



Swedish Civil
Contingencies
Agency

Henry Persson

Silo Fires

Fire extinguishing and preventive
and preparatory measures



Henry Persson works at the SP Technical Research Institute of Sweden on the Fire Safety Engineering Department. He has worked for more than 30 years with testing and research with his main focus on fire and fire safety problems in industry, and the fire service and then with fire extinguishing as his specialist field. In many cases his research projects have been of the problem-solving type, which have led to concrete results and applications, e.g. the building of the large-scale firefighting equipment for tank fires (SMC), which are now available in four locations in Sweden. For about 10 years now there has been considerable focus on biofuels, and on that he and his colleagues have worked on projects related to fire risks, emissions during fires and fire-extinguishing, both in solid biomass and waste. Several projects have focused specifically on the risks involved in the handling of wood pellets silos, the risk of spontaneous combustion and extinguishing problems.



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Author: Henry Persson

Project manager: Ingvar Hansson, MSB

Editor English version: James Butler, MSB

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Contents

Introduction	5
Chapter 1 – Summary of measures in the event of a silo fire	11
Chapter 2 – Firefighting method for silo fires	21
Workflow when inerting a silo	23
Chapter 3 – Personal safety	43
Formation of carbon monoxide (CO) and carbon dioxide (CO ₂)	43
Risks of using nitrogen gas and carbon dioxide as extinguishing agents	44
Dust and gas explosions	49
Chapter 4 – Alternative firefighting tactics	55
Extinguishing operation with foam	57
Injecting water	58
Risks associated with opening a silo	61
Environmental aspects to consider	63
Chapter 5 – Possible silo fire scenarios	65
Spontaneous ignition	65
External ignition source	73
Chapter 6 – General information about silo types and silo storage	77
Silo types	77
Silo content and fill level	82
Chapter 7 – Preventive and preparatory measures	89
Risk assessment in accordance with AFS 2003:3	90
Preparations for fire extinguishing and discharge of silos	94
Preparations at the silo top	105
Functional testing of the gas distribution system	109
Preparations for using alternative extinguishing methods	109
Chapter 8 – Mobile gas equipment	113
In-depth information and knowledge	115
References	115
Illustrations and photos	120

Introduction

Introduction

Fires at silo sites are rare occurrences for most fire & rescue brigades and are different from conventional fires in many ways. In many cases, the fires are caused by self-heating of the stored material resulting from different oxidation processes and biological activity that may cause pyrolysis, that is a smouldering fire in a highly oxygen limited environment. A fire usually occurs deep inside the material and is therefore very difficult to detect and, in such cases, measuring certain gas concentrations (such as CO and CO₂) in combination with temperature monitoring is usually the only opportunity to establish whether or not something serious is occurring. Using this method to achieve early detection is a very important component of the prevention work for which the silo site owner is responsible, and by studying trends in measurements an early indication of abnormal conditions can often be gained.

A consequence of the relatively low fire frequency is that the fire brigades have little experience in dealing with such operations and that there is insufficient appropriate extinguishing equipment. The fire development and the emergency response process 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.

Through focused efforts in recent years, significant knowledge has been gained within the area through a number of research projects carried out by the Department of Fire

Technology at SP Technical Research Institute of Sweden and financed by Brandforsk (Swedish Fire Research Board), CECOST (Centre for Combustion Science and Technology), the MSB (Swedish Civil Contingencies Agency), as well as several industry stakeholders. Using this knowledge, a number of fire & rescue brigades have been assisted during real silo fires, which provided additional valuable experience and partial confirmation of the research results. This collated knowledge serves as the basis for these recommendations.

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The recommended basic method for extinguishing a silo fire is a combination of inerting the silo with nitrogen gas from the bottom and then discharging the silo.

The recommended basic method for extinguishing a silo fire is a combination of inerting the silo with nitrogen gas from the silo bottom and subsequent discharge of the silo while monitoring and extinguishing hot material.

It should, however, be noted that experience from tests and real fires is limited to silos with a diameter of up to about 10 m and bulk material with relatively high porosity (mainly wood pellets). Fires in silos with larger diameters may naturally entail scale effects, in terms of the ignition and fire development, as well as the firefighting response respectively, which have not been predictable. Other bulk materials may also have other characteristics that differ from present knowledge (porosity, permeability etc.) that could result in increased difficulties in achieving an even distribution of gas.

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 service if preparatory measures for firefighting 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 firefighting operation. Pyrolysis also 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 fire development with a high risk of smoke gas explosions, open fires and rapid fire escalation within the plant that will result in great damage.

Silo owners often have a limited knowledge about the fire risks associated with silo storage. The risks are greatly dependent upon the type of material being stored and if operations undergo changes, new risks may arise. Therefore, previous experience and routines may not always apply and must be reviewed. The increased use and storage of different types of biofuel at both existing and new silo sites is an example of changes that pose new risks that must be taken into account.

This literature is intended for use both at emergency responses directly related to a fire, and also for preventive measures. The target group therefore includes the fire & rescue service, silo site owners, and fire safety consultants. The purpose is to provide a basic understanding of the different ways a fire can be expected to develop in a silo and the safety risks that should be considered, to give information about appropriate firefighting methods depending on the type of fire, and to demonstrate preventive measures that can be taken to avoid or minimize the consequences of fire.

This document includes the most basic information. Supplementary information, such as articles and reports gathered from various completed research projects related to fire risks and firefighting, experience from accidents and fires etc., will be published on the MSB's website.

Prevention work is obviously very important for the avoidance of explosions and fires and reducing the consequences of such occurrences as much as possible. According to the Swedish Work Environment Administration's regulations "Work in explosion risk environments", (AFS 2003:3, §7) it is the responsibility of the site owner to carry out a risk assessment to serve as the basis for establishing different types of preventive safety measures. The regulation requires a documented risk assessment to be produced and this shall among other things include "appropriate extinguishing agents and extinguishing tactics in the event of fires to prevent explosions".

Since every plant and every fire is unique, specific emergency response plans must be carried out. For this reason, emergency response planning should always be performed jointly between the current silo owner and the relevant fire & rescue service brigade. This may in turn result in certain

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Pyrolysis generates very high concentrations of toxic and flammable gases that may lead to great risks for plant personnel and the fire & rescue service.

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Emergency response planning should always be conducted in conjunction with the silo owner and the relevant fire & rescue brigade.

preparations being made, such as preparing for injecting inert gas so that the emergency response can be carried out quickly, safely and effectively. An important condition in regards to this is that the gas should be fed into the silo in a gaseous form and this requires a vaporization unit and a storage tank for the gas, equipment for pressure and flow regulation, hoses, etc. To achieve a reasonable cost/benefit balance, the hope is that all parties involved (silo operators, pellet manufacturers, heating plants) collectively invest in one or more mobile units that contain this special equipment that can be quickly deployed to a silo site in the event of a fire. See chapter 8.

It is important to stress that access to a mobile vaporization unit and associated tank with other equipment, cannot currently (2012) be guaranteed for fire emergencies in Sweden.

Summary of measures in the event of a silo fire

Chapter 1

Summary of measures in the event of a silo fire

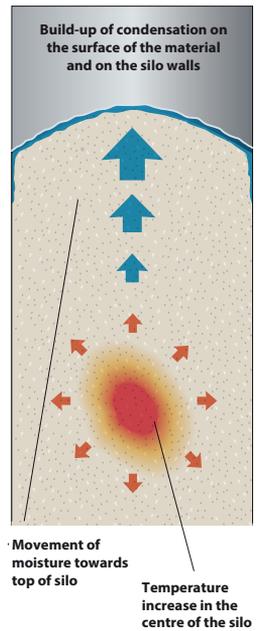
This is a general summary of decisions that must be made and measures that must be taken should a suspected/confirmed silo fire occur; this is to facilitate the emergency response by the fire & rescue service. Any existing emergency response plans should naturally be considered.

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 in the silo headspace 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? See more in chapters 5 and 6.

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. Measuring instruments must be calibrated regularly. When in doubt, use full protective gear. See more in chapter 3.

Consider the risk of fire gas/dust explosions

If possible, measure the concentration of CO and O₂ in 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 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. See more in chapter 3.



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., to restrict the possibility for air entrainment. 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 cover over an open top hatch works well as a "check valve". See more in chapter 2.



Requisition nitrogen equipment

Requisition vaporization equipment, a cryogenic tank and a tanker with liquid nitrogen (N₂) as soon as possible. Evaporation equipment is



necessary as the gas must be injected in the gas phase. Details, such as the duty number to ring to requisition equipment and gas can in Sweden be found in RIB Resurs. Note 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. See more in chapter 2.

Inject nitrogen near the bottom of the silo

Injecting nitrogen gas (N_2) close to the bottom of the silo is the safest and most effective firefighting method in most cases. The injection rate of nitrogen gas is based on the silos cross section area and should be at least 5 kg/m^2 per hour, which gives an average vertical gas filling velocity of about 8 m/h (based on 50% porosity of the bulk material). The total required gas should be estimated based on the silo's gross volume (empty silo) and a total gas requirement of $5\text{--}15 \text{ kg/m}^3$ could be expected. If needed, drill holes at the bottom of the silo and construct lances to feed the gas with. See more in chapter 2.





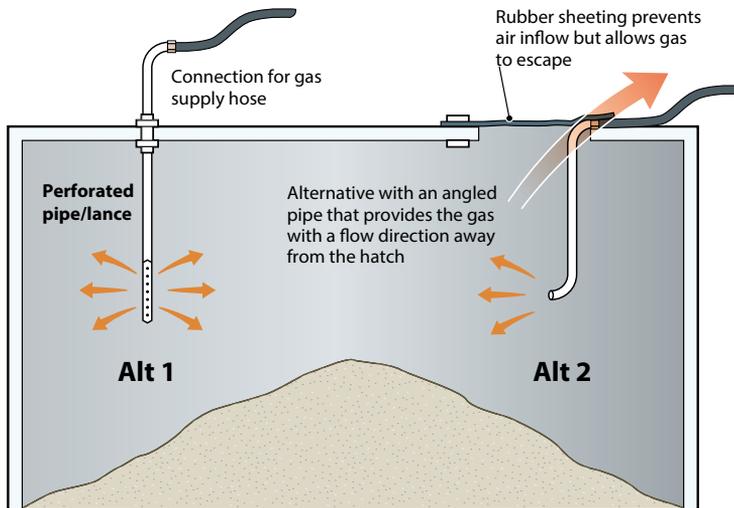
Requisition gas measuring equipment

If possible, requisition equipment for measuring the CO and O₂ concentrations in the silo headspace during the 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. Details, such as the duty number to ring to obtain equipment and gas can be found in RIB Resurs. 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. See more in chapter 2.

Apply foam in silo headspace 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 in the silo headspace may, if acceptable from a safety point of view, be covered with medium or high expansion fire extinguishing foam. The foam must also be of high quality so that drainage is minimized. If access 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 silo headspace. Additionally, attempt to minimize the risk of stirring up dust during application. Affected emergency response personnel should wear full protective gear. See more in chapter 4.





Start to inert the silo

Once the gas equipment is in place, the inerting operation of the silo should occur as soon as possible. If the explosion risk in the silo headspace is high ($\text{CO} > 2\text{--}5\%$, $\text{O}_2 > 5\%$), begin the firefighting response by injecting nitrogen gas to the silo headspace. This must be done with extreme caution to avoid a risk of explosion being caused by stirred up dust. As soon as the nitrogen injection in 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 headspace is under 5%, the gas flow to the silo headspace should be suspended and the entire gas flow should be directed to the bottom at the recommended injection rate. See more in chapter 2.

Begin discharge of the silo once the fire is under control

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 silo headspace. 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 suspended 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 firefighting response difficult. See more in chapters 2 and 6.

Plan for a long discharge operation

Plan on the discharge operation taking 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 firefighting personnel must be present at the discharge opening (and possibly at other points along the discharge system), a high number of firefighters will be required to facilitate frequent changes in staff. A large number of oxygen packages will also be required for the firefighters' respiratory equipment.

Sort discharged material

Sort the discharged material so that "undamaged" materials 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. 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 headspace and the oxygen concentration should not exceed 5%.



Warning!

Do not enter a building without personal gas monitoring equipment or breathing apparatus! High concentrations of carbon monoxide (CO), carbon dioxide (CO₂) and unburned pyrolysis gases, sometimes combined with very low levels of oxygen, present a great risk of poisoning, and in the worst case, loss of consciousness or death. See chapter 3.

Do not use water inside a silo, especially if the silo contains pellets!

This poses a risk of swelling the pellets, which may cause hangings and/or arch formations in the silo. In the worst case, this may lead to a collapse of the silo structure. Use of water may also lead to the formation of carbon monoxide (CO) and hydrogen (H₂). However, there are certain situations where water/foam is acceptable. See chapters 4 and 6.

Do not open the silo! Entrained air will oxygenate the fire, which leads to an increased smouldering intensity, which in turn may contribute to rapid fire escalation in conveyor systems before and after the silo etc., as well as serious gas and dust explosions. See chapter 2.

Liquid nitrogen (-196 °C) or very cold gas may cause damage. The gas temperature after the vaporization unit should therefore be controlled to avoid damage to hoses or other equipment due to liquid nitrogen entering the gas feeding system. Liquid nitrogen gas exposure to body parts causes immediate serious frost injuries and full protective clothing must therefore be used in the vicinity of liquid filled pipes or hoses. High concentrations of nitrogen gas in closed areas may also lead to rapid suffocation.

Firefighting method for silo fires

Chapter 2

Firefighting method for silo fires

The most difficult scenario for the fire & rescue service is to handle a deep smouldering fire since such fires are extremely difficult to access. Since the fire is also extremely difficult to detect in early stages, there is a risk that the fire is relatively widespread once it is detected. If a deep smouldering fire is not controlled, it may develop and possibly transform into an open fire in the silo headspace due to the high volume of flammable gases that are generated in the silo. This poses a threat both to the silo structure and adjoining conveyor systems.

In the following recommendations, the primary firefighting tactic is aimed at inerting the silo with inert gas (nitrogen gas) in order to displace the oxygen and gradually quench the pyrolysis. This provides the best possibility for a safe and well-controlled operation. When dealing with fires at silo plants, a long firefighting operation must be assumed in order to assure control of the fire and subsequently empty the silo in a safe manner. The firefighting method itself does not affect the stored material, which allows the operation to commence at a very early stage, even before a fire has positively been confirmed.

The use of nitrogen gas instead of carbon dioxide is recommended for three basic reasons.

- Under the conditions that exist in silo fires (flammable material, low oxygen concentration, water vapour and high temperatures), carbon dioxide can give rise to the chemical reactions that lead to the formation of high volumes of



Fire scenarios that should not need to happen if the appropriate measures are taken, both in preventive work and operational firefighting. The fires in the top of the silos are probably caused by flammable pyrolysis gases that are generated inside silos and which then ignite the top of the silo superstructures.

carbon monoxide and hydrogen, which may lead to serious deterioration of the situation.

- Liquid nitrogen is significantly easier to vaporize than carbon dioxide, more easily accessible and cheaper.
- There are no associated risks of static electricity during gas injection. See more in chapter 3.

In cases where the use of nitrogen gas for some reason is deemed not feasible, such as for large silo surface fires, there are *alternative methods* (foam application, water spraying, and water injection) that may be appropriate. The use of water-based methods to extinguish silo fires is, however, associated with a number of problems and risks, and must therefore be carefully considered. See chapter 4.

Workflow when inerting a silo

The following chapter demonstrates the workflow when inerting a silo in which a fire has been verified or the suspicion of a fire is strong enough to warrant an inerting for safety reasons. Descriptions of the different signs of a fire are given in more detail in chapter 5. Regardless of whether it is a question of a suspected fire or a confirmed fire, continuous assessments of the risks for affected personnel in regards to poisoning and gas and dust explosions must be maintained. This is emphasized below for different sub-operations, but is also described in-depth later on.

Limit access to oxygen

To reduce the intensity of the smouldering fire inside the bulk material, the silo should be sealed as quickly as possible, both in the top and the bottom. All ventilation systems should be turned off. All openings and unsealed gaps or ventilation will allow leakage of air in to the silo, which in turn contributes to maintain or intensify the fire. During sealing, it is very important to take into account the risk of gas and dust explosions, as well as risks attributed to toxic smoke gases.

The bottom of the silo should be inspected and outflow openings, inspection doors etc. should be sealed where necessary. If applicable, gaps between silo walls and the silo bottom/silo cone should also be sealed.

All hatches/openings and all "open" connections with transport systems, dust ventilation systems etc. at the top of the silo should be blocked. These connections may allow air to leak into the silo. Additionally, smoke gases and, eventually, the fire may spread to surrounding silos and other sections of the plant. Certain sealing measures, such as sealing openings between silo cells, are difficult to perform during emergencies and should therefore be taken care of as preventive measures.

To permit relief of pressure from heat and, later, gas feeding, there must be an opening at the top of the silo. In the event of an emergency, a hatch on the silo top is opened and covered with rubber rug or the equivalent, which allows gas to flow out and simultaneously prevents air from flowing in. There is also opportunity to carry out simple preparatory measures



Examples of openings, conveyor system, ventilation pipes etc., that may need to be sealed, both at the top and bottom of the silo. In older silos made of concrete, there are often openings between the silo cells under the silo roof, which may make it necessary to seal adjacent silo cells as well.

that allow the smoke gases to flow out into the open, see chapter 7. This may contribute to significantly lower cleaning costs since smoke gases consist of high volumes of tar etc. that otherwise may contaminate the superstructure and accompanying equipment.

If the silo has explosion hatches, such as a freestanding biofuel silo, one or several of these can be released in a way that permits gas to flow out when pressure is increased, but prevents air inflow due to the weight of the hatch itself. The hatch must naturally be secured so that it cannot fall down.

Do not open the silo for any reason

The silo may not under any conditions be opened so that cross ventilation is possible. This may lead to a powerful fire development and explosion. There are many examples of fires where this has caused an extensive fire escalation and significant risks for personnel.



Examples of fire scenarios that may occur if a silo wall is opened up during a smouldering fire.

Gas equipment

Nitrogen gas and gas equipment should be requisitioned as quickly as possible. Details, such as the duty number to ring to requisition equipment and gas can in Sweden be found in RIB Resurs. Nitrogen gas is delivered by a tanker that stores the gas in liquid form by keeping it cooled to $-196\text{ }^{\circ}\text{C}$. Since the gas must be in gaseous form when it is fed into the silo, vaporization equipment is required. *(Note: Access to vaporization equipment is limited at present time in Sweden. See more information below and in chapter 8).* The vaporizer works like a large heat exchanger that uses the energy of the surrounding air to vaporize the nitrogen. If possible, a mobile nitrogen gas tank should be requisitioned as well and positioned adjacent to the vaporizer. This will mean that the truck with nitrogen gas only has to fill the mobile tank and does not need to stay in place during the entire operation. If needed, the mobile tank should be refilled, which can be done without interrupting the gas flow to the silo.

Nitrogen

Melting point: -210 °C
Boiling point: -196 °C
Gas Density at 1,013 bar and 15 °C: 1.185 kg/m³
Specific volume at 1.013 bar and 21 °C: 0.862 m³/kg
Relative density (air = 1.0) at 1.013 bar and 21 °C: 0.967
(reference: www.encyclopedia.air-liquide.com)
See also chapter 3 regarding personal risks.

The vaporizer is fed with liquid nitrogen gas (-196 °C) from the nitrogen gas tank through a specially designed metal hose made to withstand such low temperatures. After the vaporizer, there should also be control equipment (although this is not absolutely necessary) that allows outgoing gas pressure and gas flow to be measured and regulated. It should also be possible to measure outgoing gas temperatures to prevent the vaporization unit from being overloaded and allowing high volumes of cold/liquid gas to reach the distributing piping/hoses and flow into the silo.

After the vaporization unit, the gas temperature is normally about 10 °C lower than the ambient temperature at the vaporizer's nominal capacity, but this is affected by the air temperature and the gas flow rate. This means that the gas can usually be distributed to the silo using some type of a hose. In situations with low feeding pressure and an appropriate gas temperature, a normal hydraulic hose (small flows), a flat-rolled "snow machine" hose) or even a normal flat-rolled fire hose may be used (see below). The benefit of using a hydraulic hose or snow machine hose is that these hoses can withstand a higher pressure and provide more secure couplings than fire hoses.

Examples of hose dimensions

Here are two examples of an approximate relation between gas flow, hose dimensions and hose length. The prerequisite is a feeding pressure of 3 bars from the vaporization unit and a pressure drop of no more than 1 bar. In other words, the pressure value should be 2 bars at the connection to the silo.

1. A hose with an internal diameter of 25 mm may be no more than about 80–100 m long if the gas flow is 100 kg/h. At 300 kg/h, the maximal hose length is between 10–15 m.
2. A hose with an internal diameter of 50 mm may be no more than about 150–180 m long if the gas flow is 500 kg/h. At 1000 kg/h, the maximal hose length is 50 m. See more in chapter 7.

The delivery time for nitrogen gas in Sweden is usually relatively short (a few hours) since the gas providers have a relatively large number of trucks in operation. The most appropriate gas provider is dependent upon variables such as where in the country the fire is located. In regards to the vaporization equipment,

delivery time may be significantly longer. The gas provider has a number of mobile vaporizations units of different sizes and capacities, but the number is limited and there is no guarantee that equipment will always be available. Even if appropriate equipment is available, it has to be picked up, loaded, transported etc. This, together with transport time, may take several hours.

Gas providers in Sweden also have mobile nitrogen gas tanks with different storage volumes for hire, but access to these is also limited and there is no availability guarantee. The gas tank is not as critical as the vaporization unit since the nitrogen gas truck can be connected to the vaporizer. This, however, results in blocking a tank vehicle in place, which may cause problems for the gas provider. To connect the gas equipment and "start" it, the gas providers have dedicated personnel that take care of this. When finished, the equipment can be handled without any problems by following the instructions provided.

If it takes a long time to acquire the vaporization equipment, it is possible to commence inertisation at the limited vaporizing capacity that can be achieved directly from the tanker. If it already in the planning stage is known that the



In some cases, one should consider purchasing one's own tank and vaporization equipment.

delivery of the vaporization equipment will take many hours, purchasing a vaporizer should be considered. Even if such equipment would provide limited capacity, it would allow a firefighting operation to begin relatively fast.

The hope for the future is that silo owners/operators in Sweden invest in a complete vaporization unit and other equipment that may be needed to extinguish possible silo fires. See chapter 8.

Considering that the delivery time for gas equipment may be relatively long, it is very important to act early if a silo fire is suspected. Since the course of the initial phase is often relatively slow, doing so will allow a firefighting operation to be launched before a large fire occurs. Since inerting with nitrogen does not cause damage to the stored material, there should be no hesitation in launching such operations as soon as a fire is suspected. If you wait too long, the fire might rapidly get worse, which increases the risk of a gas explosion and a fully developed fire that can lead to total loss.

Gas dimensioning

The gas flow rate used during inerting should be adapted to the diameter (cross section area) of the silo. The gas flow rate also serves as the basis for establishing the required capacity of vaporizer. Based on research and extinguishing tests in laboratory scale, as well as experiences from real firefighting responses, a gas flow rate of no less than about 5 kg/m^2 per hour



Inert gas system for silo fire extinguishing (Air Liquide) and photo of a mobile vaporization unit, a gas tank and a tanker (AGA).

(preferably up to 10 kg/m² per hour) is recommended during the initial phase of the firefighting operation. Observe that fine powder material, such as wood powder, may require a lower injection rate in order to avoid dust formation which could lead to a dust explosion.

The total gas consumption is very difficult to assess since it depends on the construction and sealing of the silo, how quickly the silo can be discharged etc. A rough estimate may, however, be of interest for the gas provider and others, so that planning the gas supply for the entire operation can begin during the initial phase. Such an estimate is also of interest in regards to the volume of a possible mobile nitrogen gas tank. As a guideline, based on experience with actual silo fires, a total gas consumption of 5–15 kg/m³ can be expected in relation to the gross volume of the silo.

Examples of gas dimensioning

1. A tower silo has a diameter of 8 m and a height of 45 m. The silo's cross section area is estimated to be about 50 m² and the gross volume is 2260 m³. The gas flow rate should therefore initially be at least about 250 kg/h (5 kg/m² per hour x 50 m²) and total gas consumption is estimated to about 10–35 ton (5 kg/m³ x 2260 m³ =11400 kg and 15 kg/m³ x 2260 m³ =33900 kg respectively).
2. A biofuel silo has a diameter of 25 m and a height of 30 m. The silo's cross section area is estimated to be about 490 m² and the gross volume is 14,700 m³. The gas flow rate should therefore initially be at least about 2500 kg/h (5 kg/m² per hour x 490 m²) and total gas consumption is estimated to about 75–220 ton (5 kg/m³ x 14,700 m³ =73,500 kg and 15 kg/m³ x 2260 m³ =220,500 kg respectively).

Equipment for gas injection into the silo

Nitrogen gas should primarily be injected at the bottom of the silo, but it may be required to inert the silo headspace during the initial phase in order to avoid the risk of gas and dust explosions.

Inerting via the bottom of the silo

Gas injection at or close to the bottom of the silo is done to inert the entire silo as effective as possible. To assure an even distribution of over the silo cross section area, the gas

must usually be applied at several points. The larger the silo diameter and the lower the maximal storage height, the more important the requirement for effective distribution becomes; otherwise there is a risk of only inerting a part of the silo. *All silos should preferably be prepared for extinguishing using inertation (see chapter 7), especially when dealing with large silo diameters and/or if accessibility around the silo is limited.* Often, preparations have not been made, therefore a number of examples on how to arrange the gas injection in an emergency situation using perforated lances that is pressed into the material during the operation, are shown below.

For small silo diameters, one gas inlet at or around the silo centre is normally sufficient. If the silo diameter exceed 6–8 m and/or the silo height/storage height is less than 2 x the silo diameter, the gas flow should be distributed through 2–3 inlets over the cross section area. If the diameter is significantly larger, i.e. 10–15 m, and the storage height is relatively limited, additional gas inlets will be required in order to achieve an even gas distribution over the entire cross section area. In such cases, the lances should be pushed in to at least half the silo's radius. Since this might be difficult to achieve quickly in an emergency situation, the first step should be to arrange a gas inlet to the silo centre if the silo constructions permits, for example in connection with the outflow opening if the silo has a centre outflow. Since self-ignition usually occurs relatively deep inside the material, it is then more likely that the gas will reach a pyrolysis fire in the silo centre. If any part of the silo wall indicates an increase in temperature, it may indicate that the fire has spread sideways or been caused by e.g. overheating in the screw reclaimer. In such cases, gas injection should be applied to the area as quickly as possible. To assure the entire silo is inerted several lances will probably need to be pushed in from the side as a subsequent measure. However, this can be very difficult since the pressure from certain bulk material and the friction against the lance may cause a great deal of resistance. Machine equipment, such as pressing with a front loader or using some type of drilling equipment, will probably be needed in such situation.

Therefore, one or more penetrations must be made in appropriate places in the silo wall close to the bottom of the silo in order to allow the lances to be pressed, hammered or drilled into the material. If the silo is made of concrete, concrete drilling equipment will be needed. The bottom of a concrete silo (about 1/3 of the total height) has very heavy ring reinforcement with a c/c of about 0.3 m and it is preferable to leave this reinforcement intact during the penetration work. A construction drawing is therefore very helpful. If the silo is made of steel, an appropriately sized hole-cutter should be used. In this case, it may however be important to cool the steel plate to avoid the risk of igniting the material on the inside of the plate.

Before starting the penetration work, it is also important to verify the drawings so that the hole or lances are not obstructed by any construction details or extraction equipment on the inside of the silo. The hole should allow the lance to be easily pressed in without any problems. For silos of concrete with thick walls, a larger hole is required as the lance could bind to the concrete if the bulk material presses the lance downwards.



Concrete silos are often heavily reinforced at the bottom and damage to the reinforcement should be avoided as much as possible.

Once the lance has been pressed in, it is important to seal the gap around it so that no air can leak in.

During discharge of the silo, the lance may be damaged by the slow downward movement of the bulk material in the silo. This may cause the lance to bend, which may make it difficult to get it out. Lances should therefore not be permanently mounted in a silo unless the construction can be designed so that the lance is not damaged and so that it does not prevent material from being discharged.

The diameter and perforation of the lances must be adapted to the gas flow needed and the length must be adapted to how deep into the silo the lances need to be pressed and the number of lances to be used. The lances can be made of ordinary steel pipes (water pipes) with a diameter of about 25–50 mm depending on the gas flow per lance. Generally, the gas needs to be distributed as much as possible and therefore it may be preferable for perforations to be spread out along the lance. On the other hand, it is important that no part of the perforations end up outside the silo in the case that the lance cannot be pressed in as far as planned. In the case that the gas needs to be injected deep into the material, perforations should be limited to the front of the lance. The hole-diameter should be adjusted to the dimension of the bulk material. As an example, for wood pellets that normally have a diameter of 8 mm, a hole diameter of 6 mm is appropriate. For finer particles, such as 6 mm pellets or wood powder, 4 mm holes may be used. The number of holes depends on the maximum flow rate through each lance. Perforations are preferably limited to approximately half of the lance diameter so that the perforated section can be turned downwards and to the sides, which will minimize the risk of blockage.

Examples of gas flow with different types of lance

A lance with an internal diameter of 25 mm and a total of 20 holes, with a diameter of 4 mm each, could be used for a gas flow of 80–100 kg/h. A lance with an internal diameter of 50 mm and a total of 20 holes with a diameter of 6 mm each could be used for a gas flow of 300–400 kg/h. These lances give a low pressure drop at these flow rates, but a total gas pressure of 0.5–2 bar at the lance should be expected when injecting into wood pellets or similar material. Other bulk material with lower gas permeability may of course create a higher back pressure.



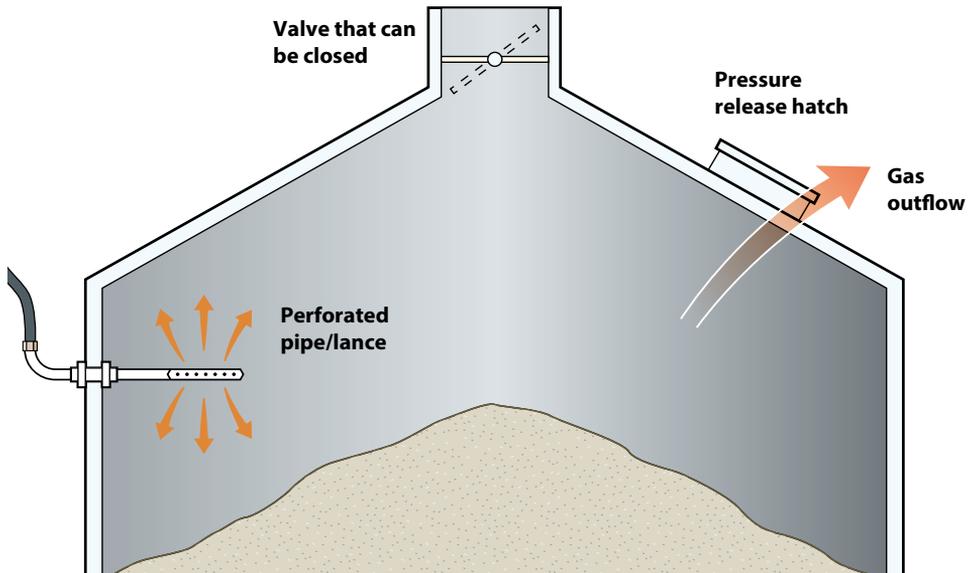
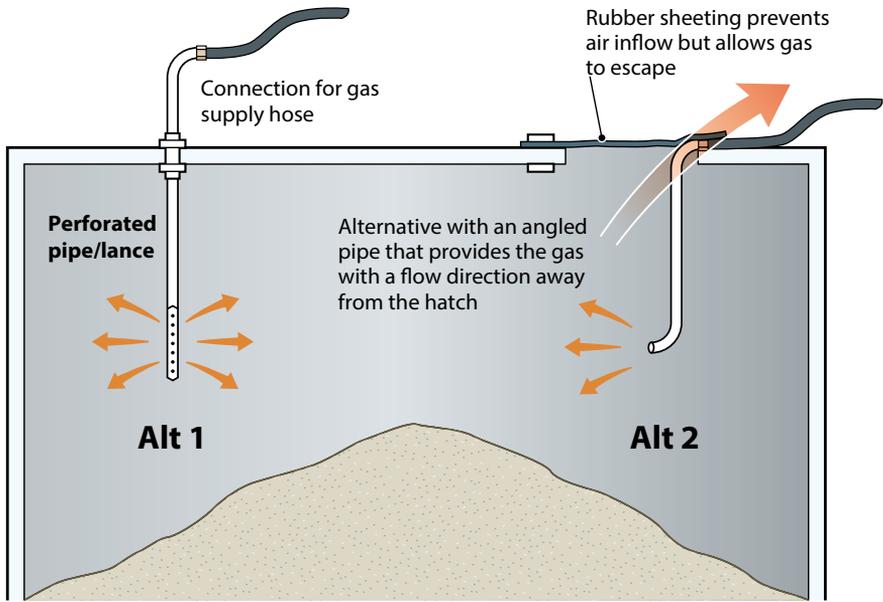
Examples of temporary gas injections at silo fires by the use of, for example, pipe shaped, perforated lances which are inserted into the material just above the bottom of the silo.

The lance should be equipped with an appropriate connection so that the gas hose from the vaporizer can be connected in a secure manner. Since the gas equipment (tank, vaporizer and metal hoses) is equipped with gas connections, some form of adaptor must be arranged. Normally, the gas provider's service personnel are provided with a large number of adapters, including normal pipe threads. The lance is therefore appropriately fitted with a pipe thread or a coupling with a pipe thread. It may be possible to use some type of flange connection, but this should be coordinated with the gas provider.

Inerting the silo headspace

If there is an imminent risk of explosion in the silo headspace (indicated by gas analyses etc.), it should be inerted as a first step. The primary aim is to reduce the oxygen level inside the headspace so that ignition cannot take place even if flammable gases are present. The target oxygen level should be less than 5%. In this case, nitrogen gas may be injected into the silo headspace using a lance or an open pipe. In this situation, penetration work (e.g. drilling) should be avoided due to safety reasons and the lance/pipe should therefore be inserted into the silo headspace through a hatch or other opening. The gas injection should be as far away as possible from the opening used for pressure relief in order to achieve the best inerting effect of the entire silo headspace. Covering/sealing the opening with rubber rug or similar to prevent air from leaking in is important in this phase as well. Some guidelines on appropriate gas flow rates when inerting the silo headspace do not exist, but a lower flow than the flow used for gas injection at the silo bottom should generally be used. 1–3 kg/m² per hour could be considered reasonable in order to avoid excessive gas loss. In order to avoid dust formation, it could be recommended to start with an even lower flow rate and slowly increase it until a certain inerting effect is achieved.

Inerting the headspace of small silos may be achieved by using compressed nitrogen gas supplied in the form of individual gas bottles or bottle packages. A bottle package with 12 connected 50 litre nitrogen gas bottles and a pressure of



Venting and gas injection into the headspace of a tower silo and a stand-alone biofuel silo.

200 bars contains a total of 120 m³ free gas, or 10m³ gas per 50 litre gas bottle.

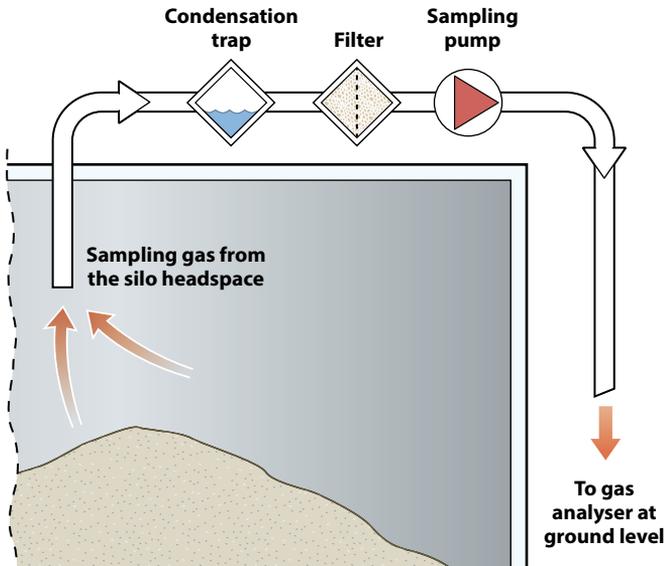
One of the most common extinguishing methods for silo fires is to inert the silo headspace with carbon dioxide. This is strongly discouraged. See more in chapter 3.

Work procedures, observations, measurements, assessments during inerting

To facilitate control of the extinguishing effect of the operation, temperature and gas composition (minimum carbon monoxide and oxygen concentrations) should be measured in the silo headspace. In practice, this is the only way to confirm that the gas injection is providing the intended extinguishing effect and that the fire is gradually suppressed. For safety reasons, measurement instruments should be placed in a safe area on ground level, which may require long sampling hoses for the gas from the top of the silo to the instruments. A high capacity gas pump is therefore necessary in order to minimize the transport time, which in turn affects the time delay of analysis data. The pump equipment and included accessories, as well as gas analysers that measure very high concentrations of CO will therefore be needed. Details, such as the duty number to ring to obtain equipment and gas in Sweden can be found in RIB Resurs. If possible, these gas measurements should begin prior to start of the gas injection in order to obtain a reference value of the initial conditions”.

The injection of nitrogen gas should commence as soon as all equipment is in place. If the delivery time for the vaporizer equipment is long, the inerting of the silo (to the headspace or at the bottom of silo) may begin by feeding gas directly from the tank vehicle, even if this will only provide a very low capacity due to the limited vaporizing capacity of the vehicle. Injecting gas to the silo headspace is normally only necessary during the initial phase and is controlled based on the results of gas analyses. When the silo headspace is deemed to be inerted, the injection can be reduced or suspended to give priority for gas injection at the silo bottom.

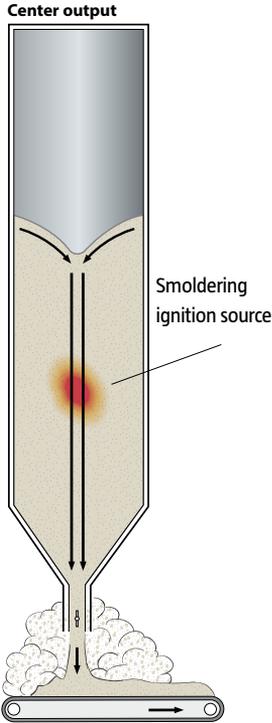
When nitrogen injection at the bottom of the silo has commenced, it will probably take a few hours before an extinguishing effect can be observed. As a guideline, an injec-



Gas sampling equipment at the top of the silo, gas analyser and data logging equipment, preferably at ground level in a protected place.



tion rate of 5 kg/m² per hour is the equivalent to an average vertical filling velocity of about 8 m/h inside the silo, provided that the material has a bulk porosity of 50% (such as wood pellets). If it is possible to additionally increase the injection rate, at least during the initial phase, the filling velocity will increase correspondingly. Initially, gas analysers connected to the silo headspace may show increased gas concentrations and visible smoke formation may increase since the nitrogen gas will gradually push the combustion gases upwards that are inside the bulk material. However, the nitrogen gas also displaces air and



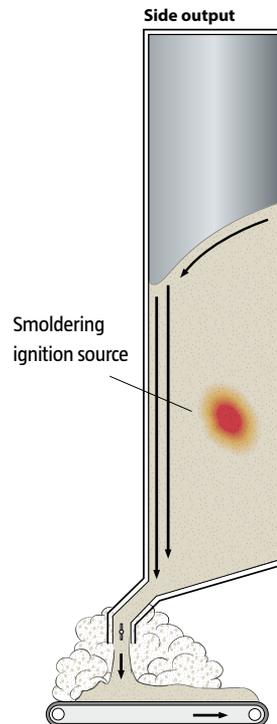
During discharge of a silo, a "core flow" is often obtained, i.e. the material forms a funnel above the discharge opening where the material from the surface flows downwards. Discharging a silo that contains a smoldering fire also poses a serious risk of dust explosion and/or a fire escalation along the conveyor system if the fire is not under control and the silo is kept fully inerted during the entire discharge operation.

oxygen, which thereby contributes to reducing the intensity of the smoldering fire inside the bulk. After some hours of gas injection (depending on the gas flow rate, silo height and fill level), the nitrogen gas will have "flushed" the bulk material and reached the silo headspace, which will result in reduced carbon monoxide and oxygen levels. (The oxygen level may be low from the start if the fire has already consumed the oxygen). Declining gas concentrations of mainly carbon monoxide is a clear sign that the fire intensity has been reduced. When the gas concentrations are stabilized at a relatively low level (carbon monoxide level below about 1% and oxygen level below about 5%), the gas flow rate can be reduced gradually with the aim of maintaining an inert environment inside the silo. The extent to which the gas flow can be reduced depends on the tightness of the silo, how effectively the gas is distributed over the cross-section area of the silo etc. and the gas flow rate must therefore be controlled based on the results of gas measurements. As a guideline, the gas flow rate should not be less than 1 kg/m² per hour. If so, it's better to use intermittent gas injection at a higher flow rate. Once again, it is important to keep in the mind the time delay between changing the gas flow rate and the effect in the silo headspace, which may be several hours. For this reason, controlling the gas flow must be done gradually based on the gas measurements in the silo headspace so that a safe environment inside the silo is maintained.

The discharge of the silo content should only begin when the fire has been stabilized, i.e. that measurements and visual observations etc. indicate that the fire is completely under control. The gas injection should continue throughout the discharge process since smoldering embers may be exposed to air during discharge, which can cause increased activity. Some types of material can stick together and form hard, solid "cakes" on the surface, in part due to condensation from the fire. This may cause serious problems since the material can stick to the silo walls (forming hangings or bridging). In some cases, smoldering fires may occur inside these formations itself, which may lead to very complicated fires and firefighting operations. In the event of smoldering fires inside such formation, the fire is very hard to access and the inert gas will have great diffi-

culties in penetrating the material. If a hanging or bridging formation has formed, it may cause extensive and instantaneous collapses of material inside the silo that may expose the fires hidden in the material, which in turn can cause dust and gas explosions if the silo is not inerted. (See more in chapter 6.) It is therefore important that the fire development inside the silo is followed during the entire discharge process based on measurements in the silo headspace and the discharge should be temporarily suspended if any signs of increased fire activity, such as increased temperature, increased oxygen concentration or increased CO concentrations, are observed. In such case the gas flow rate should be increased again to quickly regain safe conditions, after which it may be possible to decrease the gas flow again. If arching or hanging formations still remain after all free-flowing material in the silo has been discharged, this may pose great risks during subsequent work since the material somehow has to be removed from the silo wall.

It may also be of importance to understand the flow pattern of during the discharge of a silo. For free-flowing material, a "core flow" is achieved in most cases. If the discharge opening



Emptying devices in a silo facility.



It is very important that all firefighting personnel working at silo sites wear full personal protective equipment (PPE).

is placed next to the silo wall, a supposed pillar directly above the opening will flow out first, followed by material from the top flowing down into the funnel that is formed. This may cause a delay before the smouldering material is discharged. If the discharge opening is located centrally in a flat bottom silo, the core flow will form directly above the outflow. This means that a mix of smouldering and unaffected material will start to flow out relatively soon after the discharge operation has started and continue to come out throughout most of the process.

If a risk of hang or arch formation (see chapter 6) is suspected during the discharge operation, a plumb line or similar may be used to make sure that the silo contents sink correspondingly with the material discharged. During this, it is extremely important that the top of the silo is kept completely inerted before starting to use a plumb line and that hatches or similar openings are not opened more than necessary.

During the discharge operation it is of course very important that firefighters in full protective equipment monitor the material at appropriate sites in the plant, spray water onto smouldering embers, and make sure that dust formation is limited. During discharge, clumps of charred material can be expected to block the outflow openings, which may require continuous manual clearing to maintain an outflow of material. If the material cannot be discharged directly to an outdoor location, the entire conveyor system inside the plant must be monitored so that the conveyor equipment or other equipment is not ignited by smouldering material. Together, this creates a physically intensive task, which may require a lot of human resources and a large number of oxygen tanks for the firefighters' breathing apparatus.

Emptied material must be stored in an open area that is at a safe distance from adjacent buildings and facilities. Since large volumes are often involved, which may require extensive and stressful work, intensive traffic with wheel-loaders and trucks it is important to establish strict safety rules and barriers.



Discharge of material must be monitored along the entire conveyor system. The material (pellets and coal) must be sorted and stored in a safe place to allow for cooling off and to allow detection of any possible remaining embers. The black lump above is an extinguished ember.

**Personal
safety**

Personal safety

A silo fire creates a number of risks that may cause serious injuries or death, both for plant personnel and emergency services personnel. Information regarding the most acute risks can be found below.

Formation of carbon monoxide (CO) and carbon dioxide (CO₂)

Even before self-heating or a fire is detected, the formation of carbon monoxide (CO) spreading through the plant may cause serious risks. CO is completely odour-free and therefore impossible to detect without special CO detectors. Measurements in facilities have shown that CO concentrations of >100 ppm may exist under normal conditions in the silo superstructure or passageways at silo bottoms. Concentrations of >1000 ppm have been observed in these locations in connection with fires.

In the silo headspace, the gas concentrations may be significantly higher and CO concentrations of 5000–10000 ppm (0.5–1.0%) have been measured in cases of increased oxidation of the pellets. In the event of a fire, the CO concentration in the silo headspace may exceed 10%, which creates a very serious threat (see fact box). In connection with oxidation or fires, very high concentrations of carbon dioxide (CO₂), in some cases over 30% and unburned hydrocarbon may be formed, which further increases the risks.

Carbon monoxide

Carbon monoxide is an odour-free gas that has the same density as air. The Swedish Work Environment Authority has set a limit of 35 ppm for 8 hours of work and 100 ppm for 15 minutes of exposure (10000 ppm=1%). To further compare, 30 minutes of exposure to 2500–4000 ppm leads to death and 1400–1700 ppm leads to loss of consciousness. Corresponding values at 5 minutes of exposure are 12000–16000 ppm and 6000–8000 ppm respectively. Carbon monoxide is flammable within the area of 12.5 to 74 - vol %.



It is extremely important with a high level of safety planning to avoid injuries to people during silo fires.

Do not measure oxygen concentration only!

It is important not to exclusively rely on oxygen concentration measurements. Air normally contains about 21% oxygen and accepting a concentration of e.g. 20% oxygen as acceptable could lead to very serious consequences. If the reduced oxygen concentration consists of carbon monoxide, this would correspond to about 10,000 ppm, which quickly might lead to unconsciousness and death.

Risks of using nitrogen and carbon dioxide as extinguishing agents

Nitrogen

Handling of nitrogen brings risks since it lowers the oxygen level in the air and can thereby lead to suffocation. According to Swedish Regulations AFS 1997:7, a minimum oxygen level of 20% is recommended in work environments where various gases are handled and respiratory equipment must be used

if the level is less than 18%. If nitrogen is released into the open, for example during filling from the tanker vehicle to the mobile gas tank, the gas is quickly dispersed since it weighs about the same as air, which would pose no danger. In contrast, nitrogen can remain present for a long time in closed areas that have been inerted. This means that the oxygen level could be very low, which may quickly cause loss of consciousness.

Examples of critical exposure times are shown in the table:

Oxygen concentration	Leads to unconsciousness after:
7 %	1 minute
5 %	20 seconds
3,5 %	15 seconds

During the firefighting operation, there is also probably a combination of very high carbon monoxide and carbon dioxide concentrations, as well as low oxygen levels due to the fire, which makes the environment very dangerous.



An important lifesaver for all personnel that have to be inside the plant is to use a personal gas detector that measures both carbon monoxide (CO) and oxygen (O₂).

It is therefore necessary to continuously control the carbon monoxide and oxygen concentrations in the plant in the event of a fire. In the affected areas (at the bottom and top of the silo superstructure), all persons should wear complete respiratory gear. In connected areas (control rooms, personnel areas, stairwells, elevators etc.), increased concentrations may also be present, which makes it necessary to wear respiratory gear here as well unless continuous measurements guarantee a safe work environment.

An additional risk that should be taken into account is frostbite injuries that may occur when handling liquid nitrogen. Hoses between the tank and vaporizer and the vaporizer itself can become extremely cold since liquid nitrogen has a temperature of $-196\text{ }^{\circ}\text{C}$ and these surfaces should therefore not be touched without protective gloves. Mounting of the equipment and filling etc. should be handled by trained personnel, such as the gas provider's service personnel, and it must always be assured that emergency response personnel are informed of the required safety instructions. Even if the risk of hose breakage is very low, unauthorized personnel should never stay in the vicinity of equipment and hoses containing liquid nitrogen.

Liquid nitrogen or very cold nitrogen can also on direct contact cause damage to certain materials, such as non-alloy ("black") steel, plastics, rubber etc. In contrast, brass, copper and aluminium can withstand it relatively well.

Regarding the gas distribution from the vaporizer to the injection point on the silo, it is important to ensure that no leakage or hose breakage occurs. The nitrogen is distributed in gaseous form and the gas pressure is normally only a few bars, but it is important to make sure that the vaporizer's capacity is not exceeded, as this might result in very low nitrogen temperatures causing damage to the hoses.

In regards to inerting the silo headspace, nitrogen has the benefit of not causing any problems related to static electricity since it is injected in gaseous form.

Carbon dioxide

Carbon dioxide is a traditional extinguishing agent that is used in portable fire extinguishers and for fixed fire protection systems in enclosures. Typical applications are the extinguishing of small spill fires and extinguishing of fires in electrical equipment, computer rooms, etc. The extinguishing effect is mainly due to the reduction of the oxygen concentration in combination with a certain degree of cooling. When dealing with silos, there are however serious disadvantages of using carbon dioxide. Historically, carbon dioxide has been the extinguishing agent used for silo firefighting. A large number of these responses, however, have experienced problems that in several cases have led to failure. There is also a risk that using carbon dioxide may make the fire worse if used in certain situations. A summary of these risks and problems that is intended to provide an understanding of why carbon dioxide should not be used to put out silo fires is given below.

A serious risk is that carbon dioxide, in the conditions generally found in a silo fire, 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 $C + CO_2 \rightarrow 2CO$. 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 growth instead of providing a fire extinguishing effect.

An additional argument against the use of carbon dioxide is that it may cause serious practical problems. Carbon dioxide is a liquefied gas and the pressure in the tank depends on the surrounding temperature. An attribute of carbon dioxide that often creates problems is that carbon dioxide cannot exist in liquid form at a pressure below 5.2 bars. Instead, the liquid freezes into a solid (carbonic ice). This means that feeding liquid carbon dioxide through a hose or pipe system requires maintaining a pressure of at least 5.2 bars in the entire gas feeding line to avoid ice from forming and blocking the passage. In extinguishing

Carbon dioxide

Carbon dioxide is an odour-free gas that is about 1.5 times heavier than air, which can pose serious safety risks since it accumulates at low levels. Carbon dioxide is not only reducing the oxygen concentrations as nitrogen does, but it also affects the respiratory function. The Swedish Work Environment Authority has set a limit of 5000 ppm per 8 hours of work and the limit for 15 minutes of exposure is 10000 ppm (10000 ppm = 1%). When using CO₂ as an extinguishing media, the design concentration is very high, probably at least 30–50%. Loss of consciousness and cramps occur at concentrations of 20–30% in less than a minute.

systems, this minimum pressure is guaranteed by customized nozzles but maintaining the pressure is difficult when feeding the gas to the silo headspace, usually through a fire hose with some type of open pipe at the end. One solution that is normally used in these situations is to apply a very high flow rate so that the pressure drop in the hose maintains a high pressure. However, this usually results in ice formations at the end of the hose where the pressure is not high enough, which eventually leads to total blockage of the hose. At this stage, the hose upstream the blockage, contains a mixture of carbon dioxide in liquid and gaseous form and, due to heating from the surrounding, the pressure in the hose will increase quickly, which may lead to hose breakage. To avoid this, the hose can be disconnected from the pressure tank/tank vehicle and allow depressurizing backwards. This is a very risky operation that leads to the formation of a carbon dioxide cloud when the gas in the hose flows out. The action also involves great risks both in terms of;

- hose breaking,
- the hose whipping around when disconnected and
- poisonous carbon dioxide.

Another risk factor that also must be taken into account is the strong build-up of static electricity caused by the carbon dioxide flowing out and forming ice crystals. This in turn may lead to sparks that can ignite flammable gas mixtures in the silo headspace under unfavourable conditions. *Static electricity caused by the manual application of carbon dioxide from gas bottles through hatches in to the silo headspace is believed to have caused a number of silo explosions.*

Problems with ice forming also occur if you try to feed liquid carbon dioxide directly into the bulk material. As soon as the gas exits the hose or feeding pipe, the pressure drops and the gas freezes. This results in heavy ice formation in the bulk material, which leads to the blocking of the porosity of the bulk material, which then prevents continued application of gas.

Dust and gas explosions

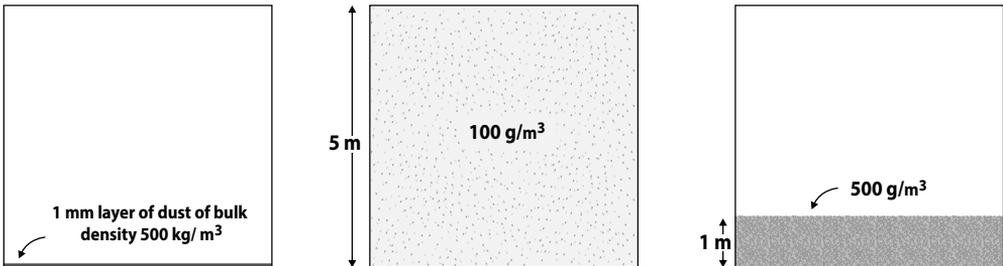
The normal handling of materials in silo plants generates always more or less dust formation, which eventually covers all horizontal surfaces and construction components with dust.

If any of this dust is dispersed to a cloud and there is an ignition source present, a dust explosion could occur. This "primary" explosion often leads to additional dust whirling up and causing a "secondary" explosion, which is often significantly more powerful than the primary explosion.

Even a thin layer of dust could create a significant risk. A 1 mm thick dust layer with a bulk density of 500 g/m³ provides a dust concentration of 500 g/m³ if whirled up to 1 m height and 100 g/m³ if whirled up to 5 m height. Since the flammability range for many types of dust varies from about 50 g/m³ to about 2000 g/m³, the risk of explosion is apparent.

During an ongoing smouldering fire in a silo, a high volume of flammable pyrolysis gases consisting of carbon monoxide and different types of unburned hydrocarbons is formed. At temperatures above about 700°C, a reaction with water may also occur, the so called water-gas reaction, $C + H_2O \rightarrow H_2 + CO$ which results in the production of hydrogen and further carbon monoxide. Water is present, both chemically bound in the stored organic materials (in a simplified form organic materials consists of hydrocarbons with the sum formula CH_2O), but water is also produced as a result of the combustion process or might be added through an extinguishing operation using water based firefighting agents. Altogether, a silo fire entails a significant risk that there is a flammable gas mixture in the silo headspace.

The illustration shows how a thin layer of deposited dust can create a flammable atmosphere in an entire enclosure. Even a partial dispersion might cause flammable conditions in part of the enclosure. In both cases, the result might be a severe dust explosion.



This may lead to a very powerful gas explosion if the gas is ignited, such as by unprotected electrical equipment, static electricity or drilling in the top of the silo as part of the extinguishing attempt. A small gas explosion may also serve as a "primary explosion" that causes a significantly more powerful secondary dust explosion.

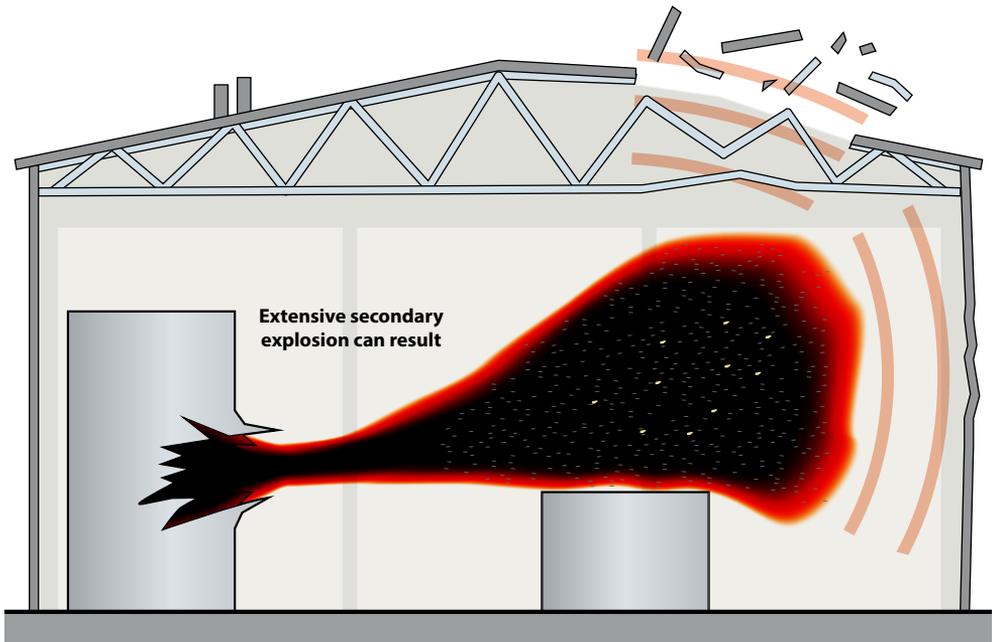
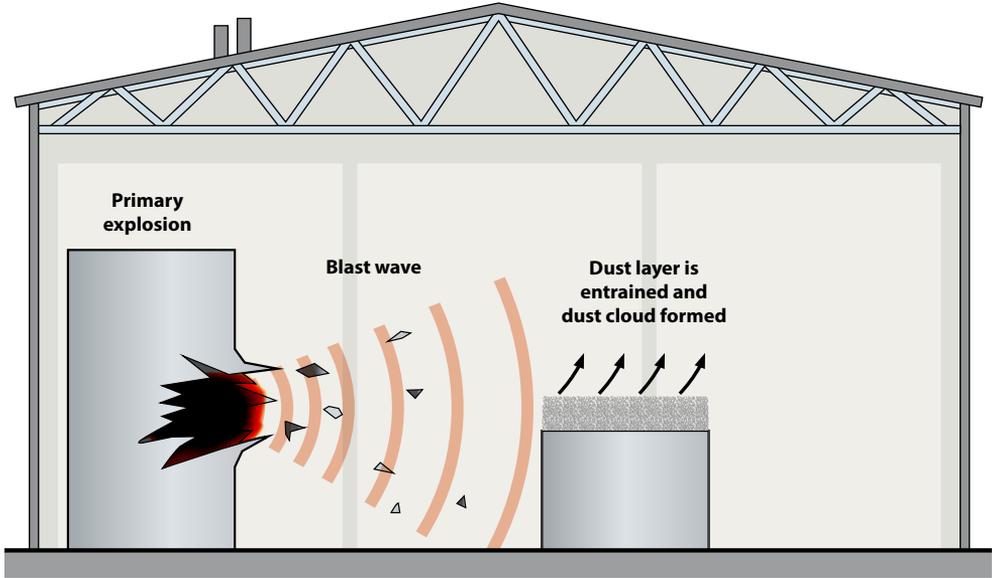
Past accidents show that gas and dust explosions may lead to very extensive damage. The entire silo roof could be thrown off and the risk of injury/death for persons on the roof is very high. There are significant risks in the form of falling construction parts etc. for persons and equipment on the ground as well. The risk of gas and dust explosions is the same for large and small silos.

Since the risk of gas and dust explosions is the most serious danger associated with silo fires, it is important to make an on-site risk assessment to establish which risk areas should be cordoned off, where to place extinguishing equipment etc. Before a firefighting response is launched, you should always assume that an explosion in the silo headspace could occur. The risk assessment must continuously be updated based on e.g. results from gas measurements in the silo headspace and visual observations. Conditions may quickly change even during the extinguishing- and discharge operations and cause a risk for explosion.

It is therefore extremely important to minimize the risk for dust and gas explosions and the suggested extinguishing technique of inerting with nitrogen gas has many advantages. Using gas provides a very controlled course of action as the gas is primarily injected at the bottom of the silo and the risk of dust formations is therefore minimal.

When inerting silos containing powdered material such as wood powder, it is important to start the gas injection with a low gas flow in order to avoid generation of a dust cloud that could result in a dust explosion. There is currently no knowledge about "safe" gas flows, but it does depend on;

- powder density,
- gas permeability,
- fill level of powder in the silo,
- how the gas is distributed inside the silo (number of gas inlets).



The illustration shows how a limited primary explosion inside a plant section could result in a very powerful explosion. The pressure wave from the primary explosion disperse dust deposits on adjacent surfaces and creates a significantly larger dust cloud that is ignited, which leads to a much more serious and dangerous secondary explosion.

When working on the top of the silo (sealing openings, mounting measurement instruments, arranging ventilation/pressure relief, preparing for the inertisation, etc.), it is very important to not generate any ignition source, flammable gas mixture or dust formation. In a developed pyrolysis fire (apparent smoke formation etc.), high concentrations are formed of CO and different types of unburned hydrocarbon which could be within the flammability range. If the oxygen concentration in the silo headspace is high enough (over 5–10%), the gases can ignite if there is a suitable ignition source. In these situations, it is important to realize that there is a risk of explosion. Manual application of carbon dioxide from gas bottles should be avoided since this may generate powerful sparks caused by static electricity.



The animation top left and the photos show the effects of a gas or dust explosion in various types of silo plants.

Attempting to use multi-gas instruments to measure the concentration of flammable gases, i.e. % LEL, (lower explosive limit) and assess the risk of explosion is not recommended. These instruments are calibrated for one specific gas, usually methane or propane, which means that correction factors must be applied in order to measure any other gas. These correction factors vary between 0.5–3.0 and since the composition of the gas mixture is unknown, the error could be significant and result in a completely incorrect decision.

If the risk of explosion is considered to be high, continued work should be minimized until the silo headspace has been inerted. See chapter 2.

Regardless of the decision to use an inerting procedure or some alternative extinguishing method (see chapter 4) it is very important to carry out this procedure in a safe way so that the operation itself does not create a gas or dust explosion inside the silo. This applies to all silos regardless of size.

Alternative extinguishing tactics

Alternative extinguishing tactics

For certain types of silos or specific fire scenarios, other extinguishing tactics than using inert gas may be appropriate. Examples of such situations and alternative suggestions can be found below. The primary extinguishing agents that could be considered are foam application or perhaps water. This may be acceptable if the silo is relatively small and/or contains material that is already moist or is not significantly affected by moisture (wood chips, sawdust and, in some cases, wood powder). It is however important to take into account that the silo construction is probably not dimensioned for the load that is applied if large volumes of water is used, which is why one should always restrict the amount of application. Some material, such as wood powder, may become sticky and heavy, which might cause overloads to extraction screws and conveyors, which could cause serious practical problems.

When dealing with dry, compressed material, such as wood pellets, *water-based extinguishing must be avoided* since the material will swell and may cause a risk of bridging or hanging. This may create very difficult situations with high risks. In unfavourable conditions it may also lead to extensive damage to the silo construction. See chapters 2 and 6.

Different bulk material have different characteristics in regards to moisture sensitivity, swelling tendency, risk of hanging, self-heating, gas permeability and additional information regarding this can be found in chapter 6.

CAFS

CAFS is the acronym for "Compressed Air Foam System", which uses compressed air to create a foam that's called CAF (or Compressed Air Foam). Water and foam are mixed together using foam proportioning equipment designed for significantly lower proportioning ratios than used in traditional equipment normally, 0.1–1%. Following the foam proportioning, pressurized air from a separate compressor is mixed into the premix solution generating homogeneous foam with small and stable bubbles. The generated (expanded) foam is then distributed through hoses to the fireman operating the hose and could be applied without any use of a foam nozzle. As the hose contains expanded foam it the weight is significantly less compared to using water and thereby much easier to manoeuvre.

A scenario where an alternative extinguishing tactic may be appropriate is if there is a developed surface fire in a silo. In this case, the primary aim is to quickly control the fire since it otherwise could lead to extensive fire damage to the silo construction and result in an apparent risk of fire escalation to surrounding plant sections. In this situation, using inert gas will probably result in too long of a response timewise and using foam/water may be a quicker alternative.

As with using inert gas, the primary measure is to try to minimize air supply to the fire. Hatches, discharge openings etc. at the bottom of the silo and in the silo walls where air could be entrained must be sealed. If the silo is completely closed, the fire will be controlled because of the oxygen deficit. In this case, high volumes of flammable gas inside the silo could form, which will render the subsequent fire-fighting operation very risky. When foam or water is to be applied to the silo, it is very important to avoid air entrainment into the silo.

In worst case, this could create a flammable gas mixture with a flashover or even a gas explosion as the result. *The risk for emergency response personnel must be carefully considered at this point.*



Wood pellets swell immensely when sprayed with water and may create a very high pressure against the silo wall and result in bridging or hanging. The result is a very hard cake with the same characteristics as a thick particle board that may need to be removed using machinery equipment.

Extinguishing operation with foam

Fire extinguishing foam has a number of significant advantages over water, primarily due to the fact that it fills the space in the silo headspace and forms a cover on the fuel that prevents further oxygen from penetrating down into the bulk material. The amount of water is also heavily reduced and the water draining from the foam consists of surface active substances, which means that the water can penetrate the material more effectively.

Medium expansion foam is preferable, but high expansion foam may be appropriate for filling larger volumes. High expansion foam, however, requires mounting a high expansion foam generator at the top of the silo or pushing the foam up to the top of the silo through a large diameter hose, which may create practical problems during an emergency. Using foam injectors may also create problems as the back pressure could become too high due to the static pressure achieved due to the height of the silo. If there is access to CAFS equipment (see fact box), it is strongly recommended to use this since it significantly reduces foam concentrate consumption and has a lower water drainage rate. From an efficiency and environmental standpoint, it is best to use Class A foam (see fact window), i.e. a foam that is specially designed for fires in fibrous material that uses a mixture of 0.1–1% of foam concentrate into the water. If Class A foam is not available, a detergent foam concentrate should be used. From an environmental perspective, the use of different types of film-forming foams (AFFF, AFFF-AR, FFFP, FFFP-AR) should be avoided since such foams contain surfactants based on different fluoro-chemicals.

Regardless of the foam equipment and type of foam used, you must always avoid ejecting air into the silo when applying foam. If possible, a hole that is appropriate for the foam branch should be made. This hole should preferably have been made as a preventive measure and should be sealed as appropriate. Ideally during emergencies, cutting extinguisher equipment should be used for making holes.

Once full foam production is achieved, the hole is opened and the foam branch is inserted. If the foam application is terminated, the foam branch should be taken out and the

Class A foam

Class A foam usually contains a mixture of surfactants that are both "oleophilic" (attracted to oil) and "hydrophilic" (attracted to water). This means that the generated A-foam has an affinity to hydrocarbons, which provides ideal conditions for the water to soak the carbon layer that usually form on typical A-fuels. In contrast to Class B foam concentrates (traditional firefighting foam), A-foam was developed to be used at much lower concentrations, normally between 0.1% and 1.0%. The environmental impact from A-foams is normally relatively low.



Application of medium expansion foam onto a peat silo fire, partly through applying the foam via an open hatch (poses a risk of gas explosion in the initial phase) and partly through a hole in the silo wall where a thermal imaging camera has been used to detect hotspots on the inside of the silo wall.

hole should be sealed again. The intensity of the fire and the amount of unburned gases are normally decreased when the fuel surface in the silo is covered with a layer of foam.

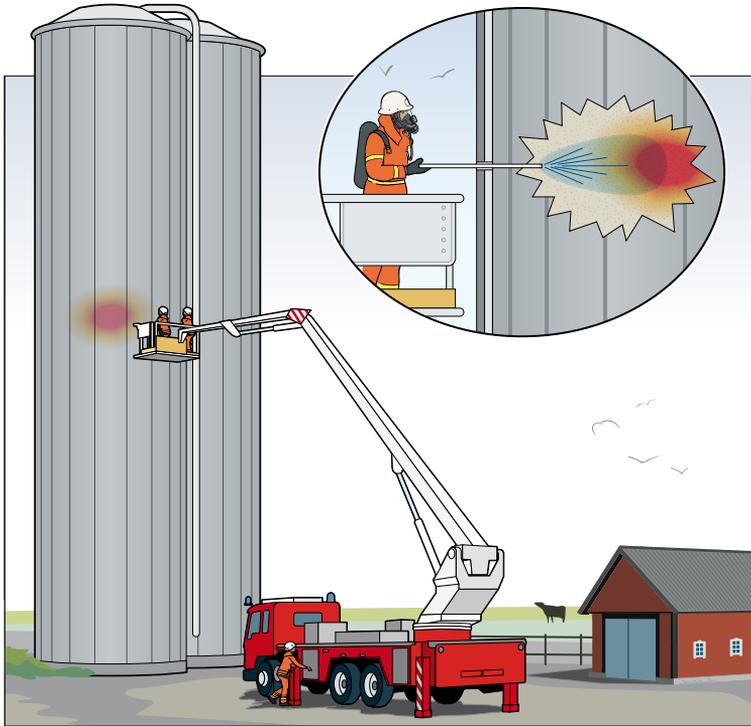
The extinguishing operation may take a long time due to inaccessible smouldering fires, air leakage in the silo wall etc., especially in larger fuel silos. This may cause environmental problems as using foam or water will generate contaminated runoff from fire, which needs to be addressed.

Injecting water

In smaller silos, such as saw dust and silage silos, an alternative may be to inject water directly into a suspected smouldering fire. If the seat of the fire can be detected by using a thermal imaging camera to measure the silo wall temperature, (see more in chapter 5), a targeted response may be launched with assistance of a cutting extinguisher equipment, or a longer lance being pressed into the material to inject water.

When putting out a silage silo fire, only clean water should be used since some of the content might be salvageable as animal feed.

In silage silos, smouldering fires are usually located 1–1.5 m from the top of the material and fighting the fire directly



Injecting water may be an alternative for small silos or fires close enough to the silo wall that they're detectable with a thermal imaging camera.

from the surface may be possible if the fire has not developed. When the smouldering fires have been extinguished, damaged material is discarded and the top layer is then treated with a 50% propionic acid solution that prevents continued fermentation. The surface is covered with a plastic cover and left untouched.

Note that using too much water may cause the water level inside the silo to rise quickly and expose the silo to a pressure level equivalent to that of a water tank with the same fill level. Silos are not designed for this purpose and the firefighting water must therefore be drained, preferably to a fertilizer tank since it may contain a very high BOD value (high oxygen consumption during biological decomposition).

A cutting extinguisher has an advantage as it is designed for penetration of various materials, e.g. a silo wall, and the high water pressure allows the water to "eat into" the bulk material. The water can be expected to flow in a few meters even if the nozzle is held against the silo wall. Prototypes for different extension nozzles that will allow penetrating deeper into the material is under development. The main problem is of course to localize the seat of the smouldering fire, but a thermal imaging camera may be of assistance if the fire is close enough to the silo wall. See more in chapter 5.

A cutting extinguisher may also be a good complement to foam application, both in the event of a smouldering fire and a developed surface fire. The penetrating hole in the silo wall is very small and by the water mist formation in combination with



Firefighting with a cutting extinguisher through the silo wall into the bulk material and from the top of the silo. (Note: Working on the top of a silo is always associated with very serious risks and should be considered very carefully).

a closed area, very rapid cooling of the pyrolysis/fire gases can be achieved, and the surface fires possibly be controlled.

As soon as the fire is considered to be under control, the material surface in the silo headspace should, if possible, be covered with foam.

Risks associated with opening a silo

Even when applying these alternative extinguishing methods, it is important to avoid opening the silo. This may lead to a rapid fire escalation that can quickly become uncontrollable and the risk of gas and dust explosions is apparent. Since these extinguishing methods usually require an active operation at the top of the silo, risks are further increased for firefighters.

Opening a silo to put the fire out through open hatches, often in combination with discharge of the contents is a poor strategy often doomed to failure.

The risk of personal injuries is apparent and the fire will probably end up causing a total loss of the silo and its contents.



At these operations the wrong tactics were used which resulted in dangerous operations and a total loss.

The environmental impact may also be great, partly due to the smoke emission and partly due to contaminated runoff water that is spread around the area.

Applying water to the outside of a silo usually has no effect and will probably only cause problems. The operation must be focused on getting the extinguishing agent inside the silo.

Trying to empty a silo by making an opening in the wall when the silo is designed to be discharged through the centre of the silo may be associated with a risk that the entire silo could collapse due to a strong uneven load on the silo walls. Therefore, before such a decision is made, consultation with the silo construction engineer is required in order to ensure that such actions are safe. Furthermore, you must be completely sure that the smouldering fire is put out so that an uncontrollable fire with gas and dust explosions does not occur.

Even if the primary plan is to use an alternative method to put out the fire, the need is apparent for preparing the silo with connections appropriate for the planned tactic. The optimum situation is achieved by installation of a foam or water sprink-

A fixed riser provides a simple and safe application of extinguishing media into the silo headspace.



ler system in the silo headspace, which the fire & rescue service can connect to from ground level, such a system could be designed to provide proper function with both water and foam, but also for injection of inert gas if needed.

Environmental aspects to consider

It is important to realize that a silo fire may last for a very long time and allowing the material to "burn out" is not realistic. This will lead to the spreading of large volumes of combustion gases that will most probably affect surrounding houses, industries etc. that in the worst case will cause them to shut down. As an example, a fire in Esbjerg, Denmark in 1998 that lasted for nearly 10 months before the silos could be emptied and the fire could be extinguished. The final result was total loss and demolition of the silo plant.

Due to the length of the operation, it could also lead to large volumes of runoff water that could be heavily contaminated. Such water must therefore be collected, analysed and possibly purified before it is released to a recipient or the municipal sewage system.



Possible silo fire scenarios

Possible silo fire scenarios

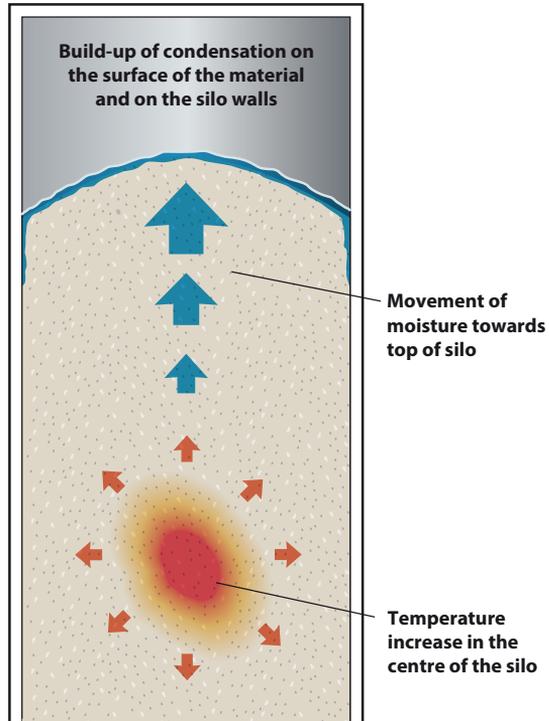
There are two main scenarios for a silo fire, self-heating resulting in spontaneous ignition or some "external" ignition source which could result in a number of different types of fires.

Spontaneous ignition

When storing biogenic material such as sawdust, wood pellets etc., self-heating might occur inside the material. This may be due to microbiological activity, chemical oxidation processes, moisture migration, moisture absorption or a combination of these. In moist material (> 15–20% water content), microbiological activity is often the main cause. Such activity causes the heating of e.g. a compost pile or a dunghill. This process usually occurs within a temperature range up to 45–75 °C since microbes die at higher temperatures. Microbial activity primarily generates carbon dioxide (CO₂) and may be detected by measuring the carbon dioxide concentration in the silo headspace. At higher temperatures, self-heating is derived from chemical oxidation processes. In dry material such as wood pellets, the cause is usually a chemical oxidation process since the pellets are more or less "sterilized" during the production process.

Practical experience shows that this oxidation process is especially likely in newly produced pellets, in part due to the oxidation of different resins contained in the wood material. In some cases, temperatures over 60 °C have been measured

Microbiological activity, chemical oxidation processes, moisture absorption lead to self-heating when storing porous material. The heating process takes place in the entire bulk material, but the temperature will usually be the highest in the centre of the silo where heat loss is lowest. If the temperature gets high enough, the heating process will be accelerated and lead to spontaneous ignition resulting in a pyrolysis fire.



on the surface of the pellet piles a few days after production. Finely grinding of the wood particles before they're made into pellets leads to a very large specific surface area that facilitates the oxidation processes and may begin already at normal room temperature. Since the wood pellets have low moisture content, normally around 6–8%, moisture absorption from surrounding air may generate heating. In practice, self-heating can be a result of both oxidation and, to a certain extent, moisture absorption. Chemical oxidation primarily generates carbon monoxide (CO).

If a spontaneous ignition occurs, it usually takes place deep inside the material. This is because the self-heating inside the material is balanced by heat losses to the surroundings through the surface of the stored material. The lowest heat loss is obtained in the centre of the stored material since surrounding material works as a very effective form of insulation due to its low heat conductivity. This means that heat loss decreases with storage volume and thereby increased

storage volumes results in a higher risk of spontaneous ignition. Unfortunately, a specific critical inside temperature of a bulk storage cannot be specified since it depends on the specific attributes of the stored material and the storage size. Research is ongoing in Sweden (at SLU, SP and others) and abroad to better understand the mechanisms of self-heating and how to calculate the risk of spontaneous ignition occurring in real storage. The only current options are to monitor the storage using temperature readings inside the bulk material and gas analyses in the storage area (see chapter 7). A temperature rise of 1–2 °C per hour can quickly cause a critical situation, especially if the bulk temperature is already elevated.

If the bulk material has a high permeability (high porosity), a marginal cooling may be achieved through free convection inside the material that removes some heat. The limited cooling capacity is due to the low specific heat of air that makes the energy contents of the flowing air very low in relation to the mass of the stored material. Instead of cooling the material and reducing the fire risk free convection can in some cases accelerate the temperature rise via the material. The cause of this is that the bulk material is oxygenated which leads to a faster oxidation process and, thereby, increased heat generation. For this reason, it is recommended to seal the silo construction as much as possible. Leaks and cracks should be sealed and openings should be kept shut when they are not being used, especially at the bottom of the silo and along the silo wall.

Since the self-heating that occurs in normal conditions generates a moisture transport up through the silo, this may cause an elevated relative humidity in the silo headspace. During certain weather conditions this may lead to condensation along the silo wall and on the inside of the silo roof, which is something that should be avoided. In normal conditions, there should therefore be some ventilation in the silo headspace, but the ventilation should be minimized if a fire is suspected.

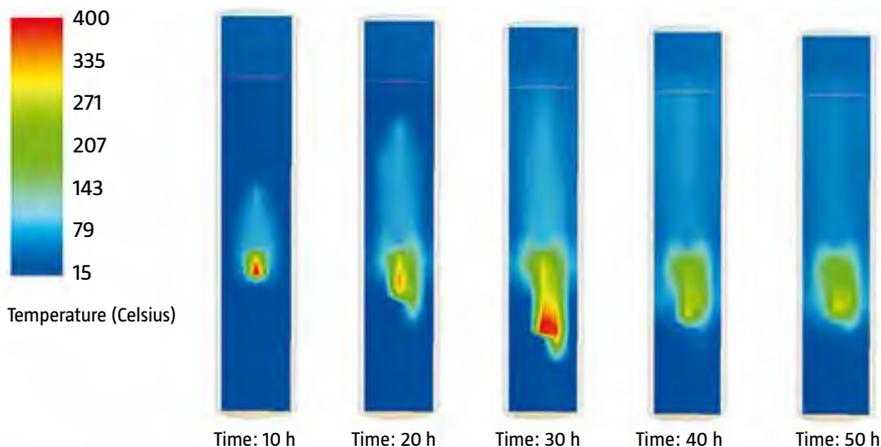
This means that the silo must be designed so that these ventilation openings can be closed easily.

If pyrolysis or a smouldering fire has occurred, an accurate sealed silo will result in a slower pyrolysis rate, and also to less gas leakage during the firefighting operation.

Fire development in a silo

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 when detected. As mentioned above, spontaneous ignition usually occurs deep inside the bulk material. The smouldering fire will consume oxygen in the air that's inside the stored material and the warm and moist combustion gases will slowly spread upwards in the silo. The pyrolysis zone will slowly move down through the material where there's still a supply of oxygen. In case there are openings in the silo, such as discharge openings, leaks and other openings, fresh air/oxygen can be entrained into the silo and thereby sustain the pyrolysis fire. Air can probably also be entrained into the material via the silo headspace 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. These tests simulated a spontaneous ignition inside the centre of a 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.



Visualization of the measured temperatures inside a mock-up silo, 1 m in diameter and 6 m in 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 reached the silo headspace after about 20 hours. Just after 30 hours, inert gas was injected at the bottom of the silo which rapidly reduced the intensity of the fire.

The tests showed that pyrolysis zone spreads very slowly downwards in the silo, while the warm and moist combustion gases slowly spread upwards through free convection. In these tests, it took about 20 hours for the "wave" of combustion gases to reach the surface in the silo headspace. This corresponded to a heat, moisture and combustion gas spreading rate of about 0.1 m/h (about 2.5 m/day) upwards in the silo and a downwards pyrolysis spreading rate of about 0.04 m/h (about 1 m/day). These spreading rates probably depend on ventilation and leakage (oxygen supply), but do show a very slow fire development. This also confirms the difficulty to obtain an early detection of a fire inside the top of a silo. On the other hand, once the fire gases reach the silo headspace, the concentrations of CO and unburned hydrocarbons increases rapidly to very high concentrations. Meanwhile, a large portion of the oxygen is consumed which results in a very low oxygen concentration. The tests indicated also that when the warm gases "breakthrough" the surface at the silo headspace, a thermal updraft is achieved in the silo which results in increased oxygen supply and an increases pyrolysis intensity.

In a real situation, this is probably the phase during which smoke becomes visible at the silo top. The production of CO and unburned hydrocarbons increases even more and the silo headspace will fill up with smoke gases that most likely are flammable and are thereby causing an apparent risk for an explosion.

The test arrangement on the next page also provided a favourable opportunity to examine the silo after completion of each test. The tests showed it is very difficult to detect a fire by measuring 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 is not providing 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.

Assessments in the event of a suspected fire

As discussed, detecting a silo fire can be very difficult, especially in early stages. Experience with real fires, however, indicates that a noticeable odour, possible abnormal temperature readings inside the material, unusual amount of condensation in the silo

IR camera

A thermal imaging camera measures the heat radiation (infrared) of an object. A thermal imaging camera can be used to very accurately measure the surface temperature of a silo and easily show single degree differences. There is a belief that a thermal imaging camera can be used to measure temperature inside the construction/material, but that is impossible. A thermal imaging camera can only be used to measure the outer surface temperature. The heat from a fire deep inside the material in a silo must first spread through the material and then affect the inside of the silo walls. In a concrete silo, the heat must then be conducted through the concrete and heat the outside of the silo wall. In other words, the probability of obtaining usable information with a thermal imaging camera in the event of a deep smouldering fire is limited and the possibilities are inversely affected by the silo diameter. If a fire occurs close nearby the silo wall, e.g. due to friction heat in an extraction equipment or similar, the thermal imaging camera may be of use to facilitate a targeted firefighting operation. See more in chapter 4.



The photos show the pellets at various levels inside the mock-up silo after completion of a test. The photo on the left shows the pellets above the ignition source where the pellet stack was formed due to the upward moisture transfer that “glued” the pellets together in the centre of the silo. The upper right photo shows how the pellets around the ignition source expanded and thus created an arch. The lower right photo shows the pyrolysis fire’s spread under the ignition source and how it is clearly delineated.

headspace etc. has normally been observed. To minimize the risk of a more developed fire, it is important to be observant and take action as early as possible and take possible warning signals seriously.

In the early stages, however, indications may be unclear and it is therefore hard to establish whether a rise in the temperature is due to the normal self-heating process or if it is an early indication of smouldering fire.

In some cases, here may also be indications of fire in the form of smell without a significant rise in temperature has been observed. The reason may be that the temperature cables are pushed towards the silo wall during the normal filling procedure of the silo, which means that the temperature is not measured deep inside the bulk material. In certain situations it could rather be the silo wall temperature being measured. See more in chapter 7.

It is therefore always important to try to quickly gather more information about the situation in order to prevent a fire from developing and if it does so, to launch the firefighting operations as quickly as possible. The following methods may be appropriate depending on the size and design of the silo.

- Seal the silo as much as possible to restrict the oxygen supply, which in turn may contribute to preventing oxidation and a smouldering fire inside the silo from being maintained.
- Measure the gas concentration of CO and O₂, and if possible also the unburned hydrocarbons in the silo headspace. In this situation, the measurement instrument used for CO must be able to measure concentrations in percentage range, preferably up to at least 10%. Information regarding appropriate instruments and competent measuring personnel can in Sweden be obtained from RIB Resurs.
- One appropriate measure may be to “ventilate” the silo with inert gas in combination with analysing gases in the silo headspace. In the event of a deep seated smouldering fire, it may take hours (or days) before combustion gases reach the silo headspace. If inert gas is injected through the bottom of the silo, these combustion gases will be pushed upwards to the surface, which results in significantly quicker ability to measure gas concentrations in the silo headspace and to assess whether or not a fire is occurring. For small silos, bottle packages of nitrogen gas can be used. For larger silos, a tank and evaporator equipment (the same equipment that is used during an inerting operation) is required. A limited gas flow could also be obtained directly from a tank vehicle. If the silo has been prepared with sampling hoses that are suspended down into the bulk material, it allows gas concentrations of CO, O₂ and other gases to be measured inside the bulk material, without “nitrogen ventilation.” See Chapter 7.
- A technique that is used during storage of grain, feed etc. is to transfer the content to another silo cell within the silo plant if a rise in temperature is detected. This, of course, requires a larger silo plant with one or more empty silo cells. The advantage is that the heated parts

of the material will be mixed with cooler material, which reduces the temperature rise. *This technique may however cause problems in some situations and should be carefully considered since the cooling of material is usually very limited and the transfer will oxygenate the bulk material, which may accelerate the oxidation process.* Some material, i.e. pellets, are damaged when handled and will generate an increased amount of fines that should preferably be removed by sieving. Otherwise, the increased amount of fines may lead to increased oxidation, as well as decreasing the gas permeability of the bulk material. If signs of a smouldering fire is noticed when transferring the material (discoloured or very hot material), transferring should be stopped immediately and the silo inerted as there is a risk for spread of the fire and dust explosions.

Depending on the gas concentrations measured in the silo headspace (or inside the bulk material), an initial assessment of the situation can be made and the table shows a number of typical guideline values that together may indicate if it's "only" a matter of oxidation or if there is an ongoing smouldering fire inside the bulk material.

	CO (%)	O ₂ (%)	CO ₂ (%)	THC*(ppm)
Oxidation	Ca 0,5-1	0-21	0-10	100-2 500
Fire	2->5	0-10	10->30	> 15 000

CO concentrations of about 0.5–1% in the silo headspace, is

*THC (Total Unburned Hydrocarbons)

The table shows the order of magnitude of gas concentrations, which in combination with each other can be used as benchmarks to determine if there is a fire or not in a silo. However, it is difficult to give specific concentration limits for a "normal" oxidation process and fire, but one may assess the magnitude. As an example, a CO content of up to 1% may be caused by an oxidation while a CO content of several percent is probably the result of an ongoing smoldering fire. If in doubt, it is important to take measurements continuously to follow the trend, possibly in combination with "venting" the silo with inert gas.

not for certain indicating an ongoing fire. Such concentrations may also simply be the result of a significant oxidation. At this point, the process should be followed very carefully through continuous measurements to monitor the trend and possibly decide to “ventilate” the silo i.e. inject inert gas in order to achieve a more accurate assessment basis.

If the gas measurements in the silo headspace show severely high concentrations of carbon monoxide (2–5% or more), as well as increased temperatures inside the material, this is a strong indication of a smouldering fire. If a strong odour, smoke and heavy condensation is also present, an ongoing fire is certain.

External ignition source

An external ignition source might consist of smouldering material fed in when loading material into the silo. The ember may derive from a smouldering fire that has occurred in the material during previous storage, such as in a larger storage of biofuels/recycled fuels, but it may also depend on spark formations or heat generation in a part of the conveyor system, e.g. by friction against material deposits, a broken roll bearing or sparks from metal parts in crushers/mills. Such smouldering material might then cause two separate fire scenarios inside the silo.

One scenario can be that the smouldering ember is quickly covered by new feedstock and then causes a deep smouldering fire just as during a spontaneous ignition.

Another scenario is that the smouldering material remains on the surface and relatively quickly develops to an open surface fire inside the silo. The extent and intensity of such a fire will be directly dependent upon the type of stored material and available oxygen. In a closed silo, available oxygen might quickly be consumed, but larger openings and/or a ventilation system could lead to an extensive smouldering fire.

There are of course several other possible causes of fires.

An example is heat generation in the extraction screw construction at the bottom of the silo which could result in a deep smouldering fire, but also quickly create fire problems in the transport system after the silo.

When dealing with ignition sources from the conveyor system, there are effective protective systems with heat detectors in combination with an extinguishing system that can prevent this type of fire spread. See chapter 7. In the case such a system is activated, you must carefully make sure that no embers did pass the extinguishing system and were brought further along the conveyor system, which could lead to fire escalation and possible dust explosions in the system.

General information about silo types and silo storage

General information about silo types and silo storage

There are many different types and sizes of silos and the properties of the stored material can vary significantly. This in itself may affect the risk of a fire occurring and the choice of extinguishing tactic. It is therefore important to establish the type of silo and stored material as early as possible. Short descriptions of a number of silo types can be found below.

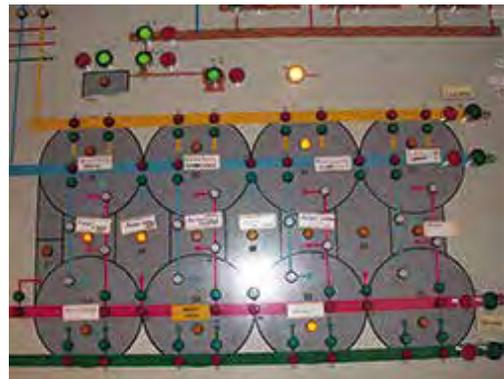
Silo types

Tower silo

A tower silo refers to a high concrete silo with a relatively small diameter. The silo plant is often very complex and may consist of several individual silos (silo cells) that are connected to a unit and is normally used to store grains. A silo plant is often an integrated section in a larger plant that contains an extensive transport system in the form of conveyors and elevators, crushers, mills, screens, dryers etc. in combination with a generally dusty environment. The height of the silo cells vary, but are normally within the range of 25–50 m and the cell diameters are between 4–12 m. Due to the circular shape of the cells, empty spaces between these cells are also used for storage and are often referred to as "interspace cells". In some larger facilities, such as factories that produce animal

feed, the tower silo section might contain 10–30 silo cells that vary in volume.

Additionally, these facilities often include several smaller silos for handling feed additives and storage of the final feed product. A tower silo plant usually has a superstructure with conveyor systems at the top of the silo cells. The material is transported to the silo top using multiple elevator systems. The silos are normally used for dry, flowing materials and have a conical/angled bottom that guides the material through a valve or a rotary valve feeder onto a conveyor system. From an operational perspective, this means that accessibility for the fire & rescue service is very limited. Due to rationalizations made in later years, the use of silo facilities for grain storage has greatly decreased. This has resulted in the use of a larger number of silo plants for storing wood pellets instead. In some cases, feed factories have been converted to pellet production plants as well.



Photos and plan layout of a tower silo plant that often contains a large number of silo cells, of which some "interspace cells" are located between the round silo towers.

Freestanding steel or concrete silos

These silos often have a relatively large diameter in the range of 15–30 m and the silo diameters are expected to increase in the future. The height of the silo is about the same as the diameter (15–30 m). The silo can be made completely of steel, in some cases the walls are made of concrete while the conical roof is made of steel. These types of silos are often found at power plants where they are used as a step in fuel management between different flat storage for different types of fuel and the boiler. The fuel may consist of pellets, chips, peat, coal, recycled fuel or different mixtures of these fuels. The silos are also used in the pellet industry for storage of produced pellets. Depending on the type of product, the silos can either be discharged by allowing the product to flow freely through a central opening in the silo floor (i.e. pellets), but for other materials a reclaim equipment may be required (i.e. in the form of a rotating screw reclaimer in the bottom of the silo).



Examples of free standing concrete and steel silos for biofuel storage/handling. Depending on the type of material used, a rotating screw reclaimer might be used at the bottom of the silo.

For maintenance/cleaning, there is sometimes a large door construction on the side of the silo that provides access for front loaders, etc.

Smaller bulk silos

Smaller bulk silos are regularly used for material management/storage/truck loading. These are often freestanding with



Different types of smaller bulk silos.

a diameter in the range of 3–10 m, a height of 5–15 m, and are normally constructed of steel. The stored bulk material varies depending on the area of application and may include saw dust, chips, pellets, wood powder, different raw material for industry processes (i.e. plastic granules, animal feed, grains) etc. The discharge device depends on the stored material and may either be based on a free-flowing concept or consist of some form of screw for bottom extraction that's specially adapted for the bulk material in question.

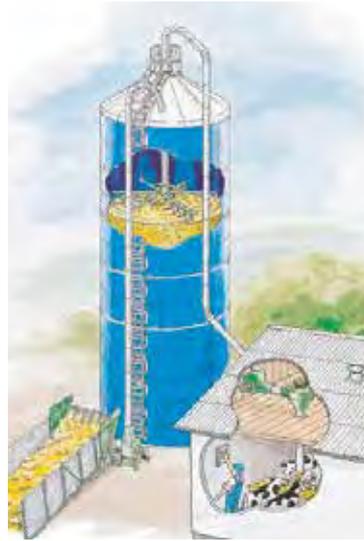
Oxygen-limited silos

Oxygen-limited silos are usually freestanding steel silos that are regularly used for storing grain or other organic material that may oxidize or otherwise react in contact with air and decrease quality. The silo is basically completely sealed and equipped with sealed valves that are closed after filling to prevent air exchange during storage. To handle the effect of different temperatures and gas generation inside the silo, it is equipped with a pressure/vacuum vent.

The gases formed inside the silo depend on the stored material and can lead to elevated levels of, e.g. carbon monoxide,



Oxygen-limited silos.



Silage silo with accompanying filling and reclaiming system.

carbon dioxide and methane, while at the same time low oxygen content prevails.

Silage silos

Silage silos are usually constructed of steel and have a diameter in the range of 5–8 m and a height up to about 25 m. In contrast to other types of silos, both filling and extraction is made from the top. Filling of silage usually occurs with the use of a fan system that transports the feed to the silo top and then allows it to drop into the silo. The silo contains a so called “fill-reclaimer” that distributes and packs the feed during filling to create a compact storage with low oxygen concentration. When reclaiming the material, the “fill-reclaimer” works in reverse order to reclaim the silage from the surface and transport the feed towards the silo centre to a telescopic suction pipe that’s connected to a suction fan. This means that the material that’s filled in first is discharged last.

Silo content and fill level

Stored material

Below are some examples of different combustible products that could be stored in silos in different industry sectors:

- Wood chips, dried saw dust, wood shavings
- Wood pellets, wood powder, dust from wood industry
- Grain (wheat, barley, oats, rye)

- Rapeseed
- Fodder (soybean meal, rapeseed meal, beet chips, corn, dried stillage)
- Wheat flour, oat flour, bran etc.
- Sugar
- Plastic granulate, dry binders
- Coal, coke,
- Fragmented recycled waste fractions

The physical properties of the stored material influence both the risk of a fire occurring (i.e. through spontaneous ignition) and the extinguishing tactics that may be appropriate. Porous organic materials (i.e. biofuels) are prone to self-heating due to biological activity, chemical oxidation and physical processes such as moisture migration within the material. The question of how this heat production might create problems is a matter of the balance between the rate of heat production in relation to the rate of heat loss from the stored material. The consequence of this is that the risk for severely increased temperatures and a possible risk of spontaneous ignition increase with increased storage volumes.

From an extinguishing perspective, the porosity and permeability of the material is of interest since these directly affect the ability of the extinguishing agent to spread within the material. A material with high porosity and permeability will be relatively easy to inject with inert gas, while achieving even distribution of inert gas will be more difficult and require higher pressure with a material having low bulk porosity/permeability. With storage of low density powder material (i.e. wood powder and flour), it is important not to stir up the material during gas injection since this may lead to a dust explosion. The risk of such dust generation is most significant at low filling levels.

The effects of moisture or water application on the material are also very important. A lot of materials stick together and create hard, solid "cakes". Pellet material (wood pellets, animal feed) expand significantly and fall apart during water application. This may result in less porosity and gas permeability, while sticking and swelling may create serious problems since the material could stick to the silo walls (create hanging or bridging) and even swell so much that the silo walls break.



A silo might tip over if there is an uneven load distribution inside the silo. If pellet material is exposed to water application, it can swell so much that the silo is forced apart.

Product	Density (ton/m ³)	Porosity	Particle diameter (mm)	Water content (%)	Swelling due to water application	Comments
Grain	0,55–0,7	0,4–0,6	4	13	Approx. 15%	Oat have a lower density and higher porosity compared to wheat
Wood pellets	0,65	0,4	8–10	10	Significant swelling*	High fine content results in higher density and lower porosity
Fodder pellets	0,6–0,75	0,4	3–6	13	Significant swelling*	Higher density at high mineral content
Soy bean meal	0,6–0,65	0,4	2–4	13		Also exists as pellets
Rapeseed meal	0,6–0,65	0,4	1–2	13		
Beet chips	0,65	0,4	6–8	10–13	Significant swelling*	

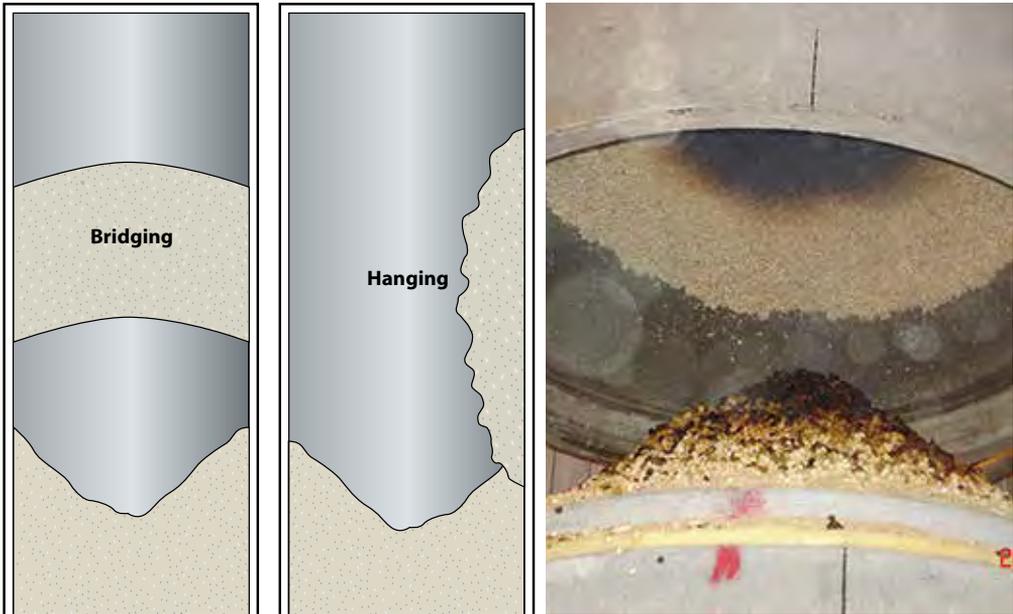
Properties of some common combustible products that can be stored in silos.

**Swelling becomes extreme when the material that is compressed during the pelleting process resumes its original volume.*

There are even examples of silos that have tipped over due to incorrect filling but also due to the increased weight of water. For this reason, water must be avoided in these cases since it not only creates serious problems for the extinguishing operation itself, but also high risks during subsequent discharge operation since the material somehow has to be removed from the silo wall.

Spontaneous ignition may also occur inside hangings and bridgings due to e.g. condensation or moisture migration which may cause very complicated fires and firefighting

operations. If a smouldering fire occurs inside such formations, the fire is very hard to access. The inert gas will also have great difficulties to penetrate in to the seat of the fire. When a bridging is produced, drilling through the stuck bulk material could be one possibility to try to access the fire. If the silo is not kept inertised, it could lead to oxygenation resulting in very fast fire development. When trying to remove bridgings or hangings, it may cause large and instantaneous collapses of material inside the silo. The smouldering fires may then be exposed, which in turn can cause dust and gas explosions if the silo is not kept inerted. If a bridging comes loose, it could generate a piston effect that generates a strong negative pressure in the silo headspace due to limited supply air area. In worst case this could lead to an implosion of the top of the silo.



Bridging and hanging along a silo wall, respectively.

Fill level

The silo's fill level is interesting from a number of perspectives and a low or high fill level could be either negative or positive.

The greatest risk of spontaneous ignition in the material normally occurs when the silo is completely full since this reduces heat loss inside the bulk. When it's appropriate to start discharging the silo following completion of the initial extinguishing phase, the discharge operation will probably take much longer than normal and require more resources which, especially in the question of large silos, may result in a very long rescue operation time.

A low fill level may cause problems when inerting, since this may complicate the possibilities to reach an even distribution of gas inside the bulk material, especially if the diameter is large in relation to the fill level. A low fill level also means a higher net volume inside the silo, which means that it will take longer for the entire silo volume to be inerted.

If the data about material level inside the silo is uncertain, the distance from one or several positions on the top of the silo could be measured using a plumb line. This data may also be useful when the discharge work is launched, especially in tower silos, where the risk for hanging and bridging is most likely. Hangings along the silo wall may be difficult to identify exclusively by use of a plumb line and will probably require a visual inspection. In a fire situation, this may be a hazardous task and should not be attempted before the fire is completely under control and not before the silo headspace has been inerted.

Preventive and preparatory measures

Chapter 7

Preventive and preparatory measures

It is important to invest in preventive and preparatory measures that generally lower the risk of fires and, in the event of a fire occurring, minimize risks and consequences for personnel and the plant itself. The requirement of carrying out such tasks is in Sweden stipulated in the Swedish Work Environment Authority's regulations AFS2003:3, titled "Work in environments with high risk of explosion", and in the Civil Protection Act (LSO).

The Civil Protection Act (SFS 2003:778) Chapter 2, §2 states *"Owners or users of buildings or other facilities must appropriately maintain fire extinguishing equipment and lifesaving equipment for fires or other accidents and otherwise carry out the measures required to prevent fire and prevent or limit injuries and damage caused by fire."*

Below are some examples of measures that may be appropriate. Priority for these must be based on judgements at each respective plant since a number of factors affect the risk situation, i.e. the size and complexity of the plant, type of material being handled and stored, handling system (e.g. conveyors, processing equipment etc.) before and after the silo, maximum storage period in the silo, and the effects of unplanned downtime.

Risk assessment in accordance with AFS 2003:3

The Swedish Work Environment Authority's regulations, AFS 2003:3, is relevant to all facilities "...in which an employee could be exposed to danger caused by an explosive atmosphere in buildings, enclosures, equipment or other technical devices and in work places in general where an explosive atmosphere may occur."

This means that the regulations basically cover all silo facilities.

In §7 of the regulations, the requirement is established that a documented risk assessment must be established by a person with appropriate education and expertise. The risk assessment must include an inventory that includes explosion characteristics of handled material, existing ignition sources, probability that an explosive environment will arise, the extent of such area and the ignition probability and consequences thereof.

The risk assessment should also include, "*appropriate extinguishing agent and extinguishing methods in the event of a fire in order to prevent an explosion.*"

In the comments to §7, silos are explicitly mentioned according to the following: "*In the event of smouldering fires in silos or other equipment, it is important to have a plan established for extinguishing the fire. Otherwise, there is a high risk that equipment or buildings will burst when large amount of water is applied or that an explosion occurs when the smouldering fire is exposed.*"

In practice, this means that it is very important to prepare for an extinguishing operation so that the fire & rescue service are not facing an unreasonable task. It is also very important to involve the fire & rescue service in establishing such an operational plan for different fire scenarios. This will facilitate invaluable knowledge sharing regarding the construction and processes of the plant, and an understanding of emergency work and, above all, the limitations thereof.

In older silo facilities used to store material other than those originally planned (i.e. storing wood pellets in a grain silo), it is very important to update the risk analysis and review applicable routines. Handling and storage of different type of bulk material may bring many new conditions (i.e. in regards to storage time, fill time, material characteristics in regards to spontaneous ignitions etc.).

Work environment aspects

From a work environment perspective, there are many risks other than the risk of explosion and fire. When handling and storing many different types of material, there is a risk of biological and chemical decomposition processes. This may result in the production of carbon dioxide and carbon monoxide etc., as well as reduce the oxygen concentration in the air, for which reason the following measures should be considered.

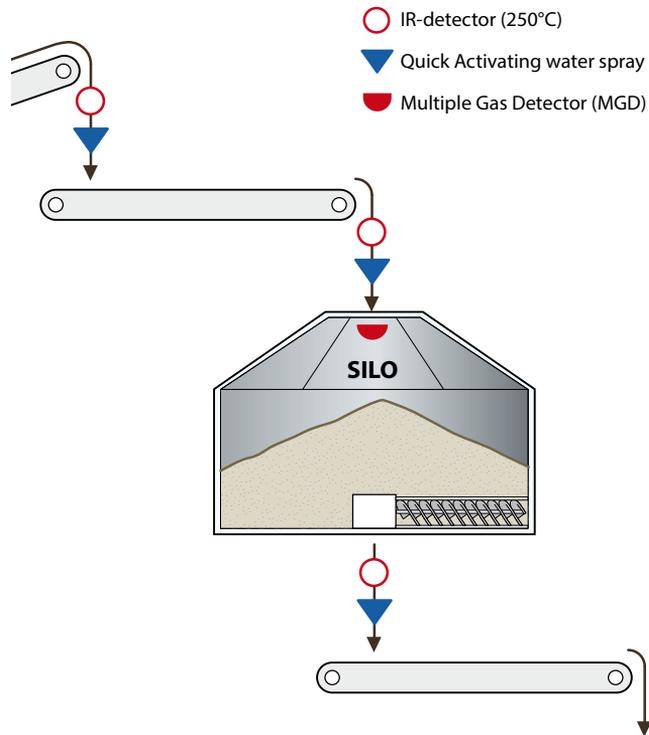
- Carbon monoxide and oxygen detectors should be installed in areas to which personnel have access and where accumulation of dangerous gases may be expected to occur in the event of emerging oxidation/spontaneous heating of the material in the silo (i.e. passageways, superstructure on top of silo etc.). To be considered safe to access, the measured gas concentrations in such areas shall not exceed 100 ppm of CO and the concentration of O₂ shall be at least 20.9%.
- If these risks could occur in several places throughout the plant, which may be difficult to define with certainty; the plant personnel should also have access to mobile measurement equipment. Such equipment should be capable of measuring CO and O₂. If the primary question is a matter of risk of biological decomposition processes (such as storage of wood chips or timber) in loading rooms on ships etc., high concentrations of carbon dioxide (CO₂) may be formed, but measurement of CO and O₂, and applying the above maximum and minimum values still provide required information.

Fire detection systems and automatic extinguishing systems

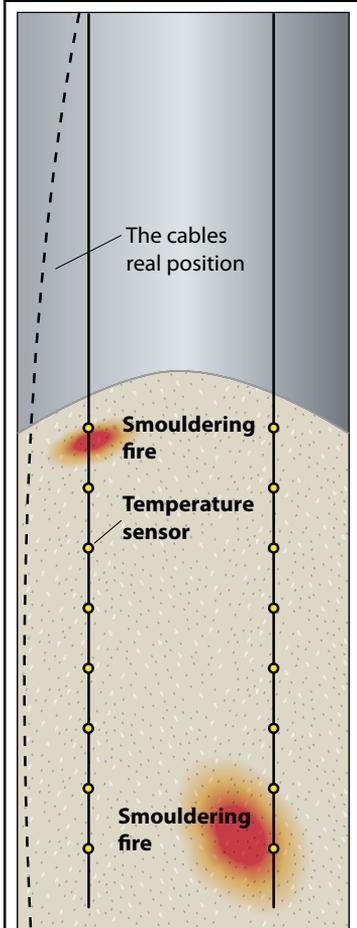
Early detection is always the most efficient way to minimize the consequences of a fire. The following measures may be relevant.

- Spark/heat detectors connected to a quick activating extinguishing system installed in transport systems (belt conveyors, elevators, dust extraction systems, crushers/mills etc.) to reduce the risk of ignition in silos (or flat storage) through external ignition sources, such as sparks, friction heat etc.

- Temperature sensor cables vertically suspended from the silo roof allowing temperature monitoring inside the bulk material. The measurement range should be at least +100 °C and the number of cables depends on the size of the silo. Recorded temperatures should be logged so that temperature history can be monitored over a long period of time. It is important to consider that the cables will be pushed towards the silo wall during filling and thereby do not hang vertically as expected. In certain cases, it might even measure the temperature of the silo wall rather than the bulk material. The reason for this is that the cables normally cannot be anchored to the bottom of the silo.
- A CO gas detector (or preferably an “electronic nose detector”) installed in an appropriate place at the silo headspace to assure that fires are detected as early as possible. If the detection system is intended to monitor a larger area (superstructure etc.), or access to the silo is restricted, aspirating gas detection systems are preferred.



Spark/heat detection systems connected to an extinguishing system in a conveyor system before and after a silo to prevent the spreading of hot particles/smouldering material. To detect spontaneous combustion in a silo a gas detection system for CO, or some type of “electronic nose” (MGD) are most appropriate.

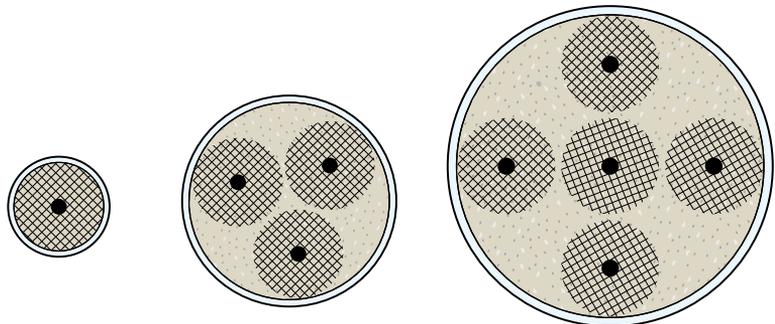


Cables with temperature sensors every 2–3 metres.



Example of cables with temperature sensors vertically suspended from the silo roof. The number of required cables depends on the silo diameter, in order to achieve a reasonable monitoring capability. Temperature sensors are often connected to a central control system.

Principle placement of one or more sensor cables depending on silo diameter; hatch-marking shows anticipated area of coverage.



Aspirating systems extract air from different places in the plant through a system of sampling hoses that are all connected to a centrally located gas detector. If the alarm is triggered, you must actively pinpoint from which sampling location the gases derive.

An effective detection system would be an aspirating system with one or multiple vertically suspended sampling hoses embedded in the bulk material (i.e. together with one or several of the temperature sensor cables) connected to gas analysis instruments that monitor the concentration of CO and O₂ etc. inside the bulk material. In this case, the conditions inside the bulk could be obtained without “ventilating” the silo with nitrogen. The larger the silo is, the more valuable this possibility would be. At this time, there is probably no such a system commercially available.

Preparations for fire extinguishing and discharge of silos

In accordance with Chapter 2, the main principle of an extinguishing operation in a silo is to inject inert gas to the bottom of the silo. In accordance with AFS 2003:3, it is important to establish an extinguishing operational plan. If no preparations are made, the fire & rescue service will be faced with a number of practical problems related to penetration of the silo wall, manufacturing lances etc. In the event of larger silos, or silos with poor access, this could in worst case make the injection of inert gas an impossible task, which result in a very lengthy process and, in worst case, result in total loss of the silo and its content. The following measures may simplify the operation significantly and should therefore be considered with regards to applicable conditions for the silo in question.

- Prepare the silo with a fixed gas distribution system to enable a quick firefighting response and an optimal gas distribution inside the silo. The system must be adapted to the diameter and construction of the silo.
- The silo construction should be reviewed and sealed as much as possible. Additionally, the silo should be prepared so that all necessary openings can be quickly and easily

sealed to reduce air entrainment and thereby reduce the intensity of an ongoing fire. This will also result in less leakage of inert gas when the inerting operation commences. Preparations should also facilitate sealing connections to conveyor systems, dust extraction systems, i.e. through the installation of valves.

- Besides reducing air entrainment, these measures contribute to minimizing the risk of fire escalation to adjacent silo cells (in tower silo plants) and other equipment/areas in the silo plant.
- If the silo is equipped with explosion relief hatches on the top of the silo and these are easily accessible, some of them may be equipped with hinges (or the equivalent) so that they can be used for relief pressure during gas injection while, at the same time, prevent air from being entrained into the silo. For tower silo facilities, a specially designed hatch equipped with a gas outlet to the open air should be created.
- A riser should be installed to the silo top, which may be used for distribution of inert gas to the silo headspace. The riser in a tower silo plant with multiple silo cells may end in an appropriate place on the top of the silo (with easy and secure access) and then connected to the silo with a hose. The riser may also be used by the fire & rescue service for water/foam supply during, for example, manual extinguishing at the top of the silo.
- Even if an extinguishing operation with inert gas is completed and the fire is suppressed, smouldering embers might still occur that could flare up again when the material is oxygenated during the discharge. Therefore, some type of emergency discharge system, should be arranged i.e. a separate conveyor or a reversible conveyor at the silo outlet, which will allow the material to be discharged to a safe place outside the silo for subsequent transport. In this way, the use of the ordinary transport system of the plant, and thereby the risk of fire spread inside the plant, is minimized.
- Regardless of the type of discharge system, the discharged material must continuously be monitored so that smoul-

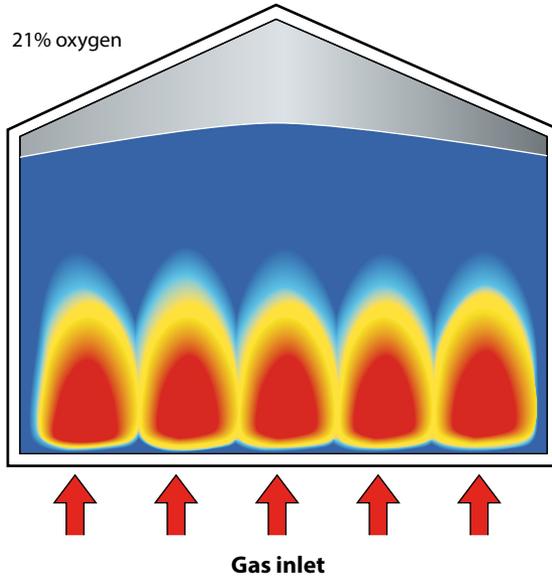
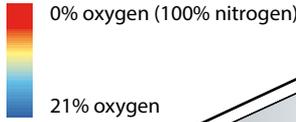
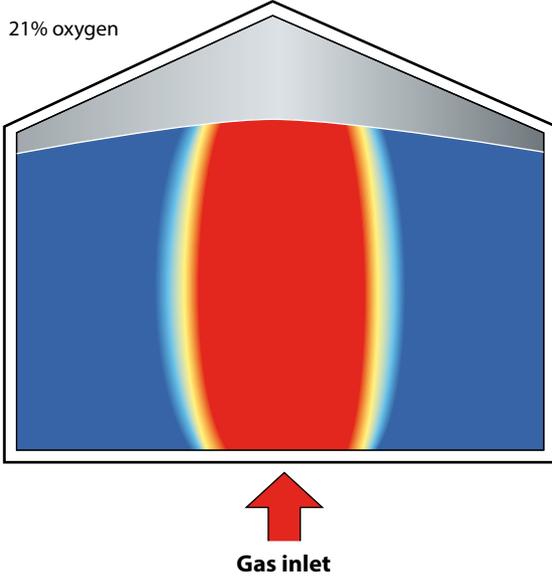
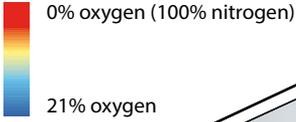
dering or "suspect" material can be applied with water. A firefighting water pipe (dry pipe system) should therefore be installed in the areas where discharged material will be handled/transported (at silo discharge outlet, along conveyor systems, etc.). This minimizes use of hoses and facilitates water supply, which helps the fire & rescue service.

- If the ordinary transport systems (conveyors, elevators etc.) must be used for emergency discharge, it is important that this system is protected so that its function is guaranteed and fire spreading in the plant is avoided. From a functional perspective, chain conveyors and screw conveyors are more appropriate since they do not utilize rubber belts or rubber straps which easily get damaged. To minimize the risk of fire spread, the transport system should be equipped with spark/heat detectors that are connected to a water sprinkler system. A fixed sprinkler system for the conveyor system should also be considered as a catastrophe protection.

Fixed gas distribution system

All silos should preferably be prepared for an extinguishing operation by having a gas distribution pipe system already installed at the silo bottom. There are two primary purposes of such a system, one being to facilitate a quick response for the fire & rescue service and the other being to assure that gas is evenly distributed so the entire silo is inerted. The importance of efficient gas distribution increases with the size of the silo, as the firefighting operation otherwise might fail as the gas might not reach the seat of the smouldering fire. A fixed gas distribution system enables an efficient operation, that could save large values, but the most important advantage is the possibility for an fast response keeping a high level of safety for all personnel.

In order to illustrate the need of an efficient gas distribution across the silo, a comparison could be made to water sprinklers. One sprinkler may be sufficient to effectively cover a small area, but a larger area will not be possible to protect with one sprinkler, regardless if the flow rate is increased. The



Gas distribution in a large diameter silo. Using only one inlet in the centre of a large silo the gas will only cover part of the silo even if injected for a very long time. Using several gas inlets will provide a quick and even distribution throughout the silo cross section area.

water coverage will still be limited and large areas will not be protected. The same restrictions apply to gas injection, and it is therefore important to assure a gas distribution across the entire silo cross section area by having several gas inlets.

If a gas distribution system is installed in conjunction with new construction, the cost will be very marginal. For existing silos, there are usually several options to complement the silo when it is empty.

The following chapter provides a number of examples of gas distribution arrangements for different silo sizes and types. It is currently important to note that the *recommendations that are currently available are based on experience, tests and simulations with wood pellets as bulk material*. Other types of material may have different characteristics (bulk porosity, permeability etc.) that could provide increase difficulties to achieve an even distribution of gas, and may thereby require additional gas inlets. *It should also be noted that experience from tests and real fires is limited to silos with relatively small diameters.*

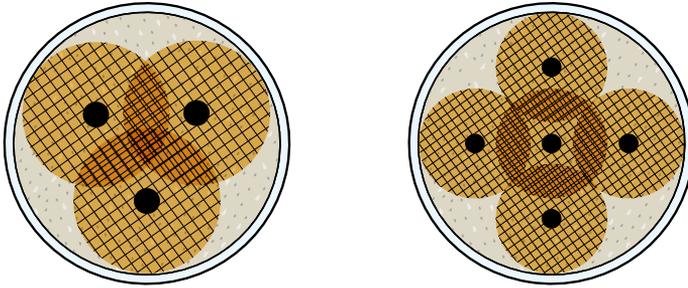
An important aspect is that the gas feeding system may not create problems or be damaged during ordinary filling and discharge of the silo. The type of silo construction, discharge system and the stored material must therefore be carefully considered.

General recommendations for dimensioning and gas distribution

The base for designing a gas distribution system should be to ensure a gas flow rate equivalent of at least about 5 kg/m² per hour, based on the silo cross section area, and that the gas distribution is as even as possible. For small silo diameters, 1-3 inlets will normally be enough. For silos with a diameter of 10–15 m or more, and a relatively limited storage height, additional gas inlets will be required. This is further explained in the below chapter.

Silos with a large diameter and a flat bottom.

To relatively quickly achieve an even gas flow over the cross section area of a large silo, a gas flow of about 200–400 kg/h per gas inlet is a good guideline. This is the equivalent of a coverage area of 40–80 m² per inlet. To allow the gas to spread radially



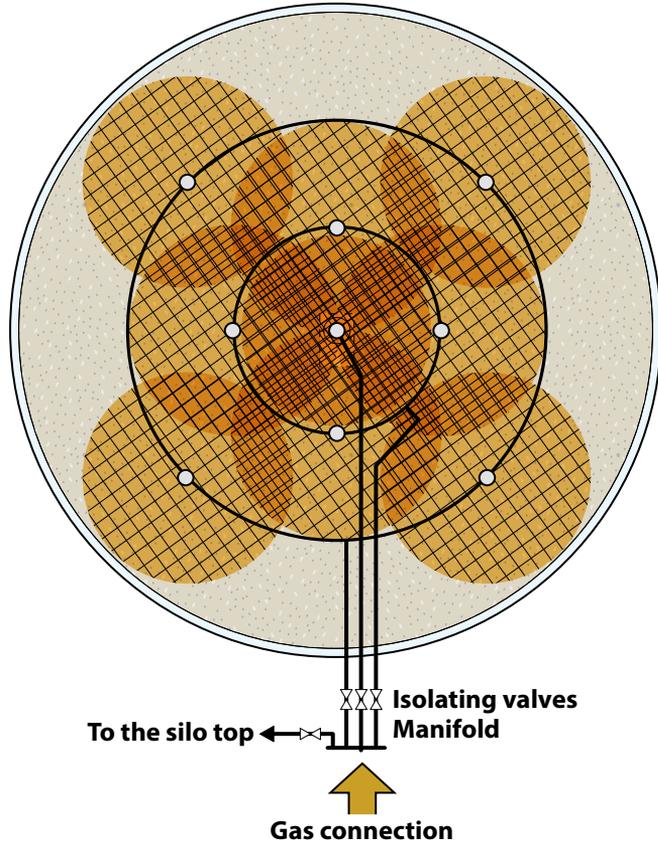
Two alternatives for gas distribution through different numbers of gas inlets depending on the diameter and height of the silo. The total gas flow should be based on the silo cross section area to achieve a gas flow rate of at least 5 kg/m² per hour, and the number of inlets is chosen based on gas flow per inlet and to obtain the best possible distribution in the silo. For larger silos with a larger number of gas inlets, the system should be split into several feeding loops to achieve flexibility.

and develop a "plug flow" on before the gas front breaks the surface of the stored material, a smaller coverage area per inlet (more inlets) is required as the silo/storage height is decreasing. Gas can be distributed in a silo by designing the number of inlets and the gas flow per inlet so that the average gas flow rate is at least 5 kg/m² per hour. The circle in the figure marks the theoretical coverage area of each inlet, which means that some overlapping will occur, but there will also be some gaps. For larger silos which require an increased number of gas inlets, the system should be split up into several feeding loops that will reduce the pipe dimensions of the system and provide more flexibility in directing the gas flow to various parts of the silo during the firefighting operation.

Example

A silo with a diameter of 20 m (314 m² cross section area) is to be equipped with a fixed gas distribution system during new construction. With a gas flow rate of 5 kg/m² per hour, this will provide a total nitrogen flowrate of about 1600 kg/hour. Since the silo in this example is assumed to have a discharge opening located centrally at the bottom, it is equipped with a total of 9 gas inlets, 8 of which are placed at alternate positions along two different radii from the silo centre, and one inlet at the discharge opening. This will provide an average gas flow of about 180 kg/h per gas inlet. In this case, the gas pipe system will be split into three feeding loops, one to the outer loop, one to the inner loop and one to the discharge opening at the silo centre. The advantage of using a loop system is that it provides the best pressure and flow balance for every gas inlet, while also minimizing the risk of blockage. Dividing the system into three sections also allows control of the gas flow to various parts of the silo during the gas injection following the initial inerting of the silo. The gas flow could then be guided towards the silo centre or the periphery depending on where the need is judged to be most urgent.

Diagram of gas supply system



Example of a silo with a total of nine gas inlets divided into two loops with four inlets on each loop and one separate feeding to an inlet in the discharge opening. Also the gas supply to the silo headspace should be prepared.

The pipe diameter of the loops and the diameter of the feeding pipe to each of these loops must of course be designed in relation to the maximum gas flow rate. The dimensions should be selected so that the total pressure drop will be low, which reduces the need for high pressure in the distribution system from the vaporizer to the silo and provides a short-term margin to exceed nominal gas flow rate. This provides also larger margins if the permeability of the stored material is lower than expected, which results in increased back pressure during gas injection. A maximum pressure of about 3–4 bars in the delivery system at nominal gas flow is therefore recommended. A loop system is preferable to achieve an even and balanced flow rate and pressure for all gas inlets.

From a pressure drop perspective, relatively small pipe dimensions could be usable for most applications. However, considering to the risk of dust deposits and that it may be used as a water drainage system from rinsing the silo during maintenance, etc., larger pipe diameters are preferable. For this reason, the pipe diameter to each gas inlet should be at least 50–75 mm, the distribution loops about 75–100 mm and the feeding pipes to the loops at least about 100 mm in diameter. The pipe system should be equipped bends and T-connections with a large radius to facilitate rinsing of the system.

Since it is often difficult to achieve a totally balanced system in practice, a number of bends and T-connections of different shapes may be required, which makes it important to allow the design engineer to perform calculations of the pressure drop and suggest a final design.

Each gas inlet in the silo should preferably end with a female pipe thread ("R3" or "R2"). The gas connection at the silo wall should be designed as a manifold where the feeding pipes to the two different loops and to the silo centre are connected. The manifold should also be prepared with a connection for a gas feeding pipe to the silo headspace. The connection for the incoming gas to the manifold should be equipped with a female pipe thread or a suitable flange. All pipes from the manifold should be equipped with a valve that prevents air entrainment into the silo and allows the flow of nitrogen gas to be controlled to each loop/inlet during an extinguishing operation. If possible, the pipe system should also be leaning towards the manifold to assure efficient draining of all pipes.

The gas manifold should be located such that it provides a good access in the event of a fire and that the gas tank, vaporizer and delivery hoses can be placed in a way that do not block traffic i.e. during discharge of the silo.

All gas pipes should be made of stainless steel. Since the pipe system is open and the feeding pressure will only reach a few bars during a normal extinguishing operation, a maximum operational pressure of 10 bars for the pipe system should be sufficient (however, needs to be verified against relevant regulations).

The pipes that are located inside the concrete foundation of the silo may be made of plastic, i.e. PE pressure pipe intended for sleeve welding. At each gas inlet point, the pipes should end with a pipe thread of stainless steel moulded into the plastic pipe as mentioned above. Since the use of plastic pipes is an unconventional solution, this should be verified with the pipe supplier of your system. When using this alternative, the ingoing gas temperature may not drop below the minimum operational temperature for the plastic during the gas injection. An intensive smouldering fire along the bottom of the silo could possibly generate heat conduction into the concrete, which could cause damage to the pipes. The exposed parts of the pipe system (i.e. manifolds and feeding pipe to top of silo) should, however, always be made of stainless steel.

The gas feeding system must be kept closed so that the outside, humid air is entrained into the silo through the gas inlets. The material at the gas inlet could then absorb moisture and form a hard cake that in turn could block the gas feed

In order to prevent the gas inlets from being blocked, each inlet must be covered. This can be achieved with a square or circular steel plate with a side/diameter of about a 0.3 –0.4 m that is mounted onto the concrete floor so that a gap of about 30 mm between the plate and floor is achieved. If the silo is equipped with a screw for the discharge, the inlet and the plate should be lowered into the floor and possibly equipped with a powerful, but relatively fine screen that prevents the material from being pressed in under the plate by the reclaimer screw.

The latter solution is also preferable if the silo floor needs to be completely smooth and driveable for e.g. wheel loaders.

Illustration of gas inlets



Gas pipe and gas inlets embedded in the silo floor.



Because the moist out-door air could flow into the silo, the stored wood pellets swelled and formed a cake at the opening.

Regardless of the construction, the plate must be removable to allow control and possible cleaning of the gas pipe system.

Note that practical experience of these arrangements is limited at this time, making it important to be observant that the pressure drop does not exceed the design values or that the inlets does not get completely blocked.

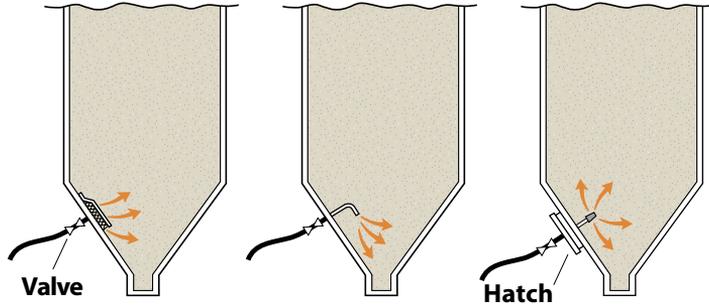
Tower silos and bulk silos for free-flowing material with limited diameters

Silos for free-flowing materials usually have some form of conical or angled bottom that guide the material to the outlet and the silos usually have a relatively small diameter.

For small silo diameters, a single gas inlet should be sufficient if the gas inlet is close to the centre of the silo. If the silo diameter exceed 5–8 m and/or the silo height/storage height is less than 2 x the silo diameter, the gas flow should be distributed via 2–3 inlets over the cross section area. If possible, these are placed diametric using two inlets and with a 120° split using three inlets. The gas inlets should not be placed directly along the vertical silo wall since this will allow a large amount of the gas to follow the silo wall and thereby limit the spread to the silo centre.

Different types of gas inlet

Examples of how gas feeding can be solved in silos with a conical bottom.



The porosity and gas permeability of the material is usually higher along the wall, which additionally enhance this effect. The gas injection point should instead be located at a distance equivalent to about half the silo radius from the silo wall.

For small silos with limited diameters, the easiest preparation is to prepare a penetration in the silo wall at appropriate locations and then cover the hole with a steel plate or other appropriate connection. One or several lances are prepared which fit the penetrations. In the event of a fire, the covering plate is loosened and the lances are pushed into the bulk-material.

It is of course preferable to complete the gas distribution system so that the distribution hose from the vaporizer can be easily connected in the event of a fire. This is preferable in larger silos that require more than one inlet and/or where access around the bottom of the silo is very limited. If the silo is equipped with a conical bottom, acceptable distribution can be

achieved by arranging the gas inlet further down on the cone so that it's located along a vertical line at a distance equivalent to about half the silo radius from the silo wall. The gas inlets should be protected by some type of cover plate, perforated plate or equivalent, in order to avoid blockage and the risk of hangings and heavy loads on the cone. If the silo has a flat floor, the inlets should preferably be placed in the bottom construction of the silo as previously described for larger silos.

Preparations at the silo top

Preparations at the silo top include primarily arranging controlled pressure relief where the smoke gases and the inert gas can be released without allowing air to entrain into the silo. Another preparatory measure is to arrange the option for gas injection into the silo headspace in the event of an immediate risk of explosion. Finally, it may be appropriate to arrange gas evacuation to the open if the silo has a superstructure. Such evacuation could significantly reduce the need and costs for decontamination.

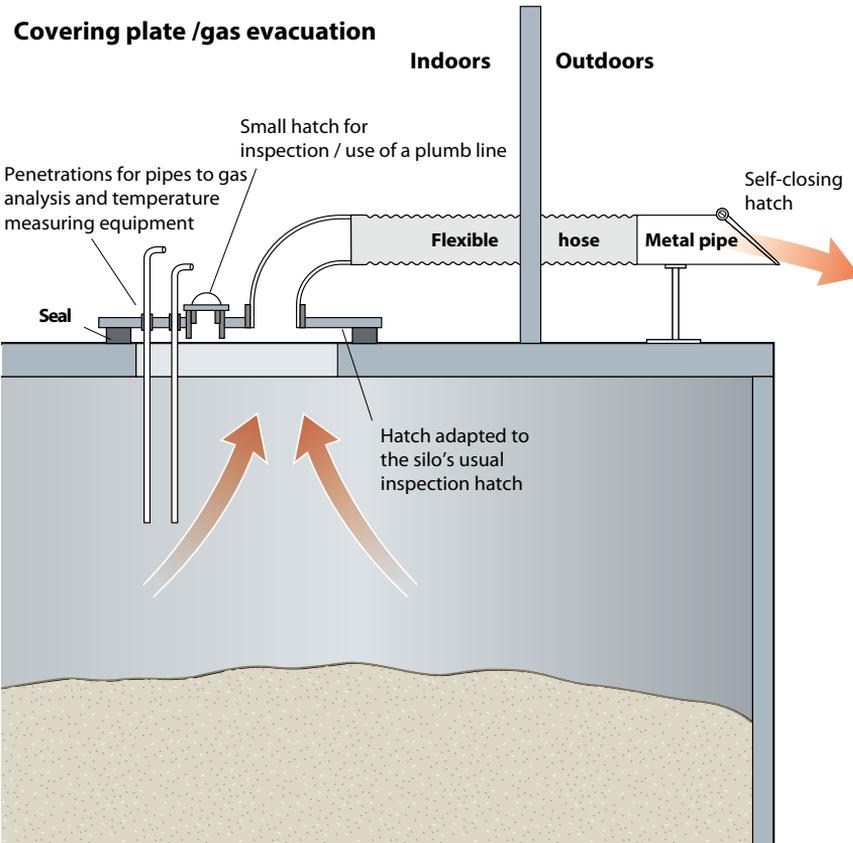
Pressure relief for pyrolysis fumes and inert gas

The problem with achieving pressure relief from the silo headspace without allowing air to entrain into the silo can be solved in many different ways depending on the type of silo and other circumstances. The advantage of preparing an opening for pressure relief is that it reduces the need for work on the silo top (drilling holes etc.) that is associated with high risks as the gases inside the silo might be flammable.

For larger freestanding silos without a superstructure, the gases can be released directly into the open air through a hatch (through an explosion relief hatch or inspection hatch, etc.). These must, however, be easily accessible in a safe manner and must be prepared to work as a combined air relief valve and a check valve. The hatch/hatches must be secured so that it/they stay in position and do not fall down.

If the silo has a superstructure where accessible hatches or openings are placed (e.g. a tower silo plant), it may be useful to try to evacuate the gases outside. The smoke gases from the silo will have high concentrations of carbon monoxide, unburned hydrocarbons and different tar substances and

The photo shows the environment in a silo superstructure, and the illustration shows the design of the covering plate and connected gas evacuation.



create a dangerous environment and may result in extensive decontamination work. The illustration shows a principle diagram of a cover arrangement that can be placed over an existing hatch in the event of a fire to allow gases to be evacuated into the open through one or several flexible hoses.

The covering plate is equipped with the necessary openings and connections so that the hatch only needs to be opened completely for a short time and then immediately covered with the covering plate. To prevent fresh air from being entrained through the flexible hose, the end of the hose has a self-closing hatch. The cover is also prepared with openings for gas analyses measurements, temperature measurements and possibilities for estimating the fill level using a plumb line.

Inerting the silo headspace

The most important preparation that can be made is to prepare a gas feeding pipe of stainless steel to an appropriate location at the top of the silo. From here, gas can be distributed through a hose to the affected silo cell or appropriate gas injection point. If the pipe has a dimension of 50 mm, it may also be used by the fire & rescue service as a riser for water/foam supply (i.e. during manual extinguishing operation at the top of the silo).

When inerting the silo headspace, it is appropriate to inject the gas as far from the outflow opening as possible in order to achieve as efficient inerting as possible of the entire volume of the silo top. If no such opportunities exist, the cover arrangement can also be equipped with a connection for an inert gas feed. The nozzle of the inlet pipe should then be angled to direct the gas flow away from the outflow opening.

As previously mentioned, there are no guidelines about appropriate gas flow rates when inerting the silo headspace.

A general judgement suggests using a lower flow rate than used at the silo bottom. A gas flow rate equivalent to 1–3 kg/m² is considered reasonable in order to avoid excessive gas loss. The gas injection should start at an even lower flow rate to avoid possible the dispersion of dust layers and could then be slowly increased when a certain inerting effect has been achieved.



Example of a dust explosion that lifted the entire silo roof and moved it out of position. The fixed riser to the silo top was also damaged.

In fixed installations, any possible damage to the top of the silo as a result of an explosion inside the silo should be considered.

The roof in some silo constructions is so weak that the entire roof acts as an explosion relief. In this case, pipe systems and connections through the roof should be avoided since these may be destroyed in the event of an explosion. Instead, the pipe systems and connections should be located at the top of the silo wall.

In some cases, the silo is equipped with hatches at the roof that are supposed to act as explosion reliefs.

Real incidents involving large silos equipped with explosion relief hatches have shown that these do not always open fast enough and this has resulted in the entire roof detaching due to the explosion.

Functional testing of the gas distribution system

To assure that the gas distribution system works as designed, it is important to test the system with a full silo when the plant is started up in order to verify that the intended gas flow rate can be obtained. This should be done in cooperation with the local fire & rescue service so that rescue operational planning could also be verified. The test should include all the equipment that would be used in a real situation (vaporizer equipment, feeding hoses etc.).

Continued control of the system should then be included as a part of ongoing maintenance plan. In larger silos with a flat bottom where the gas distribution system is moulded into a concrete foundation and where the gas outflow is protected by cover plates, it is especially important to frequently control that gas inlets are not blocked. From this perspective, it is important that the maintenance plan include complete emptying of the silo at appropriate intervals.

Preparations for using alternative extinguishing methods

Before an extinguishing operation based on an alternative method is established (i.e. using foam or water), it must be verified that the bulk material and the silo construction are designed for such a method. If so, prepare the silo with connections or openings suitable for the planned method and tactics. If water is to be used, a fixed sprinkler system may be installed inside the silo headspace to guarantee that the extinguishing agent reaches the entire cross section area of the silo. Installation of a fixed foam system (i.e. medium expansion foam generator) inside the silo may cause problems since the combustion gases in the silo headspace may have a significant foam degrading effect. In such cases, foam generators should be placed so that they use fresh air for foam generation.

Regardless of the system, a riser should be arranged so that the fire & rescue service can connect to it from ground level.

This provides the possibility to control the flow of the extinguishing agent into the silo headspace from ground level without the need to open the silo.

Preferably, the riser should also be equipped with a hose connection at the silo top that can be used by the fire & rescue service for manual extinguishing operations. In fixed installations, any possible damage to the top of the silo as a result of an internal explosion should be considered.



A fixed riser from ground level facilitates simple and safe application of extinguishing agents into the silo headspace.

**Mobile gas
equipment**

Chapter 8

Mobile gas equipment

Access to mobile vaporizer equipment and associated tank and other equipment cannot currently (2012) be guaranteed for emergency fire situations.

The two major gas companies that exist on the Swedish market, Air Liquide and AGA Linde, have some rental equipment, but neither can guarantee the availability since they often lease vaporizers on a short-term and long-term basis to e.g. process industry during reconstruction and reparations.

The capacity of the available vaporizers and gas storage tanks are also usually very limited and are not designed for the gas flow rates required for complete inerting operation of larger silos. AGA currently have a larger vaporizer and tank that fit on a trailer (see chapter 2) with a nominal evaporating capacity of about 1000 Nm³ /hour (about 1250 kg/hour).

In order for the entire concept of extinguishing fires in silos using inert gas to work in practice, suitable gas equipment must be available and able to be quickly deployed in the event of an emergency fire. One solution is that all stakeholders (food and feed industry, pellets producers, power plants etc.) that own silos make a collective investment in mobile gas equipment. In order to obtain a reasonable emergency response time, a number of units will probably be needed at various locations around the country.

The oil companies in Sweden have established a similar concept and invested in large-scale extinguishing equipment for tank fire situations. A mutual aid company has been created, Släckmedelscentralen (SMC AB), which in turn established an agreement with four fire & rescue service brigades (Sundsvall, Stockholm, Gothenburg, Malmö) to be responsible for the equipment and operational work.

An alternative is of course for gas suppliers to invest in the required equipment and guarantee availability for a annual fee.

How this will be solved is currently unknown, but the MSB will consult with affected parties to find a working solution.

In-depth Information and Knowledge

The descriptions of extinguishing methods and so on, presented in this book are a summary of experience based on research projects, existing recommendations, experience from past fires/accidents, and extinguishing operations etc. in Sweden and abroad. A significant portion of this background material but also further literature will be made available on the MSB's website, <https://www.msb.se/sv/Insats--beredskap/Brand--raddning/Brand-i-silo/>

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Gunnar Stattin allehanda media, cover and page 44.

Bergslagens Räddningstjänst, page 12 and 16 (top), 41 (right upper and middle), 45.

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Furab AB, page 80, (left middle, bottom and right bottom), 81.

Johan Sjöberg Neuero, page 82 (right upper).

Laxå Pellets AB, page 84 (right).

A fire in a silo plant is a rare event for most fire & rescue service brigades and differs in many ways from conventional fires. In many cases a silo fire starts deep into the stored material as a result of spontaneous ignition or from some external source of ignition. This means that fires are often detected at a late stage.

A consequence of silo fires occurring relatively seldom is that there is a lack of experience of this types of emergency response among fire service brigades but also a lack of suitable firefighting equipment. The progress of the fire and the duration of the operation differ significantly from conventional firefighting operations. In many cases no open flames are visible, which can lead to an underestimation of the risks and possible consequences involved with wrong decisions as a result. The duration of the operation is much longer than in for a conventional firefighting operation and usually continues for several days, whereby the plant owner and the fire service need to work together to solve the problem safely.

Silo Fires highlights an operational tactic that is primarily based on the use of nitrogen gas for inerting the silo. A silo fire entails many dangers, including the risk of gas and dust explosions, which can both lead to serious injury to personnel and a risk of the fire spreading into the associated conveyor systems which can rapidly lead to extensive damage. The use of nitrogen gas is the methodology that is considered to minimize the risks of personal injury and property damage.

Silo Fires are a result of an extensive knowledge collating project in this field, both through various research projects and through the transfer of knowledge from a number of real silo fires. This collective knowledge forms the foundation for the recommendations given in the book.

Silo Fires is intended to be used both during emergency response operations in direct connection with a fire and also in prevention work. The target group is the fire & rescue service, silo owners and fire safety consultants.

Silo Fires is complemented by additional material, which is available on the MSB website.