Swedish Civil
Contingencies
Agency

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Fire ventilation

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Fire ventilation

Cover photo: Åsa Brorsson
Text: Stefan Svensson
Editor: Kristina Malmstedt-Svensson
Printing: DanagårdLiTHO
Layout: Advant

Order Nr.: MSB1565 – May 2020
ISBN: 978-91-7927-036-0
Swedish edition: MSB1477 – februari 2020

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Preface to the revised edition

This book was first published in 2000 and was already back then based on research as well as experience. A lot has happened since then and today we are sitting on a lot of new research results and a great deal of experience regarding fire ventilation. A couple of decades certainly leaves its mark.

Nothing has really changed, it is still the fire and the production of heat and combustion products that create problems for us during fire and rescue operations. But over the years we have learned to deal with the problems that arise in various ways. In addition, a number of studies have been conducted, nationally and internationally.

Now that I have had the opportunity to revise the book, a lot of changes have been made with material being added and some older material being removed. Of course, I have also met a lot of extremely knowledgable people over the years, all of whom have made their contributions to our constant and shared learning. This is therefore more than a revised version, it is a completely reworked and considerably more complete version.

This book is about fire ventilation and all the measures the fire and rescue service takes in the event of there being a fire in a building with the release of heat or fire gases out of the building and into the open. Above all, it is about what these measures should be based on and what the consequences are. The actual execution of the measures is dealt with summarily only, as these can be carried out in a variety of ways, depending on, for example, the building, how the fire behaves and the resources available. It is simply difficult to exactly determine how fire ventilation should be implemented in every specific situation.

The book is primarily intended for use in the training of firefighting personnel in Sweden. It encompasses the basic theories and principles for fire ventilation and how fire gases spread in buildings and how they find their way out of buildings. The book also describes how fire ventilation can be practically implemented and what problems and opportunities exist when creating openings for fire ventilation in different types of structures. Material describing problems related to structural fires with respect to fire ventilation, has been added. Towards the end, there is a general discussion about tactics in fire ventilation. The concluding chapter provides some examples of situations related to fire ventilation.

The book does not make any claims to be complete, partly because a variety of variations on fire ventilation exist, and partly because there is a continuous learning process. Fire ventilation is also a fairly complex issue. I therefore assume that the reader takes what I have written and drives the development further. For those who want to know more, there is a fairly comprehensive list of recommended literature and literature that formed the basis for the revised edition, at the end. Of course, a lot has also been added to that list in this version of the book.

Major contributors to the book over the years have been Sören Lundström, Lasse Bengtsson, Magnus Nygren, Lasse Nelson, Steve Kerber, Ed Hartin, Paul Grimwood and John Chubb. Bertil Wildt-Persson was also a great source of inspiration early on. In addition, all of the students who, over the years, have asked a lot of difficult and fascinating questions have contributed to the book. My sincere thanks to everyone!

Revinge, February 20, 2020

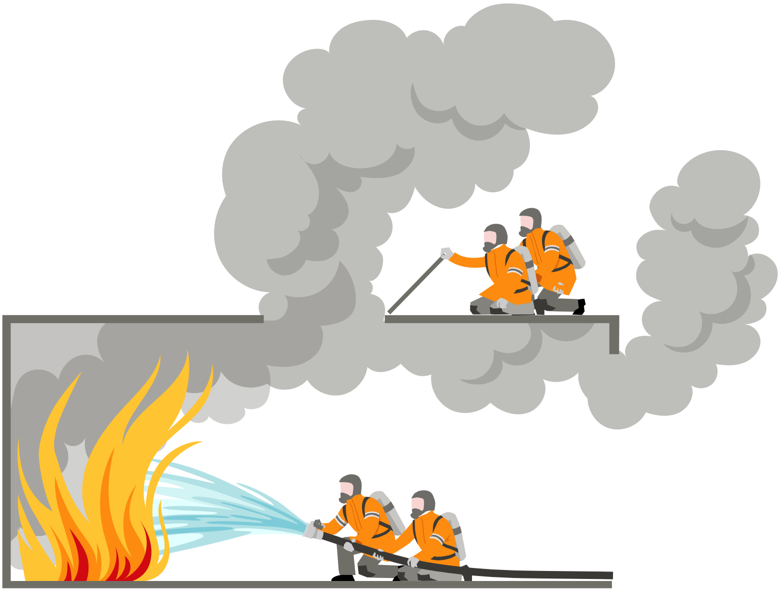
Stefan Svensson

Chapter 1

Fire ventilation – introduction

The basic principle of fire ventilation is to actively and in a controlled way change the conditions in a burning building with the intention of releasing heat or fire gases out of the building. But even a decision or action with the intention of not releasing heat or fire gases can be said to fall under the collective concept of fire ventilation. This is sometimes referred to as anti-ventilation. The working methods and the tactical design of the operation are affected by the objective of the fire and rescue operation and by the purpose of the measures that are intended to affect the flow of heat or fire gases within or out of the building. It is about being clear with what you want to achieve with fire ventilation as part of the entire fire and rescue operation.

Sometimes the term flow path is used. The flow path is the route that air takes when it flows in to feed the fire in a building and the route that heat or fire gases flow towards or through to leave the building. There is a very strong connection between fire ventilation and flow path and on most occasions they can be used synonymously or as substitutes for each other. The physics behind flow paths are the same as for fire ventilation and if we understand one we will also understand the other. In short: flow path and fire ventilation are pretty much the same thing, simply because they are both based on the same principles.



Fire ventilation can have several purposes, for example to reduce the effect of smoke and heat on trapped people and to improve working conditions for the firefighting crew.

Objective and purpose of fire ventilation

The overall objective of fire ventilation is to release heat or fire gases or otherwise change the conditions in a burning building so that heat or fire gases flow in the direction we want them to. In the vast majority of cases, this also means that air flows into the building, which can have significant consequences.

Different objectives can be achieved depending on the design and implementation of measures related to fire ventilation. We may use fire ventilation in order to

- reduce the impact of fire gases and heat on trapped people, and to facilitate their evacuation from the building
- facilitate fire and rescue operations by reducing the thermal load, and improve visibility in the building for the firefighting crew
- prevent or contain the spread of fire or fire gases through a reduction of the impact of pressure and heat in the building
- enable or facilitate salvage operations and overhaul activities at an early stage of the fire and rescue operations.

The primary purpose of fire ventilation should generally be to reduce the impact of heat and fire gases on trapped people and in particular to facilitate the evacuation of people out of the building. Therefore, a primary task for the fire and rescue service is to keep stairwells and other escape routes free of fire gases. This allows people to evacuate by themselves, which is especially important in buildings that accommodate a larger number of people, e.g. high-rise buildings or in public premises such as cinemas, restaurants and sports facilities. Putting the fire out then has to wait.

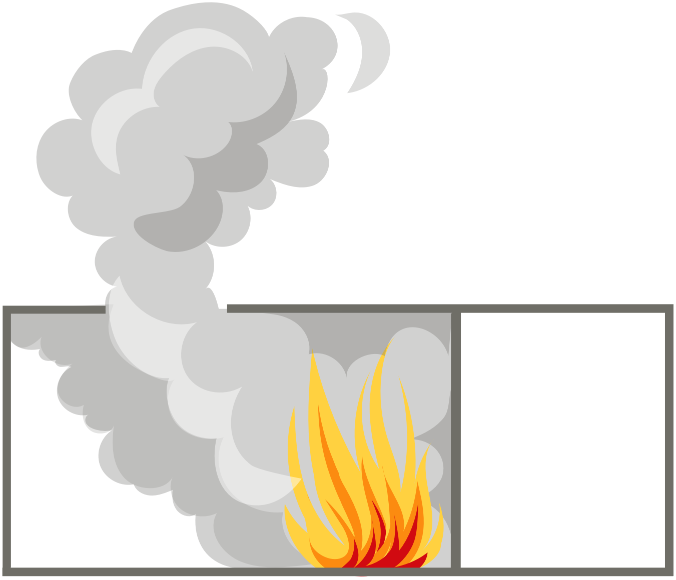
On occasions, you may also need to prioritize securing escape routes rather than rescuing people from an area exposed to fire. Helping several people evacuate must generally have a higher priority than saving single people. At the same time, the fire itself is the cause of the problems associated with fire gases and there will be an important balance between the need for different measures. Also, bear in mind that evacuation routes often function as attack routes for the fire and rescue service.

Openings and fire ventilation

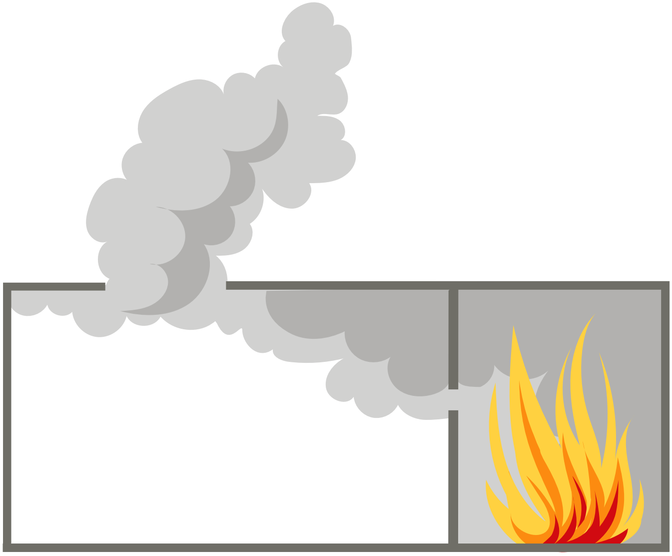
In most cases, we use existing openings to vent heat or fire gases, such as doors, windows or shutters. But sometimes this is not an option. In some cases, therefore, we need to create openings in structures, e.g. by cutting holes in a roof, if possible. However, the purpose of creating openings by cutting holes in structures is more often to access fire than to vent heat or fire gases. But the consequence of cutting holes can be that fire gases flow out and air flows in. That is, an effect similar to that of fire ventilation.

Fans are sometimes used for fire ventilation. The purpose of a fan can be for example to push fire gases out of a room that is on fire, but a fan can also be used to pressurize a staircase so that fire gases cannot spread to the staircase from a room on fire. The purpose of measures taken should always be clarified for every operation. If fans are used, then it should be clarified as to whether the purpose is to push fire gases out of the building (positive pressure ventilation) or whether it is to pressurize a space. Personnel involved in the operation must also be aware of what is happening in the building when fire gases are vented out and air, often as a direct consequence, flows in.

Creating openings can be made from the following starting points, all of which can be referred to as fire ventilation:



Venting a room exposed to fire.



Venting an adjacent room.

Venting a room exposed to fire

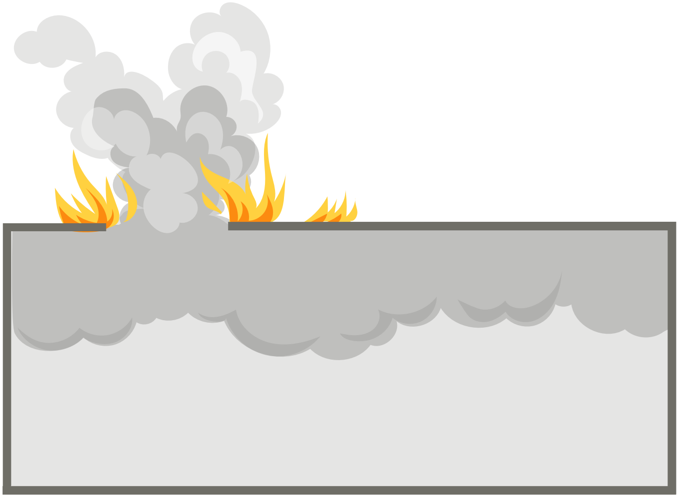
What is normally associated with the concept of fire ventilation is to actively and in a controlled way create openings to a space on fire and vent heat or fire gases from it, e.g. from a fire compartment, a room, a building or a so-called hidden space (often related to structural fires, which will be described more in detail later).

Venting of rooms adjacent to a fire room

Openings can also be made in an adjacent space. This often happens in connection with separations or boundary lines. This type of fire ventilation can fulfill at least two functions:

1. Reduce the impact of heat and pressure on the structure and on an adjacent room.
2. Physically separate the structure so that heat and fire gases cannot spread (which is related to structural fires).

A decision has to be taken on a case-by-case basis as to what side of a separating wall openings should be made. In some situations it may be best to create openings on the side exposed to the fire, while in other situations it may be better to do it on the side not exposed to fire. Decisive factors can include the type of building, the type of structure, how extensive the fire is, how fast the fire is spreading or what areas need to be prioritized and protected from fire gases.



Creating openings to access fires in or venting fire gases from hidden spaces or from inside structural elements.

Create openings to gain access to a fire that has spread into the structure (a structural fire)

It may also be necessary to create openings in order to gain access to a fire inside a structure, e.g. inside a wall or in a truss, a so-called structural fire.

Structural fires can be defined as fires in hidden areas or in spaces with limited access, which are not normally used, for example a storage area or a crawl space. In such areas, there are often exposed combustible surfaces (building materials, installations and such like). Examples of spaces where structural fires can occur include

- air gaps or other engineered cavities inside building components or structural elements
- cavities created by fire (e.g. due to molten insulation)
- cavities caused by pests
- attics
- crawl spaces
- shafts.

Creating openings at structural fires are often similar and can be confused with both "venting a room exposed to fire" as well as "the venting of rooms adjacent to the fire room". However, the purpose of creating openings in structures is primarily to access and extinguish a fire inside the structure, not to vent fire gases. But such openings can have similar effects as when the purpose is to vent a space, i.e. when heat and fire gases flow out and air flows in. Due to the conditions in such spaces, the consequences may be highly undesirable. The air flowing into a fire can cause the fire as well as the fire gases to spread quickly and violently.

Venting for mop-up, salvage and overhaul

There is often a thin line between a fire and a rescue operation and salvage and overhaul. Salvage and overhaul is often started long before the fire and rescue operation has been completed in the legal sense. Salvage and overhaul is not considered in any greater detail however in this book.

Fire ventilation measures taken during an operation can be of great importance for saving property. The earlier heat and fire gases can be removed from a building, the greater the chances of being able to save property inside the building. But there are also cases where for example the use of fans has led to an increased need for salvage and overhaul because fire gases were pushed into spaces that were previously unaffected by the fire or fire gases. Opening up walls in order to gain access to structural elements that are on fire can also lead to increased damage if you are careless or if measures are not taken as part of a plan. No matter what type of ventilation measures are taken, it must be done with some caution so that it does not cause more damage than the fire itself.

All of these principles often fall under the concept of fire ventilation as they are similar at first glance. However, they differ greatly for instance with regard to what can be achieved and how the fire is affected, which in turn affects the continued operation. Fire ventilation should not be carried out without having at least a fairly good idea of the consequences.

Different ways of venting fire gases

Fire ventilation can be performed in three different ways: horizontally, vertically or mechanically (with the help of fans). Whichever way is most suitable depends, among other things, on how inlets (openings where fresh air flows in), outlets or exhaust openings (openings where fire gases flow out) and the fire are located in relation to each other in terms of distance and height. The most appropriate way also depends on what other aids are used and other measures that are initiated. Be aware that the different ways of venting have consequences of different kinds.

Horizontal fire ventilation

Fire ventilation is horizontal when exhaust openings are on the same plane as the fire and fire gases flow sideways (horizontally). So, for example, this can be the case for apartment fires or for certain types of industrial buildings where the building only has one level or where there are no skylights or roof vents.

Vertical fire ventilation

Fire ventilation is vertical when exhaust openings are located higher than the fire and the fire gases flow upwards (vertically) out of the building. Exhaust openings should be located as high as possible in the building in order to utilize thermal buoyancy as much as possible. Existing windows, skylights or roof vents can be used as exhaust openings. But sometimes it may also be necessary to create openings in a roof. Exhaust openings that are higher than the fire produce different flow conditions than when the openings are at the same level as the fire, even though the fire is in line with the inlet opening. Thermal buoyancy can be better utilized through vertical fire ventilation.

A special case with vertical fire ventilation is in the case of basement fires. Since basements are below ground level, ventilation will normally always be vertical. In addition, ventilation openings often also become attack routes for the fire and rescue service. As a result, we are often forced to use an attack route where hot fire gases flow out, this entails a number of risks and problems. Although there may be several attack routes, it may be difficult to prevent the spread of fire gases through these attack routes due to the thermal buoyancy in the fire gases or due to wind.

Mechanical fire ventilation

With the help of fans, positive or a negative pressure can be created. Mechanical ventilation must be combined with creating inlets as well as exhaust openings so that either horizontal or vertical ventilation occurs.

Fans can also be used to pressurize an adjoining room (i.e. a space that is not exposed to fire). The purpose is then to prevent or limit the spread of fire gases (or fire) to such an adjacent space. In such pressurization, no exhaust openings are made, except through openings in the building (normal leakage), because it is the pressure in the adjoining space that is desired.

The boundary between these different methods is not always clear or obvious. In some situations, we must also combine one or more methods to vent a fire.

Fundamental principles

Fire ventilation means that fire gases must be vented out, but also that fresh air will flow in (generally). This supply of air normally affects the fire in such a way that the rate of heat release from the fire increases or the fire spreads faster. Conversely, this of course also means that in some cases a fire can be limited by not performing fire ventilation. This is sometimes referred to as anti-ventilation. However, seen over the course of an operation, fire ventilation rarely degrades the result of an operation provided that the ventilation measure is controlled and coordinated with other measures, e.g. suppression. Fire ventilation can, however, make the situation worse locally, but at the same time making it possible to influence the fire in such a way that any problems can be dealt with.

> Fire ventilation should be carried out as early as possible during an operation and should be combined with extinguishing measures. Crucial to the result of fire ventilation is to a large extent if the fire is fuel controlled or ventilation controlled when the operation is carried out.

Attempting to close a fire compartment (or similar) so that the fire self-extinguishes works only in some very special cases and also requires patience, as this type of action can take a very long time. But while it is usually not possible to completely quench the fire by closing it in, it can temporarily limit the fire's size or rate of spread. Therefore, when entering a building that is on fire, it can often be important that fire fighters close the door behind them as far as possible, or that you have other means to control what happens at the attack point. Particular attention should be paid to rapid changes in the flow of air or fire gases into or out of the building, respectively.

Flames pushing out of openings is usually an indicator of a ventilation controlled fire.

Fuel control or ventilation control

The decisive factor to the result of fire ventilation can essentially be said to be whether the fire is fuel controlled or ventilation controlled when the measure is implemented. A fuel controlled fire is mainly controlled by the amount of available fuel, how the fuel is located and the fuel's properties. A ventilation controlled fire is mainly controlled by how much air the fire has access to, which in practice is based on how many openings there are (e.g. doors and windows), how big they are and where they are located in relation to the fire. If fire ventilation can be carried out early during the fire, i.e. possibly when the fire is still fuel controlled, this can prevent or at least delay the fire being ventilation controlled. This means that a fully developed fire can possibly be avoided or delayed. The spread of fire can be more easily prevented and fire damage can be limited. However, to affect the fire in this way is normally only possible in larger premises where the amount of fuel is relatively small in relation to the size of the space or when the fire has full access to air for other reasons. This is rarely the case during building fires and especially not during structural fires.

Fire gases pushing out through gaps in the building often indicate that the fire is ventilation controlled.

During emergency response operations to fires in buildings, the fire is normally ventilation controlled. This often means that internal suppression and fire attack are more difficult to carry out. As an example, a ventilation controlled fire in a closed space can accelerate violently when measures taken to vent the fire, such as creating openings, provide the fire access to air, especially if the fire has been going on for a long time in a closed space and there is strong ventilation control. The rate of heat release can increase fast, the fire will spread faster, more fire gases can be produced and the fire can be much more difficult to get under control. If the fire spreads quickly, for example into spaces other than where the fire started, or to the structure, it can be much more difficult and time-consuming to extinguish the fire or to get it under control. The impact of heat is greater both on enclosing structures and for personnel. It also generates more fire gases that can lead to the fire spreading.

Venting the space exposed to fire or venting adjacent spaces

Venting spaces with a fully developed fire can have significant consequences, not least because a fully developed room fire is normally ventilation controlled. Since fire ventilation also causes more air to be supplied to the fire, the fire can increase in size and in its rate of heat release. It may therefore be wise to instead ventilate adjacent areas where the fire has not spread or where the damage is not so great. But at the same time bear in mind that fire ventilation can in itself spread both fire gases and fire into new spaces. It is therefore important to have control over how and why fire gases (and fire) can be spread. Sometimes it is also advisable to vent spaces that are exposed to fire, e.g. by using positive pressure ventilation (fans). This is dealt with in more detail later on.

Particular caution is required in ventilation controlled fires in very large or inaccessible spaces, e.g. in the case of structural fires. Above all, coordination with other measures at an accident site is required, in particular the suppression of the fire. The fire is likely to increase rapidly in intensity after an opening is made. If air is supplied to a ventilation controlled fire, in the worst case, backdraft can occur. And if an opening is created to a structural fire, the air then supplied can help spread both fire gases and fire further inside the structure or into hidden spaces.

Suppression first or venting first

Getting extinguishing media onto a fire in any way possible must always be considered as a first step. Sometimes an immediate extinguishing solution solves the problem, thus reducing the need for other measures. But there may also be reasons to carry out fire ventilation as soon as possible during an operation, in particular to ensure that escape routes are kept free from fire gases. Thus, if fire ventilation is deemed to be able to facilitate evacuation or suppression, it may be advisable to first vent before evacuation or suppression begins. Regardless of which, extinguishing media should always be available when carrying out any measures for fire ventilation. However, putting extinguishing media into a space with no or very little heat, is in most cases wasted.

Chapter 2

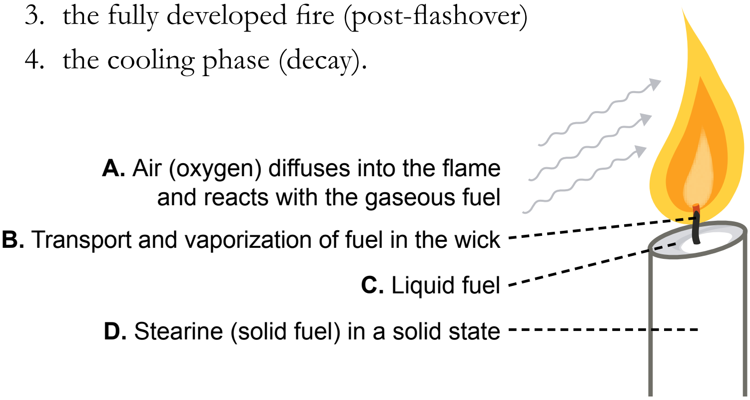
Fire behavior

In order for a fire to start and develop, heat, fuel and air are required. Normally in the case of fires in buildings, the fuel, e.g. in the form of a TV or a sofa, and the air are available separately (we disregard the air that is, for example, in the cushioning of the sofa). The fuel and the air are not mixed until the combustion itself or just before the combustion. The type of flame that then is created, is called a diffusion flame. A good example of such a flame is the flame of an ordinary candle. The fuel (stearine) melts, is transported up through the wick and is gasified. Air enters the gasified fuel from the sides, i.e. ambient air and fuel in the form of gasified stearine diffuses into the combustion zone. The combustion takes place in the contact surface between the fuel and the oxygen i.e. in the combustion zone.

The four phases of a room fire

A fire in a building or in a room is generally characterized by four phases, which taken together constitute the fire behavior in a building or in a room:

1. the initial stage (pre-flashover)
2. flashover
3. the fully developed fire (post-flashover)
4. the cooling phase (decay).



A flame from a candle is an example of a diffusion flame.

The initial stage

During the initial stage of the fire, a single or only a few objects are burning, e.g. a TV or a sofa (so-called initial fire, i.e. the first fire in the room). Fire gases are created by the fire which rise upwards and create a hot layer of fire gases closest to the ceiling. This layer of hot gases grows in volume and gets hotter as more fire gases and more energy from the fire are added. This part of the process is relatively calm and undramatic. The fire is fuel controlled during the initial stage, i.e. the development of the fire is mainly driven by the amount of available fuel and how it is located.

Often you can stay in the room without major problems and in most cases the fire is relatively easy to extinguish with a fire extinguisher, a blanket, a carpet or such like.

Eventually, however, it becomes impossible to stay in the room due to the buildup of fire gases as well as heat. The fire and the hot fire gases that are produced emit heat radiation within the immediate vicinity of the fire and the space in general. This means that the fire gradually increases in intensity in terms of heat release rate and at an accelerating rate.

Flashover

When the initial fire has grown large enough and the room's ceilings, walls, floors and furnishings are hot enough to ignite (assuming they are combustible), a so-called flashover can occur. The flashover is the transitional stage between the initial stage of the fire and the fully developed fire. At this stage, the fire changes from involving one or a few individual objects in the room to, within a few seconds, all of the objects and surfaces in the room. The whole room is filled with flames. Important prerequisites for a flashover to occur are partly that there is a certain minimum amount of combustible material in the room, and that there is enough air in the space or that air is supplied in sufficient quantity. Otherwise, no flashover occurs but the fire quickly decreases in intensity and becomes ventilation controlled.

Also, in large premises it is not always possible to describe the process in terms of flashover. A flashover can of course also occur in large premises, but due to the nature of the space, the process is different. Rather, the process can be equated with the spread of fire between objects. For large premises, the rate of fire spread may thus be more relevant. But the fire gases will of course also be of importance.

Provided there is enough fuel in the room, the rate of heat release from the fire is largely determined by the ratio of the amount of fuel to the amount of air.

During a fully developed room fire, flames can push out through openings. The fire is then ventilation controlled.

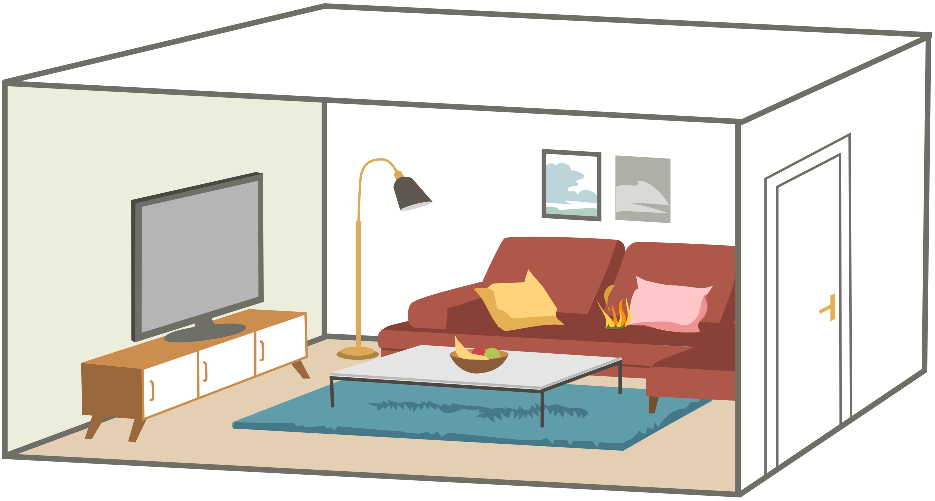
The fully developed fire

Flashover normally results in a fully developed fire. Flames pushes out through openings and the impact of heat is strong on surrounding structures, through radiation and convection (heat transfer through air movements), as well as through conduction (heat transfer inside materials). At this stage, there is an imminent risk of the fire spreading to nearby rooms or buildings. The impact of the fire on the surrounding structure is also strong.

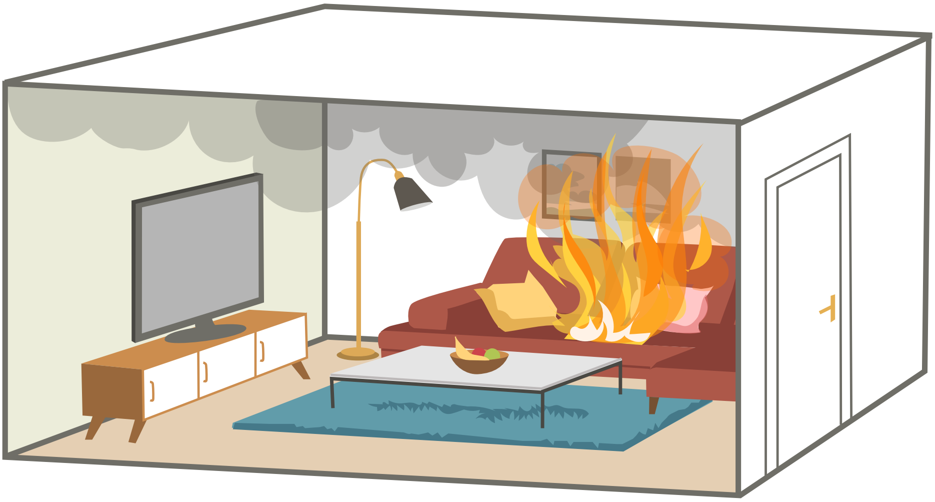
A fully developed room fire is normally ventilation controlled, i.e. the development of the fire is mainly controlled by how much air the fire has access to, which in practice is based on the number, size and location of openings such as windows or doors. The reason a large part of the flaming combustion takes place outside of the room is because there is not enough air inside the room.

The flashover can therefore also generally be said to be the transition phase from fuel control to ventilation control.

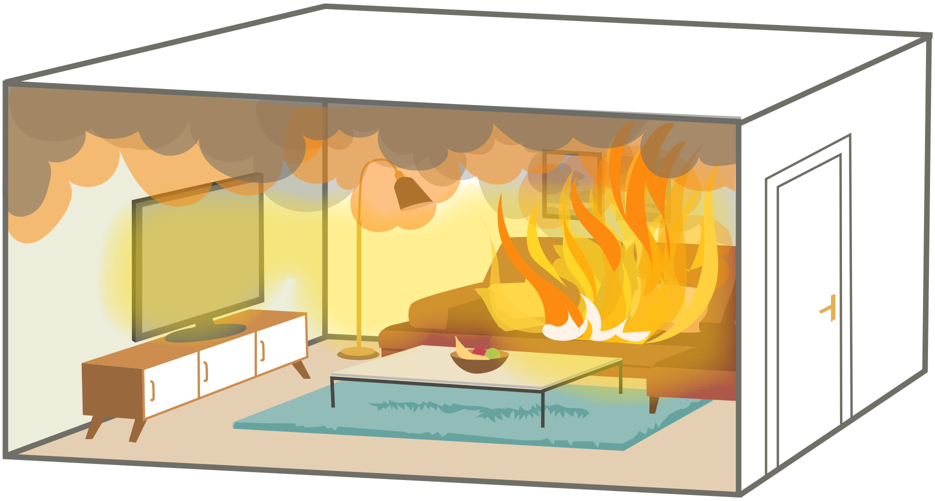
An exception where flashover does not result in a fully developed room fire, may be if the air in the room or in the building is depleted in connection with the flashover. Then, the extent and rate of the spread of the fire will decrease. As in the case with a fully developed room fire, where flames may be pushed out of openings, in this case with oxygen depletion, the fire becomes ventilation controlled but it does not push flames out through openings and the fire can still be limited to one or a few objects.



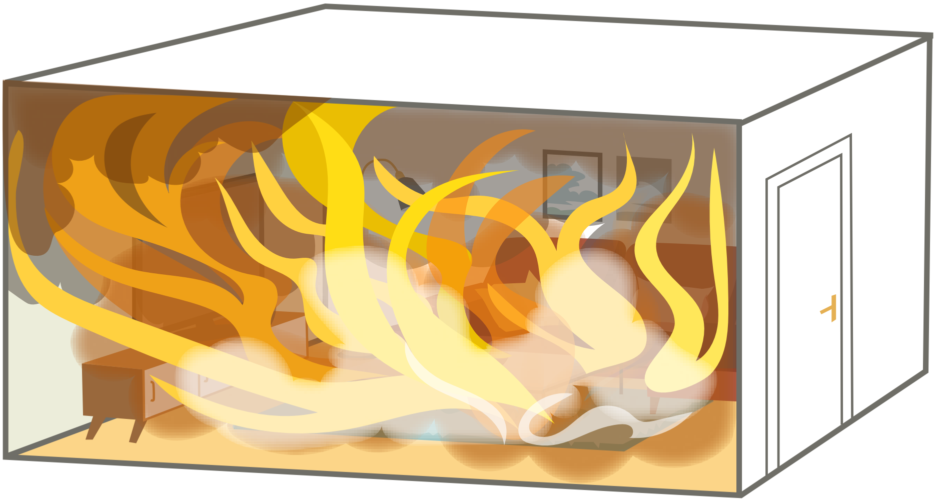
The initial fire is often small at first, and can be diffcult to detect.



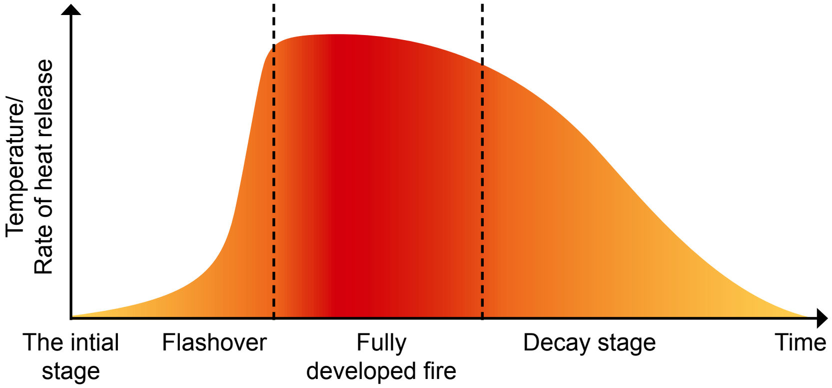
As the fire grows, more and more hot gases are formed, which rise upwards and fill the upper part of the room.



After several minutes, the smoke can be very hot, and it the contributes to heating up the walls and ceiling of the room.



If there is sufficient air in the room all the objects will be heated up to such an extent that the entire room can eventually be ignited during a relatively short period. This transition period is called flashover.



Development of temperature/rate of heat release over time during room fire. Note that figure is not in scale, especially not the x-axis.

The cooling phase

When the fire starts to run out of fuel, the fire decreases its rate of heat release. It enters its cooling phase and the temperature eventually drops. The fire will eventually be fuel controlled again during this phase.

Fires involving several rooms, larger rooms or most parts of a building

A room fire that spreads to several rooms or to the entire building is more complex to describe. Such a fire can also cover large parts of the structure. In such cases, it is usually not possible to describe the fire as easily in four phases. In different parts of the building, the fire can also be in different phases simultaneously.

You cannot describe a fire in a large room (large floor area or high ceiling height) in this way. If, for example, the fuel is limited to only a small part of the room, the fire cannot spread as easily. The amount of fire gases can still be significant, but not necessarily enough to cause a flashover. In corridors or narrow rooms, the spread of fire and the development of fire can also take place in a different way than in a room with normal dimensions.

Backdraft

The combustion of unburned fire gases that can occur when air is introduced into a space whose oxygen content is greatly reduced due to the fire, but where the temperature is still high. This phenomenon can give rise to flames that expel rapidly and with great force from the building.

In such situations, when a fire has an impact on the entire building in various ways, fire ventilation can be very important. The venting of only a single room with "normal" dimensions or of a smaller apartment where there is no risk of the fire spreading is rarely a major problem for the fire service. In all other cases, it is especially important that you have good knowledge of how a fire can behave in a building with for example consideration to the building's geometry, the different fuel properties and how openings affect a fire.

From fuel control to ventilation control

If it is hot enough in the room and if the room has a small opening or no openings at all, more pyrolysis gases, i.e. flammable gases from solid objects will be produced than can be combusted (because there is insufficient air). These gases then accumulate closest to the ceiling in the room and form a hot upper layer. If a door is opened, more air will flow to the fire, more fuel can be combusted and the rate of heat release increases. Under certain conditions, the unburned gases that accumulate can also ignite and burn, either outside or in the room, or both inside and outside the room.

A fuel controlled fire burns with excess air, e.g. a fire in a very large room or in a room with very large openings, and already has enough air. Additional openings (for example, if a door is opened) will not increase the combustion appreciably and thus not directly affect the rate of heat release from the fire significantly. Additional openings can however impact on the fire after a while.

> **Pyrolys**
>
> Exposed to heat, combustible solids are decomposed to form combustible gases. This chemical process is called pyrolysis.

During the early stages of the fire, the fire is normally fuel controlled, while a fully developed fire is normally ventilation controlled. The flashover is thus the transition stage from fuel control to ventilation control. When the fire is ventilation controlled it may burn with a limited rate of heat release or with a slow rate of spread, which is determined by the amount of available air. What can often happen during fire ventilation (i.e. when venting measures are taken) is that the conditions change so that the rate of heat release and the rate of fire spread increase more or less rapidly. What is missing during a ventilation

During the early stages of a room fire, the fire is usually fuel controlled.

controlled fire is, of course, air, and through ventilation measures, the air needed to make the fire grow and spread is added. The other way around, turning the conditions from ventilation control to fuel control using fire ventilation measures is normally not possible and is therefore not recommended.

> **Flashover**
>
> During a room fire, there may be a stage where the thermal radiation from the fire, the hot gases and the hot enclosing surfaces cause all combustible surfaces in the fire room to pyrolyse and eventually ignite. This sudden and coherent transition stage of the growing fire is called flashover.

The starting point when determining what to do when fighting a fire in a building should normally be that the fire is ventilation controlled, as it is the type of situation that places the highest demands on precision with regard to the measures taken by the fire service. It is during ventilation control that fire gas ventilation can cause considerable problems, if you are not aware of this and take countermeasures. In other words, it is very important to coordinate ventilation measures with, among other things, fire suppression measures, whether in the case of a room fire or structural fire and whether it is a large or small building, one room or several rooms that are on fire.

This simple qualitative description of fire behavior applies primarily to a single or possibly to a few rooms, e.g. in case of more "ordinary" building fires. In more complex buildings, such as larger public premises, buildings with several connected fire compartments or similar, the process and thus the spread of fire gases and fire can be much more complicated. In such cases, it is especially important to be clear about the factors that affect the spread of fire gases and how we can influence this through different types of ventilation measures.

> **Fire gas explosion/smoke explosion**
>
> When fire gases leak into spaces adjacent to the fire room, they can be mixed with air. This mixture may fill all or part of the volume and be within the flammability range. If the mixture ignites, the pressure increase can become very strong. This phenomenon is called fire gas explosion (or smoke explosion).

> Crucial to the outcome of fire ventilation is essentially whether the fire is fuel controlled or ventilation controlled when the operation is carried out.

Chapter 3

Fire gases

During a fire, fire gases are always produced. They are usually toxic, and can also be combustible and often react easily with different materials and result in consequential damage such as corrosion. This chapter deals with the composition and properties of fire gases.

Fire gases consist of air and combustion products

The fire gases generated by fires consist of two components:

- air
- combustion products, e.g. carbon dioxide and soot.

The absolute largest component is air, which is heated by the fire and is relatively unaffected by the chemical reactions that occur in the fire. However, some of the air contained in the building or supplied to the building will participate in and affect the combustion process itself.

The second component consists of combustion products that are produced during the fire. Such combustion products are, for example, gases such as carbon dioxide, carbon monoxide, nitrogen oxides, hydrogen sulphide, water vapor and cyano hydrogen, but also solids (soot) or liquid particles (e.g. heavier hydrocarbon compounds). This second component is relatively small in both weight and volume compared to the air in the fire gases. The physical properties of fire gases are therefore largely the same as for air. Therefore, the flow of fire gases can be treated as a flow of heated air in both calculations and in tactical assessments of fires. The flow conditions are not affected even if the production of fire gases is considerable and contain a lot of particles and therefore have low transparency since the amount of heated air supplied to the fire gases is many times greater than the other components. However, it is not possible to completely ignore the mass that is supplied to the fire gases during combustion. This will be elucidated in more detail later.

The exact composition of the fire gases is determined, among other things, by the conditions prevailing in the fire – partly the composition and properties of the fuel and partly the amount of air available for combustion. Thus, the composition can be changed during fire ventilation, i.e. when the fire's access to air changes. In addition, the composition of the fire gases is affected by the temperature. And since the temperature in a fire room is affected by the supply of air (and thus also by the possible ventilation measures), this means that a room fire is a very complex process in terms of the substances contained in the fire gases and how much of these substances there are.

Depending, among other things, on the ratio of the components, fuel and air, different combustion products and different amounts of these combustion products are formed.

Properties of fire gases

There are five aspects to consider when it comes to the properties of fire gases:

1. Fire gases can have low or no transparency, thus limiting vision.
2. Fire gases can be combustible, even if they are completely transparent.
3. Fire gases are generally toxic and affect the body in both the short and the long term.
4. Fire gases can be reactive and can then affect and destroy interiors, tools or other equipment.
5. Fire gases may be hot.

Transparency of fire gases

The first aspect, limited transparency, gives us the advantage that we can see where the fire gases are. This can give us some clues, for example about where the fire is, how large the fire is or how fast it is spreading. Sometimes it is also possible to visually assess whether for example the temperature of the fire gases is high or low, which requires a trained eye. Sometimes it is also possible to visually assess the situation based on the color of the fire gases. This is quite complex, since the color of the fire gases is influenced by a number of factors such as the properties of the fuel, the ventilation conditions and the temperature.

The disadvantage of limited transparency is that we cannot see through fire gases. It can be difficult to orientate both inside a building and outside and difficult to find missing people or objects inside the building. A tool used to deal with such problems is a so-called IR (infrared) camera, also known as a thermal camera or thermal imager. Such IR cameras detect radiation from objects, including surfaces, flames, soot and (in some cases) gases. The cameras translate this into a visual image on a screen, which increases our ability to see through and orient us in fire gases. But even the IR camera has its limitations in that it detects both direct radiation and reflected radiation. It is important therefore to be trained in interpreting the image on the screen. It also only detects radiation from surfaces (including particles but in some cases also from gases). It should also be borne in mind that water vapor blocks a large part of the infrared radiation, which can affect the image the IR camera shows.

Flammability of fire gases

The second aspect, the flammability of fire gases, is somewhat more difficult to quantify and determine. The combustion process during fires in buildings is almost always incomplete. Combustion products are formed that are more or less combustible and which may burn under certain circumstances. These combustion products form part of the fire gases and are collected in an upper layer of fire gases in a room. An example of a combustible gas produced during room fires is carbon monoxide. The flammability range for carbon monoxide is between 11 and 74 percent at room temperature, but this range increases with increasing temperature. The mixing of the gases and particles produced by room fires also affects both the flammability range and the flammability, which makes the flammability of fire gases extremely complex. Also, the flammability of fire gases cannot easily be equated with the flammability of a single gas.

The mixture of gases and particles that fire gases consist of can increase or decrease flammability. Certain types of particles may for example cause the flammability to decrease as the particles act as a kind of "thermal load" (increasing ignition temperature). But the particles can also cause flammability to increase, as they can help raise the temperature or keep the temperature high for a long time. Some type of particles may also be flammable in themselves.

Fully transparent fire gases can also be flammable. Carbon monoxide is an example of an invisible but flammable gas. Since we do not know the exact composition of the fire gases, and thus their exact properties, it is very difficult to determine the flammability of the fire gases based on transparency. As there is a risk that large quantities of transparent fire gases are produced, fire services personnel should use full protective equipment including breathing apparatus and there should be direct access to extinguishing agents when entering a building where transparent fire gases can be present.

> **Flammability**
>
> The flammability of a substance describes how combustible it is, i.e. how easily it catches fire and burns. A certain minimum amount of air is also required for a substance to burn.

Toxicity of fire gases

Fire gases are also toxic and affect the body in both the short and the long term. In addition, the particles in the fire gases can be very irritating to the eyes, mucous membranes and the respiratory tract. Most combustion products produced by fires are toxic, and together there can also be a series of synergies that make the gases even more toxic.

> **Toxicity**
>
> Toxicity describes how toxic a particular substance is. Since fire gases are a mixture, this can aggravate the toxicity as there are then several different substances that affect.

Examples of combustion products and their health effects

Carbon dioxide (CO2) – Is not acutely toxic, but stimulates the rate of respiration (breathing) and can thus help increase the absorption of other combustion products. Carbon dioxide also suppresses the air's oxygen which then, of course, affects the body by reducing oxygen content.

Carbon monoxide (CO) – Causes oxygen deficiency as the blood absorbs carbon monoxide many times easier than oxygen. The gas therefore has an immediate suffocating effect.

Nitric oxides (NOx) – Affects the respiratory system and is also suspected of causing cancer.

Respiratory protection (breathing apparatus) must be used for all work in fire gases.

Since fire gases are toxic, respiratory protection is normally required even during overhaul.

Hydrogen halides (HX) – Is a collective name for halogen (fluorine, bromine, iodine, chlorine) compounds formed together with hydrogen. Of these, hydrogen chloride (HCl) causes corrosive damage to mucous membranes. Hydrogen fluoride (HF) is a substance that is classified as very toxic. Its molecule is small and can easily pass through biological membranes. In humans, contact with HF can cause everything from irritation of the eyes, nose and throat to severe burns, chest pain and cardiac arrest. Hydrogen cyanide (HCN) is extremely toxic and quickly leads to unconsciousness, respiratory paralysis and death. It cannot be ruled out that HCN is a strong contributing cause of fatalities during fires.

In recent years, batteries have become increasingly common, even in our homes. Products that are increasingly common and that contain different types of batteries include mobile phones, tablets, electric bikes and cars. In addition, the storage of energy in batteries from for example photovoltaic panels is increasingly more common. The type of batteries that are often used are so-called lithium-ion batteries. As well as being extremely difficult to extinguish these types of batteries, large amounts of hydrogen fluoride, hydrogen cyanide and hydrogen chloride are formed as they burn, which makes the gases even more toxic and reactive than normal room fires. At the time of writing, there is no indication that we would not have adequate protection with the fire and rescue services' normal protective equipment including breathing apparatus, at least for a short time. However, equipment must be checked carefully if there is any suspicion of being exposed to these types of combustion products. Equipment may need to be discarded after exposure, obviously depending on dose. There has also been fairly extensive development of battery technology as of late and it is expected that other types of batteries will appear in our households, in workplaces and in vehicles.

Also, the toxicity of fire gases cannot be determined based on transparency. Nor can sense of smell be used to determine toxicity, other than as possibly a first and early indicator of the presence of fire gases. If you feel a strong smell of fire gases, some form of respiratory protection should be used. But even more or less odor-free environments can contain a variety of combustion products that are directly unhealthy. Carbon monoxide is a good example of such a combustion product. At the same time, your sense of smell is a poor indicator of the hazards of fire gases, as it is very sensitive to some odors and completely insensitive to others and thus does not give a true and fair view of the toxicity of fire gases.

Protective equipment, including breathing apparatus, which has been exposed to fire gases can become contaminated and carry large amounts of condensed particles and gases in and on the equipment. Combustion products can therefore be spread through so-called cross-contamination. This may lead to harmful products being spread from our equipment in vehicle cabins to our private clothing and into our homes. It is therefore important to employ routines when handling contaminated equipment directly at the scene of a fire when an operation has been completed and that equipment is transported safely in order to be cleaned.

Reactivity of fire gases

Fire gases are also many times reactive and can contribute to the corrosion of different types of equipment, damage that may not be visible until after a relatively long time. An example of a corrosive combustion product is hydrogen chloride (HCl), which forms hydrochloric acid when dissolved in water. Another combustion product is sulfur dioxide

(SO2), which upon contact with water, may form sulfuric acid. Both of these products can cause major damage and prolonged shutdowns for example of industrial processes.

The vast majority of the combustion products that fire gases consist of have several different simultaneous impacts. It is therefore important not to expose fire and rescue services personnel to these products, and that protective equipment is used when needed. It is also important to try to remove the fire gases from the building as quickly as possible through various measures (fire ventilation), so that people trapped inside the building and equipment are exposed as little as possible. As previously mentioned, one of the primary tasks of the fire and rescue services should be to secure the buildings' escape routes in the event of fire.

Reactivity

Substances that react easily with other substances are said to have high reactivity. Since fire gases are a mixture, this can increase reactivity as several different substances affect.

Hot fire gases

Finally, fre gases can of course be hot, which affects things in a large variety of ways. On the one hand, it gives us the basic mechanisms for spreading fire and fire gases, mainly through thermal buoyancy but also thermal expansion. On the other hand, hot fire gases can cause damage to the structure of the building as well as to furnishings, machinery, etc.

But hot fire gases can also contribute to the spread of fire, even at great distances from the primary fire room. The heat in the fire gases is also a major contributory cause of, among other things, flashovers in rooms, not least as a result of radiation from the fire gases to surfaces and objects in the room.

Several of these properties related to hot fire gases and the energy content of fire gases are discussed in more detail elsewhere in the book.

Fire ventilation can affect the composition and properties of the fire gases. During tactical assessments, the flammability, toxicity and reactivity of the fire gases must be taken into account.

Chapter 4

The spread of fire gases

Fire gases flow from higher pressure to lower. It is then, among other things, the difference between the higher and the lower pressure that determines how large the flow of fire gases is and how fast this flow occurs. Normally, only small differences in pressure occur in fires, with a few exceptions. In addition, any pressure differences strive to be equalized, which also contributes to the pressure differences normally being small. Actual and measurable pressure differences really only occur when the flow of fire gases (or air) or the expansion of fire gases is limited or restricted for some reason.

But there are also a number of other factors that affect how fire gases flow and how gases are spread within the building and out of buildings. Examples include the number of openings between rooms, the size of the openings, wind conditions, the size of the fire, how the fire develops and spreads, and ventilation systems (for comfort) in the building. In addition, the density of the fire gases (the thermal buoyancy) has a major impact, possibly more so than other pressure differences. These factors can cause fire gases and fire to spread long distances and in ways that are not always easy to predict. With knowledge of the factors and how they affect each other, the spread of fire gases can still be predicted or prevented to some extent. Sometimes it is even possible to change the flow path of the fire gases and direct the fire gases through and out of a building so that fire ventilation is to our benefit and is carried out in a controlled manner. However, it can be very difficult to create an overall picture of how all these factors affect the spread and flow of fire gases in buildings.

The flow and spread of fire gases

It is well known how fire gases flow and spread in a room with a fire in it and between rooms when there is a fire in a building. But when the whole building is affected by fire, the problem becomes more complex. Then there are a large number of factors to consider and all these factors are rarely known, especially not during firefighting operations. In addition, during a fire, there is rarely or never any opportunity to make a more comprehensive analysis of the factors affecting the flow and spread of fire gases. However, it is important to understand what the important factors are and how they affect each other on the whole. Otherwise, it will be difficult to be able to control the flow and the spread of fire gases in a building and out of the building in a controlled way.

The factors that mainly control and influence how fire gases flow and spread inside and out of a building are

- thermal buoyancy (differences in density)
- thermal expansion
- production of combustion products
- temperature differences between indoor and outdoor air
- external wind conditions
- ventilation systems for comfort.

The latter three are factors that can be considered normal, in the sense that they always exist regardless of whether there is a fire or not. The first three, on the other hand, are factors that arise when a fire starts in a building. Broadly speaking, these three, or at least the first two, are based on the energy supplied by the fire. It is therefore mainly how the fire develops and the supply of energy that has an impact on the flow of fire gases inside and out of a room or building as well as the amount of air flowing in. If we can limit this supply of energy in different ways, e.g. by getting extinguishing agents on the fire, we have also limited the production of fire gases. Bear in mind that thermal buoyancy can apply even when it is not burning, especially in tall buildings.

In addition, when fans are used, they produce direct pressure differences. This is done by the fans creating a high pressure in a space or towards an opening, which then leads to differences in pressure between different spaces in the building or between the building and its surroundings. By using fans we add pressure energy and kinetic energy, and that energy is used to counteract the fire's supply of energy.

Consequently, some of these factors occur under normal conditions, i.e. when there is no fire, while others occur when there is a fire. In some cases, the factors themselves are the same, but become more pronounced or change in character when a fire occurs.

The Bernoulli principle

The Bernoulli principle describes the relationship between pressure and velocity in a frictionless flow of incompressible fluids (gases and liquids). It applies only under highly idealized conditions: the flow should be stationary, incompressible, isothermal, friction-free and adiabatic. It is thus not really applicable to fire gases (or air) but still works well enough in calculations of, for example, flow of fire gases.

Pressure and velocity for flowing fire gases can then be described according to the following equation (the Bernoulli equation) provided that no heat is applied to the fluid or no mechanical work is done:

$$\frac{P}{\rho g} + \frac{v^2}{2g} + h = \text{constant}$$

Where

P = static pressure [Pa]

ρ = density [kg/m³]

g = gravity, 9.81 m/s²

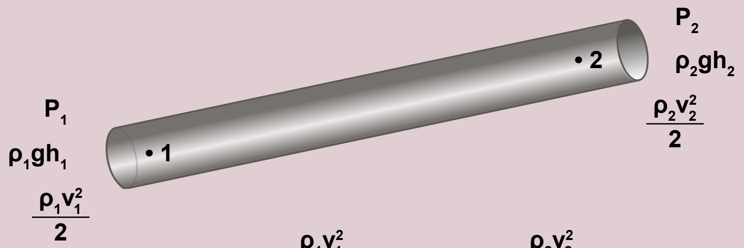
v = velocity [m/s]

h = height above a reference level

A practical application of the Bernoulli equation is to be able to calculate the velocity of the gas using a so-called pitot tube (or a so-called bi-directional probe, which is often used in fire science). By measuring the pressure difference across the pitot tube, the velocity can be determined using:

$$\Delta P = \frac{\rho v^2}{2}$$

Using the Bernoulli equation, it is possible to derive and analyze what the flow may look like in a building and thus also get an image of how fire gases can flow.



$$P_1 + \rho_1 g h_1 + \frac{\rho_1 v_1^2}{2} = P_2 + \rho_2 g h_2 + \frac{\rho_2 v_2^2}{2}$$

Hot fire gases have a lower density than the surrounding cooler air. The fire gases therefore rise upwards and form an upper layer of hot fire gases below the ceiling.

Thermal buoyancy

Hot air is lighter than cold air and the same applies to fire gases. The density of fire gases is inversely proportional to the temperature, which means that as the temperature increases, density decreases. For example, air at 20 °C has a density of 1.2 kg/m^3. Air (and fire gases, by assumption) with a temperature of 300 °C has a density of 0.6 kg/m^3. If the temperature is 500 °C, the density of the fire gases is 0.45 kg/m^3. We call this thermal buoyancy, i.e. the ability of fire gases (and air) to rise and flow upwards as they are heated.

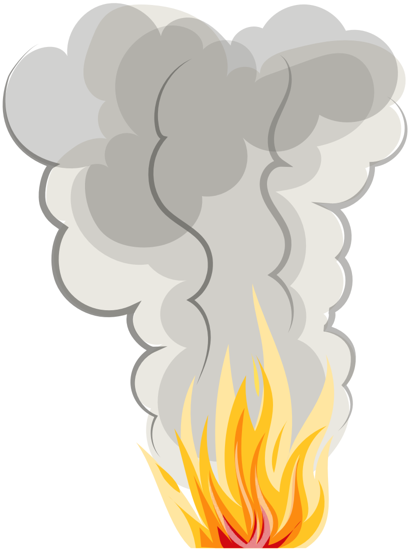
The combustion products from the fire form a so-called plume – an upward-flowing "cone" of gases and particles above the fire – which is warmer than ambient air and thus will rise upwards. In addition to air flowing into the fire itself and participating in the combustion, air is also mixed into the plume as it flows upward. This air is then heated. The combustion products and the heated air together form the fire gases, which then have a lower density than the surrounding cooler air.

The lower density of the hot fire gases causes them to rise upwards and form a layer of hot fire gases which collects under the ceiling.

How thick this hot layer of fire gases gets depends, among other things, on the volume of the space, the height of the openings, the rate of heat release from the fire and the rate of growth of the fire. At the same time, we get a lower colder layer, which for the most part consists of unaffected air. An example of thermal buoyancy can be when hot fire gases flow upwards and fill a staircase. It can also be seen in openings to a building or to a fire room, where hot fire gases flow out through the upper parts of the openings and fresh air flows in through the lower.

The fire gases are cooled as they rise, partly because they mix with colder air, and partly because of heat transfer, mainly convection against the walls (or objects in the room). This means that the fire gases in tall buildings may not reach the roof, but may instead stop or even sink. This can happen especially on hot summer days when the air closest to the roof or in the upper part of the staircase can be warmer than the fire gases. Similarly, fire gases can sink to the floor as they flow in a long corridor, or in a tunnel, and cool off against ceilings and walls.

The fact that a hot upper layer of fire gases is formed and that the fire gases flow out through the upper part of openings is based on differences in density and thermal buoyancy.



Hot fire gases have a lower density than the surrounding cooler air and rise upwards.

Thermal boyancy

The pressure differential over a hot layer of fire gases, due to thermal boyancy, can be calculated through the use of the following expression:

$$\Delta P = (\rho_a - \rho_g)\, gh$$

where ρ_a is the density of the air below the hot fire gases, ρ_g is the mean density of the fire gases, **g** is gravity and **h** is the height (depth) of the hot layer of fire gases. This can be rewritten as:

$$\Delta P = \left(\frac{353}{T_a - T_g}\right) gh$$

where T_a is the air temperature below the hot fire gases, and T_g is the mean temperature of the fire gases. Temperature should be given in Kelvin.

Assume a room with a 1 m deep layer of fire gases. The mean temperature of the fire gases is 400°C. The pressure differential due to thermal boyancy over the layer (from underneath the hot layer to the top of the hot layer) is approximately 9 Pa. However, this does not correspond to an actual pressure in the fire gases.

Thermal expansion

In addition to the fire gases being hot, having a lower density than colder air and thus rising upwards, the air flowing into the plume will heat up and expand. The heated air takes up more space than the cold air.

In the event of a fire in a completely closed room, a pressure buildup will occur as a result of the air heating up and expanding. It does not have to burn in order for such thermal expansion to occur, but in spaces without fire the pressure becomes small. However, during a room fire where the temperature can reach several hundreds of degrees, this pressure differential can have a significant effect, especially if the fire develops rapidly or in small spaces (low volume).

Normally, there is some air leakage in the fire room, e.g. in the form of ventilation for comfort or leaks around windows and doors. Since a fire in a room is normally growing, the pressure due to leaks will be leveled off gradually. Therefore, the pressure increase will normally only be in the order of a few single Pascal, if there is even a pressure increase in the room at all. This is largely due to the size of the openings in relation to the fire's growth rate, but also the time matters as there is a pressure equalization over time.

If a fire room is closed, an increase in pressure occurs in the room. Fire gases can then be pushed, for example, out through window cracks.

Fire gases that are heated, expand and take up more volume, which causes the pressure in a closed room to increase.

Pascal

Pressure is measured in the unit Pascal [Pa]. 1 Pa is the same as 1 N/m^2 (1 Newton per square meter) or 10^{-5} bar (0.00001 or ten millionth part bar). 1 Pa corresponds to roughly the pressure of a regular A4 paper lying on a table exerted against the table surface. The normal air pressure is 101 325 Pa.

Thermal expansion

During a fire in a completely sealed room, there will be an increase in pressure as a consequence of the heating and expansion of the air in the room. This increase in pressure can be calculated using the following expression:

$$\Delta P = P_a \frac{\dot{Q}t}{V\rho_a c_p T_a}$$

where $\mathbf{P_a}$ is the surrounding pressure (initial pressure), $\dot{\mathbf{Q}}$ is the rate of heat release, **t** is time, **V** is the volume of the room, $\boldsymbol{\rho_a}$ is the mean density of the air in the room, $\mathbf{c_p}$ is specific heat capacity of air and $\mathbf{T_a}$ is the mean temperature in the room.

For a sealed room with a volume of 60 m^3 and with a stationary fire of the size of 100 kW, the maximum pressure build-up is approximately 1500 Pa per second (the pressure grows linearly with time). However, as the space is heated by the fire, the pressure build-up will decrease gradually. But for a sealed room, the pressure can be considerable even for a relatively small fire.

For a more realistic room with leaks at floor-level, the pressure build-up can be calculated using the following expression:

$$\Delta P = \left(\frac{\dot{Q}}{c_p T_e A_e}\right)^2 \frac{1}{2\rho_e}$$

where $\boldsymbol{\rho_e}$ is the density of the air flowing out, $\mathbf{c_p}$ specific heat capacity of the air flowing out, $\mathbf{T_e}$ is the temperature of the air flowing out and $\mathbf{A_e}$ is the area of the opening (the leakage).

In such a room with a leakage area of 0.02 m^2 (i.e. an opening measuring 10×20 cm), the maximum pressure will be approximately 100 Pa. If the room has an open window 1 m^2 in size, the maximum pressure will be approximately 0.1 Pa, i.e. very small.

In a room with a growing fire, i.e. what usually is referred to as a normal room fire, the pressure due to thermal expansion will in reality be non-existing.

Production of combustion products

The fire adds combustion products that affect how fire gases are spread inside and out of the building. Although fire gases can broadly be regarded as heated air in calculations or estimates of the flow and its spread, it is not possible to completely ignore how the production of fire gases affects this flow. The difficulty with this is that the amount of fire gases produced is dependent on properties of the fuel. It also distinguishes between fuel controlled fires and ventilation controlled fires.

The amount of combustion products from the fire supplied to the fire gases (in the upper layer) will, for a closed room, also contribute to the pressure buildup in the room, in the same way as the thermal expansion. But even in this case, this pressure will be relieved relatively quickly, due to leaks in the design (comfort ventilation, window and door leaks, etc.). And even in a closed room, the amount of combustion products supplied is very small and its impact on the pressure buildup becomes small.

Production of combustion products

During fuel control, wood produces approximately 1.33 grams of CO_2 per gram of fuel, while propane produces 2.85 grams of CO_2 per gram of fuel. During the ventilation controlled case, wood produces 0.14 grams and propane 0.23 grams of CO_2 per gram of fuel.

Temperature differences between indoor and outdoor air

Air is normally warmer indoors than outdoors, particularly in Sweden. As previously described, air expands when heated, takes up more space and also has lower density than cold air. This causes the air supplied to a building to heat up and rise. Virtually all buildings have leakages or openings higher up in the building. The heated air flows out of the building through these leakages higher up in the building. Also, the expansion that occurs when the air is heated will help the heated air to flow out as it takes up more space. Thus, since a building is rarely or never completely tight, (heated) air will always flow out of from the building and, at least eventually, be replaced by cold air flowing in. If the openings are small, there may be a pressure buildup inside the building. However, the pressure differences that arise are small. In addition, the pressure differences are evened out as the air flowing into the building heats up and flows out again. The main driving force for this flow of air is thermal buoyancy (warm air rising upwards).

Flow or air into a building normally occurs through one opening and outflow through another. If the openings are large, inflow and outflow can occur through the same opening. The warm indoor air rises upwards, which means that outflows normally occur through high orifices and inflow through low orifices. Just as when there is a fire, it is mainly thermal buoyancy (density differences) that drive this flow, even though the density differences in normal mode are smaller than in the case of fire. Thus, in low buildings or on the same floor, the differences in density are relatively small, while in tall buildings they can be very large (even when there is no fire). This may apply to multi-storey high-rise buildings, but also warehouses or industrial halls with high ceilings. In tall buildings with vertical shafts, e.g. stairwells or elevators, then an upward flow of air is formed in the shaft. This upward flow of air can affect how both fresh air and fire gases flow into or out of the shaft and give rise to complex dispersion conditions.

In high-rise buildings or in buildings with a high ceiling, especially during hot days, there can be a volume of warm air closest to the ceiling or at the top of a staircase. If there is a fire producing fire gases, and these fire gases maintain a relatively low temperature (or are cooled as the rises), this volume of warm air can counteract the fire gases rising upwards. The heated air inside the building is simply warmer than the fire gases, which can make it difficult to ventilate the fire gases.

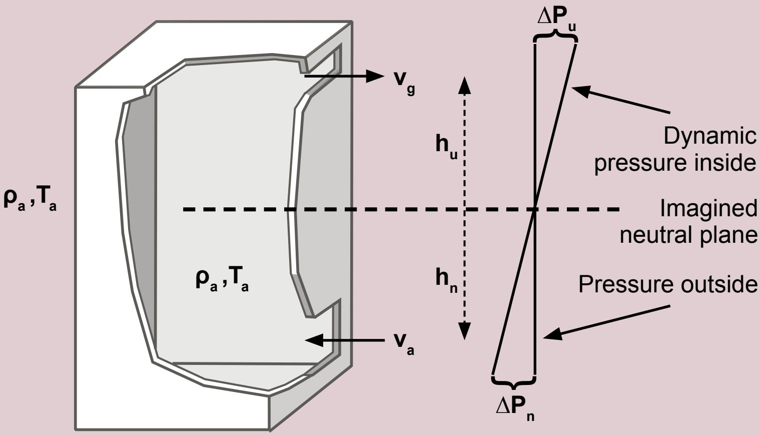
In buildings with openings both at the top and at the bottom, a so-called stack effect can occur. This is similar to what can be observed for example in a stove with a chimney, where fresh air flows in at the bottom, is heated by the fire, rises upwards and flows out at the top of the chimney. The flow of the gases can be calculated using Bernoulli's equation. This stack effect can be particularly noticeable in so-called structural fires, since the spaces where such fires occur and spread can in some cases be similar to a chimney. The cross-sectional area is relatively small in relation to the height (or length) of the space.

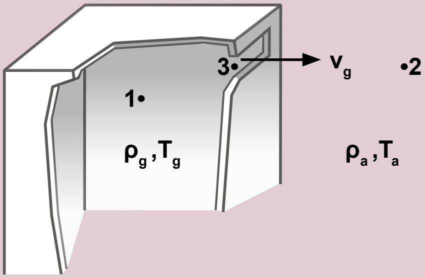
In tall buildings with staircases, the stack effect may be the dominant cause of the spread of fire gases. For such buildings, the flow of fire gases can be extremely complex, and extensive and time-consuming calculations would be required to investigate it. This is not possible during fire and rescue operations. The stack effect, which is basically based on thermal buoyancy can cause fire gases that spread to the staircase to be pushed into apartments in the upper parts of the building, while air can be sucked into the staircase from the apartments in the lower parts of the staircase. However, there are major uncertainties in this assumption, not least because there are several complicating factors that can have an impact. Examples of such factors can include external wind conditions, the height of the staircase, the level (floor) where the fire is, if there are any openings between the staircase and apartments, openings between apartments and the outside of the building, the size of such openings, etc. But in particular in high-rise buildings, it is important that staircases are kept free of fire gases to the greatest possible extent, to facilitate evacuation.

Stack effect

Let us assume we have a stove with an opening at the bottom and an opening at the top (i.e. a stove with a chimney). The air flowing into the bottom is heated in the stove. The ambient air has the temperature $\mathbf{T_a}$ and the density $\boldsymbol{\rho_a}$ and the heated air in the chimney has the temperature $\mathbf{T_g}$ and the density $\boldsymbol{\rho_g}$. The upper opening (the top of the chimney) is at a height $\mathbf{h_u}$ above the neutral plane, i.e. an imagined plane where the dynamic pressure inside the chimney is equal to the pressure outside. The lower opening is at height $\mathbf{h_n}$ below this intended neutral plane.

In order to calculate the velocity and flow of the flowing gas, we first need to calculate the pressure difference at the openings, $\Delta \mathbf{P_u}$ and $\Delta \mathbf{P_n}$, respectively. Note that these calculated pressure differences are only valid at the openings.





We simplify the problem by studying only points 1, 2 and 3 in the upper part of the chimney. The hydrostatic pressure difference between point 1 and point 2 is calculated by:

$$v_1 = v_2 = 0$$

$$P_1 - P_2 = \rho_2 g h_2 - \rho_1 g h_1 \qquad \Delta P_u = h_u g(p_a - p_g)$$

Equation 1

The dynamic pressure differential between points 1 and 3 calculated by:

$$v_1 = 0 \qquad \rho_1 = \rho_3 = \rho_g, \qquad h_1 = h_3 = h_u$$

$$P_1 - P_3 = \frac{\rho_3 v_3^2}{2}$$

$$\Delta P_u = \frac{\rho_g v_g^2}{2}$$

Equation 2

The velocity through the upper opening can be detemined using equations (2) and (3):

$$\frac{\rho_g v_g^2}{2} = h_u g(\rho_a - \rho_g)$$

$$v_g = \sqrt{\frac{2h_u g(\rho_a - \rho_g)}{\rho_g}}$$

Equation 3

The relationship between temperature and density is given by the ideal gas law, and we can use this to determine the relationship between density and temperature. For atmospheric pressure we get the ratio:

$PM = \rho RT$	ideal gas law
$P = 101.3\ \text{kPa}$	atmospheric pressure
$M = 0.0289\ \text{kg/mol}$	molar mass for air
$R = 8.314\ \text{J/Kmol}$	Boltzmann's constant (ideal gas constant)
$\rho = \frac{353}{T}$	simplified correlation between density and temperature (T in Kelvin)

Mass flow in an opening is given by: $\dot{m} = C_d A v \rho$

Determining the flow into the lower opening correspondingly and equating the results, an expression of the position of the neutral plane in relation to the size of the openings is obtained:

$$\frac{h_n}{h_u} = \left(\frac{A_u}{A_n}\right)^2 \frac{\rho_g}{\rho_a}$$

Equation 4

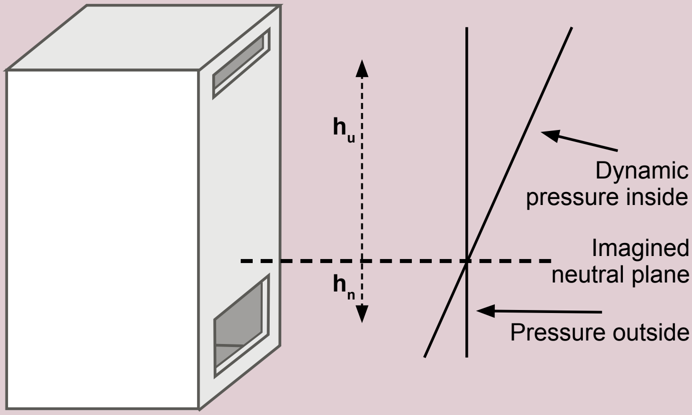
or, expressed in terms of temperature:

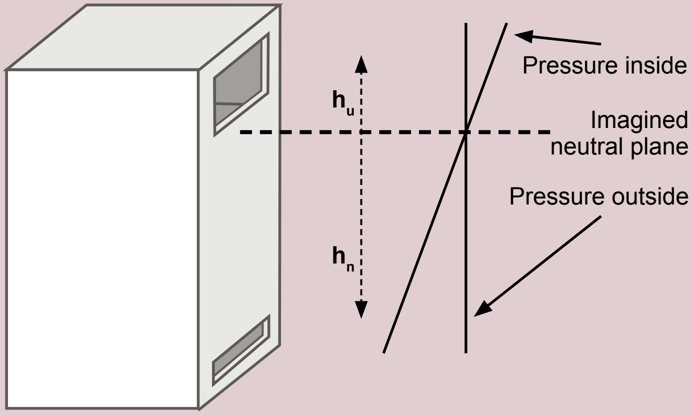
$$\frac{h_n}{h_u} = \left(\frac{A_u}{A_n}\right)^2 \frac{T_g}{T_a}$$

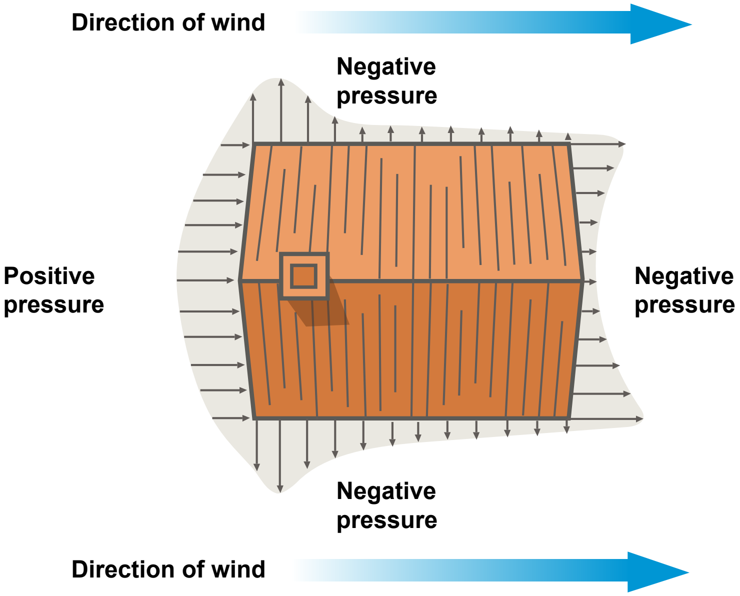
Equation 5

This implies that if $\mathbf{A}_n$ is large in relation to $\mathbf{A}_u$, $\mathbf{h}_n$ becomes small, which results in a large pressure differential over $\mathbf{A}_u$. This is desirable, for example, in a chimney to get good "draft" (stack effect), but also in the case of thermal fire ventilation (using thermal boyancy only). Equation 5 thus provides an indication of how the relationship between the size of inlet openings and exhaust openings should be, in the case of using thermal buoyancy only. Note, however, that it must be the size of the exhaust opening that is decisive for the size of the inlet opening, not the other way around. Thus, the need for exhaust opening, its size, placement etc. must be determined first.

Keep in mind that this doesn't necessarily correspond to any actual pressures in the fire gases. It is merely a way to calculate flow and velocity in openings, ducts or similar.







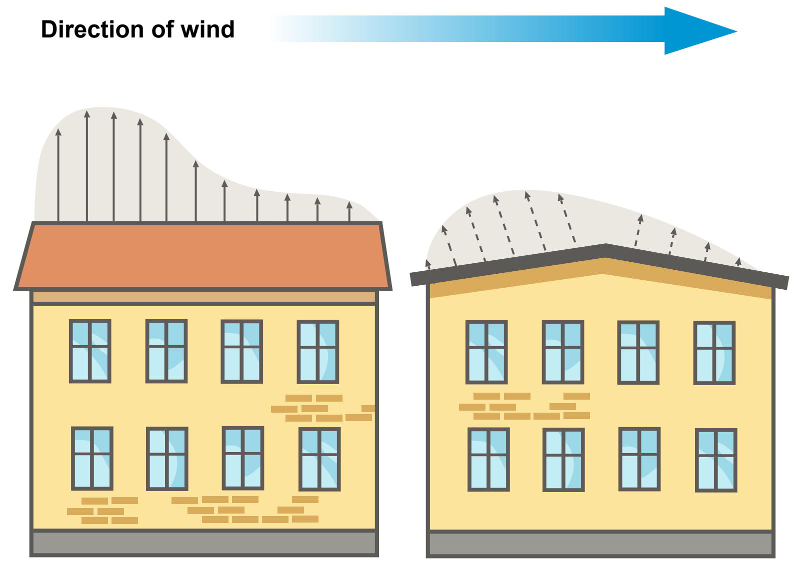
Pressure distribution due to wind on a building (view from top).

External wind conditions

All buildings more or less have leaks and in many cases the wind can have a very big impact on how fire gases flow into or out of a building. And although the building is relatively sealed, the wind will put pressure on the building's exterior walls. This in turn can cause pressure differences between the various sides of the building which also may affect the flow of fire gases out of the building and the flow of air into the building.

The wind pressure towards a building is proportional to the wind speed squared. This means that if the wind speed increases from 1 m/s to 10 m/s, then the pressure on the windward side of the building increases from e.g. 0.4 Pa to 40 Pa or from 0.6 Pa to 60 Pa (typical values). Even a relatively mild wind can cause pressure differentials between the different sides of the building which affect the flow of fire gases and air.

Vertical surfaces (walls) normally get an overpressure on the windward side (perpendicular to the wind) and negative pressure on the leeward side (opposite/parallel side to the windward side). The negative pressure on the leeward side is about half of the overpressure on the windward side. On roof surfaces exposed to wind, the pressure depends on the angle of the roof. At roof angles above approximately 45°, an overpressure is created on the windward side and a negative pressure on the leeward side. Both the overpressure and the underpressure are greatest at the eaves and gradually decrease towards the ridge of the roof. At roof angles below about 30°, the entire roof is exposed to a negative pressure.



Roof angle <30°

The distribution of pressure over a flat roof. There is normally a negative pressure over the entire surface of the roof.

Roof angle 30–45°

Roof angle >45°

The pressure varies from negative pressure to positive pressure, depending on the angle of the roof and where you are located on the roof.

This negative pressure is greatest towards the windward side of the building. But at roof angles between approximately 30° and 45° there can also be negative pressure on the windward side closest to the roof ridge.

Gable roofs can be subjected to negative pressure on the entire surface (both sides) if the wind blows parallel to the roof ridge, regardless of the roof angle.

The pressure differentials that occur depending on the roof angle can in some cases be exploited to produce an improved fire ventilation effect than if only thermal buoyancy is used.

Fire ventilation through windows and doors can be improved if exhaust openings are made on the leeward side of the building while inlet openings are made on the windward side. This places great demands on the openings being chosen with care and that the wind direction can be determined with some certainty. This is not always possible. If there is uncertainty regarding wind conditions and how this can affect the flow of fire gases inside or outside of the building, you should avoid smashing windows or producing openings. Should the ventilation measures not work, it will be difficult to close the opening again if for example a window is broken.

Due to the friction against the ground surface, the wind speed, and also the pressure towards buildings, also varies with the height. Friction varies depending on the characteristics of the surface.

The wind can behave quite differently when blowing within and past many buildings compared to wind blowing in open terrain or at high altitudes. Along streets, it can be constricted so that air velocity is greater than expected. In addition, the turbulence that is often created around buildings can cause the wind to take a completely different direction than expected. In open areas (squares and parks) where streets meet, very complex wind conditions can occur.

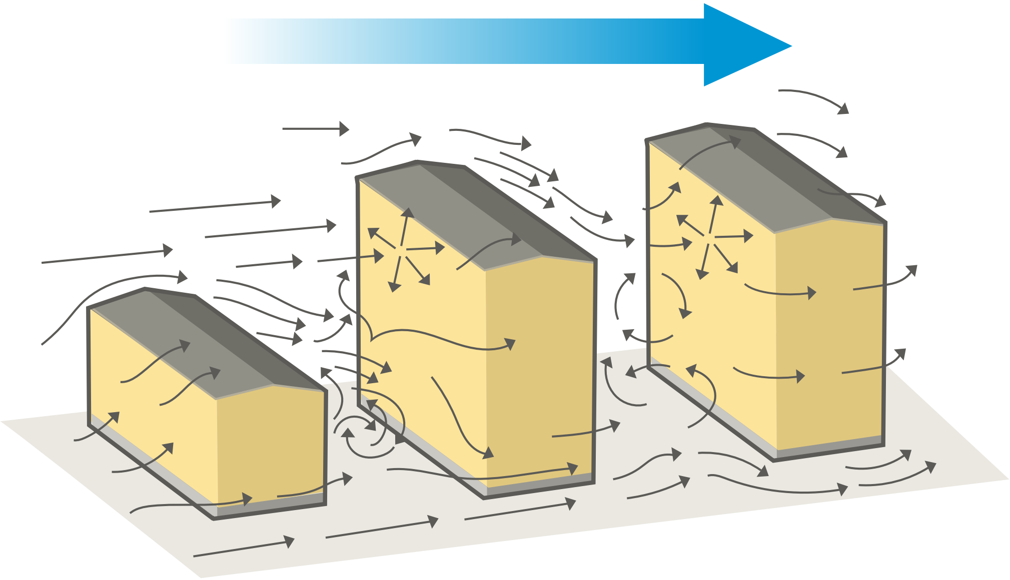
In summary, the wind is an aggravating factor for fire ventilation. In part, it can be difficult to determine the wind force, other than in terms of high or low. Secondly, it can be difficult to determine the wind direction, which then causes difficulties in determining where it is best to create inlets and exhaust openings, respectively. It is also difficult to determine how much pressure the wind contributes, other than in terms of large or small. It should be kept in mind that if fire ventilation measures do not work, it may be because the wind conditions are not favorable.

Calculating pressure due to wind

The stationary pressure exerted by the wind on a building can be calculated by:

$$\Delta p = 0{,}5 c_f \rho_a v^2$$

where c_f is the form factor, ρ_a is the density of the air and v is the velocity of the wind. The form factor varies depending on the ground surface as well as on the size and shape of the building. It varies from 1 (corresponding to 100% overpressure) to -1 (corresponding to 100% negative pressure). The expression is used for the design of buildings against wind load, but it may also give us an idea about how wind creates pressure on and around a building.



There can be very complex wind conditions around squares, parks, streets and buildings in the center of a city.

Wind-driven fires

In a number of notable cases, especially internationally, and as a result of these cases, a phenomenon called wind-driven fires has been shown to occur. These are fires in buildings that spread rapidly or that otherwise become violent as a direct result of more or less severe wind conditions.

The cases that have occurred and which clearly exhibited this phenomenon have mainly been in tall buildings where the wind has had a clear impact on the various sides of the building. This phenomenon can be likened to the draft that can be created when we open windows on both sides of a building to air.

A typical example could be when a window on the windward side of a building has failed and fallen out as a result of a room fire. If the fire service makes an opening on the leeward side of the building (as an attack route), then conditions can be created for the wind to be able to "push" fire from the fire room towards firefighting personnel. There are few, if any, ways to counter this once it has occurred. Instead, attacks must be made from the windward side, or the inlet opening on the windward side has to be closed again.

Wind-driven fires can cause major concerns for the fire and rescue service. Especially if there is a strong wind against an opening to a room fire so that heat, flames and fire gases are pushed against personnel. In the picture, the inlet opening is on the other side of the building, causing the wind to push flames out on this side.

In order to be able to close windows on the windward side, the New York Fire Department has developed a "curtain" that can be dropped from the floor above. This is mainly the situation when buildings are so high that ladder platform vehicles cannot reach the floor exposed to fire. This method also requires that the window to the fire room can be easily reached from the floor above. This is usually difficult to achieve in modern tall buildings, since it is not always possible to open the windows there, and they can also be difficult to break.

In the Swedish case, the number of high-rise buildings is increasing where this type of phenomenon could possibly occur, and the problem should, of course, be addressed. At the same time, windows in such buildings should normally be able to withstand fire for a relatively long time. The risk of wind-driven fires is thus small, but cannot be excluded.

This phenomenon can also occur in buildings that are lower, possibly even in single-storey buildings, if the wind conditions are unfavorable. Particular attention should therefore be paid to this problem during firefighting operations in buildings in windy conditions.

On roof surfaces, a positive pressure is generally created on the windward side and a negative pressure on the leeward side. Even gabled roofs can be subjected to negative pressure over the entire surface if the wind blows parallel to the roof.

Ventilation systems for comfort

Ventilation systems are designed to let fresh air in and to vent our heat, residual products from our breathing (carbon dioxide), moisture and cooking smells. In the latter case, the term kitchen flue is used for vents from stoves and cooking ovens if they are ventilation ducts specifically from kitchens. These ducts are usually separated from other ducts and also from building components, due to the risk of fire.

There are essentially two types of ventilation systems for comfort:

- natural ventilation
- mechanical ventilation.

Comfort ventilation systems are normally designed to limit the spread of fire and fire gases to adjacent fire compartments. This is achieved for example by insulating ventilation ducts with non-combustible insulation. The ducts are provided with different types of dampers that automatically close when a fire occurs. The ventilation ducts can also be completely separated between the different fire compartments. The ventilation system should in principle have corresponding protection to help combat the spread of fire and fire gases as in the rest of the building, i.e. the ventilation system must correspond to the fire compartment's level of protection against the spread of fire and fire gases.

It should be noted that the description of ventilations systems here, is primarily valid for the Swedish case.

Natural ventilation

Ventilation systems based on natural ventilation work by making use of the temperature differences that occur naturally in buildings, in buildings' shafts and in ducts. These systems are designed as exhaust air systems, i.e. the ventilation ducts are normally intended for exhaust air only. Supply air is taken in through natural leaks in the building or through air vents in the facade. In older buildings, fireplaces and stoves are often used as exhaust ducts. From the 1920s, separate ducts were often installed for supply and exhaust air, respectively. Natural ventilation is now almost exclusively found in vacation homes due to higher demands on energy conservation, so that even smaller single-family homes (and similar) often recycle exhaust air so that heat is returned to the supply air.

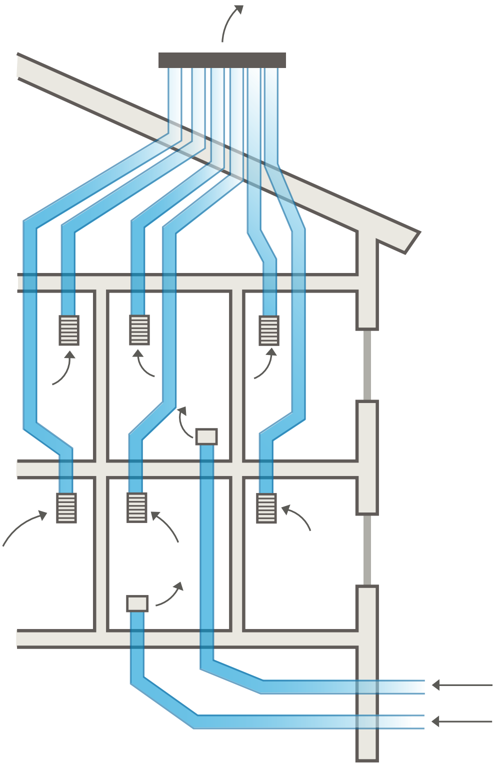
Natural ventilation systems normally do not contribute to the spread of fire gases between fire compartments since this type of ventilation usually has separate ducts. On the other hand, such systems can also allow fires that are ventilation controlled to continue, as the fire still has access to air flowing in. If there is a spread of fire to the ventilation ducts, there may be a risk of structural fires and a risk of fire spread to adjoining rooms, as the temperature can get high inside the ducts, just as in chimney fires.

Mechanical ventilation

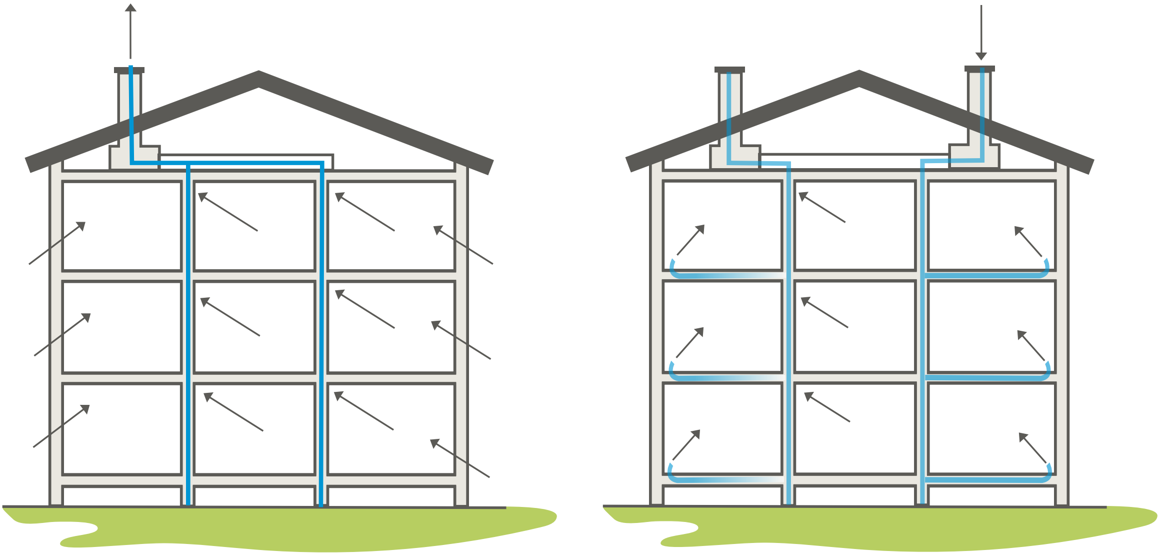
Mechanical ventilation systems can be designed in one of the following ways:

- **Supply air systems:** Fans supply air through ventilation ducts. The exhaust air is pushed out through leaks or adjacent spaces. The system creates a more or less large overpressure in the fire compartment, depending on how it is designed.
- **Exhaust air systems:** Fans extract air through ventilation ducts. The supply air is drawn in through leaks, from adjoining rooms or through vents in the facade. The system creates a more or less large negative pressure in the fire compartment, depending on how it is designed. The exhaust air in these systems is normally taken from the kitchen, laundry or bathroom.
- **Open supply and exhaust system:** Fans connected to a room will provide supply air and exhaust air through separate ducts. Exhaust air is also allowed to flow through leaks both to the surroundings and to adjacent spaces.
- **Closed supply and exhaust system:** Fans connected to a room will provide supply air and exhaust air through separate ducts. This type of system is becoming more common, due to demands for energy conservation.

Normally, the risk of the spread of fire gases to adjacent areas within the building is small, as long as the mechanical ventilation systems are in operation. If all or part of the mechanical ventilation systems cease to function, this can greatly contribute to the spread of fire gases within buildings. This can be a problem especially with open and closed supply and exhaust systems since the various fire compartments can be connected through ventilation ducts. Normally, the spread of



Natural ventilation is common in buildings from the 1920s.



In buildings erected since approximately the 1960s it is common to find different types of mechanical ventilation systems.

fire gases (and also of cooking odor, etc.) is prevented by the pressure difference above the ventilation device ("the hole in the wall"). If the ventilation system ceases to function, this pressure difference disappears and fire gases can easily spread through the ventilation ducts between the various fire compartments or rooms. When mechanical ventilation systems are functioning, the risk of fire gases spreading through the ventilation system is small. If the ventilation system ceases to function, this can contribute to the spread of fire gases between fire cells within buildings.

A modern ventilation system can be an integral part of the building's protection against fire, especially in public premises, office premises or similar. The design and function of the ventilation system is then based on how a fire may develop. The system can, for example, be controlled so that escape routes are pressurized or by opening ventilators in the fire-exposed compartment only. By ensuring the functioning of the ventilation system even in the event of fire and as long as the dimensioned fire protection is not exceeded, the system may manage to prevent the spread of fire and fire gases for quite some time. In such cases, it is important to ensure that the ventilation system continues to function, for example through the fire and rescue service putting in place additional measures to protect the system. There may also be reasons to check and ensure penetrations (for cables and similar) or the like, especially in walls, trusses and boundaries to fire compartments, so that fire gases do not spread.

Spread of fire gases in practice – a holistic view

The flow of fire gases that move within and move out of a building where there is a fire, is affected mainly by six factors, as described in this chapter:

- thermal buoyancy (differences in density)
- thermal expansion
- production of combustion products
- temperature differences between indoor and outdoor air
- external wind conditions
- ventilation systems for comfort.

The different forces and mechanisms in and around a burning building are of the same order of magnitude. This means that the spread of fire gases is extremely complex and difficult to assess.

In reality, it is not possible to consider these forces separately, but we must deal with them simultaneously. However, in order to try to simplify and provide some kind of overall picture, the following argument will disregard the factors external wind conditions, comfort ventilation and temperature differences between indoor and outdoor air. Consequently, already at this point I have made significant limitations to the flow of fire gases.

Let's assume that we have a room that is completely closed and that a fire starts in this closed room. Thus, there is no exchange with the outside environment with respect to either gases or particles. As the fire starts, the temperature in the room rises due to the addition of energy from the combustion. As a direct result of the increase in temperature, the pressure in the room will also increase. This pressure increase is directly proportional to the temperature increase.

In addition, the combustion process itself adds mass to the gas in the room. The fuel, in this case in solid or possibly liquid form, forms combustion products as it burns. Thus, a portion of the mass that initially forms the fuel will be supplied to the room in gaseous form or as particles. This will also to some extent add to the increase in pressure in the room, although this is most likely a very small contribution.

If the room has one or more openings, the increase in pressure will be equalized as the fire gases flow out of the opening. The speed of this equalization depends, among other things, on the size of the opening or openings. In part, it may also depend on how far away from the fire the opening or openings are. This is mainly the case for very large buildings or if the building has several rooms that connect the primary fire room with the opening or openings to the exterior. It will then be the opening or openings between these rooms that will determine how quickly the pressure in the fire room (and also in other rooms) equalizes.

In a room that has a small opening relative to the size of the room, or in a room where a fire is growing rapidly, the pressure in the room may be relatively high for a long time. From the outside, this can be seen by the fact that fire gases clearly flow out through openings, possibly at some velocity or flow perceived as "high" or "large".

This can also cause the pressure to drop as the temperature drops in a relatively closed room or in a relatively closed building. For example, this may occur when the fire becomes ventilation controlled, pre-flashover or post-flashover. If this occurs, it may not be possible to see there is a fire in the building. As the temperature and thus the pressure in the building drops, air will flow into the building and no fire gases will necessarily be visible from the outside, although there is still an ongoing (ventilation controlled) fire in the building. Eventually, the pressure will be equalized by air flowing in. This addition of air then allows the fire to grow again, the temperature and thus also the pressure will increase and fire gases will be pushed out. This pulsating effect can continue for a long time and result in a strong ventilation controlled fire in a room where the temperature is still high. If the space is opened, a so-called backdraft can occur.

What is described above is the pressure that results from thermal expansion in closed rooms or in a closed building. In addition, combustion products are produced which also may contribute to increasing pressure in the room. It also describes what happens if the room, or the building, has a relatively small opening. This is usually the case in most buildings, which usually have leakages in some way. Although pressure builds up in the building as a result of fire, this will normally be equalized relatively quickly.

Instead, let us assume that we have a room with a relatively large opening in relation to the size of the room. It may, for example, be an ordinary bedroom with the dimensions 5 × 3 m and a 2.5 m ceiling height and with a door which is 2 × 0.8 m. In this room a fire is started. Since the room is open and the opening is relatively large in relation to both the total volume of the room and in relation to the fire (and to the growth of the fire), there will be no actual pressure in the room (or a very small pressure). The pressure is simply equalized, as fire gases flow out and air flows in.

The combustion products from the fire form a plume that is warmer than the ambient air and which will rise upwards (this of course also happens in a closed room). The air that flows into the room which flows into the plume will heat up also. The combustion products and the heated air then have a lower density than the surrounding cooler air. As described earlier, for simplicity's sake, we can consider the fire gases that are formed as hot air. The density of these fire gases is inversely proportional to the temperature. As previously discussed, air at 20°C has a density of 1.2 kg/m^3. When the temperature of the air (and fire gases) is 300°C, the density of the air is 0.6 kg/m^3. If the temperature is 500°C, the density of the fire gases is 0.45 kg/m^3. The density differences quickly become large even though we have relatively small temperature increases.

The lower density of the hot fire gases causes them to rise upwards and form a hot upper layer of fire gases which collect under the ceiling. The thickness of this layer of fire gases and the increase in its volume depends, among other things, on the volume of the space, the height of the openings, the size of the fire and the growth rate and the properties of the fuel. As the fire gases reach down to the top of the door, they will flow out of the room and into the next room (or out into the open).

Because the room is open, either directly to the exterior or to one or more other rooms connected to the outside, no greater pressure will arise in any part of the room (or rooms). We are of course assuming here that the opening or openings are large enough so that the outflow of fire gases is not restricted in any way. Instead, it is to a large extent the lower density of the fire gases, thermal buoyancy, which results in a flow of fire gases out of the room and a flow of air into the room. The fire is said to be an "engine" which, by supplying energy (but also mass), drives fire gases upwards and "forces" air to be sucked into the room and up into the plume. But also the thermal expansion and the supply of mass to the fire gases during combustion will of course contribute to the flow of fire gases. The fire gases that are produced simply have to go somewhere, i.e. upwards and outwards from the fire, and as a direct consequence, air will also flow into the room, replacing the air that flows out. This inflow of air normally occurs at floor level because the cold air flowing in has a higher density than the hot fire gases that flow out.

Again, assuming that the room is open either directly to the exterior or to one or more other rooms which are open to the exterior, basically no increase in pressure occurs in the room. Instead, it will be the differences in density that will mainly be the driving force resulting in a flow of fire gases, both inside the room and out of the room (or the building). The hot upper layer of fire gases formed inside the room, and possibly also in a connecting room is then also formed as a direct result of differences in density (thermal buoyancy). There is in many cases a clear difference between the temperature of the different gas layers and thus also the density at the "dividing line" between the hot upper layer of fire gases and the lower layer of more or less fresh air (some mixing normally occurs). It is often possible to clearly feel this difference in temperature between the upper layer and the lower layer. This so-called neutral plane (also known as neutral layer, zero plane, etc.) is thus a boundary where there is a clear difference in density between the upper layer of fire gases and the lower layer of air.

This neutral plane that occurs in a fire room (and possibly also in connected rooms) is largely due to differences in density. As a consequence of this density difference, but also as a result of thermal expansion and the supply of combustion products that occur, fire gases will flow out of the room above this neutral plane and fresh air will flow into the room below the neutral plane (according to the law of conservation of mass).

The conclusion of this discussion is that differences in density (thermal buoyancy) are the main driving forces for the creation of a hot upper layer of fire gases, and that fire gases flow out of the fire room and either into other rooms or directly to the exterior. If the room, or the entire building, is completely or partially closed, differences in pressure can also arise as a direct result of the increase in heat in the room. But this pressure buildup will be equalized relatively quickly for normal buildings, as there are a lot of leakage areas. The equalizing effect causes fire gases to flow from a higher pressure area to a lower pressure area. In addition, the fire produces combustion products, which can also add to the increase in pressure in a closed or almost closed room. This pressure will also equalize relatively quickly in normal buildings as the fire gases flow out through openings or leakage areas.

It is important to remember that the driving forces for the flow of fire gases are of the same magnitude, irrespective of the differences are in terms of density, actual pressure differences between rooms and the effect of the wind on the building, etc. Relatively small changes in the location or size of openings, the size of the fire or changes in wind conditions can have a major impact on how fire gases are spread inside and outside of a building. The purpose of fire ventilation is to change and utilize the conditions in and around buildings in such a way that fire gases (and heat) flow out of the building in a controlled way. At the same time, air flows into the building, which can have consequences for the spread of the fire and for the production of fire gases. This route taken by this air flow is also known as the flow path.

The larger or more complex a building is, the more important it is to make an overall assessment of the situation before doing any fire ventilation.

With different fires in different types of buildings with different conditions, some or all of the factors described above may be more or less dominant. Those making decisions about fire ventilation must therefore determine or make assumptions as to which factors dominate, and take a decision as to what sort of fire ventilation measures are required based on this.

In very tall buildings with shafts (such as staircases), temperature differences between the outdoor and indoor air can cause considerable differences in density between the upper and lower parts of the building. These differences in density can be large, especially in very cold or very warm weather.

Wind can have a very large impact on the spread of fire gases, both within buildings and to other buildings, especially in certain geographical locations or in high buildings.

Ventilation systems for comfort in some types of buildings, especially those with open or closed supply and exhaust air systems, can cause problems with the spread of fire gas. Especially if the ventilation system ceases to function properly.

Fires in closed or semi-closed buildings or rooms create pressure differences due to thermal expansion, i.e. when hot fire gases are restricted from expanding freely and because of the production of combustion products. In fires with large rate of heat release, fires that grow rapidly, or in buildings where the openings are relatively small, these pressure differences can become considerable and contribute to the spread of fire gases. The spread of fire or fire gases is always from an area of higher pressure to an area of lower pressure.

If a fire compartment is defective or if the structure is weakened, for example due to fire, such pressure differences can further weaken the fire compartment or the structure, especially in the event of a very violent or rapid fire development or at high temperatures. Special phenomena such as backdrafts or fire gas explosions can cause building components to break. However, this is unusual. The reason why building components break is rather due to the heat from the fire.

The factors that have the greatest impact vary from case to case. If the wind is heavy, it can produce the greatest pressure difference and thus have the greatest impact on the flow of fire gases. If the fire is very intense and the temperature is high in the fire room and also in the surrounding room, pressure differences due to thermal expansion can have the greatest impact. Correspondingly, it can be thermal buoyancy, which can be the main contributory factor for the spread of fire gases, especially at high temperatures or in tall buildings. The factor or factors that have the greatest impact can also vary during the fire. In the early stages of the fire or in the case of small fires, it may be the comfort ventilation system that has the greatest influence on the spread of fire gases, especially the flow of fire gases that occurs within the fire compartment due to air movements created by the ventilation system. Later on during the fire, the ventilation system can contribute to the spread of fire gases to other fire compartments, especially if the temperature is high or the fire is fully developed.

It is extremely complex to determine how the fire and rescue services should act in these different situations, and the tactical problems must be assessed in each separate case. In the case of fire ventilation the aim should be to get the various factors that influence the spread of fire gases to work together to achieve the intended result.

Chapter 5

Working with fire ventilation

The purpose of fire ventilation is to try to change the flow conditions of the fire gases in a burning building in order to release fire gases to the exterior. These flow conditions change in different ways depending on how fire ventilation is carried out. It can be carried out mainly in two different ways, horizontally or vertically. Fans can also be employed – mechanical fire ventilation. In some cases, a method called hydraulic ventilation can be employed. It is also possible to install smoke curtains in openings to prevent or limit the spread of fire gases. Sometimes there is a risk of so-called wind-driven fires, as described above. You should then consider closing the opening that is on the windward side of the building and avoid further openings before the fire is put out.

As mentioned earlier, sometimes the term flow path is used. The flow path is the route that air takes when it flows in to "feed" the fire in a building and the route that heat or fire gases flow towards or through, to leave the building. The purpose of fire ventilation will then be to change or control the flow conditions in a building so that we can control the flow path . Bear in mind that the physics behind flow-paths is the same as for fire ventilation and if we understand one we will also understand the other. In short: flow path and fire ventilation are pretty much the same thing, simply because they are both based on the same principles.

In general, it is always better to first try to get extinguishing media on the fire, before fire ventilation is carried out.

Size of openings

In general, it is not possible (or it is at least very difficult, especially during an ongoing operation) to specify absolute values for how large openings should be during firefighting operations. However, it is possible to specify certain guidelines for how different openings affect a fire or the flow of fire gases. In order for fire ventilation to have the intended effect, it must be carried out at the right time and in the right place in relation to the location, size and development of the fire. Above all, it is important that both inlet openings and exhaust openings are of a certain minimum size. Crucial to the size of the exhaust openings is, among other things, the temperature in the fire room, which in turn is determined by the size and development of the fire. It is also important what your goals are with a specific fire ventilation measure. There must also be a certain relationship between the size of the inlet openings and the size of the exhaust openings in order for fire ventilation to function as effectively as possible. In order for a certain amount of fire gases to be able to flow out, the corresponding amount of air (at least) must also be able to flow in. When a fan is used, the problem is basically the opposite: since we push large amounts of air into the building, at least the corresponding amount of fire gases must be able to flow out somewhere.

For practical reasons, it can sometimes be difficult to create openings that are sufficiently large. Supporting beams and trusses, supporting or separating walls, and the size of windows or doors can be limiting factors. However, there are certain factors that directly affect how large the openings should be. As an example, a consequence of high temperature in a fire room is that large openings should be made. A high temperature may indicate that the fire is large and produces a lot of fire gases, that there may be considerable thermal expansion and that thermal buoyancy is also considerable. The amount and type of fuel in the room will also affect the production of fire gases. If the production of fire gases is significant, larger openings are required for these to be vented out.

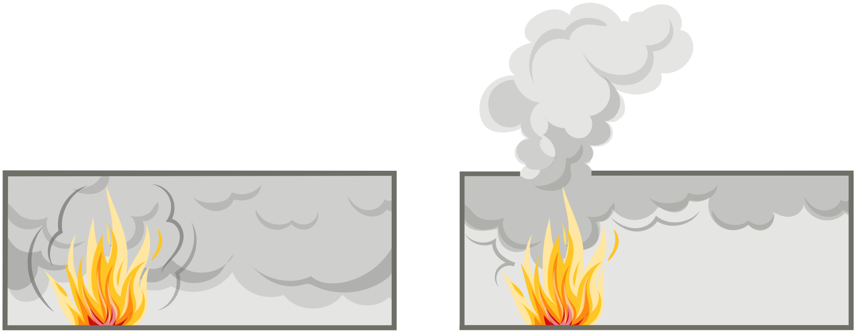
But it is not necessarily beneficial for the openings to be made too large since the inflow of air and the outflow of fire gases can then take place through the same opening, inducing mixing, and large openings may also be sensitive to wind. It may be better to make several smaller openings than one large one. However, small openings also have disadvantages, for example greater flow losses (greater resistance to the escaping fire gases) in relation to the amount of fire gases to be vented. If there is a large amount of high temperature fire gases, the velocity of the escaping fire gases will be greater if the opening is small. This means that the flow resistance in the opening becomes large and that the opening will not be large enough for the fire gases that are produced

During fire ventilation, heat and fire gases flow out through the upper parts of exhaust openings.

to be vented out. This reduces the effectiveness of fire ventilation and can also cause the space to continue to be filled with fire gases. What the ventilation measure mainly contributes to is the supply of air to the fire which can cause the fire to spread or increase in size.

The purpose of a specific measure for fire ventilation will also determine the number and size of the openings that are needed. If the purpose, besides venting heat and fire gases, is also to physically separate structures to prevent fire spread, it is of course better with a large opening, e.g. across a roof and with a certain minimum width so that fire cannot spread in the structure.

What must also be borne in mind is that creating openings in a structure (such as a wall or a roof) can be very time-consuming. Thus, it is usually more efficient and safer to use existing openings such as doors and windows rather than trying to create holes in structural elements. Creating openings in structural elements should normally only be carried out in order to access hidden fires (structural fires), and great care must then be taken. However, if openings are to be made, it does not take much longer to make a larger opening than a smaller one. What takes a lot of time is often the actual work preparation, such as fall protection for personnel and tools.



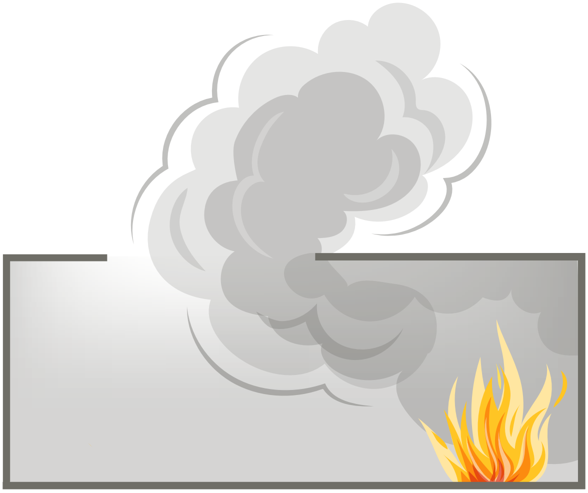
When openings have been created, an increase in the layer of hot gases can be seen, i.e. a zone relatively clear from fire gases is created in the lower parts of the room, and the working conditions for personnel is greatly improved.

Exhaust openings

Exhaust openings are openings where mainly fire gases flow out of the building. These may consist of existing openings, such as windows or doors, or if no other alternatives exist, openings that are created through the use of various tools. Generally, exhaust openings should be made as high as possible, so that the thermal buoyancy of the fire gases can be utilized as much as possible. In some cases, you can also take advantage of the prevailing wind conditions. Exhaust openings should therefore be made where it is at its hottest, regardless of whether the ventilation is directed at the compartment exposed to fire or to an adjoining space. The problem is that it can be more difficult for personnel to create the openings due to the high temperatures or large amounts of fire gases. In addition, exhaust openings should preferably be made on the leeward side of the building, but we do not always have the option of choosing side. This may also mean that personnel must work in the escaping fire gases.

The size of the exhaust openings is mainly determined by the temperature of the fire gases and the amount of fire gases produced. If the fire is extensive or has been going on for a long time, a larger exhaust opening is generally required to provide sufficient venting of hot fire gases. The greater the height increase of the gas layer that is sought or the more fire gases to be vented, the greater the opening required. A common criterion for ventilation measures is that so much fire gases should be vented out that visibility is improved for personnel working inside the building. But the ability of evacuees to escape and the flammability of fire gases must also be taken into account. Normally, you will want to vent as much fire gases as possible and as quickly as possible.

Often relatively small openings are required to achieve a significant improvement of the environment in a fire room or in a building. In spaces with up to a few hundred square meters of floor space and with



Large exhaust openings can cause fresh air to flow in and cool the fire gases. Then the effectiveness of fire ventilation decreases.

fires of a few megawatts up to a few tens of megawatts, openings of a few square meters are often enough to produce a noticeable effect from fire ventilation.

The following guidelines can be given:

- The greater the increase in height of the fire gas layer that is sought, i.e. the greater the effect of the fire ventilation that is sought, the greater the exhaust air opening required. (Note the maximum size of exhaust air openings, as larger openings may also function as inlet openings.)
- The higher the temperature in the fire compartment, the greater the exhaust opening required to achieve the intended effect. High temperature normally means that the rate of heat release is large in relation to the volume of the space, which also means that a lot of fire gases are created.
- The more fire gases that are produced, even if the temperature is low, for example in the case of smoldering fires, the greater the exhaust opening required. In this case, however, the effect of fire ventilation may be low due to limited thermal buoyancy.

The single largest parameter that affects the size of the exhaust openings is the temperature, which we can often make a rough assessment of. The temperature is often directly related to the rate of heat release from the fire. High temperature normally corresponds to high heat release rates and also normally causes more fire gases to be produced, but also greater thermal buoyancy (lower density of the fire gases). The need to increase the size of the opening or openings generally increases with the rate of heat release from the fire.

In order to achieve the greatest impact in terms of efficiency of fire ventilation, it is important not to make too large openings in relation to the fire and the depth of the fire gas layer. If the exhaust opening is too large, fresh air from inlet openings can flow directly out with the fire gases. Then, of course, the effect of the fire ventilation measures decreases. Large exhaust openings can also cause the exhaust opening to become an inlet opening as well. However, these cases are usually minor problems in the context of a fire and rescue operation.

Also, be observant that fire gases that flow out through exhaust openings do not flow back into the building through inlet openings or that personnel on the outside of the building are not affected by the fire gases flowing out.

Rate of heat release

Rate of heat release is measured in watts [W], which is the same as energy Joule [J] delivered per second [s], [J/s]. Rate of heat release from a fire is usually expressed in kilowatts [kW] (thousands of watts) or megawatts [MW] (millions of watts).

Examples of characteristic maximum rate of heat releases

Trash can approximately 50–300 kW, sofa approximately 1–2 MW, bedroom approximately 3–5 MW, passenger car approximately 3–7 MW.

Exhaust openings should be located where the temperature is highest, i.e. as high as possible, to make the most of the thermal boyancy. The size and development of the fire (the temperature of the fire gases) and the size of the premises are decisive for the size of the exhaust openings, but 1–4 m^2 can serve as guide value (smaller for small houses and larger or much larger for industrial buildings). Primarily high located windows, doors or vents should be used as exhaust openings. It can often be better to make several smaller exhaust openings than a few large ones, for practical reasons.

Calculating maximum size of exhaust opening

The maximum size of the exhaust opening is determined, among other things, by using Froude's number, which describes the square root of the relationship between either inertia and gravity, or kinetic energy and potential energy. From critical values of Froude's number, a simple rule of thumb for the maximum opening area can be deduced (single openings):

$$A_v < 2d^2$$

where **d** is the depth of the hot layer of fire gases.

This means, for example, that in an industrial building entirely filled with fire gases with a ceiling height of 3 m, it is desirable to raise the gas layer to half the ceiling height, each opening (or group of openings directly adjacent to each other) should not be made larger than approximately:

$$A_{v,\,max} \approx 2\ \frac{3}{2}^{2} = 4{,}5\ m^2$$

In total, however, a larger opening area may be required. This can then be achieved by creating multiple openings that are smaller than this maximum opening area.

Inlet openings

More often than not, fire ventilation is associated with creating openings to vent fire gases, i.e. to create exhaust openings. But what is just as important to be able to vent fire gases is that there are inlet openings where air can flow in and replace the fire gases that flow out.

It can sometimes be more difficult to create inlet openings than exhaust openings. Generally, inlet openings should be below the fire gases in the building, i.e. at the same level as or below the fire, as warm fire gases rise upwards (due to thermal buoyancy) and fresh air should then be replenished from below. Sometimes, for practical reasons, the supply of air flowing into a building must be arranged far from both the fire and the exhaust openings.

In some cases, exhaust openings in the form of roof vents can be used as supply openings (inlets). However, this requires that the roof vents are located in the ceiling of adjacent spaces that are not directly exposed to fire or fire gases, and that there are internal openings between these spaces and the fire-exposed spaces. In addition, in such cases it may be necessary to take advantage of external wind conditions, so that roof vents designed to act as inlet openings end up on the windward side of the building/roof.

Since fire gases consist mainly of fresh air which has been supplied to the fire, which is then heated and expanded, the size of the inlet openings should be in proportion to the exhaust openings approximately at a ratio of 1:1 and preferably up to 2:1, i.e. inlet openings should be at least as large as and preferably up to twice as large as exhaust openings. Making even larger inlet openings normally has no great impact. It should already be noted here that in the case of positive pressure ventilation, i.e. when fans are used to push air into a building, the ratio between inlets and exhaust openings should be the opposite (see below). Because the layout of rooms in a building, the openings between rooms and the location of furniture and similar limit the flow of air, it is almost always advisable to aim for slightly larger inlet openings than exhaust openings, especially if there is a great distance between the inlet and the exhaust openings. Even larger inlet openings result in only a small or non-existent increase in the intended effect.

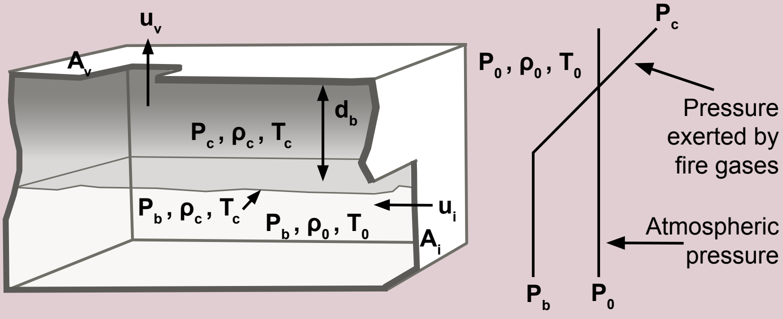
> Inlet openings should be located as low as possible. The total area of the inlet openings should be at least as large as and preferably up to twice the size of the total area of the exhaust openings.

The downside of creating inlet openings is that the air that flows in will also affect the behavior of the fire. In ventilation controlled fires it is especially important to bear this in mind, but also fuel controlled fires will of course eventually be affected. If possible, some form of fire extinguishing measure should be made, with the aim of dampening the fire or limiting its ability to spread, before inlet openings and exhaust openings are created.

Always be aware that air is supplied to the fire during fire ventilation, and that this can greatly affect the fire. In the worst case scenario, as a consequence of the air supply, fire ventilation can cause the building to be lost, as the supply of air can cause an undesirable and rapid spread of fire or fire gases. On the other hand, fire ventilation can, at least temporarily, improve the situation and facilitate the search for missing persons for example.

The relationship between the size of inlet and exhaust openings during thermal ventilation

Consider a room with an upper layer of hot fire gases, with the thickness **d_b**, the pressure **P_c**, the density **ρ_c** and the temperature **T_c**. In the lower part of the room, the pressure is **P_b**, the density **ρ_0** (the same as for the ambient air) and the temperature **T_0** (the same as for the ambient air). The velocity of the escaping fire gases out through the exhaust opening in the ceiling, with area **A_v**, is **u_v**. The velocity of the inflowing air through the inlet opening, with area **A_i**, is **u_i**.



The pressure differential over the exhaust opening is:

$$P_c - P_0$$

The pressure differential over the inlet opening is:

$$P_0 - P_b$$

The Bernoulli equation tells us that:

$$P_c - P_0 = \frac{\rho_c u_v^2}{2}$$

Equation 1

$$P_0 - P_b = \frac{\rho_0 u_i^2}{2}$$

Equation 2

The static pressure due to the temperature in the fire gases is given by:

$$P_c - P_b = (\rho_0 - \rho_c) d_b g$$

Equation 3

The relation between temperature and density is given by:

$$\rho_0 T_0 = \rho_c T_c \Rightarrow \frac{T_o}{2} = \frac{\rho_c}{\rho_0}$$

Equation 4

The temperature differential is:

$$\theta_c = T_c - T_0$$

Equation 5

Equations (1)–(2) results in:

$$P_c - P_b = P_0 + \frac{\rho_c u_v^2}{2} - P_0 + \frac{\rho_0 u_i^2}{2} = \frac{\rho_c u_v^2}{2} + \frac{\rho_0 u_i^2}{2}$$

Together with equation (3) shows that:

$$\frac{\rho_c u_v^2}{2} + \frac{\rho_0 u_i^2}{2} = (\rho_0 - \rho_c) d_b g$$

Division by density ρ_0 gives us:

$$\frac{\rho_c u_v^2}{\rho_0 2} + \frac{u_i^2}{2} = d_b g - \frac{\rho_c}{\rho_0} d_b g$$

which together with equations (4) and (5) is:

$$\frac{T_0 u_v^2}{T_c 2} + \frac{u_i^2}{2} = \frac{d_b \theta_c}{T_c} g$$

Equation 6

The mass flow through the inlet opening can be described as:

$$\mathbf{M_i = C_i A_i \rho_0 u_i}$$

Equation 7

Similar for the exhaust opening together with equation (4) gives:

$$\mathbf{M_v = C_v A_v \rho_c u_v = C_v A_v \rho_0 u_v \frac{T_0}{T_c}}$$

Equation 8

If **A**$_i$ and **A**$_v$ are similar in size and uniform, then the flow coefficients are the same

$$\mathbf{C_i = C_v}$$

Equation 9

We then assume that all inflow is through **A**$_i$ and all outflow is through **A**$_v$. We also ignore the massflow from the fuel, i.e.

$$\mathbf{M_i = M_v}$$

Equation 10

Equations (6)–(10) then gives us:

$$\mathbf{M_v = \frac{C_v A_v \rho_0 (2 g d_b \theta_c T_0)^{½}}{T_c^{½} (T_c + A_v^2 \frac{T_0}{A_i^2})^{½}}}$$

Equation 11

If **A**$_i$ goes to infinity, i.e. there is an unlimited amount of air flowing in, equation (11) then becomes:

$$\mathbf{M_v = \frac{C_v A_v \rho_0 (2 g d_b \theta_c T_0)^2}{T_0 + \theta_c}}$$

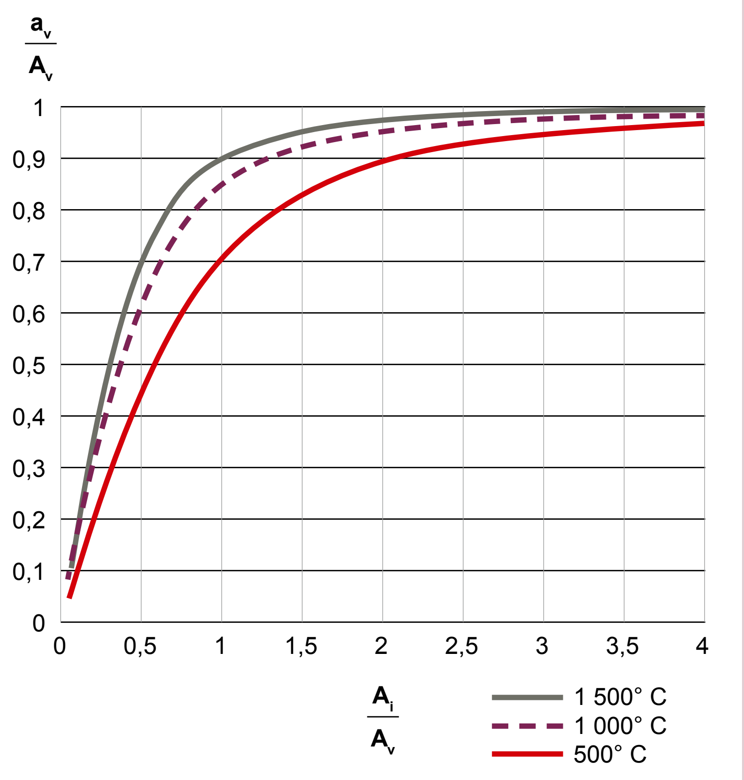
Equation 12

Equations (11) and (12) are identical if **A**$_v$ is replaced by a “corrected” ventilation area, **a**$_v$, defined by:

$$\mathbf{\frac{1}{a_v^2} = \frac{1}{A_v^2} + \frac{1}{A_i^2} \frac{T_0}{T_c}}$$

Equation 13

In a diagram, let us draw the ratio between the inlet opening area, **A**$_i$, and the exhaust opening area, **A**$_v$, against the ratio of **a**$_v$ and **A**$_v$, which becomes a measure of efficiency on the exhaust opening. Consequently, there is greater efficiency the larger the inlet opening. From the diagram it can be concluded that the inlet opening should be at least as large as the exhaust opening, preferably twice as large, since the efficiency at this point will be approximately 90%. Also note that the ratio is temperature dependent, although this does not change the conclusion. Note that this calculation does not necessarily describe the actual pressure differentials. It is merely a way to calculate a relationship.

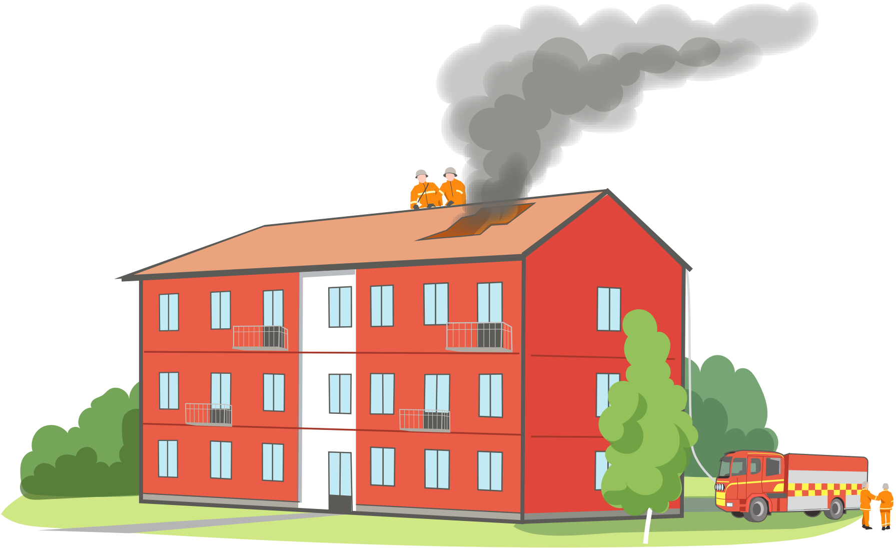

$\frac{a_v}{A_v}$
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0
0,5
1
1,5
2
2,5
3
3,5
4
$\frac{A_i}{A_v}$
1 500° C
1 000° C
500° C

Creating openings and fire ventilation can be done by utilizing windows and doors, so-called horizontal fire ventilation.

Horizontal fire ventilation of fire-exposed spaces

In many buildings, it is not possible to create suitable openings above the fire, for example, in the event of a fire in a single story industrial building with lightweight concrete roofs where there are no roof vents. Or an apartment fire in a residential building where ventilation through existing windows or door openings is the only possibility. So-called horizontal ventilation requires that exhaust openings are on the same level as the fire. This normally does not create much of a flow of fire gases upwards in the building and air density differences so thermal buoyancy cannot fully be utilized. But the fire gases that flow horizontally through exhaust openings (normally windows or doors) are still mainly driven by thermal buoyancy.

Horizontal ventilation is carried out by using the building's ordinary openings (windows, doors or shutters) to the greatest extent possible to vent fire gases. Highly located openings on the leeward side should be used as exhaust openings. Low-located openings on the windward side should be used as inlet openings. In this way, the thermal buoyancy of the fire gases can be utilized as much as possible, and partly also the pressure of the wind, to vent the fire gases. However, be aware of the problems that can arise with so-called wind-driven fires, i.e. that the



Creating openings and fire ventilation can sometimes be done through openings or vents in the roof, so-called vertical fire ventilation. The fire gases flow vertically from the fire room and out through openings in the roof.

wind contributes to a rapid spread of fire gases and fire, possibly in such a way that fire service personnel are injured.

The effect of horizontal fire gas ventilation can be enhanced with the help of fans. This is described in greater detail later.

> Horizontal fire ventilation is when exhaust openings are on the same level as the fire. This reduces the use of the thermal boyancy , but is often the only way to achieve fire ventilate in e.g. apartment fires.

Vertical fire ventilation of fire-exposed spaces

Vertical fire ventilation means that exhaust openings are above the fire, often as high as possible in the building. The fire gases then flow vertically, i.e. upwards, from the fire or from the fire room and out through exhaust openings. In contrast, inlet openings, on the other hand (as described above) should be at or below the level of the fire. The greater the difference in height between the inlet and the exhaust openings, the more thermal buoyancy can be utilized.

Highly located exhaust openings are normally created by using existing openings (windows, skylights or roof vents). It may also be possible to create openings in the structure itself, but such measures can take a long time and have special demands on the safety and equipment used.

Problems can often develop during basement fires, where exhaust openings can be arranged above the fire, but where also inlet openings have to be above the fire. It is then especially important to take into account the wind or use fans. In some cases, you may have to use the same opening for inlet as well as for exhaust. In addition, fire services personnel may have to enter through the same route as where fire gases are flowing out, which can pose significant risks to personnel.

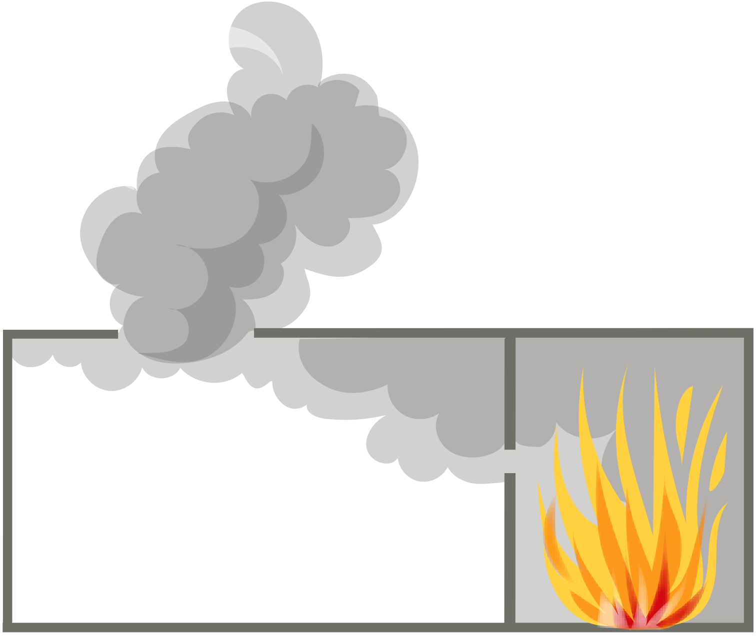
The effect of vertical fire ventilation can be enhanced with the help of fans. This is described in greater detail later.

> Vertical fire ventilation is when the exhaust openings are above the fire, often as high as possible in a building. In this way, the thermal boyancy is better utilized.

Fire ventilation of spaces adjacent to the fire room

If the fire in a room is fully developed or if the room can be considered to be lost for any other reason, it may be more appropriate to ventilate adjacent spaces than to ventilate the space where the fire is. The main purpose of this may be to secure escape routes for people who are still in the building. The measure can prevent the spread of fire (direct flames) and fire gas, to non-exposed areas such as adjacent fire compartments.

Fire ventilation of adjacent spaces can be carried out by increasing the pressure in the adjacent spaces with the help of fans (see below), but of course also by using existing windows, doors or other openings to vent heat and fire gases directly to the exterior. In some cases it can be done by producing an opening in the structure. Creating openings can then be done as a boundary line, by cutting an opening in the roof between a part of the building that is on fire and a part of the building that is still undamaged. This type of fire ventilation can also be made



When a space or fire compartment is considered to be lost, it may often be better to focus on protecting adjacent spaces, for example, through openings and fire ventilation of such adjacent spaces.

both horizontally and vertically and can be combined with mechanical ventilation. Bear in mind that creating openings by cutting holes in the structure often takes longer than expected and may also impose special requirements on safety.

Bear in mind that the venting of adjacent spaces can also supply air to a fire. Either to the fire-exposed space via the adjoining space or in such a way as to increase the risk of spreading fire and fire gases to the adjacent space.

Mechanical ventilation using fans

Fans can be used for mechanical fire ventilation and also for pressurizing adjacent spaces. Mechanical ventilation can be done with negative pressure or positive pressure. Negative pressure ventilation means that fire gases are extracted from the fire room or adjacent room using one or more fans. Positive pressure ventilation means that the fire gases are pushed out of a fire-exposed space with the help of fans, preferably combined with a fast extinguishing attack to the fire. You can also pressurize adjacent spaces. The impact differences between the pressurization of adjacent spaces and positive pressure ventilation can sometimes be very subtle. For example, using positive pressure ventilation during an operation in an apartment fire in a multi-story residential building can simultaneously pressurize the stairwell. It is also possible to carry out different types of positive pressure ventilation.

During mechanical fire ventilation, inlet and exhaust openings must be created so that horizontal or vertical ventilation is created. On the other hand, no exhaust air openings are made when pressurizing adjacent spaces. Instead, the room should be kept as tightly sealed as possible so that pressure is created. Pressurization is not really fire ventilation, since fire gases are not vented out of the building. But the conditions created through pressurization are similar to fire ventilation in such a way that by means of ventilation measures we influence the flow of fire gases and heat, the aim being to prevent the spread of fire gases (and heat) into an adjacent space. In addition, there are normally leakages in buildings, so even during pressurization there will be some flow of air from the pressurized space to adjacent spaces or out of the building.

Mechanical fire ventilation and the use of fans are based on large quantities of air being supplied (or removed) from the room or building. Therefore, one must be particularly observant to these types of measures, and constantly make active decisions about the use of fans. The fans may need to be switched off only after a short while in order to assess the situation. It can, for example, be difficult to see if the large airflow has caused fire to spread into the structure or to previously unaffected parts of the building. A decision to use fans must be continuously re-evaluated during an operation. A fan is an active tool. A fan must be started when needed and, above all, switched off when needed and must not normally be left unattended regardless of how it is used.

It is worth mentioning that the earliest reference found for the use of mechanical fire ventilation is a Norwegian publication published in 1947 by the Norwegian Fire Protection Association entitled Fenno-Vent written by Leo Pesonen. It describes negative pressure ventilation as well as positive pressure ventilation and pressurization of adjacent spaces.

> Mechanical fire ventilation can affect the fire process quickly and significantly. This type of ventilation must therefore be assessed continuously and possibly interrupted if there are indications that the situation is deteriorating.

There are a number of different types of fans on the market that can be used for mechanical ventilation, from turbine-powered (with water) to gasoline-powered and electric-powered (battery or with cable connection).

Negative pressure ventilation

Negative ventilation is based on the fact that pressure can be reduced in an opening to the fire room or to the fire-exposed space with the help of a fan. Alternatively, a reduction in pressure can be created using a fan in the middle of the room or in the building. This fan is then coupled to the surroundings by using for example a large-diameter hose. The fan can also be placed outside the building, with a suction hose into the building. Then a stiff, large-diameter hose has to be used.

Negative pressure ventilation can be used as a tactical measure during fire and rescue operations, but is most commonly used after the fire is over and during salvage operations. The method requires several work steps. If the fan is placed in an opening, the rest of the opening must be covered to achieve full power. A hose used for the transport of hot fire gases may also need to be fitted.

Situations where negative pressure ventilation may be suitable are fires in basements or other spaces that do not have direct connection to the outdoors and where fire gases must be transported through rooms that have not yet been affected, e.g. via a stairwell. Negative pressure ventilation can also be used if the same opening must be

When pressurizing adjacent spaces, the spread of fire gases can often be effectively limited.

used both as an inlet opening and as an exhaust opening. After a fire has been extinguished and during salvage operations, the method can be used to improve the working environment for personnel who, for example, must tear down a ceiling or walls to access structural fires.

If negative pressure ventilation is used, inlet openings can be made separately. If a large-diameter hose is used, the same opening can be used as an inlet opening where the hose is applied. If the same opening is used as an inlet opening as well as exhaust opening (through the hose), the hose should be pushed so far into the exposed space that fresh air does not flow directly from the inlet opening to the hose and directly into the open again.

A large-diameter hose placed on the negative pressure side should be self-supporting and stiff, while a hose on the pressure side may be soft. Bear in mind that in both cases the hose must be designed for high temperatures. Soft hoses made of polyethylene or equivalent, so-called disposable hoses, can withstand a maximum of approx. 100°C, and are therefore not suitable for use as exhaust outlets when ventilating rooms with hot fire gases. However, this type of hose can be useful during salvage operations when temperatures should be lower.

A stiff hose on the negative pressure side is placed as far into the room as possible and preferably also high to access hot fire gases below the ceiling. An extra fan may need to be placed in the room that moves the fire gases around so that no stagnant pockets are formed in corners etc. Various techniques exist for placing a fan or stiff hose under the roof. An example is placing an expanding rod in a doorway and hanging the fan on it. There are also custom-made adjustable fan stands.

Negative pressure ventilation puts great demands on the fan, e.g. to withstand high temperatures. If the fan is powered by a combustion engine, the power output may be reduced due to the influence of the fire gases.

The amount of fire gases that can be vented by means of negative pressure ventilation is limited by the capacity of the fan, but also by the flow resistance in a large-diameter hose. The longer or narrower the hose, the greater the resistance and therefore less flow (as with a hose for water). Traditionally, electric fans have been used for negative pressure ventilation. These fans have a relatively small capacity, about 2,000–8,000 m3/h (about 0.5–2 m3/s). The greater the capacity needed, the larger the fan has to be. Today, there are battery-powered fans with relatively good capacity. These are designed for positive pressure ventilation or pressurization (see below), but may also be used for negative ventilation.

Modern electrical fans have good capacity, up to about 45,000 m3/h. Even battery-powered fans have fairly good capacity, up to about 25,000 m3/h. Both of these types can be used with a stiff hose and can therefore also function for negative pressure ventilation.

Negative pressure ventilation is useful in both small and large fires, although its greatest value is in smaller fires or during salvage operations. The larger the fan used (the greater capacity), and the smaller the space, the faster the venting of fire gases.

Negative pressure ventilation can also be used in the ventilation of spaces where flammable, explosive or toxic gases have leaked. If the exhaust opening can be limited to a hose from the affected space, further spreading of gases in the building can be prevented. The supply air is then taken only through the building's natural leakage areas. It is extremely important that the fan is explosion protected, especially when working with flammable or explosive gases. Static electricity can build up in the hose, which increases the risk of an explosion. When venting toxic gases, it is also important to consider where the gases are transported and that the outlet of the hose is placed so that further damage does not occur.

> Negative pressure ventilation is normally used during the final efforts to extinguish the fire and during overhaul. Bear in mind that hot fire gases can destroy the hose as well as the fan. Negative pressure ventilation is suitable for basement fires, as fire gases must be transported through areas that have not yet been affected, or when the same opening must be used as an inlet as well as an exhaust opening. The method can also be used for the ventilation of spaces where flammable, explosive or toxic gases have leaked.

Experience has also shown that what works really well for one operation may not work at all next time despite a similar situation. This can be for example due to the fact that negative pressure ventilation is sensitive to where the fan is located and where the exhaust and inlet openings are placed in relation to each other and to the fire.

At the time of writing, there have been no real investigations on negative pressure ventilation and it is therefore difficult to draw any conclusions about its function or usefulness. It is also a method that has come to be used less and less over the years. Negative pressure ventilation is rarely used, although it might very well be a useful method in many situations.

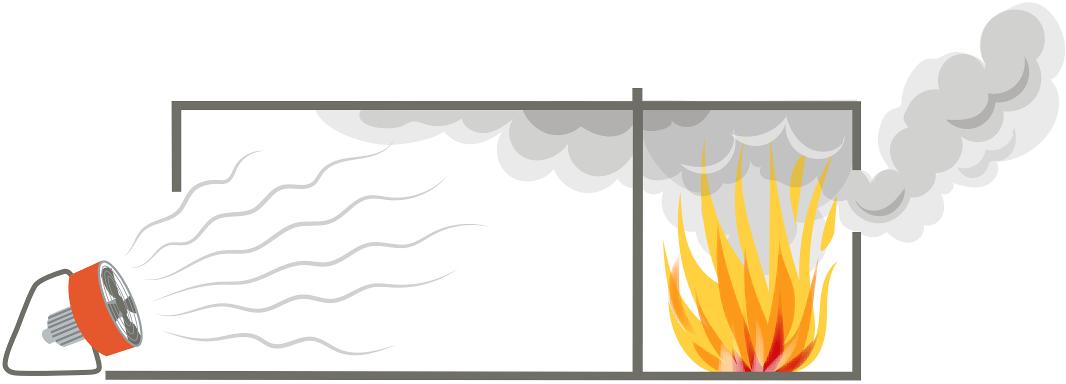
A special situation where negative pressure ventilation is used is during the filling of spaces with high expansion foam. To extract air quickly from the room to be filled with high expansion foam, a "suction" fan is installed at the exhaust opening. It has proven to be a useful solution for faster high expansion foam filling of a space and getting the foam to fill the space better. This requires that the fan is placed correctly.

Pressurization of adjoining rooms

Pressurization of adjoining rooms means that a fan creates a greater pressure in adjoining rooms, i.e. in rooms not exposed to fire. The purpose is to prevent the spread of fire and fire gases to adjacent pressurized rooms. This can be an appropriate measure if the fire is large or difficult to reach, if it is difficult to vent the fire room or the fire compartment or if the fire is otherwise difficult to extinguish. However, it is normally required (or at least desirable) that walls or other separating elements have a certain resistance to fire, i.e. that they can withstand flames, high temperatures or fire gases for a certain period of time without fire or fire gases spreading through them. The fire room (or rooms) should be compartmentalized for the best effect.

Adjacent rooms or compartments can be pressurized by creating an inlet opening only and placing a fan in there. This is usually sufficient if the spread of fire gases to the pressurized space is not too extensive. If, on the other hand, hotter fire gases have already spread to the adjacent space, the pressurization should be complemented with exhaust openings. Then you start by venting fire gases, and then, when the compartment is free of fire gases, you close the exhaust opening and pressurize the compartment. It can, for example, be suitable in a staircase filled with fire gases in the case of an apartment fire.

An alternative is to connect a large-diameter hose to the fan, which brings fresh air into the adjoining space. In such cases, a disposable hose made of polyethylene can be used because the temperature



When a space or fire compartment is considered lost, it can often be better to focus on protecting adjacent spaces, for example, by using fans to pressurize the adjacent space.

Fans can be placed in series, i.e. one after another. However, this has been shown to have limited effect, but can be used, for example, by adding a fan outside the building with another fan further into the building or higher up in a staircase.

of the hose is reduced as air flows through it. This can be a suitable measure if the rooms to be protected are located far into the building or in rooms/compartments of special value (archives, computer rooms, museums, etc.). It is then important that any openings, other than the opening for the hose for the supply air, are sealed so that the overpressure is as great as possible in the room or compartment to be protected. There are also fans that have a so-called door adapter. This is then mounted between the fan and the inlet opening and ensures that as much air as possible is pushed into the room.

During pressurization, fans can be placed in parallel, i.e. side by side, to provide greater pressure in the space, or to cover areas where the air supply is substantial, such as a garage door.

Fans can also be placed in series, i.e. one after another. However, this has been shown to have limited effect. The pressure does not increase significantly with fans placed one after the other. The exception may be for larger or more complex buildings, where a fan outside the building

Fans can be placed in parallel, i.e. side by side, to provide greater pressure in the space, or to cover large inlet openings, e.g. a garage door.

can be supplemented with another fan (or more) further into the building in connection with separate spaces that need to be pressurized.

Also note that the pressurization of adjacent premises is not really fire ventilation, since no fire gases are vented out. When deciding on pressurization, it is therefore important to be particularly clear about the purpose of the measure, i.e. that the space should be pressurized and not vented.

Positive pressure ventilation

Positive pressure ventilation means that heat and fire gases are pushed out through an exhaust opening with the help of powerful fans. Large quantities of air are thus supplied to the fire room, the fire-exposed compartment or the building with the help of powerful these fans. The measure is normally combined with a swift fire attack. It is of the

Positive pressure ventilation means that fire gases and heat are pushed out through exhaust openings with the help of powerful fans.

utmost importance that there are one or more exhaust openings. Otherwise, the air supplied by the fan only leads to an increase and spread of fire as well as fire gases.

The purpose of positive pressure ventilation is to be able to quickly locate the fire and get rid of heat and fire gases so that the spread of fire is suppressed and so that personnel can quickly start searching for victims or putting the fire out. The working environment for the personnel is greatly improved as temperatures drop and visibility improves significantly. People evacuating the building are also given a greater opportunity to get away from heat and dangerous fire gases and fire service personnel are more likely to find trapped people faster. Positive pressure ventilation often makes it possible to facilitate fast, internal fire attacks safely. But there are also risks with positive pressure ventilation, which are described later in this section.

The use of fans must be based on a continuous assessment of the situation and a fan should not be left unattended.

The method is based on placing one or more fans near one or more inlet openings to push in air and thereby vent heat and fire gases through exhaust openings. A basic approach is to:

1. prepare for an internal fire attack/search for victims
2. locate the fire room
3. make an exhaust opening, preferably in the fire room or as close to the fire as possible
4. start the fan and position it so that it blows air in through the inlet opening
5. start the fire attack/search for victims.

> In the case of positive pressure ventilation, the fan's use and effectiveness must be continuously evaluated and assessed. A fan should not be left unattended and must not be run longer than necessary.

In the event of positive pressure ventilation in residential buildings, the fan should be located outside the building.

Fans suitable for positive pressure ventilation are either driven by a combustion engine or by a water turbine, but there are also electric fans, including battery operated ones, which have proven to work well. The capacity of these fans is approximately 8,000–50,000 m^3/h (2–14 m^3/s) or more, depending on the capacity of the engine or turbine, fan diameter and fan blade design. Generally, a fan that has a larger diameter produces larger flows, and turbine-driven fans produce larger flows than fans driven by a combustion engine (if the size is otherwise equal). Electrical fans normally produce lower flows, but this is largely dependent on the amount of power that can be taken from the power source. A three-phase fan thus has a higher capacity than a battery-powered fan, but over time we should expect to see increasingly powerful battery-powered fans. The flow through the fire compartment depends on the geometry of the compartment, the size and location of the exhaust opening, the location of the fan and the internal arrangement of the fire room (interior fittings, amount and location). The size and rate of growth of the fire, and thus also the production of fire gases, can be decisive with regard to the capacity the fan needs to have.

So that fire gases do not escape through an inlet opening, it is important that the airflow covers all or as much of the inlet opening as possible. For normal size openings, such as apartment doors or staircase doors, the distance between the fan and the opening should be approx. 1–3 meters, depending on the type and size of the fan. It is relatively easy to test and to make some simple measurements in order to find a suitable distance during training for example. There are also fans that are designed to be located further from the inlet opening. It is therefore important to check and possibly test the fan(s) to be used to become aware of its function and capacity in different types of situations. However, bear in mind that when testing fans it is the flow in the exhaust opening that should be analyzed. This can be done by measuring the velocity in the opening and multiplying it with the size of the opening. If multiple openings are used, this procedure has to be done for all of the openings and then adding the calculated flows for the different openings.

In case of positive pressure ventilation, fans can be placed in parallel, i.e. side by side, to achieve a larger volumetric flow rate, or to cover large inlet openings, such as a garage door.

Fans can also be placed in series, i.e. one after another. However, this has been shown to have limited effect for normal buildings such as detached houses and for most apartment buildings. The volumetric flow rate does not increase significantly with fans placed in series. One exception might be high staircases where you can place a fan outside the staircase and another fan approximately every twelfth to fifteenth floor. It significantly increases the effect of the positive pressure ventilation which thus works well with only one fan up to about these heights (twelve to fifteen floors), provided that there are otherwise good conditions for positive pressure ventilation. Over approximately twelve to fifteen floors, additional fans should be placed further up in the staircase to enhance the effect.

Losses in the air flow can be considerable. Among other things, the air stream rotates and turns off due to the turbulence of the fan. Parts of the airflow will hit both the ground and the wall surfaces. This means that a lot of the air flow does not reach the inlet opening at all.

On the path between the inlet and exhaust opening (i.e. inside the building), losses occur at each constriction, e.g. in doorways and in furniture or other large objects. Losses also occur for example in long corridors or if the flow path turns. Examples of this may be in high staircases, where an airflow must follow the staircase around. Firefighters moving inside the room can also cause losses, especially if they are standing in openings between rooms, thus limiting airflow.

In order to obtain the best possible result from positive pressure ventilation, the ratio between the area of inlet openings and exhaust openings should be at least 1:1 and preferably 1:2. This means that the exhaust opening should be at least as large as the inlet opening, preferably up to twice the size. In case of positive pressure ventilation, in contrast to ventilation measures when the fan is not used, it is important to have a sufficiently large exhaust opening so that the entire fan capacity is utilized. To a great extent, it is the size and location of the exhaust opening that is decisive for the result when positive pressure ventilation is used, not the location of the fan. But even all the spaces and interior doors that can exist between the inlet opening and the exhaust opening can affect the result.

A large exhaust opening produces a greater volume flow through the fire compartment, but probably at the same time increases the sensitivity to wind. Therefore, if the exhaust opening cannot be made on the leeward side of a building, a smaller exhaust opening than 1:1 ratio should be considered. At the same time, this can cause the effect of the positive pressure ventilation to be less than required.

Positive pressure ventilation is a useful method, especially in apartments and detached houses, where floor area as well as ceiling height are relatively limited (approximately 100–200 m^2 floor area, 2–3 m ceiling height). We get the best results if the rooms are in succession, so that there is a clear flow path from an inlet opening (where the fan is located) to an exhaust opening.

In general, it can be said that the method is useful in fires in detached houses, apartments and high-rise buildings where the fire gases can be transported through stairwells or corridors. The method can also work well in office premises, care facilities and the like.

The exhaust opening should preferably be made in the fire room or as close to the fire room as possible, so that the transport route to the outside for the fire gases produced and the energy supplied by the fire is as short as possible. But it is often difficult to determine where the fire is. There may be problems for example if an apartment consists of two rooms and a kitchen connected only through a hallway with no other interconnections. If an exhaust air opening is made in a room other than the fire room, this can increase the risk of the fire

If the exhaust opening is too small during positive pressure ventilation, flames can emit through the inlet opening and make working conditions hard for personnel.

spreading, it can also increase the fire's rate of heat release and considerably increase the risk that the fire gases will spread to other rooms as the fan may push the fire and the fire gases to other rooms. The positive effects of positive pressure ventilation will then be absent in whole or in part.

Positive pressure ventilation should be avoided in the event of fire in larger premises, such as large workshops, shopping malls or similar. In many cases, it can work well there too, as the outflow of fire gases and heat increases. But there is a great risk that positive pressure ventilation will worsen the situation. Initially well-layered fire gases, which are hot in the upper parts of the room and cooler in the lower part of the room, may be mixed so that visibility worsens and the heat increases throughout the space. In these cases, it may be better to initially pressurize adjacent spaces.

It should also be borne in mind that positive pressure ventilation adds air to the fire. The rate of heat release from the fire will increase, and smoldering fires can ignite and spread quickly. The air flow causes

When using positive pressure ventilation, a fan can be used to push heat and fire gases forward and out through an exhaust opening, so that the working environment for the personnel is improved.

the fire to spread (possibly to the structure and into building components) and the heat between the fire and the exhaust opening can be considerable. Positive pressure ventilation should be used with caution in any of the following conditions:

- if conditions for a potential backdraft are present, i.e. in case of strong ventilation control and where fire/pyrolysis has been going on for a long time
- during structural fires, i.e. when the fire has penetrated into hidden spaces or into the building's structural elements
- if the fire room cannot be determined with certainty
- if people can be located between the fire and the exhaust opening.

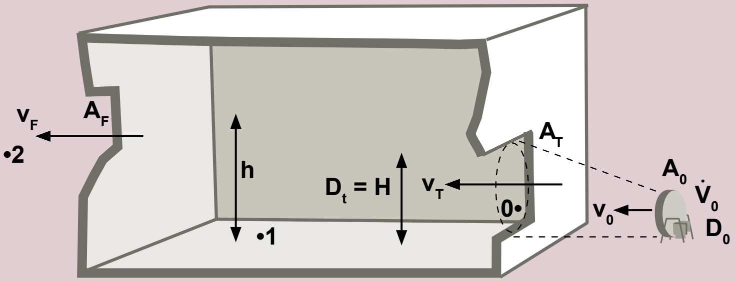
There are of course a number of variants on how positive pressure ventilation can be carried out. But the basic principle is the same: that fire gases are pushed through exhaust openings with the help of a fan placed at the inlet opening.

For example, when fighting apartment fires, staircases can often become filled with fire gases. Since it is important to secure escape routes, the staircase should first be made free of fire gases before an attack is made on the fire apartment itself. Positive pressure ventilation can then be used to first vent the staircase for fire gases by opening the stairwell as high up as possible. If the exhaust opening is then closed, the staircase is pressurized and the continued spread of fire gases is restricted or prevented. When the door to the fire apartment is opened, the air flow (and pressure) from the fan will cause the fire gases to be pushed back into the apartment. This assumes that there is an exhaust opening somewhere in the fire apartment. Otherwise, there is again a risk that fire gases spread to the stairwell.

In apartment fires above ground level, it can be difficult to create exhaust openings before an internal attack is made. One way to solve this is to create an exhaust opening from the inside. This may mean that the fire must be knocked down or extinguished first. Another alternative is that firefighting personnel first enter the fire apartment, create an exhaust opening and return to the staircase before the fan starts. Again, bear in mind that the fan adds considerable amounts of air in a short period of time and can quickly affect the behavior of the fire. The personnel should therefore be on guard and maintain a high readiness in order to be able to quickly apply extinguishing agents.

In case of positive pressure ventilation, it is also important to continuously assess the effect of using the fan and the need for continued positive pressure ventilation. A fan should normally not be run any longer than until most of the fire gases have been pushed out and the fire has been knocked down or extinguished. The fan should then normally be switched off so that the situation can be assessed for any possible fire spread or residual fires etc. If necessary, the fan can then be restarted to push out additional fire gases before switching off again. The fan must be handled actively and based on a continuous assessment of the situation. A fan that is "forgotten" can easily lead to the fire or fire gases spreading in an uncontrolled manner and in such a way that the entire building is lost.

The relationship between the size of inlets and exhaust openings during positive pressure ventilation



Consider a space with an inlet opening with an area $\mathbf{A_T}$, the air velocity $\mathbf{v_T}$ and the height **H** (**=**$\mathbf{D_T}$, the height/diameter of the air cone from the fan), and with an exhaust opening with an area $\mathbf{A_F}$ and gas velocity $\mathbf{v_F}$. The fan has an area $\mathbf{A_0}$, diameter $\mathbf{D_0}$ and the velocity of the air from the fan is $\mathbf{v_0}$. We assume that the air cone from the fan completely covers the inlet opening.

In this case, we ignore the fire. We also disregard the impact of any wind.

Conservation of energy gives:

$$v_T D_T = v_0 D_0 \text{ dvs. } v_T = \frac{v_0 D_0}{D_T}$$

Equation 1

The dynamic pressure exerted by the air cone (from the fan) towards the inlet opening is given by:

$$P_{dyn} = \frac{\rho_0 v_T^2}{2}$$

Equation 2

Flow from the fan is given by:

$$\dot{V}_0 = v_0 A_0 = v_0 \frac{\pi D_0^2}{4}$$

Equation 3

The volumetric flow in the exhaust opening is given by:

$$\dot{V}_F = C_d v_F A_F$$

Equation 4

where $\mathbf{C_d}$ is the flow coefficient which depends on size and shape of the opening.

For locations 0, 1 och 2 in the figure above, the Bernoulli's equation is applied. Difference in height between locations 0/1 and location 2 is h. This will give us:

$$P_0 + P_{dyn} = P_1 + \frac{1}{2}\xi\rho_0 v_T^2 + \frac{1}{2}\rho_0 v_1^2$$

Equation a

$$P_1 + \frac{1}{2}\rho_0 v_1^2 = P_2 + \frac{1}{2}\xi\rho_0 v_F^2 + g\rho_0 h$$

Equation b

$$P_2 = P_0 - g\rho_0 h$$

Equation c

where ξ is the flow loss coefficient in inlets and exhaust openings. Also, we know that:

$$v_T = \frac{v_F A_F}{A_T} \qquad V_1 \approx 0,\ V_2 \approx 0$$

Applying equations (b) and (c) to (a), gives us:

$$v_F = \sqrt{\frac{P_{dyn}}{\frac{1}{2}\xi\rho_0\left[\left(\frac{A_F}{A_T}\right) + 1\right]}}$$

Equation 5

Together with equations (1), (2) and (3) we get an expression for the dynamic pressure exerted by the fan towards the inlet.

$$P_{dyn} = 8\rho_0\left(\frac{\dot{V}_0}{\pi D_0 H}\right)^2$$

Equation 6

Note that if the width of the opening is larger than **H**, use the width instead.

Together with equations (1)–(6) we also arrive at:

$$\dot{V}_f = \frac{2.44}{\pi\sqrt{\xi}}\,\frac{H\dot{V}_0}{D_0}\,\frac{\frac{A_F}{A_T}}{\sqrt{1 + \left(\frac{A_F}{A_T}\right)^2}}$$

Equation 7

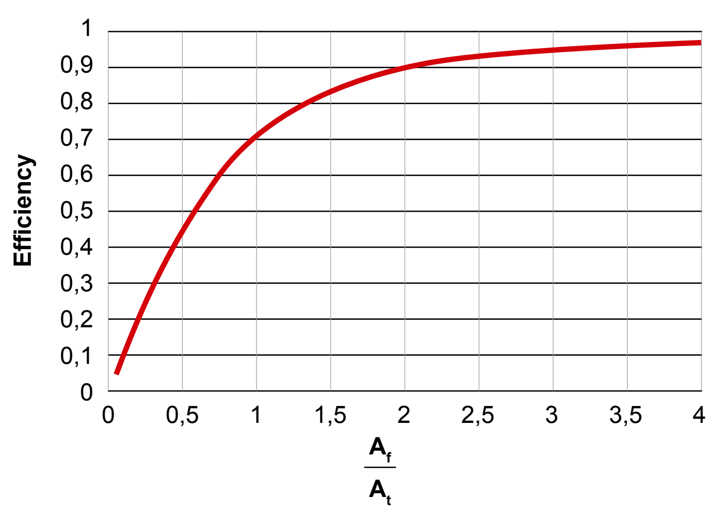
The expression in the large bracket defines a so-called “ventilation factor”. We can now draw the relation between exhaust opening, $\mathbf{A_F}$, and inlet opening, $\mathbf{A_T}$, against values of this ventilation factor, from 0 to 1, see diagram.

$$A_f >> A_t \Rightarrow \frac{\frac{A_F}{A_T}}{\sqrt{1 + \frac{A_F}{A_T}^2}} = \text{Ventilation factor} \Rightarrow 1$$

Equation 8

If the exhaust opening is much larger than the inlet opening, the expression in brackets in equation (8) goes towards 1. From this and from the diagram it can thus be concluded that the efficiency of positive pressure ventilation becomes higher, the larger the exhaust opening is. Also, in the diagram we see that the exhaust opening should be at least as large as the inlet opening, preferably twice as large, which gives a ventilation factor of about 90%.

Note that this calculation does not necessarily describe the actual pressure differentials. It is merely a way to calculate a relationship.



To take into consideration during positive pressure ventilation:

- Create exhaust openings (one or several).
- The ratio between the inlet and exhaust opening should be 1:2, i.e. the exhaust should be twice as large as the inlets.
- Do not push the fire or fire gases to adjacent rooms or buildings.
- Do not push the fire or fire gases towards trapped persons, or firefighting personnel.
- Do not implement positive pressure ventilation without having extinguishing water on hand.
- Coordinate positive pressure ventilation with other measures, for example, creating openings, attacking the fire and searching for trapped people. This will achieve the greatest advantages with this method.

Smoke curtains

The smoke curtain is a relatively recent development, but has already spread widely in several countries. It is a fairly simple device that can be placed in a doorway to prevent fire gases from spreading to, for example, a staircase. At the same time, it permits passage through the opening as it can be attached to the top of a door while the lower part hangs freely. After a curtain has been installed, the door to the affected area can be opened and used for the evacuation of people without the spread of fire gases or heat in the building.

Research and experiences have shown that smoke curtains effectively prevent the spread of fire gases.

In Sweden, doors that open outwards are common which makes it more difficult to install a smoke curtain because a door must be opened before the curtain can be fitted. This can cause a large amount of fire gases to spread to the staircase, for example. Nevertheless, smoke curtains can be an appropriate measure to secure escape routes, such as staircases, not least in high-rise buildings.

There have been demands for many years in Sweden for, among other things, fire ventilation measures in staircases for multi-family houses and fire separating compartments between escape routes (staircases) and apartments. It can therefore be assumed that smoke curtains will play a less important role in Sweden but may often be a

A smoke curtain can be used to reduce the flow of fire gases into a staircase for example.

Hydraulic ventilation can be an initial method to increase the flow of fire gases out from the building after extinguishing has been completed.

useful tool for minimizing the spread of fire gases to escape routes for example. A smoke curtain also partly limits the inflow of fresh air to the fire, but not entirely.

Hydraulic ventilation

Hydraulic ventilation is a method that can be used to fight apartment fires. After the fire is put out, a jet of water is directed through a spray nozzle through a window so that the stream of water draws the fire gases out through the opening. It is important that the stream of water is positioned in such a way that the cone that is formed by the water covers the opening as well as possible. At the same time, we do not want any water on walls and floors inside the room.

This method can be good as a first step in order to remove as much of the fire gases as possible before working with for example final extinguishing or tearing down walls or ceilings. However, if it is possible to use a fan, this is often preferred, as hydraulic ventilation is fairly inefficient, in relation to the effect and the human resources required.

Research has shown that the amount of air that a fog nozzle can move can be in the order of 4–5 m3/s. This, of course, depends on both the pressure and flow from the nozzle, as well as the cone angle of the flowing water. Higher flow rate, higher pressure or greater cone angle gives greater air flow and vice versa.

The method should be used with care so that it does not cause unnecessary water damage. The nozzle should therefore be opened outside the window. Then you back into the room until the ventilation effect arises. Check what is outside the window so that the water does not cause damage outside the building. Also, bear in mind that personnel are needed to handle both the nozzle and the water.

There are also discussions that fog nozzles can supply air to the fire during fire attack, which has also been demonstrated by experimental research. But if the fog is used correctly during fire attack this should not be a big problem, since an extinguishing media (water) is being added. In the case of fire suppression inside a room (or inside a building), it is mainly the air (and the fire gases) that are inside the room that will be moved around and supplied to the fire.

Chapter 6

Structural fires and fire ventilation

What has been described so far has mainly been about fire ventilation of one or more rooms in both large and small buildings. Bear in mind that fire ventilation and the flow of fire gases out of buildings and the flow of fresh air into buildings becomes more complex:

- if several rooms are involved
- if there is more than one inlet or more than one exhaust opening
- if the building has multiple floors.

All of these cases or conditions should be considered normal in the event of a fire in a building. Fire ventilation is therefore a fairly complex and difficult to manage problem.

A special case that further complicates fire ventilation is so-called structural fires, i.e. where the fire has occurred inside or spread into the structure of the building or into structural elements of the building (cavities, shafts or similar). This topic is covered in this chapter. Examples are given of different types of structures where the venting of fire gases can be relevant. Also, various tools are presented which can be helpful when creating openings for fire ventilation or for creating access to structural fires.

Structural fires – fires in hidden spaces

A structural fire can be defined as fire in hidden spaces or surfaces with limited access, often with exposed combustible surfaces such as building materials and installations, spaces or areas which are not normally used for storage or habitation. It is essentially the structure and its components in themselves that constitute fuel for the fire, not the interior fittings and furniture or similar. In addition, size as well as geometry are different in relation to "ordinary" room geometries, which impacts on the spread of fire gases and fire.

In the event of a structural fire, such as an attic fire, extinguishing agents are often required before creating openings and accessing the fire.

Examples of such hidden spaces are

- small spaces such as:
  - air gaps in facades, eaves or insulated roofs
  - cavities in building components that are there for design reasons
  - voids arising from fire, for example, due to insulation materials that have melted
  - cavities created by vermin
  - uninsulated interior walls.
- larger horizontal cavities such as:
  - uninsulated attics
  - low-ceiling attics
  - crawl spaces under floors.
- larger vertical cavities such as:
  - shafts.

It is also possible to distinguish between exterior and interior structural fires. Internal structural fires are then included in the definition above, i.e. fire in hidden areas with limited or no access. Exterior structural fires are instead, fires that are not in hidden spaces, but which largely fulfill the other parts of the definition above, mainly limited access.

Structural fires often requires that large parts of the structure must be demolished.

External structural fires

External structural fires can be defined as fires in spaces or rather in areas where there is limited access, often with exposed combustible surfaces such as building materials and installations. Examples of such spaces or surfaces may include facades, exterior roof surfaces, the exterior of the eaves or similar.

Other types of spaces or areas with limited access where structural fires may occur may for example be areas where the height-to-length (or width) ratio is very small. This refers mainly to a surface that is very high in relation to its width (such as an exterior facade on a tall building). In some cases, it is also conceivable that the relationship is the other way round, i.e. a very wide surface in relation to its length. It is then mainly the height (or length/width) that limits accessibility, but it also means that the spread of fire and fire gases are given other conditions than in the event of a room fire. Simply put, it can be said that the fire and rescue service in the event of this type of fire simply cannot reach the fire.

Internal structural fires

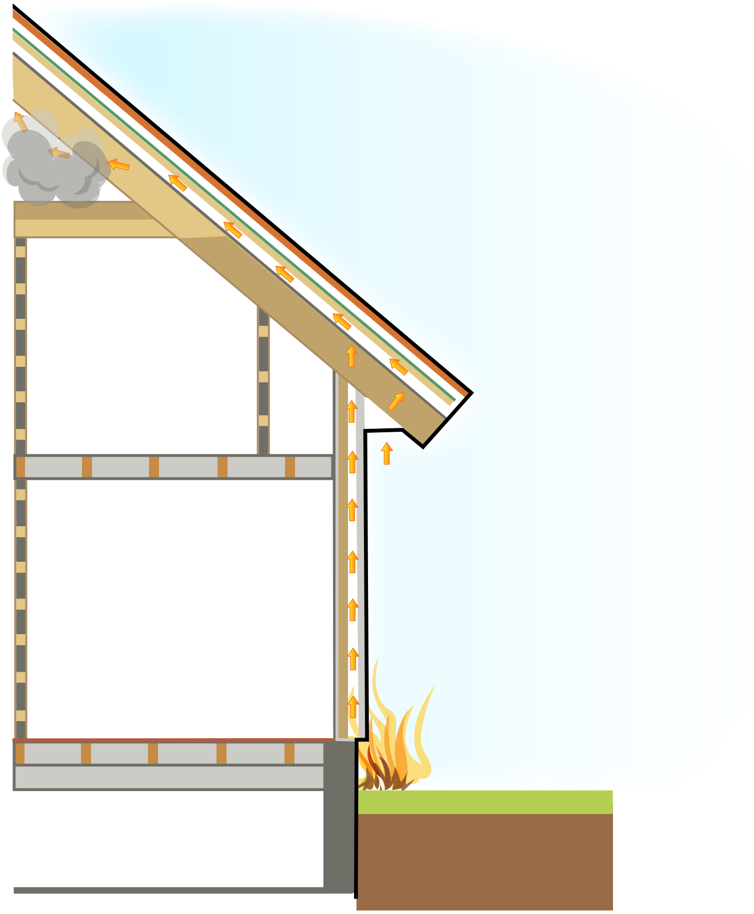
In the event of an internal structural fire, the distance between opposing surfaces can be very small, for example, the distance between the floor and the ceiling in a small/narrow/low loft space. This means that accessibility is limited and that the conditions have changed for the spread of fire and the spread of fire gases. In addition, the ratio of the surrounding surfaces to volume can be very large. The smaller the volume in terms of space, the larger the enclosing area, relatively speaking. Nor can it be ruled out that spaces or areas where structural fires may occur also have other properties. Spaces with limited accessibility can also collect a lot of dust and other particles, which can contribute to the production of fire gases as well as the spread of fire.

> A structural fire can be defined as fire in hidden spaces or surfaces with limited access, often with exposed combustible surfaces such as building materials and installations, spaces or areas which are not normally used for storage or habitation.
>
> Exterior structural fires can be characterized, among other things, by surfaces that are very high in relation to the area's width, such as exterior façades on tall buildings.
>
> Internal design fires can be characterized by, for example, having a very small distance between opposing surfaces or that the ratio of the surrounding surfaces to volume is very large. In the event of a structural fire, it is to a large extent the structure itself that constitutes the fuel.

The spread of fire and fire gases during structural fires

The production of fire gases and the spread of fire in buildings largely depends on whether a fire is fuel controlled or ventilation controlled. This is also true in structural fires, even though volumes or surfaces there have completely different properties than "normal" rooms. Combined, fire gases and thus even fire will be given completely different conditions for spreading. And if we make the wrong assumptions with regard to the production and spread of fire gases, it may mean that the measures taken by the fire and rescue service to vent a structural fire lead to fire gases and fire spreading in an uncontrolled manner.

> When applying fire ventilation measures during structural fires, it is important to first try to apply extinguishing agents, to minimize the risk of the unwanted and rapid spread of fire gases or fire when openings are made.



Stack effects can occur when an opening is created during a structural fire, so that fire gases and fire spread rapidly.

Fire ventilation of larger cavities

In the case of fire ventilation of larger cavities such as in uninsulated attics, low-ceiling attics or crawl spaces under floors, the development of the fire depends to a large extent on whether the fire is ventilation controlled or not, and also on the degree of ventilation control. A fuel controlled fire does not cause problems to the same extent, but rather it is the accessibility itself which is a problem (although fuel controlled fires are perhaps mainly a problem in the event of external structural fires, which still can be a major problem). After all, a ventilation controlled fire lacks air, so any attempt to open the space will supply air to the fire. This, in turn, can cause fire gases and fire to spread rapidly and uncontrollably during fire ventilation, if no other measures are taken. The effects of fire gases on the spread of fire are significant, especially in structural fires.

In shafts, the problem is mainly due to the fact that when openings are made, or if the structural elements (such as walls) burn through, so-called stack effects occur; this has been described earlier. The stack effect develops because of differences in air densities, where hot air has a lower density than cold air and therefore flows upwards. If this occurs inside a shaft (or a chimney) with a cross-sectional area that is small in relation to the height of the shaft, the hot air that flows upwards may have a high velocity. If a fire has occurred inside the shaft, the density differences due to the elevated temperature become large and thus the velocity is many times greater than it is at normal temperatures. The consequence is that fire gases flow upwards at high speed, and that convection, i.e. the heat transfer from the hot gas into the walls of the shaft, increases. This in turn means that the fire can spread faster upwards in the shaft, as the surfaces are heated faster by the upwardly flowing hot fire gases.

Fire ventilation of smaller cavities

In smaller cavities, the starting point should always be that the fire is ventilation controlled. Such a fire can cause major problems if openings are made and no other action is taken (such as fire suppression). The problem with smaller cavities is that they can be more difficult to identify, and that it can be difficult to determine how far such cavities extend. We simply do not know how far these cavities extend.

Smaller cavities may be vertical or horizontal. If they are vertical, stack effects can occur, which can then spread fire and fire gases both quickly and over great distances. If the smaller cavities are horizontal, fire and fire gases may spread more slowly, but since the cavities are hidden, the fire may spread into unexpected locations. The consequence of making openings with the purpose of venting fire gases may result in the fire gases and fire spreading to the entire building which may result in the building being totally lost.

The consequences of a structural fire may be that the production of fire gases and then even the spread of fire accelerates much faster than with fires in spaces of more normal dimensions, i.e. ordinary rooms (a bedroom, kitchen, etc.). If the volume of the space is then also relatively small, more fire gases can accumulate in relation to available fuel, which further increases the heat transfer to unignited fuel.

And as there may be a significant production of fire gases in relation to the size or geometry of the space, the concentration of oxygen is more quickly limited, which means in turn, that the fire may become ventilation

Fog nails or cutting extinguishers can be used to apply extinguishing agents to a structural fire, before opening up the structure.

controlled more quickly. And, as previously described, it is especially in the case of strong ventilation control that a number of problems can arise when creating openings in order to vent the fire gases and to extinguish the fire. If the space is high and narrow, measures taken to ventilate the fire by creating openings can lead to the creation of a "chimney" which can quickly spread both fire and fire gases over long distances.

Creating openings in structural elements are hazardous but often necessary

Creating openings in hidden spaces is often an important step in order to access and extinguish a fire. However, because the openings then causes fresh air to flow into the fire, it can lead to a number of undesirable consequences, for example that both fire gases and fire spread quickly and across long distances inside the structure. The damage that can occur can be considerable. The ventilation of concealed areas with strong ventilation control can even cause fire gases and fire to spread in a way that results in a total loss of the building.

In the case of fire ventilation of structural fires, whether the purpose is to vent fire gases or to access the fire to extinguish it, some type of extinguishing agent should normally be used before openings are made. To achieve this end, fog nails and cutting extinguishers can be used. It is also possible to use ordinary fog nozzles if you first make a smaller opening. The choice of suppression system, extinguishing method and extinguishing media is based on, among other things, the volume of the space and the expected effect of the measure. Applying extinguishing media in hidden spaces has limited or no effect unless there is a fire in the space or if the temperature is relatively low. Of course, water can have a certain delaying effect, but this must then be set against the risk of water damage.

Methods for creating openings for accessing structural fires

Creating openings can in some cases be an essential part of the work with fire ventilation, especially for structural fires. This refers to the methods where openings are manually created with the help of hand tools. Explosive frames and cutting with fluids at high pressure are methods that require special training and special equipment. They are therefore only briefly dealt with here. Cutting with fluids (e.g. cutting extinguishers) has come to be relatively common. However, the equipment for this available today is rarely used to create actual openings, but rather to be able to apply extinguishing agents inside hidden spaces using only a small hole. The original intent with this type of equipment was to cut actual openings in more or less any type of material.

There are no general methods that can be used for creating openings for fire ventilation or to gain access to structural fires during an operation. However, there are a large number of tools that are suitable to use and some guidelines can be established to create openings in some common types of structures. But exactly how openings should be made or how best to approach a structural fire must be decided on a case-by-case basis.

Several factors affect how successful ventilation can be achieved by creating openings. Examples of such factors are:

- fire behavior and the intensity of the fire (rate of heat release)
- volumes of spaces and their geometries
- the size and location of inlet openings

If fire has spread into the building's structure, parts or all of the structure must often be opened up and exposed.

- prevailing wind conditions
- if mechanical ventilation is used or not
- the capacity of the staff
- tools available
- the type of structure.

The type of structure affects the tactics employed during an operation. The design of a structure also influences where openings should be made, how large they should be, when they should be made as well as the type of problems that can arise during the procedure. It is also important to consider staff safety and whether there is a need for special equipment. If the right equipment is available, including the appropriate extinguishing media and extinguishing equipment, and the design of a structure allows for it to be opened quickly, then the fire gases can most likely be vented out and the fire extinguished.

The following sections describe common tools for creating openings in a few different types of structural elements. There are also some examples of creating openings in different types of structures that are common in the Swedish case. Unconventional methods are not dealt with, such as the demolition of walls and roofs using excavators or crane trucks. In some cases, such methods may very well be suitable solutions to tactical problems, but they should be used with some caution.

> Always be careful when creating openings, especially when working above ground level. And since a structural fire often is ventilation controlled, creating openings may spread fire and fire gases rapidly and uncontrolled.

Tools for creating openings

The tools shown here are generally available by the fire and rescue services, and are used for the purpose of creating openings for ventilation or to gain access to structural fires. They are divided up into electric power tools, internal combustion engine tools, hand tools, and special equipment.

Electric power tools

An electric power tool is often smaller and lighter than an equivalent tool with an internal combustion engine. The function of an electrically powered tool is not impaired by fire gases when creating openings for fire ventilation. One of the disadvantages is that freedom of movement is limited by cables, and that access to electricity can be restricted in certain situations. Another disadvantage is that electrically powered tools often have a lower power output than equivalent tools that have internal combustion engines.

On the other hand, battery-powered power tools have improved and their capacity continues to develop. It is probably no longer possible to find any major differences in power between wired and battery-powered power tools. However, for heavier or longer work, it is still an advantage to be able to connect power tools to a fixed power source.

Combustion engine powered tools

Combustion engine powered tools are used independently of an external power source and develop a comparatively large power output. However, they are usually quite heavy and the engine can be affected by fire gases when it is in use. If there are large quantities of fire gases, the engine can stop in a worst case scenario. It is important to know how to use

The picture on the left shows a reciprocal saw, the picture on the right shows a circular saw.

the tools, partly because of the relatively large power output and their weight. In addition, the greater power output and weight may require special protective equipment with a higher protection rating than standard equipment and in some cases special training may also be required.

Examples of various tools and their basic functions

The reciprocal saw works with reciprocating movements (back and forth). It can be used for cutting wood, plaster and metal. For sheet metal cutting, the cutting speed is lower than for rotating tools, but there is less noise and sparks. The saw blade is normally about 15 cm long, but there are both shorter and longer blades. The thicker the material, the lower the cutting speed. The reciprocal saw has proven to be a good tool for creating openings in a large variety of structures.

The circular saw is used to cut into softer materials such as wood and plaster. It is efficient and relatively easy to carry during an operation. It can be used for cutting covering boards (walls/ceilings) as well as support elements in wooden roof structures. The depth of the saw blade varies between 30 and 70 mm, depending on the make and type.

A power driver, a special machine or battery-powered drill combined with bits or a nut sleeve, is a very versatile tool. Screw joints and the fixation of sheet materials with screws are much more common today than before, when nails were used more frequently. The power driver is therefore of great advantage when loosening various structural elements instead of breaking them. On many occasions it can produce an opening that is easier to cover up again, for example in case the chosen fire ventilation measures do not work.

The chainsaw is easy to use when creating openings in wood structures. The function can be downgraded by nails and sheet metal in the structure. When creating openings in a wooden roof that is covered with tar paper, the chain may be covered in tar thus reducing its

The picture on the left shows a powerdriver (an electrical screwdriver), the picture on the right shows a chainsaw.

efficiency. An internal combustion engine saw has greater power and often a longer cutting bar than an electric motor saw, making it a more versatile tool. Compared to a chainsaw driven by a combustion engine, the power output of an electrical chain saw is relatively limited.

The power cutter is a powerful tool that can be fitted with different blades depending on what is to be cut. The power cutter, like other combustion engine-driven tools, requires knowledge of proper handling in order to use it safely and efficiently. The power cutter should be used at full capacity and be allowed to "eat" itself through the material without it having to be pushed.

The electric power cutter is common for home use, but is limited when creating openings in different types of structures, mainly due to its limited power and limited cutting depth. It can be fitted with different blades and is mainly used for cutting metal parts in various roof structures, e.g. metal rods, sheet metal doors etc.

The twin power cutter cuts with two metal blades mounted next to each other and rotates in different directions. It can cut stainless steel, aluminum, wood, plastics and more. However, it cannot cut through glass, stone, concrete or ceramics. The maximum cutting depth is 60–65 mm. It is probably a relatively unusual tool and is only used in special situations.

Different types of hand tools include iron bars, pincers, jemmies, crowbars, fireman’s axes, and cutting axes.

Applicable safety regulations should be used for all machines and tools. Several types of machines and tools also require special training.

The picture on the left shows a power cutter, the picture on the right shows a drill.

Special tools

The jaws of the sheet metal extractor grip the sheet metal to be pulled down from the roof. It is of course easier on low roofs. If the sheet metal is securely attached to the roof it can be difficult to pull off from a high roof as the torque is considerable. The fixing screws in the sheet metal can be unscrewed to simplify removal on high roofs.

Explosive cutting frames are mainly used to create openings in roofs with folded metal sheeting on tongue and grooved boarding. The blasting frame consists of a rigid cellular plastic frame, which can be mounted together with other frames to enable the blasting of larger openings. The frame can be carried by one person and lifted through standard roof hatches (width 0.60 m). An explosive strip of a plastic explosive is placed in the frame with a directional explosive effect, a copper material that cuts through the roof, foam plastic that holds the component parts together, and tape for adhesion to the underlayer.

Hydraulic (eccentric) cutting machines have a major advantage in that the blade works eccentrically, i.e. not on the normal center axis. The blade can therefore work in material with a depth greater than the radius of the blade (typical working depth approx. 25 cm). It can work in most materials. The disadvantage of the machine is that it requires hydraulic power by means of a separate hydraulic unit, and that it requires cooling. Machines powered by electricity are available as well as those powered by combustion engines.

Water cutting involves using water at high pressure to cut an opening in a structure. The pressure can vary, depending on the equipment, from 200 to 300 bar. The water flow normally varies from 25 l/min. to 50 l/min. An abrasive additive (cutting agent) is often needed to cut through hard materials (roof materials etc.). A cooling and suppression effect is also achieved in conjunction with making an opening. Equipment for water cutting can normally cut through all materials commonly found.

This type of equipment usually requires specialized training, due to the risks associated with the equipment.

Chapter 7

Safety when working at heights

There are always risks associated with working at heights, for example when creating openings in different types of structures in connection with fire ventilation. The safety of such work requires that staff have good equipment, are well trained and aware of the risks associated with the work.

The equipment and procedures described in this section, are based on Swedish regulations at the time of writing. These regulations may not apply to other countries.

Fall protection

When working at heights above 2 m, some kind of fall protection device is required. A distinction can be made between common and personal fall protection devices. Common fall protection devices include fall protection rails, scaffolding and work platforms. In the case of ventilation measures or other measures at heights during fire and rescue operations, it is primarily work platforms that are relevant to use. Of course, a building may have fall protection rails, but it should be carefully considered as to whether or not they provide adequate protection. If the building is on fire, the fall protection rail may lose its protective function during the operation.

There are a number of rules when working on platforms. Among other things, the platform should be designed so that:

- there are appropriate devices that prevent the risk of the work platform falling or tipping.
- the user is prevented from falling from the work platform.
- the user does not risk getting trapped or pushed, especially by involuntary contact with an object.
- safety is guaranteed for people who are trapped as a result of a downtime or other event and that they can be evacuated.

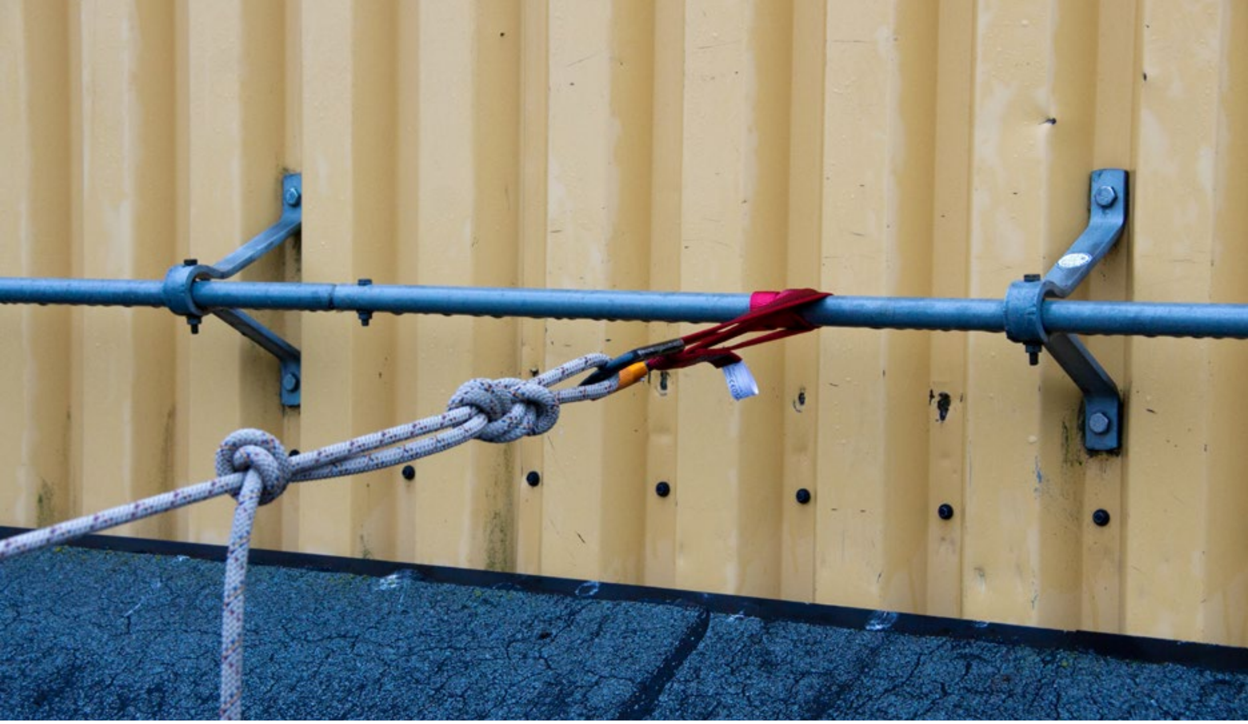
Support systems and fall protection systems require separate anchor points.

Above all, those who are on the work platform should normally also use personal fall protection equipment.

Using only personal fall protection equipment should be considered only if there are no other options for work involving fall risks. Even if personal fall protection equipment is used, there is a risk that a fall will result in injuries. A fall can cause great stress on the body, even if the fall height is low.

Personal fall protection equipment should slow a fall down and stop it. It consists of a full harness, a coupling system with a damping function and an anchoring device. There are four different types of coupling systems with a damping function to use with the full harness:

- shock-absorbing lanyard
- safety block with a function that dampens a fall
- controlled zipper on fixed anchored line or rail
- guided zipper on flexible anchor line.



Examples of an anchor point for a fall protection system or support system.

The anchoring device used must withstand the weight of the user if he/she falls. Anyone using the equipment should also be trained in how to use, connect and test the equipment before use, as well as know the risks of using the equipment incorrectly and how to operate and maintain it.

The rules allow for certain exceptions, i.e. when fall protection does not have to be used, this is when a worker must:

- perform the odd job for a short period of time from a ground ladder.
- start his/her work by either affixing an anchor point, or by first connecting the equipment to an existing anchor point.
- work on a flat roof (maximum 6 degree slope) as long as the distance to the edge is at least 2 meters and no other risks exist, such as slipping.

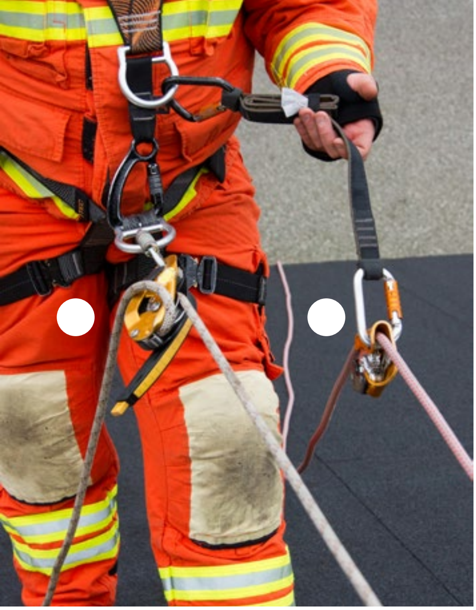
Tools must also be anchored, for example, with a separate line (or similar) attached to the harness.

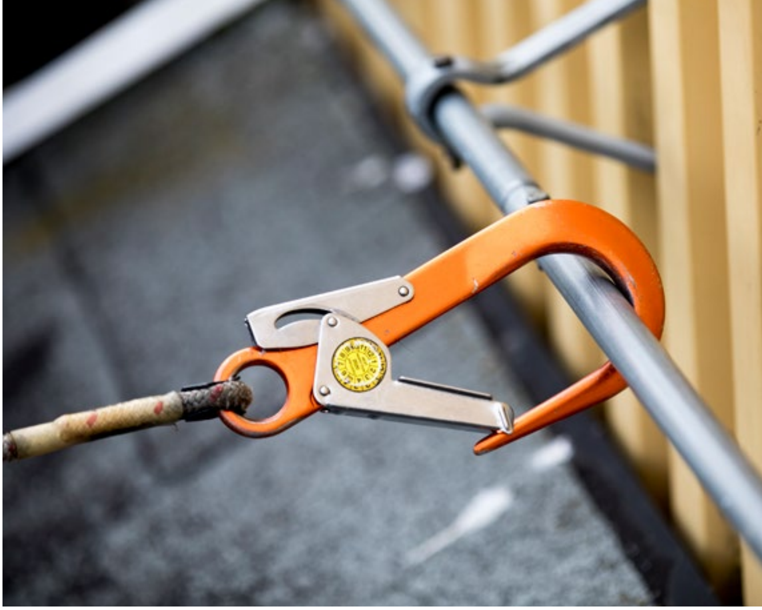
All equipment used must be CE marked and meet the applicable standards. It is important that personnel have had training in the use of work platforms, such as platform vehicles. Training is also required when using personal fall protection devices (mainly full harness with accessories) and when special protective gear is used.

The exception that is probably most common in connection with fire and rescue operations is work from a ground ladder. The following conditions must then be met:

- The work can be carried out with one hand, the other hand should be used to hold on to the ladder.
- The ladder used must be no higher than 5 meters (but when affixing an anchor point for a safety rope or equivalent a climb of up to 7 meters is permitted).
- The time it takes erect the ground ladder, do the work and return to the ground again must be less than 15 minutes.
- Work on a ground ladder may only be done on a few occasions during an operation.

The ladder must also stand firmly and usually needs to be widened at the bottom or anchored. Accidents involving ladders slipping or overturning are common.





Full harness with support system (1) and fall protection system, with shock-absorbing lanyard (2).

A so-called large hook can be a good way of anchoring the fall-protection system or support system.

All equipment used must of course be CE marked and meet the applicable standards. The use of both common and personal fall protection devices normally also requires training, for example when working on ladder platform vehicles and when using a full harness with accessories.

When working at heights during fire and rescue operations, support systems can also be used, i.e. a belt or a half harness. This equipment is mainly used to provide support during work. Thus, a support system must not be used as fall protection. The coupling line used with the system should limit a possible fall to 0.5 meters. The length of the coupling line must also not exceed 2 meters.

Please note that what is described in this section does not include so-called rope work. During rope work it is possible to hang freely from a rope and at the same time do the work. It is also possible to vertically descend or ascend from or to a height and perform work without any solid ground to form a support. The type of work dealt with in this section is also carried out with ropes and lines, but requires something to stand on and is not regarded as rope work. However, the requirements for ropes and lines are the same as for rope work. Rope work places special demands on both equipment and training.

Left photo: If a ladder is used, for example, on a roof, it must anchorded properly.

Examples of support systems anchored to a ladder. Note that two systems are used, fixed in two separate rungs, since one only normally does not withstand the load.

Working at heights

Protective measures must be taken when work is carried out in such an environment that there is a risk of falling. A risk assessment must always be carried out when working on roofs or from elevated vehicles in connection with fire ventilation. The risks that the work entails must be set against partly what can be achieved with the measure and partly against the possibility of taking other measures with a similar effect but with less risks involved.

Examples of support systems anchored to a platform vehicle.

Safety when working from a ground ladder and a ladder platform vehicle

It is common practice to work from ground ladders as well as from ladder platform vehicles. The easiest way to remain safe when working on ladders and platform vehicles is to attach your coupling line to the ladder or to the ladder platform vehicle (at the top or in the basket). Besides a belt or harness, only the coupling line is used (a support system), not a coupling system with a damping function. Try to ensure that the line is as short as possible; it must be a maximum of 2 meters and a possible fall should be limited to 0.5 meters. The coupling line may consist of synthetic rope, ribbon, wire or a chain. The coupling line to the belt traditionally consists of a chain with a carbine hook. The areas where you can use a harness with a coupling line or a belt with a chain are quite limited for natural reasons. It is a support system only for working on a ladder or from a ladder platform vehicle.

In order to achieve a larger working area on a roof, a ladder platform vehicle can be used as an anchor point. This requires that a protection system with a damping function is used (see above).

Safety when working without a ladder platform vehicle

Another common situation is work on roofs where there is no possibility of using an anchor point on a ladder platform vehicle or that for practical reasons you want to step off the ground ladder or the vehicle in order to be able to work more freely within a larger area. An anchor point is then needed where the protection system with a damping function can be attached. This anchor point must withstand the load that occurs in the event of a fall. You could use a chimney stack, a roof ladder or a railing.

A safe escape route should always be available, for example, by laying and anchoring a ladder on the roof. This should be used as a working platform and as much as possible.

Creating an opening, accessing a hidden space or accessing a structural fire should be carried out in such a way that a safe haven is available at all times. The first cuts on for example on a roof should be made away from the work platform (the ladder or the platform vehicle), so that the last sections when creating the opening can be made standing on the platform (the ladder or the platform vehicle).

It is often appropriate to develop a standard operating procedure for working at heights, based on the regulations that exist for such work. The objective is to enable the work to be carried out as safely as possible, for example, by creating a safe escape route and a safe starting point for work.

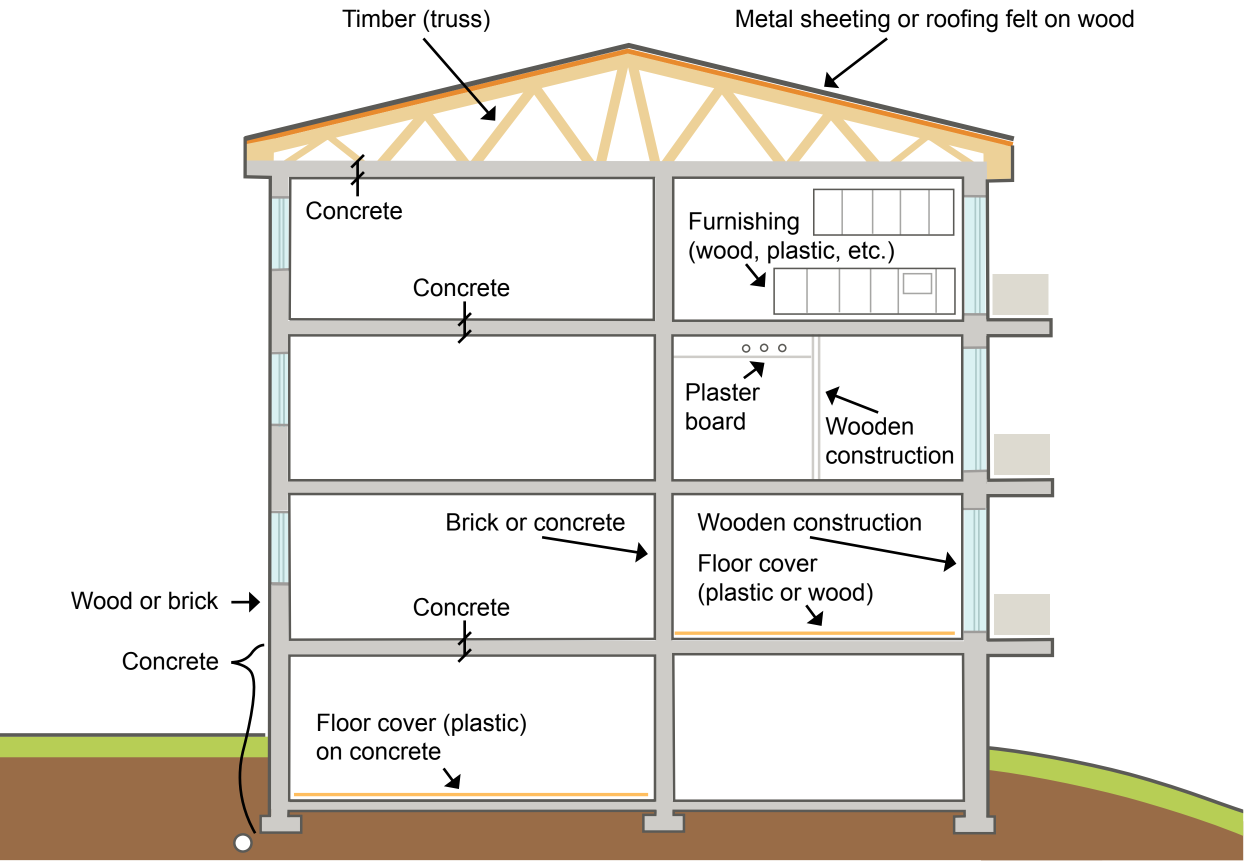
Chapter 8

Examples of various structures

The way to construct and build houses has of course changed over the years. The driving force behind this development has been energy conservation, changes in building technologies and building materials, plus the need for other types of buildings than before. In addition, architectural trends have also left their mark on the development of buildings. There are also regional differences because buildings have historically been erected with building materials that were readily available locally.

Building materials, structural solutions and the building methods used have also changed over the years. Therefore, there is no general method of creating openings or cutting structural elements that can be applied to all the different types of structures found. Simple structures with wood or thinner metal frames can usually be machined relatively easily so that openings for fire ventilation can be created or for identifying and extinguishing structurale fires during an operation. Structures containing concrete or steel may be considered more or less impervious. However, there are tools designed to cut concrete, such as hydraulic eccentric cutters with a greater power output or cutting machinery that use high pressure fluids. However, cutting through concrete or steel can take a lot of time and this type of machinery is therefore only used in special cases.

In cases where openings are made for fire ventilation, it is important that both the exhaust and inlet openings are sufficiently large. The size of the fire and the size of the space determine the size of the opening – an exhaust opening of 1–4 m^2 can serve as a guide. In cases where openings are made in conjunction with structural fires, even smaller openings can quickly have negative consequences for an operation. This was discussed in more detail above. But small openings can also allow us to quickly apply extinguishing agents. After that, larger openings can be made, so that the fire can be reached and finally be extinguished and the fire gases vented out.



A building is often a complex composition of a variety of building components made of different building materials.

It also takes time to create openings for fire ventilation or to deal with structural fires. Regardless of the method selected and used, the time aspect must be taken into account. The fire process is constantly evolving and changing, it is dynamic and often exponential. This means that the situation can be quite different when the work of creating openings has been completed than compared to when the work was started or when the decision to create the opening was taken.

The work must be coordinated when working with structural fires, for whatever purpose, in order to be successful. All personnel participating in the operation must coordinate their work efforts and be well trained to use the tools and methods suitable for cutting or creating openings in different types of structures. When cutting or creating openings in a structure, there should be at least two staff members, preferably three, available. They must also be using the requisite personal protective equipment for the work as well as have the training that the work requires.

However, the number of personnel who are assigned to the task is determined by the size of the fire, the type of structure and the choice of tool/method. Safety aspects for staff must be considered. It is directly crucial for how and if the work is to be done at all.

Below are some examples of how ventilation openings are made in different types of structures that are common in Sweden, mainly roof structures as these are more complex with regard to their construction. It is a good idea to prepare for the work and to take a look at different types of structures in the area you operate, especially in more complex buildings such as larger public premises, densely populated areas and possibly older buildings in an inner city or in larger industrial areas.

It is important to bear in mind when creating openings in structures above ground level that they should be carried out in such a way that there is a safe haven available at all times, as described in the previous chapter. The first cut made in for example a roof or high up on a wall should be made away from the work platform (ladder or platform vehicle), so that the last sections that are cut can be made standing on this work platform.

In cases where openings are made with the purpose of accessing a fire that has spread into the structure, so-called structural fires (see earlier description of this), there are a number of things that must be considered. In such cases, openings are not normally made with the purpose of venting heat or fire gases, the purpose is instead to access the fire that has spread into the structure in order to put it out. But on many occasions it can be difficult to distinguish between these two purposes. The most common purpose of opening up structures is to access fires inside the structure.

This means, in part, that openings must be made where the fire actually is, or at least in the vicinity of the area that is exposed to fire. It is not always appropriate to create both an inlet and an exhaust opening. Instead, opening up the structure should be carried out with some caution, so that the air supplied when the structure is opened up does not cause fire or fire gases to spread further into the structure. The nature of structural fires means that it can be difficult to determine where the inlet and exhaust openings are, in addition to those created by fire services personnel. We also do not always know if the openings that are made become inlets or exhaust openings, as there may be other openings that we are not aware of.

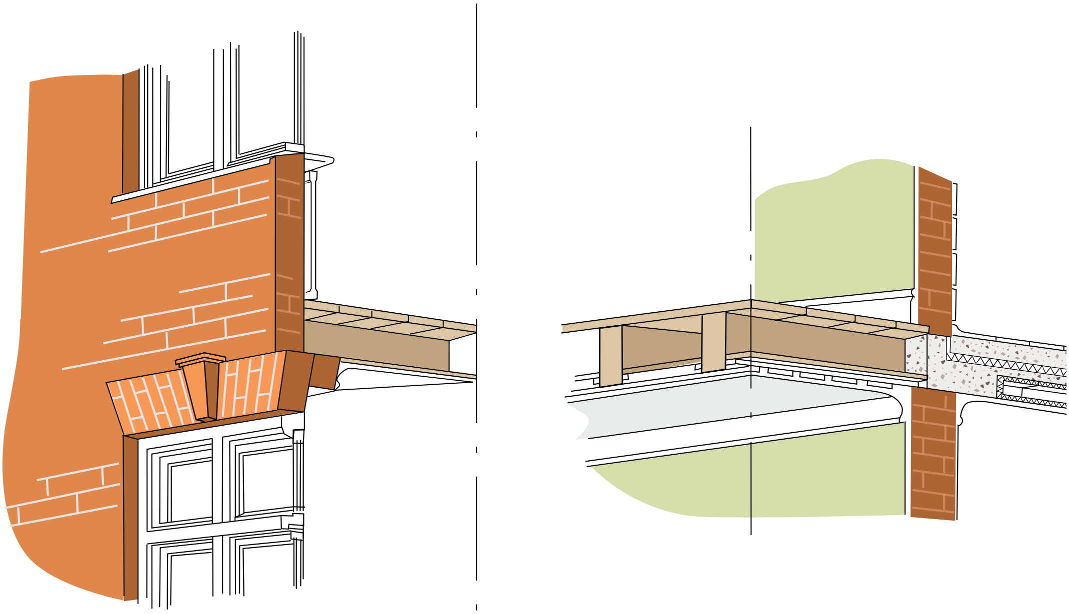
Normally, it is advisable to first take certain fire suppression measures or measures that otherwise reduce the risk that fire or fire gases will spread. An example of such a measure could be the use of fog nails, with which we can apply extinguishing media in hidden spaces without first creating an opening. To identify where the fire is in the hidden space or in the structure, a thermal imager (infrared camera) can be a good tool. However, it must be noted that it takes some time for heat to transfer through the structure so that the thermal imager can detect increased heat from the surface. And once the heat has penetrated, the fire may have spread in the hidden space or in the structure. The thermal imager can, so to speak, only see history.

In order to extinguish a fire and thus prevent further production and the spread of fire gases, the extinguishing agent is normally required to hit the fuel. And in order to achieve this, in most cases we must sooner or later open up or break the structure to access the fuel surfaces. Extinguishing media that do not reach the fire or hot spaces normally have no or only a very limited effect.

The methods used to create openings in structures described below apply in applicable parts even when the purpose is not fire ventilation, but to access fire inside the structure (structural fires). The important thing to be aware is the design of the building, so that openings can be made in a suitable place and as efficiently as possible. In order to access fire that has spread inside the structure, a relatively large part of the structure often has to be exposed.

Above all, it is important to understand that a wall, a truss or a roof structure can be a very complex composition of different components and materials. This composition varies, depending on building type, how old the building is and what part of the building you are trying to open up, etc. It cannot be emphasized enough the importance of understanding how buildings are designed, how different materials react to fire and the difference between fire behavior in rooms and fire behavior inside hidden spaces and a building's structural components.

> When creating openings, it is important to understand what the structure is made of, whether the purpose is to vent fire gases or whether it is to access fire inside the structure.

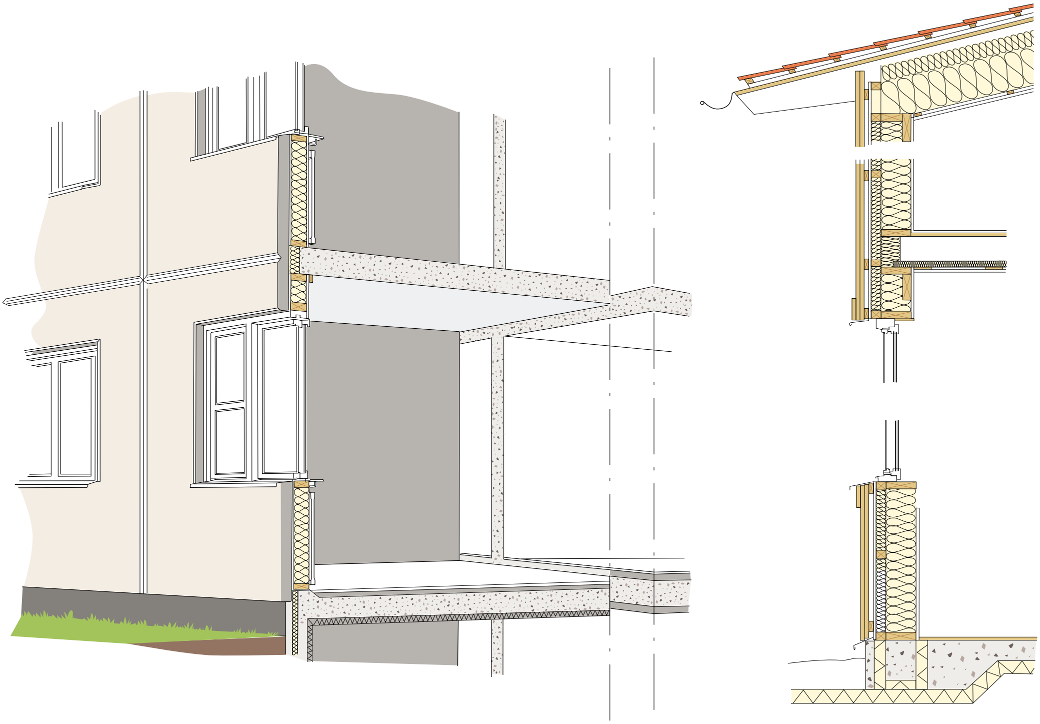


Cross-section of an older brick exterior wall and a wooden floor. At the far right is an attached concrete floor.

Exterior walls

Many types of exterior walls have a so-called air gap in the wall, mainly to prevent moisture from entering the building. This is especially common in buildings with wooden walls, but is also prevalent in exterior walls with steel beams or with lightweight concrete. The air gap is simply an open part of the wall where fresh air can flow more or less freely, with the aim of venting moisture out of the structure. Unfortunately, this also means that there is a space where fire can spread relatively easily. In tall buildings, however, there must be some form of protection against fire spreading inside the facade, between the floors.

In older detached timber-frame houses and outer walls made with wooden planks, there may also be additional cavities inside the structure, for example, if old insulation has collapsed or if vermin have made paths or walkways inside the insulation. Older buildings can also have flammable insulation inside the walls, which further complicates the problem.



To the left is an example of a site-cast starting frame with insulated concrete sandwich elements in the facade. To the right is a cross-section of a timber frame wall on a concrete slab.

The exterior wall on a timber-frame home with standing wooden panels on the outside may consist of the following, from outside in:

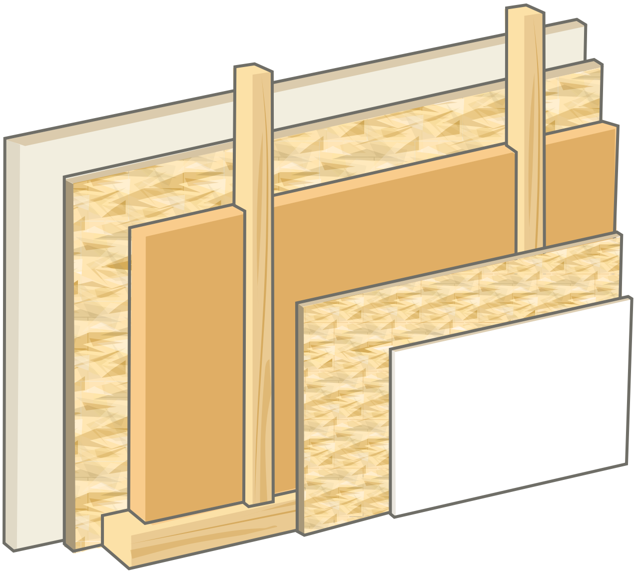
- cover boarding (vertical), bottom board and nailing batten (horizontal)
- air gap (moisture barrier), about 20–35 mm wide
- bituminized paper board (as wind protection)
- standing wood studs with insulation in between, normally 145–195 mm thick
- diffusion-proof vapor barrier (plastic film)
- wood studs with insulation in between, normally at least 45 mm thick
- interior board cover (OSB board + plasterboard).

If a fire has developed on the inside of the outer structure or spreads into these types of structures, there are several things that need to be considered. Firstly, be careful when making openings (which is valid for more or less any type of structure). Of the openings that are created, air is supplied to the fire, which can lead to a form a stack effect spreading fire gases as well as fire quickly further into the structure (see previous chapter on creating openings). Secondly, large parts of the structure must normally be inspected and possibly removed. Demolishing large parts of a facade can be time-consuming and laborious, but sometimes absolutely crucial to prevent fire gases and fire from spreading.

Opening these types of structures can be carried out in a variety of ways and with the help of different types of tools. The important thing is that once you have started to create an opening, then it must be completed as quickly as possible. The tools and methods chosen, among other things, must be based on the need for speed. It is often a good idea to try to apply extinguishing agents before openings are made, with the help of fog nails for example. If this is not done, you have to be prepared to apply extinguishing agents at the same time as the opening is made, for example with an ordinary nozzle. Either way, some type of extinguishing agent must be available when the opening is being made, even if an extinguishing agent has been introduced into the structure before any openings are cut.

Openings should normally be made from the outside and inwards, unless there are clear signs that the fire can be reached from the inside of the building only. If openings need to be made on floors above ground level, they may also need to be made from the outside. Such work above ground level increases the risk of injury to personnel. In the event of room fires, the structure should of course be checked from the inside. It might also be necessary to check if fire gases or fire have spread through windows to the exterior façade. If this is the case, the spread of fire and fire gases needs to be stopped quickly.

In the exterior walls of high-rise buildings there can be extensive systems with facade cladding and air gaps. There are several examples around the world where fire has spread very quickly up high facades. This is not dealt with in detail here, but be aware of this and do an inventory on such structures especially related to high-rise buildings. External fires on high-rise buildings pose special problems and special risks to people in the building as well as to firefighting personnel.



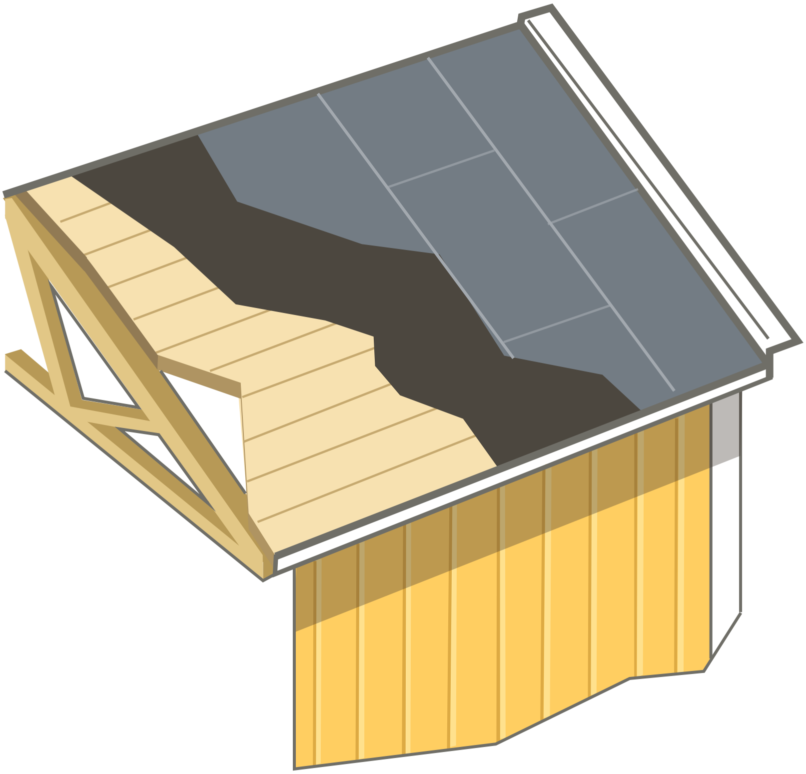
Cross-section of an interior wall.

Interior walls

Unlike exterior walls, interior walls are often (but not always) uninsulated. They are also thinner or of a simpler structure. The exception is, among other things, walls between apartments, which also have a fire-separating function. These can be both thicker and more well insulated than interior walls that do not have a corresponding function.

Interior walls can also have air gaps, especially uninsulated walls inside apartments (or similar). Of course, problems with voids are less in buildings erected mainly with non-combustible materials, such as cast concrete or various types of prefabricated concrete elements. But even in such designs, there can be cavities where fire gases and fire can spread. Horizontal as well as vertical shafts for electricity, ventilation, water and sewage can be included. In addition to such shafts which are often made out of plastic, they can also contain large amounts of combustible material such as cables.

There are also a variety of ways to deal with interior walls (creating openings or otherwise breaking them). And just as for exterior walls, it is important that any openings are made as soon as possible, once you have started. Here, too, it is advisable to have some type of extinguishing agent available when the openings are being made. Thermal imagers (infrared cameras) are valuable tools for assessing and identifying the spread of fire and fire gases in both exterior walls and interior walls (but of course also for other occasions or situations). A thermal



Cross-section of sheet metal roofing with board and wooden planks.

imager allows us to see relatively small changes in radiation from the surface of a wall for example. However, it cannot detect radiation from within the structure or heat at the back of a wall, but only the radiation from the surface. And since heat conducted through the wall material takes time, the thermal imager only will see "history". The heat on the outside of a surface does not always match what is on the other side of the surface, i.e. inside the structure.

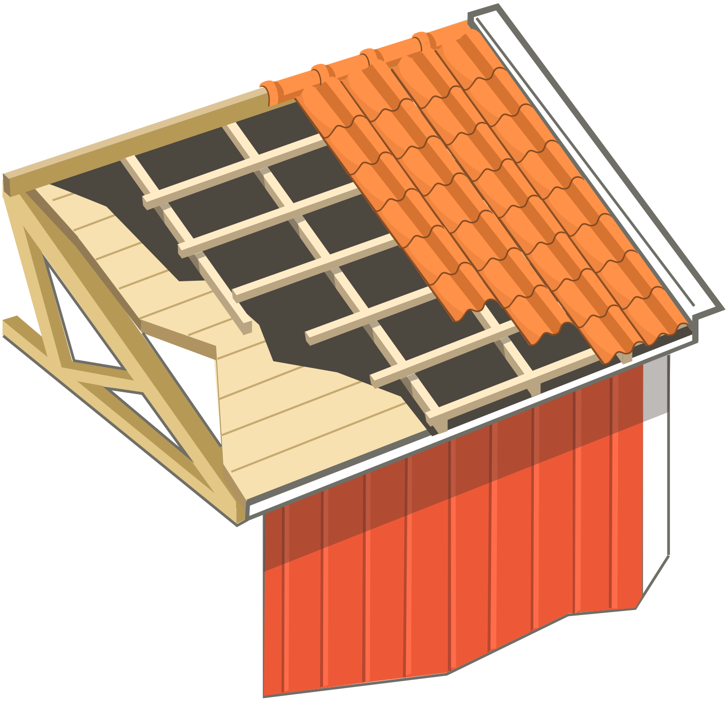
Sheet metal roofing on older buildings

Sheet metal roofing on older building may consist of the following, inside and out:

- wooden roof trusses
- wooden roof board (tongued and grooved board)
- underlay felt, where appropriate
- seamed metal sheeting.

The opening is made between the roof trusses. On roofs with seamed metal sheeting it is difficult to see where the roof trusses are. On certain buildings they may extrude at the base of the roof. There is often metal jointing or other metal objects just beside the roof trusses, ridge and base of the roof. Leave an edge of approximately ten centimeters from these.

To make an opening for fire ventilation or to create access to hidden fires, the by means of seamed metal sheeting can be penetrated in different ways. One way is to cut it with a power cutter, and if the power cutter is powerful enough it will also be possible to saw through the roof boarding at the same time. For the power cutter to work effectively it must be run at full speed. It should work its way through on its own, without using excessive manual force. If the roof boarding is not removed at the same time it can be sawn when the metal sheeting has been removed, for example with a chainsaw or circular saw.



Cross-section of a tiled roof.

One advantage of removing the metal sheeting first, and then sawing the roof boarding, is that the nails become exposed at the roof trusses, which makes it easy to locate the roof trusses. Another method of removing the metal sheeting is to knock up the seams with a club or a large hammer. Once the seams round the sheeting have been knocked up, it can be lifted or pulled off. If the sheeting is difficult to remove, an extractor tool can be used. The sheet metal extractor's chain can be fixed to a ladder platform vehicle so that the metal sheeting can then be lifted off from the ladder. However, this requires that the vehicle can handle the load and that the load is constantly checked.

Tiled roofs

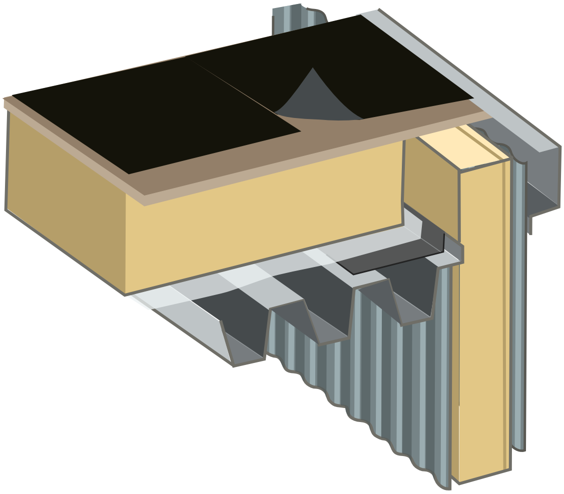
A tiled roof is built up as follows, from the inside to the outside:

- wooden roof trusses
- roof boarding
- roofing felt
- battens
- roof tiles.

The roof tiles are removed from the place where the opening is to be made. The opening is made between the roof trusses, with a remaining edge of about ten centimeters to the roof trusses, ridge and base of the roof. The location of the roof trusses is easily determined on structures where they protrude from the base of the roof, otherwise the nails can be exposed by removing the roofing felt. It is also possible to determine the location of the roof trusses by tapping with a hammer on the roof boarding and listening to where it sounds most hollow.

Once the tiles are removed the opening can be made by sawing through the roof boarding with a power cutter, a chainsaw or a circular saw. The easiest thing is to start at the ridge, and then saw the edges of the opening and finally along the base of the roof. A jimmy or crowbar is often needed to remove the roof boarding and battens completely.

Loose tiles pose a special risk with tiled roofs, and can drop down on personnel standing on the ground or on a ladder. In the case of an intense fire, roof tiles can be blown off, and therefore personnel, vehicles and equipment should be placed at a safe distance from the building. The roof tiles that are removed should be placed on



Cross-section of a roof with tarred roofing felt.

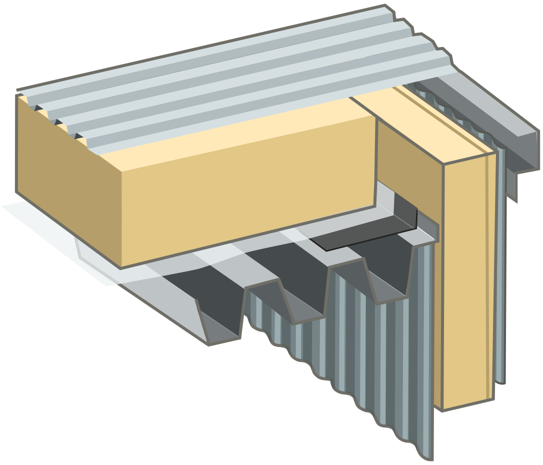
the ground. On older buildings the roof tiles may be attached to the battens or roof boarding with a cut-off nail that sticks out one or two centimeters. When the roof tiles have been removed it is easy to injure oneself on these nails when making an opening, or when balancing oneself against the roof.

Roofs with tarred roofing felt/waterproof paper roof

Tarred roofing felt can be laid on mineral wool boarding, roof boarding or the like, and can be difficult to identify from the outside. Below this there is often insulation, and below the insulation the supporting structure. This can be roof trusses, or corrugated metal sheeting laid on steel girders (see next section).

It can be difficult to get through tarred roofing felt. If a chainsaw is used the tar can cause the chain to stick. A power cutter with an emergency blade can manage to cut through, but to avoid the problem the tarred roofing felt can be removed with a scraper where the cuts are to be made. Even cutting through the cardboard with a knife can cause great concern.

Make an opening in the surface under the roofing felt, and remove the insulation. The location of the roof trusses or the supporting girders can then be determined.



Cross-section of a roof with corrugated metal sheeting.

Roofs with corrugated metal sheeting

A roof with corrugated metal sheeting can consist of, from the inside to the outside:

- profiled metal sheeting
- plastic sheeting
- insulation (mineral wool, rock wool or cellular plastic)
- possibly asphalt boarding, possibly also felt
- profiled metal sheeting.

In such a structure the interior metal sheeting provides the support and is laid on steel girders.

To make an opening for fire ventilation, both the outer and inner profiled metal sheeting must be cut through. The outer profiled metal sheeting is often not as deeply profiled, and can therefore be sawn with a power cutter. Another alternative can be to use a sheet metal extractor, but this assumes that the attachments can be broken without using too much force.

Perhaps the easier way of removing the outer profiled metal sheeting is to use a screwdriver. The fastenings can be removed with a battery operated drill fitting with a fixed socket or a screwdriver bit. The sheeting can then easily be removed and lifted down. If the sheeting is fastened with screws it is relatively easy to make a large opening in the outer roof.

It is a good idea if the outer opening is oversized to facilitate making the inner opening for fire ventilation. The following method can be used to gain access with the power cutter in the grooves of the metal sheeting:

1. Saw two parallel slots across the grooves of the sheeting. The space between them should be wider than the power cutter.
2. Press down the sheeting between the slots.
3. Saw the sheeting in the bottom of the grooves.
4. Do the same thing on the other side of the opening.
5. Saw the short sides of the opening up on a seam in the sheeting. If these slots are sawn first this increases the risk of falling through when the sheeting between the two parallel slots is to be pressed down.

If the sheeting is fastened with screws to each other and in the girders, it can be relatively easy to remove a complete sheet instead of sawing up the opening.

Special problems with this type of roof include melting tar from the tarred roof base paste board running down in the bottom of the grooves in the sheeting. If the roof is also at an angle the fire can therefore spread under the insulation.

The roofing felt and insulation should therefore be removed a good bit from the ventilation opening. If the roof is so hot that the tar melts before an opening has been made for fire ventilation, an opening should be made instead to prevent the spread of the fire in the roof structure.

Bear in mind that tar runs quickly, and also that the separation at fire compartment limits beneath the metal sheeting may not be very well executed on this type of roof.

Basements should normally have fixed installations for fire ventilation.

Fixed installations for fire ventilation

Many types of buildings have pre-installed systems for venting fire gases. Partly to facilitate evacuation, and partly to protect the property or to facilitate any fire and rescue operation.

For example, in multi-family buildings with three or more storeys, features for fire ventilation in staircases have been required for many years. There has to be openable windows at least every two floors or a hatch at the top of the staircase. If the staircase is above a certain height, normally more than eight storeys, it should be possible to open this hatch from the ground floor. Also in attics used as storage in multi-family buildings, there may be fixed installations for fire ventilation.

In buildings with more than eight but not more than 16 storeys, dwellings and premises shall be designed with access to at least one staircase of so-called type Tr2. In buildings with more than 16 storeys, dwellings and premises shall be designed with access to at least one staircase of so-called type Tr1.

A staircase Tr1 and Tr2 shall be designed with a separating structure so that the spread of fire and fire gases to the staircase is limited. For staircase type Tr1, this means, among other things, that the stairwell should only be connected to other spaces through a fire door that is open to the exterior. For staircase type Tr2, this means that some types of residential buildings should only be connected to the staircase through a space in their own fire cell, in practice a room that is a

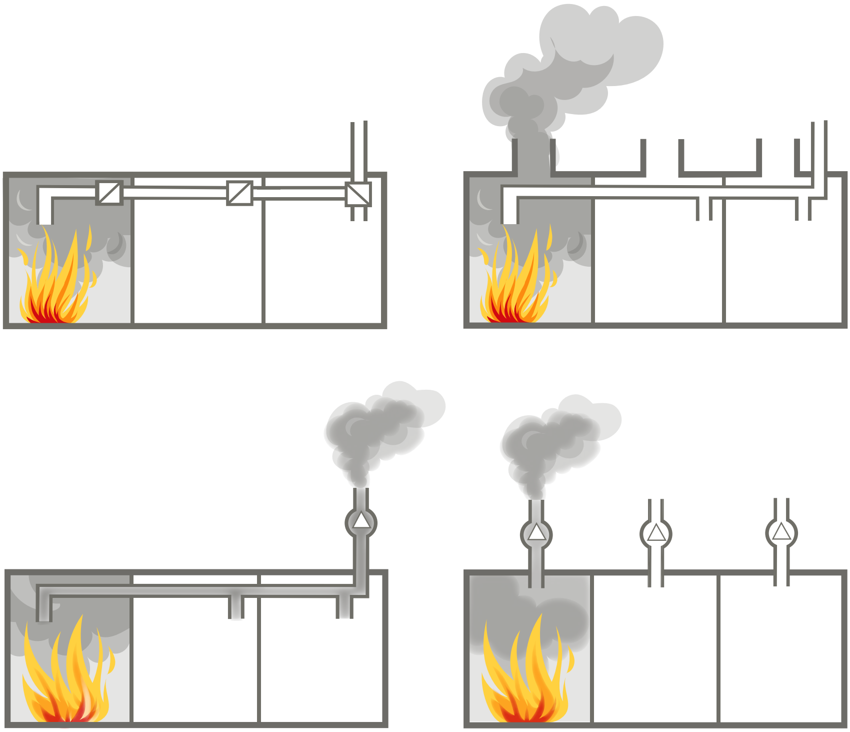
Openings (exhaust openings) for fire ventilation from basements can be located in the façade of buildings.

separate fire compartment. The staircase itself must of course also be a separate fire compartment.

Spaces where people gather more than temporarily should also be designed with access to at least two independent escape routes, which also provides advantages in connection with fire ventilation.

Basements should normally have fixed installations for fire ventilation, regardless of type of building. In buildings with more than one basement level below ground, there should normally be separate fire ventilation for each level. In multi-family buildings, staircases should normally not be used for fire ventilation of basements.

Also in, for example, industrial buildings and larger public premises (such as shopping centers), there may be fixed installations for fire ventilation, so-called ventilators or fire vents. They are normally designed to emit fire gases using the thermal buoyancy of the fire gases and can be designed as hatches or as light inlets (skylights). In some cases, these are combined with fixed fans. Ventilators open automatically or manually in case of fire. If they are opened automatically, they are either connected to an automatic fire alarm or there are so-called fuses. Fuses do not occur in more modern buildings, but used to consist of two brazed metals that will melt at a certain temperature so that the ventilator opens. In even older buildings, instead of brazed metals, there may be a so-called nitrated wire that ignites at low temperature. However, these days neither brazed metals nor nitrated wire are very common.



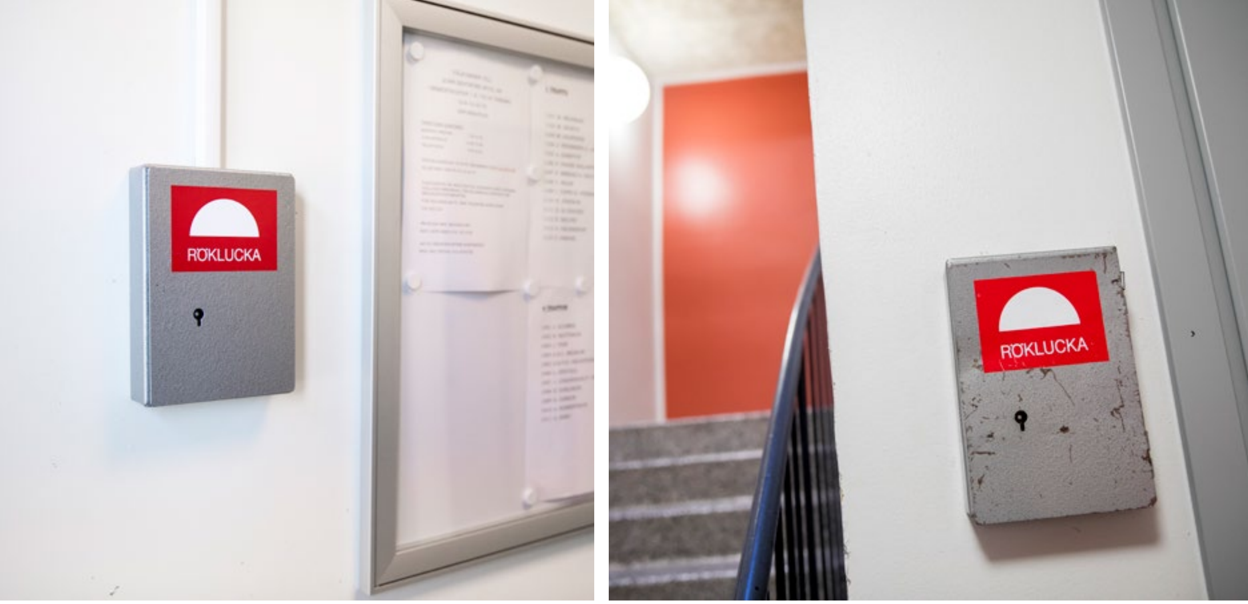
Examples of different systems for controlling supply and exhaust air flows using detection systems and dampers.

In barns and stables, the fire vents may consist of plastic sheets (light inlets), intended to burn through at an early stage of the fire.

Vents that are opened manually can be opened with the help of controls, for example via a fire alarm center. The vents are kept closed by means of magnets. When the power is switched off, the vents open. Another alternative is that the vents are spring loaded and that there is a handle near the vent, connected to a locking device with a handle. The vent is then opened by pulling the handle. This is common when fire ventilation is required in staircases, i.e. when there are more than eight stories.

A manual ventilator, often in the form of a skylight, must be opened by removing a locking device and removing the skylight. Often a hammer, screwdriver or crowbar is needed.

Ventilation systems in buildings are normally designed to prevent the spread of fire and fire gases, for example by insulating the ventilation ducts. But in some cases the ventilation systems can also be designed and used to facilitate evacuation and fire and rescue operations in a more active way. Often, in these contexts, we talk about smoke-control systems or smoke-management systems – systems designed for the management and control of fire gases. It is a holistic concept providing



Staircases with more than 8 floors should have a vent that can be opened from the ground floor.

safety to people, limiting damage to property and facilitating the work of the fire and rescues service. Part of this overall concept may consist of mechanical ventilation systems being designed to:

- facilitate the evacuation of the building
- prevent or limit the spread of fire gases throughout the building
- facilitate fire and rescue operations.

The possibility of using mechanical ventilation systems as an active part in the fire safety design of the building is limited by the nature and characteristics of the building. It is less suitable in smaller buildings with many small and confined premises. However, such designs are more useful in shopping malls, larger industrial buildings or warehouses. Normally, these systems use two different principles, pressure relief and pressurization, often in combination.

Pressure relief is a measure aimed at the fire room or the starting fire compartment, e.g. in larger spaces such as assembly halls or industrial buildings. Pressure relief is achieved by opening one or more shutters or windows so that fire gases are discharged. Another solution is that pressure relief is done through special shafts. Both shafts and shutters (ventilators) can be equipped with a temperature-resistant fan that starts when the system is activated in the event of fire.

Vents and shutters for fire ventilation in staircases can have different designs.

Fire ventilation in staircases to multi-family homes can be made of openable windows, at least every two floors.

Pressurization can also be used as an alternative or complement to pressure relief. This action is then mainly applied to adjoining spaces, such as evacuation routes (staircases, corridors or the like). The main purpose of the measure is to keep the escape routes free of fire gases so that both evacuation and fire and rescue operations are facilitated. As described earlier, ensuring the function of escape routes is a priority task in the event of fire in buildings.

Fire ventilation systems can be integrated with comfort ventilation, but they can also be completely separated. In integrated systems, the comfort ventilation system can be controlled by means of detectors so that the supply air to the fire compartment and the exhaust air in adjoining rooms is switched off.

In systems specifically designed for pressurization, there is normally a separate fan system that starts in the event of fire and which sets certain spaces e.g. evacuation routes under overpressure. If such a system is put into operation, the building's normal ventilation system might be turned off.

To facilitate evacuation, it is important that the mechanical ventilation systems start early. Therefore, these are normally connected to a detection system. The system starts when there a fire is detected. However, in some cases, the system may be dependent on manual control.

Existing and functioning ventilation systems should not normally be shut down, as they can be part of the building's fire protection system.

In buildings that have a system for smoke control, consider the following:

- Staircases are not always in connection with an exterior wall.
- Compartmentation of escape routes can be simplified.
- Evacuation routes can be longer than normal.
- The number of staircases may be limited.
- The smoke control system can make doors difficult to open or close.

Chapter 9

Tactics

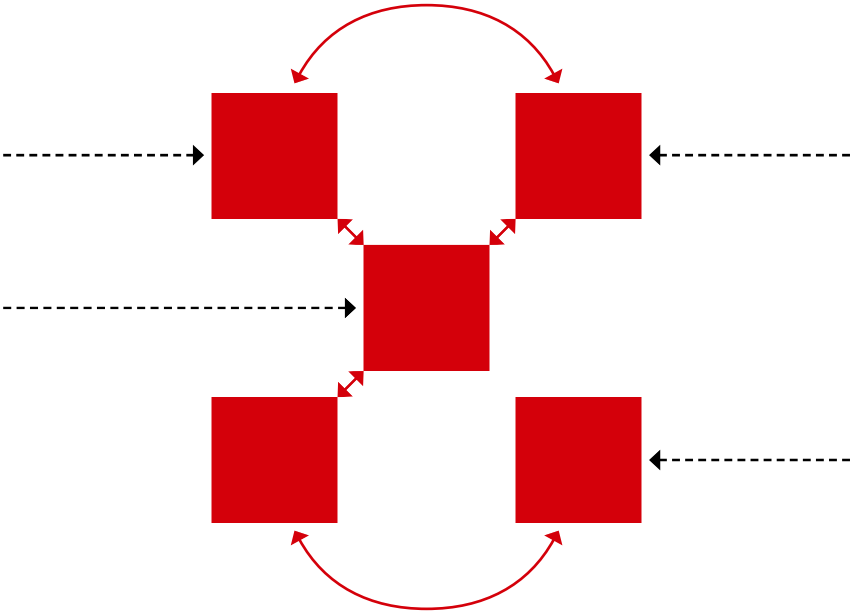
Tactics is doing the right things at the right time. Tactics related to fire and rescue operations are called firefighting tactics. A definition that has been used for several years says that firefighting tactics can be seen as a pattern of thinking and acting in order to achieve the best possible outcome, based on the overall purpose of preventing or limiting damage to people or property or the environment.

> Tactics are about how the different parts in a fire and rescue operation are put together, structured and form an overall solution. This overall solution is part of a wider context, and should be arranged in the best possible way.

Using resources effectively

Tactics is about using resources as effectively as possible in relation to the need for assistance, the dynamics of the situation and other demands posed by the situation, with the purpose of gaining and maintaining control. Tactics therefore describe what and how something should be done, not who does it.

When resources are used in different ways, for example at the scene of an accident, certain measures are initiated, coordinated and implemented. Measures are therefore implemented by resources that are allocated tasks. In certain cases the resource is designated as a unit that is an organizational support for the resource, i.e. that the resource is linked to a certain place in an organization. Such a unit normally consists of both people (personnel) and machines (technical aids). Measures are therefore produced with the help of units. Both the number of people and the amount of machinery and other equipment the unit consists of can vary. Units are defined in advance, before any fire and rescue operations are started, but they can also be created or defined during an operation.



The measures that are initiated, coordinated and implemented in association with fire and rescue operations are put together in tactical patterns, where they are linked to each other and depend on each other in different ways. They are also part of a specific context.

Coordinated measures

As a rule several measures are implemented at the same time. It can be said that the measures are put together in tactical patterns, where several different measures are linked to each other and depend on each other in different ways. This for example can be the case with positive pressure ventilation, where the positioning of fans is coordinated with the creation of outlets and internal fire suppression.

Measures are also initiated, coordinated and implemented in a specific context. In the case with fire ventilation, the context is mainly the characteristics of the building forming the basis for how and why fire gases are spread throughout and out of the building. The context is important to determine which measures, taking everything into consideration, must, can or should be initiated, coordinated and implemented, and in which order this must, can or should be done. It is therefore essential to be able to identify the context and the problems that must be solved in the short and long term. The context therefore influences both the choice of measures and in which way or in which order they are initiated, coordinated and implemented in the tactical pattern. When this concerns fire ventilation the context is, among other things, the identification and understanding of which pressure forces have to be handled, and what the pressure conditions look like inside the building.

The measures that are initiated, coordinated and implemented create, together with the accident scenario, a dynamic relationship, i.e. dependency in time and space, between different types of measures, between respective measures and the accident scenario, and between the tactical pattern and the accident scenario. It should also be kept in mind that the accident scenario will continue regardless of whether measures are initiated, coordinated and implemented or not. It is from these dynamics, i.e. the interaction between the measures and the accident, that tactics develop. Tactics are therefore what connect the measures to the accident scenario. In the case of fire ventilation, for example, consideration must be taken to the time it takes to create openings in relation to how the fire develops. It is important that measures are initiated in good time.

It is of great importance that all those involved in fire and rescue operations have first-rate knowledge of the dynamics that affect the way accidents develop and the chain of events, regardless of whether measures are taken or not. It is also important to link these dynamics to the impact accidents have on the people affected, property or the environment, since it is the need for assistance as a result of an accident or imminent danger of an accident that must be in focus. It should also be kept in mind that in some cases fire ventilation can lead to an undesired sequence of events and impact on people, property or the environment. It should again be emphasized that the air that in most cases flows into the fire as fire gases flow out can give rise to a rapid and undesirable spread of fire gases and fire.

Gaining and maintaining control

It is possible to define an overall purpose for fire and rescue operations – to gain and maintain control. To gain and maintain control it is usually necessary to satisfy four general conditions:

- There must be a goal (the goal condition).
- It must be possible to determine the state of the system to be controlled (the observability condition).
- It must be possible to change the state of the system (the change condition).
- There must be a model of the system that describes what will happen if we do something to the system (the model condition).

It is only through control that a sequence of events can be guided in the intended direction, and it is by initiating, coordinating and implementing measures that control is achieved and maintained.

Tactical patterns during fire ventilation

Fire ventilation is a collective concept for several different types of measures, with the common objective of venting out fire gases. Depending on what the purpose is in a specific situation, one or more ventilation measures are implemented. This is part of the goal condition, to achieve and maintain control – fire ventilation must have a goal. The observability condition will tell us, depending on the context and which resources (units) are available, that fire ventilation can be implemented in different ways, i.e. in different tactical patterns. It may, for example, in certain situations be better to vent first and then make a traditional attack, while in other situations it might not be possible to vent until a much later stage in the operation. Sometimes it is perhaps better not to vent at all. To a large extent this depends on the context. If the goal is to vent out fire gases, it must also be possible to change the state of the system – it must be possible to effect a change in the intended way with the help of fire ventilation.

One of the most important starting points that must be identified in the event of a fire in a building is whether the fire is ventilation controlled or fuel controlled. If there is a minimum of uncertainty, the fire should be considered to be ventilation controlled. This is the most complicated case, since fire ventilation also adds air to the fire. If the fire is then ventilation controlled, the supply of air can cause the fire to increase in size, spread out of control, that phenomena such as backdraft occur etc. Fire ventilation of ventilation controlled fires should be made with great caution or even avoided, before any extinguishing measures are taken.

In ventilation controlled fires, especially structural fires, ventilation measures should normally be preceded by extinguishing agents being added to the space or even better, directly on the fire. An exception may be when positive pressure ventilation is carried out or in premises where extinguishing agents for various reasons are unlikely to have any effect. It may not be possible to locate or reach the fire from the outside. If fire ventilation is then implemented, it is important to combine this with other measures. The purpose of the ventilation measures that are then implemented should be to facilitate other measures, among other things.

Fire ventilation is only part of the measures that normally need to be implemented, and such ventilation often needs to be combined with other measures to ensure the best possible results. It is not only about what and how we do fire ventilation, it is also about when and where we do it.

> Tactics involves using resources as effectively as possible in relation to the need for assistance, the dynamics of the situation and the other demands posed by the situation, with a view to achieving and maintaining control.

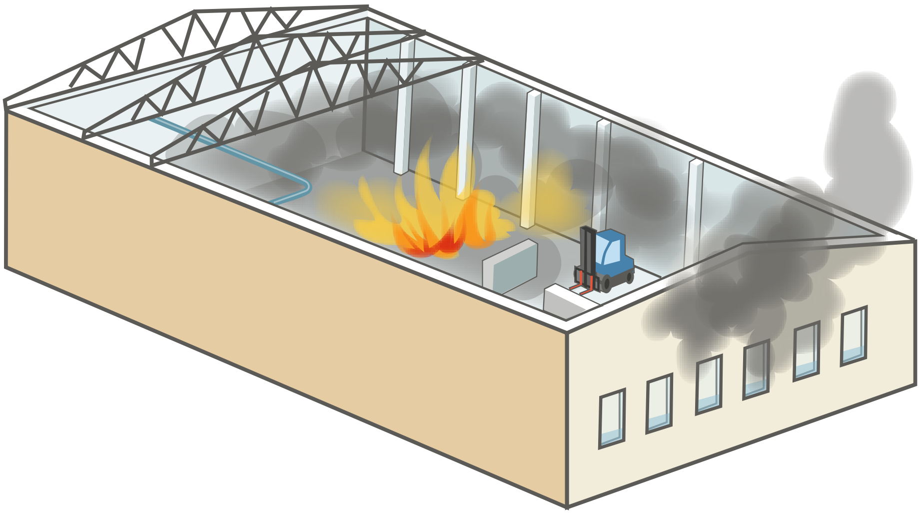
Chapter 10

Examples of firefighting situations

Earlier in this book, fire ventilation has largely been treated as an individual measure (or a collection of measures). But we also need to link fire ventilation with other parts and other measures during the fire and rescue operation, depending on, among other things, what the fire looks like, how the building and the fire room look, what resources are available and any other measures that need to be implemented. After all, we want our fire ventilation measures to fulfill a certain purpose and thus produce an effect that we can benefit from. Fire ventilation can affect the fire and rescue operation several ways at the same time, and we must try to create a holistic picture of the event, whether or not fire ventilation is implemented.

A number of general examples of possible firefighting situations are described below, where fire ventilation may be an appropriate measure. The exemplified situations are designed to ask questions and present problems and opportunities specifically related to fire ventilation. In real fires it is rarely this easy. Above all, there is a time aspect to consider that is difficult to describe in writing. In addition, several of the examples described below can exist simultaneously, for example, both hot and cold fire gases in a staircase can be due to a basement fire. In addition, in virtually all building fires, we should take into account the risk of structural fires and the problems that they pose with regard to fire ventilation. The purpose of the examples is only to create a picture of what some different, but likely, situations may look like and how we might deal with them.

Regardless of the situation, there are usually two things that should be prioritized. Firstly, to ensure that the escape routes are free of fire gases. Secondly, to get extinguishing media on the fire as soon as possible. Of course, both must be done as safely as possible. However, appropriately venting fire gases and heat usually facilitates the effort from several perspectives, whether it is early or late.



A small fire in a large room can cause low temperature fire gases with limited thermal buoyancy.

Small fire in relation to the size of the room

If the fire is small in relation to the size of the room and especially if the amount of fuel is limited, the fire process rarely reaches a fully developed room fire. Then the fire can remain fuel controlled as long as there's fuel. However, the fire can still develop a large amount of fire gases that need to be vented.

This may be the case for example in large industrial premises with a relatively limited fire, or if it has a high ceiling. The higher the ceiling, the more air is mixed into the fire gases. The volume of fire gases then becomes large, but relatively cold and diluted. Due to the large premises, the fire will be fuel controlled for a long time. It may not be ventilation controlled at all.

The risks associated with fire ventilation are small in this situation, especially considering that the fire is fuel controlled. Ventilation measures, which also supply air, will then not have a direct impact on the spread and behavior of the fire, although it can affect it after some time.

It is also possible that a similar situation arises in the event of apartment fires. Ceiling and wall surfaces can be non-combustible (e.g. plaster) and the furnishings can be placed in such a way that fire in a single object does not spread to other objects. The fire can then remain fuel controlled throughout its course, or alternatively become ventilation controlled later on. Either way, it does not spread but stays in one or a few objects in the room. The fire can even extinguish itself when it runs out of fuel. The risks associated with fire ventilation in these situations are relatively small.

However, a small fire can increase rapidly during fire ventilation if it is a structural fire, that is, if it burns inside, for example, trusses, walls or in other confined spaces. This poses significant tactical requirements, especially in the form of getting more resource to the scene. Although the room is well ventilated, there may be hidden spaces that are poorly ventilated.

Since the fire gases have a relatively low temperature and very limited thermal buoyancy, the exhaust openings should be made as high as possible, preferably in the ceiling. Inlet openings should be made as low as possible. Mechanical ventilation is not always suitable in these types of situations. Positive pressure ventilation can be difficult to implement due to practical problems, partly because the room may be very large. Furthermore, in large buildings, positive pressure ventilation can be difficult or even inappropriate because the air supplied by a fan creates turbulence, which can destroy any layering of fire gases. Due to the size of the building, it can take a long time to vent the fire gases, which can make the situation worse for firefighting personnel.

However, pressurization of adjoining spaces is a measure that may be appropriate if the fire is small in relation to the size of the room. Pressure is of course then created in non-exposed areas of the building.

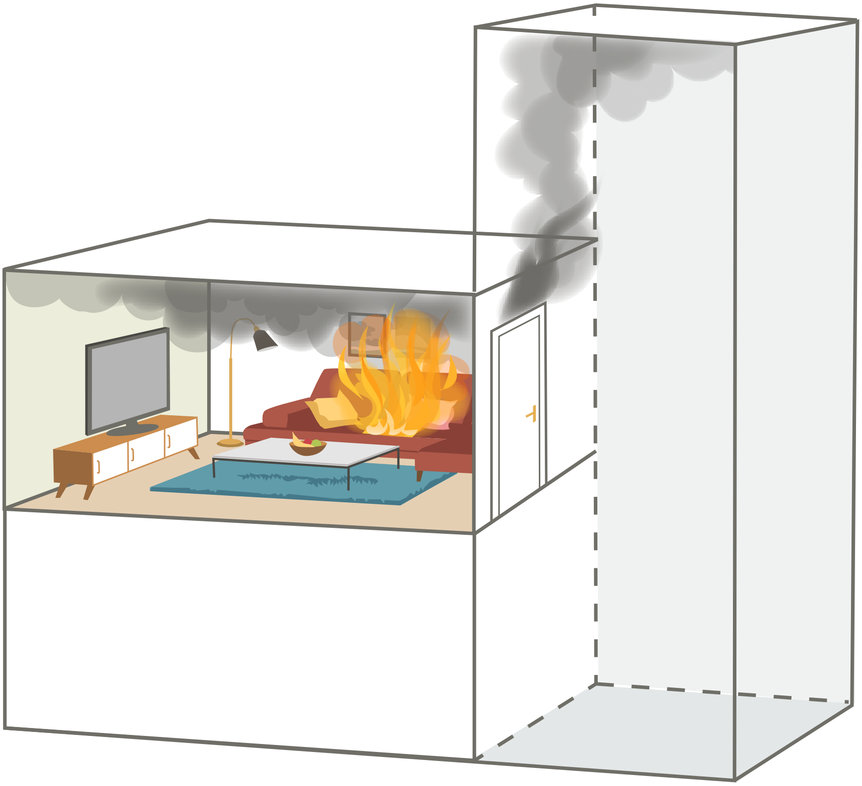
> Things to consider during a small fire in relation to the size of the room: positive pressure ventilation can cause problems when the fire gases become mixed in the room and worsening the conditions.

During the initial stages of the fire, hot fire gases and flames will heat up ceiling and wall surfaces as well as objects in the room.

The initial stages of the fire

The fire may still be in its early stages when the fire and rescue service arrives, e.g. if detection and alarms occur early or if the response time is short, or in certain types of premises with relatively low fire load. The fire gases can be hot, flashover has not yet taken place and inlet openings allow relatively free inflow of air. Hot fire gases flow out through the upper parts of the openings and fresh air flows through the lower parts. The fire can be very calm, stationary, very intense or rapidly growing, depending on for example the geometry of the premises, the location of the fuel or the material on the roof and wall surfaces.

Because the fire gases are hot, natural ventilation can be used with good results. This means creating openings in the upper part of the fire room or building (by opening existing doors or windows) and ensuring that the inlet openings are at least 1–2 times the size of the exhaust openings.



Flashover has not yet occured and the risks with fire ventilation are fairly small.

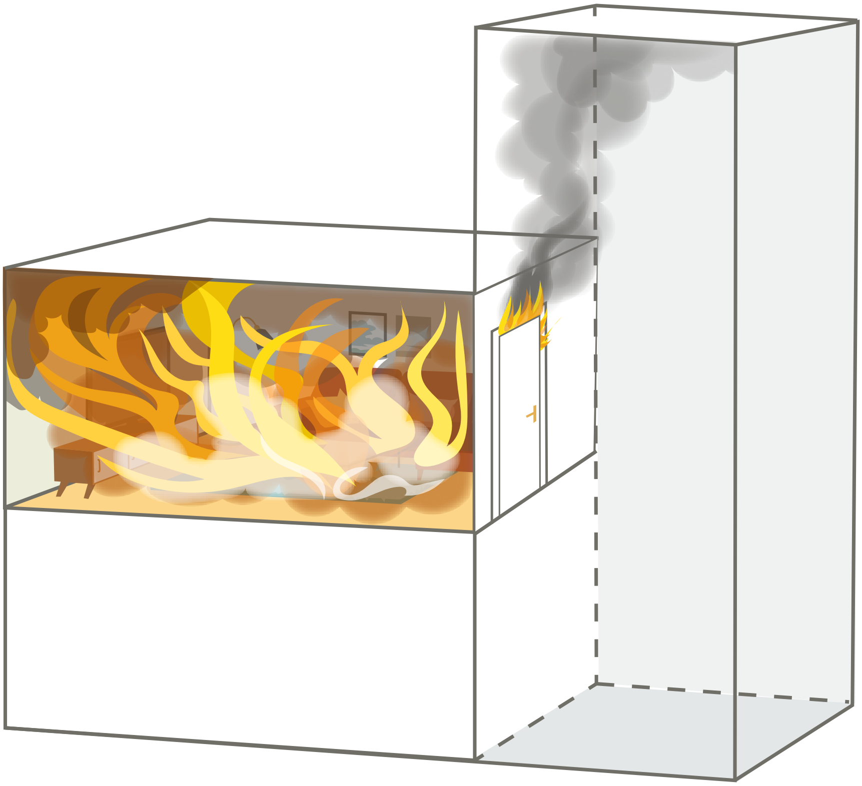
Positive pressure ventilation can be used to improve the effect of fire ventilations. Positive pressure ventilation also reduces the requirement for the location of the exhaust openings. But we must clearly determine where we should have inlets as well as exhaust air openings so that we get a clear flow of fire gases out of the building (creating a flow path). Of course, exhaust openings should also not be placed so that there is a risk of the fire spreading to the outside of the opening, in case the fire increases in intensity and possibly flashes over and turns into a fully developed room fire. Positive pressure ventilation can also increase the risk of the fire spreading to the structure or to other cavities, even if the fire is small. In the case of positive pressure ventilation, the exhaust openings should be 1–2 times as large as the inlet openings.

The rate of heat release of the fire can increase rapidly due to increased air supply during fire ventilation and because combustible materials and surfaces in the room are heated. Possibly the fire also reaches flashover. In the case of fire ventilation, there is a risk related to whether the fire is still in its early stages, but this can also be of great advantage. This advantage should be exploited, especially through the use of speed.

During the initial stages of the fire, fire gases are collected below the ceiling and flow out through the upper part of openings.

Getting extinguishing media quickly on the fire is always important. But if the fire is further in the building and cannot be reached from the outside, it can be difficult. Applying extinguishing media to fire gases, especially if they are flowing out of the building, has a limited or no effect. But it can be a measure to safely reach the fire.

> To consider during the initial stages of the fire: Choose exhaust openings with care as combustible gases can ignite in the openings. Observe any changes in the situation before any internal action is initiated. Carry out a quick extinguishing effort to stop increasing rate of heat release. Use positive pressure ventilation if possible.



Flashover has occurred and the fire is fully developed. The risk of fire spread is imminent.

The fully developed fire

In many cases, the fire is fully developed and ventilation controlled when the fire and rescue service arrives. Flames are coming out through openings and there is a great risk that the fire will spread to adjacent premises or buildings. In room(s) where flashover has occurred and where the fire is fully developed, it is not usually beneficial with fire ventilation or to try to save lives. In adjoining spaces, however, this can be justified and of the highest priority. There, fire gas ventilation can facilitate both victims and firefighting personnel.

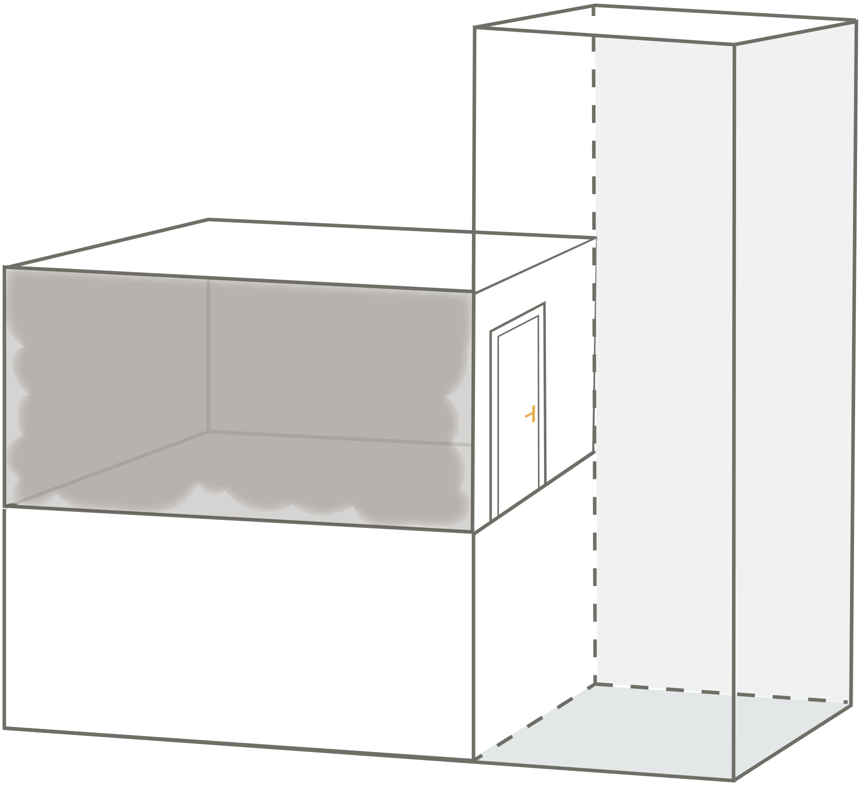
Since the fire gases are hot, natural can be used with good results (i.e. using thermal buoyancy only). Then the exhaust openings should be made in the upper part of the space (in the roof) and the inlet openings should be at least 1–2 times the exhaust openings.

As in the case with the early stages of the fire, positive pressure ventilation can be used to improve the effectiveness of fire ventilation. Positive pressure ventilation reduces the requirement for the location of exhaust openings. But we must clearly determine where we should have inlet as well as exhaust openings, so that we get a clear flow of fire gases out of the building (creating a flow path). In order to utilize thermal buoyancy, exhaust openings should be in the upper part of the space. Exhaust openings should also be created so that there is no risk of the fire spreading to what is the outside of the opening if the fire increases in extent and spreads in the room. The risk of fire or fire gases spreading to adjoining rooms may increase, but above all, one should pay attention to external spreading to the façade for example. Positive pressure ventilation can also increase the risk of a fire from spreading to the structure or to other cavities. In the case of positivie pressure ventilation, the exhaust openings should be 1–2 times larger than the inlet openings.

It is not obvious to ventilate in the fire room itself. Since the fire is ventilation controlled, the rate of heat release will increase further if openings are made so that air flows into the fire. If openings are closed instead, the rate of heat release from the fire will decrease. In certain situations, if extinguishing for various reasons is not possible as a first measure, it may therefore be more favorable to try to close the fire room and ventilate adjacent spaces instead. This may be a suitable measure as resources are not available to directly attack the fire, as saving lives in adjacent areas must take place first. A prerequisite is, of course, that openings can be closed, which can be difficult or even impossible if windows have been broken or if roofs or walls have been broken.

However, it is usually of the highest priority to get extinguishing media on the fire. If this is the case, the spread of fire gases and the risks of spreading fire quickly decrease. In the fully developed fire, the risks and problems are considerable but also often clear. The fire gases burn in contact with the air and the entire fire room is involved. In addition to saving lives, the primary tasks of the fire and rescue service should be to prevent the spread of fire and fire gases.

> To consider during a fully developed fire: Great caution should be taken when choosing exhaust openings, given the flames coming out of the fire compartment. Have a well-planned and coordinated ventilation and extinguishing operation, as air supply will increase rate of heat release. Consider alternative methods to attack the fire.



The entire space is filled with fire gases that can also be hot. If the fire compartment is opened, air can flow in and any ignition can occur quickly and the pressure wave can become considerable.

Ventilation controlled fire

In the case of a ventilation controlled fire, the fire may have developed into a fully developed fire. Or, which usually is a larger problem, the fire may have developed towards flashover, but then declined and decreased in terms of the rate of heat release due to lack of oxygen. However, the fire is not completely asphyxiated and the temperature may in some cases be high at perhaps 200–400°C. At these temperatures, large amounts of unburned gases can be produced. The concentration of these varies, but are often sufficient to be flammable when air is supplied, especially if the fire gases are hot. If fire ventilation takes place, a rapid flashover can occur or the risk of backdraft may be imminent. However, for a backdraft to occur very special conditions are required and this is relatively uncommon.

In this type of situation, no doors or windows are open. The air exchange takes place only through small leakage surfaces, e.g. through comfort ventilation or through gaps. Large amounts of unburned gases can also be spread to adjacent spaces.

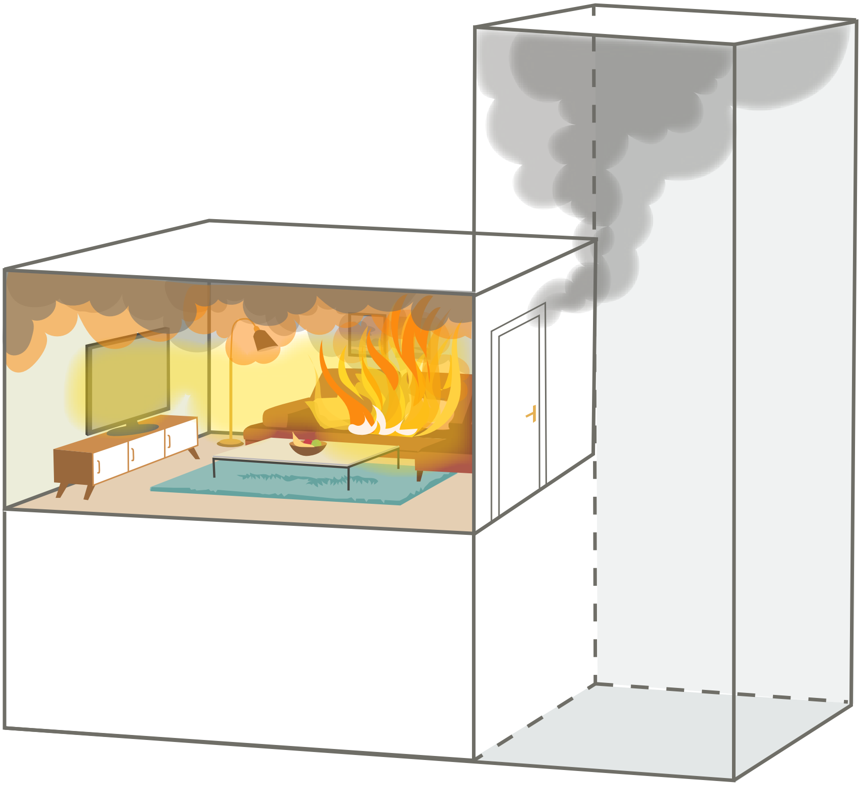
The purpose of the fire ventilation of enclosed spaces with a ventilation controlled fire can be to reduce the spread of fire gases by reducing the pressure buildup of hot fire gases in the fire room or in adjoining rooms. In exceptional cases, the purpose may also be to force the fire process and allow flashover to take place under controlled forms. Avoid this if possible. But in some rooms it can be difficult for various reasons to apply extinguishing media before ventilation, and this can possibly be a way forward. If extinguishing media are immediately available when the space is opened, it should be possible to deal with any flashover or other rapid fire spreading phenomena.

If the fire is strongly ventilation controlled, alternatives to fire ventilation should be considered. However, in the case of strong ventilation control, it is often appropriate to first do some kind of fire suppression from the outside. Extinguishing a fire from the outside, through a window or a small hole through the structure, is often appropriate before fire ventilation or any internal fire suppression takes place.

If the fire gases can first be cooled down in this way, fire ventilation or an internal fire attack can then be carried out with significantly less risks. Many times it may also be advisable to first secure adjoining rooms or buildings, before taking action on the fire area. However, in ventilation controlled fires there can be lives to save in the fire room, as the heat effect on trapped people can be relatively moderate.

Ventilation controlled fires pose great risks, as the fire gases contain large amounts of unburned gases. The rapid addition of large amounts of air causes the risk of backdraft. Above all, there is a risk of a very rapid flashover processes when fire ventilation is carried out.

To consider during ventilation controlled fires: Consider alternative methods to fire ventilation e.g. cooling of fire gases without opening any openings. Take great care when applying fire ventilation. Exercise great care when choosing exhaust openings. Avoid turbulent inflow of fresh air into the fire gases. Have a well-planned and coordinated ventilation and extinguishing operation, since air supply will increase the rate of heat release and the risks of spreading fire and fire gases.



The upper parts of the staircase are filled with hot fire gases.

Staircase with hot fire gases

In the event of apartment fires, relatively hot fire gases can in some cases enter the staircase, especially if the door to the fire apartment has been left open. The layering in the stairwell becomes clear with an upper layer of hot fire gases and a lower part that is more or less free from fire gases. It will then be difficult to evacuate from the upper apartments.

There is also a risk of fire gases entering the upper apartments. This risk depends, among other things, on the nature of the comfort ventilation, the temperature of the fire gases and the quality of the doors.

Since the fire gases have a relatively high temperature, natural ventilation using thermal buoyancy can be used with good results. However, this requires that there is an openable hatch or window in the upper part of the staircase, which should be the case in staircases with more than three floors. Using positive pressure ventilation entails certain risks. If the fan is placed at ground level outside the staircase, the entire staircase is pressurized and then fire gases can be pushed into the upper apartments. However, it can work very well using positive pressure ventilation, if it is properly coordinated with the fire extinguisher against the fire apartment and if the fire gases in the staircase is vented before the fan is started.

In the event of apartment fires above ground level, it can be difficult to apply extinguishing media before fire ventilation takes place or before the space is opened for other reasons. Extinguishing media that do not reach the fire room or at least a warm room is generally not of any benefit, rather the opposite.

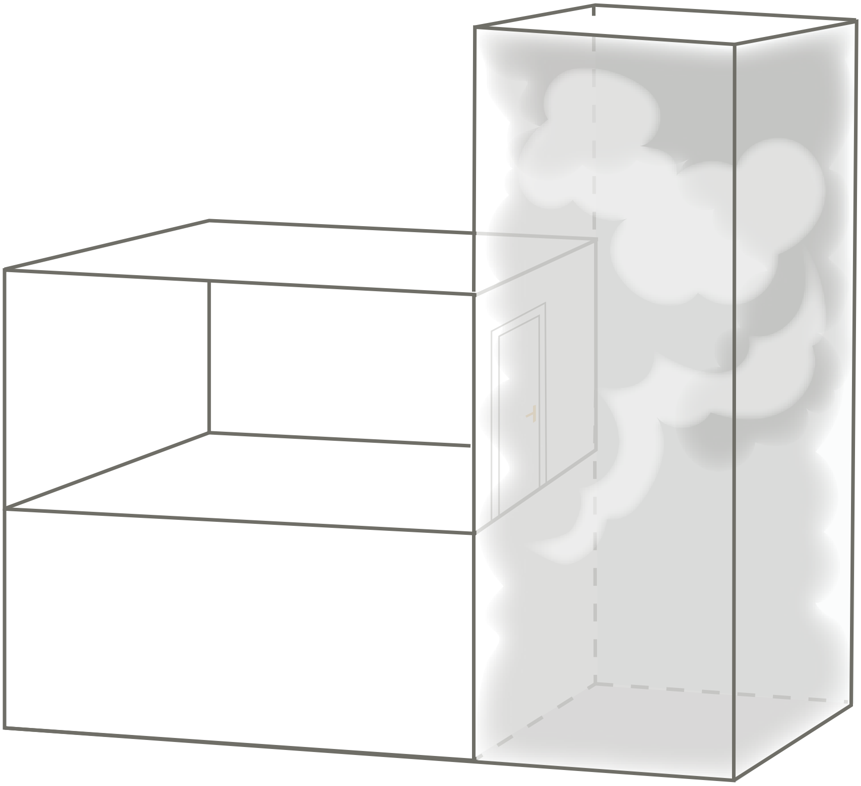
The primary purpose of fire and rescue operations should be to facilitate the evacuation of people in buildings. Therefore, a basic task must be to ensure that staircases are free of fire gases. This allows people to get out themselves, which is especially important in buildings that accommodate a larger number of people, e.g. high-rise buildings or public premises such as cinemas, restaurants and sports facilities. Fighting the fire then has to wait.

> To consider when approaching a staircase filled with hot fire gases: Fire ventilation of staircases should be carried out immediately, so that the escape route is secured and so that the risk of spreading fire gases is reduced. Consider pressurization of the staircase and positive pressure ventilation when attacking the fire compartment. Also consider an alternate attack route, for example through windows, to minimize the spread of fire gases to the staircase. The risk of flashover or flame spread to the staircase must be considered.

Staircases with cold fire gases

In the event of apartment fires, if the fire effect is small in relation to the size of the fire apartment, fire gases with relatively low temperature can flow or leak into the staircase. Or, relatively small amounts of hot fire gases are mixed up with fresh air and cooled down as they enter the staircase. In this case, there is no clear layering between fresh air and fire gases in the staircase.

The effect of natural ventilation is therefore poor and any openings in the upper part of the staircase should be supplemented with positive pressure ventilation. In this case, the conditions for positive pressure ventilation, coordinated with a fire attack, are good, since the operation



A staircase filled with cold fire gases can be difficult to ventilate.

can be carried out without especially much fire gases spreading to the stairwell. But then it is necessary to create an exhaust opening in the fire apartment.

The primary purpose of fire and rescue operations should be to facilitate the evacuation of people in the building. Therefore, a basic task must be to ensure that staircases are free from fire gases. This allows people to get out themselves, which is especially important in buildings that accommodate a larger number of people, e.g. high-rise buildings or public premises such as cinemas, restaurants and sports facilities. Fighting the fire then has to wait.

To consider when approaching a staircase filled with cold fire gases: Fire ventilation of the staircase should be carried out immediately, so that the escape route is secured and so that the risk of spreading fire gases is reduced. Consider pressurization of the staircse and positive pressure ventilation when attacking the fire compartment. Also consider alternate attack routes, for example through windows, to minimize the spread of fire gases to the staircase.

In the event of a fire in a basement, it is important to stop and prevent the spread of fire gases to the staircase, so that the building can be evacuated safely.

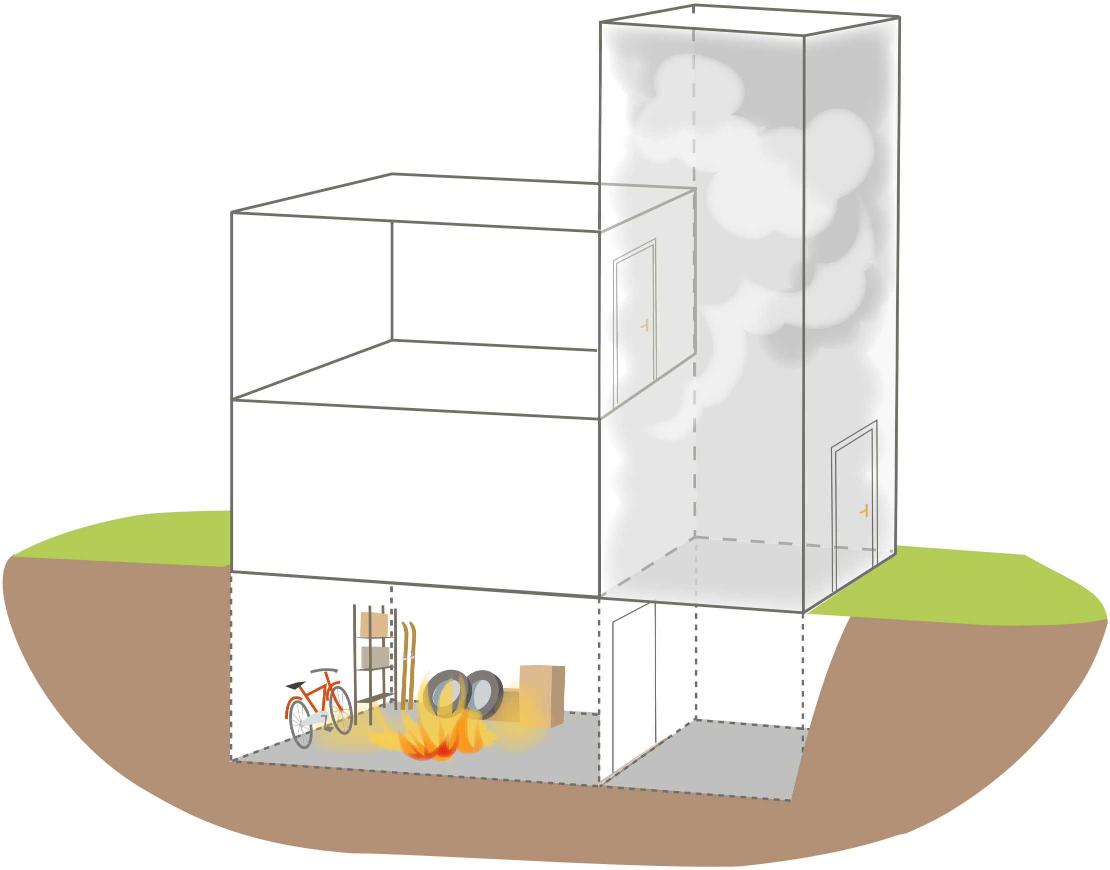
Basement fires

Basement fires pose a particular problem, and it is difficult to specify any specific tactics for how such fires should be handled as regards fire ventilation. However, it is usually important to try to get extinguishing media on the fire before ventilation. Several of the aspects that make basement fires particularly difficult to handle also apply to other types of underground premises.

The problem is mainly that the driving force for the spreading of fire gases is thermal buoyancy. In the event of a fire below ground level, such as in a basement, thermal buoyancy allows the fire gases to be spread to all spaces above ground in the building. The fire protection in the building, such as in fire compartments and evacuation routes, is often decisive for the spread of fire gases and heat.

The risk of basement fires quickly becoming ventilation controlled is also greater than in many other types of space in buildings. Because the space is below ground, it is often more closed and has less access to air.

Thermal buoyancy means that all paths to the basement are basically



Basement fires can be extremely hazardous and pose special problems to firefighting personnel.

like a chimney where fire gases and heat are released. Fire gases and heat are rising upwards and therefore strive to flow out through openings that are high up or through paths leading to such openings.

In the case of basement fires, it is especially important that escape routes are kept free from fire gases, especially in multi-family buildings. Therefore, as far as possible, avoid attacking the basement via the staircase. Instead, openings directly to the exterior should be used for fire ventilation. Bear in mind that any opening made to the basement will affect the flow of fire gases, as thermal buoyancy can be very noticeable.

In single-family homes and similar buildings, there is normally an entrance to the basement from the outside. If so, such openings should be used primarily for fire ventilation or fire attack. If there are no external pathways or openings for fire ventilation directly from the basement and to the exterior, fans or smoke curtains may be useful to prevent or limit the spread of fire gases to staircases. If fans are used, the staircase must then be pressurized before openings are made to the basement.

To consider during basement fires: Escape routes as well as attack routes will lead to spaces or openings located above the basement. Because of the thermal boyancy, fire gases and heat will strive to rise upward through these escape routes and attack routes. Efforts against basement fires, but also against other types of underground facilities, will therefore be like making attacks through a chimney. In the case of basement fires, but also in other types of underground installations, extinguishing media should be applied to the fire before ventilation is initiated.

Structural fires

If it is suspected that a fire has started or has spread into the structure, i.e. in a hidden space, it is important that the operation is carried out with great caution. Preferably, extinguishing media should be applied to the hidden space before it is opened and there are a variety of ways to do this. The purpose of opening up the structure is mainly to enable the use of an extinguishing agent. However, when the design is opened up, several of the effects described earlier can occur.

For example, due to the geometry of hidden spaces, the stack effect (thermal buoyancy) may strongly affect any measures against such spaces. The geometry of the spaces can also cause structural fires to become ventilation controlled fast. The consequences of opening up a structure where a fire has occurred or where a fire has spread can be that the production of fire gas and then even the spread of fire can accelerate much faster than in fires in ordinary rooms. If the volume is then also relatively small, more fire gases can be accumulated in relation to available fuel, which further increases the heat transfer to unignited fuel. Any measure that causes air to enter the space can cause fire gases to spread uncontrollably and that fire may arise at great distances from where openings are made.

Creating openings in hidden spaces is normally an important measure in order to be able to access and extinguish a fire and to vent fire gases.

Before opening a structure for checking, extinguishing or venting fire gases, extinguishing media must be provided so that it can be immediately applied to the inside of the structure. It is then important to remember that the extinguishing media must as far as possible hit the fuel surfaces. In some cases, it may be necessary to apply water, for

Fire ventilation, including openings to access the fire, during structural fires can cause fire gases and fire to spread out of control.

example, with the help of fog nails, cutting extinguishers or the equivalent before any openings are made. Note that the choice of extinguishing system, extinguishing method or extinguishing media depends, among other things, on the volume of the space but also the effect of the measure expected and what the structure looks like. Applying extinguishing media in concealed areas has limited or no effect if there is no fire in the room or if the temperature is relatively low. Of course, water may have some delaying effect, but this must then be set against the risk of water damage.

Locate the fire if possible. In some cases, a thermal imager (infrared camera) may be useful, but bear in mind that the thermal imager only detects heat on the outside of the structure. Since it may take some time for the heat to transfer from the hidden space to the outside, the fire may have spread far from where heat on the outside can be detected. Knowledge and understanding of what the structure is supposed to look like is an important tool for managing design fires effectively.

Once the hidden space has been identified, try to apply extinguishing agent if possible before making any openings. If this is not possible, creating an opening must be done carefully and in such a way that extinguishing media can be applied immediately when the opening is made.

On horizontal surfaces, it is normally advisable to create openings on the windward side, primarily to avoid personnel exposing themselves to fire gases or heat. On vertical surfaces it is not possible to give any general guidelines as to where openings should best be made. When creating openings below where the fire is expected, thermal buoyancy will cause air to flow in, which can worsen the situation. The advantage is that the stack effect may help to get extinguishing media into the hidden space (small drops of water, dry chemical, etc.). When creating openings above where the fire is expected, thermal buoyancy will cause the opening to be an exhaust opening and that personnel will then be exposed to heat or fire gases. The advantage is that the risk of the fire spreading further inside the structure may be reduced, at least for some time. In both cases, there is an increased temperature in the hidden space.

The actual openings are made according to the type of structure. A wooden structure can normally be torn down or opened with simpler hand tools such as a crowbar. A sheet metal structure usually requires either the sheet to be unscrewed or a power cutter capable of cutting metal. Concrete and brick normally require access to the space from elsewhere, for example from another space. Bear in mind that most types of designs are composed of several different types of materials in multiple layers.

Creating openings takes time. During this time, a structural fire may spread further inside the structure.

When openings are made, it is important to get extinguishing media into the hidden space as soon as possible. It is also important that enough of the structure is removed so that fire cannot continue or recur (as a result of smoldering fires etc.).

> To consider during construction fires: Creating openings to hidden spaces can cause fresh air to flow into the fire, which can lead to a number of undesirable consequences. Ventilation of hidden spaces with strong ventilation controll can cause fire gases and fire to spread in a way that results in a total loss to the building. For any ventilation effort, including accessing the fire, one should normally apply some type of extinguishing agent before openings are made. But applying extinguishing agents in hidden spaces has limited or no effect if there is no fire in the space or if the temperature is relatively low.

Some final words

What is covered in this book is fire ventilation in situations that are relatively common in Sweden. Examples of such situations include:

- apartment fires
- fires in single family houses
- fires in fairly small office buildings or shops
- fires in fairly small industrial buildings and warehouses.

What is not explicitly dealt with, is fire ventilation in, for example tunnels, larger underground parking garages, a large shopping mall or similar.

However, the basic principles of fire, what fire gases contain and how fire gases spread are the same. For example structural fires can also occur in more complex or larger buildings. Such cases require more thought, more knowledge and a greater understanding of the situation. Experiences may no longer be sufficient, due to the complexity of the building. Sometimes it may be worth spending some time planning the measures for fire ventilation, before commencing them. However, in some cases speed is required. The trick is to be able to understand and differentiate between these situations.

Anyone who claims to know for sure how fire gases spread in buildings and what the consequences are, should probably think again. There are always a number of factors that we have no control over or that are currently unknown. It may be enough that an interior door that we do not know is open or closed, making the conditions change completely. Or that the wind conditions change just slightly. Or that the fire has spread to the structure.

Whoever said that fire ventilation is easy?

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Order Nr.: MSB1565 – May 2020 ISBN 978-91-7927-036-0