straw biomass

Grains like wheat, rye, barley and oats are mostly used as fuels in smaller heat production units. Their use is not so common in large scale heat/energy production. The different grains have different combustion properties. Oats for instance have a softer core than the other grains and are thereby easier to ignite. Grains need to be stored in a dry environment, in silos for example [73]. The risk for self-heating in storage is not that critical. However, off-gassing can cause a toxic environment.

Straw can be used as fuel for heating purposes, both as it is produced or refined to pellets/briquettes. Straw is not a uniform fuel. Different types/sorts of straw have different

combustion properties. Parameters like geography and weather conditions also influence the quality of the fuel. Handling of straw or bales with straw can cause dust but that is more a work environment problem than a risk for dust explosions. The risk for self-ignition is not large either, but the risk of fire spreading in the dry straw is high if the fuel is ignited by an external source [73].

Many other types of straw are currently under tested for use as solid biofuels. These include switchgrass, canary grass, giant reed etc. Corn stover and bagasse are other high volume biomass materials currently used as solid biofuels.

2.2.3 Biomass for anaerobic digestion

Many types of biomass can be used for anaerobic digestion (AD) and the production of biogas and biomethane. Biomass can be either produced as an energy crop, or it can be a residue from food crops, a waste from food processing or a waste from animals or humans. Crops and crop residues are produced seasonally and therefore they are stored for year-round use in biogas plants. The main crops used are maize and a range of grasses and these are stored in silage clamps of various designs, all of which aim to exclude air that would result in significant degradation with respect to methane production potential. Residues including the stalks and leaves of cereal and legume crops are stored in similar manner for year-round use. Self-heating is not a significant problem with these forms of biomass and the manner of storage. Dust is also not a significant problem and can be readily managed.

Biological risks are associated with AD feedstocks derived from food residues and wastes and animal wastes such as manure and slurries. For example, bacteria may be present in and may also form during storage of AD feedstocks such as food waste [49]. It is common practice in the biogas sector to co-digest feedstocks, partly to ensure a stable AD process with high methane production, and partly to benefit from feedstock flexibility and reduced operating costs. Biological health and safety risks associated with a potentially wide range of biomass for AD feedstocks must therefore be taken into account.

2.2.4 Municipal Solid Waste and other types of waste

In addition to the relatively clean and well defined types of biomass listed above, there are various types of waste (such as municipal solid waste) that contain a biological component and may therefore contribute to generation of renewable energy. The main health and safety hazards associated with waste streams are related to biological health risks such as hazardous bacteria, fungi and moulds, but also trauma hazards related to injury from sharps is a significant and specific factor that needs to be dealt with.

3 HAZARDS FROM SELF-HEATING AND FIRE

Fires as a result of self-heating of solid biofuels are not uncommon, but fires can arise from many different sources: self-heating, friction, overheating, sparks, vehicle fires, arson. There is limited statistical information on ignition sources for the different types of solid biofuels.

In 2002, an investigation was carried out on fires at landfills in Sweden [152]. There are, of course, differences between waste and biofuels, both in composition and in how some of the material is handled. The storage and handling processes are, however, in some cases relatively similar and some plants handle both waste and solid biofuels. The investigation from 2002 gave the following ignition sources: self-heating (38 %), embers from incoming material (17 %), arson (13 %), sparks from vehicles (6 %), landfill gas (1 %) and unknown (25 %). Some of these sources are not so relevant for solid biofuels, but a comparison could still be interesting.

In 2012 two projects started that are of importance for this field: the EU project SafePellets and a Swedish project financed by the Swedish Fire Research Board. In both cases SP is responsible for collecting and analysing statistics and information from incidents and fires in connection with storage of pellets (SafePellets) and other solid biofuels and waste. The aim of the work is both to update the investigation from 2002 and to broaden the study to include the storage of biofuel.

Fire risks with wood pellets have been studied extensively by SP Technical Research Institute of Sweden [46-48, 109, 142-145], while gas emissions have been studied by the Swedish University of Agricultural Sciences (SLU) [34, 35]. This work has formed the basis for much of the text and advice in the sections below. Work by SP has been included in a Nordtest guideline for storing and handling of solid biofuels, NT ENVIR 010 [134]. In a number of cases advice and recommendations have been extracted from NT ENVIR 010, which is gratefully acknowledged.

3.1 Self-heating

Self-heating is a well-recognized problem, which has been observed for many different materials and in different situations. The most well-known material prone to self-heating and spontaneous combustions is probably oily rags. However, any material that can either decompose or be oxidized by air can exothermically reach spontaneous combustion [39]. Self-heating can be seen as the first step in a process that might finally result in spontaneous combustion. Babrauskas [39] defines these steps as:

1. Self-heating: an increase in temperature due to exothermal reactions in the fuel.
2. Thermal runaway: self-heating which rapidly accelerates to high temperatures
3. Spontaneous combustion: visible smouldering or flaming by thermal runaway.

This means that by these definitions spontaneous combustion could, but does not have to, mean open flames. Open flames can develop when the reaction front reaches a surface open to air or when gases produced in the bulk material mix with air in the head space of the silo and ignite. Open flames are seldom present inside the pile of material since the channels present in the porous material are normally smaller than the quenching diameter. Since the spread of the reaction front is affected by the availability of oxygen, the spread is not always symmetrical, but follows the oxygen, which can lead to strange smouldering patterns in a pile of material. Due to the importance of the relationship between the heating and cooling processes, self-heating would be most pronounced in the centre of a pile but, if the material is non-homogenous or the availability of oxygen is non-symmetrical, the self-heating can occur in regions that are not at the centre. If storing material in a pile, there is a risk of development of open flames when material is removed from the pile, allowing oxygen to come closer to the parts where a smouldering process might be occurring.

In materials prone to self-heating, the self-heating process occurs throughout all of the material. The temperature rise is then controlled by the removal of heat. The heating processes increases with increasing temperature, but there are also different processes active in different temperature ranges (see e.g. Section 3.1.1). A system where the ambient temperature is such that the temperature of the material will increase until ignition (if nothing is changed) is called a supercritical system. A system where the ambient temperature and other conditions are such that the cooling is larger than the generated heat is called a subcritical system. This means that increasing thermal conductivity or decreasing the heat of reaction will decrease the propensity for self-heating. The processes, however, depend differently on the dimensions of the storage. The generation of heat is proportional to the volume of the material, while the cooling is proportional to the exposed surface area. Therefore, the self-heating tendency is proportional to the volume/surface ratio.

Self-heating problems in connection with storage of hay and other agricultural products have been known for a long time, were studied scientifically in the 18th century and are also relevant for solid biofuels [39]. Self-heating in biomass is a well-recognised phenomenon [102] although the chemical process involved is not well understood, particularly for pellets. The hammer milling of the raw material during manufacturing of pellets opens up

the cell structure and exposes the cellulose, hemicellulose, lignin and the extractives (including the unsaturated fatty acids) to oxidation, which are believed to be the primary cause of off gassing. Oxidation takes place above 5 °C and generates heat, non-condensable gases (mainly CO, CO₂ and CH₄) plus a number of condensable gases (e.g. aldehydes and ketones). The higher the temperature is, the higher the rate of off gassing becomes [98].

The materials are generally porous and susceptible to heat generating processes from biological metabolic reactions (microbiological growth), exothermic chemical reactions (chemical oxidation) and heat-producing physical processes (e.g. moisture absorption) and are thus prone to self-heating and spontaneous ignition. These three processes can act alone or in combination, where the dominating process depends on the conditions, e.g. temperature and moisture content. The oxidation reactions involved take place on the surface of the material particles (involving solid phase reactions) meaning that the problem of self-heating and spontaneous combustion arises for porous material with a large surface area to volume ratio. Cell respiration can continue for some time after harvesting, as an exothermic process. This process stops if the material is dried and will not restart when rewetted. Oxidation of fatty acids in sawdust and other moist fuels is accelerated by microbial activity with mesophilic bacteria and fungi up to approximately 40 °C and by thermophilic bacteria up to approximately 70 °C. Above this temperature chemical oxidation becomes dominant and further raises the temperature, in many cases up to an uncontrolled temperature range.

As mentioned above, self-heating occurs in many different materials (e.g. most organic substances, agricultural products, and foodstuff), but it becomes a problem only if the generated heat cannot be transported away without increasing the temperature in the material. This cooling process is dependent on the properties of the material, the size and shape of the storage and the ambient conditions.

The humidity of the material can affect the self-heating risk in different ways. For high water contents the water will either absorb heat or evaporate to such extent that the self-heating is limited. At the other end, increasing the water content above approximately 16 % can start biological processes [97]. More information on these processes is given in Section 3.1.1. For dry materials, addition of water leads to temperature rise due to the heat of adsorption/condensation. The reasons could be a leakage of rain water in the roof or that the bulk storage is cooled by forced ventilation using air with high humidity. The thermal conductivity of porous material is significantly affected by the moisture content, especially for material at temperatures 60 °C to 100 °C [39].

It is important to realize that different types of solid biomass fuels, e.g. different types of biomass



Figure 3.1. A stack of freshly produced pellets in a flat storage where the pellets have elevated temperatures due to self-heating of the pellets. The “smoke” visible on the picture is probably a combination of water moisture and various gases (off-gassing); (courtesy of Ingvar Hansson, Swedish Civil Contingencies Agency)

pellets, behave very differently when it comes to self-heating and off-gassing when stored. There are several ongoing projects dealing with self-heating and off-gassing in connection with storage of pellets, e.g. the Danish research project LUBA- Large Scale Utilization of Biopellets for Energy Application [109] and the EU project SafePellets (Safety and quality assurance measures along the pellets supply chain). The fact that both dust formation, off-gassing and self-heating are important safety issues has drawn the attention to the ISO standardisation work on solid biofuels and in ISO TC238/WG4, there is a discussion to include these issues in their scope of work.

Smouldering fires inside a silo might appear harmless as there are usually no flames visible. However, the silo headspace might be filled with high concentrations of flammable combustion gases (CO , unburnt hydrocarbons) which can cause severe explosions. Figure 3.2 shows a real silo explosion which occurred in a silo when an attempt was made to extinguish the fire via a hatch at the silo top using CO_2 . The cause of ignition was probably sparks due to static electricity at the CO_2 nozzle.

3.1.1 Self-heating of moist solid biomass fuels

Wood pellets are made from sawdust (sometimes including bark), which is first naturally dried and/or dried in a thermal dryer from a moisture content exceeding 50 % to a moisture content of 10-15 % before pelletisation. Research has shown that storing sawdust for some time before further drying will benefit the pellet quality, e.g. pellets made of stored pine fraction have higher bulk densities and better durability properties than pellets made of fresh pine sawdust at constant process parameters [37, 155]. This is due to the fact that in the first 12 weeks of storage of pine and spruce sawdust, the amount of fatty and resin acids reduces substantially. Storing for an additional 4 weeks does not further reduce the amount of fatty and resin acids, thus one can say that the sawdust is mature after 12 weeks of storage [37]. An industrial experimental design has confirmed that there is a direct correlation between stored sawdust and process parameters like energy consumption during pelletisation [36].

It is therefore quite common to store fresh lignocellulosic material like sawdust, wood chips or bark outdoors for



Figure 3.2. A real silo explosion which most likely occurred due ignition of headspace gases by an electrostatic discharge in an attempt to extinguish a smouldering fire. (courtesy of Dag Botnen, Hallingdal brann- og redningstenste iks, Norway)

a period of time before pelletisation. This may, however, lead to self-heating processes where several physical, biochemical, microbiological, and chemical processes heat the biomaterial. The degree to which these processes occur depends on various parameters such as temperature, moisture content, oxidation ability of the material, etc.

These materials have relatively high moisture content and are a suitable environment for microbial growth. The reason is that microorganisms use nutrients that are dissolved in water. The raw material is important. Kotoyori showed that sawdust from different wood species show very different self-heating properties [39]. In the same way as raw material from different wood species can have an effect on the self-heating tendency, wood chips from different parts of a tree have different properties. The following ranking can be found (from highest propensity to self-heating to the lowest): 1. foliage, 2. bark, 3. whole-wood chips and 4. debarked chips. Raw solid biomass, such as sawdust and other feedstock used in pellet production have a moisture content exceeding 15 wt.% (w.b.), typically even between 35 and 55 wt.% (w.b.), and are often stored outdoor before pelletizing to secure high plant production capacity of pellets during winter time.

SLU in Uppsala, Sweden has undertaken research on the storage of moist wood fuels and self-heating of stored

forest fuels and residues. Thörnqvist studied fires that had occurred in piles of comminuted wood fuel during 1986 and 1987 [175]. In total 13 different fires were studied with piles ranging from 3,000 m³ to 93,000 m³. The cause of the fires was assumed to be different permeability in various parts of the piles. Most of the fires started in the border regions between compact and uncompact fuel or in regions between different assortments of wood fuel. The study resulted in recommendations for storage of comminuted wood fuel. These recommendations are summarized in Section 3.5.1.1. Thörnqvist was also responsible for a large experimental study on large-scale seasonal storage of wood fuel where the variation in different parameters over time was studied [174]. The materials studied were oak chips and chipped logging residues. Increased temperatures were observed, with the highest temperatures measured in the piles with chipped logging residues, over 300 °C in the lower central part. The results and recommendations of Thörnqvist are included and summarized in a handbook on storage by Lehtikangas [104] together with other studies. These recommendations are still used today and are further discussed in Section 3.5.1.1.

Jirjis working at the Swedish University of Agricultural Sciences with CRA-ISMA in Italy performed large-scale tests with different types of wood fuels. [94]. They

noticed that microbial activity led to mass and energy loss in all types of storage of the material that was studied. An uncompact covered pile was the method that worked best, while a compacted pile gave the highest temperature and the largest risk for self-heating.

Microbial activities are also very sensitive to the temperature in the pile. Microorganisms are divided into three groups as a function of their sensitivity to temperature: psychrophilic, mesophilic and thermophilic. Psychrophilic microorganisms are capable of growth and reproduction at low temperatures, ranging from -15 °C to +10 °C. Mesophilic microorganisms have a temperature optimum between 20–40 °C. The rate of reproduction of mesophilic microorganisms will be very limited at 40 °C. Thermophilic micro-organisms will survive up to 70 °C. The development of microflora also depends on nutrition e.g. in form of hydrolyses of carbohydrates; and the increased temperature.

Chemical degradation (oxidation of wood constituents) normally starts to have some influence from 40 °C, and generally becomes the dominating process at temperatures above 50 °C. As the heat generation processes proceed, heat is transported from the interior of the heap towards the surface. The centre of the heap is drying and water is transported out from the centre, condensing on the outside layers. The outcome of the self-heating process is a balance between the heat production rate and the rate of heat consumption and dissipation. Thermodynamically, the larger the size of the storage, the greater the risk for spontaneous ignition. Spontaneous ignition starts as pyrolysis in the interior of the heap in cases when the heat production exceeds the heat losses (conduction, convection and radiation) in bulk material. The spontaneous ignition results in flaming combustion in cases when the pyrolysis spreads to the surface of the heap. Open flames in solid biofuels require the presence of oxygen (air) and sufficiently high self-heating temperature caused often by a combination of microbial activity, chemical oxidation and migration of moisture in the material.

To summarize, there may be several processes such as physical biochemical, microbiological and chemical processes involved in self-heating of biomaterial. The domination of one or more of those processes depends on several parameters such as temperature, moisture content and oxidations ability of the material, etc. The degradation of wood by fungi and bacteria results in a temperature increase in the stored fuel. Peak temperatures from microbial self-heating vary between 20 °C and 80 °C, depending on the type of microorganisms [102].

Rain can enhance the self-heating in piles of wood chips. Metals that accidentally have ended up in a pile can also increase self-heating through catalytic effects.

3.1.2 Self-heating of dry solid biomass fuels

Dry solid biofuels such as wood pellets, briquettes and other dry solid biofuels require protected storage to keep the structure and low moisture content of the fuel. This can be done in silos or indoors, e.g. in A-frame buildings. The raw material for fuel pellet production is normally wood (sawdust, cutter, etc.). Wood is a complex material and contains cellulose, hemicellulose and lignin and some extractive compounds such as terpenes, fatty and resin acids and phenols, etc. Different kinds of tree species have different amounts of these compounds; and also seasonal variation may occur.

A number of serious incidents of self-heating and spontaneous ignition of wood pellets in storage have occurred [108, 142]. There are examples of fires caused by self-heating both in silos and in flat storage facilities. There is also a fire risk from various external ignition sources in storage and especially connected to the handling and transport of pellets.

Due to the low moisture content, the growth of microorganisms is normally limited in stored pellets. In addition, during wood pellets production process, the drying temperature of sawdust is typically 90°C to 170 °C, but often exceeds 190 °C. Therefore, it is unlikely that any microorganism could survive in such environment, which means that microbial activities should be very limited, if at all, in pellets during storage. If microbial activities are found in pellets piles it is most likely that these are initiated afterwards by contamination in the storage room. At low temperature drying processes of less than 100 °C, microbial activities may not be eliminated. However, during pelletisation, temperatures of 100 °C to 170 °C are reached in pellet mills because of friction. The combined effect of relatively high temperature regimes in pellet production and the low moisture content of the resultant pellets are sufficient to limit the biological activities.

Self-heating of fuel pellets does, however, occur in large-scale storage and also in some cases in smaller piles stored at normal ambient temperatures. For wood pellets, the tendency for self-heating seems to vary between different qualities of pellets and is most pronounced relatively shortly after production. It has been observed that during storage of pellets the temperature in the pile or silo can increase a few days or even hours after production. The temperature can vary, depending on the pellets raw material and most often is around 60 to 65°C [34, 35]. The temperature increase can sometimes be higher (for certain pellet qualities up to 90 °C), but at such temperatures the risk of a run-away temperature resulting in a spontaneous ignition will increase, especially if the volume of the pile is large or the pellets are stored in a silo. The most common procedure for handling such temperatures is to distribute the pellets in thin layers over the pile surface to allow maximum

cooling. Filling a silo at a high filling rate with these types of pellets will limit the cooling possibilities and increase the risk of a run-away temperature situation. Mixing of pellets of different moisture content is another potential source of heat production as heat is produced in the process of balancing out the moisture in the pile.

Part of the heat production is most probably due to low temperature oxidation of easily oxidised components in the material. It has been suggested that a high content of unsaturated fatty acids in the fuel increases the problem with low temperature oxidation and self-heating of wood pellets [35]. The oxidation process is very complicated. The oxidation reactions are chain reactions (radical reactions). In these reactions the fatty acids in pellets are oxidized to aldehydes and ketones, accompanied by the generation of heat, i.e. it is an exothermic process. Further oxidation of these aldehydes and ketones will produce low molecular carboxylic acids [35]. These volatile organic compounds have been detected during pellet storage. Fresh pine sawdust contains high amounts of unsaturated fatty acids.

In addition, absorption of moisture in pellets is an exothermic process, i.e. it generates heat. There are two phenomenon involved: condensation heat and differential heat. Pellets are hygroscopic and may, at high air humidity, absorb water vapour from the air, especially if the pellet surface temperature is lower than that of the air [34]. Once absorbed, water vapour condensates on the pellet surface which then causes the release of condensation heat.

Differential heat of sorption is released when the moisture content increases in the interval from initial set point up to the fibre saturation point. The condensation heat released is much larger than that of differential heat when moisture is absorbed from air. An initial process in self-heating may be caused by the exchange of moisture between pelletized materials of different moisture contents in storage, i.e. between pellets but also within single pellets. When water molecules are transported by diffusion from molecule layers that are more loosely bound to surfaces in pellets to layers that are more tightly bound, energy is emitted as differential heat. This process may increase the temperature in stored pellets only by some degrees centigrade, but this could be sufficient to give rise to air flows within the mass of pellets that already exist in the pile along the outer border of the pile towards the centre of the pile. It has been shown that the potential of differential heat release can be predicted by infrared spectroscopy (a fast analytical tool) [105]. This method, once fully developed and established, has a potential to establish limits for a safe mixing of pellets with different moisture contents. The lower the initial moisture content of the pellets and/or the higher the air humidity is, the higher the risk of heat generation via moisture absorption. Pellets

with low initial moisture content (around 5 to 6 wt% (w.b.) are more reactive and will absorb moisture more easily than pellets with higher initial moisture content (around 8 to 10 % mass on wet basis). Lignocellulosic material with 5 wt% (w.b.) at an air and material temperature of 20 °C (at relative humidity of 70 %) will display a raise of the temperature to 100 °C when the moisture content increases by 4.5 to 9.5 wt% (w.b.) [40]. The moisture diffusion rates depend on several physical and chemical properties of pellets. Pellets with higher amount of particles (fines) will absorb moisture more easily and have higher risk of self-heating. Other parameters such as pile geometry, size and moisture in the surrounding air are important for moisture absorption as well as homogeneity in moisture content of different pellet layers in the storage [105].

When pellets with propensity to exhibit one or more of the heat generating processes are stored in a large volume, the temperature will increase within the pile, which may lead to spontaneous ignition in pellet storage facilities. The main risks resulting from the self-heating process of stored pellets are the following, in the order of occurrence:

- Release of asphyxiating (e.g. CO) and irritating gases (e.g. aldehydes and terpenes), see also chapter 4.
- Spontaneous ignition resulting in pyrolysis of bulk material and release of pyrolysis/combustion gases.
- Gas and/or dust explosion, typically as a result of personnel approaching top compartment of a silo in a fire rescue work, see also section 3.5 and chapter 5.
- Surface fire and spread of fire, typically as a result of an explosion in a silo.

Soybeans must be stored so that insect infestations are avoided. Furthermore, for storage the moisture content cannot be too high; otherwise spoilage is likely. There is a critical limit at 13 % moisture content. For long time storage (over one year), the moisture content needs to be even lower (below 11 %). Both soybeans and soybeans products have a high propensity for self-heating. They have a high content of unsaturated oils, which leads to release of energy due to oxidation and thermal polymerization at higher temperatures. At lower temperatures, the self-heating is mainly due to microbial heating. The stored soybeans must be protected from additional water, since increased moisture promotes hydrolytic or enzymatic fat cleavage. The increased respiration could lead to self-heating [176].

3.1.3 Analysis methods for self-heating potential

There are several methods for determining self-heating potential and self-ignition of materials. Most involve experimental calorimetric methods are performed at small scale giving results from which kinetic parameters such as the heat of reaction (Q) and the activation energy (E) can be calculated. The kinetic parameters obtained are

then extrapolated using the Frank-Kamenetskii theory to predict self-heating potential at larger scale. Some small scale tests used for determining kinetic parameters and thereby self-heating potential are described below [46].

3.1.3.1 Oven basket test - FRS method

Oven basket tests are the most common test methods used for small scale self-heating testing. There are several versions of these methods, including analytical methods for research purposes and standardized methods used for the testing of dangerous goods for various modes of transport.

The first Oven basket tests were historically introduced by Philip Bowes and colleagues at the UK Fire Research Station (FRS) and have been developed and refined over decades. The researcher Paula Beever has summarized this test method in the SFPE Handbook [45]. With the FRS technique a sample is placed inside a wire mesh cube, which is located inside an oven at a fixed temperature. The temperature is then measured in the oven and at the centre of the sample. In some cases the surface temperature of the sample is also measured to make sure that the temperature of the surface of the specimen is approximately the same as the oven temperature. This is important since one of the conditions for the method is that the Biot number approaches infinity. A fan is, therefore, used inside the oven to increase the thermal convection and thereby the Biot number. It is assumed that if the flow velocity exceeds 10 m/s, the Biot number becomes infinite [39].

A sample is located inside the oven and the centre temperature is measured over time. Three different temperature patterns can be observed (see Figure 3.3):

- A. Subcritical. The temperature in the centre increases slowly towards the oven temperature, but never exceeds it. No self-heating behaviour is observed.
- B. Critical. The temperature in the centre of the sample increase only a little above the oven temperature, reaches a plateau, and then decreases.
- C. Supercritical. The temperature in the centre increase, sometimes reaches a plateau, before rising rapidly above oven temperature. Self-heating has occurred.

Tests are repeated with increased oven temperature until the supercritical temperature (T_o) occurs. There is usually a distinct line between critical and supercritical temperature, differing by only 1-2 °C. When the supercritical temperature has been found for one basket size, the procedure is repeated with other basket sizes. Normal basket sizes are 25, 50, 100 and 200 mm and at least 3 sizes need to be tested. This is, therefore, a time consuming test method that requires many tests. It is also important to recognise that there are two different critical temperatures discussed in the literature: one is the critical ambient temperature (CAT) and the other is the critical stacking temperature (CST), which is the temperature of the material. The latter may be 20 °C to 30 °C higher than the critical ambient temperature [39].

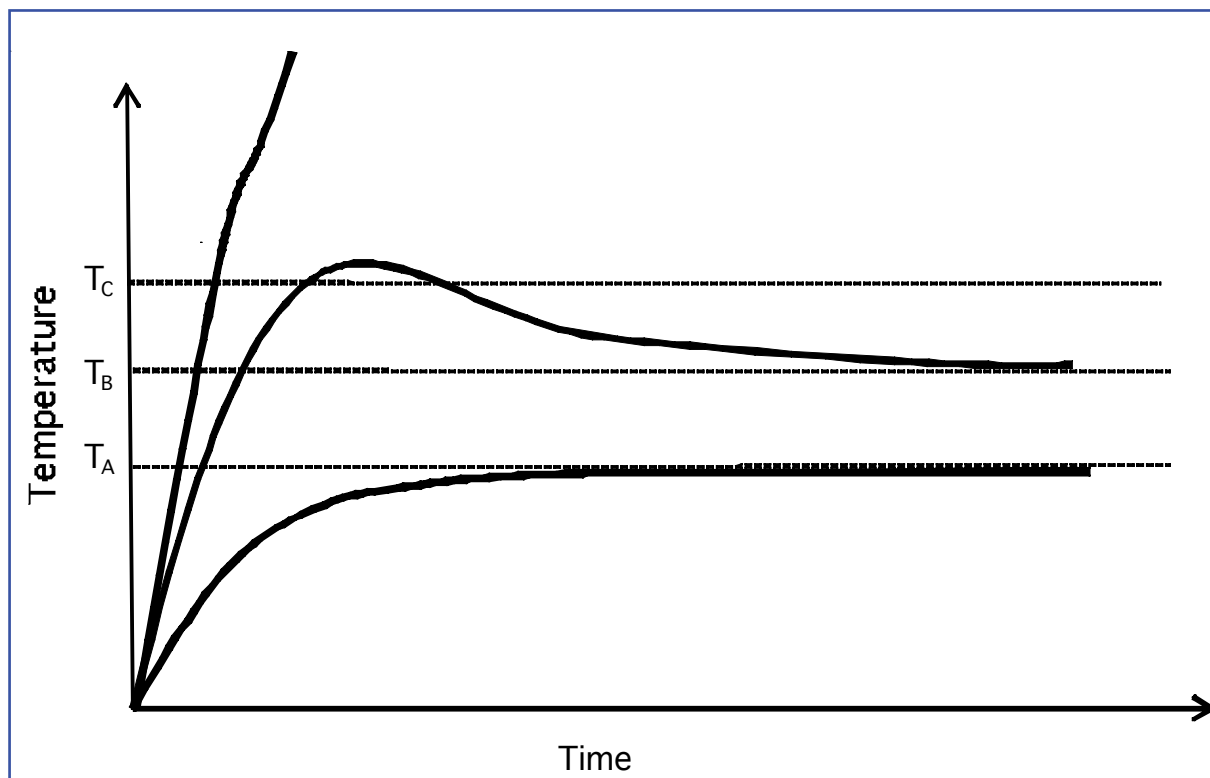


Figure 3.3. Possible thermal patterns during basket tests; A) subcritical, (B) critical or (C) supercritical [77].

The analysis mostly used in combination with the FRS method is called Frank-Kamenetskii (F-K for short). Frank-Kamenetskii developed a theory for self-ignition in the 1930s that is based on the following assumptions:

- The self-heating reaction is generated by a single reaction that is a function of temperature. The reaction is not time dependent. The reaction activity is thereby constant at a specific temperature and increases exponentially with increased temperature according to the Arrhenius equation below:
- $$\dot{q}' = \rho Q A e^{-E/RT}$$
- The activation energy is assumed to be sufficiently high so that $\varepsilon = \frac{RT_0}{E} \ll 1$ where T_0 is the ambient temperature.
 - All heat transfer inside the sample is assumed to be by conduction.
 - The heat transfer from the sample surface of the specimen to the surroundings by convention and radiation is assumed to be so extensive that the surface temperature of the sample is the same as the oven temperature. This means that the Biot number $\rightarrow \infty$.
 - The material is assumed to be isotropic and homogenous, with physical properties that are not temperature dependent.

Based on these assumptions, Frank-Kamenetskii developed an equation [45]:

$$\delta = \frac{\rho Q A}{\lambda} \cdot \frac{E r^2}{R T_0^2} \cdot e^{-E/RT_0}$$

Where:

- δ = the Frank-Kamenetskii parameter (-)
- ρ = bulk density (kg m⁻³)
- Q = heat of reaction (J kg⁻¹)
- A = the pre-exponential factor in the Arrhenius expression for heat production in a body (s⁻¹)
- λ = thermal conductivity (W m⁻¹ K⁻¹)
- E = activation energy (J mol⁻¹)
- r = characteristic length for the storage configuration (m)
- R = the universal gas constant ($R=8,314$ J mol⁻¹ K⁻¹)
- T_0 = ambient temperature (K)

The equation can be rewritten as:

$$n \left(\frac{\delta_c T_0^2}{r^2} \right) = P - \frac{E}{RT_0}$$

Where:

$$P = \ln \left(\frac{E}{R} \rho \frac{QA}{\lambda} \right)$$

The experimental results from a number of tests with different sample sizes are plotted, with $1/T_0$ on the x-axis and $\left(\frac{\delta_c T_0^2}{r^2} \right)$ on the y-axis. A straight line is then formed and the slope of the line represents $-E/R$ and the y-axis intercept represent P . The critical value of δ_c can either be calculated by known methods or values for δ_c for different geometries can also be obtained from literature, for example in the Ignition Handbook, table 2-12.1 [39]. The equations are then used to calculate the heat production rate and activation energy (QA and E), which is then used to predict self-heating at larger scale. Due to the many assumptions, which are not always met in reality, a number of corrections can be made to δ_c , some more important than others. For more information about this, see the SFPE Handbook [45].

3.1.3.2 Oven basket test – Crossing Point method

The Crossing Point (CP) method was introduced to speed up the testing procedure used for FRS tests. In traditional CP testing, a sample is located inside a wire mesh cube, which is located inside an oven. The oven temperature is ramped up at a moderately slow rate. Temperature is measured in the oven and at the centre of the sample and when the centre thermocouple exceeds the oven temperature; the Crossing Point temperature is obtained. However, the test suggests that small oven samples will undergo self-heating at the same temperature as in the real scale, which is not true. As a result these CP results are without much value and cannot be used to predict self-heating at larger scale, only for comparing one sample to another.

An alternative, more robust CP method for determination of the kinetic parameters in self-heating substances is the method described by Chen and Chong [55]. This method involves the periphery heating of an initially “cold” exothermic material being subjected to a hot environment with a constant/isotherm temperature, and is based on analysis of the non-steady solution of the energy conservation equation. Initially the temperature at the centre is lower than the periphery temperature, but at a certain time the centre temperature exceeds the other temperatures between the centre and the periphery. The centre temperature at this point is defined as the crossing point temperature.

The Crossing Point method by Chen and Chong [55] has been used by SP Technical Research Institute for self-heating tests of wood pellets [107]. For each pellet type a series of tests were performed where the ambient (oven) temperature was different for each test. Temperatures were recorded throughout the heating process until and beyond crossing point. The Crossing Point was determined

from the temperature recordings as described above. The following procedure was then used to calculate the heat production rate and activation energy (QA and E):

- $\ln(\partial T/\partial t)$ at crossing point is plotted against $1/TP$ for each ambient temperature.
- These points are interpolated to a linear expression
- Since, according to Chen et al, [55]:

$$\ln\left(\frac{\partial T}{\partial t}\right) = \ln\left(\frac{QA}{C_p}\right) - \frac{E}{RT}$$

- E/R must be the coefficient in the linear expression and $\ln(QA/C_p)$ is the constant

Once the kinetic parameters have been evaluated with the Crossing Point method, the Frank-Kamenetskii theory can be used in the same way as for FRS to predict self-heating.

Cuzzillo has evaluated the CP method in detail in his thesis [58] and includes a detailed error analysis of the method. Cuzzillo shows several advantages of the CP method over the standard FRS method. First, almost every test results in a useful data point in the graph. Further, it eliminates the need to measure or estimate the Biot number in the laboratory tests because δ_c need not to be evaluated in these tests. This means that the heat transfer properties of the oven and the conductivity of the sample need not to be known in the laboratory tests for determining the kinetic parameters.

Note: Despite the many assumptions and simplifications, the F-K models are used widely and appear to be working with satisfaction in many cases. There are, however, a number of limitations with the model. Examples are that in the models no account is taken of moisture

transport and the accompanying phenomena of hydrolysis, evaporation and condensation. This is an important factor, especially in moist material. The tests (FRS or CP) are further performed at high temperatures (usually above 100 °C) and no consideration is therefore taken of low-temperature processes that take place before the oxidative reactions commence [39, 45, 46, 84].

3.1.3.3 Isothermal calorimetry

One method used for characterization of self-heating is often called micro calorimetry, but the more general and descriptive term is isothermal calorimetry. The isothermal calorimeter is used to very accurately (mW-scale) measure the heat of reaction and by that self-heating caused by oxidation processes in a material. Experimental work to develop small scale screening methods to assess the propensity for self-heating of different type of pellets has been performed by SP Technical Research Institute of Sweden [109]. The equipment used is the eight channel TAM Air 3116-2 isothermal calorimeter. The instrument has a temperature range between 5 °C and 90 °C. For each channel a test ampoule of 20 mL is used in combination with a reference sample. The sample is put in the ampoule, which is sealed and then inserted into the TAM Air (see Figure 3.4).

Inside the TAM AIR, the ampoule is in contact with a heat flow sensor, which is also in contact with a heat sink. This means that when heat is produced inside the ampoule, a temperature gradient is developed across the sensor. The voltage, which thereby is generated, is then measured. The voltage signal is proportional to the heat flow across the sensor and thereby to the rate of the process taking place in the sample ampoule [24]. The volt-signal is converted into a heat release rate result (mW). The results are time dependent and in most cases a clear maximum is reached relatively quickly, followed by a long period of decrease in the heat release rate.



Figure 3.4. Left: The eight channel TAM Air 3116-2 isothermal calorimeter. Right: Examples of pellets samples in glass ampoules.

Some typical heat release rate curves are presented in Figure 3.5. [107, 109] The pellets presented in Figure 3.5 represent one active (L) and one relatively inactive (M) type of pellets. The test method shows good repeatability and a clear difference between an active and an inactive pellet. During the tests performed by SP, the maximum heat release rates for different kind of wood pellets varied from 0.02 – 0.99 mW/g when 4 g of pellets was tested at 60 °C. However, one should be aware that the heat release rates vary with temperature and the amount of pellets inside the ampoule.

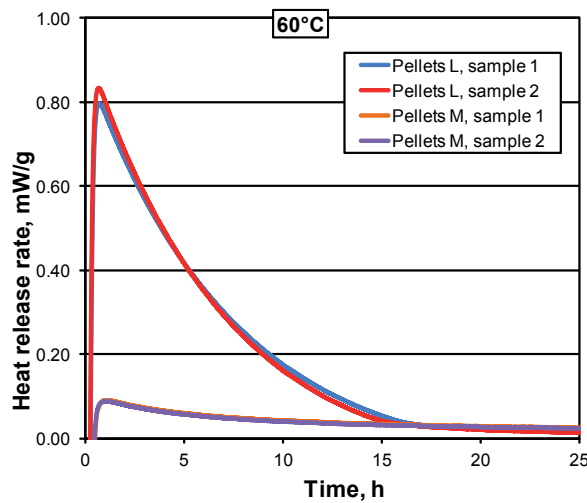


Figure 3.5. Examples of heat release curves from the micro calorimeter for two different types of pellets, one “active” (L) and one “inactive” (M) [109].

By measuring the maximum heat release rate at different temperatures, a table of temperature vs. heat release rate can be formed. The data from the tests can then analysed the same way as for the FRS-method. $1/T$ is plotted on the x-axis and $\ln(\dot{q})$ is plotted on the y-axis. The results then fall on a straight line and the activation energy E can be obtained from the slope of the line, which equals $-E/RT$. The intercept of the y-axis represent $\ln(QA)$ [39, 107].

$$\ln(\dot{q}) = \ln(QA) - \frac{E}{RT}$$

As for the oven basket tests, there are many assumptions and simplifications related to this analysis method. The micro calorimeter tests are performed at more realistic (lower) temperatures compared to oven basket tests, but on the other hand the sample amount is also a lot smaller; only a few grams. Micro calorimetry test results, and oven basket tests results for that matter, also offer a very good method for screening and comparing different samples to each other. However, using the quantified results, based on micro calorimeter or oven basket data, to predict self-heating at full scale are still quite unreliable and more development is needed.

3.1.3.4 Thermogravimetry

In thermo gravimetric analysis (TGA) the mass of a substance is measured as a function of temperature, while the substance is subjected to a controlled temperature programme. The most common methodology for self-heating tests is heating the substance at a linear rate [77, 148].

The analysis usually consists of a high-precision balance with a pan (generally platinum) loaded with the sample. That pan is located inside a furnace and is heated (or cooled) during the experiment. It is also possible to control the atmosphere during a test, for instance by having an inert gas to prevent oxidation or having an oxygen surplus to promote oxidation. Analysis is carried out by raising the temperature of the sample gradually and plotting mass against temperature or time [178]. Another useful and complementary method is to plot the first differential equation of TGA mass graph with respect to temperature or time, the so called DTG-curve. Mass changes in the TGA-graph are shown more clearly as peaks in a DTG-graph. Figure 3.6 shows a TGA and DTG test curve with the characteristic points marked on it (called TG and dTG in the figure). The maximum weight loss temperature (MLT) is an indication of the reactivity of the product. By running measurements at different heating rates, the TGA results can be used to calculate the activation energy E for the sample. IW is the increase in weight at the beginning of the heating process, which shows the capability of oxygen adsorption during initial heating and the initial oxidation of the sample. Combustion induction temperature (IT) is the temperature when combustion starts [77, 178].

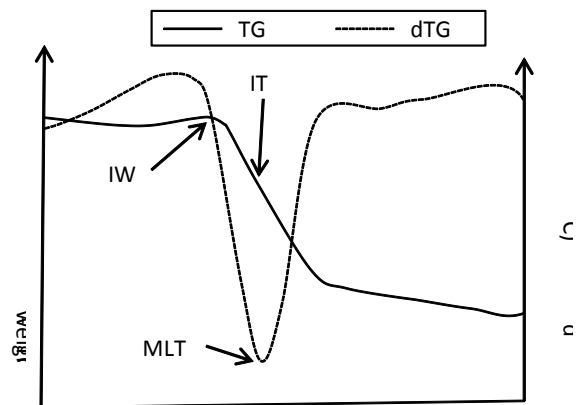


Figure 3.6. Example of Thermogravimetry results [77] TGA is of limited applicability to a self-heating problem since only mass and not heat is measured. Only the activation energy E can be obtained from the measurement, but not the heat of reaction (Q) [39].

3.1.3.5 Differential Scanning Calorimeter

In Differential Scanning Calorimetry (DSC) a sample is heated at a predetermined rate while the heat flow from the sample is measured. The heat flow is measured by measuring the difference in heating between the sample

and a reference as a function of temperature. The change of the slope of the temperature curve (CST), from when the temperature starts rising (oxidations starts) until the oxidation reaches its maximum temperature, is a measurement of the reactivity of the sample [77, 178].

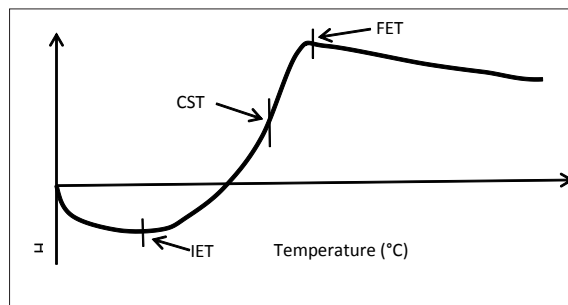


Figure 3.7. Example of DSC results. IET is the initial temperature when oxidation starts. FET is the final or maximum oxidation temperature [77].

With DSC it is possible to obtain the activation energy E and the heat of reaction (Q). According to Babrauskas [39] the DSC do not produce results with the highest precision. The thermal analysis technique is best used for rough estimates, rather than data for predicting results at full scale.

3.2 External ignition sources

In addition to spontaneous ignition, there are a number of possible causes that could result in a potential fire. Some common causes are sparks generated by metal pieces, stones, etc. that are present in the bulk material by accident. Other causes could be overheating of electric motors, bearings in conveyor and elevator systems, friction between e.g. a conveyor belt and accumulated material, fines and/or dust or careless hot work. The ignition could also be a secondary effect of a spontaneous ignition if material containing small pieces of smouldering material ("hot spots"), is transported to a new storage location by mistake, e.g. via conveyors. In heat generation plants, ignition might also be a result of back-fire or sparks near the boilers. A risk that should not be neglected is the possibility for a fire in wheel loaders, which are frequently used for unloading material from heaps. In some situations there is also a risk of intentional fires (arson). The most important measures to avoid these risks are to

- Include control measures for impurities when receiving the material, e.g. magnetic separators, sieves, etc.
- Spark detectors connected to an extinguishing system by fast acting valves at strategic locations in the transport system.
- Install a full sprinkler protection system in large conveyor systems, as these are often located at elevated positions and/or in underground spaces making a manual fire fighting operation very difficult.

- Control schemes to check the condition of bearings (temperature measurement)
- Control schemes for cleaning to avoid accumulation of material in conveyers, elevators etc.
- Control schemes for hot work within the facility
- Routines for observations and controls

3.3 Experiences from real fire examples

Below some examples of real fire incidents are described briefly. The examples involve both fires in wood pellets in silos and flat storage and wet biofuel fires in heaps outdoors. The examples involve also some successful fire extinguishing operations.

Westermann described a fire in a silo in **Esbjerg in Denmark** 1998 where the fire started in a cell with wood pellets and lasted for nine months [181]. Several problems occurred during the duration of the fire, affecting the outcome. These problems can be summarized as:

- Explosions in pyrolysis gases due to opening up the side of the silo wall.
- The initial self-heating increased the temperature in neighbouring cells, leading to additional self-heating.
- The increase in water content due to the different methods used to extinguish the fire, which made the silo content to clump together. This effect was further increased by the heat. This made the silo content compact and difficult to transport. Internal bridges across the silo were formed.
- It was difficult to access the silo.
- The rescue services are seldom prepared for long duration operations.

Eckhoff reported many **subsequent explosions** in 1988 and 1989. The main reasons for the explosions were said to be large heat transfer between the silo cells due to large contact surfaces between the cells and buckwheat and wheat grain with higher moisture content than was supposed to be stored in that kind of facility [181]. As in many other cases, the silo was opened for inspection increasing the combustion due to the availability of fresh air.

In **Härnösand, Sweden**, 2004, a concrete silo complex consisting of five separate silo cells was involved in a fire [8]. The silos were 34 m high, three silo cells were 11.5 m in diameter and two were 8 m in diameter, corresponding to an effective storage volume of 2700 m³ and 1350 m³, respectively. The silo was used by a nearby



Figure 3.8. A detector indicating sparks and hot particles in a ventilation duct. These detectors are often connected to a fast activating water spray system downstream the detector (not in this picture) (courtesy of Firefly).

pellet manufacturer for storage of wood pellets, as their normal storage capacity (an A-frame storage) was not enough. Filling of the silos began during the period from the 4th to the 23rd of August and the filling time of each individual silo cell varied from 7 to 25 days. On the 7th of September, a smell was noticed in the area close to the silos and in the morning on the 8th heavy smoke and a “rain” of tar particles was observed from silo no 4 and smouldering pellets were observed as the discharge equipment was started and the discharge was therefore stopped. As there were severe problems due to heavy smoke moving directly towards the city centre, it was decided to use the combined tactics of foam application at the top, CO₂ injection at the bottom and discharge of pellets by making an opening in the silo wall. From experience it was recognised that large water monitors should be used to control the fire in discharged material.

At midnight (8-9th), foam was applied into the silo top and at about 05:30 (9th), CO₂ was injected through a lance close to the silo bottom. There were significant problems as ice formation in the pellets blocked further gas injection. At about 06:00, a 1-1.5 m² opening was made in the silo wall and undamaged pellets started to flow out. After about 2 hours, dark coloured and partly smouldering pellets were observed and at 10:20, the pyrolysis gases formed due to the increased ventilation were ignited in the silo top, which spread to the entire building construction. Due to the high level of water

application, the fire in the opening and in the discharged pellets could be controlled and the silo was emptied at about 08:00 on the 10th. In order to prevent similar situations in the other silos, it was decided to inject CO₂ in the four other silos at well. However, on the morning of the 11th, heavy smoke was observed from the top of silo 5 and some “activity” was also observed in silo 1 and 2. The same procedure (water monitors and discharging through the silo wall) was also used for this silo and also later on for silo 1. During the extinguishing operation, several gas explosions occurred in the openings and at the discharge opening at the bottom of the silo 1; in some cases of flames jetting more than 50 m were observed. Fortunately, no injuries occurred. The three silos, the building construction and conveyor system at the silo top were completely destroyed and the silos were later demolished. Most of the pellets were destroyed as a result of the use of water.

In September 2007, auto ignition occurred in a silo in **Kristinehamn, Sweden** [141]. The silo was 47 m high and 8 m in diameter, filled to about 40 m with wood pellets. Elevated temperatures had been noted for some period of time and it was planned to empty the silo if the temperatures did not decrease within the next few days. However, before this decision was taken, smoke was noted from the top of the silo on the 29th and the fire brigade was called to the location. A first extinguishing attempt was made by intermittent



Figure 3.9. Fire in silo storage of wood pellets. (Courtesy of the Fire and Rescue Service in Härnösand, Sweden)

application (due to freezing problems) of CO_2 in liquid phase into the silo headspace. During approximately 18 h, about 35 ton of CO_2 was applied. The application seemed to control the fire but there was no possibility of verifying the extinguishing effect of the CO_2 application.

Preparations were, therefore, made to inject nitrogen close to the silo bottom according to the recommendations from the silo experiments in 2006 [146]. A gas tank with liquefied nitrogen and a vaporization unit was ordered. A hole was drilled close to the bottom of the silo and a lance was manufactured which was introduced into the hole. In order to control the effect of the gas injection, temperatures and the concentrations of CO , CO_2 and O_2 were measured in the silo top. The gas measurements were started in the afternoon on the 1st of October, just before the start of nitrogen injection. The measurements indicated a very high concentration of CO (>10 %), a sign of on-going pyrolysis activity. After about 3.5 hours, the first indication of a decreasing CO concentration was observed. In the morning of 2nd October, the CO -concentration had been reduced to about 2 % and the O_2 -concentration was 0 %, and it was decided to start the discharge of the silo content. This work continued until 05:00 on 4th October when the silo was declared empty and during this work, there was a continuous injection of nitrogen. The unloading work had to be stopped at times for safety reasons due to high temperatures and increasing

oxygen concentration in the silo top. This was probably due to the fact that the seat of the fire was exposed.

The gas injection continued for almost 65 hours without interruption. In total, approximately 14 ton of nitrogen was used, which corresponds to an average injection rate of about $4 \text{ kg/m}^2 \text{ h}$. The gross volume of the silo was about 2500 m^3 , which gives a total gas consumption of 5.6 kg/m^3 . The use of the 35 tonne of CO_2 gas in the beginning of the operation corresponds to 14 kg/m^3 . The gas injection rate and the total gas consumption during the nitrogen inerting operation were reasonably in line with the recommendations given in the report (see also chapter 7.2.2).

In 2005, a flat storage in **Ramvik, Sweden**, containing 9000 ton of wood pellets ignited due to self-heating [8]. The building was $150 \text{ m} \times 50 \text{ m}$. The fire fighting operation was started by applying water by firemen wearing SCBA equipment in combination with moving the stacks to an outdoor area using five wheel loaders. During the operation, it was observed that one steel column was heavily affected by heat and the work with the wheel loaders was interrupted. As the building was completely filled with smoke making further visual observations impossible, an excavator was used to open up the walls to improve visibility and enable fire fighting from the outside using both water and foam. When the smoke was cleared, the decision was made

to start the use of the wheel loaders again as the risk for building collapse was not considered acute. The fire fighting operation lasted for about 30 hours. Both the building and the pellets were destroyed.

In the middle of September 2009, a fire incident occurred in a flat storage (A-frame building) at a pellet manufacturer in **Luleå, Sweden** [1, personal communication Lars Stenberg]. The storage building was about 100 × 20 m with a maximum storage height of about 8 m, corresponding to a storage capacity of 8000 ton. At the time of the incident, the storage contained about 5000 ton. No pellets had been put onto the pile involved since midsummer. A wheel loader was operating in the storage building at about 20:00 at some distance from the pile but the driver did not notice anything strange. At 21:30, an internal alarm was set off by the aspirating smoke detection system inside the building. Smoke was observed and the fire brigade called. The seat of the fire seemed to be high up in the pile, some meters from the edge. In order to prevent a dust explosion, the area was sprayed with water. Also some beams with dust deposits were sprayed. When the situation was deemed to be under control, the pellets were moved outdoor using wheel loaders. In total 1800 ton was moved and the work was finished at about 03:00 the following morning without any further damage to the building or the adjacent piles of pellets. All pellets that were moved out of the building were damaged by the water application but no open flames were noticed during the operation. The volume that had been involved in the smouldering fire was estimated to be only about 1 m³ and was located a couple of meters below the surface.

The cause of the fire is not fully clear. One theory is that slag or embers caused by an accident at a nearby steel mill could have penetrated the roof and started the fire. Another theory is that a small leakage in the roof could have caused wetting of the pile, causing self-heating and auto ignition.

In May 2008, a fire started in a large outdoor store of wood chips at a paper mill industry in **Norrköping, Sweden**. According to the local fire department it was due to self-heating. An employee tried to extinguish the initial fire with a fire extinguisher but did not succeed and the fire brigade was alarmed. The initial fire fighting operation was delayed due to problems with water supply, as some of the water hydrants had been covered by the wood chip stacks. A supply of water had to be arranged with several pumps and hose lines from an open water located about 800 m away. Due to strong winds, embers spread the fire rapidly to adjacent stacks of wood chips but also to the roof of several nearby industrial buildings at the paper mill plant and to conveyor systems, causing fires in two silos. In addition a water treatment building containing a number of hazardous chemicals was threatened. The fire brigade had to focus

on protecting these buildings, which allowed the fire spread to a nearby forest area. The fire fighting operation continued for several days, involving water application in large amounts onto the stacks, in combination with moving of the material with wheel loaders, discharge of the silo contents, etc. The paper mill production had to be stopped as a water treatment system was damaged, causing a down time cost of about SEK 1 million per day.

In August 2012, a fire in a conveyor system caused a fire in two silos at the Avedøre power plant in **Copenhagen, Denmark** [27]. Two employees at the power plant observed smoke from a conveyor connected to the top of two large silos (45,000 m³ and 100,000 m³, respectively) used for pellets storage. The fire and rescue service was called, but as the conveyor was located at 30 m height above the ground, the fire fighting operation became very difficult and the fire spread into the smaller silo, causing a surface fire. Attempts at extinguishing the fire were made using water nozzles and water monitors, but the fire could not be extinguished as it had already created a deep seated fire. Due to the heating of the silo construction and the use of water causing the pellets to swell, it was considered there could be a risk that the silo would collapse and it was decided to empty the silo as quickly as possible using large dozers. This work was finalized about 12 days later.

In order to prevent fire spread to the large silo, large resources were deployed to protect this silo during the first part of the fire fighting operation. Unfortunately, although the damper between the conveyor and the silo was closed, some glowing embers made its way into the silo. In order to protect the silo and extinguish the fires in the pellet bulk, inert gas, both nitrogen and CO₂ were injected into the silo. Large amounts of gas were used and delivery of gas was obtained from Denmark and Sweden. A decision was made to discharge the silo by continuously combusting the discharged pellets in the power plant and this operation was estimated to take about 4 weeks.

The fire fighting operation was very complex, involving a lot of personnel and equipment, both from various fire brigades, the power plant and chartered companies. During the entire operation, priority was given to safety aspects and considerations about the risk for gas and/or dust explosions, collapse of constructions, etc. had to be made continuously. The cause of the fire in the conveyor system is still under investigation and an overall evaluation of the fire fighting operation is on-going.

3.4 Anatomy of silo fires

Experience from real silo fires indicate that a fire is usually difficult to detect and that it probably has been going on for an extended period of time by the time of detection. Spontaneous ignition usually occurs deep inside the bulk material although it may develop in any part of a silo depending on the specific circumstances. Stratified layers of material with variance in permeability or a small air leakage into the bulk material are two examples of such conditions that could cause problems. The smouldering fire will consume oxygen in the air inside the stored material and the warm and moist combustion gases will slowly spread upwards in the silo. The pyrolysis zone will slowly move downwards from the location of the ignition, through the material where there is still a supply of oxygen. In the case where there are openings in the silo, such as outlet openings, leaks and other openings, fresh air/oxygen can be entrained into the silo and thereby sustain the pyrolysis fire. There are cases where the forensic investigation uncovered long strings of carbonised material leading downwards/sideways from the centre of the smouldering fire zone to a spot where oxygen (air) had entered the silo through holes at the bottom or at the silo wall. Air can probably also be entrained into the material from the top of the silo along its walls.

This has been demonstrated during fires and extinguishing tests that have been carried out in small scale silos with a diameter of 1 m, a height of 6 m and a fill level of about 5 m [146]. These tests simulated spontaneous ignition inside the centre of the silo using a heat cable to trigger a smouldering fire in the pellets. The development of the

fire could then be followed inside the bulk material using extensive temperature and gas measurements, see Figure 3.10. The figures are a visualisation of the temperature measurements inside the silo and the red colour in the point of ignition indicates smouldering zone. The faint horizontal line in the upper section of the column is the surface of pellets in the headspace. It can be seen that the temperature (and gas) wave breaks the surface and enters the headspace after about 20 h, corresponding to a spreading rate of about 0.1 m/h (about 2.5 m/day). The downward pyrolysis spreading rate is about 0.04 m/h (about 1 m/day). These spreading rates probably depend on ventilation and leakage, but do show a very slow fire development. This also confirms the difficulty of obtaining early detection of a fire inside the top of a silo. However, once the fire gases reach the top of the silo, the concentrations of CO and unburned hydrocarbons increase rapidly to very high concentrations while the oxygen is consumed resulting in a very low oxygen concentration. The tests indicated also that when the warm gases “break through” the surface at the top of the silo, a thermal updraft is achieved in the silo which results in increased oxygen supply from the air inlet at the bottom of the silo and an increase in pyrolysis intensity. The same phenomena have been seen in real silo fire incidents where it has probably taken several days before a spontaneous ignition has been detected, often by smoke being observed at the silo top. At this stage, the production of CO and unburned hydrocarbons increases even more and the silo top will fill up with smoke gases that most likely are flammable and are thereby causing an apparent risk for an explosion. In real silos, it is also

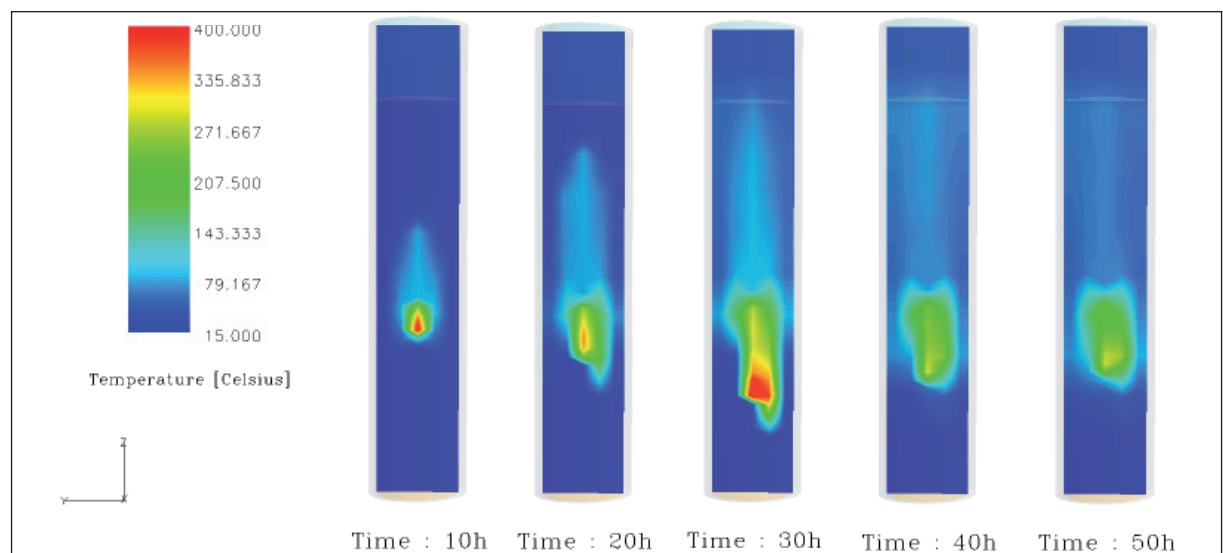


Figure 3.10. Visualization of the measured temperatures inside a mock-up silo, 1 m diameter and 6 m height. The smouldering fire was triggered in the middle of the silo and then allowed to develop freely which resulted in a slow fire spread downwards in the silo. The combustion gases did not reach the top of the silo until about 20 hours. After about 30 hours, inert gas was applied through the bottom of the silo which resulted in a fast reduction of the smouldering intensity [146].

likely that a downdraft of air from the silo headspace along the silo walls could reach the pyrolysis zone.

In the example shown in Figure 3.10 the nitrogen is injected just after 30 hours and after about 40 hours (10 hours of gas injection) the temperature has decreased, and continue to decrease gradually, but slowly and the risk of gas explosion decreases also over time.

The test arrangement also provided a favourable opportunity to examine the silo after completion. Figure 3.11 shows a photograph of the pellets about 1 m above the ignition source and Figure 3.12 shows a photograph about 0.5 m under the ignition source. The pellets above the ignition source are glued together by heat and moisture and the width of the fire under the ignition source has a very limited width. This makes it very difficult to detect a fire by reading temperatures on the surface of the silo with a thermal imaging camera. Even the use of one or several cables with temperature sensors into the material does not provide a guarantee of detection since the cables could very well end up to the side of the pyrolysis zone and thereby not detect the fire.

3.5 Fire prevention and fire fighting

This section provides the most important recommendations for fire prevention and fire fighting in biofuel storage facilities. As indoor storage is mainly used for dry solid biofuels and most experience is

gained from wood pellet storage, the recommendations below frequently refer to wood pellets but are in general terms also valid for other solid biofuels.

3.5.1 Prevention measures

The following general recommendations and advice should be considered to avoid self-heating and spontaneous ignition in biomass storage:

- Avoid storage and transport of large volumes if the fuel's tendency of self-heating is unknown.
- Be conscious of the risk of self-heating and spontaneous ignition in large storage volumes.
- Avoid storing biomass with moisture contents greater than 15 wt.% (w.b.). Moisture damaged pellets from a rail car or ocean shipment should never be put into the storage, instead they should be dumped in a rejection bin or directly burned.
- Avoid mixing different types of biomass fuels in the storage.
- Avoid mixing fuel batches with different moisture contents.
- Avoid large amounts of fines in the fuel bulk.
- Measure and monitor the distribution of temperature and gas composition within the stored material. Frequent visual inspection is recommended.
- Monitor both the storage compartment and adjacent spaces for CO and O₂ to avoid entry into hazardous environment.
- Limit the storage time.
- Watch the storage principle "first-in-first-out"
- Clean the store before filling in new fuel.
- Control the delivery of fuel with respect to allowed maximum temperature

As mentioned in Section 3.1, low temperature oxidation of pellets will result in the formation of aldehydes and low molecular carboxylic acids, CO₂, CO and methane which constitute health and safety risks [170]. Under certain circumstances, especially in enclosed areas



Figure 3.11. Agglomerated pellets about 1 m above the pyrolysis zone in the test silo [146].



Figure 3.12. Pyrolysis zone about 0.5 m below the ignition source in the test silo [146].

with low ventilation, this might result in acutely toxic environment with very high concentrations of these gases.

In silos and similar storage buildings with low ventilation, a CO sensing system is recommended to monitor the atmosphere at the top of a silo complex as well as in adjacent premises for occupational health concerns.

It is also recommended that both operating and fire rescue personnel wear a personal CO gas detector when entering these storage areas, especially if there are any signs of heat generation, sticky smell or smoke. As the 15 min threshold value for CO is 100 ppm and CO is acute toxic at a concentration of about 1200 ppm (0.12 vol.%), it is not sufficient to measure and rely on the oxygen concentration alone.

For small-scale pellet storage units, which are not air-tight, warning signs stipulating ventilation instructions prior to entering the pellet storage unit are currently developed by both the German and the Austrian wood pellets associations [63]. Further investigations with the aim to develop a new standard for wood pellets storage are on-going/will be initiated.

Since the size of the storage and the possibility for cooling of the material as well as the access to oxygen are important factors for the risk for a thermal runaway, bagging can be a solution for some commodities. Even if the bags are stacked in large stacks there are often more gaps in such storage compare to a compact pile. This means larger possibilities for cooling. If the material, which the bags are made of, is relatively air-tight it might also slow down the process.

The availability of air significantly influences the self-heating and spread of the smouldering kernel. Therefore, it is important to understand both how the air enters a storage facility, e.g. a silo, and how the air is transported inside storage since different materials behave differently, e.g. when it comes to the tightness towards the wall.

3.5.1.1 Outdoor storage

Forest fuels e.g. wood chips, bark and sawdust are normally stored outside as there is no great need for protection from the weather for these types of unprocessed fuels [134]. Also recycled woodfuels are normally stored outdoor.

Logging residues are stored in small road-side heaps and piles. The pile size depends on local factors; however, to promote drying the piles should not be too high. A preferable size is 3 m wide at the base and 2 m high. Comminuted fuels to be stored in larger piles are wood chips, bark, chunks and shredded hog fuel. Large pile sizes are commonly used for e.g. wood chips where the size of a single pile can be up to 15 m in height, a width of close to one hundred meters, and a length of up to two hundred meters [80].

Typical fuels stored as bales are straw, reed canary grass and some logging residues. Individual bales or especially piles of bales are sometimes covered to prevent uptake of moisture.

Recommendations for outdoor storage are often based on experience from real storage situations and incidents that have occurred [175], but there are also some results from storage tests that have made basis for future guidelines [174]. The recommendations can be summarized as follows [175]:

- Different types of wood fuels should be stored in separate piles.
- Limit the differences in moisture within the same pile.
- Do not compact decomposed logging residues.
- Avoid metal objects in the pile.
- Store the wood fuels in long stacks with the base of the cross section twice as long as the height.
- Avoid hollows and elevations along the sides of the stack.
- Construct the stack along the main wind direction.
- Avoid exceeding the heights given in Table 3.1

The recommendations given in Table 3.1 are used also in many other guidelines. More specific recommendations about storage of moist biomass in heaps can be found in the literature and e.g. maximum width and storage height will vary depending on the type of biomass [102, 134].

In many cases the final storage solutions are based on an agreement between authorities, the local rescue services, and/or insurance company on one side and the storage owner on the other side. In Canada one example of guidelines for outdoor storage is the one by Office of the Fire Marshal in Ontario. According to the Ontario Fire Code, the maximum

Table 3.1. Maximum storage heights for different types of wood fuels [175].

	Non-compacted stacks (m height)	Compacted stacks (m height)
Chips from stemwood incl. bark	15	12
Whole wood chips from hardwood	12	9
Whole wood chips from softwood	10	7
Decomposed logging residues	7	-
Bark	7	4
Sawdust	6	4

sizes of piles should not exceed 18 m in height, 90 m in width and 150 m in length unless water pipes with hose connections are laid on the top of the pile [15].

Another available guideline is the guideline by VGB PowerTech on Protection against fire and explosion in biomass power plants [177]. It is not specifically on outdoor storage, but does include recommendations on the handling of fuel during the process, storage in silos and how to limit the risk for explosions. It does, however, include some advice also for how to store biomass safely in piles. Most of the content is included in this document as well.



Figure 3.13. Example of a remote controlled water cannon installed on the capstone of a fuel storage facility for a first fire extinguishing [86].

3.5.1.2 Indoor storage in heaps

Floor storage of the A-frame flat storage type is probably the most common form of large storage for pellets, often used at pellet manufacturing plants or at power plants. These storage facilities range from 15,000 m³ to 100,000 m³ [138]. There is also a similar, more general purpose flat storage used for example in ports for storage of bulk or commodities. Flat stores require a larger foot-print area for a certain storage volume compared to silos. The charging of the store is often made via a conveyor system located along the ridge of the building. By the use of movable scrapers on the conveyer system, the material can be put into a single pile or distributed along the entire length of the building. During discharge of the material, large wheel loaders are often used to bring the material from the heap to a hopper connected to a conveyor system.

The storage volumes in indoor heaps are often very large. An ignition caused by an external ignition source is probably detected relatively quickly by attending personnel, while a spontaneous ignition might be much more difficult to detect. The self-heating process inside the bulk of the heap will create a moisture transport to the surface, which normally will be visible as a “white smoke” (water vapour) from the pellet surface. The water vapour might also condense on the pellet surface and cause the pellets to fall apart to wet sawdust again. These “condensation areas” are easy to detect visually.

Temperature monitoring is complex in flat stores. The temperature on and close to the surface can be measured with a temperature probe inserted into the pellet bulk or by temperature cables incorporated in dividing walls, cross bars etc.

In order to have a more general supervision of the store, a gas analyser for CO or a more advanced fire detection system based on gas sensors (“electronic nose”) could be located at the ceiling of a flat store and thereby monitor a fairly large floor footprint. The latter system indicates when significant changes occur in the gas composition and is able to differentiate between fire gases and exhaust gases from e.g. vehicles. However, as ventilation in the indoor storage might be considerable, these systems do not typically provide the same early warning as sensors embedded in the material.

A better approach to verifying a suspected self-heating/ fire is to insert a CO probe at suspected locations 0.5 to 1.0 m into the pellet bulk. Measurements of very high values of CO (2 to >5 %) would be a strong indication of spontaneous ignition resulted from self-heating. As the CO concentrations might be very high, a self-contained breathing apparatus (SCBA) should be used by the personnel.

In order to limit the consequences of a spontaneous ignition in a large heap, it could be advisable to sub-divide the heap into several cells. This could be accomplished by separating concrete walls which will prevent the pyrolysis zone to spread large distances inside the bulk before it is detected.

In some countries, a modern storage facility for pellets could also contain a forced ventilation system for controlling the thermal conditions in the stored pellets. However, in areas with high relative air humidity, the effects of injecting outside air into the storage have to be considered in view of the equilibrium moisture concentration (EMC) characteristics of pellets. An increased humidity in the pellets will contribute to increased microbial activity. Humid air can also make the pellets swell. Furthermore, in the case of high ambient temperature as compared to the temperature in the pellets, the thermal content of the injected water



Figure 3.14. A pile of pellets in a flat storage. A wireless temperature monitoring spear is used for temperature control. To the bottom right, a separating concrete wall is also visible, which acts as a fire barrier in case of a fire incident.

vapour will contribute to the heating of the pellets (see section 4.1.3). In other words, under certain circumstances, ventilating storage with air containing high relative humidity may in fact lead to temperature escalation in the storage rather than to temperature decrease. In order to avoid this uncontrolled condition, the ventilation system should include a dehumidifier to control the amount of moisture injected into the storage.

3.5.1.3 Storage in silos

A protected storage is needed for refined (dry) fuels. The use of silo is a relatively common type of storage for pellets. When pellet production was started during the 1980s, pellets were often stored in old grain silos. These are made of concrete, very high with a relatively small diameter, often with several silo cells built to one complex and is commonly defined as tower silos. Each silo cell has a volume of typical 1000- 3000 m³. However on industrial plants, the silos are often free-standing and there are mainly two types: tapered (hopper) bottom and flat bottom silos. In the case with tapered bottom, gravity is used to discharge the bulk material at the bottom of the silo and requires that the material is flowing. In

recent years, the trend is towards specially designed free-standing silos with flat bottom and significant large diameter and larger storage volume. Today silos up to 25-30 m in diameter and a similar wall height are commonly used at pellet production plants and at large pellet consumers. However, silos with a diameter up to 70 m and a total storage volume of 100,000 m³ have been built.

These types of silos are also commonly used for e.g. wood chips and various waste fractions as intermediate/ short term storage on e.g. power plants in order to provide an automated handling of the fuel supply during nights and weekends. In the case with a silo with a flat bottom, which can be used both for flowing and non-flowing material, a circulating auger is installed at the silo bottom to discharge the material towards the discharge opening at the silo centre. In all types of silos, the material is often discharged onto a conveyor system located in a tunnel below the silo.

Pellets in silo storage will heat up due to a combination of factors including oxidation processes of the pellets and ambient conditions (such as heating of the walls



Figure 3.15. Temperature spears could be used for checking the temperature in the upper layer of bulk storage in e.g. a flat storage. The spears are often 2-3 m long and are introduced manually into the stack. The picture shows two different spears: one with a hand-held instrument and one (blue) transmitting the data wirelessly to a controller unit (Courtesy of Sensite Solutions B.V.)

from exposure to the sun). Continuous temperature control by sensors embedded in the stored product is therefore required to minimise the risk of fire. Vertically suspended cables containing sensors at certain intervals are an example of how the temperature can be monitored and logged by a computer with alarm functions. The measurement system should be able to measure temperatures of up to 100 °C at a minimum.

However, there are practical problems with vertically suspended cables, which should be considered. If the cables are not secured at the bottom (which is the most common situation), they will be pushed outwards by the pellets, sometimes more or less all the way to the silo wall. This might result in erroneous measurements, measuring the silo wall temperature rather than the bulk material temperature. If the cables are secured at the silo bottom, the forces when filling a silo with pellets could be so large that the roof (if suspended from the roof) could be damaged.

Wood pellets have a low thermal conductivity, normally between 0.18 and 0.24 W/m/K (at a moisture content of 4 and 8 wt.% (w.b.) respectively [87]). The number of sensors needed, therefore, depends on the silo diameter and the sensors need to be distributed at a certain

distance from one to the other throughout the bulk of the heap in order to detect hot spots. However, as the area of a hot spot might be very limited in an early stage of a self-heating process and it is not guaranteed that these are detected by the temperature sensors. The most important measure is, therefore, to use the monitoring system to observe the general temperature trend in the bulk material. A temperature increase of 1-2°C per hour could quickly generate a critical situation, especially if the bulk temperature is already elevated.

As described in section 3.1, the temperature in storages for pellets in bulk can often reach to about 60°C, especially in fresh produced pellets. All pellet storage types need to be able to facilitate emergency discharge of pellets in case the temperature approaches the run-away temperature, which for some types of pellets is around 80°C. The emergency discharge can be done by re-locating the product in another storage facility or in an outdoor location. This process allows pellets to be aerated during which the pellets are cooled down and hot spots are broken up. Large power plants using pellets as a fuel often have a limit of 45 °C above which shipments are rejected.

In order to control the bulk temperature in large silos, ventilation is increasingly used in North America. In many



Figure 3.16. Monitoring of the temperature trends inside bulk storage is important to indicate if there is an unusual self-heating on-going. The black lines from the roof in the picture show temperature sensor cables normally used for such monitoring. . This silo (20 m in diameter) is equipped with one line in the silo centre and six lines distributed at half the radius. All together the seven lines include 37 temperature sensors which are connected to a control system. (Photo Anders Lönnermark, SP)

cases the wood pellets have a high initial temperature due to hot weather, combined with a pellet production using reactive raw material with high oxidative substances. The ventilation air flow is generated by strong fans and the air is always distributed through gaps in the bottom of the silos. Venting is done through dampers at the top of the silos. The temperature is monitored with a number of temperature cables described above, where the sensor configuration needs to be designed with consideration given to the thermal conductivity characteristics, the permeability and variance in permeability, ventilation fan capacity and the geometry of the fresh air inlets. The temperature monitoring system will present a

picture of the temperature distribution in the bulk material and will give alarm when the temperature exceeds a certain level, e.g. 45 °C. The fans are normally controlled by the temperature monitoring system which turns on and off to maintain the temperature within predetermined margins. In some installations, the fans run continuously and are switched off only if the inlet ventilation air temperature exceeds the temperature of the bulk material.

The fan capacity is calculated using the bulk permeability of the material and the geometry of the silo. The fan capacity must be high enough to provide enough cooling. If the fan capacity is too low, the ventilation might make the situation worse, as the increased oxygen supply into the material will increase the oxidation process and thereby result in a temperature escalation rather than to temperature decrease. Due to this, the fans normally have a backup power supply in case of a failure of the normal supply. As mentioned in section 3.5.1.2, a high humidity in the inlet air might cause problems and in order to avoid this, it might be necessary to turn off the ventilation if the relative humidity exceeds e.g. 80 % or to install a dehumidifier system.

The ventilation system can be combined with

the injection of inert gas if the temperature rises above critical values. In this situation it is extremely important to design the ventilation system so that the air supply can be completely blocked to facilitate the inerting operation (see section 3.5.2.2).

It is not possible to give a recommendation on which storage size such measures must be used, since self-heating and off gassing are a function of several parameters such as moisture in the pellets, reactivity related to the species (e.g. pine is generally more reactive than other species), ambient temperature and temperature transients and length of storage.

Self-heating has been observed in stores as small as 25 tonnes and even in heaps of pellets on the ground with as little as 5 tonnes of pellets.

Visual inspection of a silo by working personnel cannot normally be done as in the case of indoor heap storage. A silo should therefore also be equipped with a gas detection system in the silo headspace as a complement to the temperature monitoring system. As described in section 3.5.1.2, a gas analyser for CO or an advanced fire detection system based on gas sensors ("electronic nose") could be used to achieve early indications of a possible spontaneous ignition.

In the case of a suspected fire, specific gas analysers both for CO and O₂ should be used to measure the atmosphere in the headspace volume of the silo. As very high CO concentrations can be expected, the gas analyser should have a measuring range of at least 10 % CO. Both the CO and O₂ concentrations would also become valuable indicators during an extinguishing operation using inert gas, as they can be used to ensure an inert atmosphere has been reached in the silo (see 7.2.2).

In summary, the following general recommendations for storage control and detection in silos should be considered:

- Temperature monitoring of the pellet storage is the most important measure to take. Monitor the temperature at several different locations in the fuel bulk and follow the general temperature trend.
- Measurement of the CO concentration in the air above the pellet surface is a suitable method for detection of any "activity" in the bulk. Other detection methods include "electronic nose" type of detectors.
- The first sign of an on-going self-heating process is often a sticky and irritating smell (probably from aldehydes and low molecular carboxylic acids).
- If "fire smell" is sensed from the storage and/or if smoke (not water vapour) is observed from the storage there is already pyrolysis taking place somewhere in the fuel bulk and a fire fighting operation has to be initiated.
- Advice in case of self-heating/spontaneous ignition and actions for extinguishing a fire are given in section 3.5.2.
- Protect people from hazards of high concentrations of CO and CO₂. Such hazardous situations can arise in rooms or enclosed spaces near a silo or other type of storage with an on-going self-heating process.

3.5.2 Fire fighting

Different types of biomass and different types of storage call for different types of extinguishing media and tactics. Fire fighting of pellets is very different from fire fighting of most other products since water is not recommended, especially in silos. Wetted pellets swell very quickly and

the resulting material becomes extremely hard, often requiring removal by a jack hammer. The fact that pellets expand to about 3.5 times of their original size (see Figure 3.17), when wetted, limits the choices of extinguishing media. The wet media would be suitable for surface fires where the swelling does not cause bridging or potential cracking of the containment walls. However, fires as a result of self-heating usually occur deep inside a pile or containment and are often not detectable until the fire ball is well developed and headspace is filled with combustible gases. This can take many hours [146].



Figure 3.17. The swelling effect of water application to pellets.

Methods for extinguishing fires inside silos or bunkers have been developed by the SP Technical Research Institute of Sweden [142-145] over several years.

The recommended methods for extinguishing a fire in pellet storage and the actions to handle an incipient fire are different for storage in indoor located heaps and storage in silos and are summarised in Section 3.5.2.1 and 3.5.2.2, respectively.

3.5.2.1 Fire fighting of heaps in indoor or outdoor storage

When a fire with open flames is detected, the first measure is to suppress the flames as quickly as possible. Fire development might be quite fast and a delay in the extinguishing operation might increase the risk of total storage loss. Water usage in general should be restricted, except for the purpose of preventing dust clouds formation which might increase the fire intensity. If possible, water sprays should be used but in case the fire is too large, compared to the throw length of the water spray, solid water streams might be used.

If possible, the use of fire fighting foam can improve the operation. If available, the use of a Compressed Air Foam System (CAFS) is probably the most efficient alternative. This provides the possibility of applying a high quality and slow draining foam with good adhesive properties to leading surfaces. Also conventional foam, applied as

low or medium expansion foam, can be used. The foam concentrate should preferably be a Class A-foam, which is a foam concentrate specially developed to be used against class A-fires, i.e. materials causing smouldering fires. Class A-foams are normally also used in CAF-systems. Low expansion foam is foam with an expansion ratio less than 20 (the expansion ratio is the ratio of the volume of foam to the volume of foam solution from which it was made). Medium expansion foam is foam with an expansion ratio greater than or equal to 20 but less than 200. CAFS or low expansion is used where a longer throw length is required while medium expansion foam (and CAFS) can be used if a close approach to the fire is possible. Several benefits of using foam are as follows:

- Foam can be applied more gently than water.
- Foam reduces the risk of dust formation.
- Foam provides a sustained cover for the pellet surface reducing heat radiation towards the surface and thereby the risk of a fast fire spread.
- Foam extinguishing requires less water, which in turn reduces water damage to the pellets.
- Foam is more effective compared to plain water specifically in case of a fire in a wheel loader where a potential for fire to spread to oils, plastics, rubber etc. is high.

If spontaneous ignition occurs inside the pellet bulk, the most probable locations of the smouldering fire should be identified first. The material involved has to be removed by a wheel loader to a safe place. Each bucket should be carefully inspected for the presence of smouldering material. The "safe material" should be separated from material that contains very hot or glowing matter. The latter should be spread out to allow it to cool down and smouldering material should be carefully extinguished with water spray.

During the removing operation, it is important to continuously extinguish any open fire and protect the remaining stack of pellets. The opening of the stack will provide the smouldering material with oxygen which will result in an increase in fire intensity and possibly a "rain" of sparks. Water spray can be used, but fire fighting foam is more effective. The foam layer on top of the pellet stack also limits the oxygen supply to the smouldering areas in the remaining stack and thereby reduces the possible flare up of fire.

Due to the possibility of very high concentrations of CO, self-contained breathing apparatus (SCBA) should be used by all personnel, including the drivers of the wheel loaders.

3.5.2.2 Fire fighting in silos

A consequence of the relatively low fire frequency of silo fires is that the fire brigades in general lack of experience in dealing with these types of incidents and

there is usually insufficient appropriate extinguishing equipment available. The silo fire development and the required emergency response are significantly different from conventional fire extinguishing. In order for the emergency response to be as safe and effective as possible, it is important to consider the specific conditions of silo fires. The information presented in this section is a brief summary of recommendations provided in the book "Fires in silos" recently published by the Swedish Civil Contingency Agency (MSB) [139]. The background material to the book is based on both research projects and from experiences from real fires and the evaluation of fire fighting operations compiled by Persson, Krause and others [8, 97, 140-146, 181], some of which are also available at the MSB web site.

The extinguishing technique for silo fires is completely different from "normal" fire fighting procedures. In contrast to building fires, silo fires pose very limited response alternatives since access to the silo top and bottom is usually very limited. In cases of fire in freestanding silos, such as those for storing biofuel, the silo diameter is normally in the range of 20-30 m, which will cause serious practical problems for the fire & rescue services if preparatory measures for fire fighting operations have not been taken. The most common fire scenario is a pyrolysis deep inside the silo's stored material, which makes it very difficult to locate the centre of the fire and carry out a targeted fire fighting operation. However, there are also examples where the fire has started as a result of small embers brought to the silo through the incoming conveyor system. Such embers could either cause an open surface fire or become buried by the incoming material and cause a pyrolysis fire similar to a spontaneous ignition scenario. The pyrolysis generates high concentrations of toxic and flammable gases that may cause high levels of danger to the plant personnel and the fire & rescue service. Opening the silo for improved access leads to an even worse development with a high risk of smoke gas explosions, open fire and rapid fire escalation within the plant that will result in great damage.

Extinguishing a silo fire is a lengthy process that normally takes several days to complete. The recommended technique is based on injection of inert gas and preventing air (oxygen) to reach the smouldering fire zone. The inert gas should be injected close to the silo bottom to ensure that the entire silo volume is made inert, and the gas must be injected in gaseous phase. Several successfully prevented incidents in Scandinavia [136, 140, 141] provided much valuable evidence for the viability of this method. One of the key factors is to understand the anatomy of a silo fire, which is described in Section 3.4.

In order to minimise the consequences of a silo fire and ensure an effective extinguishment, the following fire management aspects need to be considered:

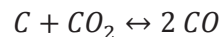
- Suitable equipment for the gas supply must be readily available (delivery of gas, vaporisation unit and preferably a storage tank for the liquid gas).
- Possibilities to inject and distribute the gas close to the silo bottom. For large diameter silos, the silo needs to be equipped with a fixed pipe system to enable gas injection and gas distribution inside the silo in an emergency situation. For small diameter silos, penetrations of the silo wall to insert lances for gas injection might be possible to arrange during the acute situation.
- The silo construction should be as airtight as possible in order to reduce the infiltration of air (oxygen) into the silo compartment.
- There should be possibilities to evacuate the combustion gases at the top of the silo through a "check valve" arrangement which prevents inflow of air (oxygen) into the silo headspace.
- There should be preparations for an emergency discharge of the silo content following the inertisation of the silo.

Normally, it is not necessary to install a fixed gas tank and vaporization unit to every silo facility. In Sweden, it is proposed to use mobile emergency equipment which is transported to the silo when a fire is suspected or detected. As a silo fire develops slowly in the early stages, and the use of temperature monitoring and gas detection systems provide the possibilities for an early detection, there will normally be several hours available to bring in the mobile equipment. Figure 3.18 shows a picture of such mobile equipment that has been successfully used at some silo fires in Sweden.



Nitrogen is recommended for the inertisation as it is normally easily available and the vaporisation unit does not need any energy supply as the vaporisation energy is taken from the surrounding air.

Carbon dioxide would provide the same inertisation effect but requires a powerful external heat source for the vaporisation unit making it less suitable for emergency situations. Trying to use carbon dioxide without a vaporisation unit has caused many unsuccessful extinguishing operations as the supply hoses/pipes, nozzles/lances and the bulk material close to the injection point tends to freeze quickly and thereby completely block further gas injection. Further, there could be a serious risk in using carbon dioxide during the conditions generally found in a silo fire as it might contribute to an increased production of carbon monoxide. At temperatures above 650-700 °C in combination with limited oxygen supply, CO can be formed from CO₂ through the reaction



In such cases, the addition of CO₂ from an inerting operation will cause a contribution to the production of the flammable gas CO. The use of carbon dioxide could, therefore, result in a more severe fire instead of providing a fire extinguishing effect.

The nitrogen should be injected close to the silo bottom. This ensures that the air/combustion gases are replaced by an inert atmosphere quenching the smouldering fire. As the smouldering fire zone has a tendency to spread downwards in the silo, gas injection from below ensures that the smouldering zone is reached by the inert gas. This technique has also the advantage of pushing the combustion gases inside the bulk material towards the



Figure 3.18. Mobile fire fighting unit for silo fire fighting. Example of 47 m high silo (left) fire successfully extinguished in Sweden 2007 by injection of nitrogen using mobile equipment (right) consisting of a vaporisation unit and a tank for liquefied nitrogen; [141].

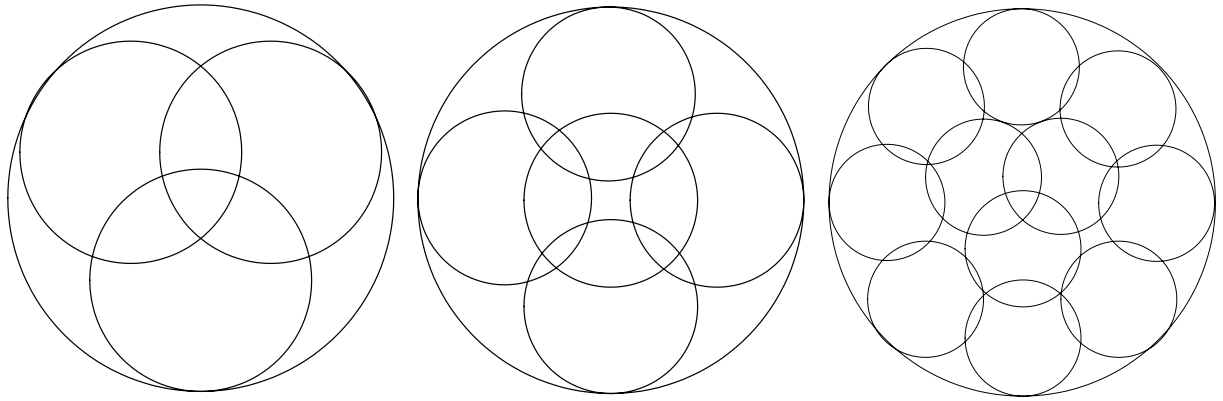


Figure 3.19. Principle sketch of distributed gas injection in silos. The number of gas injection points will depend on the silo diameter and the gas flow rate per injection point; data source [145].

headspace in the silo. Measuring the gas concentrations in the headspace (primarily CO and O₂) provides a verification of the extinguishing process as a reduced CO concentration indicates that the pyrolysis activity is controlled. Low oxygen content in the headspace is important to minimise the risk for gas or dust explosions.

In small diameter silos (5 to 6 m), one gas injection point close to the centre of the silo will normally be sufficient. At larger diameters, one inlet will not ensure an even distribution over the cross section area. Several inlets are therefore recommended as shown in Figure 3.19 and the number of required inlets will depend on the silo diameter and the gas flow rate at each inlet.

For small diameter silos it might be possible to arrange a provisional gas injection in an emergency by using one or several lances made of steel pipes (see Figure 3.20). For large diameter silos, exceeding 10 to 15 m in diameter, it will be probably be impossible to insert the lances deep enough in the bulk material. It is, therefore, important to prepare the silo for gas injection during the design and construction phase. If the silo is equipped with a ventilation system for cooling, the duct system could be used for the gas distribution. However, it is extremely important that the fans can be completely sealed in order to prevent air entrainment and loss of nitrogen.

If there is a risk for a gas or dust explosion, the oxygen concentration in the silo head space needs to be lowered below the lower oxygen limit (LOL), i.e. the concentration of oxygen in a confinement volume below which combustion cannot be sustained. The LOL depends on the material as a rule of thumb the advice to keep the oxygen concentration below 5 % to avoid a gas or dust explosion [97]. It is important to note that water should not be used in a silo fire containing wood pellets as this will cause



Figure 3.20. A 50 mm perforated steel pipe (left) used for gas injection in a silo fire in Sweden 2007. The lance was inserted through a drilled hole (right) close to the silo bottom and connected to the vaporisation unit by a hose; data source [141].

significant swelling of the pellets (cf. Figure 3.17). Swelling could lead pellets to stick to the silo wall and create bridging or hangings high up in the silo. Extinguishing operation and subsequent unloading can easily be hindered through the swelling process. The forces from the swelling might also lead to severe damage and even make the silo construction to collapse. Water could also cause formation of combustible hydrogen inside the silo presenting a risk of severe

explosions. The potential dangers and risks involved with water extinguishing should be recognised in order to ensure the safety of the personnel involved.

From the personnel health and safety perspective, it is very important not to open up or start to unload a silo with an on-going fire as this might cause severe gas and dust explosions. There are several examples of total losses, both of the bulk material and the entire silo construction when attempts have been made to discharge the bulk material without first controlling the pyrolysis fire. In the example shown in Figure 3.21 severe flames were achieved when a concrete silo filled with wood pellets was opened up for emergency discharge. Jet flames up to 50 m long occurred due to gas explosions inside the silo.

The most important steps to fight a fire in a silo are summarized below while further detailed information for each step is provided in the silo handbook [139]:

- **Identify the type of silo and fire scenario.** Is it a smouldering fire or a fully developed surface fire with open flames? Has the smouldering fire been confirmed, for example, by heavy smoke, discovery of smouldering material during discharge of material, etc.? Is it a suspected smouldering fire detected by

a sharp odour, increased temperatures in the silo, increased concentrations of carbon monoxide, heavy condensation at the silo top etc.? A smouldering fire often occurs deep in the material and slowly spreads downwards, while pyrolysis/smoke gases and moisture slowly spread upwards and may take days to show clear observable signs of fire. What kind of material is in the silo and what is the fill level?

- **Carry out an initial risk assessment and establish access rules.** Be aware that a suspected or verified smouldering fire may cause high levels of carbon monoxide on site. Dangerous concentrations may even be present in personnel areas, control rooms, etc. Measuring instruments that show **both** carbon monoxide (CO) **and** oxygen (O₂) levels should be used to continuously assess the risk area. When in doubt, use full protective gear.
- **Consider the risk of fire gas/dust explosions.** If possible, measure the concentration of CO and O₂ inside the silo headspace. If significantly increased concentrations of CO of >2-5 % and an oxygen concentration higher than 5 % are identified, there is a risk that the gases may be flammable, which entails the possibility of a gas explosion. If this is



Figure 3.21. Flames on the outside of a silo caused by an opening in the silo wall [8].

the case, one should not be at the silo top unless absolutely necessary. Expand the risk area at ground level in case an explosion should occur.

- **Close the silo to minimize air entrainment.** Close gaps, seal openings on the silo and shut off the ventilation system, close dampers/seal channels/connections etc. There must, however, be a small opening at the top of the silo to release combustion gases and restrict air from entering the silo. A rubber flap over an open top hatch works well as a "check valve".
- **Mobilise equipment.** Mobilise vaporization equipment, a cryogenic tank and a tanker with liquid nitrogen (N_2) as soon as possible. Evaporation equipment is necessary as the gas must be injected in gas phase. Identification of suppliers of gas and gas equipment and emergency contact details should be part of the pre-planning process. Be aware that the equipment requires a relatively large ground area and it should be placed outside the "risk zone". Make sure that the required hoses do not block necessary traffic in the area. It may be possible to extract a limited flow of gas directly from the tanker during the initial phase.
- **Inject nitrogen at the silo bottom.** Injecting nitrogen gas (N_2) close to the bottom of the silo is the safest and most effective fire fighting method in most cases. The injection rate of nitrogen gas is based on the silo cross section area and should be at least 5 kg/m² per hour, which gives an average vertical gas filling velocity of about 8 m/h (based on 50 % porosity in the bulk of the material). The total required gas should be established based on the silo's gross volume (empty silo) and a total gas requirement of 5-15 kg/m³. If the silo has not been prepared for gas injection, drill holes at the bottom of the silo and prepare lances for the injection of the gas (if considered possible from a safety and practical point of view).
- **Mobilize gas measuring equipment.** If possible, mobilize measurement equipment in order to measure the CO and O_2 concentrations in the silo headspace during inerting- and discharge operation. Observe that the measurement instrument for CO must be capable of measuring extremely high concentrations, preferably at least 10 % CO, in order to provide relevant information (Identification of suppliers of suitable instruments should be part of the pre-planning process). For safety reasons, the instruments should be placed a safe distance from the silo, which requires a powerful gas pump. The gas line must also be equipped with condensation traps, particle filters and drying agents to protect the gas instrument.
- **Apply foam in the silo top if necessary.** If delivery of the gas equipment takes a long time and/or there is a significant risk of an open fire, the stored material may, if acceptable from a safety point of view, be covered with medium or high expansion foam. The foam must also be of high quality so that drainage is minimized. If access is available to a CAFS equipment (Compressed Air Foam System), this may be greatly beneficial. It is important to not open the silo more than necessary. Doing so will oxygenate the pyrolysis gases in the top of the silo. Additionally, attempt to minimize the risk of dust formation during application. Affected emergency response personnel should wear full protective gear.
- **Start to inert the silo.** Once the gas equipment is in place, the inerting operation of the silo should start as soon as possible. If the measurements indicate a potential risk for an explosion in the silo top ($CO > 2-5 \%$, $O_2 > 5 \%$), inject nitrogen into the silo headspace. This must be done with extreme caution to avoid a risk of explosion being caused by dust formation. As soon as the nitrogen injection into the silo headspace has started, the injection through the silo bottom should begin as well, possibly at limited capacity. When the oxygen concentration in the silo top is under 5 %, the gas flow to the top of the silo should be terminated and the entire gas flow should be directed to the bottom at the recommended injection rate.
- **Begin discharge of the silo.** Begin the discharge operation only when the fire is deemed to be under control, which is when the oxygen content is less than 5 % and the CO-concentration significantly reduced. Fire & rescue personnel with full protective gear must be present at the discharge opening in order to extinguish any smouldering material and, when needed, to clear clumps or 'carbonised' material from the outflow opening. Constantly assess the situation inside the silo using the gas readings in the top of the silo. An increasing concentration of carbon monoxide signifies increased "activity" in the silo, while increasing oxygen content may be a result of air leaking in. If the oxygen level is over 5 %, the discharge operation should be temporary terminated and the nitrogen injection rate should be increased until these levels drop and the oxygen level is below 5 % again. If possible, gas injection through the silo top may be an option in the event of increased oxygen levels. Remain observant of possible bridging or hangings in the silo that may cause problems when discharging the silo and make the fire fighting response even more difficult.
- **Plan for a long discharge operation.** Count on the discharge operation to take several hours and sometimes even several days. Base your judgement on the maximal discharge capacity and count on the discharge taking at least 2-4 times longer. Since fire fighting personnel must be present at the discharge opening (and possibly at other points along the discharge system), a high number of fire-fighters might be required to facilitate frequent changes in

staff. A large number of oxygen packages might also be required for the fire-fighters' SCBA equipment.

- **Sort discharged material.** Sort the discharged material so that "undamaged" material is sorted separately from discoloured or smouldering material, which are usually in large charcoal-like clumps. Monitor the pile and carry out subsequent extinguishing of the material when needed. If dry material, e.g. wood pellets, tarpaulins may be used to protect undamaged material from precipitation. Observe that this handling may require large storage spaces.
- Continue to inject gas into the silo. Gas feeding through the bottom of the silo should continue throughout the entire discharge process. The injection rate is controlled based on the oxygen readings in the silo top and the oxygen concentration should not exceed 5 %.

4. OFF-GASSING FROM LIGNOCELLULOSIC BIOMASS

4.1 Introduction

As stated before, forestry by-products is an important bioenergy resource used either directly or for the production of wood pellets. These by-products may originate from different species and may have undergone different forms of pre-treatment. For example, two common raw materials in Sweden are sawdust from Scots pine (*Pinus sylvestris*) and sawdust from Norway spruce (*Picea abies*). This material is first dried at high temperatures before extrusion at high pressure and temperature to form the pellets. The kind of raw material, its treatment prior to production, as well as the pellets manufacturing conditions influence an important phenomenon known as off-gassing. This term refers to the emission of different volatile compounds by wood pellets along the supply chain, that is, from manufacturing to customers use. The compounds that have been found can be divided into condensable gases and non-condensable gases.

The ISO Technical Committee 238 Solid Biofuels has drafted a standard methodology which can be used when establishing emission factors for biomass at various temperatures in un-ventilated spaces [3].

4.2 Condensable gases

Wood is composed of cellulose, hemicellulose, lignin, and lipophilic compounds such as fatty acids and resins, which are commonly referred to as part of extractives. During thermochemical conversion, these lipophilic compounds yield carbonyl compounds (aldehydes and ketones) and also complex terpenes. Several research

studies have been done to understand the physical and chemical mechanisms underlying this phenomenon. According to Nielsen *et al.* [135], resins and fatty acids migrate to the surface of wood particles during high temperature drying. This migration may make them more prone to undergo hydrolysis and oxidation, which may decrease small molecular size fatty acids and diterpenoid structures during storage, while polymerization may increase the amounts of larger molecular size compounds.

4.2.1 Aldehydes & ketones

Aldehydes emitted by lignocellulosic biomass are considered the result of the oxidation of the unsaturated fatty acids double bonds [34]. The aldehydes formed during storage depend, as stated before, on the storage conditions, the biomass species and characteristics, and eventually its pre-treatment and pellet manufacturing parameters. The aldehydes and ketones that have been reported as emissions from lignocellulosic biomass are methanal, ethanal, acrolein, 2-propanone, propanal, butanal, benzaldehyde, pentanal, toloulaldehyde, hexanal, octanal, and nonanal [34]. The age of the biomass is also important. A comparison between newly produced (fresh) and stored pellets has shown that higher levels of emissions are released from short time stored pellets. In a study made by Arshadi and Gref, a three-week-old pellet is observed to emit about 28 times more pentanal and 8 times more hexanal than the reference pellets [35]. In industrial warehouses, Svedberg *et al.* also found heptanal, 2-heptanal, and decanal. Hexanal is the component found in major proportion both in laboratory and industrial scale [170].

There are two main mechanisms through which lipids can deteriorate. The first of these is lipolysis, which is a hydrolysis of triacylglyceride ester bonds resulting in fatty acids being released. This reaction can be catalysed by high temperatures and by the action of lipases. The other mechanism is oxidation, which occurs in double bonds of unsaturated fatty acids. Some authors refer to it as autoxidation because the intermediate products of the reaction maintain it and accelerate it. The reaction is favoured by temperatures above 60 °C, and its speed doubles per each 15 °C increase. Also, iron catalyses this reaction in concentrations as low as 1ppm. Fatty acids released from hydrolysis are more prone to oxidation than when they are in the esterified form. Autoxidation starts with the formation of free radicals that in presence of oxygen, hydroxyperoxide radicals are formed. They can interact with an unsaturated fatty acid producing two hydroxyperoxides and a new free radical. Hydroxyperoxides are very reactive and cause other transformations. A very important one is their rupture. When their oxygen-oxygen bond breaks, an alkoxy radical is produced (Figure 4.1). When their carbon-carbon bond breaks, aldehydes, acids, hydrocarbons, and ketoacids are formed

(Figure 4.2). All these compounds can react further in oxidation, hydrolysis, and polymerization reactions, creating a wide range of volatile substances [42].

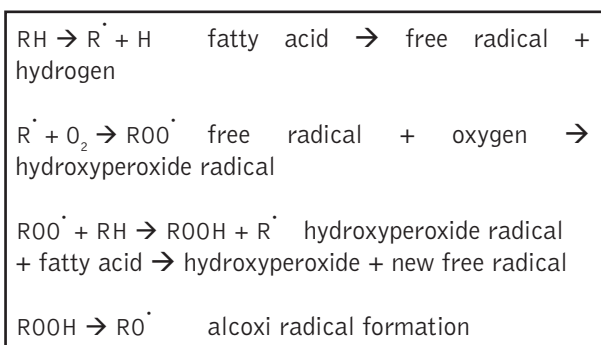


Figure 4.1. Mechanism of fatty acids autoxidation (Adapted from [42]).

Eleven different pellets qualities of mixtures of fresh pine and spruce were made according to an industrial experimental design. About 7 tonnes of each pellet type were stored in 11 different, separate piles for 1 month. The temperature in the piles of pellets made of mostly pine sawdust increased to maximum 55 °C. During the storage period, the total amount of fatty and resin acids decreased by about 40 % and aldehydes and ketones decreased by about 45 % due to oxidation of fatty acids. Resin acids are also oxidised, e.g. most of the dehydroabietic acid in the stored pellets oxidised to 7-oxo-dehydroabietic acid during the four weeks of storage. Pellets made of 100 % spruce contain less fatty and resin acids and therefore emissions (off-gassing) of volatile aldehydes and ketones were limited [34].

4.2.2 Low molecular carboxylic acids

Further auto-oxidation of aldehydes and ketones leads to corresponding carboxylic acids. For example,

hexanal continues to oxidize and is often converted to hexanoic acid [34]. Off-gassing of these carboxylic acids, like butanoic acids and octanoic acids, results in a pungent smell. Moreover, some of these volatile organic compounds (VOC) may have a negative impact on human health, e.g. irritation of the eyes and upper airways.

4.2.3 Terpenes

Terpenoids are chemical compounds whose backbone is isoprene, $\text{CH}_2=\text{C}(\text{CH}_3)-\text{CH}=\text{CH}_2$ (C_5H_8). They are biosynthesized in plants; thus, they naturally exist in tree resins. In conifers, they are present in large quantities and participate in mechanisms of defence against hostile biological and mechanical agents. The predominating kind are formed of two molecules of isoprene, known as monoterpenes, and contribute to the characteristic odour of wood [41]. Granström reported the emission of terpenes as the major volatile compounds in stored wood pellets [82], detecting α -pinene, β -pinene, myrcene, 3-carene, limonene, and terpinolene, all of them monoterpenes (Figure 4.3) Monoterpenes are unsaturated compounds, in consequence, very reactive in photochemical reactions in the troposphere [41].

It has been reported that extractives in wood before storage contain diterpenoid structures ($\text{C}_{20}\text{H}_{32}$), and that after storage, triterpenoid ($\text{C}_{30}\text{H}_{48}$) and steroidal structures are found instead [135]. Granström describes that monoterpenes ($\text{C}_{10}\text{H}_{16}$) and sesquiterpenes ($\text{C}_{15}\text{H}_{24}$) are important volatile compounds emitted during drying [81]. Sesquiterpenes are more reactive in the atmosphere, but are not as volatile as monoterpenes, although they are naturally emitted to air from conifers, being humulenes and caryophyllenes (Figure 4.4) the most extensively reported [41]. Emissions of terpenes are influenced by intrinsic factors, such as the conifer genetics load, and by extrinsic factors, such as environmental conditions [41].

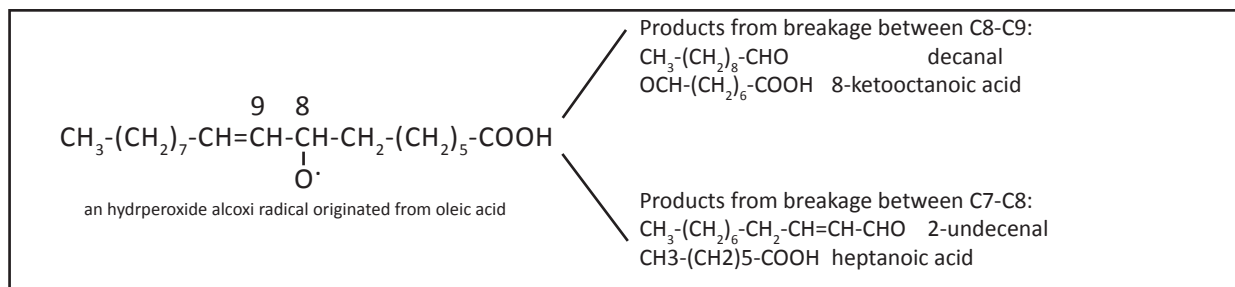


Figure 4.2. Products formed from hydroxyperoxide carbon breakage (Adapted from [42]).

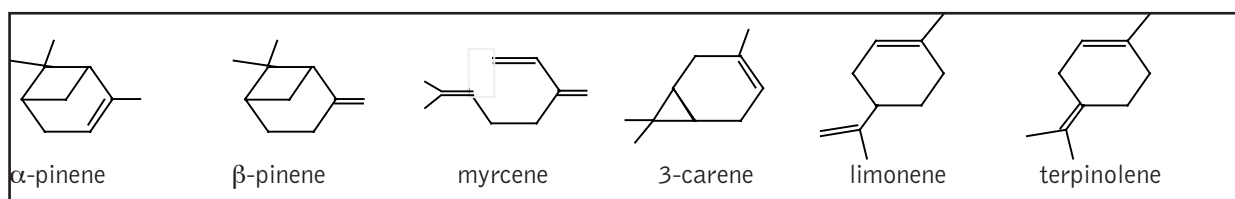


Figure 4.3. Structural formulas of prevailing monoterpenes in conifers.

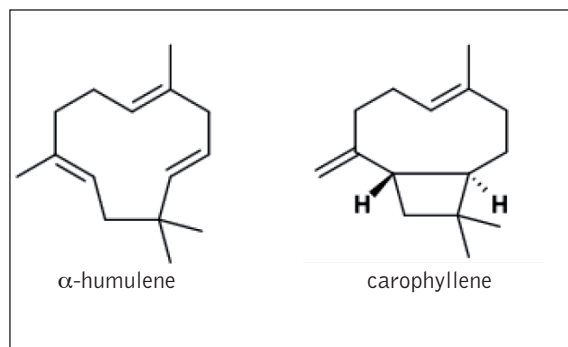


Figure 4.4. Structural formulas of two prevailing sesquiterpenes.

Biogenic terpenes, those emitted from naturally grown forests contribute to a low rise of terpene levels in air. However, high loads of terpene emissions derived from the activities of man in the forests, the so called anthropogenic terpenes, are considered pollutants. This is a topic of concern, as terpenes are highly reactive and may contribute to the formation of photochemical oxidants, such as ground-level ozone, peroxides, and organic nitrates. These photochemical oxidants are considered a major cause of forest decline [41]. Emissions of terpenes are observed to be low in stored wood pellets as most of them are thought to be eliminated early during wood processing.

4.3 Non-condensable gases

4.3.1 CO, CO₂, CH₄

During storage, most types of lignocellulosic biomass emit non-condensable gases, mainly carbon monoxide, carbon dioxide and methane. It is important to know the amount and rate of off-gassing when designing a particular storage system safely. This depends on several parameters, such as the type and origin of the lignocellulosic material, the way it was produced, moisture content, etc.

As these non-condensable gases result in oxygen depletion and may in some case be poisonous, sufficient ventilation of storage rooms is necessary. This is particularly the case for CO₂, which is heavier than air and may therefore tend to settle in a storage bunker or flow to lower placed fuel discharge areas.

4.4 Analysis methods for off-gassing

4.4.1 Analyses of aldehydes and ketones

One way to analyse aldehydes and ketones in biomass has been described previously [34]: The biomass samples are placed in a closed system and heated to 55 °C. The off-gassing is forced through sampler (cartridges made of DNPH, dinitrophenylhydrazine) by a vacuum pump during a certain time. The aldehydes and ketones are converted to corresponding hydrazones by reacting them with dinitrophenylhydrazine inside

the cartridges. The hydrazones are released by elution with acetonitrile. The solution is analysed by high pressure liquid chromatography (HPLC) to determine the exact amount of each aldehyde and ketone.

4.4.2 Analyses of terpenes

One common way to sample terpenes is using gas chromatography. Strömwall and Petersson measured terpene emissions from pulp mills processing wood using these adsorbent cartridges connected to portable air sampling pumps and analysed them by thermal desorption (200°C) and temperature-programmed (2 °C per min increase from 0 °C) gas chromatography with FID detector [167]. Granström used static headspace gas chromatography (SHS-GC), in which a sample is sealed in a vial and often heated to enrich the headspace with volatiles [82]. A portion of this headspace is injected into a gas chromatograph with a non-polar capillary column. It is also possible to analyse volatile organic compounds like terpenes by Solid Phase Microextraction (SPME) combined with GC-MS [96].

Spectroscopy has also been used to measure terpene emissions. Svedberg et al. used Fourier Transform Infrared Spectroscopy (FTIR) and a tracer gas method to measure these compounds in the sawmill industry, making it possible to eliminate the difficulty of assessing diffuse emissions. The diffuse airflow factor had been until then an important factor of uncertainty in these studies [172]. By using this technique the diffuse airflow can be characterized, allowing efficient experimental set-ups for long-term measurements [168].

4.4.3 Analyses of CO and CO₂

There are several ways to analyse CO and CO₂, e.g. headspace analyses of a fuel storage silo by gas chromatography in combination with mass spectroscopy (GC-MS). The gas samples are injected to a GC-MS equipment and the amount of CO and CO₂ are evaluated.

Other methods include non-dispersive IR and FTIR; and the use of gas analysers such as Palgo's ECOM J2KN Pro, which measures high levels of CO (up to 63,000 ppm) by electrochemical and IR techniques. This equipment also measures CO₂ and CH₄.

4.5 Safety aspects of off-gassing

The safety aspects of off-gassing for lignocellulosic biomass were ignored for years. It was not until the decade of 2000, after the Rotterdam and Helsingborg fatal accidents with wood pellet shipment, that industry and research institutions joined efforts to do in depth investigation of wood pellets properties that included off-gassing, and the influence of storage parameters (e.g. moisture and temperature) on this phenomena. This work resulted in new industrial safety guidelines on the handling of raw material and finished product and materials safety data sheets (MSDS) have been issued [113, 114].

However, there are still two main challenges to overcome. One of them is better understanding of the mechanisms that cause off-gassing and how these mechanisms are influenced by raw material characteristics, process parameters, and storage conditions. The second challenge is to strengthen the safety capability of industry by having simple and precise standard methods expressed in standard operating procedures (SOP), ensuring compliance from their trained personnel. The aim is to have a 100 % safe biofuel supply chain, from production to end user delivery and consumption.

Safety is a critical element that must exist in any industrial and domestic setting. Since wood pellets are increasingly traded and used as a standard fuel, this section provides particular information on this type of fuel. Wood pellets need to be handled following specific guidelines to prevent health and safety incidents. In this section we discuss the reasons underlying the health and safety issues caused by pellets off-gassing.

As all lignocellulosic biomass types, wood pellets are organic material undergoing biological degradation and chemical autoxidation, producing heat and emissions of CO, CO₂, CH₄, and VOC. In addition, they suffer mechanical degradation producing fine dust particles, which represent a health risk if inhaled and a safety risk for fires and explosions [138], as detailed in chapter 3.

Fatty and resin acids are a part of wood extractives and are present in fresh lignocellulosic biomass in approximately 0.6 % [35]. Depending on the raw material combination used these compounds undergo an autoxidation mechanism, producing volatile organic compounds like the aldehydes pentanal and hexanal (the latter being the most significant component). It has been shown that self-heating may be correlated to auto-oxidation of organic compounds, mostly these fatty and resin acids [34]. It has also been suggested that carbon monoxide may be formed during autoxidation [170]. However, the reason and mechanism of carbon monoxide off-gassing has not yet been revealed.

Because the level of off-gassing depends on the amount of unsaturated fatty acids and resins, pellets with higher content of these extractives tend to emit higher levels of VOC and CO. This can be observed by comparing pellets made of Scots pine (*Pinus sylvestris*) with those made of Norway spruce (*Picea abies*) (the former having a higher content of fatty and resin acids and thus the highest emission of volatile organic compounds [35]).

4.5.1 Safety aspects of volatile organic compounds

Emission of aldehydes is a health issue. Pentanal and hexanal are emitted at high levels from stored pellets. According to Svedberg *et al.*, hexanal is known to be a substance that causes skin and upper airways

irritation, as it may enter the body by contact with skin or by inhalation, and therefore, it may be considered an occupational and domestic health hazard [170]. Ernstgård *et al.* evaluated the effects of hexanal on the health of individuals exposed to known concentrations for short periods of time and found that individuals presented mild irritation symptoms, measured as headaches, discomfort on eyes and nose, during exposure to 10 ppm hexanal. However, no significant differences in inflammatory markers CRP and IL-6 after exposure were found. They concluded that 10 ppm is the “lowest observed adverse effect level” and 2 ppm the “no observed effect level” [74]. With reference to aldehydes, levels in domestic sites and warehouses have been found at levels of 98±4 mg/m³ and 111±32 mg/m³, respectively [170], i.e. 10 times the “lowest observed adverse effect level” is found in these settings. Therefore these conditions constitute a health hazard and require attention and preventive measures to be taken. Other aldehydes, such as methanal and ethanal, are suspected to be carcinogenic in high doses and may also have some short time effect on human health. There are several guidelines issued by government official institutes that describe the effect these aldehydes have on human health depending on exposure time and level. Table 4.1 shows exposure limits for some aldehydes:

Monoterpenes are VOC of health concern too. It is known that monoterpenes cause eyes and respiratory system irritation [82]. It has also been observed that these compounds are present in fresh woody biomass, but in very low concentrations in finished pellets during storage [170]. High terpene emissions occur early in the wood processing. According to Strömvall and Petersson, “large amounts of monoterpenes are released to the air from de-barking”, which is a common process step before the wood is used in sawmills [41]. During storage of wood pellets, emissions of monoterpenes α -pinene and 3-carene predominate compared to other terpenes, and they dramatically decrease after twenty days after pelleting [82]. Sesquiterpenes, another class of terpenes, have been detected in significant amounts during the drying process of sawdust from Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*).

Considering these levels along with those of monoterpenes emitted during the same process, the occupational exposure limit (OEL) for turpentine is sometimes exceeded [83], so preventive measures must be taken to decrease or avoid exposure for workers during pellet production. Turpentine is a mixture of terpenes obtained by distilling resins of *pinus* species and is used as a reference to calculate the OEL of terpenes. Regarding the risk of explosion, during a study of toxic gases in sea transportation of logs and wood chips, Svedberg *et al.* recorded 160 ppm of α -pinene, which corresponds to 2 % of the lowest explosion limit (LEL) for turpentine, 8000 ppm [171]. This suggests that it is

Table 4.1. Exposure limits for some common aldehydes (Adapted from [32].

Aldehyde	C/S	Cas nr	EL ^a	STEL ^b
Acetaldehyde	C	75-07-0	25 ppm (45 mg/m ³)	50 ppm (90 mg/m ³)
Formaldehyde	C, S	50-00-0	0.3 ppm (0.37 mg/m ³)	0.6 ppm (0.74 mg/m ³)
Furfural	C	98-01-01	2 ppm (8 mg/m ³)	5 ppm (20 mg/m ³)
Glutaraldehyde	S	111-30-8	-	0.1 ppm (0.4 mg/m ³)

a. EL: exposure limit for a work day

b. STEL: exposure limit during a 15 minute period

unlikely that monoterpenes emitted from wood pellets or from their raw materials could cause an explosion.

4.5.2 Safety aspects of CO

Carbon monoxide is a non-condensable gas that is flammable at certain concentrations. It has a LEL of 12.5 % [137]. The highest levels that has been measured in an ocean transportation vessel was 14,650 ppm [173] and in different heights in silos was 10 % [146]. This means that CO accumulation in fuel storages does not constitute a risk of explosion on itself, but may possibly act synergistically with self-heating and/or high level of fine dust to contribute to ignition or explosion incidents. However, fatal accidents that have occurred so far that have involved losses of human lives have been due to CO poisoning.

As mentioned before, it has been suggested that CO is a product from the autoxidation process of fats in biomass and its emission is often correlated to that of hexanal [170]. CO is a noxious substance because it has a 245 times stronger chemical affinity to haemoglobin than oxygen, even though its rate of binding to this protein is 20 % slower than the binding rate to oxygen [137]. Haemoglobin is the blood protein that carries oxygen to every tissue in our body, and to do so it binds to oxygen forming oxyhaemoglobin. When there is a high concentration of CO present in the environment and a low concentration of oxygen, the haemoglobin binds to CO, forming carboxyhaemoglobin (COHb). The presence of COHb not only causes less oxygen to be bound to haemoglobin, it also influences the oxyhaemoglobin dissociation, with the end result that the tissue oxygen partial pressure decreases causing tissue hypoxia [137]. The lack of oxygen in tissues damages them, and tissues like those in heart and brain that require higher oxygen levels are more susceptible.

Symptoms of high or prolonged exposure to carbon dioxide include headache, increased heart rate, dizziness, fatigue, rapid breathing, visual and hearing dysfunctions. Exposure to higher levels may cause unconsciousness or death within minutes of exposure. Above 2%, carbon dioxide may cause a feeling of heaviness in the chest and/or more frequent and deeper respirations. The breathing rate doubles at 3% CO₂ and is four times the normal rate at 5% CO₂. At levels above 5%, concentration CO₂ is directly toxic.

More carbon dioxide may mean less oxygen also and reduction of oxygen level may have an effect on human health. When there are low levels of oxygen in the environment, the organism experiences hyperventilation, in which the body breathes more rapidly in order to get more air, but under oxygen depletion with CO present, hyperventilation only results in a faster uptake of CO and in an increase of COHb in the blood stream. Normal levels for COHb in our bodies are 0.5-0.8 %, while smokers may present concentrations as high as 8 %. The lethal threshold level is considered to be 40 % [137]. According to the U.S. Environmental Protection Agency, an exposure to CO above 420 ppm for 10 min or 150 ppm for 30 min may cause irreversible or serious, long lasting adverse health effects, or an impaired ability to escape, including susceptible individuals (people suffering cardiovascular diseases). While an exposure above 1700 ppm for 10 min, 600 ppm for 30 min, or 330 ppm for 60 min may cause life-threatening health effects or death [137]. Therefore, it is recommended to maintain a minimum oxygen level of 19.5 % and monitor the level of CO at the same time. The International Maritime Organization (IMO) forbids entry to spaces unless there is a minimum of 20.7 % oxygen in combination with a maximum of 100 ppm CO [138].

Safety guidelines available today to avoid CO poisoning consider a proper ventilation of the area, the use of gas meters for both CO and O₂, the use of self-

contained breathing apparatus when the levels of these gases are not in the safe range [138]. The strict use of these guidelines has helped to ensure a safe wood pellets handling and avoid CO poisoning accidents. These guidelines are summarised in Chapter 8.

4.5.3 Safety aspects of methane

Methane gas is an important greenhouse gas. Methane is not very toxic; however, it is extremely flammable and may form explosive mixtures with air. Methane gas can be very explosive when it's concentrated.

Due to oxygen depletion, possible health effects of breathing in methane at high concentrations are increased breathing and pulse rates, lack of muscular coordination, emotional upset, nausea and vomiting, loss of consciousness, respiratory collapse and death.

4.5.4 Safety aspects of CO₂

As for other gases mentioned above, CO₂ is formed as a product of autooxidation, both in fresh biomass and matured biomass. Due to higher molecular mass, there is an increased risk of oxygen depletion. The associated health risks are increased breathing and pulse rates, lack of muscular coordination, emotional upset, nausea and vomiting, loss of consciousness, respiratory collapse and death. Sufficient ventilation in storage rooms and lower placed fuel discharge areas is therefore essential.

- Whether the particles are suspended in the air as a cloud or lodged as a layer
- Volumetric concentration of dust particles in a cloud
- Thickness of a dust layer
- Access to air (oxygen)
- Turbidity of the air
- Energy in the ignition source
- Temperature of the ambient air
- Temperature of the dust

In order for a dust cloud explosion to take place there are five factors that need to be present. These are illustrated in Figure 5.1, which shows the "explosion pentagon".

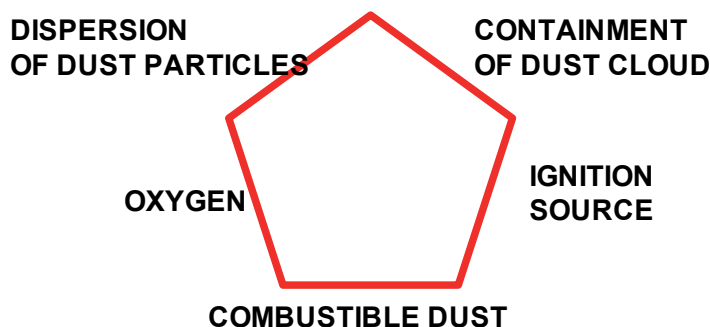


Figure 5.1. The "explosion pentagon".

A dust explosion is in most cases not a single event. The most common scenario is initial ignition of a dust cloud or a dust layer due to overheating, together with a mechanical spark caused by a stone or piece of tramp metal entrained in the material flow, a spark from hot welding work, arc from malfunctioning electrical equipment or electrostatic discharge. The initial event may start as a very small explosive fire, which in turn generates a pressure wave that shakes loose dust lodged on the floor, beams, ledges, equipment etc. The liberated dust typically has a high concentration and access to air (oxygen) and ignites easily, becoming a fire ball that propagates close to the speed of sound (343 m/s at room temperature) as long as the dust concentration exceeds the required minimum concentration and there is oxygen present. The exothermic chemistry within this propagating fire ball is called deflagration and in essence is an explosive fast moving fire, often referred to as the secondary explosion. In many cases there is a noticeable lag time between the primary explosion and the secondary explosion. Typically, this secondary explosion is more violent than the primary explosion for several reasons. First of all it has a lot more fuel than the initial ignition; secondly it is moving very fast; and thirdly it exposes everything in its path to burning particles that not only will tear structures apart, but will also deposit burning particles on surfaces for several seconds or even minutes until the fuel has been exhausted. For example, humans exposed to deflagration suffer terrible burns since the particles land on their skin and continue

5 DUST AND GAS EXPLOSIONS

In the bioenergy sector, dust explosions are a major cause of damages and injuries, next to physical injuries in the forest and agriculture. While major explosions that involve injuries or major material damages to facilities are reported, it is likely that small incidents are not reflected in official statistics simply because they are dealt with quickly by the pellet producers or terminal operators.

Informal interviews, however, disclose that minor incidents happen on a frequent basis, typically several times per year for a pellet plant, but are not reported to the authorities and handling of incidents and are, in many cases, considered part of a normal "safety routine". Closer analysis reveals that the knowledge among operations personnel of what type of dust causes explosions and the criticality of diligent housekeeping is often limited. Part of the problem is that the explosion properties of dust are very complex and characterized by several parameters, such as:

- Chemical composition and freshness (reactivity) of the dust material
- Particle size of the dust

to burn for a while resulting in severe deep wounds or severe separation of skin tissue from exposed limbs or the face. In the following sections the characteristics of explosible dust and how to quantify them will be covered.

During fires, particularly smouldering fires, large amounts of pyrolysis gases are generated and dispersed in areas where they can accumulate in high concentrations. These concentrations may reach explosibility limits and could easily ignite if an ignition source is present. A gas explosion is different from a dust deflagration and is instead characterized as a detonation, which means a super-sonic propagation (propagation speed higher the speed of sound) of the exothermic event due to the very fast movement of gas molecules. Pyrolysis or smouldering of biomass generates a spectrum of gases, each with different limits of explosibility. The explosibility of this spectrum of gases becomes complex to predict, even with the knowledge of the components of the composite gas mixture. In section 5.4.2 the limit values for explosible composite gas will be discussed.

5.1 Definition of explosible dust

Particles of combustible materials smaller than 425 micron (US Standard Testing Sieve mesh 40) are

classified as explosible dust [4]. The size of a particle is determined by means of Aerodynamic Equivalent Diameter (AED) [93] and relates to the density and form factor (shape) of the particle. Figure 5.2 provides a perspective on the size spectrum of factory generated wood dust particles in relation to other common particles.

To give a perspective on the size of particulates, cement dust ranges from 2-100 μm , diesel exhaust 0.001-1 μm and a human hair 20-180 μm . The actual size of particles is difficult to measure with any accuracy, since they almost always appear in large numbers with individual shapes and sizes and each particle is almost always irregular in shape, often with porosity. The shape and size is often also affected by changes in moisture and temperature. In the industry, the size of particles is often determined by mechanical sieving with results affected by the geometry and duration of the vibrations of the sieving equipment. The result of mechanical sieving is often questionable, since the mesh through which the material is passing has no way of discriminating particles of different density and particles with non-spherical (ideal) shape or particles smaller than a certain diameter. Particles such as fibres with an aspect ratio larger than 1:5 are particularly difficult to classify by mechanical sieving.

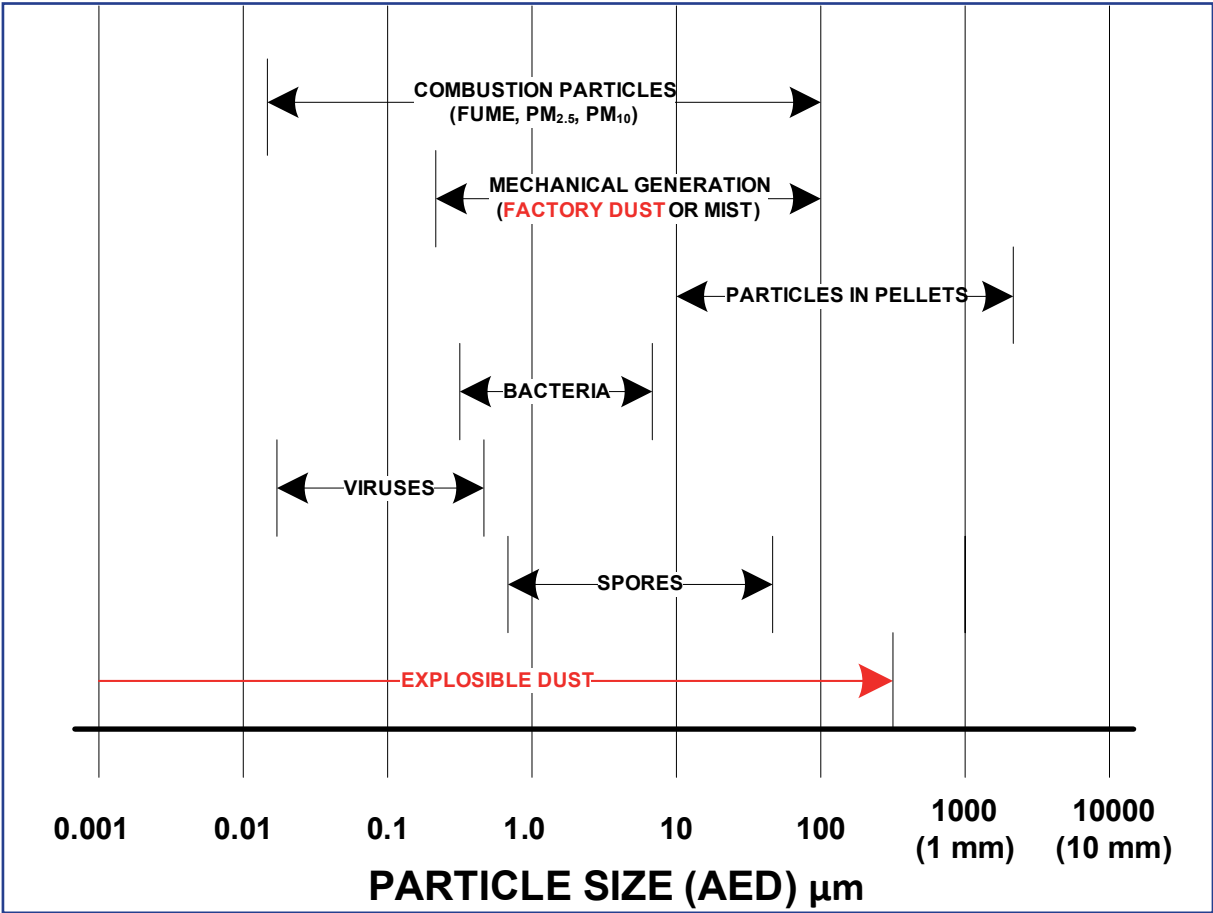


Figure 5.2. Size spectrum of factory generated wood dust particles in relation to other common particles.

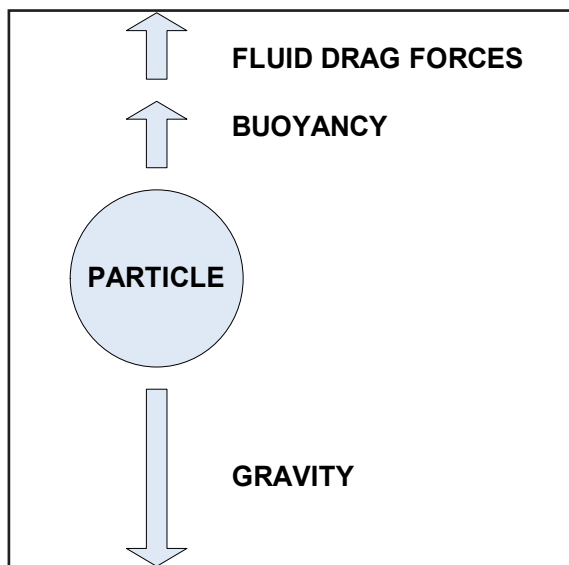


Figure 5.3. Forces on a particle

An alternative method of classifying particles is machine vision using a high resolution scanner and image processing software. Both methods are approximations although the machine vision should be considered more accurate.

Particles that are not in the sedimentary state are often in an agitated and lofted stage by the media in which they habitat. The agitation is due to external forces acting on the particles such as turbulence, buoyancy, fluid drag, static electricity, Brownian forces, Van der Waal forces and gravity. The dynamics of how particles propagate in a media, such as air, is of fundamental importance in dust control. Practically all particles are non-uniform in shape and have different density depending on material

and porosity and therefore are transported at different speed in air due to the forces of gravity, buoyancy and fluid drag forces as illustrated in Figure 5.3.

Some of the critical factors for all airborne dust (often referred to as aerosols) is the concentration in any given area and the speed at which concentrations may occur. An understanding of the net effect of the forces exerted on the particle is essential and is quantified in terms of sedimentation (settling) speed of the particles under still as well as turbulent conditions. The sedimentation speed can be estimated using Stokes Law [151] and is primarily affected by the physical size, surface structure, density of the particle and the drag forces of the medium (air) in which they sink, as illustrated in Figure 5.4. The relative settling time for particles is in the range 0.5 to 100 micron. It can be concluded that significant amounts of factory dust stay suspended in still air for hours and in turbulent air conditions they may never settle on a surface. This has serious implications in areas where conditions satisfied by the "explosion pentagon" are present.

Sampling of dust collected from pine pellets manufactured in British Columbia, Canada and hardwood pellets (mainly bark) manufactured in Nova Scotia, Canada and softwood pellets (Southern Yellow Pine, SYP) in South-eastern USA are illustrated in Figure 5.5.

5.1.1 Sampling of dust

Sampling of dust for the purpose of determining the explosibility has to be done with care in order to obtain a representative sample. Dust for testing purposes cannot be manufactured in, for example, a hammer mill since the particles generated are not representative of the dust on the shop floor. Also, use of dust from

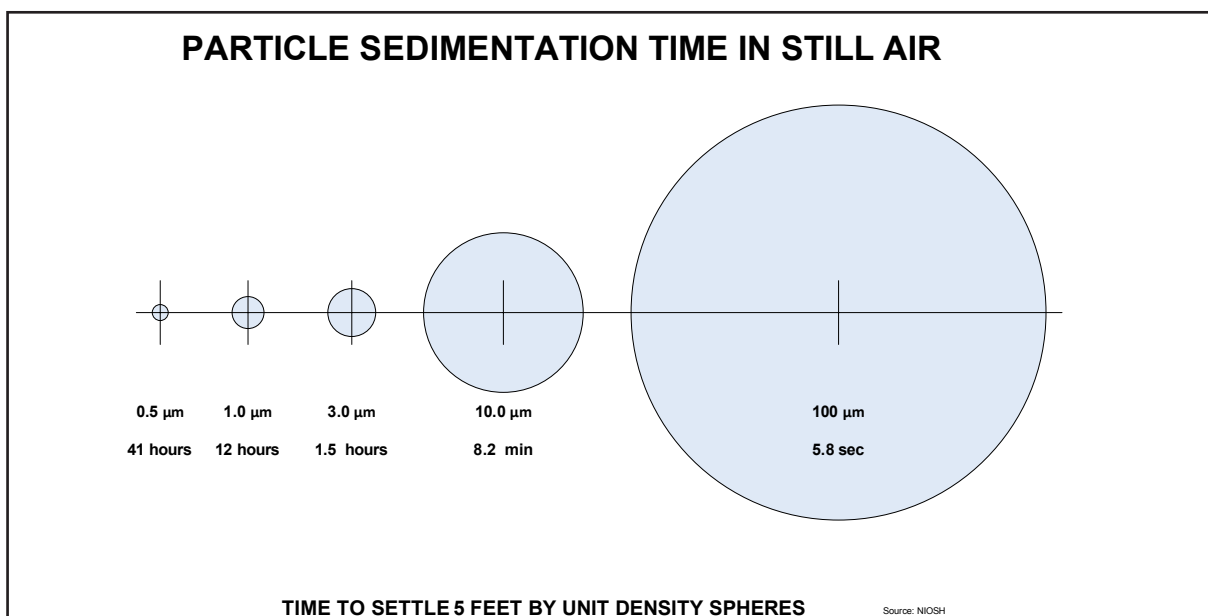


Figure 5.4. Particle sedimentation time in still air.

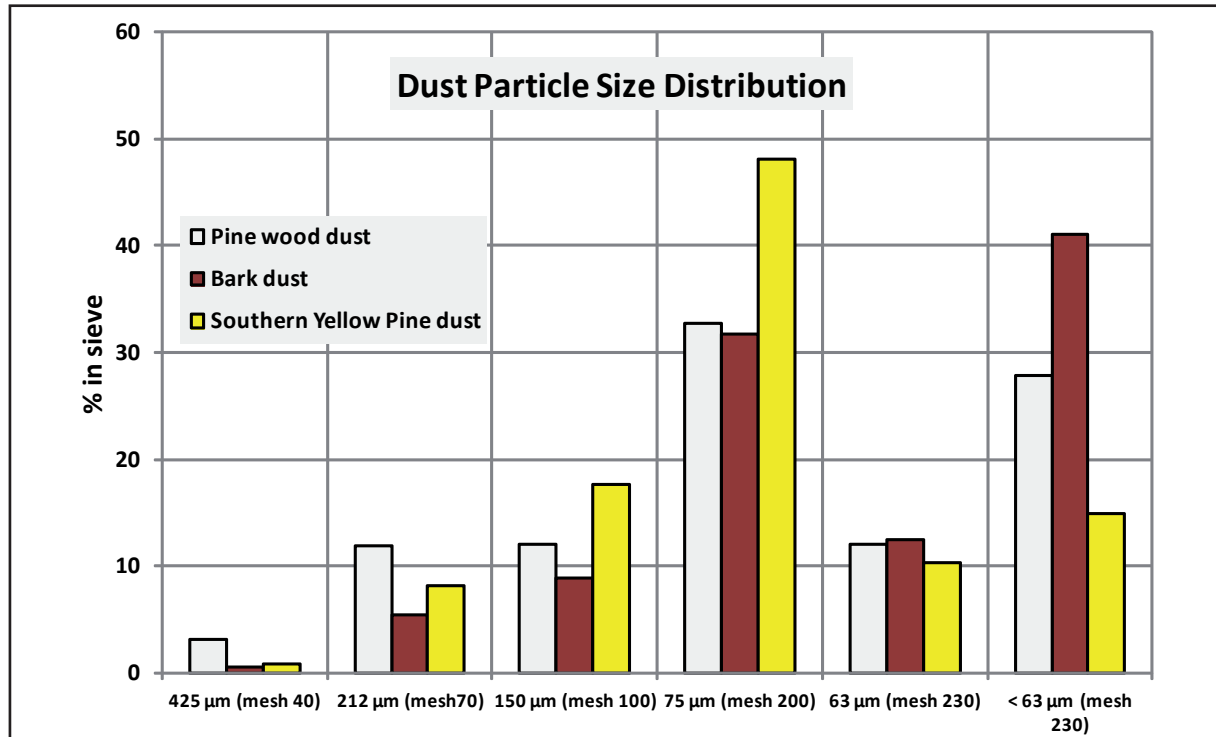


Figure 5.5. Dust particle size distribution.

sieving from a stream of material such as wood pellets may not necessarily provide a representative picture of the dust on the shop floor. The designation “fines” used in the pellets industry is not the same as dust although dust is entrained in “fines”. The air is almost never still in a factory environment and dust of various sizes are constantly floating around and only the larger particles will eventually settle on surfaces. Once settled, the physics of the dust changes radically as can be seen in the test results in Table 5.1. The larger

particles will settle closer to the source of the dust and the smaller particles will settle further away. For manual collection in areas with working equipment such as conveyor systems, grinders, hammer mills, the sampling should be done in several locations to provide a reasonably representative sample for testing. One alternative is to collect dust from bag filters since this dust usually contains a good average representation of particle sizes collected from material in motion.

Table 5.1. Ignition and explosion parameters for pellets.

Test Mode	Test Parameter (dust < 63 µm)		Measure	Pine dust	Bark dust	SYP dust	Coal dust	Testing Standards
Dust cloud	Auto ignition temp (Godbert-Greenwald)	T_c	°C	450	450	455	585	ASTM E1491
	Min Ignition Energy	MIE	mJ	17	17	20	110	ASTM E2019
	Max Explosion Pressure	P_{max}	bar	8.1	8.4	7.7	7.3	ASTM E1226
	Max Explosion Pressure Rate	dP/dt_{max}	Bar/s	537	595	360	426	ASTM E1226
	Deflagration Index	K_{st}	Bar-m/s	146	162	98	12.4	ASTM E1226
	Min Explosible Concentration	MEC	g/m ³	70	70	25	65	ASTM E1515
	Limiting Oxygen Concentration	LOC	%	10.5	10.5	13.5	12.5	ASTM E1515 mod
Dust layer	Hot Surface Ignition Temp (5 mm)	T_s	°C	300	310	320		ASTM E2021
	Hot Surface Ignition Temp (19 mm)	T_s	°C	260	250	270		ASTM E2021
	Auto Ignition Temp	T_L	°C	225	215	220		USBM (Bureau of Mines) RI5624
	Dust Class (>0 to 200 bar.m/s)			St1	St1	St1	St1	ASTM E1226
	Dust Class (Explosion Severity ES>0.5)			Class II	Class II	Class II		OSHA CPL 03-00-06

5.1.2 Testing of dust from pellets

The testing of dust includes testing of the characteristics in the two phases by which dust appear in a factory or handling facility. The most critical is **explosibility** of dust suspended in a **dust cloud**. However, the **ignitability** of **dust in layers** is also important from a safety perspective. Table 5.1 summarizes the parameters usually tested to gain understanding of the risks involved with handling a biomass product which generates dust during handling and storage. The data is from the same material illustrated in Figure 5.5 [112].

The following things are of particular interest to point out in Table 5.1:

1. The moisture contents of the samples tested were all 5 % or less. However, the particle size was somewhat different as illustrated in Figure 5.5.
2. The smaller the particle is, the higher the explosibility. The bark dust contains noticeably higher percentage smaller particles compared to the white dust (see Figure 5.5). This translates in to higher explosion pressure.
3. The extremely low MIE (around 20 mJ at room temperature) in combination with the MEC for wood dust is the major concern. It should be mentioned that electrostatic discharge from person to a metal surface during summertime is typically 20 mJ and about 60-80 mJ during wintertime when the humidity in the surrounding air is lower. For zone risk classification see section 5.4.1 See also section 5.2 for more on electrostatics.
4. The auto-ignition temperature for a dust layer is half of the corresponding temperature for dust clouds. In addition, the thicker the layer, the lower the ignition temperature becomes due to the energy density within a layer.
5. The relatively lower explosion pressure for SYP species is counter-balanced by the extremely low MEC.
6. The Kst is the basis for Dust Explosibility Classification in three ranges as per Table 5.2. (St comes from the German 'Staub', which means dust).

7. The US Code of Federal Regulations 29 CFR 1910.307 stipulate certain standards for equipment located in locations where hazardous dusts are present under normal operating conditions. The US National Fire Prevention Association guidelines NFPA 70 *National Electrical Code* define the conditions in more detail. The US National Materials Advisory Board NMAB 353-3-80 *Classification of Combustible Dusts in Accordance with the National Electrical Code* defines dusts having Ignition Sensitivity (IS) greater than or equal to 0.2, or Explosion Severity (ES) greater than or equal to 0.5 to be appreciable explosion hazards requiring electrical equipment suitable for Class II locations (see section 5.4.1)

$$\text{Explosion Severity (ES)} = \frac{\left[P_{\max} \times \frac{dP}{dt}_{\max} \right]_2}{\left[P_{\max} \times \frac{dP}{dt}_{\max} \right]_1}$$

where

- subscript 1 refers to Pittsburgh seam bituminous coal dust (3110 bar²/s)
- subscript 2 refers to the dust under evaluation

The data obtained from testing dust cloud from the pine pellets and bark pellets dust in Table 5.1 and is summarized in Table 5.3 to illustrate how the ES number is calculated.

From this test data it can be concluded that installations exposed to pine pellet dust as well as the bark pellets dust require equipment classified as Class II compatible.

Ignition sensitivity is another measure for classifying the explosibility of dust and is calculated in accordance with the following formula:

Table 5.2. Kst explosibility classes

Dust explosibility Class	Kst [bar.m/s]
St1	>0-200
St2	201-300
St3	>300

Table 5.3. Calculation of the ES number.

Parameter	Measure	Pine dust	Bark dust
$P_{\max}$	bar	8.1	8.4
$dP/dt_{\max}$	bar/s	537	595
$P_{\max} \times dP/dt_{\max}$	bar ² /s	4,350	4,998
ES		1.40	1.61
Explosion Severity (ES)		Class II combustible	Class II combustible

$$\text{Ignition Sensitivity (IS)} = \frac{[T_c \times MIE \times MEC]_1}{[T_c \times MIE \times MEC]_2}$$

where T_c , MIE and MEC are found in Table 5.4 for the Pittsburgh coal (index 1) and pine pellets dust (index 2).

Besides the ASTM Standards documents listed in Table 5.1, for more detailed description of testing procedures for dust, see [112]. Table 5.5 is listing the Corresponding EN testing standards for dust. There are some important differences between the ASTM and EN standards, which should be noted. The ASTM Standards allow for hammer milling material to size before testing but stipulate a maximum moisture content of 5 %. The EN recommends the use of collected dust but specifies moisture content as received. Neither the ASTM nor the EN standards consider the importance of sampling of the dust to make sure the samples are fully representative of the dust on the shop floor (see section 5.1.1). The ISO Technical Committee 238 for Solid Biofuels is addressing these discrepancies and is expected to come out with a comprehensive family of ISO testing standards to provide a reliable methodology.

The ASTM family of testing standards for explosibility is currently more complete than the corresponding EN Standards.

The ISO 6184-1 Standard [91] specifies a methodology used for determination of the explosibility characteristics such as P_{max} , Kst and dP/dt for dusts. The standard is similar to ISO 6184-2 used for gases (see section 6.2.2).

The flammability index for dust layers is established based on the UN MTC Test N.1 Class 4 Division 4.1 Substances Standard [122].

5.2 Electrostatic characteristics of dust

Once dry, wood dust has a very high DC resistivity which means that surface electrons generated during friction may accumulate over time to very high levels and eventually discharge in a spark to an adjacent conducting surface. This spark may have sufficient energy to ignite a dust cloud which in turn would cause an explosion to occur. The electrical charge generated on the surface is sometimes referred to as tribo-electric charge and comes from the friction between dry biomass (e.g. pellets) and friction between for example a moving conveyor belt and pellets. Also, a conveyor belt can be charged as it moves on rollers, idlers and between guide-rollers. A conveyor belt should preferably be made of antistatic material to avoid build-up of static charge which may otherwise be transferred to the pellets riding on the belt. If pellets, including the entrained dust retaining electrostatic charge

Table 5.4. Ignition sensitivity for pine dust and Pittsburgh coal.

Parameter	Measure	Pine dust	Pittsburgh coal
T_c	°C	450	585
MIE	mJ	17	110
MEC	g/m ³	70	65
$T_c \times MIE \times MEC$	°C mJ g/m ³	4,182,750	535,500
Ratio		7.81	
Ignition Sensitivity (IS)		Class II combustible (7.81 > 0.2)	

Table 5.5. Explosibility testing standards.

Dust condition	Parameter	ASTM	EN	ISO	USBM	UNMTC
Dust cloud	Auto ignition temp	E1491				
	Min Ignition Energy	E2019	13821			
	Max Explosion Pressure	E1226	14034-2	6184-1		
	Max Explosion Pressure Rate	E1226	14034-2			
	Deflagration Index	E1226	14034-2			
	Min Explosible Concentration	E1515	14034-3			
	Limiting Oxygen Concentration	E1515	14034-4			
Dust layer	Min Hot Surface Ignition Temp	E2021	50281			
	Min Auto Ignition Temp				RI5624	
	DC Resistance	D257				
	Flammability					Test 1

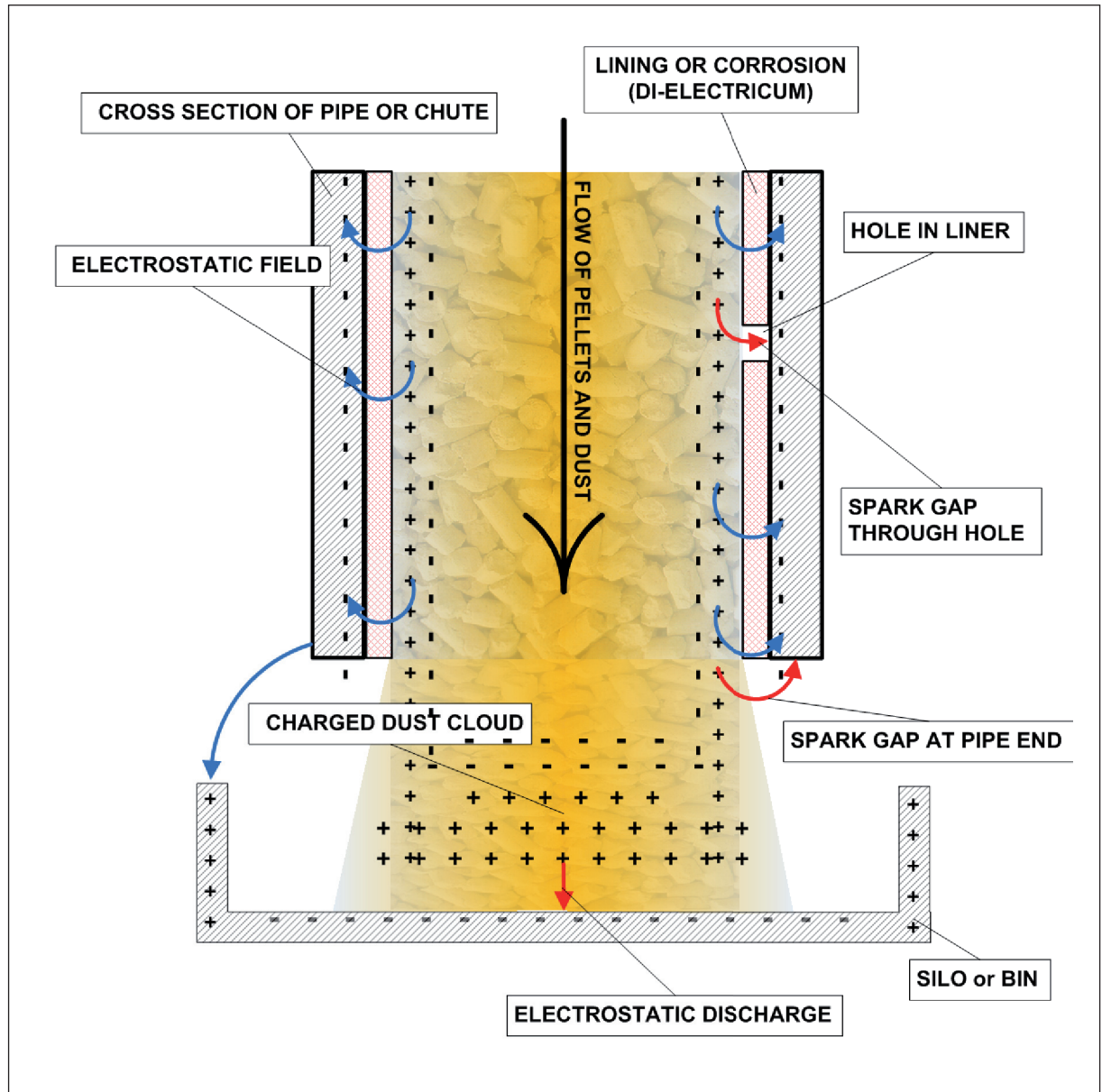


Figure 5.6. Electrostatic charge built up in a pipe with an insulating liner.

from handling, are dropped into a silo to the bottom, an electrostatically charged dust cloud may be generated.

The DC resistivity of wood powder is an important parameter, since it provides a measure of the electrostatic capacity of the material. A typical value for wood dust is 2×10^{12} ohm-meter in comparison with coal dust (PRB – Powder River Basin sub-bituminous coal) which is about 5×10^{10} ohm-meter or lower (a factor 400), which means the coal is able to dissipate (bleed off) electrostatic charge much faster. The high resistivity of wood dust in combination with very low minimum ignition energy (see Table 5.1 with comments) therefore indicates that wood powder is generally much more explosible than coal dust.

Grounding/bonding/earthing is the key preventive measure to control electrostatic build-up and considerable

attention is paid to this issue in the NFPA as well as the ATEX codes. Figure 5.6 illustrates how electrostatic charge can build up when transporting dusty material through a pipe with an insulating liner [115]. An electrostatic field is generated between the outer steel pipe and the dust particles entrained in the material flow inside the pipe with the liner representing a dielectricum. The electrostatically charged dust particles cause adjacent dust particle in the flow to assume the opposite charge. The particle with the opposite charge accumulates as a charged cloud in the collecting bin and may discharge to the wall of the bin. Another scenario is the potential for a discharge through a pinhole through the liner inside the pipe. Both discharges could cause explosions as the material is transported through the pipe. The conclusion is that dusty materials should not be in contact with insulating surfaces or equipment

made from insulative materials such as tubes with liners, hoppers with insulative protective coatings etc. The electrostatic charge should be given a chance to bleed off to a conducting surface as much as possible. In some cases anti-static belts are used in conveyor systems to bleed of the charge on the particles being transported.

If pellets are dropped into a bunker there is dust generated and suspended for a considerable time at the bottom of the bunker due to the impact (see Figure 5.4). If the entrained dust following the pellets is electrostatically charged the mix of dust at the bottom of the bunker could reach the Minimum Explosibility Concentration (MEC see section 5.1.2). The dust concentration in combination with the accumulated electrostatic charge could cause an explosion.

Guidelines for estimation of electrostatic charge by calculating the energy on the basis of electrostatic voltage and electrical capacitance for typical material bodies are available in engineering handbooks. The calculation of the molecular breakdown voltage on the basis of dielectric characteristics is also available [95, 147]. It is evident that the electrostatic aspects for fresh biomass fuels are less challenging, however here also sufficient grounding is required.

5.3 Dust housekeeping

Housekeeping in wood processing facilities has not traditionally had the priority it deserves for a number of reasons. The issue of cleaning has a connotation of lower significance than keeping a plant operating and producing revenue generating products. Cleaning of floors is a nuisance since the generation of dust never

stops. It is, however, as important as regular maintenance of machinery. This section describes a methodology for evaluating how much dust on floors, girders and beams is acceptable in order to stay within reasonable margins of safety. Several guidelines are published on this subject but are not necessarily accessible without substantial effort. For specific biomass processing plants, specific guidelines are needed based on the specific characteristics of the type of dust. Lab testing of a couple of fundamental the parametric values in Table 5.1 will allow the operator of a biomass processing plant to evaluate if a plant is operating under safe conditions.

NFPA 664 [131] focuses on dust in the wood working industry, see particularly Chapter 11 and Annex A, paragraph 6.4.2.2 or NFPA 499 [132]. Chapter 5 stipulates a dust layer thickness of more than 1/8" (3.2 mm) is considered unsafe if the dust is covering a certain percentage of floor or other flat surfaces in a facility. The bulk density of wood dust varies between 250 - 550 kg/m³. A procedure for estimation of dust concentration in a space volume and the risk of a secondary explosion is illustrated below. The result is evaluated using the Minimum Explosible Concentration (MEC) value in Table 5.1 and some assumptions regarding the space volume in a pellets manufacturing plant.

Due to the violent turbulence of the dust when dislodged by the initial pressure wave it is not possible to accurately predict the concentration of the dust in a space volume. For illustrative purposes the assumption made here is that the concentration as an average is fairly even throughout the space volume. This allows for a straight forward modelling of a critical dust concentration

Example

Area selected = 15 m × 25 m = 375 m²

Dust layer thickness = 1/8" = 3.2 mm

Bulk density = 500 kg/m³ @ moisture content 5 %

Floor area covered with dust = 5 %

Total amount of dust in the selected area = 375 × 0.0032 × 500 × 5/100 = 30 kg

Height of the selected area = 4 m

Total space volume in the selected area = 375 × 4 = 1500 m³

Concentration of dust in the space volume = 30/1500 = 0.020 kg/m³ = 20 g/m³

The 20 g/m³ compared to 70 g/m³ (as per Table 5.1) provides a good safety margin of 71 %. If the area covered with dust is 30 % the calculation looks as follows;

Dust in the layer = 375 × 0.0032 × 500 × 30/100 = 180 kg

Concentration = 180/1500 = 0.120 kg/m³ = 120 g/m³

The 120 g/m³ is unsafe and would easily sustain a deflagration if a primary explosion were to trigger a secondary explosion.

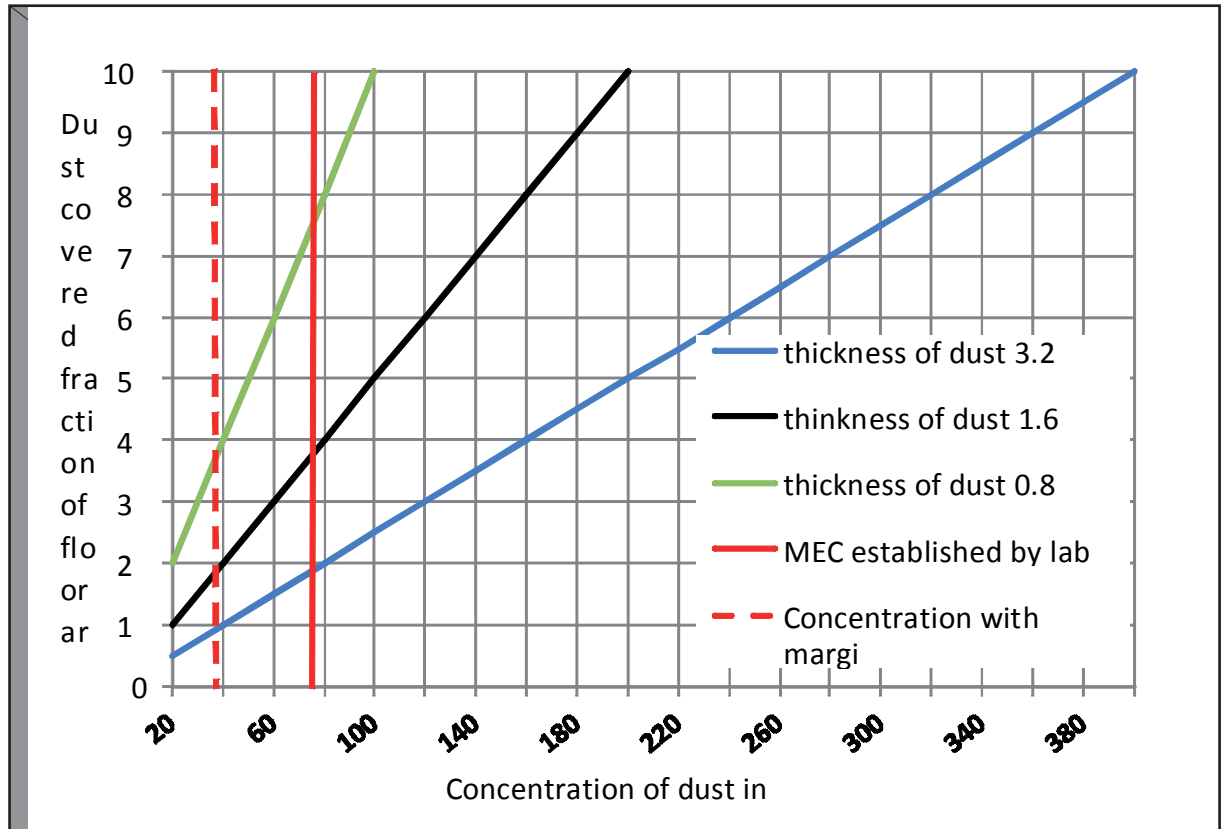


Figure 5.7. Calculated concentration of dust based on dust layer on the floor.

scenario. The larger the area covered by a layer of dust, the more critical the conditions become. A spreadsheet model was developed [30] for evaluation of the safety margin for explosions based on the following parameters;

- Estimated average thickness of a dust layer within selected floor area
- Bulk density of the dust (from lab test)
- Minimum Explosible Concentration (MEC) of the dust (from lab test)
- Floor area
- Ceiling height
- Horizontal surface area within the space volume of beams, girders, railings etc.
- Estimated percentage of selected floor area covered by dust
- Estimated amount of lofted dust in space volume
- Average dust concentration suspended in the air in space volume
- Selected safety margin in relation to measured MEC

An example of the output from this model is illustrated in Figure 5.7. This particular graph is valid for dust with MEC 70 g/m³ and a bulk density of 500 kg/m³.

The concentration of dust C_d is inversely proportional to the space volume V . This means that a space

volume twice as large would produce the same dust concentration for a dust layer that is twice as thick:

$$C_d = \frac{1000 \times d_{th} \times A_d \times A \times d_b}{V}$$

where

C_d	= concentration of dust in space volume	[g/m³]
d_{th}	= dust layer thickness	[mm]
A_d	= fraction of floor area that is covered by dust	[%]
A	= total floor area	[m²]
d_b	= dust bulk density	[kg/m³]
V	= space volume	[m³]

From Figure 5.7 it can be concluded that a dust layer with a thickness of 3.2 mm (1/8th inch) covering 20 % of the selected floor area the concentration of dust is estimated to be about 80 g/m³. With a MEC of 70 g/m³ for dust generated in typical pellet plants in British Columbia, a secondary deflagration could be propagated throughout a building as a result of a primary explosion. A safety margin of 50 % to the MEC (50 % of 70 g/m³ = 35 g/m³ from Table 5.1) is recommended. If 10 % of the floor area is covered by a 3.2 mm layer of dust, the estimated dust concentration is 40 g/m³, which is less than the MEC for the dust on Table 5.1 and

provides a safety margin of 43 %. This safety margin may be sufficient although 50 % safety margin should be the target. A housekeeping guideline stipulating a maximum thickness of a dust layer of 1.6 mm would provide a safety margin of 50 % or better even if the dust layer is covering approximately 20 % of the floor area. Alternatively, a thickness of the dust layer of 3.2 mm covering less than 5 % of the floor would also be within the 50 % safety margin. This illustrates the importance of keeping as large an area as possible clean.

The MEC is a measure related to the characteristics of the dust such as chemical composition of the material, moisture content, Limiting Oxygen Concentration (LOC), particle size distribution and shape of the dust particles. The NFPA 499 and NFPA 664 [131, 132] are not necessarily accounting for the explosibility characteristics as measured by lab test for a particular dust in question.

With MEC established at 70 g/m³ for the material as per Table 5.1 and a safety margin of 50 % the maximum allowed dust concentration should be less than 35 g/m³, keeping in mind that the MEC is tested at room temperature (as per Standard) while the reactivity of most materials increase with temperature. The shop floor temperature in an operating pellets plant may, in certain areas, be considerably higher causing a more reactive initial state of the dust which would justify the 50 % safety margin to be on the safe side. The MEC as well as the bulk density of the dust are essential parameters when determining guidelines for housekeeping to keep a manufacturing plant safe. Without those values the guidelines becomes a gamble and the housekeeping may not achieve what it is supposed to achieve – as safe working environment as possible.

Research has proven [116] that it is possible to measure the thickness of dust layers on shop floors using laser technology with an accuracy of ± 0.15 mm and could in principle be used in pre-designated areas to monitor to establish the rate of dust accumulation which might provide guidance to housekeeping routines.

5.3.1 Preventive measures

The guidelines documented by NFPA [124-133] are considered the industry standard. Most spaces in a pellet plant should be classified as Class II Division 1 (see NFPA 499, Chapter 4.1 [132]). The wood dust itself is classified as Group G (see NFPA 70 [128], Chapter 500.6). Each area of a manufacturing plant shall be classified in accordance with the Hazardous Zone definitions in NFPA 70, Chapter 506 [128]. Most of the production areas of a pellet plant would be Zone 20. It is recommended that a site evaluation is done for any specific area to make sure the guideline for robust maximum dust layer thickness is established. Such evaluation should be done in

areas where dust is systematically accumulating and where housekeeping is difficult to maintain.

5.3.2 Dust characterization for operations

Each pellet mill should have the MEC established by a **certified lab** in accordance with testing standards given in Table 5.1. Equally important is to establish the **bulk density of the dust** generated in the plant to make sure the fundamentals are met for establishing a safe limit for dust layer thickness as well as housekeeping guidelines to keep the floor areas sufficiently clean and the dust level below the allowable limit. Both of these parameters are unique for each pellet plant since it relates to the feedstock used as well as the comminution technology used for processing the feedstock.

Without knowing the MEC and dust bulk density the safety rules for a production plant and safety management becomes a guessing game. A safety margin policy of 50 % or better should be established for any pellet manufacturing plant.

5.3.3 Dust management

A successful scheme to control dust explosions must include, besides actual characterization of the dust, a split responsibility between management, operations and maintenance and has to be based on robust and measurable data. Whoever is assigned the responsible of controlling the dust level in a manufacturing plant should be familiar with the methodology outlined above regarding estimation of safe level of dust. Inspections and recordings needs to be done at pre-set intervals. This should be done every time just before vacuuming takes place.

- Frequent accumulation of explosive dust is an indication that a preventive measure such as redesign of a piece of machinery or change of operating procedures is likely to be needed. The responsibility falls on plant or corporate management to act in this respect.
- Awareness of recorded data of dust layers promotes a more frequent and diligent housekeeping routine. This responsibility falls on the housekeeping or maintenance crew to act in this respect.
- The record shall be available to inspection and safety audit bodies for determination if the safety certification for the plant can be upheld. The dust certification should be part of the safety approval process which affects occupational safety fees if applicable as well as insurance rates.

5.4 Safety rules and recommendations

Extensive guidelines have been developed for classification of facilities as well as equipment where dust is present in terms of risk for fires and explosions. In Europe the ATEX (ATmospheriques EXplosives) [66, 67, 69] regulation is an implementation of Directives issued

by the European Union and compliance is mandatory since July 1, 2003 and are augmented with national standards within each member state of the union. In North America the NFPA [124-133] guidelines are in place and augmented with State regulations in USA and provincial regulations in Canada. The intent is to eliminate the risks for incidents as much as possible and at the same time facilitate trade of certified equipment across the borders. There are several companies specialised in providing certification according to ATEX or NFPA. Apart from legislative requirements, it is typically also demanded by insurance companies involved.

ATEX 100 [66] specifies the responsibilities of the manufacturers of equipment and ATEX 137 [69] specifies the obligations of the users of the equipment and the operating environment (facilities) where dust may occur. ATEX being a mandatory system consists of three components: harmonized technical standards, audits of operating facilities and certification of notifying bodies and test laboratories. NFPA is not written in the federal law in USA but is mandated regionally on State or Local laws. The NFPA and ATEX both lay the burden on cooperation between equipment manufacturers, installers and end-users to take the responsibility for providing a secure environment for workers.

The International Electrotechnical Commission (IEC) is a non-governmental body parallel to International Standards Organization (ISO), both of which are developing technical standards. IEC is focused on standards related to electrical and electronics.

The European Committee for Electrotechnical Standardization (CENELEC) is another body developing standards in the electro technical field and has focused on implementation of the Essential Health and Safety Requirements (EHSR) stated in the Directives issued by the European Union which resulted in the ATEX 100 [66] and 137 [69]. We can expect that the standards issued by CENELEC, IEC, ATEX and NFPA are gradually going to be harmonized.

The NFPA documentation is partly arranged to address issues within certain sectors of the industry such as chemical and wood working but also have overall encompassing documents such as the National Electrical Code. NFPA is a very extensive family of documents (over 10,000 pages) and the bibliography includes a reference list for the reader to explore in more detail. NFPA as an organization was founded 1896 in USA and the National Electrical Code (NEC) issued by NFPA is accepted by the American National Standards Institute (ANSI) has adopted NEC as the standard in USA. The NFPA code covers much more than explosion and fire prevention while the ATEX is focused on explosion and fire prevention.

The Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) is the implementation of the ATEX code in UK. Canada has its own set of standards (for example the Canadian Electrical Code – CEC) but has to a large extent adopted the essence of the NFPA Code.

ATEX 100 [66] is applicable to electrical as well as non-electrical equipment that contains or constitutes a potential ignition source and which requires certain design or installation procedures to prevent explosions. The regulations cover controls and communication devices as well as monitoring and detection equipment. The regulations also cover safety and control devices installed outside the areas classified as hazardous which provides an explosion protection function such as fast-acting shut-off and pressure relief valves. The NFPA guidelines offer equivalent recommendations.

ATEX 137 [69] specifies the minimum requirement for improving the health and maintaining the safety of workers potentially at risk and includes a risk zone classification system and stipulates safety classification for equipment installed within a risk zone. The document focuses on analysing and describing risks and maintenance practices to minimize risk. ATEX focuses on the duties of the end-user to make sure workers are trained and made aware of the hazards in the working areas. The end user is also responsible for repair of equipment and maintenance to make sure equipment is in safe working order. The employer is responsible for assessment of hazards and sources of potential ignition and to provide appropriate markings of hazards, entry and exit points. Explosion Protection Documents (EPD) is part of the responsibility for the employer.

The risk classification for sea-going vessels is regulated under the International Maritime Solid Bulk Cargoes (IMSB) Code [88]. This code is administrated by the International Maritime Organization (IMO). For vessels operating in US water the NFPA 306 also applies [127].

The risk classification for road transportation in Europe is regulated governed by Directive 94/55/EC [67] and 98/91/EC (ADR) [68] and in USA by US Department of Transportation and in Canada by Transport Canada regulations.

5.4.1 Risk zone classification for dust under IEC, NFPA and ATEX

The risk zone classification of work areas shall be done on the basis of the properties of the dust present in that location and the likelihood of explosible concentrations to occur. Table 5.6 summarizes the criteria for zone classification defined under the ATEX and NFPA systems.

A difference in the approach by the two systems is that NFPA is performance oriented and specifies the

Table 5.6. Criteria for zone classification according to the ATEX and NFPA systems

Zone	Classification criteria		Typical locations
	ANSI/NFPA	IEC and ATEX	
20	Area where combustible dust or ignitable fibres/flyings are present continuously or for long periods of time in quantities sufficient to be hazardous	Dust cloud likely to be present continuously or for long periods	Hopper, silos, cyclones, filters, dust transport systems (vacuums), blenders, mills, dryers, bagging equipment
21	Area where combustible dust or ignitable fibres/flyings are likely to exist occasionally under normal operation in quantities sufficient to be hazardous	Dust cloud likely to be present occasionally in normal operation	Locations outside dust containments, filling and emptying points, feed belts, sampling points, rail car and truck dump stations, belt dump over-points
22	Area where combustible dust or ignitable fibres/flyings are not likely to exist occasionally under normal operation in quantities sufficient to be hazardous	Dust cloud unlikely to occur in normal operation, but if it does, will only exist for short period	Outlets from bag filter vents, flexible connections to pneumatic equipment that may become disconnected or damaged, storage locations where bags of containers may rupture and spill dust, location where controllable dust layers may form if cleaning is not routinely done and the dust level may raise to explosive level

conditions of the locations where equipment is intended to operate. By inference this means that the equipment has to offer sufficient safety when installed and operating in that environment. The ATEX on the other hand has a prescriptive orientation and stipulate direct design features required for the equipment for safe operation.

National Fire Protection Association (NFPA) Classifications

NFPA has a large library of generic Standards and Recommended Practices documents and several documents for specific industry sectors, some of which are partly applicable to the biomass based industry as listed here [124-126, 128-133]:

The documents most applicable for the biomass sector and explosion safety in North America are NFPA 70/77/654/664. In North America the risk classification of most of the locations for preparation of feedstock, production of pellets, handling and storage falls within Class II, Division 1 as highlighted in Table 5.7. The equipment intended to operate in the locations classified as Class II, Division 1 has to be tested and certified for that environment. The NFPA guidelines are classifying materials in Groups in accordance with their propensity to ignite and cause explosions or fires in Table 5.8.

NFPA 1	Fire Prevention Code
NFPA 68	Standard on Explosion Protection by Deflagration Venting
NFPA 69	Standard on Explosion Prevention Systems
NFPA 70	National Electrical Code (NEC)
NFPA 77	Recommended Practice on Static Electricity
NFPA 497	Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Processing Areas
NFPA 499	Recommended Practices for the Classification of Combustible Dusts and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas
NFPA 654	Standards for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing and Handling of Combustible Particulate Solids
NFPA 664	Standard for the Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities

Table 5.7. Classification of locations according to NFPA 70-500.5

Location Class	Division	Description	Dust materials
II	1	Location in which dust is in the air under normal operating conditions in quantities sufficient to produce explosive or ignitable mixtures	
		Locations where mechanical failure or abnormal operation of machinery and equipment might cause such explosive or ignitable mixtures to be produced, and might also provide a source of ignition through simultaneous failure of electrical equipment, through operation of protection devices, or from other causes	
		Location in which Group E combustible dust may be present in sufficient quantities to be hazardous	Group E
	2	Locations in which combustible dust may be present in the air due to abnormal operations, in quantities sufficient to produce explosive or ignitable mixtures	
		Locations where dust accumulations are present but are normally insufficient to interfere with the normal operation of electrical equipment or other apparatus, but could as a result of infrequent malfunctioning of handling or processing equipment become suspended in the air	
		Locations in which dust accumulations of, in, or in the vicinity of the electrical equipment could be sufficient to interfere with the safe dissipation of heat from electrical equipment, or could be ignitable by abnormal operation or failure of electrical equipment	
II	1	Locations in which easily ignitable fibres/flyings are handled, manufactured, or used such as cotton mills, flax processing plants, clothing manufacturing plants, woodworking plants etc.	Rayon, cotton, sisal, henequen, istle, jute, hemp, tow, cocoa fibre, oakum, baled waste kapok, Spanish moss, excelsior etc.
	2	Locations in which easily ignitable fibres/flying are stored or handled other than in the process of manufacturing	

Table 5.8. Explosion classification.

Inflammable material	IEC		ANSI/NFPA/CEC		
	Zone	Group	Class	Division	Group
Acetylene	0/1/2	IIC	I	1 or 2	A
Hydrogen	0/1/2	IIB + H2	I	1 or 2	B
Propylene oxide, Ethyl oxide, Butadiene	0/1/2	IIB	I	1 or 2	B
Cyclopropane, ethyle ether, ethylene	0/1/2	IIB	I	1 or 2	C
Acetone, benzene, butane, hexane, paint solvents, natural gas	0/1/2	IIA	I	1 or 2	D
Aluminium/magnesium and their commercial alloys, zirconium, thorium, uranium	20/21/22	IIC	II	1 or 2	E
Coal, carbon black, charcoal, coke	20/21/22	IIC	II/III	1 or 2	F
Grain dust	20/21/22	IIB	II/III	1 or 2	G
Wood, paper, cotton	20/21/22	IIA	II/III	1 or 2	G
Plastics, chemicals	20/21/22		II/III	1 or 2	G

Table 5.9. Maximum surface temperatures for Class II electrical equipment.

Level of protection	Category		Performance of protection	Conditions of operation
	Group I	Group II		
Very high	M1		Two independent means of protection or safe even when two faults occur independently of each other	Equipment remains energized and functioning when explosive atmosphere present
Very high		1	Two independent means of protection or safe even when two faults occur independently of each other	Equipment remains energized and functioning in Zones 0,1,2 (G) and/or 20,21,22 (D)
High	M2		Suitable for normal operation and severe operating conditions	Equipment de-energised when explosive atmosphere is recognised
High		2	Suitable for normal operation and frequently occurring disturbances or equipment where faults are normally taken into account	Equipment remains energized and functioning in Zones 1,2 (G) and/or 20,21,22 (D)
Normal		3	Suitable for normal operation	Equipment remains energized and functioning in Zone 2 (G) and/or 22 (D)

The IEC and NFPA guidelines also specify maximum surface temperature ranges for electrical equipment as summarized in Table 5.9.

Atmospheriques Explosives (ATEX) Classifications

The ATEX Code is an implementation of Directives issued by the European Union. The major documents are as listed here:

- **Initial Framework Directive**
Directive 89/391/EEC Council on the introduction of measures to encourage improvements in safety and health of workers at work
- **ATEX 100 Directive**
Directive 94/9/EC of the European Parliament and the Council of 23 March 1994 on the approximation of the laws of Members States concerning equipment and protective systems intended for use in potentially explosive atmospheres.

- **ATEX 137 Directive**

Directive 1999/92/EC of the European Parliament and of the Council of 16 December 1999 on minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres (15th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC).

Classification of locations under ATEX is organized in Groups and Categories based on the level of protection required as summarized in Table 5.10 (excerpt from 94/9/EC ATEX Guidelines, second edition August 2008).

- **Group I** comprises equipment intended for use in underground parts of mines, and to those parts of surface installations of such mines, likely to become endangered by firedamp and/or combustible dust

Table 5.10. Classification of location under ATEX.

Maximum surface temperature (°C)	IEC	CEC	ANSI/NFPA
≤ 450	T1	T1	T1
≤ 300	T2	T2	T2
≤ 280	T2	T2A	T2A
≤ 260	T2	T2B	T2B
≤ 230	T2	T2C	T2C
≤ 215	T2	T2D	T2D
≤ 200	T3	T3	T3
≤ 180	T3	T3A	T3A
≤ 165	T3	T3B	T3B
≤ 160	T3	T3C	T3C
≤ 135	T4	T4	T4
≤ 120	T4	T4A	T4A
≤ 100	T5	T5	T5
≤ 85	T6	T6	T6

- **Group II** comprises equipment intended for use in other places likely to become endangered by explosive atmospheres

Category I comprises products designed to be capable of remaining within its operational parameters, stated by the manufacturer, and ensuring a very high level of protection for its intended use in areas in which explosive atmospheres caused by mixtures of air and gases, vapours, mists or **air/dusts mixtures are highly likely to occur** and are present continuously, for long periods of time or frequently.

Equipment of this Category is characterized by integrated explosion protection measures functioning in such a way that:

- in the event of a failure of one integrated measure, at least a second independent means of protection provides for a sufficient level of safety; or,
- in the event of two faults occurring independently of each other a sufficient level of safety is ensured

It is also considered that equipment may be classed as category 1, if the manufacturer provides a combination of protective measures to prevent an ignition source becoming active under fault conditions, and in addition an integrated protective system, which will control the ignition hazard from a rare malfunction of the equipment.

Category 2 comprises products designed to be capable of remaining within their operational parameters, stated by the manufacturer, and based on a high level of protection for their intended use, in areas in which explosive atmospheres caused by mixtures of air and gases, vapours, mists or **air/dust mixtures are likely to occur**.

The explosion protection relating to this Category must function in such a way as to provide a sufficient level of safety even in the event of equipment with operating faults or in dangerous operating conditions which normally have to be taken into account.

Category 3 comprises products designed to be capable of keeping within its operational parameters, stated by the manufacturer, and based upon a normal level of protection for its intended use, considering areas in which explosive atmospheres caused by mixtures of air and gases, vapours, mists or **air/dust mixtures are unlikely to occur** and if they do occur, do so infrequently and for a short period of time only.

The design of the products of this category must provide a sufficient level of safety during normal operation.

Many areas where biomass or pellets are produced or handled would fall in to Group II Category 1 or 2.

5.4.1.1 Dust collection

Hoods and enclosures should be designed and located such that wood dust or particles generated will fall, be projected, or be drawn into the hood or enclosure so as to minimize fugitive dust emissions without interfering with the safe and satisfactory operation of machines and other equipment. All hoods and enclosures shall be of non-combustible construction unless protected with automatic sprinklers [131]. Fans and blowers for transportation of dust shall be located downstream or upstream in relation to the collector in accordance with certain rules depending on moisture content of the dust, particle size of the dust and the Minimum Explosibility Concentration (MEC – see section 5.1.2) established for the material.

Vacuum systems, including pipes and wand, shall be compatible with NFPA Class II Division 1 or should be fixed pipe suction system with air separator exhaustor and dust separator remotely located [131]. Depending on local conditions, the separator may have to be located outside a building. Fixed pipe system shall be of conducting material and cam lock joints or equivalent with ground clip to make sure grounding is provided upstream as well as downstream. Exhaust air from the final air-material separator shall be discharged outside to a restricted area and away from air intakes.

Exhaust air from dust collection systems should not be re-circulated back in to a building if the dust is deemed to represent deflagration hazard.

5.4.1.2 Dust suppression

If the product is generating dust during handling there are ways of suppressing the dust by spraying water, mist, oil or chemical palliatives over the area where dust is generated or accumulated. However, water or mist is degrading the calorific content of biofuels and can only be done in extremely small amounts using a fine spray or atomizer. The use of oil or chemicals is not acceptable in many cases since it may be seen as a contaminant and could have serious consequences during handling, storage and combustion. In addition, anything deposited on the surface of pellets may leave traces on conveyor belts, hoppers, inside rail cars or trucks as well as on the walls in ship holds. Cleaning of such surfaces may be very expensive and may be prohibited, since it could contaminate other commodities transported through the same system.

The other approach for dust suppression is to blend a binder in the feedstock used for pellets and briquettes and thereby minimize the generation of dust.

However, the simplest method is to avoid products being dropped on hard surfaces and thereby avoid in-elastic impact. When products are dropped on the product itself, the impact is elastic and therefore generates less dust. A consideration is to avoid emptying silos completely and always leave some product at the bottom.

5.4.1.3 Explosion prevention

Explosions and fires can be prevented if the oxygen content is kept below the Limiting Oxygen Concentration (LOC) as indicated in Table 5.1 for the material in question. A safety margin of 1-4 % below the LOC is recommended. Control of the oxygen concentration can be achieved in several different ways such as inertation with nitrogen, steam, carbon-dioxide (see section 3.5.2.2 regarding use of CO₂) or oxygen deprived exhaust gas. This may apply to reactors, pulverisers, hammer mills, mixers, dryers, cyclones, dust collectors, conveyors, screw feeders, bucket elevators, hoppers, silos etc. If inertation is used it is important to make sure the vessel does not contain air-pockets or that the inertation media is not by-passing space volumes on its way through a system. Equally important is that air locks such as vessels filled with material do not develop rat-holes or channels through which air could penetrate an inerted space volume.

It should be pointed out however that smouldering may continue even below LOC in wood materials once the material has been ignited and is hot enough due to the fact that wood contains over 40 % chemically bound oxygen which at high temperature is sufficient to sustain smouldering.

5.4.1.4 Explosion containment

Explosion containment is the fundamental and most desirable level of design, but is often prohibitively expensive and, in many cases, not practical. In addition, pressure piling may occur in certain design configurations with linked vessels, which are very complex to analyse. The objective with explosion containment is to design equipment in such a way as to withstand the maximum explosion pressure P_{max} and explosion pressure rate dp/dt_{max} as established by testing (see Table 5.1) in single vessel configuration. The hammer mill is an example of equipment designed for explosion containment, which essentially is a single vessel and typically can withstand an internal explosion.

5.4.1.5 Spark extinguishing

Spark detection systems are common in the manufacturing sector and react to the energy content of the spark using detectors sensitive to the wave length spectrum emitted by sparks. The detection system is usually connected to a deluge water system, inertation system (e.g. carbon-dioxide or nitrogen flooding), steam snuffing or abort gate to extinguish or divert a spark to a safe area [126]. The sensitivity level of the detection system can usually be set to a practical level which means that smaller sparks may be detected but may not have sufficient energy to ignite material in its path and therefore would not initiate an extinguishing operation to avoid unnecessary disruption of a production line. Spark detection systems may be used in situations when the sparks are transported at about the same speed as the material and the distance

between the detector and the extinguishing device shall be such that the extinguishing device is given sufficient time to react to avoid the spark to by-pass.

5.4.1.6 Explosion suppression

It typically takes 30-100 milliseconds for the pressure in an enclosure from an explosion to become destructive. In order to suppress an explosion the pressure has to be detected early enough to initiate release of a suppressant to stop the development of a fire ball in the enclosure [124]. Also, the rate of release has to be sufficiently fast to extinguish all flames before destructive overpressure develops. Explosion suppression is expensive and is typically only used when

- it is not possible to protect by means of explosion containment or relief venting, or
- when explosion venting cannot be done to a safe location, or
- the capacity of the venting cannot be achieved.

Sometimes explosion suppression safe-guarding is used in combination with explosion venting to protect the integrity of an enclosure. Figure 5.8 illustrates the typical pressure-time relationship for an explosion. Curve A illustrates the "normal" progression of the pressure wave. If the enclosure is designed to withstand for example 0.25 bar overpressure corresponding to the pressure after 50 milliseconds the explosion suppression system needs to be able to entrain the suppressant in the flame front before the pressure reaches the overpressure for which the enclosure was designed, in this case 50 milliseconds. Curve B illustrates the desired suppression of the pressure wave.

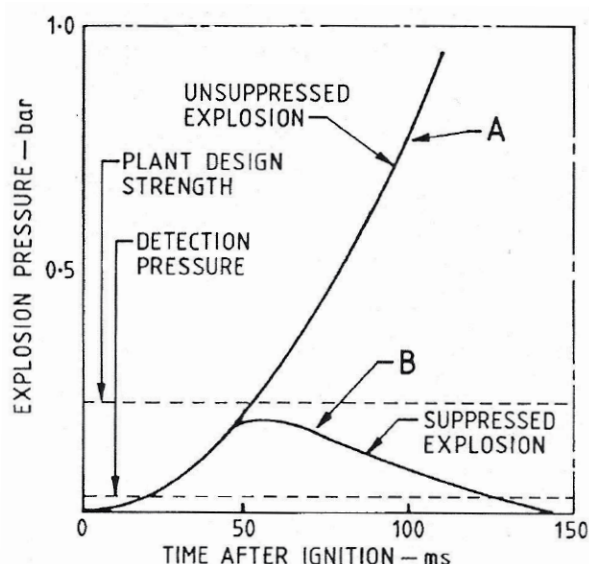


Figure 5.8. Illustration of pressure as function of time during an explosion.

The explosion suppression method can be used for small enclosures less than 1 cubic meter up to 1,000 cubic meters or even larger if several suppression devices are used. The technique is based on extremely

sensitive pressure sensors for detection of the pressure wave connected to suppressor devices for distribution of flame retarding chemicals or water. There are several types of pressure sensors on the market, such as membrane or dynamic piezo-electric devices. The suppressor devices often have a chemical detonator delivering the suppressant at a speed of 200 m/s with a volume of 5-10 litres within 10-30 milliseconds. The suppressant may be a vaporizing liquid, such as water, or dry powder for absorption of the energy in the flame front of the explosion. The suppressant may quench the flame front by dispersing heat, chemically react within the flame front, wetting of burning particles or cause oxygen depletion by means of inertation.

5.4.1.7 Explosion venting

Explosion venting is a protective measure to eliminate pressure to build above the pressure for which the enclosure is designed and discharge the pressure wave in a safe place to avoid injury and damage to equipment. Weak areas, so called explosion panels, of the enclosure especially designed to break open at a predetermined pressure relieve the pressure. Figure 5.9 illustrates the principles of explosion venting. Curve A illustrate the "normal" progression of the pressure wave. The "Strength of vessel" is the maximum pressure for which the vessel (enclosure) is designed, including access doors, manhole covers etc.. Curve C P_{red} illustrates the reduced pressure after the explosion panels of sufficient size has ruptured. Curve B illustrates the reduced pressure after smaller size explosion panels have ruptured.

The K_{st} and P_{max} values representative of the dust likely to be contained in the enclosure are

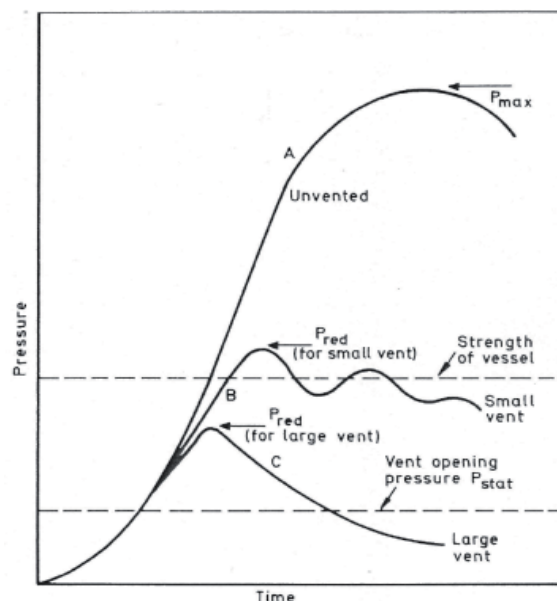


Figure 5.9. Illustration of explosion venting.

essential for calculating the size as well as the P_{stat} (rupture pressure) characteristics of the material in the explosion panels. Well-developed models are available for calculation of explosion vents [124].

5.4.2 Risk zone classification for gas, liquids and vapours

The risk zone classification of work areas shall be done on the basis of the properties of the gas, vapours or mist present in the location and the likelihood of explosible concentrations to occur [69]. Table 5.11 summarizes the criteria for zone classification defined under the NFPA and ATEX systems.

Table 5.11. Zone classification under NFPA and ATEX systems.

Zone	Classification criteria		Typical locations
	ANSI/NFPA	ATEX	
0	Area where flammable atmosphere is likely to be present – may be present for long periods or even continuously	A place in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapour or mist is present continuously or for long periods or frequently	During transfer of volatile liquids or flammable gases from one container to another; spray booths, open tanks, solvent drying operations, gas generator rooms, pump rooms
1	Area where flammable atmosphere is possible but unlikely to be present for long periods	A place in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapour or mist is likely to occur in normal operation occasionally	Inside inadequately vented containers or tanks, between inner and outer roofs of floating fuel tanks, interior of venting ducts for ignitable gases
2	Area where flammable atmosphere is unlikely to be present except for short periods of time – typically as a result of process fault condition	A place in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapour or mist is not likely to occur in normal operation, but if it does, will persist for a short period only	

The ISO 6184-2 Standard [92] specifies a methodology used for determination of the explosibility characteristics such as P_{max} , K_{st} and dP/dt for gases. The standard is similar to ISO 6184-1 used for dust [91] (see section 5.1.2).

Escaping gas and vapours typically do not burn but rather explode when ignited due to the fast moving molecules of gas.

As discussed below, there are two scenarios to be concerned about, the potential flammable concentration of off-gasses during storage, and handling and concentration of flammable gases during the partly developed pyrolysis during the early stage of fires.

Potential flammable concentration from off-gassing

Off-gasses from pellets contain condensable as well as non-condensable gases [99-101, 173], see chapter 4. Of concern from an explosion and fire perspective are the non-condensable gases such as carbon-monoxide (CO), methane (CH_4) and hydrogen (H_2) which are all flammable in certain concentrations as indicated in Table 5.12. In addition, most of the condensable gases emitted are flammable but are generated in relatively small amounts (see section 4.2).

If the flammable constituents of the composite gas are known, the explosible concentration can be calculated in accordance with ISO 10156 [93]. Research conducted at UBC to determine the concentration of levels of the significant gases emitted during storage of pellets made of pine with moisture contents 4/9/15/35/50 at +25/40/60°C found that flammable concentration was not reached under any of the conditions using the model prescribed in ISO

10156 for calculation of the risk for composite gas with full complement of oxygen (air) present.

During ocean transportation the oxygen level in the cargo spaces decreases rapidly from 21.9 to less than 5 % in a matter of days [117, 119] and the condition can therefore be considered inert since a flame cannot be sustained in at such low oxygen concentrations. In addition, any accumulation of dust cannot sustain combustion at oxygen levels lower than the LOC (see Table 5.1).

Potential flammable concentration of pyrolysis gases during fire incidents

The experience from fire extinguishing in silos indicates that large amounts of highly flammable gas are generated [139]. The exothermic process inside a silo can be characterized as an under-stoichiometric pyrolysis resulting in large amounts of CO being generated. If an ignition source and oxygen (air) is present the gas will easily ignite and generate an explosion or a violent fire (see section 3.5.2.2).

5.5. Safety certification

The Wood Pellet Association of Canada (WPAC) together with the British Columbia Forest Safety Council (BCFSC) in 2011 developed a safety certification scheme for the pellets industry in Canada. The scheme consists of annual on-site audits of production facilities with review of safety based on a rigorous protocol for all handling and processing facilities and the building fire codes (<http://www.bcforestsafe.org/other/Base.htm>). A similar scheme is also under development for the saw milling industry in British Columbia after a series of disastrous explosions during the last 18 month causing 4 fatalities and dozens of badly injured workers. Dust is suspected to be the cause of the incidents. Facilities qualifying for the certification receive a discount on insurance premiums.

Table 5.12. Flammability limits of selected non-condensable gases.

Gas species	Flammable concentration range in % of volume in air
Carbon monoxide (CO)	Between 12 and 75
Methane (CH_4)	Between 5 and 15
Hydrogen (H_2)	Between 4 and 75

6 BIOLOGICAL HEALTH RISKS

In addition to the fire and explosion hazards covered in the preceding chapters, the handling, processing and storage of biomass can introduce biological health hazards. Much of the work on these hazards have been done in the agriculture and waste sectors, particularly relating to compost and the safe handling of waste. The section below examines these potential hazards, which include hazards arising from bioaerosols, including dust, allergic and pathogenic responses. The section examines these issues for handling and storage of biomass; but it also considers arisings that occur in the transport stage. This issue is important for all biomass materials considered for use in combustion plant; and it is also important for anaerobic digestion.

6.1 Introduction

The health and safety effects resulting from the preparation and use of biomass fuels that derive from the biological nature of the biomass and waste mainly result from the formation of dusts and "bioaerosols".

Bioaerosols are a broad term for airborne pollutants, specifically particulate matter usually associated with compounds of biological origin. A more comprehensive definition is given in Box 6.1. Bioaerosols can be generated in a number of ways, for example as liquid droplets or as dry materials which are suspended in the air either individually, as clusters or carried on other organic material.

Bioaerosols are ubiquitous in ambient air and are generated by physical disturbance of biological material and by biological activities, such as breathing and coughing. They can be carried short or long distances by varying air currents and exposure to them is a normal part of life. As a result, human physiology has mechanisms to deal with the environmental exposure, which complicates assessing the risk factors from the use of biomass or waste fuels. However, exposure (both occupational and domestic) is greatly increased as more organic material is stored and/or reprocessed. In these circumstances, depending on the material and the type of reprocessing, it is possible to create a potentially high level source of bioaerosols within the natural environment.

The main hazard threat posed by bioaerosols to humans and animals is the increased risk of health related

problems, which include respiratory diseases, acute toxic effects, allergies and cancer. These effects are due to the physical size and ability of the microorganisms and their associated products to be inhaled deep into the respiratory tract. Prolonged exposure to elevated levels significantly increases this risk.

While many of the impacts result from bioaerosols in general, there are also species specific impacts from the different forms of bioaerosols. Consequently a broad discussion of "bioaerosols" has similarities to a discussion of the impacts of "chemicals," - the term is too generic to be useful. To gain greater resolution, subdivisions are identified through segregation of bioaerosols by bacteria, viruses and fungi as well, as the chemical compounds that induce effects such as β -glucans and endotoxins; but even these sub-divisions are aggregate forms of analyses.

The hazards from bioaerosols fall into three broad classes, which will be described hereafter:

6.1.1 Physical interaction

This is the same for any dust of similar particle size, whether biological or inert, and there is substantive data and regulation on the risks from these sources. Regulations for dusts tend to link to the depth to which the dust particles will tend to enter the respiratory tract and thus inhalable, thoracic and respirable limits are set in many countries. The hazard being greater the further into the lung the particles can travel:

- Inhalable Dust (PM₁₀₀)
Airborne particles which can enter the nose and mouth during normal breathing. Particles of 100 μ m diameter or less.
- Thoracic Dust (PM₁₀)
Particles that will pass through the nose and throat, reaching the lungs. Particles of 10 μ m diameter and less. Generally referred to as PM₁₀.
- Respirable Dust (PM_{2.5})
Particles that will penetrate into the gas exchange region of the lungs. A hazardous particulate size less than 5 μ m. Often limit values cite particle sizes of 2.5 μ m (PM_{2.5}).

Depending on size, aerosol particles easily deposit in various parts of our airways (Figure 6.1) as we inhale and subsequently causes illnesses such as acute reactions, chronic reactions or tumours (see MSDS for wood pellets [114]). The most serious damage is done by respirable dust particles which are able to enter our

Physical

Where the physical interaction of the particle with the respiratory tract generates health impacts.

Irritant/ allergenic

Where the biological particle generates an immunological response from the biological nature in the host such that adverse health effects are experienced

Pathogenic

Where a viable organism is inhaled and the organism propagates and infects the host causing disease.

bloodstream through the alveoli where the gas exchange (oxygen uptake) takes place in our lungs. The medical field is using the following classifications for particles with penetration illustrated in the figure below;

To put this in context, it is estimated that during a lifetime an average person inhales over 10 m³ of air per 24 hours, which translates in to about 4,000 m³ per year or 320,000 m³ during an 80 year lifespan. A typical outdoor particle concentration is about 3 µg/m³ inhaled. This translates to about 3 g of particulates inhaled during a lifetime, which is about 3 teaspoons full of particles [85]. The surface of the head region exposed to air is about 0.5 m², the bronchial-thoracic region about 2 m² and the respiratory alveoli region about 100 m².

Bioaerosols are typically derived from cells or cell fragments and will have a particle size of 1-20 µm. However, in some circumstances larger particles are generated from either agglomerates or material dusts generated by degradation of the biomass e.g. wood dusts in sawmills or chipping plant.

In most biomass fuel environments dust will be the most significant risk factor and typical limit values for dust are presented in Table 6.1. General dust level limits exist in most countries based on occupational exposure levels, for industries that pose higher risk levels due to the nature of the dusts created more stringent levels are enforced to deal with the additional risks posed whether they be inert (e.g. asbestos, silica) or organic (e.g. flour, cotton, woodworking).

Sources:

UK: Occupational dust limit <http://www.legislation.gov.uk/ukxi/2010/1001/contents/made>

Norway: http://www.klif.no/artikkel____34960.aspx

US: National Ambient Air Quality Standard: 71 FR 61144, Oct 17, 2006, <http://epa.gov/air/criteria.html>

Australia: <http://www.environment.gov.au/atmosphere/airquality/standards.html#air>

Canada: <http://www.hc-sc.gc.ca/ewh-semt/air/out-ext/reg-eng.php#a2>

6.1.2 Irritant/allergic hazards

The organic nature of some dusts and particles can pose additional hazards due to the biological response that the body and immune system provide.

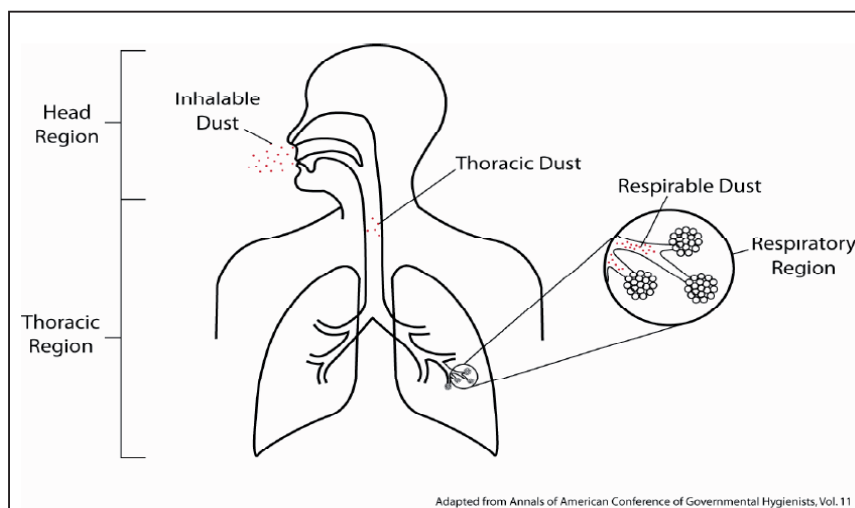


Figure 6.1. Regional Particle Deposition in the Airways (Adapted from Annals of American Conference of Governmental Hygienists, Vol 11).

This response is highly specific to the individual, which makes developing guidelines complex.

In a general sense the body reacts to markers in biological material that allow the body to identify the appropriate response to counteract the threat posed by the organisms or material. These mechanisms deal with normal day to day exposure and by and large do not cause health impacts. There are common exceptions to this in the form of allergic responses e.g. asthma and milder effects such as hay fever.

The nature of the response mechanism results in the response being related to the organism/material but in general there are two groups of conditions:

- Allergic - Allergic Alveolitis (sometimes called hypersensitive pneumonitis), Asthma and Allergic Rhinitis; and
- Organic Dust Toxic Syndrome (ODTS).

The main distinction between these is that the allergic responses will be generated by immunological sensitisation towards a specific agent and will cause the production of a specific immunoglobulin E response, whilst ODTS is a more generic and non-specific response without long lasting effects.

The allergic effects are added to by the toxic effects of some of the biological materials and thus fungal (mycotoxins) and Gram-negative bacterial toxins (exo- and endotoxins) also play a role in the health impacts. Whilst at this stage these effects are not fully understood, the mechanisms are likely to be easier to develop dose response relationships as the mechanisms are less likely to be specific individual response as in immune responses to allergens.

Table 6.1 Examples of national and international dust limits

Country	Limit	Value
UK	Occupational dust OEL _{8 hour}	10 mg/m ³
UK except Scotland	Ambient air quality annual mean PM ₁₀ daily limit PM ₁₀ annual mean PM _{2.5} target for urban background (PM _{2.5})	40 µg/m ³ 50 µg/m ³ 25 µg/m ³ 15% reduction by 2020
Scotland	Ambient air quality annual mean PM ₁₀ annual mean PM _{2.5}	18 µg/m ³ 12 µg/m ³
Germany	Occupational dust inhalable respirable	10 mg/m ³ 3 mg/m ³
	Ambient air quality Annual limit PM ₁₀ Daily limit PM ₁₀ Limit PM _{2.5}	40 µg/m ³ 30 µg/m ³ 25 µg/m ³ (target, limit from 2015) 20 µg/m ³ (AEI 2013-15)
Denmark	Occupational dust (avg. over 8 h) Mineral dust (total) Mineral dust (respirable) Organic dust (resp.) Wood dust (inhalable.) Peak levels (avg. 15 min)	10 mg/m ³ 5 mg/m ³ 3 mg/m ³ 1 mg/m ³ Max 2x limit.
Denmark	Ambient air quality Annual limit PM ₁₀ Daily limit PM ₁₀ Limit PM _{2.5}	40 µg/m ³ 30 µg/m ³ 25 µg/m ³ (from 1.1.2015) 20 µg/m ³ (AEI 2013-15)
Norway	PM10 Daily limit PM10 annual limit	50 µg/m ³ (not to be exceeded more than 35 times per year). 40 µg/m ³
European Union (2008) [71]	Annual limit PM ₁₀ Daily limit PM ₁₀ Target for PM _{2.5}	40 µg/m ³ 50 µg/m ³ (not to be exceeded more than 35 times a year). 25 µg/m ³ by 2015 20 µg/m ³ by 2020
US	PM ₁₀ daily limit (note no annual PM ₁₀) PM _{2.5} daily limit PM _{2.5} annual limit	150 µg/m ³ (not to be exceeded more than once per year on average over 3 years) 35 µg/m ³ (98 th percentile, 3y av) 15 µg/m ³ (ann mean, av in 3 y)
Australia	PM ₁₀ daily PM _{2.5} daily limit PM _{2.5} annual	50 µg/m ³ not exceeded more than 5 days per year. 25 µg/m ³ 8 µg/m ³
Canada	PM _{2.5} Daily limit	30 µg/m ³
WHO (2005) guidelines [11]	PM ₁₀ annual mean PM ₁₀ daily mean PM _{2.5} annual mean PM _{2.5} daily mean	20 µg/m ³ 50 µg/m ³ 10 µg/m ³ 25 µg/m ³

The impacts of these conditions vary, but have a similar range of symptoms, including influenza like symptoms, chills, fever, dry cough, malaise breathlessness and weight loss. The principal distinction is that allergic responses are chronic conditions that once the individual is sensitised by repeated exposure at low (non-toxic) doses causes a reaction; and ODTS is an acute condition that is a

response to an exposure to a toxic level of the hazard that, in general, does not lead to long term health effects.

The literature has many papers that indicate the levels of bioaerosols in environments where subjects are experiencing health effects, but there is little data on the dose response relationship. Thus there is great

Table 6.2. Reported exposure and background levels

Agent	Level	Source
aflatoxin	250-400 ng /g dust ground nut processing	[33, 62, 65]
	10 ⁷ ng/m ³ Maize processing	[52-54]
Fungi	Background 114-816 cfu/m ³ Down wind of composting plant 367 cfu/m ³ Operational composting 733-2.83x10 ³ cfu/m ³	[61]
	10 ⁸ cfu/m ³ spores for acute symptoms Allergic alveolitis	[153]
	0.6-4.5 x 10 ⁹ cfu on Allergic alveolitis affected farms 0.6-4.5 x 10 ⁹ cfu on ODTS affected farms 1-80 x 10 ⁶ cfu background levels on farms	[111]
	Typical levels 10 ³ -10 ⁶ cfu/m ³ Sensitisation level >10 ⁸ cfu/m ³ Cork processing background 10 ⁶ -10 ⁷ cfu/m ³ Peak 9x 10 ⁷ cfu/m ³ Cotton mills 4.0 x 10 ⁵ – 1.2x 10 ⁷ cfu/m ³	[103]
	Various studies on mean domestic levels Indoors - 34-2296 cfu/m ³	[5]
	Outdoors 882-1131 cfu/m ³ Open windrow composting sites Background 547-1.19x10 ³ cfu/m ³ Downwind of Composting activities 51-5.68x10 ³ cfu/m ³ Landfill with Open windrow Composting sites Background 28-577 cfu/m ³ Downwind of Site activities 11-789 cfu/m ³ Landfill average 155-3.63x10 ³ cfu/m ³	[163] [162] [164]
	18-34 µg/m ³ worst case condition farm operations Background 0.017-0.161 ng/m ³	[111]
	Down wind of composting plant 0.236 ng/m ³ Operational composting 20.7 ng/m ³	[61]
Endotoxin	Grain and animal feed 0-285 EU/m ³ (inhalable) Pig farming 900-2400 EU/m ³ (inhalable) Chicken farming 38-98 EU/m ³ (inhalable) Cotton industry 200-3700 EU/m ³ respirable)	[6]
	Operational composting 966x10 ³ cfu/m ³ Open windrow composting sites Background 0 cfu/m ³ Downwind of Composting activities 5-15 cfu/m ³ Landfill with Open windrow Composting sites Background 0-42 cfu/m ³ Downwind of Site activities 2-74 cfu/m ³ Landfill average 154-1.48x10 ³ cfu/m ³	[61] [162, 163] [161, 164]
	Background 311-433 cfu/m ³ Down wind of composting plant 3x10 ³ cfu/m ³ Operational composting 7.67x10 ⁴ cfu/m ³	[61]
	Various studies on mean domestic levels Indoors – 253-5200 cfu/m ³ Outdoors 16-275 cfu/m ³	[5]
Total bacteria	Open windrow composting sites Background 25-854 cfu/m ³ Downwind of Composting activities 15->1.3x10 ⁴ cfu/m ³ Landfill with Open windrow Composting sites Background 7-807 cfu/m ³ Downwind of Site activities 32-4.29x10 ³ cfu/m ³ Landfill average 283-8.21x10 ³ cfu/m ³	[162, 163] [161, 164]
	Aspergillus fumigatus Background 0-80 cfu/m ³ Down wind of composting plant 200 cfu/m ³ Operational composting 2.03x10 ³ cfu/m ³	[61]
	Cryptostroma corticale – Maple bark processing 1.3x10 ⁷ cfu/m ³	[180]

Table 6.3 Bioaerosol guidance and limits

Country	Parameter	Limit value	Source/comment
UK	Bioaerosols Bacteria	1000 CFU/m ³	HSE R786 [165] and Environment Agency [21] guidance, based on risk zone and providing risk assessment within 250 meters of composting plants. Scottish Environmental Protection Agency specify 1000 CFU/m ³ as part of the waste management license limits for composting activities, based upon the Environment Agency Policy 405_07 Levels of bacteria and fungi and gram negative bacteria for guidance only, not definitive limit values.
	Fungi Gram negative bacteria	500 CFU/m ³ 300 CFU/m ³	
	Aspergillus fumigatus	500 CFU/m ³	
Germany	Bioaerosols	10000 CFU/m ³	MAK (max. occupational conc.),
	Bacteria		
	Fungi	1000 CFU/m ³	Guidance values, no limits
	Gram negative bacteria	1000 CFU/m ³	Guidance values, no limits
	Endotoxins	1000 EU/m ³	Guidance values, no limits
Denmark			No official guidance or limit
Finland	Endotoxins	25ng/m ³	No regulatory exposure limits, only recommendations
USA	Bioaerosols	There are no ambient or occupational exposure limits for bioaerosols in the US at present	http://www.calrecycle.ca.gov/swfacilities/Compostables/Emissions/Health.htm Compost Facilities: Off-Site Air Emissions and Health (2007) Cornell Waste Management Institute - http://cwmi.css.cornell.edu/compostairemissions.pdf
EU	Biological Agents	None given.	E-Facts (53) Risk Assessment for biological Agents [75] provides guidance to comply with EC Directive 2000/54/EC on the protection of workers from risks related to exposure to biological agents at work [70].

difficulty in determining limit values to which health effects can be ascribed. The general consensus is that exposure to high concentrations bioaerosols should be avoided, especially where single species are dominant in the population. The definition of "high" in this context is also a point of conjecture, but obviously relates to the type of exposure i.e. occupational, domestic or environmental and the potency of the hazard.

This lack of ability to agree on defined limit values is due to a number of factors, including the wide variability in ambient and occupational exposure; difficulty in measuring the specific antigen or compounds responsible for the condition; and partly due to the wide individual response to these agents. Typical classifications used are fungi, bacterial, Gram negative bacteria and more recently the impacts of β -glucan, mycotoxins and endotoxins is also being recognised and thus limits and measurements for these are also beginning to be published. Some literature data is presented in Table 6.2.

The data in Table 6.2 shows that there is a wide variation between both background levels and various industrial sources. The key summary of this is that background levels average at values less than $2-3 \times 10^3$ cfu/m³ for fungi and bacteria. However, depending on the sources of bioaerosols in the environment, weather conditions and the time of year, higher levels up to 10^6 cfu/m³ are not unusual. The waste management sector provides and actively encourages microorganisms to thrive in composting and anaerobic digestion (AD) processes, as they are essential to the task of breaking down the organic material into useful products. These (and other industrial and agricultural settings where organic matter may be concentrated) vary considerably (and so do the type of microorganisms present in the material), but by and large the following is observed:

- In areas where organic materials are stored or treated in a way that may promote mould growth high fungal levels can be present. This applies to a number of situations, for example wood processing, composting, farming activities for straw and grain.

- Processes that deal with moist biological material, such as food waste and faecal matter may lead to high bacteria and endotoxin levels.

The nature of the type of storage and processing involved can encourage organic material to become airborne as bioaerosols, which should be minimised and controlled where possible.

The concentrations of the bioaerosols monitored in these conditions vary considerably (Composting Association 2003). As indicated earlier, measurement of bioaerosols and the various subdivisions can be imprecise when relating to specific conditions or sources. It would be impractical to regulate each and every organism or compound that presents a hazard for general exposure to bioaerosols although more specific regulation might be possible for situations known to have associated specific hazards. Current guidance for evaluating bioaerosols and guidelines for acceptable exposure limits for occupational workers and the general public have been outlined in the UK by the Environment Agency for England and Wales and the Health and Safety Executive. This guidance suggests that downwind bioaerosol emissions from a landfill and or composting facility up to 250 m distant should not exceed the maximum exposure thresholds for individual bioaerosol components which are grouped into broader categories. Specific guidance from various countries is presented in Table 6.3.

6.1.3 Pathogenic hazards

Microbial pathogen hazards are derived from viable organisms entering the host and then propagating within the body, resulting in disease. Pathogens in bioaerosols from biofuels will be mainly fungi and bacteria, although the presence of viruses, prions, protozoa pathogens cannot be ruled out, particularly if the biofuel is derived from materials (e.g. sewage sludge, animal manures and animal by-products) likely to contain these pathogens.

The properties of individual pathogens, such as their survival or growth during preparation, storage and transport of the biofuel, and survival in airborne bioaerosols, vary from pathogen species to pathogen species. To have an impact the organisms must remain viable in the biofuel and survive transport (by bioaerosol or other route) to the vulnerable receptor. The dose-response for pathogens is complex and definitive safe exposure levels are difficult to define. This is because most receptors have varying degrees of resistance to the pathogen and it is theoretically possible that, because the pathogens grow in the host, that exposure to a single organism may cause disease in very sensitive individuals. Some pathogenic bacteria require specific conditions to remain viable, and it is possible to reduce their impact if these conditions are not present. Classic examples of this are conditions such as *Legionella*, which requires a water based environment to remain viable. Thus the environment for fuel production and storage will not encourage the propagation of the bacteria required for spread of this

condition, but environments where moisture is present are more at risk of resulting in infection. Other pathogens may produce resistant spore, e.g. the fungus *Aspergillus* and the bacterial genera *Bacillus* and *Clostridium* which will be resistant to heat, cold, desiccation and sunlight. Hence these may survive in bioaerosols.

Unfortunately the outcomes of infection by some of the organisms concerned can be serious and some deaths have been linked to pathogens in composting plants and compost products (*Aspergilliosis* [150], *Legionella* [182]). Processing conditions in most composting and AD facilities provide heat treatment that kill and attenuate the risks from most non-sporing pathogens. However this may not be the case in organic matter derived fuels that have allowed microbes to grow at mesophilic temperatures or if the feedstock contains bacteria that produce heat resistant spores. For example, the presence of the spore-forming *Clostridium botulinum* has been observed in composts and digestates.

Whilst the majority of the population has developed adequate protective mechanisms to avoid impacts from small numbers of viable organisms entering their body, issues arise when the subjects are immuno-compromised or are exposed to large numbers of infective agents, or to infectious agents that may cause disease from exposure to very low numbers, which then overwhelm the body's defences. The latter is highly unlikely in normal operations, due to the controls in normal operations that limit exposure (e.g. dust controls, protective equipment for operatives etc.). However there is a need to maintain controls to ensure continued effective operation. While it may be assumed that immuno-compromised individuals are unlikely to be in the workforce, environmental exposure should be minimised.

Box 6.2 provides a commentary on the methods available to monitor bioaerosols in the workplace.

6.2 Preventing biological health risks

An appreciation of two basic factors provides the key to addressing the causes of the biological health risks associated with the handling and preparation of biofuels:

- Prevention of the proliferation of microbial growth
- Prevention of the development of aerosols or suspension in air of organic dusts and biologically active material

The activities and conditions that result in microbial growth or development of bioaerosols vary with the biomass and the method of treatment and thus we only discuss the general principals below.

6.2.1 Exposure to organic dusts

As all biomass fuels are predominantly organic in nature and have the potential to create organic dusts, the biomass industry must consider issues arising from the presence of organic dust. The key issue

Box 6.2 Measurement of biological agents

The European Agency for Safety and Health at Work [12] has reviewed and commented on the methods available for monitoring air borne exposure to biological agents in the environment. It lists available methods as:

1. Cultivation of microorganisms in air or settle dust samples. Specific culture mediums are required for particular bacteria or fungal groups.
2. Sampling of non-culturable bioaerosols can be based on air filtration or liquid impinge methods. Fast and sensitive techniques based on light scattering spectrometry can be used to determine microorganism presence in liquid samples. Electron microscopy or scanning electron microscopy could also be used and allow better determination of biological agents. Simple light microscopy may be used to count microorganisms. However, caution is advised on interpreting results as the methods do not differentiate between living and dead microorganisms.
3. Use of cellular components as markers of groups of microorganisms e.g. VOCs as markers for fungal growth or polysaccharides and ergosterol or immunoassays for identification of fungal biomass. Endotoxins may also be markers of biological agents. For these methods to be quantitative a relationship between the marker and the agent is necessary and as yet none has been shown to be adequate.

In addition the report comments that many of these techniques are not yet commercially available; that they show significant variability between laboratories; that they are expensive; that there are difficulties in taking representative samples (because of the ability of microorganisms to reproduce rapidly), which means that repeated sampling is necessary; and that some microorganisms and spores are extremely resilient while others may be easily degraded in the sampling process.

This report concludes that "the measurement methods available, even the more established ones, have not yet been fully validated and routinely applied. There is a need to develop adequate sampling techniques and analytical methods further to allow for better identification and for quantitative exposure assessment of biological agents in the workplace, which are essential steps towards a proper risk assessment."

will be the propensity for the creation of dusts that are inhalable. The points where dust creation can occur are in the processing of the fuel if the biomass feedstock is agitated or size reduced such as:

- Size reduction to make wood chips, straw chopping or similar processes, e.g. at sawmills;
- Shredding of wastes for solid recovered fuel (SRF) or refuse derived fuel (RDF) production;
- Sorting processes to remove contaminants:
 - This largely applies to waste fuels that require a variety of processes, such as screening and air separation that result in a great deal of agitation of the waste. Waste sorting and re-processing facilities should have appropriate air control strategies for dust and odour filtration fitted as standard. Whilst there are no specific regulations that control this, the standard dust controls will need to be applied for keeping dust levels below occupational requirements but also to avoid dust build up with associated housekeeping and dust explosion issues.
- Pelletisation processes
 - The process of generating a solid pellet will also generate fine dusts that will need to be controlled.

These issues are in the domain of the biomass fuel generator, who should be equipped to provide the containment and dust extraction required. Dust will also be generated at the user's site as a result of transport and loading/unloading activity; and the control of this dust must also be considered.

Dust generation is high when the waste is dry. As most fuels for thermal processes will need to be relatively dry this means that precautions to deal with dust are required at the heat or power plant. Moisture present in the material provides a degree of adhesion between dust particles that will cause the agglomerated particles to fall to ground quickly or prevent them from becoming airborne. Once the moisture content falls below a critical level the particles do not stick together and the smaller particles are able to move with air flow. Once particles are in the air flow then they can be breathed in and potentially add to the effects identified in section 6.1..

In summary organic dust generation from biomass fuel are caused by the following:

- Agitation
- Low moisture content
- High air flow
- Lack of containment

6.2.2 Exposure to bioaerosols

Microbial growth that leads to the more harmful effects discussed in section 6.1 results either from pathogens present in the original biomass material or subsequent growth of organisms in the supply chain (particularly during storage of feedstock prior to processing, any biological processing steps such as composting and AD, and storage of the biomass fuel).

The minimisation of the risk of exposure from bioaerosols from harmful levels of pathogens and micro-organisms is by selection of feedstocks with low contamination, or by using processes that reduce and control the level of contamination in the biofuel and their release as bioaerosols.

For example, forestry products are generally low in animal pathogens (although there will be a population of indigenous microorganisms that may include opportunistic pathogens). If the forest has been recently fertilised using un-sanitised sewage sludge or manure, then the pathogen contamination may be much higher. Thus the selection procedures of the feedstock for a wood chip production plant can influence the initial microbial contamination present. However drying of the fuel may either attenuate the levels of most pathogen contamination if carried out at temperatures that are typical of or above temperatures used in pasteurisation (~70 °C). As micro-organisms require a certain moisture level for growth, the potential for re-growth in the dried product will be minimised. Low temperature drying (up to 50 °C) may encourage growth, however; at least until the moisture content has dropped to levels that prevent growth. Different organisms react differently to the conditions; enteric bacteria are likely to be killed by temperature and low moisture, but some fungi will proliferate in the warm moist early stage and then form spores once the wood dries out. Sporulating bacteria may also survive the drying processes as heat resistant spores.

Other types of feedstock will inherently be contaminated e.g. untreated municipal solid waste may contain many materials such as nappies, pet animal faeces, food waste containing animal by-products and solid recovered fuel derived from municipal solid waste may contain contamination from the same sources as well as potential contamination from growth during processing. Thus the handling and use of such fuels will require specific controls to be adopted in the preparation, handling and combustion facilities. This contamination may be reduced in some of the production processes that heat the waste during processing, which may lead to sanitised fuels with lower levels of active micro-organisms. Biodrying and Mechanical Biological Treatment (MBT) processes involve heating the waste through composting to temperatures of about 70 °C. Mechanical Heat Treatment (MHT) processes involve heating to temperatures above 160 °C for an hour or more in autoclaves. These conditions will kill off virtually all micro-organisms, even the most heat resistant spores, although prions may still survive such harsh conditions.

6.2.3 Size reduction

When organic matter is broken up, or aggressively handled, dust is created. This is true whether it is a raw biomass material, such as wood or agricultural products or processed biomass, such as the biomass fraction in solid recovered fuel. In most fuel systems the particle

size is controlled to some extent by size reduction or screening. These processes generate dusts that pose the hazards noted above. These processes will generally be undertaken in closely controlled environment where dust control systems can be installed to control the dust emissions. For the same reasons, care has to be taken when mobile plant is used to shred or process biomass in the field. In this circumstance the ability to control fugitive emission of dust or aerosols is more constrained and attention has to be paid to minimising the exposure for both operators and the public.

Generation of dusts also occurs in operations other than shredding, for example, sawmills, abrasion in screw conveyors or screening plant, and deposition of product in storage bays from overhead conveyors or chutes. In addition pelletisation processes which reduce dust in subsequent handling, will result in an amount of fine dust during production that has to be managed.

6.2.4 Loading/unloading

The transportation of the fuel will expose operatives for whom the biomass may not be their core business. Consequently these operatives should be required to attend safety instruction and to use appropriate procedures and safety equipment. Without this training they may be less aware of the controls measures necessary for dust and microbial hazards. Thus the control measures employed should be more automatic rather than procedure based to ensure adequate protection.

A key exposure here will be in the loading/unloading operations which necessarily rely on agitation or moving the biomass, which generate air flows that will entrain fine particulates. Pneumatic systems are commonly used in the industry and these will pose higher risks as a result of their much higher velocity and volume of air which will maximise the aerosolisation of any microorganisms or organic dusts. This will need to be controlled by ensuring the airflows are filtered and the storage area is sealed to avoid leaking of dusty air from this area.

Further information on the dust and other hazards in transportation is provided in Chapter 1.

6.3 Mitigation of hazardous dust

The health risk that arises from biomass fuels is composed of two parts, namely the hazard or severity (dose- response) of any impact, and the frequency or likelihood of the impact occurring (exposure to a level that causes harm).

Most actions for mitigation primarily reduce the level of hazard in the dust and the release of dust into the environment of the sensitive receptor e.g. working environment and /or neighbouring third parties. A summary of the risk and mitigations for physical dust effects and bioaerosols is provided in Table 6.4.

6.3.1 Minimizing the formation of hazardous dust

Key methodologies for minimizing formation of hazardous dust are:

1. Ensuring that fuel sources are selected from uncontaminated sources.
2. Sanitising sources of biomass that will be inherently contaminated with pathogens and other microorganisms (e.g. waste based solid recovered fuel, chicken litter or other contaminated biomass fuels)
 - a. For example, waste based solid recovered fuels will contain a wide range of pathogens. Drying and heating processes reduce the viable microbiological load and thereby the risk of exposure to levels of pathogenic organisms that result in disease.
 - b. Ensuring crop based biomass is not taken from sites that have been recently applied with contaminated materials or fertilizers.
3. Preventing the growth of pathogenic microorganisms in biomass during the production and use as a fuel, e.g. ensuring that damp conditions do not exist in fuel storage, as these conditions promote microbial and fungal growth
 - a. Storage bunkers should be suitably ventilated, such that condensation does not wet the fuel leading to fungal growth;
 - b. Storage of biomass fuels should be protected from the weather, so that precipitation does not allow microbial growth.
4. Agglomeration or pelletisation of finely divided biomass e.g. sawdust, so that dust generation is minimised in the transport and subsequent handling operations.
5. Controlling the size reduction and handling methodologies so that less very finely divided dust is generated:
 - a. Cutting systems rather than impact mechanisms and slow speed rather than high speed systems will lead to reduced generation of fine particles [183].
 - b. Ensuring the process and handling systems do not include a mechanical agitation that is too aggressive for the operation required.

6.3.2 Minimizing exposure to hazardous dust

Methodologies for reducing the likelihood of hazards include actions that minimise the **exposure** to the organic dusts and microorganisms by reducing the tendency of fine particles to become aerosols and reducing the dispersion of any dusts generated. In general dusts can be minimised by applying suitable ventilation, the design of the processing units and the type and condition of the material being processed;

1. Ensure that processing and storage facilities are enclosed, so that any generated dusts are contained within the building
 - a. This can be a combination of physical means e.g. rapid closing doors, dual door systems; or

operational practices that minimise time that doors are open by programming vehicle movements.

- b. Liquid (generally water) sprays are a common method used in the storage of potentially dusty material, both in the open and indoors to dampen the stored materials surface, reducing the amount of material that is lifted by air currents. Electrostatic space charge systems have shown promise in the reduction of dust in poultry houses [121, 149] which has the potential to be applied to other areas of industry. Obviously care is required when using liquid sprays, as this added moisture may lead to reduction in value of the material as a fuel or it may encourage microbial proliferation, but the latter hazard can be controlled if aerolisation can be prevented.
 - c. Optimising the design of external storage facilities that minimise the wind to material interaction. This can be achieved by using the topography of the site and utilising "smart" locations in the site structure, which have to be incorporated at the planning stage through the use of dispersion modelling and take the land topography into account. Currently, such models are developed from odour and dust dispersion models. Other risk mitigation measures may be included in the design of the storage facilities. For example, the use of recessed or silo storage; or building up of walls/soil banks or even the planting of trees and foliage around sites helps to act as a barrier to reduce the amount of material interacting or being carried downwind.
2. Ensure that human intervention with the biomass is minimised. This is particularly relevant to potentially contaminated biomass fuels (e.g. solid recovered fuel):
 - a. Where human intervention is required, ensure that respiratory protection is provided in the form of protected working environment systems (e.g. dust filtering of vehicle cabs, filtered air for picking stations and the provision of PPE (personal protective equipment, respirators with clean filtered air supply, dust mask, gloves, goggles and clothes etc.).
 - b. Where operatives are continually exposed to the dusts from the biomass, periodic health screening should be considered due to the issues related to individual response to the various allergen and irritants that may be present.
3. Provide dust extraction systems to collect and capture generated dusts
 - a. Dust collection should be sited at transfer points where dust is liberated or associated with physical processes that generate dust e.g. shredding of pelletisation, as well as general air ventilation keeping the building under negative air pressure, preventing fugitive dust emissions. The air from these will need to be filtered through a dust filtration system.
 - b. Provision of dust capture systems such as electrostatic space charge systems which

Table 6.4

Summary of risks and mitigations

Hazard	Process	Level of risk	Mitigation/comments
Physical dust effects			Dependent on particle size, smallest particles causing the most harm
In fuel preparation process	Storage of biomass for fuel preparation	Low risk for moist biomass. For dry biomass, particularly waste wood, there may be a potential for release of dust on dry, windy days.	Issues with dust from dry and waste wood can be minimised by the use of moisture spraying if storage is out doors.
	Operations to shred or size reduce biomass fuel	High level of dust release	Can be minimised by selection of slow speed and cutting machines rather than high speed impact shredders. Release can be minimised by enclosing the operation (where possible) and using dust extraction and air filtration. Use of dust masks or respirators (of an appropriate quality to control the smallest particles e.g. P3) is recommended and breathing protection should be considered for some very dusty operations.
	Conveying, other processes	Dust generation is highest at agitation points e.g. transfer points in conveying systems	Design should try to minimise transfer points in conveying systems Enclosure of system so that dust is contained. Use of extractive dust control systems. Consider Personal Protective Equipment (PPE) for operatives.
	Transport and loading/unloading	Where controls can be installed, risk should be low. Where levels of controls may be less (such as small users and non-specialised operations) risks will higher	Ensure that air management is employed in loading and unloading operations so that displaced air is not vented without filtration Management of biomass fuel should not be outdoors if it is prone to dust release. Ensure that enclosed methods are used to minimise dust release. Consider moisture content control to minimise dust generation.
In combustion plant	Bunkers and feeding equipment	Risks low as most likely to be a contained and defined operation with engineered controls.	Feeders should operate in an enclosed method to prevent the release of dust. Operators should not be expected to work in the "air zone" of the feeding equipment
Bioaerosols			
Natural occurring in fuel		Varies with micro-organisms and individual, so specific risk level is difficult to generalise. However, bioaerosols are prevalent in the natural environment and thus to the majority of the population the risk is low.	Bioaerosols release shall be minimised by the same controls as for dusts. Whilst the hazards are different they are still physical particles. This should control the more minor impacts such as ODS and low level allergic responses. Additional controls are required where dusts from a biofuel are more likely to be biologically active or pathogenic or where the growth of a microorganism will lead to greater exposure.

Hazard	Process	Level of risk	Mitigation/comments
	Naturally infected fuels e.g. wastes based fuels, SRF, chicken litter etc.	Risk inherent in operation can be minimised by controls	Minimising human contact with the fuel. Drying or heating the fuel to inactivate microorganisms e.g. autoclaves, thermal drying, biodrying. Care is required to not provide suitable conditions for spore formation. Rapid processing of fuel and reduced storage decreases potential for microbial growth. Appropriate training and education of operatives in production, transport and use of the hazards associated with fuel and personal hygiene requirements. Provision of appropriate PPE, masks, gloves overalls etc. including laundering services where appropriate. Dust control measures in processes as above.
	Natural products not expected to have high contamination levels		Selection of fuel sources where contamination is unlikely e.g. avoiding forest products that have been recently applied with sewage sludge. Ensuring storage of the fuel does not promote microbial growth e.g. ensure that feedstock stores are kept ventilated and dry.
In fuel preparation process		Low	There is unlikely to be an increase in biological activity in most production processes, as the duration of operation is short. However, ensuring the biofuel is ventilated and kept dry is a good precaution.
In transport, storage and loading/unloading		Low in transport, Medium in storage	Most transport options will not pose any additional bio-hazards, as the duration is unlikely to be long enough to promote growth. Nevertheless, care should be taken that the fuel is not wetted so that growth can occur in the subsequent storage. Thus ensuring containers are covered is important for avoidance of the release of dust and of water ingress. One exception may be sea transport that may expose the fuel to moisture and longer durations. Conditions for storage at sea should be monitored and controlled for overheating due to degradation and these same systems can be used to monitor potential for microbial growth and contamination. In some biomass fuels (e.g. cakes from the extraction of oils) 'souring' may occur in anoxic conditions. A sign of this is increased acidity, so for such fuels measurement of acidity is important. The main risk in storage is the proliferation of moulds and fungi which are the release in to the air on agitation. This type of growth can be long lasting, as the storage vessel can become the infection source, resulting in a long term problem and long term exposure. Operators should ensure biomass fuel in storage facilities is well ventilated and kept dry. In addition it is good practice to ensure a good rotation of fuels (first in first out), so that fuel is not stored for excessively long periods at the back of the bunker.

have shown some promise in the reduction of dust in poultry houses [121, 149]

- c. Some ammonia/odour scrubber control systems also provide reduced bioaerosol emission [185] but unless specifically designed for the purpose they may be ineffective, as has been seen in some cases [31]. Modifications such as the addition of peracetic acid can effectively control pathogen release [120]
- 4. Ensure that loading and unloading systems have systems to contain and capture the dusts and related airflows linked to the movement of the biomass fuel. Further measures are provided in [12].

Indoor processes and vessel/silo storage with inbuilt ventilation also generally incorporate one or more of dust filters, chemical scrubbers and biological filters to treat ventilation air before discharge. However, these may fail to control emissions of pathogenic agents responsible for animal diseases, particularly if the systems are not designed to deal with the type or quantity of material they are subjected to, or are poorly maintained. This has important implications for site emergency plans and management, and disease epidemic management. For example, a dual bioscrubber-chemfilter system operating to reduce odour and ammonia emissions also significantly reduced emissions of airborne dust, endotoxins, and bacteria at an intensive duck facility [185], although it was reported that existing odour and ammonia scrubbers failed to prevent bioaerosols during a swine fever outbreak in the Netherlands [31]. Biofilters themselves may be source of bioaerosols from the microorganisms growing in the biofilter media being released into the vented air stream. As these and other mitigation technologies are developed and evaluated further for industry, it will be important to confirm their effects on the emissions of bioaerosols, and associated pathogens.

6.4 Biogenic risks associated with anaerobic digestion

Anaerobic digestion (AD) is considered additionally here, as it often concerns the handling and preparation of materials that are wetter than conventional combustion based biofuels. In this section we are not considering AD of sewage sludge, as this is an established technology for which there are existing guidelines. The biomass feedstocks for AD considered here include animal manure and slurries, household waste, food waste, organic waste from industries etc.

The level of health and safety risk is relatively low and is mainly caused by pathogenic microorganisms, and microbial constituents or metabolic products, such as organic dust and endo-toxins. As with the biofuels discussed above, the risks are generally airborne, and therefore likely to occur through inhalation of bioaerosols, but there are also ingestion risks, often through hand-mouth contact or from infection of wounds.

There have been concerns about supply of AD feedstock contaminated with *Clostridium botulinum*, which occurs widely in natural environments in soils, sediments and animal intestinal tracts. Therefore most AD feedstocks may be naturally contaminated with *C. botulinum* [43, 60, 106, 159, 160]. There are also concerns that the bacterium may be able to grow in stored AD feedstocks such as food waste [49] and, being an anaerobic bacterium able to grow through the AD process [22]. In Germany there have been suspicions of increased botulism in farm animals and occasional farm workers related farms use of organic fertilisers, including digestates [22, 50]. Most clostridia including *C. botulinum* can survive AD processes (including pasteurization) as spores [43]. Although it may not grow well and no hard evidence for significant growth has been published, the potential for some growth cannot be ruled out [43, 179]. Regrowth in stored products cannot also be ruled out, as long term survival of clostridia in stored digestates has been demonstrated [44].

The mitigation of pathogens by composting has been the subject of risk assessments in the UK as part of the development of the composting quality protocol and PAS100 [78, 79]. These studies attempted to cover AD as well, but were limited by available data. Few studies have been published on the survival potential of many specific pathogens in AD systems, although it is thought that most (apart from sporulating forms) would be attenuated [154]. The AD processing conditions incorporating a pasteurisation step for compliance with Animal-by-Product Regulations (1 hour treatment at 70 °C) will mitigate the levels of most other non-sporulating pathogens such as enteric bacteria and viruses. Fungi such as *Aspergillus* would not proliferate in the anaerobic conditions, although the survival of any spores already present in the feedstock is unknown.

Post AD processing of digestates often involves mechanical de-watering to give a cake with a moisture content of about 70 % by weight. Further thermal drying may be applied (using waste heat from biogas combustion) to reduce the moisture contents to about 30 %, which means the digestate has a sufficiently high calorific value to be considered as a biomass solid fuel. Such drying processes heat the digestate to high temperatures in excess of 90 °C, which would provide some attenuation of most clostridial spores. This would reduce the risks from these bacteria that might have survived the AD process.

6.4.1 Mitigation

As with the other biofuels discussed above, potential health problems and safety risks caused by exposure to biogenic factors in AD can be avoided through implementation of specific preventive measures along the entire chain of biogas production. Most exposure risks will

be associated with management of feedstocks, digestate product and ventilation air. Such measures should include:

- Establishing closed process cycle and "closed areas"
- Thorough cleaning routine of working places, vehicles, equipment, clothing and surrounding area
- High personal hygiene for the employees (including regular cleaning and changing of working or protective clothing; separate storage of private and working clothing; provision of facilities for hand washing; avoidance of contact with eye, nose and mouth with unwashed hands etc.)
- Personal protection and adequate protection equipment
- Implementation of "self-control" programme (see below)
- Prevention of by-pass whereby sanitized product is re-contaminated with untreated material.

Transport of food waste from restaurants, household waste and organic wastes from various industries also carry a risk of cross-contamination between feedstock types or re-contamination of any digestate that has already been sanitised. This can involve the introduction of pathogens that are not normally found in the farming sector. This problem can be avoided by strictly implementing basic measures:

- Transport of food waste from restaurants, household waste and organic wastes should be completely separated from transport of fresh manure.
- Transport vehicles should be sent through a delimited area for cleaning, washing and disinfection of biomass transport vehicles, before driving away from the biogas plant. This includes specific washing/disinfection procedures for biomass transport vehicles, including specific requirements for water temperature, quantity used, duration of cleaning and concentration of disinfectant. Wash water is collected and let back to a pre-storage tank.
- There should be complete separation between "clean" and "dirty" areas on the biogas plant and around it. In particular the digestate product must be kept separate from any untreated waste to prevent re-contamination.
- Precise responsibility for wash and disinfection.
- Registration of daily deliveries so that records are in place should contamination occur.
- Sanitization of specific wastes where the producer is known to have particular contamination of their wastes.

Further information is available from the European Agency for Safety and Health at Work [75].

6.4.2 Self-control programme

After BSE and mononucleosis episodes in Europe in 2002, the European Union adopted the Animal by-product regulation (1774/02 of 2 October 2002), which stipulates the health rules for treatment and handling of animal by-products not intended for human consumption. The regulation requires all biogas plants treating animal by-products to be approved by

the appropriate national authority. Furthermore, the biogas plants must elaborate a so called "self-control programme", with the aim of surveying and documenting the implementation and the efficiency of their health and safety measures. The surveillance procedures guarantee that the production related activities and the end products do not pose any health and safety risks to humans, animals and the environment, and to make sure that the corresponding legislation is implemented.

The self-control programme must contain as minimum:

- Identification of critical set-points
- Establishment of surveillance procedure
- Limit values for surveillance results
- Establishment of procedure for solving situations when the limit values are exceeded
- Regularly revision and up-dating of the programme, corresponding to the plant activity.
- Provision of documentation for the regulatory authority.

Examples of self-control critical set-points, specific for AD feedstock are:

- The introduction of new AD feedstocks
- Transport of animal manures and slurries from the farms and of digestate to the farms
- Transport of food waste from restaurants and households and of organic waste from industries
- Maintenance of storage facilities and of all feedstock handling and transport equipment
- Calibration of measurement instruments
- Cleaning and disinfection of spaces, storage tanks and biomass transport vehicles
- Pest control on and around the biogas plant
- Consequent training and education of the personal at all levels
- Clear protocol and procedures for visitors and for access of unauthorized persons

Preventive measures

- All AD feedstock must be supplied through documented contracts with respective suppliers.
- Evaluation of biogenic risks and pathogen load for each feedstock type allowed by law to be treated in AD plants
- Registration and control of documentation from supplier of each delivery, prior to storage at the AD plant
- No access for feedstock that are not part of a supplier contract, or do not correspond qualitatively to contractual prescriptions

Useful health and safety guidelines

- Before work starts the employees must be given instructions and training about the work process, which should be based on an established work plan. The work plan must always contain explicit descriptions of potential risks related both to work processes and the materials handled. It should

also include the corresponding rules of personal protection; and description, location and use of protection equipment and of other safety equipment. If work is undertaken by external personal, they must first be instructed on the above.

- When work is done inside biomass storage tanks, particularly where gas emissions can occur, thorough cleaning of the inside of the tank and of the surrounding area must be done first, followed by measurements of gas emission.
- Cleaning an emptied biomass storage tank or a digester tank must always be done by personal wearing protection masks and fresh air supply equipment, safety belts and safety lines, fastened to a fixed lifting installation. There should always be a second worker standing by outside the tank, equipped with the same protection facilities, continuously supervising and ready for intervention in case of emergency. The second worker is not allowed to leave the standby place during the whole operation and must be in permanent voice contact with the worker inside the tank through radio, phone etc.

Directive 2000/54/EC [70] lays the principle for the assessment and management of biological risks in the workplace.

6.5 Summary of health hazards from dust and bioaerosols

In summary the risks posed by biomass fuels in the form of dusts and bioaerosols come from both the physical particle and size effects. As particles become smaller they pose greater hazard. As a result limits on PM_{10} and $PM_{2.5}$ (particles less than $10\text{ }\mu\text{m}$ or $2.5\text{ }\mu\text{m}$ respectively) are becoming more prevalent in national regulations. In addition the organic nature of biomass fuels may result in additional impacts through either allergenic or pathogenic routes. The most prevalent feature will be the allergenic responses and the majority of the effects will be minor and short lived; but increasing severity of impact will also be linked to falling incidence of response. In the same way pathogenic responses will be a rare occurrence, but potentially result in severe hazards.

The potential significance to health exposure during the waste management process for most of the bioaerosols can be assessed as low for waste collection, transfer and sorting and moderate for composting (pending quantitative information on emissions during composting) [51]. European work [12] suggests that biohazards in waste treatment are not completely identified yet. However, a review of bioaerosols health issues concluded that workers on compost facilities are potentially exposed to higher concentrations of bioaerosols and that microbial components of compost bioaerosols have been known to cause respiratory ill health; and that workers are at greatest risk of exposure to bioaerosols during movement of the compost, particularly unloading and cleaning of vessels [7]. The same report also says

that at that time there was no documented evidence of a significant excess of serious chronic work related disease, such as asthma and extrinsic allergic Alveolitis (hypersensitivity pneumonitis) in compost workers compared to workers in other industries. Although this work applies to compost, it demonstrates the potential level of risks to workers dealing with other organic materials (e.g. wastes) as well as compost.

Other biomass sectors e.g. agriculture, forestry, sawmills etc., will have similar issues from dust generation that need to be minimised in processing, handling and transport and awareness of the potential hazards is the key first step in addressing and problems. Mitigation of dust and bioaerosol generation as well as avoiding the conditions that will allow growth of moulds and bacteria in storage are the key to ensuring that both operatives and the public are protected.

7 SHARPS AND TRAUMA HAZARDS

7.1 What are sharps and trauma injuries?

There are few statistics on trauma and sharps injuries in bioenergy or energy from waste, as these types of injuries tend to be recorded on a sector-wide basis: i.e. as part of forestry or waste management activities. Consequently it is not possible for us to separate out the impact of trauma and sharps injuries related to energy generation in these sectors. However, we do know that in the forestry and waste management sectors by far the most common health and safety issues relate to trauma injuries and that the risk of these hazards occurring are much higher than the other H&S issues discussed in this report.

Typically trauma injuries in the forestry and waste management sectors are slips, trips, falls, handling heavy loads and accidents associated with moving vehicles or mechanical equipment. Generally they cause injury and result in work days lost; but more severe injuries also occur. Additionally in the waste area there are injuries from sharps that occur due to handling of waste.

This section examines the nature of these hazards and their potential importance in both production of biomass fuels as well as waste to energy, but it does not examine the issue in great detail. This is because trauma injuries are a well-developed topic on which there is already ample legislation and guidance in many countries. Consequently, this section is intended instead to provide context for the other chapters of this report.

7.1.1 Forestry and agricultural biomass

In the preparation, storage and handling of biomass for energy in the forestry and agricultural sectors it is likely that workers are exposed to the same level of trauma as for related forestry and agricultural

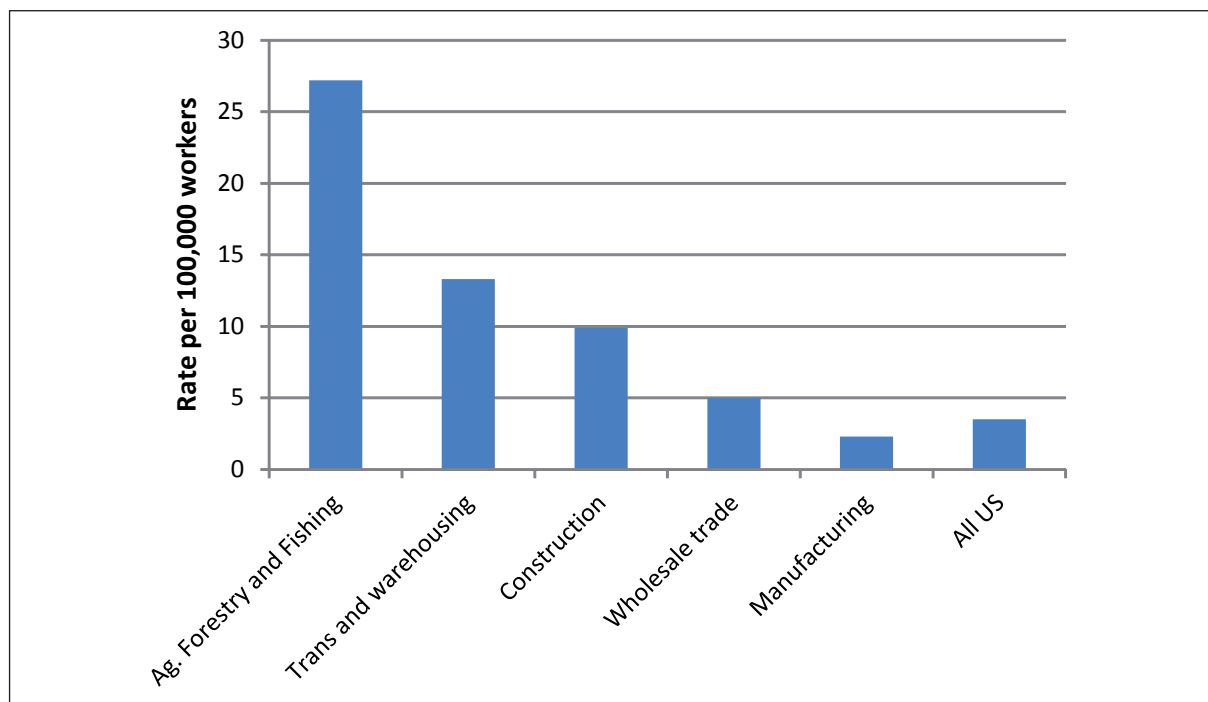


Figure 7.1. Occupational fatalities in the forest sector in the US compared to other industry sectors. Data for 2009 [18]

activities. As for waste, trauma injuries may occur because of lifting, exertion, vibration, mechanical machinery and equipment, vehicle accidents etc.

The forestry sector has historically had a high level of health and safety incidents, which are due to a combination of the type of work undertaken in the forest, the physical nature of many of the jobs (including the physical demands on the workers), the economics of forestry, and the mechanical machinery and vehicles involved [38]. As a result there have been many efforts to address the issue, with guidance and legislation.

Despite this, the International Labour Organisation (ILO) reports² that “forestry continues to be one of the most hazardous industrial sectors in most countries.” In Canada the British Columbia Forest Service [23] reported that “while the forest industry has come a long way in improving the safety outcomes for workers and their families; the industry still has some of the highest accidents rates of any industrial sector.” BCFS lists forestry incidents on its web site.³ These are mainly physical trauma injuries – struck by object, fall, caught between equipment, mobile equipment, motor vehicle accident etc. It also lists investigations such as “worker struck by equipment”, “worker pinned between forklift

load and pile of veneer”, “windfall slides of rock bluff, crushes faller, tree breaks off, strikes faller, arms of log processor crush worker during maintenance”. The BCFS report provides statistics to show where the majority of the issues are. For example, for integrated forestry the percentage health and safety issues are: 20 % of accidents involve being struck by something; 17 % by falls from elevation; 14 % due to over exertion; 12 % due to falls on same level; 10 % as a result of moving vehicle accidents; and 27 % are due to other accidents. In examining the causes of these incidents, it says most are caused by working surfaces, trees/plants, machines, vehicles and other sources.⁴ Many occur in chainsaw and skidder operators, logging and forestry labourers, truck drivers and logging machine operators.

Similar statistics can be found in most developed countries where forestry is a major industry. For example, in the USA the National Institute for Occupational Safety and Health (NIOSH) reports relatively high fatality rates for US forestry sector workers.⁵ NIOSH report figures for fatalities in industrial sectors in the USA (see Figure 7.1). The largest numbers of injuries occurred in crop production and were related to transport or ‘contact with object’. Forestry fatalities were much lower, but also due to the same causes.

²http://www.ilo.org/safework/normative/codes/WCMS_107793/lang--en/index.htm

³http://www.bcforestsafety.org/safety_info/noi.html

⁴http://www.bcforestsafety.org/other/safety_info_and_tools/statistics/2011-03-08/703008_files/frame.htm

⁵<http://www.cdc.gov/niosh/programs/agff/>

⁶<http://www.cdc.gov/niosh/topics/logging/default.html>

NIOSH also report statistics of 55.6 deaths per 100,000 workers for logging workers in the USA in 2009, which is over 16 times higher than the overall fatality rate in the US in 2008 (3.3 deaths per 100,000).⁶

The European Agency for Safety and Health at Work has also produced a summary ('E-Fact') of occupational safety and health in Europe's forests, together with a summary of mitigation and legislation [76]. This reports similar causes for accidents as other reports:

- Falling trees and branches
- Accidents with vehicles
- Slips and trips
- Accidents with work equipment

The report concludes that the "self-employed, farmers, and contractors appear to be particularly at risk. The reasons for this may be that the self-employed and farmers may use forestry tools for only part of their job and so may lack experience and knowledge in the tasks, while forestry contractors have to carry out work in short periods of time, frequently changing their workplace. A lack of organisation between the host employer and the contractor may also be a contributory factor."

In Europe reported statistics for fatal accidents between 1994-2002 for the agricultural hunting and forestry sector was 12.6 per 100,000 workers/year and the sector non-fatal accidents was also among the highest for any sector after construction at 6,000 per 100,000 workers/year.⁷

Neely and Wilhelmson [123] monitored self-reported incidents and accidents in small scale forestry workers in Sweden in 2006. 40 % of their respondents had a work related accident in the two years prior to the study; half of these reported that they were not fully using their safety gear at the time of the accident. They reported that fatal accidents in farming and fishing industries in Sweden are increasing. Respondents indicated that the worst incidents were due to accidents related to falling trees/limbs or machinery/equipment. They conclude that these results indicate that better planning during felling processes may be the key to reducing the number of accidents for this population.

Driscoll *et. al.* [64] also reported a high incidence of health and safety incidents in forestry workers, particularly for loggers in Australia.

These issues are well known and most developed countries provide good guidance on health and safety in forestry operations, together with analysis and annual statistics on where incidents occur (see national web sites for occupational safety and health). Internationally ILO also monitors incidents and provide general guidance on

mitigation [19]. The US NIOSH provides an extensive range of literature on safety in the forestry sector [2].

These statistics demonstrate that the forestry and waste sectors have a higher incidence than other sectors, as part of the routine activities undertaken by workers in these sectors. The processing of these sources of biomass to fuels simply adds an additional processing stage; and it is likely that workers in the fuel supply chains in these sectors face similar hazards to workers in the sectors in general.

In summary, the major incidents in forestry are due to falls, trips, being hit by something, mechanical equipment and vehicles. Many of these issues are also likely to apply to harvest, collection, transport and preparation of forest residues for bioenergy. There are no statistics that separate out trauma incidents due to the preparation of forest products for bioenergy. In developed countries these types of health and safety hazards are well regulated; they are also included in standards (such as PEFC) and we will not discuss them further, except to recommend that these regulations are applied in general. Most forestry sector customers (e.g. mills) demand compliance from their suppliers.

7.1.2 Waste

As indicated above, statistics and information on sharps and trauma injuries related to recovery of energy from waste tend to be part of data on injuries in the waste sector as a whole and are not separated out. We have used the general waste management data and assume that workers in the energy recovery from waste area are exposed to the same (or similar) hazards as workers in the waste sector as a whole. In reality this is probably true; although there may be some additional potential for injury as part of the operations to separate waste in mechanical biological treatment plants where refuse derived fuels are produced.

The nature of waste and the operations involved in its processing (particularly separation and recycling) results in workers being potentially exposed to risk of sharps and traumas injuries. In waste management trauma injuries may occur because of accidents with moving vehicles, lifting, exertion, vibration, the use of mechanical machinery and equipment. Sharps injuries may result from handling of refuse and separation or recycling activities: picking and other waste separation activities leads to increased exposure to potential injuries from sharp objects, such as cans, glass and needles. Most developed countries now have regulations that address these potential issues. Despite this, the waste sector worldwide remains above average for injuries and accidents.

⁷http://osha.europa.eu/en/sector/agriculture/eu_stats - this site also provides information on mitigation of accidents and injuries at work.

A report for World Bank [57] found that for solid waste management many health and safety related issues still need to be regulated and/or the regulations enforced in developing countries. The report lists back and joint injuries and puncture wounds among common issues associated with waste management. Although many developing countries produce waste that is too wet for use in energy from waste, these are issues that need to be addressed if energy is to be recovered from waste in these countries.

UNEP [10] reviewed solid waste management safety hazards and included "muscular-skeletal disorders resulting from the handling of heavy containers and wounds, most often infected wounds, resulting from contact with sharp waste" as major issues at waste plants in developing countries.

Sharps and trauma injuries are in the top five hazards in the waste sector in the UK [51]. They are, therefore, likely to impact workers in waste preparation for energy plant. Particularly trips, falls, handling and sprain injuries predominate. According to the UK Health and Safety Executive (HSE), the most common causes of absence in the waste sector in the UK are muscular-skeletal disorders (22.5 % of absences) [17]. In Sweden as well, high risks of work-related accidents are reported in the recycling industry, particularly resulting from manual lifting of waste and from accidents with vehicles [72].

In the past two years the Dutch Association of waste processors (vereniging afvalbedrijven) has done a project aimed at preventing trauma injuries in waste processing companies. This is because in the past five years there were 11 fatalities due to trauma incidents in the companies that are members of this association. This work includes online safety instructions.⁸ A further project was recently launched in the Netherlands to drive the results home.⁹

Cointreau's 2006 World Bank study [57] provides statistics for Danish and US waste collection workers compared to control baseline workers, showing that the relative trauma risk to waste workers was 5.6 times more in Denmark and 10 times more in USA. This report also examines the situation in developing countries. Examples of their findings are:

- A New York study that showed that most injuries were experienced during waste loading (60 %) and driving (30 %), with over 60 % of all injuries occurring towards the end of the work shift, suggesting a fatigue factor. Injury reports indicated that nearly 50 % of the New York collectors were either standing or bending when they were hurt.

- A study in Sacramento, California, USA, which showed that most collection work related injuries occurred in the lower back, then the legs, followed by the arms and shoulders. Improper lifting and falls were the greatest causes of incidents.
- A Brazilian study that reported accident levels of about 700 per 1000 waste collectors per year. Brazilian waste collectors averaged 9.5 lost working days per year due to occupational accidents. This study found that the legs were the most injured part of the body during waste collection, followed by the arms.
- A one-month health survey in Cairo, Egypt conducted with 1530 waste collectors/recyclers from 199 families in which, 2 % of the waste collector/recyclers were injured.

Statistics on health and safety incidents in the waste industry indicate that 82 % of reported incidents relate to accidents in manual handling, being hit by moving objects or slips and trips [26]. In more detail, the occupational hazards for workers in the waste sector include [14]:

- Crushed – whole body;
- Trapped – individual limbs;
- Entanglement;
- Falling (including slips and trips) whether at height or not;
- Being hit;
- Cut;
- Violence;
- Noise;
- Vibration;
- Musculoskeletal disorders;
- Exposure via puncture;
- Exposure via contact; and
- Stress (plus physical effects).

Similar hazards were identified in a workshop on safety in 'green jobs' ran by NIOSH [20] that reported "many haulers who collect these wastes are.... still at risk from inattentive drivers, from lifting heavy containers, from crushing via the compactor, and from exposure to improperly disposed hazardous materials in the communities they serve. Luckily, the green economy also includes attempts to make these jobs safer for workers through the increased use of collection trucks that have automated arms and compactors, thus reducing the need for the workers to directly contact the wastes, the compactor, and other traffic during collection" ... "It used to be that households were asked to segregate their various recyclable materials, which then allowed haulers to just collect material and transport it directly to the appropriate materials recovery facility. However, in the green economy, recyclables are increasingly being collected as a single-stream process (which) ... requires new, more highly mechanized sorting lines.

⁸See <http://www.afvalbranche.dearbocatalogus.nl/>

⁹See <http://www.afvalonline.nl/bericht?id=15664>

In these processes, fewer people are required to hand sort materials and thus have reduced exposure to physical hazards. But mechanized equipment requires maintenance to correct or prevent upset conditions, and this increased maintenance activity carries a higher risk of injury. Risks include greater exposure to noise; flying debris (due to use of magnets); improperly recycled materials such as propane tanks, pool chemicals, and aerosol cans; and bioactive contaminants (pharmaceuticals, infectious agents, and solvents)."

7.2 Hazards: What are the risks/issues?

7.2.1 Forestry

The major issues/risks have been identified in the section above and are related to the nature of the work in the forestry sector. Often workers are working along or as part of a small team; and frequently they are in remote areas. The work involves handling mechanised equipment, sometimes working in restricted spaces in close proximity with moving vehicles; and it also requires lifting and manoeuvring heavy objects. Under these circumstances the hazards are obvious and the major causes of injuries are hardly surprising: muscular-skeletal injuries; accidents with moving vehicles; slips, trips and falls; and accidents due to falling trees and branches. Statistics show that these hazards are by far the most common in the forestry sector.

7.2.2 Waste

As indicated above, typical trauma injuries for people working in the area of preparation of waste for use in energy are likely to be similar to those in the waste sector as a whole and include factors that influence working in the recycling sectors as well. In work on the developing world, the major trauma hazards faced in the waste sector are in the following areas [57]:

- The handling of waste (e.g., working in traffic, shovelling, lifting, equipment vibrations, accidents);
- The processing of wastes (e.g., odour, noise, vibration, accidents, air and water emissions, residuals, explosions, fires);
- The disposal of wastes (e.g., odour, noise, vibration, stability of waste piles, air and water emissions, explosions, fires).
- Heavy loads, lifting exertion and vibration

The waste sector is also subject to injuries from sharps, such as glass, nails, cans and needles, which have become more important as the level of handling waste in recycling, separation and treatment has increased. Table 7.1 assesses the level of hazards from sharps as high risk of occurrence and medium to high level of impact.

In the USA, the Bureau of Labour Statistics' annual Survey of Occupational Injuries and Illnesses [18] provides statistics for 1992-97 showing that 2161 refuse collectors suffered non-fatal job injuries and illnesses every year from 1992 to 1997 due to cuts, lacerations, punctures, bruises; sprains, strains and muscle tears; and fractures. Sharps injuries are the fourth most common non-fatal accident – behind handling injuries and trips; and the stage at which these issues are most likely to happen are those where waste is handled, particularly refuse collection [51]. However, this source also says that there is a high level of awareness of hazard from sharps in the waste sector and that injury from broken glass does not appear to present a significant problem (in the UK), provided the correct safety clothing is worn.

In the UK, HSE data indicates that picking stations are typically where operatives are most likely to encounter needles and sharps. They recommend that operatives should be issued with Personal Protection Equipment

Table 7.1 Hazards in the waste sector [51]. Colours indicate risks with increasing likelihood and/or impact

		Impact			
		Low	Low to medium	Medium to high	High
Likelihood	High		Lift putdown Sharp Other - handling	Other - trip Other - hit object	
	Medium to high		Push pull Bodymove Slip wet Low fall Trip uneven Other Trip obstruct Fall equip Unknown - trip structure	Forward Machinery	
	Low to medium	Unknown - handling Unknown - object Physical assault		Carrying Vehicle Fall unspec	

(PPE): particularly safety shoes and gloves. Needle stick injury and Weil's disease were reported to be the major risks to picking staff. In addition, HSE identified cuts and grazes as a major route for infectious agents to body [9].

7.3 Mitigation

Good regulation, guidance and good practice has been shown to cut these injuries and many countries have developed regulations and guidance for this purpose.

An example of this is the European Union framework for health and safety regulations that should be applied generally in the EU, including in the forestry sector (see Box 3). Other national agencies, such as the UK HSE,¹⁰ the Canadian Centre for Occupational Health and Safety and the US NIOSH also provide extensive information and guidance. The major forestry countries in Europe also have occupational health regulations and guidance, which is available from Government Occupational Health organisations in the language of the country.¹¹

The following Health and Safety Directives are relevant for the European forestry sector:

- Directive 89/656/EEC of 21 December 1989 on the approximation of the laws of the Member States relating to personal protective equipment (the "Personal Protective Equipment Directive").
- Directive 98/37/EC of 22 June 1998 on the approximation of the laws of the Member States relating to machinery (the "Machinery Directive").
- Directive 89/391/EEC of 12 June 1989 on the introduction of measures to encourage improvements in the safety and health of workers at work (the "Framework Directive").
- Directive 89/655/EEC of 30 November 1989 concerning the minimum safety and health requirements for the use of work equipment by workers at work (the "Use of Work Equipment Directive") and its two Amendments 95/63/EC of 5 December 1995 (regarding lifting operations) and 2001/45/EC of 27 June 2001 (regarding working at heights).

There are also other workplace directives relating to the use of chemicals, the use of personal protective equipment and manual handling.

The general approach has been to mix regulation with guidance. For example, regulations on site permitting can include obligations to ensure accident prevention and limitation of damage; and occupational health regulations can provide a framework for the mitigation of hazards. On the other hand, health and safety guidelines provide examples of how these legal obligations may be met, by outlining options

and best practice. Guidance is provided at a number of levels, national, European and International (for example, UN or ILO both provide guidance).¹² The ILO guidance is often adopted for the forestry sector by countries in South East Asia and South America.

An example of guidance is that produced by the HSE in the UK, on a range of guidance on topics related to the waste and recycling issues, hazard risk assessment and guidance on mitigation^[13, 14, 16]. An outline of the sort of approach recommended by HSE is:

- Risk Assessment, including identification of risks, of those potentially at risk and the main hazardous areas. This process includes identifying the level of risk from a specific hazard (i.e. the ranking of the hazard e.g. how often workers might be exposed to this hazard), the probability of any harm from this hazard and the consequences (HSE 2008).
- Discussion of hazards with the work force to identify further hazards, how operatives carry out activities and typical variations in behaviour.
- Control of hazard – reduction of risk at source, provision of equipment (such as personal protection equipment e.g. clothing such as gloves, boots and high visibility jackets, picking tongs, good lighting etc.), promotion of good personal hygiene, promotion of good operational practice (e.g. in the use of equipment, guidelines for lifting and carrying loads and concerning moving vehicles), ensuring that workers understand the hazards, know what to do in an accident and that reporting arrangements are clear.
- Health surveillance where necessary, including regular checks and monitoring to ensure system are working as planned and are followed.
- Provision of adequate first aid equipment.
- Ensure all procedures are practical and can be followed.

8 OCCUPATIONAL HAZARDS IN TRANSPORTING SOLID BIOFUELS

This chapter gives an overview of some of the main occupational hazards in transportation of solid biofuels, for the most common fuels and modes of transport. The size, shape, moisture content and the type of raw material directly influence the transport, handling and storage

¹⁰See, for example: HSE(2003) Managing Health and safety in forestry

¹¹For example information for Germany, Switzerland and Austria can be found under <http://de.wikipedia.org/wiki/Arbeitsschutz> and <http://www.baua.de/en/Homepage.html>

¹²For example, the ILO produce a Code of Practice for Health and Safety in Forestry, which forms the basis of advice provided in a number of the Asian and South American Forestry sectors. See: http://www.ilo.org/global/publications/ilo-bookstore/order-online/books/WCMS_PUBL_9221108260_EN/lang--en/index.htm. Information is also provided by the European Union Guidance on risk assessment at work: <http://osha.europa.eu/en/topics/riskassessment/guidance.pdf>

properties of a solid biofuel. Types of solid biofuels can be specified in accordance with ISO 17225 based on traded forms, and the relevant types to discuss in this chapter are wood chips, pellets, whole trees and big square straw bales. As chapter 6 describes, one important health and safety risk in handling and transporting solid biofuels is connected to inhaling dust (particularly in situations where biomass is (un)loaded). The harm from dust depends on chemical (and mineralogical) composition, dust concentration and particle size and shape. Handling wet solid biofuels provides a favourable environment for the growth of many species of bacteria and fungi. These micro-organisms produce large numbers of microspores (< 5 µm in diameter) which are easily inhalable and they can penetrate the respiratory system and cause allergic reactions.

With regard to gaseous emissions, there might be exposure to low oxygen concentration, or specific gases released from the material as described in detail in chapter 3.5. This is particularly the case in enclosed spaces such as cargo holds in ocean vessels [173]. Aldehydes and terpenes are emitted in bulk storages of wood pellets and briquettes. Typical compounds found are hexanal, pentanal and monoterpenes. The formation of CO and CO₂ is however not only a problem during ocean transportation but also during bulk storage, in silos.

Concentrations of CO close to 1 vol-% have been measured in silos, and several fatalities from CO poisoning have occurred in cargo spaces in ships during unloading [173]. The combination of low oxygen concentration and the presence of CO is of particular concern since the body is reacting with hypo-ventilation which aggravates the exposure even more (see section 4.5).

8.1 Truck transport of wood chips and wood pellets

Truck transport with solid biomass is done over relatively short distances. It mainly concerns

- transport of wood chips from a producer/harbour to an end user
- transport of pellets from producer/harbour to an intermediate storage or end user
- transport of sawdust for pellets production from producer to pellets factory.

The health risks from these operations result mainly during loading and unloading where high dust concentrations may result in a risk of dust explosions and human exposure to dust and microspores.

There are two types of trucks for transport of pellets: tank trucks that pneumatically blow the pellets to the customer, and trucks with flatbed for unloading by rear tipping (Figure 8.1). The latter can be equipped with a rotary valve and air compress system so the pellets can be blown into the storage similar to trucks with tanks.

One of the largest pellet distributors in Denmark is DLG with 250 trucks in service. DLG supplies farmers with feed from its own factories, seed grain, fertilizer, agricultural lime, crop protection, fuel and up to 200.000 tons wood pellets per year. The tank trucks have a closed pipe system that minimizes the spillage of dust during unloading. Loading of flatbed trucks is done with frontend loaders or conveyor belt (Figure 8.2) and can cause heavy dust exposure to buildings, equipment and personnel. There are instructions for the driver to keep safe distance and use breathing mask if necessary. An indoor loading facility for pellets using frontend loader caused a heavy dust explosion



Figure 8.1. Wood chips unloaded at a Danish district heating plant. Very high concentrations of mould spores may prevail around the truck and inside the store during unloading, requiring personal protection for employers [157].



Figure 8.2. Loading of wood pellets in a truck at indoor storage with conveyor belt causes a high dust load in the vicinity [158].

Table 8.1 Exposure and Toxicological Data for wood pellets (from MSDS for wood pellets in bulk [114])

Feedstock	PEL (OSHA)	REL (NIOSH)	TLV (ACGIH)	Health Effects
Softwood such as fir, pine, spruce and hemlock.	15 mg/m ³ Total Dust	TWA = 1 mg/m ³ for 10 hours @ 40 hours/week	TWA = 5 mg/m ³ for 8 hours @ 40 h/week	Acute or chronic dermatitis, asthma, erythema, blistering, scaling and itching (ACGIH).
	5 mg/m ³ Respirable Dust		STEL = 10 mg/m ³ for 15 minutes, max 4 times/day, each episode max 60 minutes	
Hardwood such as alder, aspen, cottonwood, hickory, maple and poplar.	15 mg/m ³ Total Dust	TWA = 1 mg/m ³ for 10 hours @ 40 hours/week	TWA = 5 mg/m ³ for 8 hours @ 40 hours week	Acute or chronic dermatitis, asthma, erythema, blistering, scaling and itching (ACGIH). Suspected tumorigenic at site of penetration (IARC).
	5 mg/m ³ Respirable Dust		STEL = 10 mg/m ³ for 15 min., max 4 times/day, each episode max 60 min.	
Oak, walnut and beech.	15 mg/m ³ Total Dust	TWA = 1 mg/m ³ for 10 hours @ 40 hours/week	TWA = 1 mg/m ³ for 8 hours @ 40 hours week	Suspected tumorigenic at site of penetration (ACGIH).
	5 mg/m ³ Respirable Dust			
Western Red Cedar.	15 mg/m ³ Total Dust	TWA = 1 mg/m ³ for 10 hours @ 40 hours/week	TWA = 5 mg/m ³ for 8 hours @ 40 hours week	Acute or chronic rhinitis, dermatitis, asthma (ACGIH).
	5 mg/m ³ Respirable Dust	TWA = 1 mg/m ³ for 10 hours @ 40 hours/week	STEL = 10 mg/m ³ for 15 minutes, max 4 times/day, each episode max 60 minutes	

Note: PEL = Permissible Exposure Limit; REL = Recommended Exposure Limit; TLV = Threshold Limit Value; TWA = Time Weighted Average; STEL = Short Term Exposure Limit

in a Danish pellet factory in 2010. Static electricity can cause dust explosion during unloading if the hose from the truck to the storage is rubber and not metal (see also section 5.2). Incorrect hoses with bends can cause attrition of the pellets resulting in generation of fines and more dust in the air [28]. The source/type of feedstock used in pellet manufacturing is the basis of the toxicological characteristics of pellets and applies primarily to the dust from wood pellets. Table 8.1 provides exposure value limits recommended by various regulatory bodies as referenced in the MSDS for wood pellets. In this table, Respirable Dust means particles with an AED<10 µm capable of deposition in nasal, thoracic and respiratory regions.

Dust from certain hardwoods has been identified by IARC as a positive human carcinogen. An excess risk of nasal adeno-carcinoma has been reported mainly in those workers in this industry exposed to wood dusts. Some studies suggest workers in the sawmilling, pulp and paper and secondary wood industries may have an increased incidence of nasal cancers and Hodgkin's disease. However, IARC concludes that the epidemiological data does not permit a definite assessment.

Dust from Western Red Cedar is considered a "Nuisance Dust" (= containing less than 1 % silicates (OSHA)) with

no documented respiratory carcinogenic health effects (ACGIH). Cedar oil is a skin and respiratory irritant.

The photos and figures below illustrate that workers involved in loading and unloading of wood pellets in storage and trucks may be exposed to very high dust concentrations in practice, and limits may be exceeded.

In USA, The Northeast Pellet Delivery and Storage Committee makes recommendations for transport and intermediate storage of wood pellets to maintain quality between the producer and the combustion systems. This is intended to help pellet manufacturers, distributors, and traders avoid mistakes and thus ensure end-user satisfaction and safety to the delivery persons and property. Recommendations for the conveyance and storage of the pellets at site of end use are made in a separate Northeast Biomass Thermal Working Group (NEBTWG) Pellet Storage Recommendations document [29].

8.2 Truck transport of straw

Denmark has 25 years of experience in handling large amount of straw in big bales for energy production. The small scale district heating plants with only heat production use around 350 ktons of straw annually. The larger power plants consume around



Figure 8.3. Wood dust load (mg / m³ air) by unloading pellets (left bar), see Figure 8.4. The dust concentration is many times the limit values as indicated in Table 8.1. The middle bar shows the dust load in a storage with different transport activities with pellets. The dust concentration is again many times the limit value. The right bar shows the dust load in a storage without activities [158].

900 ktons per year of straw in the form of big bales, each weighing 500 kg. This is a significant logistic challenge which needs a very well planned transport and handling system in order to avoid incidents.

Health and safety challenges in straw handling at the farms are limited since loading of bales on the truck takes place in open air with tractors using fork lifts. The compressed bales are not emitting significant amounts of spores or dust. The truck load of straw is covered with a net in order to prevent loose straw to end up along the roads.

If the straw is delivered to a district heating plant, individual straw bales are typically unloaded using a fork lift in an indoor storage hall. This type of operation can expose the employees to significant dust concentrations and precautions are needed.

If the straw is delivered at the power plant, the truck with straw bales enters the straw storage where an automatic crane discharges 12 bales at a time. The truck driver is not involved in this operation and stays inside the truck cab during unloading. Before departure however, he has to clean the truck from loose straw using a vacuum cleaner. This can lead to a certain exposure to mould and dust.

8.3 Ship transport

Current a large proportion of the wood pellets produced worldwide are shipped by ocean vessels. The safety is regulated by the International Maritime Organization (IMO) and there are significant safety issues onboard vessels, in terminal storage and during handling. This section briefly reflects how these key issues can be addressed.

Several fatal accidents happened have been recorded, which have resulted from exposure to harmful gas emissions from biofuels, particularly in enclosed spaces such as storage silos, flat storage buildings and cargo holds in ocean vessels. Accidents aboard ocean vessels are frequently reported by Urban Svedberg, Sundsvalls Hospital in Sweden [28, 169, 173]. At the conference Pellets 2012 in Stockholm, Urban Svedberg reported following list of fatal accidents caused by toxic gases emitted from wood pellets, wood chips and whole trees during transport or storage. Table 8.4 provides measurements of toxic gases and oxygen content in cargo holds.

The IMO regulate the transportation of pellets in ocean vessels and prescribe conditions under which wood pellets can be carried. Cargo holds are sealed during ocean voyage which results in very fast

oxygen depletion and generation of CO, CO₂, CH₄ and some H₂. Entry in to cargo holds and communicating spaces are prohibited unless the spaces have been thoroughly ventilated and the gas concentration has been verified by a combination of oxygen and CO measurements [28, 59, 119, 156, 169, 173]

The most detailed study of emissions during sea transport is reported in the EWDOT research report [119], which was initiated after two serious accidents occurred during discharge of wood pellets from ocean vessels. The EWDOT Research Project was initiated by the Wood Pellet Association of Canada and carried out onboard the vessel MV Saga Horizon during the period January 26 and March 17, 2007 by researchers in Canada and Sweden. The findings of the research are described in some detail in this Report and can be summarized as follows;



Figure 8.4. Unloading pellets in an indoor storage [158].

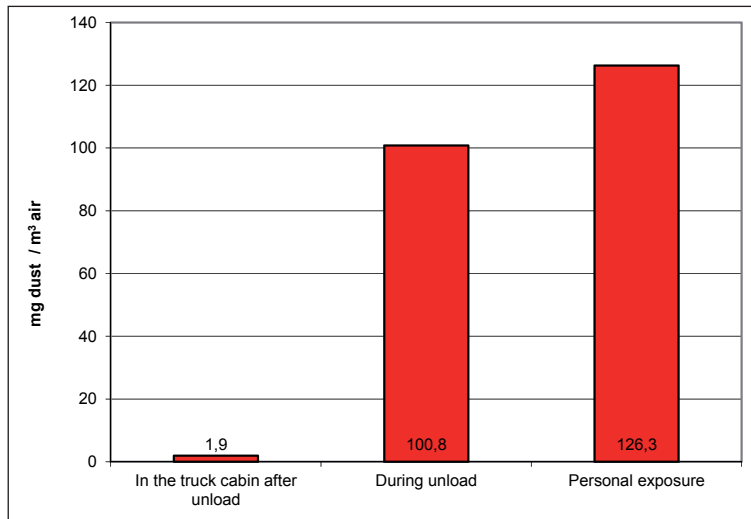


Figure 8.5. Wood dust load by unloading pellets at private end users, expressed in mg dust per cubic meter air and as compared to the limit values for the situation as in Figure 8.6. The pellets are blown to a nearby storage. The left bar shows that when driving away, a dust load inside the truck cab about double the limit value exists. This indicates that precautions must be taken if the driver sits in the cab during unloading. The middle bar shows that the dust load besides the truck is many times over the limit value. The right bar shows that dust load from a dust meter placed on the truck driver is many times the limit value [158].

- lethal concentrations of the highly toxic carbon-monoxide (CO) is registered in the stairway adjacent to the cargo hatch filled with wood pellets
- oxygen is depleted down to a lethal level
- gas generated in the cargo space leaks in to the enclosed stairway when the cargo hatch is closed
- due to the very limited circulation in the stairway space there has to be forced circulation of the air from the bottom up prior to entry by personnel or alternatively continuous air circulation of the stairway space as long as the cargo hatch is sealed, including sea time



Figure 8.6. Heavy dust load around the truck by wood pellet delivery to private household, see Figure 8.5. The silo in the house is without cyclone which means that the transport air has to escape through the open window in the yellow wall. This causes the heavy dust load around the truck and the driver [158]

- established operational procedures for safe entry in to stairway or cargo space should be strictly enforced and safe conditions should be established by simultaneous measurements of CO and oxygen concentrations. One or the other is not sufficient and could cause exposure to life threatening conditions
- the complex intra-relationship between the ambient conditions such as air temperature, humidity, barometric pressure as well as ocean water temperature was established and may be used for developing guidelines for safer ocean as well as land transportation of wood pellets
- the emission of gases from wood pellets can be decreased to a degree by a gentler handling in terms of less fines (dust) since dust is likely increasing the gas generation due to increased surface area and exposure to oxygen
- water temperature rather than air temperature is affecting the thermal dynamics in the cargo hatch due to thermal conduction through the hull of the vessel

The IMO regulations

stipulate that (page 9 in [119])

1. When transporting a bulk cargo that is liable to emit a toxic or flammable gas, or cause oxygen depletion in the cargo space, an appropriate instrument for measuring the concentration of gas or oxygen in the air shall be provided together with detailed instructions for its use
2. The shipper has to provide a Shipper Cargo Information Sheet to the master of the ocean vessel about the properties of the cargo
3. Many products are classified as Material Hazardous in Bulk (MHB), including wood in such forms



Figure 8.7. A better way to deliver pellets to a private end user compared to Figure 8.6. The pellets are blown from the truck in the pipe at the top of the picture and delivered to the silo through the open pipe in the bottom of the cyclone. The transport air is separated from the pellets in the cyclone and is blown in a tube through the hole in the wall to the open air far away from the truck and the driver [158].



Figure 8.8. Truck with 24 big bales of straw waiting for unloading at a Danish straw pellet factory. The bales are arranged at the truck and at the trailer so the automatic crane in the straw storage can remove the bales from the truck in 2 lifts with 12 bales in each lift. (Photo: Lars Nikolaisen)



Figure 8.9. During unloading the driver and or employee at the heating plant remove the net. This gives an exposure to dust and spores from the straw [110]

as packaged timber, roundwood, logs, pulpwood, props (pit props and other propwood), woodchips, wood shavings, wood pulp pellets, wood pellets and sawdust. Such products are subject to restrictions in handling, stowage and segregation, ventilation and emergency actions in case of fire

The current safety code for transportation of wood pellets in the International Maritime Safety Bulk Cargoes (IMSBC) Code have a conditional requirement stipulating that carriage should be done onboard vessels with fixed gas fire extinguishing equipment since the schedule for Wood Pellets says that wood pellets may emit flammable gases. Recent research [118, 184] has however proven that the gas mixture emitted (CO , CH_4 and H_2), even if the pellets are damaged by water up to 15% or higher and stored in temperature up to $+60^\circ\text{C}$, does not reach flammable concentrations. Application has been done by WPAC to re-classify wood pellets and allow carriage in regular vessels and a new classification is expected to be in force as soon as IMO has reviewed the application.

An additional requirement has recently been added as a condition regarding self-heating for all cargoes carried in ocean vessels and stipulates that a sample of the material to be shipped shall be tested at $+140^\circ\text{C}$ and if the temperature of the material increases more than 60°C in 24 hours the material can not be shipped as bulk cargo and therefore needs to be packaged in smaller parcels to avoid overheating. Recent research [118, 184] conducted on wood pellets using the Crossing Point Method referred to in section 3.1.3.2 clearly indicated that it can be shipped in bulk.

8.4 Train transport

Pellets are transported by tank or grain cars with a capacity ranging from 60 to 110 tons in large volumes from pellet plants to power plants or to shipping ports. In Canada and USA a train may have 120 cars loaded with pellets for 3-5 days before reaching the destination. It is crucial to make sure the pellets are cool (below $+30^\circ\text{C}$) before leaving the pellet plant in order to avoid overheating during transportation during

Table 8.2 Accidents with wood pellets [169].

Year	Location	Accident with wood pellets
2002	Rotterdam	One death in the stairway to the cargo hold with pellets at the ship Weaver Arrow
2006	Helsingborg	One death in the stairway to the cargo hold with pellets at the ship Saga Spray. More persons injured.
2007	Finland	One death in a 10 tons storage in private house
2008	Finland	One death in a 10 tons storage in private house
2009	Bornholm, Denmark	Two death in the stairway to the cargo hold with pellets at the ship Amirante. The ship was loaded the day before
2010	Germany	One death in a 150 tons storage
2010	Ireland	One death in a 7 tons storage in private house
2011	Switzerland	A pregnant woman died in a 40 tons storage

Table 8.3 Accidents with wood chips and whole trees [169]

Year	Location	Accident with wood chips and whole trees
2005	Gruvön, Sweden	One death in the stairway to the cargo hold with whole trees at the ship Eken
2006	Skelleftehamn, Sweden	One death in the stairway to the cargo hold with wood chips at the ship Noren
2007	Timrå, Sweden	Two death in the stairway to the cargo hold with whole trees at the ship Fembria
2010	New Zealand	Two death in the stairway to the cargo hold with whole trees at the ship TPC Wellington

Table 8.4 Results from measurements in 5 transatlantic ships with wood pellets [169, 173]

Ship no.	1	2	3	4	4	5	5
Place	Cargo hold	Cargo hold	Cargo hold	Stairway	Stairway	Cargo hold	Stairway
Date	Nov 2006	Jan 2007	Feb 2007	Feb 2007	Mar 2007	Oct 2007	Oct 2007
CO ppm	5850	6980	14650	10960	11510	11950	7710
CO ₂ ppm	9340	3240	7070	5450	5160	21570	12360
O ₂ %	n/a	n/a	n/a	n/a	5	0,8	8,4

n/a = not available

summertime. This is a challenge for example in southeastern USA where the temperature often is +35°C to 40°C and with a humidity often surpassing 90%. In Canada, the day temperature may hover around +35°C during daytime in the interior. When a rail car is exposed to the hot sun the temperature inside is known to reach +50°C or even 65°C. At this temperature the air can hold a lot of moisture. When the rail cars approaches the coast the temperature during night time may approach +5°C which means that the moisture will condensate inside the railcars and cause wetting of the pellets at the top. A layer of dissolved pellets about 5 cm thick is sometimes found inside rail cars and if this cycle of heating and cooling is repeated a number times it creates an ideal condition for microbial growth followed by self-heating. The rail cars are often dedicated for pellet transportation and contain a culture of microbes and act like an incubator. Cleaning of rail cars is therefore recommended. The liquefied moisture inside a rail car also causes cyclical hydro-dynamic moisture migration, which also contributes to heat developing in the upper sections of the pile inside rail car. The third phenomenon referred to as oxidation is promoted by the microbial growth and the hydro-dynamic migration. These three phenomena all conspire to degrade the pellets, potentially causing dust generation. Similar phenomenon are found in large silo storages. It is important to minimize the time pellets



Figure 8.10. Loading of biomass in a wood terminal or sawmill [[89]]

are kept in rail cars and to make sure the pellets are as cool as possible before loaded in to rail cars. Ventilated railcars are not common and are not always the best since they may allow air with high moisture to enter the rail cars. Rail cars should be painted white or be made of shiny metal in order to reflect the sun light. During parking the rail cars should be protected by sun shade.

During discharge of pellets from rail cars substantial amounts of gas is entrained in the flow and will accumulate in the pit in which the pellets are dumped. CO₂ is 1.5 times as heavy as air and oxygen may have been displaced by the gas. In addition, CO and CH₄ are only slightly lighter than air and may also easily accumulate in low lying spaces. Personnel should not be allowed to enter such areas. In addition, the accumulation of dust may also reach very high concentrations, which can be a health threat explosion risk.

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Appendix A. Excerpt from ISO 17225-1 Solid Biofuels – Fuel Specifications and Classes – Part 1 General Requirements

Table X — Classification of origin and sources of solid biofuels

1. Woody biomass	1.1 Forest, plantation and other virgin wood	1.1.1 Whole trees without roots	1.1.1.1 Broad-leaf
			1.1.1.2 Coniferous
			1.1.1.3 Short rotation coppice
			1.1.1.4 Bushes
			1.1.1.5 Blends and mixtures
		1.1.2 Whole trees with roots	1.1.2.1 Broad-leaf
			1.1.2.2 Coniferous
			1.1.2.3 Short rotation coppice
			1.1.2.4 Bushes
			1.1.2.5 Blends and mixtures
		1.1.3 Stemwood	1.1.3.1 Without bark, Broad-leaf
			1.1.3.2 Without bark, Coniferous
			1.1.3.3 With bark, Broad-leaf
			1.1.3.4 With bark, Coniferous
			1.1.3.5 Blends and mixtures
		1.1.4 Logging residues	1.1.4.1 Fresh/Green, Broad-leaf (including leaves)
			1.1.4.2 Fresh/Green, Coniferous (including needles)
			1.1.4.3 Stored, Broad-leaf
			1.1.4.4 Stored, Coniferous
			1.1.4.5 Blends and mixtures
		1.1.5 Stumps/roots	1.1.5.1 Broad-leaf
			1.1.5.2 Coniferous
			1.1.5.3 Short rotation coppice
			1.1.5.4 Bushes
			1.1.5.5 Blends and mixtures
		1.1.6 Bark (from forestry operations)	
		1.1.7 Segregated wood from gardens, parks, roadside maintenance, vineyards, fruit orchards and driftwood from freshwater	
		1.1.8 Blends and mixtures	
	1.2 By-products and residues from wood processing industry	1.2.1 Chemically untreated wood residues	1.2.1.1 Without bark, Broad-leaf
			1.2.1.2 Without bark, Coniferous
			1.2.1.3 With bark, Broad-leaf
			1.2.1.4 With bark, Coniferous
			1.2.1.5 Bark (from industry operations)
		1.2.2 Chemically treated wood residues, fibres and wood constituents	1.2.2.1 Without bark
			1.2.2.2 With bark
			1.2.2.3 Bark (from industry operations)
			1.2.2.4 Fibres and wood constituents
		1.2.3 Blends and mixtures	
	1.3 Used wood	1.3.1 Chemically untreated wood	1.3.1.1 Without bark
			1.3.1.2 With bark
			1.3.1.3 Bark
		1.3.2 Chemically treated wood	1.3.2.1 Without bark
			1.3.2.2 With bark
			1.3.2.3 Bark
		1.3.3 Blends and mixtures	
	1.4 Blends and mixtures		

NOTE 1 If appropriate, also the actual species (e.g. spruce, wheat) of biomass may be stated according to EN 13556, Round and sawn timber — Nomenclature of timbers used in Europe[1].

NOTE 2 Driftwood from saltwater is not recommended as a fuel.

Table X — (continued)

2. Herbaceous biomass	2.1 Herbaceous biomass from agriculture and horticulture	2.1.1 Cereal crops	2.1.1.1 Whole plant
			2.1.1.2 Straw parts
			2.1.1.3 Grains or seeds
			2.1.1.4 Husks or shells
			2.1.1.5 Blends and mixtures
		2.1.2 Grasses	2.1.2.1 Whole plant
			2.1.2.2 Straw parts
			2.1.2.3 Seeds
			2.1.2.4 Shells
			2.1.2.5 Blends and mixtures
		2.1.3 Oil seed crops	2.1.3.1 Whole plant
			2.1.3.2 Stalks and leaves
			2.1.3.3 Seeds
			2.1.3.4 Husks or shells
			2.1.3.5 Blends and mixtures
		2.1.4 Root crops	2.1.4.1 Whole plant
			2.1.4.2 Stalks and leaves
			2.1.4.3 Root
			2.1.4.4 Blends and mixtures
		2.1.5 Legume crops	2.1.5.1 Whole plant
	2.1.5.2 Stalks and leaves		
	2.1.5.3 Fruit		
	2.1.5.4 Pods		
	2.1.5.5 Blends and mixtures		
	2.1.6 Flowers	2.1.6.1 Whole plant	
		2.1.6.2 Stalks and leaves	
		2.1.6.3 Seeds	
		2.1.6.4 Blends and mixtures	
	2.1.7 Segregated herbaceous biomass from gardens, parks, roadside maintenance, vineyards, and fruit orchards		
	2.1.8 Blends and mixtures		
	2.2 By-products and residues from food and herbaceous processing industry	2.2.1 Chemically untreated herbaceous residues	2.2.1.1 Cereal crops and grasses
			2.2.1.2 Oil seed crops
			2.2.1.3 Root crops
			2.2.1.4 Legume crops
			2.2.1.5 Flowers
			2.2.1.6 Blends and mixtures
		2.2.2 Chemically treated herbaceous residues	2.2.2.1 Cereal crops and grasses
2.2.2.2 Oil seed crops			
2.2.2.3 Root crops			
2.2.2.4 Legume crops			
2.2.2.5 Flowers			
2.2.2.6 Blends and mixtures			
2.2.3 Blends and mixtures			
2.3 Blends and mixtures			

Table X— (continued)

3. Fruit biomass	3.1 Orchard and horticulture fruit	3.1.1 Berries	3.1.1.1 Whole berries
			3.1.1.2 Flesh
			3.1.1.3 Seeds
			3.1.1.4 Blends and mixtures
		3.1.2 Stone/kernel fruits	3.1.2.1 Whole fruit
			3.1.2.2 Flesh
			3.1.2.3 Stone/kernel/fruit fibre
			3.1.2.4 Blends and mixtures
		3.1.3 Nuts and acorns	3.1.3.1 Whole nuts
			3.1.3.2 Shells/husks
			3.1.3.3 Kernels
			3.1.3.4 Blends and mixtures
		3.1.4 Blends and mixtures	
	3.2 By-products and residues from food and fruit processing industry	3.2.1 Chemically untreated fruit residues	3.2.1.1 Berries
			3.2.1.2 Stone/kernel fruits/fruit fibre
			3.2.1.3 Nuts and acorns
			3.2.1.4 Crude olive cake
			3.2.1.5 Blends and mixtures
		3.2.2 Chemically treated fruit residues	3.2.2.1 Berries
			3.2.2.2 Stone/kernel fruits
			3.2.2.3 Nuts and acorns
			3.2.2.4 Exhausted olive cake
			3.2.2.5 Blends and mixtures
		3.2.3 Blends and mixtures	
	3.3 Blends and mixtures		
4. Aquatic biomass	4.1 Algae	4.1.1 Micro algae	
		4.1.2 Macro algae	
		4.1.3 Blends and mixtures	
	4.2 Water hyacinth		
	4.3 Sea and lake weed	4.3.1 Lake weed	
		4.3.2 Sea weed	4.3.2.1 Blue sea weed
			4.3.2.2 Green sea weed
			4.3.2.3 Blue-green sea weed
			4.3.2.4 Brown sea weed
			4.3.2.5 Red sea weed
	4.5 Blends and mixtures		
	4.4 Blends and mixtures		
	4.5 Reeds	4.5.1 Common reed	
		4.5.2 Other reed	
5 Blends and mixtures	5.1 Blends		
	5.2 Mixtures		

NOTE

Group 5 “Blends and mixtures” include blends and mixtures from the main origin-based solid biofuel groups 1 to 4.



IEA Bioenergy

IEA Bioenergy is an international collaboration set-up in 1978 by the International Energy Agency to improve international co-operation and information exchange between national bioenergy RD&D programmes.

IEA Bioenergy's vision is to achieve a substantial bioenergy contribution to future global energy demands by accelerating the production and use of environmentally sound, socially accepted, and cost-competitive bioenergy on a sustainable basis, thus providing the increased security of supply whilst reducing greenhouse gas emissions from energy use. Currently, IEA Bioenergy has 24 Members and is operating on the basis of 12 Tasks covering all aspects of the bioenergy chain, from resource to the supply of energy services to the consumer.

Within the IEA Bioenergy agreement, Task 32: Biomass Combustion and Co-firing works on further expansion of the use of biomass combustion for heat and power generation, varying from small scale stoves and boilers to industrial CHP plants and utilities co-firing biomass with coal in traditional coal-fired boilers. This is done by generating and disseminating information on technical and on non-technical barriers and anticipated solutions. Task 32 currently has 13 member countries, namely Austria, Belgium, Denmark, Finland, Germany, Ireland, Japan, Netherlands, Norway, South Africa, Sweden, Switzerland and UK.

Further information

More information can be found on the IEA Bioenergy website (www.ieabioenergy.com), the website of IEA Bioenergy Task32 (www.ieabioenergytask32.com) or directly through the Task leader or Operating Agent of Task 32:

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