



Swedish Civil Defence  
and Resilience Agency

# Fires in buildings



## **Biography – Dr. Stefan Svensson**

Stefan Svensson began his career as a conscripted firefighter in the Swedish Air Force in 1986. Stefan holds a PhD in fire safety engineering and is an associate professor in fire safety engineering at Lund University. He has worked for several years as an instructor at The Swedish Civil Defence and Resilience Agency and its predecessors in Revinge but has also been employed at Lund University as head of their fire laboratory. He has also worked as a part-time firefighter and a crew commander. For many years, he has been involved in a number of experimental and theoretical studies on methods, tactics and command for municipal rescue services. Stefan has written several books, reports and articles and has over the years conducted extensive national and international development work for the fire and rescue services.



Photo: Stefan Svensson

### **Fires in buildings**

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# Preface

Much has been written about fires, not least in buildings and especially about how best to fight them. In 1876, Sir Massey Shaw wrote a manual for how the fire department in London should work, and there are certainly even earlier works than that. Corresponding writings also existed for Swedish conditions. Later in time, interest with a more scientific basis increased regarding how fires develop, and there are several books written in this area. The starting point for safely and effectively handling fires in buildings must be that we understand why and how such fires develop.

The vast majority of literature available regarding fire is theoretical, with mathematical descriptions of how different factors that affect the onset and spread of fires relate to each other. These theories are well supported by experimental work and are important for a deeper understanding of fire. However, they are not always directly useful in connection with firefighting operations. The deep knowledge that exists about fire must be able to be broken down and described from more pragmatic perspectives. The ambition of this book has been to write about fire, and the factors that affect the development and spread of fire in buildings, in such a way that we can together handle firefighting operations safely and effectively in the event of fire in a building.

In the late 1990s, a project was started at the then Swedish Rescue Services Agency (SRV) with the title “indicating flashover”. The purpose of the project was to find a device or indicator that could give early warning to firefighting personnel of an impending flashover. Early on during the project, however, it became apparent that the problem was something completely different than anticipated: there was a considerable gap in the knowledge, views and use of concepts between the fire services and the scientific world regarding fire progression in rooms.

So instead of a gadget, the project ended with a book: knowledge collected in one place. The book “Enclosure Fires”, written by Lasse Bengtsson, has served the training of firefighting personnel well for many years, but knowledge does not stand still, and we are constantly learning more about fire and how fires develop, spread and affect (and are affected by) the environment. It was time to write a new book, with a different approach and with updated content, but this work would, of course, not have been possible to begin, carry out or complete without the help of a number of people.

I would therefore like to express my sincere gratitude to all the students and colleagues, nationally and internationally, who have contributed in various ways to the knowledge and preparatory work over the years. I would especially like to thank Stefan Särdaqvist, Lasse Nelson, Nicklas Bylund and Lasse Bengtsson for their cooperation and wise opinions during the work on this book.

Stefan Svensson  
Revinge, January 2026

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The ambition of this book has been to write about fire, and the factors that affect the development and spread of fire in buildings, in such a way that we can together handle firefighting operations safely and effectively in the event of fire in a building.

– Stefan Svensson



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# Chapter 1

# Introduction

The fire services handle a wide variety of incidents. Some examples include traffic accidents, releases of hazardous substances, domestic animals getting stuck in ditches and people getting their fingers, arms and legs stuck in the most unlikely places. Fires in buildings comprise only about 10 percent of all incidents or missions the fire services handle. However, there is a high expectation that fires in buildings can be handled professionally and with good precision, just like all other types of incidents and situations that the fire services encounter. In addition, the costs of fires in buildings are a major burden on society, regardless of whether they occur in garbage dumps or large industries. There are countless examples of major accidents that have either started with or resulted in fires. We simply must have good skills in handling fires in buildings, and in order to do that, we must have good knowledge of why fires spread and develop the way they do.

In order to be able to handle fires in buildings safely and effectively, and to avoid being caught by surprise and ending up in situations we shouldn't be in, we must have knowledge of all the factors that affect the development of the fire. This includes basic knowledge and a good understanding of, among other things, how different types of materials react when exposed to heat in different ways, how such materials contribute to the spread and development of a fire, and how the environment, such as a room or a surrounding wind, can affect the development and spread of the fire.

Fire is a combustion process that has gotten out of hand. It is a process, an uncontrolled chemical reaction in the gas phase that emits visible light in the form of a flame. In a somewhat simplified way, fuel, oxygen and heat are required for a fire to start and continue. We often describe fire with the so-called fire triangle, which consists of these three elements. This simple description often works well, but in reality, the problems

surrounding fire are much more complex than that, especially when it comes to fires in buildings, since there is then an interaction between the fire and the building's contents, design and construction. The fire itself develops based on several parameters and factors, but in combination with a building and its complexity, it quickly becomes difficult to gain a complete picture of how fires develop in buildings.

Everything that happens from the start of a fire until the entire building erupts in flames depends fundamentally on a relatively small number of factors and parameters, but when these factors and parameters are combined or varied, an almost infinite number of ways for a fire to develop and spread in a building arise. Such factors and parameters are, for example:

- the properties of combustible materials;
- how different combustible materials are placed in relation to each other;
- how these different combustible materials are placed in rooms and buildings;
- the layout of rooms and buildings;
- the number of openings and their size; and
- the construction of the building.

It is these factors and parameters, including at least some of the possible combinations, that this book will address. Some areas and topics are covered in more detail, while others are only briefly touched upon. The areas covered in more detail are those that most directly concern room fires and building fires.

This book is primarily written for basic training courses in the fire service, but this does not, of course, exclude its usefulness in other contexts or for other target groups. The emphasis is on understanding the processes behind fires in buildings. The content is more practical than theoretical, more qualitative than quantitative. The book does not claim to be comprehensive. In addition, science is discovering new things all the time, which makes it impossible to try to cover everything. New fire risks are also emerging. Electrification has increased and with it the use of batteries, among other things. More and more complex buildings

are being built in wood. These are things that affect the development and spread of fires in buildings, and not always in a positive direction. Nevertheless, the basics of how fires develop remain, and that is where we must start.

The content of the book is largely based on knowledge well known to the fire science community for a long time, but there is also some knowledge that has been added in recent years. The intention of the book is therefore to compile the state of knowledge in a way that will hopefully be able to provide some guidance, regardless of whether the reader is completely new to the field or simply looking for a certain degree of in-depth knowledge. For those who want to read even more, there is a reference list at the end of the book with sources on which the book is based. This reference list is highly recommended.

Large parts of the book are based on Drysdale (1985), Karlsson et.al. (1999) and the SFPE Handbook of Fire Protection Engineering (2016). These are highly recommended for those who really want to delve into the theoretical background.

The book is also based on considerable experience gained over many years, both pedagogically and in practice. Most of it should not come as any major surprise to those already knowledgeable about fire, but the content has been adjusted, updated and adapted, and some new perspectives and angles have been added in relation to previous literature in the field. Also, it should be noted that the book is written based on a Swedish context, especially when it comes to the description of fire safety in buildings.

# Chapter 2

# The history of fire

Fire has been an important part of human life for millennia. We have used fire for cooking, heating, manufacturing, but also to destroy things. For those knowledgeable, fire is a tool that can be of great benefit to humanity, but the same knowledge can also cause humanity great suffering. Fire is a good friend but a dangerous enemy. This also characterises mythology, where fire occurs in a variety of ways, in different guises, often as an instrument in different types of rituals. Below are some examples of how fire is described in mythology.

The Phoenix is a mythical bird associated with several cultures, and there are several variations of its story. The lowest common denominator is of the Phoenix as a fantastic golden-red bird whose body radiates the rays of the sun. Only one Phoenix could exist at a time. When the bird felt that death was near, which did not happen very often, it built a nest and set it on fire. The bird disappeared in the flames and from the ashes an egg emerged and hatched. The newly hatched Phoenix embalmed its predecessor and flew with it to the city of the sun, where the ashes were placed on the altar of the sun god. In Egypt, the Phoenix bird was usually depicted as a heron, but in classical literature, it was portrayed as a peacock or an eagle.

In Greek mythology, Prometheus stole fire from Olympus and gave it to humans. With it came technology, knowledge and civilisation, and for his act Prometheus was sentenced to eternal torment. Fire was thus seen as both a blessing and a curse.

In Norse mythology, Loge was a personification of fire. Loge and Loki competed to see who could eat the fastest. They ate the food equally quickly, but Loki had only eaten the meat. Loge won, as he had eaten both the meat and the bones and had eaten them out of the trough. This says something about the destructive power of fire.

**Figure 1.** The Phoenix bird



The science of fire and combustion has long fascinated people. In the 17th century, interest in science increased, and the so-called phlogiston theory emerged as an attempt to explain fire. This theory claimed that a special substance, phlogiston, was bound in all combustible substances. Phlogiston was released when something burned and absorbed by the air until it became saturated and no further combustion could take place. The theory claimed that the more phlogiston a substance contained, the better it burned. This was demonstrated with simple experiments that involved showing that the ashes of something consumed by fire weigh much less than the original substance. Since phlogiston disappears during combustion, the remains of the fire are, of course, much lighter, where a highly flammable substance loses more weight during combustion than a difficult-to-ignite one. The evidence for the existence of phlogiston could not have been clearer.

In the latter part of the 18th century, the French chemist Antoine Lavoisier laid the foundation for what later replaced the phlogiston theory, namely that oxygen was the basis for combustion. The phlogiston theory was certainly on the right track, but it had been turned upside down. It is

not a substance leaving the burning material but rather the oxygen in the air combined with the substances found in the material being burned that give rise to combustion. The weight decreases simply because the combustion products are gaseous and leave the fuel. It is possible to conduct simple experiments that show that the residual products after combustion can weigh more than the original fuel, even though gaseous combustion products have been formed. This is because oxygen in the air has combined with the fuel and formed new substances.

Today we know a great deal about fire and combustion, but the modern science of fire is relatively young compared to, for example, medicine or the study of solids. Today's fire science can be said to have emerged sometime after the Second World War. There is still much we do not know, and it is important that fire research continues, not least because fire is of great importance to the safety of humanity and has a major impact on the functionality of modern society. Unfortunately, it has often been major fire disasters that have driven forward development. Perhaps the clearest example is the fire at the Stardust nightclub in Dublin in 1981, where 48 people died (The Irish Health Repository, 1981). There are many other examples of major events that either started with a fire or resulted in a fire, including the Chernobyl accident in 1986 (The Swedish Radiation Protection Institute, 2001). In addition to the radiation problem with the radioactive material itself, there were enormous problems with fighting the fires that broke out. These, in turn, contributed to spreading radioactive material over a large area. Consider also the attack on the World Trade Center in New York in 2001, where the fires that broke out caused several buildings to collapse and the rubble burned for several days afterwards (NIST, 2005).

There are also other more recent events that have received significant attention. Examples include the fire on Herkulesgatan in Gothenburg in 1998, where 63 young people died, and the fire at the Copenhagen Stock Exchange in 2024, where objects of great cultural value literally went up in smoke.



Fire research is often experimental. The image shows two thermocouples (to measure temperature) each mounted on so-called bi-directional probe (to measure and calculate the velocity of gases). Photo: Stefan Svensson.

Today's fire science is about improving and developing knowledge and creating an even better understanding of how fire starts and spreads, including how different types of materials react in a fire. It is also about creating better mathematical models for fire. The purpose of these models is primarily to recreate and, above all, predict how a fire will develop and affect people, property and the environment, without having to conduct overly extensive experiments. However, it is also about creating better knowledge-based conditions for the fire service in dealing with fires in buildings.

The research involves, for example, developing testing methods for building components or investigating how new technology behaves in a fire. In short: fire engineering science aims to make society safer and more resilient to fire, through continuous knowledge creation.

Fire experiments are often expensive and can be difficult to replicate. There are also many parameters that affect, which makes it difficult to control fire experiments. Small-scale experiments are easier, but then realism is lost. Repeatability is difficult to achieve because the experimental setup simply burns up. Moreover, it is not always easy to accurately recreate an experimental setup, especially large-scale experiments. However, experimental work on both small and large scales is still important for increasing understanding of fire.

# Chapter 3

# A simplified description of the problem

There are several factors that influence how a fire starts and develops in a building. The following description can be valuable as a first, but very rough, overview of such a process. The description is, of course, not a general truth, since there are always a number of factors and variables that influence the course of a fire.

This first brief description uses many terms and expressions that will be explained in more detail later in the book. The chemical and physical factors and phenomena that lie behind, control and influence the entire development of the fire will also be described and explained. In order to understand and assess how a fire develops in a building, it is important to understand all these factors and phenomena, but let's start in the simplest way.

A fire starts on an armchair in a room. How the fire starts is usually relatively uninteresting for the course of the fire itself, although there are a number of exceptions where the cause of the fire can influence its development somewhat differently than what is described in this section. Nevertheless, let us now return to the fire that started on the armchair.

## A simplified description of the problem



A fire is often small at first, but can quickly grow large. Photo: Kicki Nilsson.

After a fire has started, it begins to produce combustion products in the form of gases, liquid droplets and particles. The combustion products mix with air, and because they are hot, they rise up into the room, hit the ceiling and spread in all directions along the ceiling. We call this mixture fire gases. The amount and properties of the fire gases are the single largest contributing factor to how the fire develops and spreads, but all surfaces in the room also affect how the fire develops and spreads, regardless of whether the surfaces are combustible and regardless of whether they are walls, ceilings, floors or objects in the room.



Fire gases formed in the fire have a huge impact on the continued spread of the fire.  
Photo: Stefan Svensson.

## A simplified description of the problem

The flames from the fire in the sofa heat up the surrounding surfaces, that is, the parts of the sofa that are not yet burning, as well as other surfaces in the room. This occurs mainly through heat radiation but also through convection (air movement). As the surfaces of the sofa heat up, they ignite, and the fire spreads over the sofa. The fire gases that are formed also heat up the various surfaces of the room, especially the ceiling and the upper parts of the walls. At this stage, the fire is fuel-controlled, that is, the development of the fire is controlled by the properties and amount of the fuel.

If there is enough fuel and large enough openings in the room to allow air to enter, the heating of the room's surfaces and objects will eventually reach a point where the fire spreads rapidly to all objects in the room. A flashover occurs, that is, a stage in the fire process where the spread occurs over a relatively short period of time from one or a few objects in the room to all objects in the room. Now everything in the room is burning, and flames are escaping through the room's openings. The fire then becomes ventilation-controlled, that is, the development of the fire is controlled by the availability of air.



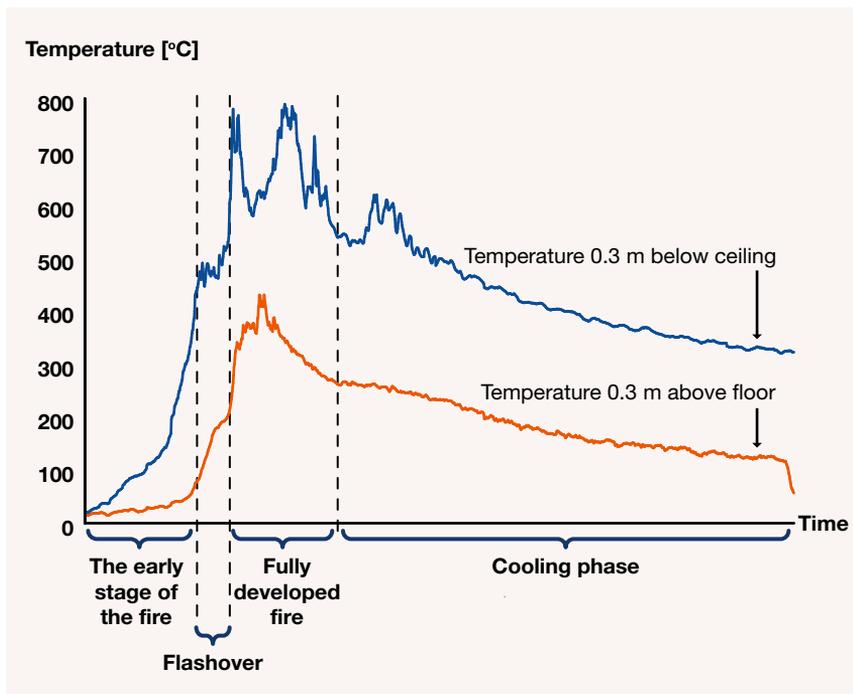
After a flashover, everything combustible in the room is engulfed by the fire, and it becomes ventilation-controlled. Photo: Johnér Bildbyrå.

After the flashover, we say that the fire is fully developed. When the fire is fully developed in a room, there is little chance that there is any life to be saved in that room. However, there may be a possibility of survival in other areas of the building, although conditions can quickly deteriorate.

The fact that flames are shooting out through the openings in the room is a clear sign that the fire is fully developed and ventilation controlled. The flames shooting out through openings indicate that there is no longer enough air inside the room for the combustion taking place.

When the fuel starts to run out, the fire enters a cooling phase and then becomes fuel-controlled again. This description assumes, however, that the fire does not spread outside the room and that it is not extinguished by the fire service.

**Figure 2.** The temperature in a fire room changes over time



The figure shows an example of how the temperature in a fire room can change over time. Differences between different rooms can be, for example, different maximum temperatures or the duration of the different phases. The temperature can also differ greatly between different parts of the room.

## A simplified description of the problem

If the room in which the fire started is in a building where several rooms or spaces are connected, the fire will continue to spread from one room to the next. Even when the fire in the sofa starts, fire gases begin to spread from the first room to the other rooms. These fire gases then heat, most significantly, the ceiling surfaces and the upper parts of the rooms.

When the fire has grown large enough, it will grow faster and faster. If the ceiling and walls of the building are already heated by the fire gases formed by the fire, the fire will spread quite quickly to or into other rooms. Note that a fire cannot spread in any way; there are several limitations. The most important limitations are the amount and type of fuel available and the size, number and location of any openings. In addition, environmental factors such as wind and the properties of the surrounding surfaces can have an impact.

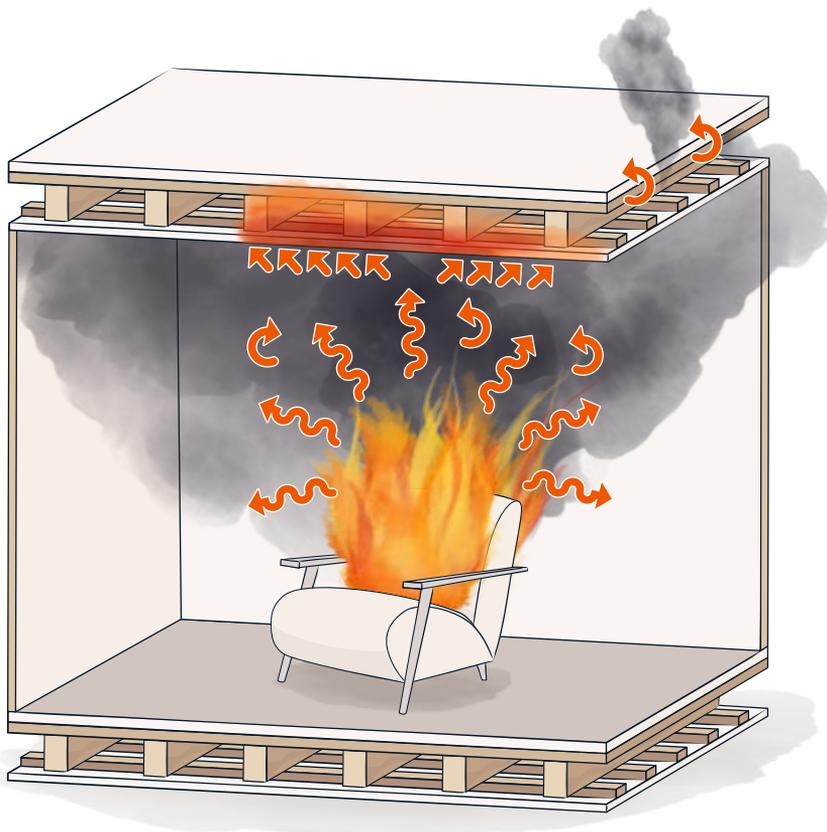


A fire in a single object can quickly grow and spread to large parts of or the entire building. Photo: Johnér Bildbyrå.

In connection with fires in buildings, the fire can spread from one object to other objects, to the entire room and to several rooms. It is often mainly the furnishings and other objects in the room that are the fuel and burn, but flammable surfaces in the building itself also participate in the fire, in the same way as the objects.

The fire can also spread to, or originate in, the building itself and the parts and components that the building consists of. The fire can spread through walls, floors or ceilings, and also inside the building's structure, where there are often many cavities or other spaces. We are then dealing with so-called structural fires. These can be difficult to deal with, not least because they are hidden. We cannot see where they are, because they spread inside the walls, ceilings or floors, and if we try to break up walls or floors with the intention of extinguishing them, there is also a risk that we will spread the fire further because we will thereby add air to the fire. Now it's not just the content of the room that is on fire, but the building itself is burning.

**Figure 3.** A fire can spread to the structure of the building



A simplified description of the problem



A backdraft is a phenomenon that requires special circumstances to occur, but can cause great damage. The time shown is given as seconds and hundredths of a second. Photo: Hans Loo.

In addition to the problem of structural fires, many other phenomena can also arise that complicate conditions inside or outside the building. Examples of such phenomena are fire gas explosion and backdraft. In both these cases, the course of events depends to a large extent on how fire gases spread in the building, the properties of these fire gases (temperature, content, etc.), the shape of the rooms in the building and, not least, how many openings there are and their size.

Large spaces, as well as those underground or high above the ground, pose special problems and provide slightly different conditions for the spread of fire. These types of fires cannot be described as simply as those that occur in more “normal” buildings or spaces. Therefore, it is particularly important to have a good understanding of the underlying factors.

We need to have a basic understanding of several things in order to better understand how a fire can develop in a building and the phenomena that can occur in connection with this. These include the structure and properties of matter, physical states, energy, energy principles and chemical reactions. These different factors can be divided into the areas of fire chemistry and fire physics. Let's start from the beginning.

# Chapter 4

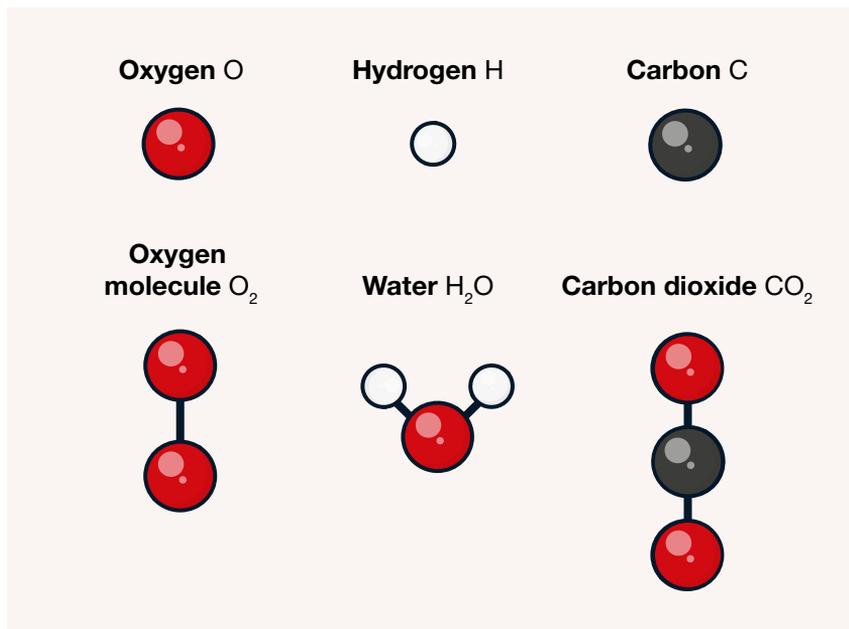
# Fire chemistry

Fire chemistry is a specialised area of chemistry that includes the chemistry that underlies fire and combustion. The section will also shed some light on more basic chemistry to create a better understanding of fire and combustion. Most of this knowledge can be found in any basic chemistry textbook.

## The structure and properties of matter

Everything around us is made up of atoms. These atoms normally combine with other atoms to form some kind of substance. A substance that consists of molecules with only one kind of atom is called an element. Each element has a chemical designation, which consists of one or two letters. For example, oxygen has the designation O and the metal sodium has the designation Na.

**Figure 4.** Everything around us is made up of atoms that form molecules



The word atom comes from the Greek and means indivisible, but atoms also consist of even smaller parts: protons, neutrons and electrons. Protons and neutrons are found in the atom's nucleus, whereas electrons are found in the atom's "shell", that is, they move around the nucleus at dizzying speed. The atomic nucleus comprises almost the entire mass of the atom, since the proton and neutron are both about 1,800 times heavier than the electron. The electrons are located in a so-called electron cloud, which surrounds the nucleus. This electron cloud is many times larger than the nucleus.

Electrons are negatively charged, protons are positively charged, while neutrons are neutrally charged. The atom is normally electrically neutral, meaning there are as many electrons as protons.

Note that atoms are very small, on the order of 0.1 nanometres, that is, 0.1 billionth of a millimetre or 0.000000001 metres. The atom is the smallest unit of an element that defines its chemical properties.

In the periodic table of the elements, the elements are arranged according to increasing number of protons in the atomic nucleus, and are grouped according to similar chemical and physical properties. Hydrogen (H) has the number 1, because the atomic nucleus contains one proton. Oxygen (O) is number 8 because it has eight protons in the nucleus. Normally, atoms have the same number of electrons as protons. If this changes, the atom, and thus also the substance that the atoms comprise, can have completely different properties. The chemical sign (symbol) stands for an atom of the element.

# The periodic table

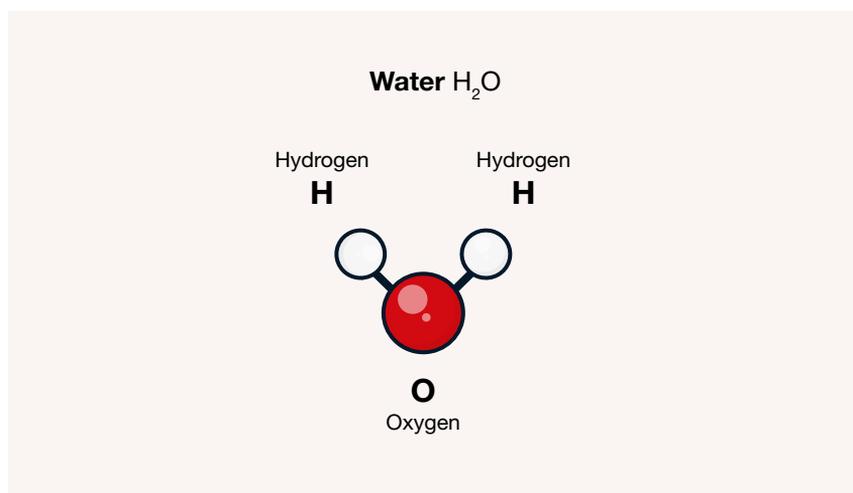
**Figure 5.** The periodic table shows the properties of the elements and how they relate to each other.

Category		Physical state																
		Gaseic	Liquid	Solid	Unknown													
★	Alkali metal	▲	Lanthanides	▲	Semimetal						He 2 Helium							
◆	Alkaline earth metal	●	Actinides	◆	Nonmetal						Ne 10 Neon							
☾	Transition metal	☾	Other metal	☾	Noble gas						Ar 18 Argon							
■	Unknown chemical properties																	
H 1 Hydrogen		Be 4 Beryllium	Mg 12 Magnesium	Ca 20 Calcium	Sr 38 Strontium	Ba 56 Barium	Ra 88 Radium	Fr 87 Francium	Cs 55 Cesium	Rb 37 Rubidium	K 19 Potassium	Na 11 Sodium	Li 3 Lithium					
Sc 21 Scandium	Ti 22 Titanium	V 23 Vanadium	Cr 24 Chromium	Mn 25 Manganese	Fe 26 Iron	Co 27 Cobalt	Ni 28 Nickel	Cu 29 Copper	Zn 30 Zinc	Ga 31 Gallium	Ge 32 Germanium	As 33 Arsenic	Se 34 Selenium	Br 35 Bromine	Kr 36 Krypton	Xe 54 Xenon	Rn 86 Radon	Og 118 Oganesson
Y 39 Yttrium	Zr 40 Zirconium	Nb 41 Niobium	Mo 42 Molybdenum	Tc 43 Technetium	Ru 44 Ruthenium	Rh 45 Rhodium	Pd 46 Palladium	Ag 47 Silver	Cd 48 Cadmium	In 49 Indium	Sn 50 Tin	Sb 51 Antimony	Te 52 Tellurium	I 53 Iodine	Xe 54 Xenon	Rn 86 Radon	Og 118 Oganesson	
5-71 Lanthanoids	Hf 72 Hafnium	Ta 73 Tantalum	W 74 Tungsten	Re 75 Rhenium	Os 76 Osmium	Ir 77 Iridium	Pt 78 Platinum	Au 79 Gold	Hg 80 Mercury	Tl 81 Thallium	Pb 82 Lead	Bi 83 Bismuth	Po 84 Polonium	At 85 Astatine	Xe 54 Xenon	Rn 86 Radon	Og 118 Oganesson	
89-103 Actinoids	Rf 104 Rutherfordium	Db 105 Dubnium	Sg 106 Seaborgium	Bh 107 Bohrium	Hs 108 Hassium	Mt 109 Meitnerium	Ds 110 Darmstadtium	Rg 111 Roentgenium	Cn 112 Copernicium	Nh 113 Nihonium	Fl 114 Flerovium	Mc 115 Moscovium	Lv 116 Livermorium	Ts 117 Tennessine	Xe 54 Xenon	Rn 86 Radon	Og 118 Oganesson	
La 57 Lanthanum	Ce 58 Cerium	Pr 59 Praseodymium	Nd 60 Neodymium	Pm 61 Promethium	Sm 62 Samarium	Eu 63 Europium	Gd 64 Gadolinium	Tb 65 Terbium	Dy 66 Dysprosium	Ho 67 Holmium	Er 68 Erbium	Tm 69 Thulium	Yb 70 Ytterbium	Lu 71 Lutetium	Xe 54 Xenon	Rn 86 Radon	Og 118 Oganesson	
Ac 89 Actinium	Th 90 Thorium	Pa 91 Protactinium	U 92 Uranium	Np 93 Neptunium	Pu 94 Plutonium	Am 95 Americium	Cm 96 Curium	Bk 97 Berkelium	Cf 98 Californium	Es 99 Einsteinium	Fm 100 Fermium	Md 101 Mendelevium	No 102 Nobelium	Lr 103 Lawrencium	Xe 54 Xenon	Rn 86 Radon	Og 118 Oganesson	

An element is distinguished by its own typical properties, such as smell, taste, colour, density (weight per unit volume), boiling point, melting point, etc. The elements are divided into two groups according to their properties, metals and non-metals. In metals, the atoms are densely packed in metal crystals.

In total, there are approximately 118 known elements, of which 94 occur naturally, while the remainder can be produced artificially. In nature, the elements are normally included in various chemical compounds and then form new substances, with properties that can differ significantly from the constituent elements. Elements are rarely found in nature in their basic form. For example, a water molecule consists of two hydrogen atoms and one oxygen atom (which is written as  $H_2O$ ), while a carbon dioxide molecule consists of one carbon atom and two oxygen atoms (which is written as  $CO_2$ ). However, air consists mostly of oxygen and nitrogen, which are then in their respective basic forms and have not formed any new substance. This can be considered an exception, but an important one, since the oxygen in the air affects the spread and development of fires. Air is thus a mixture of several different substances, not a compound. Nitrogen makes up the largest part (approximately 79 percent) of the mixture.

**Figure 6.** Water molecules are made up of two hydrogen atoms and one oxygen atom



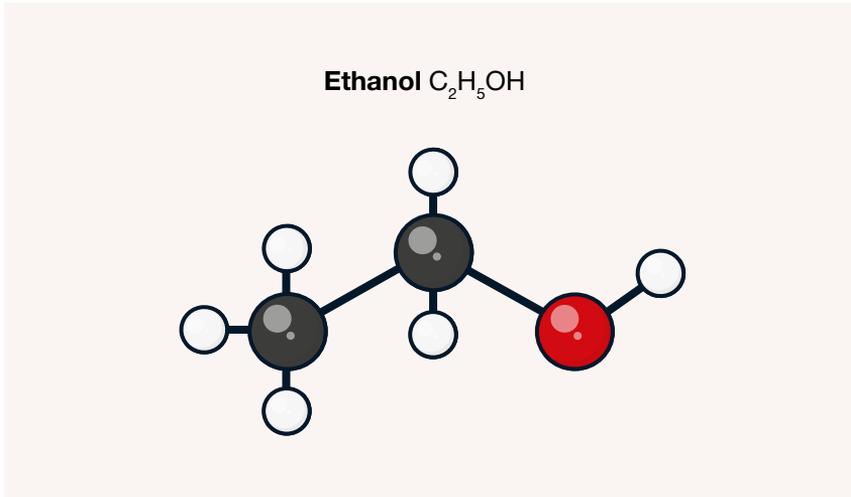
Compounds consisting of several elements, where atoms of different types have formed common molecules, always have different properties than the individual elements involved. However, mixtures of different elements or molecules can also have different properties than the individual components. This can be important in the event of fire and combustion as the properties of the different substances that form a compound or mixture affect each other when the temperature increases.

Some chemical compounds are made up of ions, that is, electrically charged atoms or groups of atoms. An ion has a different number of protons in the nucleus and electrons in the “shell”. The charge of an ion can be negative (more electrons than protons) or positive (fewer electrons than protons).

Compounds of ions are also called salts. The ionic compound common salt, i.e., sodium chloride (NaCl), consists of an equal number of positively charged sodium ions (Na<sup>+</sup>) and negatively charged chloride ions (Cl<sup>-</sup>). The compound between these positively and negatively charged ions is electrically neutral. Ionic bonds, i.e., the bonds that hold atoms (ions) together to form molecules, are considered relatively strong bonds.

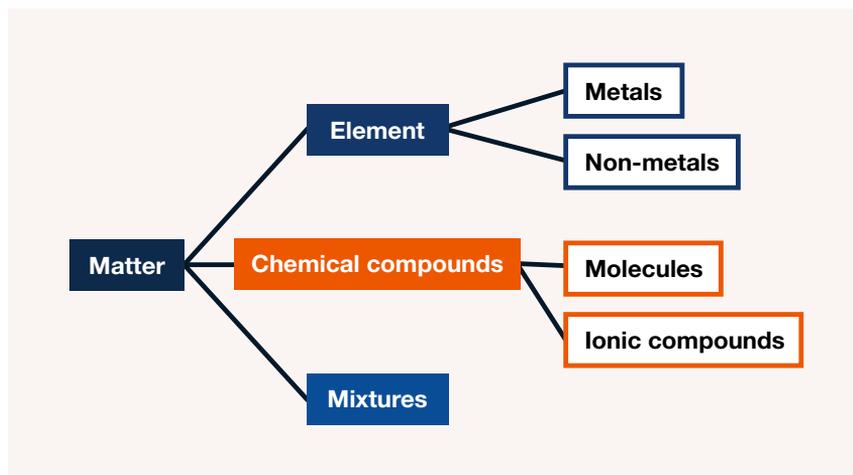
A very large number of compounds contain the element carbon as the main component, often together with hydrogen, oxygen or nitrogen. Such compounds are called organic compounds and are mostly flammable. They can then react with oxygen from, for example, the air. Organic compounds are an important ingredient for a fire to start and continue. An example of a flammable organic compound is ethanol, which is what we commonly call alcohol. Ethanol has the chemical name C<sub>2</sub>H<sub>5</sub>OH, which means it consists of two carbon atoms, five hydrogen atoms and a so-called hydroxyl group (OH) consisting of one oxygen atom and one hydrogen atom.

**Figure 7.** Organic compounds are built around the element carbon



The figure shows how the ethanol molecule is structured. It consists of two carbon atoms, five hydrogen atoms and a so-called hydroxyl group which consists of one oxygen atom and one hydrogen atom.

Most of the materials and substances we encounter in everyday life are mixtures of different chemical compounds. A mixture is a composition of two or more substances that are not chemically bonded to each other. A distinction is made between homogeneous mixtures, where the constituent substances cannot be distinguished with the naked eye, and heterogeneous mixtures, where the different substances can be distinguished. Petrol is a mixture of a variety of hydrocarbon compounds in liquid form, while LPG is a mixture of gaseous hydrocarbon compounds (mainly propane and butane). Mixtures can in principle consist of gases as well as liquids or solids. Depending on which substances are mixed, the mixture takes on different properties, which can have a major impact on how a fire starts and spreads. When certain substances are mixed, a chemical reaction can occur, creating new substances that form compounds. Sometimes heat is generated during such chemical reactions; other times, heat (energy) must be added for the chemical reaction to take place. Both of these cases are relevant in the case of fire, as it is these mechanisms and chemical reactions that are the basis of a fire's spread and development.

**Figure 8.** Substances and compounds relate to each other in different ways

The force that holds atoms and molecules together is energy. The heat that needs to be supplied for a fire to start and the heat that develops once the fire has started is also energy. If enough energy is supplied to a substance or mixture in the right way, the molecules involved are affected such that new substances are formed. To understand fire, we therefore also need to understand what energy is, how energy is transferred and how it works.

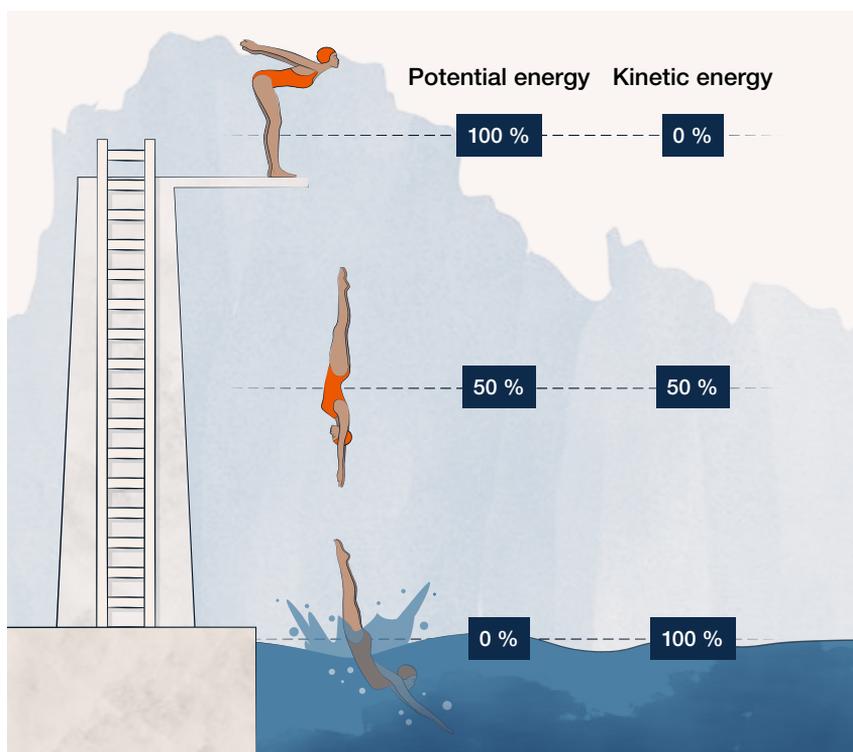
## Energy and energy principles

We often use the words energy and heat more or less synonymously, that is, as equivalents. In fact, energy occurs in different forms – heat being an example. Other examples of different forms of energy are electricity, mechanical energy, light and sound. These different forms of energy do not take up space, weigh nothing and are immaterial. Note, however, that based on Einstein's special theory of relativity, mass and energy can be considered two sides of the same coin and that there is a relationship between them, but we leave this aside in this book.

Energy is something that causes changes in matter. Heat can change water from ice to water vapour; electrical energy can power an engine; mechanical energy can move a sofa; and chemical energy can heat our homes – or cause damage, for instance, in a fire.

We also talk about potential energy, which can occur in several different forms. For example, if I lift a stone, the stone has a certain potential energy in its lifted position. We call this form of energy potential energy. An object that is moving has in the same way kinetic energy. Fuel also has a certain potential energy, in the form of chemically bound energy, which can be released, for example, in a fire. We can thus describe the fuel in terms of its combustion energy or heat of combustion. This becomes a kind of measurement of the chemically bound energy that can be released in a fire. We will return to this later.

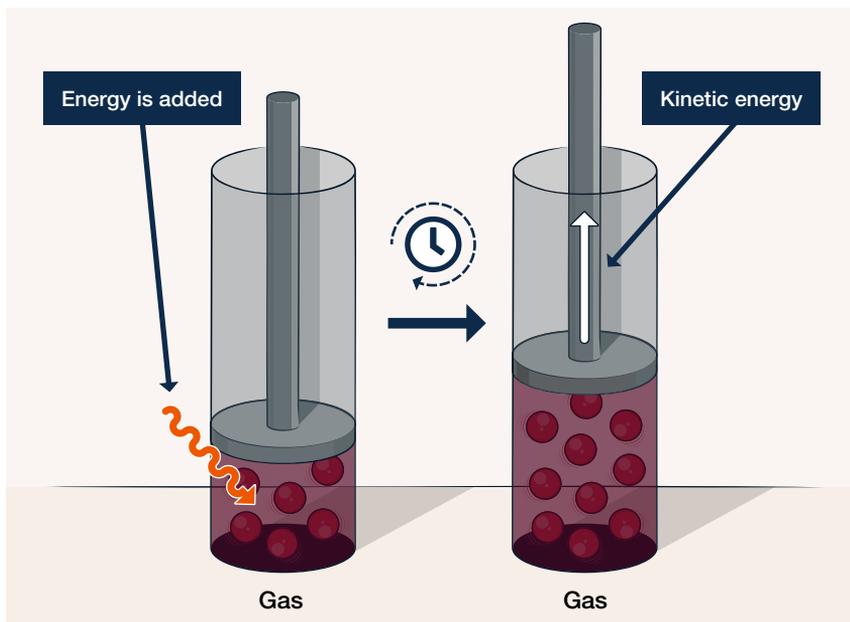
**Figure 9.** Potential energy and kinetic energy



At the top of the trampoline, the kinetic energy is zero, because the swimmer has not yet jumped. At the jump, the potential energy is converted into kinetic energy. Just before impact with the water, the kinetic energy reaches its maximum while the potential energy reaches its minimum.

The energy principle states that energy cannot be destroyed, only converted from one form to another. This means that all forms of energy are equivalent. For example, mechanical energy can be converted into heat through friction. This happens when a car breaks: The rotation of the wheel (brake disc) is prevented when the brake is applied, which causes the so-called brake shoes to become hot. This energy principle, that energy cannot be destroyed but only converted from one form to another, is also called the law of conservation of energy or the first law of thermodynamics.

**Figure 10.** First law of thermodynamics



The first law of thermodynamics states that energy can neither be created nor destroyed, only converted from one form to another. Heat energy is supplied to the container on the left, the gas in the container heats up and expands. The piston is then pushed upwards (the container on the right). Heat energy has been converted into kinetic energy.

The first law of thermodynamics is also valid in connection with other types of accidents, not only fire. In a traffic accident, for instance, the kinetic energy of the vehicles involved in a collision is converted into changes in sheet metal and plastic parts: the vehicles are deformed. This kinetic energy is also transferred to the vehicles' driver, causing damage to tissue, bones and internal organs. The faster a vehicle is traveling, the worse the damage can be.

There are several so-called fundamental laws of thermodynamics, the science that deals with heat and work and the changes-of-state associated with these energy exchanges. In physics, the word work is used for the amount of energy that is converted when a movement occurs, under the influence of a force. An important fundamental law of thermodynamics is the so-called zeroth law, which states that:

” Two bodies that are each in thermal equilibrium with a third body are also in thermal equilibrium with each other.

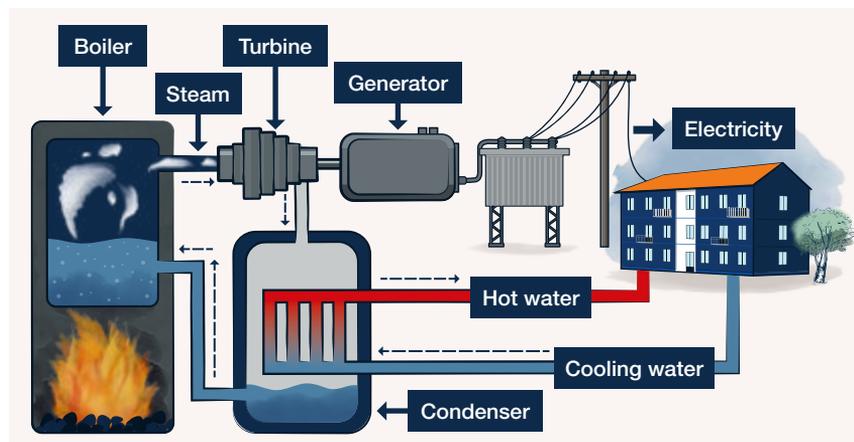
This means that two bodies in contact with each other assume the same temperature by the heat energy in the warmer body flowing to the colder body. The zeroth law of thermodynamics is important for temperature measurements, among other things. A thermometer, for example, is affected by the surrounding air by heat being transferred either from the warm air to the cold thermometer or from the warm thermometer to the cold air.



If we open the front door on a cold winter day, we are not letting cold in, but we are letting heat flow out of the building. As a consequence, cold air naturally flows in, but it is the warm air that flows out that is the driving force. Photo: Stefan Svensson.

Heat is a form of energy that affects the movement of molecules. Heat is generated during chemical reactions, such as combustion. The unit for heat – and for energy – is the joule (J). As an example, it takes about 4,180 Joules (4.18 kJ) to heat 1 kg of water 1 °C. Heat energy can in turn be converted into kinetic energy, for example in a steam engine where water is evaporated to drive a piston which in turn drives a wheel. In many cases, the conversion from heat energy or kinetic energy occurs through electrical energy to other motion. An example of this would be a nuclear power plant, where the splitting of atoms (chemical energy) in the nuclear reactor generates heat in the surrounding water. This hot water is then used in a turbine to generate electricity. The heat energy in the water generates motion in the turbine, which produces electrical energy in a generator. The electricity is sent out through wires to our homes. There we use this electrical energy to heat homes or charge an electric car, which then converts the electrical energy into movement again. In a diesel or petrol engine, however, the conversion does not take place via electrical energy. There, heat is generated when the fuel is burned, and this heat is then converted into kinetic energy and work. The use of engines powered by the thermal energy provided by the combustion of diesel or petrol is today the most widespread way of utilising the conversion of thermal energy into movement and work.

**Figure 11.** Energy conversion in a power plant



When the fuel is burned, the chemically stored energy is converted into heat energy that heats the water. In the turbine, the heat energy in the water is converted into kinetic energy, which in turn is converted into electrical energy in a generator. The heat energy in the water is also used to heat our homes, where the heat energy in the water is transferred to the air.

Energy can occur in several different forms. The forms that are most important in connection with combustion and fire are chemical energy, electromagnetic radiation and thermal energy (heat energy).

Chemical energy is energy that is “stored” in an object, in its molecular structure. In connection with combustion and fire, chemical energy is an important potential energy. The chemical energy is stored in the bonds of the atom, and when a fuel is burned (combusted), the bonds are broken and new bonds with lower energy are formed. The reaction is exothermic, that is, there is an excess of energy. This excess chemical energy is released as radiation (including visible light) and thermal energy (heat energy).

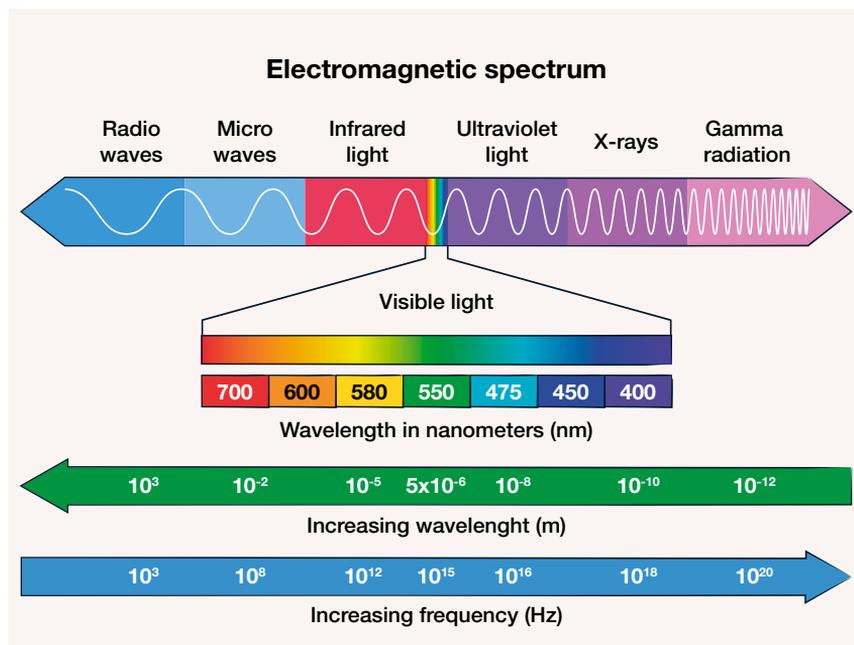
Differences in potential energy between different gas masses can, for example, create flows of fire gases. High velocity of fire gases gives higher kinetic energy than low velocity. Potential energy actually means the energy an object "has stored" within it and which can be converted into other forms of energy.

When a fire occurs, one or rather several chemical reactions start. The bonds of the molecules are broken, the chemical energy is released and converted into radiant energy and heat energy. In other words, the fire gives rise to heat and light. The residual products that are formed contain a smaller amount of chemical energy than the original fuel, but the energy does not disappear, it is converted from one form to another, according to the first law of thermodynamics. The spread of fire through hot fire gases is due, among other things, to the fact that the heat energy in the fire gases is transferred to the ceiling and wall surfaces of the room and similar surfaces. When enough energy has been transferred from the hot fire gases to the ceiling surfaces, the materials that the ceiling surfaces are made of begin to burn.

The light emitted by a fire is energy in the form of electromagnetic radiation. Electromagnetic radiation is an extremely important form of energy, which we find in a wide variety of applications. The energy in electromagnetic radiation can be somewhat simplified as particles that propagate as a wave motion. Electromagnetic radiation can propagate with different wavelengths, which is the most important property of

electromagnetic radiation. The wavelength tells us how much energy the radiation has. Electromagnetic radiation with a short wavelength has greater energy than electromagnetic radiation with a long wavelength.

**Figure 12.** Electromagnetic radiation occurs in different wavelengths, with different properties.



Depending on the wavelength of the radiation, we call it different things:

- radio waves (where the wavelengths can be kilometres long and where the energy is low)
- microwaves
- infrared light
- visible light
- ultraviolet light
- X-rays
- gamma rays (picometre-long wavelengths, 10–12 metres, a billionth of a millimetre, and where the energy is high).

The part of the electromagnetic radiation that we perceive as light is only a very small part of all the possible wavelengths (frequencies) that the radiation can have. A fire emits electromagnetic radiation in a wide wavelength spectrum. It mainly consists of infrared light, visible light and ultraviolet light. We can use some of this radiation in thermal cameras, also called IR cameras or thermal imagers, with which we can “see” objects through, for example, fire gases. When it comes to heat transfer, thermal radiation is an important component for understanding, among other things, how fire spreads. We will therefore return to this topic later, in the section on heat transport and heat transfer.



Using an IR camera, we can detect and identify, for example, various objects through fire gases. Photo: Stefan Svensson.

Another form of energy that is important in combustion and fire is, of course, thermal energy. In a somewhat simplified way, one can say that thermal energy is related to how fast the molecules in a substance move. In addition to the fact that we can feel thermal energy through higher temperature, the movement of the molecules determines in which physical state (form) a substance appears.

## Physical states

Different materials and substances can occur in solid, liquid or gaseous form. These three forms – solid, liquid and gas – are called physical states, states of aggregation or phases. It is mainly temperature but also pressure that determines which state a substance is in.



Water in solid, liquid and gaseous form. Photo: Johnér Bildbyrå.

In a solid, atoms, molecules, or ions are arranged in a certain structure. In ionic compounds, most often salts, the cohesive forces provide a strong bond between the molecules, and the structure is often very clear. For example, look at the salt crystals in common table salt with a magnifying glass.

Atoms and molecules are constantly in motion. These movements become more intense if the temperature increases, that is, if we add energy. At a sufficiently high temperature in a solid material, that is, if we have added enough energy, the movements become so great that the molecules tear themselves away from their places. We then say that the solid material melts. This occurs at a certain temperature (melting point) at a certain pressure for each substance. Normally, the melting point of a material is stated at normal air pressure (101.3 kPa). The heat energy needed for a solid to change to a liquid phase is called the heat of fusion.



The temperature at which a solid material melts is called the melting point, and the heat energy needed for the solid material to melt is called the melting heat.  
Photo: Stefan Svensson.

In liquids, the particles can move quite freely, although there is still some structure. The movement is greater than in the solid state, so great that the binding forces cannot produce an ordered structure. Nevertheless, the volume of the liquid is constant at a certain temperature. If we increase the temperature further, the movement of the particles becomes increasingly greater. The pressure in the liquid rises, and when it becomes equal to the external pressure (for example, atmospheric pressure), the liquid has reached the boiling point. We call the pressure just above the liquid the vapour pressure of the liquid. An increasing number of particles then leave the liquid and change to a gaseous state. In a boiling liquid, the vapour pressure of the liquid has thus become equal to, or greater than, the atmospheric pressure.

### Vapor pressure

Vapor pressure is the pressure at which equilibrium exists between the vapor and the solid or liquid phase of the substance. When the ambient pressure is equal to the vapor pressure of a liquid, the liquid and its vapor are in equilibrium. The boiling point of a substance is thus the temperature at which the vapor pressure of the substance in the liquid state is equal to the ambient pressure. Below this temperature, the vapor will condense into a liquid, and above it, the liquid will boil, i.e. turn into vapor.

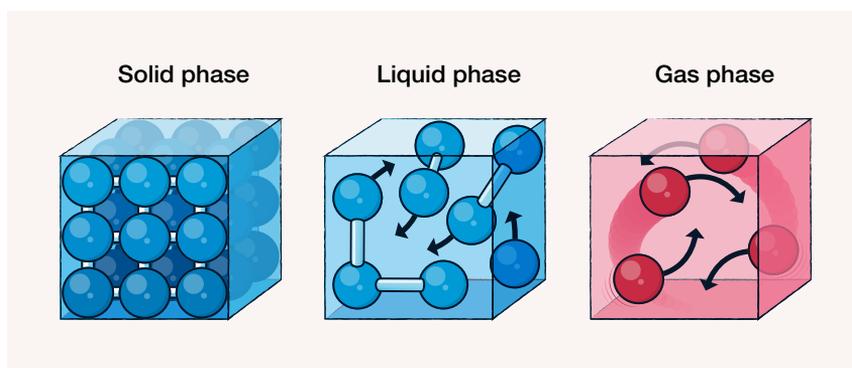
**Figure 13.** At high altitudes, where air pressure is lower, water boils at a lower temperature.



At sea level, water boils at 100°C. If we move up to the top of Mount Everest, water boils at about 70°C. At this altitude, the air pressure is much lower than at sea level, and a lower temperature of the water is enough for the vapor pressure to be equal to atmospheric pressure. At high altitudes, it can take longer to boil eggs, as egg whites solidify at about 62°C.

The molecules in a gas are very far apart, and the cohesive force between the molecules is then relatively small. The molecules in a gas are also in rapid motion. In air at room temperature, the average speed of the molecules is about 500 m/s, and the speed increases the higher the temperature. A high temperature of a gas can thus be said to correspond to a high energy of the gas. The gas “contains” more energy at a high temperature than at a low temperature.

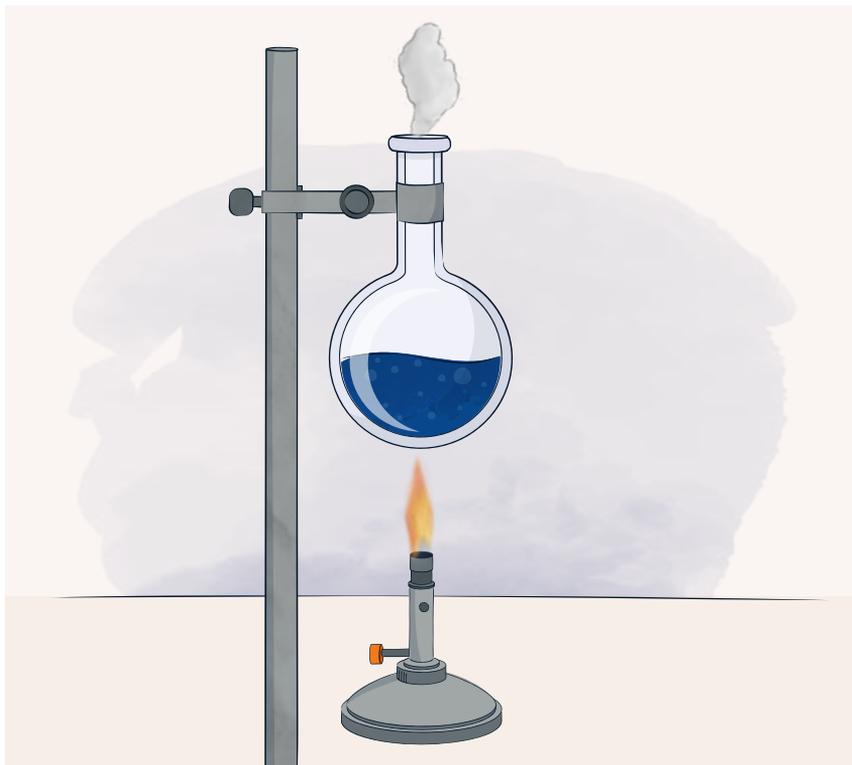
**Figure 14.** Molecules are located at different distances from each other depending on which phase the substance is in



The molecules in a gas collide with each other and with surrounding walls. In the latter case, the collisions become noticeable as pressure, which we can often measure, for example, in a gas bottle. In the case of air, which is a mixture of mainly oxygen and nitrogen, we call this pressure atmospheric pressure.

The transition from solid to liquid and then to gas requires energy (thermal energy). The energy needed for a solid to change to liquid is called the heat of fusion. The energy needed for a liquid to change to gas is called heat of vapourisation. If the temperature drops and the gas changes from liquid to solid, energy is released (thermal energy).

**Figure 15.** The energy needed for a liquid to change to a gas is called heat of vaporization



But it is not always necessary for the transition from solid to gas phase to occur via liquid phase. Direct transition from solid to gas phase is also possible. This is the case, for example, with carbon dioxide ( $\text{CO}_2$ ), which goes directly from solid phase (“dry ice”) to gas and then appears to smoke. This process requires a significantly greater amount of energy than the transition from solid to liquid or from liquid to gas.

### Heat of vaporization, $\Delta H_v$

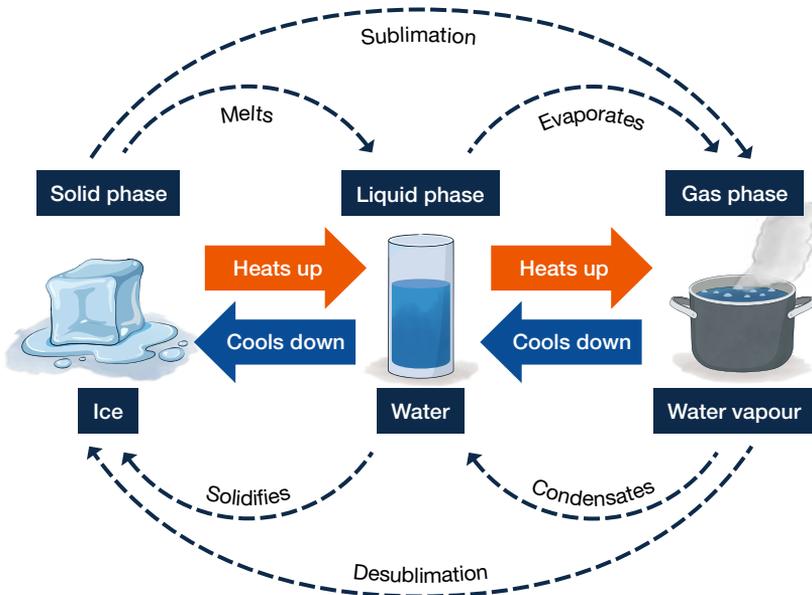
A measure of how much energy is needed for a certain amount of a substance to evaporate. Heat of vaporization is normally given in kJ/g or MJ/kg.

To evaporate 1 kg of ice that has a temperature just below  $^{\circ}\text{C}$ , we must first melt it into water and then heat the water to  $100^{\circ}\text{C}$ . This requires the following amount of energy:

- Melting the ice requires 0.334 MJ (i.e., 334,000 Joules).
- Heating the water from  $0^{\circ}\text{C}$  to  $100^{\circ}\text{C}$  requires 0.419 MJ.
- Evaporating the water at  $100^{\circ}\text{C}$  requires 2.263 MJ.
- Total: 3.016 MJ.

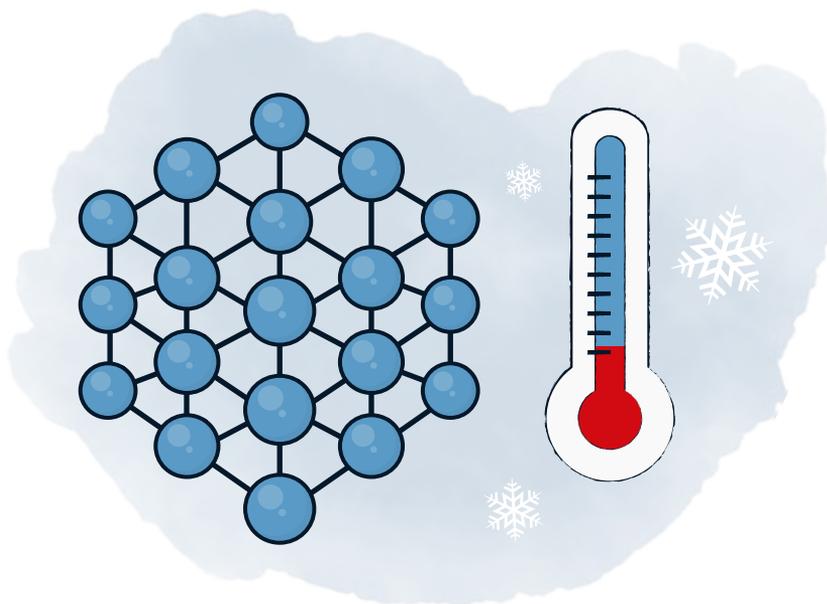
Melting ice and evaporating the water formed at  $100^{\circ}\text{C}$  thus requires a total of 3.016 MJ/kg. Approximately 86 percent of the total energy is used to change the physical states (from ice to liquid and from liquid to gas) and only 14 percent to increase the temperature of the water from  $0^{\circ}\text{C}$  to  $100^{\circ}\text{C}$ . When we extinguish a fire with water, we exploit the fact that water requires large amounts of energy to heat up and, in particular, to evaporate. Fire extinguishing is largely about lowering the temperature of the fuel below its ignition temperature, and for this purpose water is an excellent extinguishing agent. Water's ability to absorb energy is very good, which means that when extinguishing a fire we lower the temperature so that the fire goes out. The temperature of the extinguishing agent is relatively unimportant; completely different mechanisms are decisive.

**Figure 16.** Phase transitions are reversible, meaning they can go in both directions.



Phase transitions are reversible, meaning they can go in both directions. From solid phase, via liquid phase to gas phase, or from gas phase, via liquid phase to solid phase. We say that a solid that changes to liquid melts and that a liquid that changes to gas phase evaporates, vapourises or boils. Moreover, a gas that changes to liquid condenses, while a liquid that changes to solid phase solidifies. In some cases, a solid can change to gas directly without first changing to liquid. This is called sublimation. The opposite, that is, the direct change from gas to solid, is called deposition or desublimation.

**Figure 17.** At absolute zero,  $-273.15\text{ }^{\circ}\text{C}$ , atoms and molecules stand completely still.



## Chemical energy and chemical reactions

A chemical reaction occurs when one or more substances react with each other. Combustion is an example of a type of chemical reaction. When wood, for example, is burned, chemically bound carbon and hydrogen in the wood react with oxygen from the air. Such a chemical reaction with oxygen, that is, where oxygen binds to another substance and forms a new substance, is called oxidation. The product that is formed is an oxide. In a complete reaction between carbon, hydrogen and oxygen, that is, when the mixture consists of “enough” large proportions of each substance, carbon dioxide and water are formed.

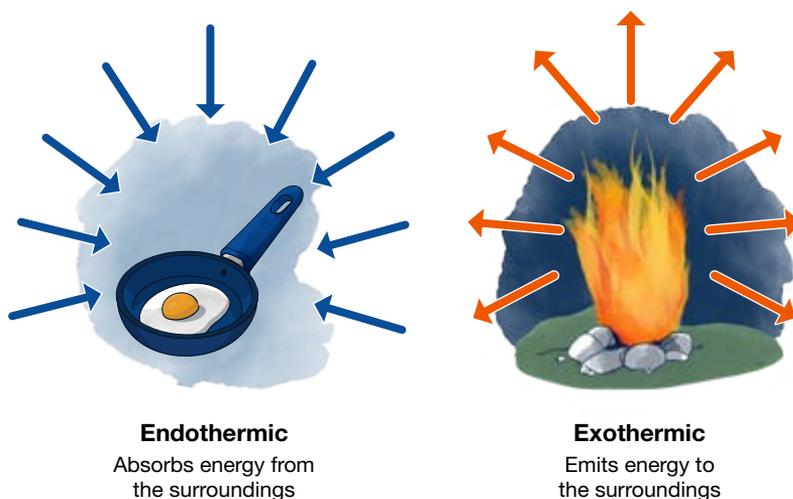
In a substance, there is energy bound partly by the forces that hold the atoms together into molecules, and partly by the movements that exist in the atoms and molecules. We call this energy chemically bound energy.

When we burn different types of fuels, energy is released. During combustion, the chemically bound potential energy in the fuel is converted into heat energy, into radiant energy (electromagnetic radiation) and into other chemically bound energy in the substances formed during combustion.

In chemical reactions, heat is absorbed or released. When burning different types of fuel, we use the term heat of combustion. The heat of combustion of a fuel tells us how much potential energy is in the fuel and can be released during a chemical reaction (combustion). Heat of combustion will be discussed in more detail later, in the section on fuels and fuel properties. It is an important measure of how different materials can contribute to the development and spread of fire.

A chemical reaction in which heat is released is called exothermic, and a reaction in which heat is absorbed is called endothermic. Combustion is thus an exothermic reaction, in which the energy content of what is burning decreases and is released. Especially in fires, the energy that is released will help the chemical reaction to continue. It simply continues to burn as long as there is fuel left and as long as the energy released is sufficient to maintain combustion. Substances that are not flammable or have low flammability do not release enough energy for combustion to continue. Such substances may require additional energy to burn, for example by other objects or substances burning in their vicinity.

**Figure 18.** Chemical reactions can be endothermic or exothermic



Combustion and fire are exothermic chemical reactions, meaning they give off heat. The opposite is an endothermic reaction, which absorbs heat.

Some substances do not react at all with any other substance, for example the noble gases helium, neon and argon. There are also substances, for example some metals, that oxidise very quickly in air, others more slowly. Some do not oxidise at all, like gold. There are substances that react already at low temperatures, others only at elevated temperatures. This depends on the structure of the atoms that the substance is made of.

A high concentration of certain substances in a reaction means that the particles are closer together. Then they “collide” more often, and the reaction goes faster. A high concentration of a substance can be achieved, for example, by increasing the pressure. Even with increased temperature, the movements of the molecules become faster, there are more collisions and a faster chemical reaction. In the case of a fire, this is clear. A high ambient temperature can cause the fire to increase in intensity, that is, the chemical reactions go faster. This is one of the mechanisms behind the fact that the spread of fire often occurs exponentially, that is, the extent or spread of the fire increases at an ever-increasing rate.

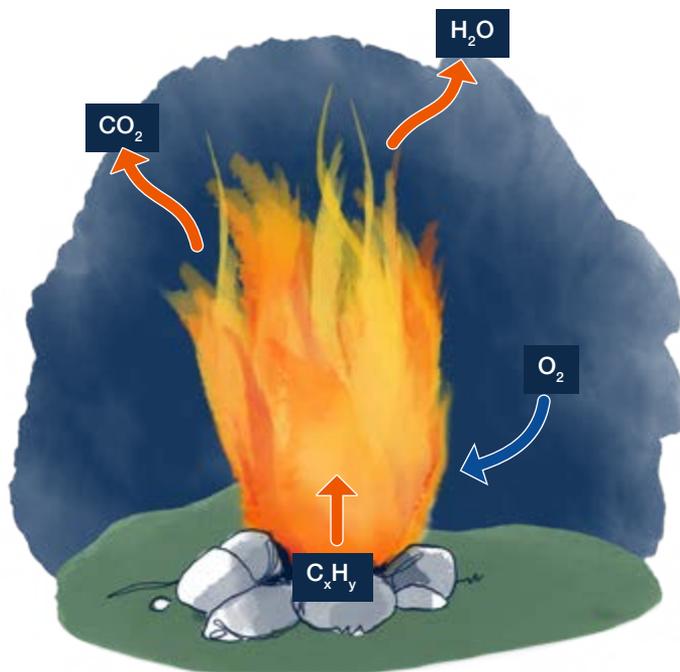
The speed of a chemical reaction also depends on the surface area of the substances involved. The more finely divided a substance is, that is, the larger the surface area of the particles in relation to its volume, the faster the chemical reaction will be. This means that more molecules are simultaneously exposed to, for example, heat energy and can be involved in the chemical reaction. We can see this in fires, when fire gases ignite. Fire gases consist, among other things, of a large amount of very small particles. These will ignite if there is a sufficiently high concentration of particles in combination with a sufficiently high temperature.

## Combustion

We frequently use the words fire and combustion almost synonymously. To clarify the concepts, we can say that a fire is combustion that has broken loose, that is, an uncontrolled fire. Also, fire is combustion in the gas phase. Combustion is then a chemical process, consisting of a number of chemical reactions, where a reaction occurs between oxygen and fuel (oxidation). Combustion even of simple substances is a complex process that takes place in several different steps. In most of these reaction steps, radicals are formed, that is, single atoms such as hydrogen radicals, oxygen radicals or hydroxyl radicals (groups of an oxygen and a hydrogen atom). Radicals are fragments of molecules, and they can only exist if the temperature is high enough. They are usually very reactive and therefore not very long-lived.

Combustion releases heat and light. Combustion is thus a chemical phenomenon (one or more reactions) accompanied by physical effects (release of heat and light). The heat is the energy that is developed during the chemical process (thermal energy). Light is the physical consequence of the energy that is released during this chemical process. During combustion, heat is developed at the same time as heat is consumed, or rather: more energy is developed than is needed to keep the process going. In the type of combustion that is the focus of this book, a fire in a building, the chemical reactions involved develop more heat than is consumed. We call such a chemical process exothermic, that is, that heat is developed. The opposite is endothermic, that is, a process that absorbs heat. The consequence of this exothermic process is fire and the spread of fire.

**Figure 19.** Fire is a chemical process in which a variety of chemical reactions occur that emit light and heat



In a fire, the oxidising agent is usually the oxygen in the air, but not necessarily. The oxygen can also be chemically bound in a substance. This oxygen is released when heated by the substance undergoing a chemical process and breaking down so that the oxygen is released. Examples of such substances that can sustain combustion even without the oxygen in the air are hydrogen peroxide, sodium chlorate, potassium permanganate and potassium chromate. These substances are included, for example, in explosives or fireworks, to achieve an efficient and often controlled combustion process.

But there are also other oxidising agents than oxygen. One such oxidising agent is chlorine. In general, an oxidising agent (an oxidant) is a substance that in a chemical reaction easily absorbs electrons from another substance, which is then reduced.

### **Combustion rate**

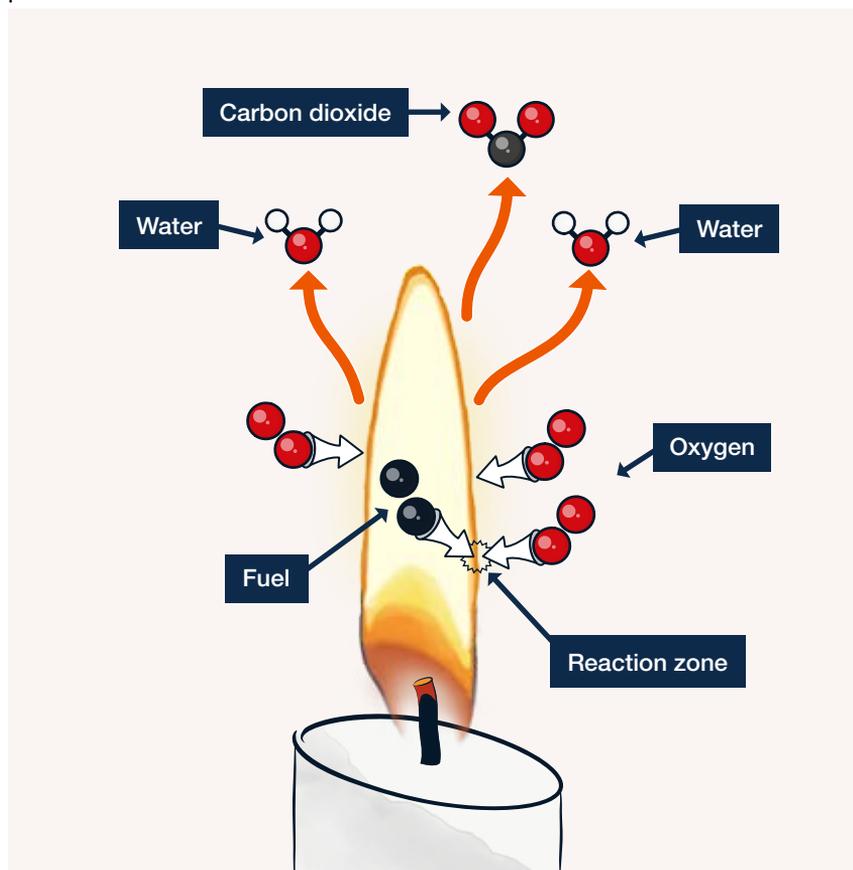
The velocity in m/s at which a flame moves through a flammable gas.

The combustion rate of a combustible gas mixture, i.e., how quickly the gas burns, depends, among other things, on the composition and temperature of the mixture. The mixture of fuel gas and oxygen must have a certain concentration and a certain temperature to become combustible. The more molecules there are, i.e., the higher the concentration of fuel and oxygen, the greater the probability that they will collide, and the faster the molecules move, i.e., the higher the temperature, the greater the probability that they will collide.

If the concentration of fuel gas is too low or too high in relation to the concentration of oxygen, the mixture cannot be combusted. If, on the other hand, the concentrations of fuel gas and oxygen are mixed in a certain “perfect” ratio to each other, it is sufficient to supply very little energy for the combustion process to start. In some cases, combustion can occur at a high speed, which we can sometimes perceive as an explosion. We can then also speak of the flammability limits and flammability range of mixtures. This will be discussed in more detail later.

A simple example of a combustion process is the flame from a regular candle. The stearin (in solid form) melts and is transported up through the wick, where it vapourises. The melted and vapourised stearin (the fuel gas) continues outward and upward where it meets the oxygen in the air. A reaction occurs and energy is released. We see some of this energy as a flame. Some of the energy is also used to heat the stearin so that combustion can continue.

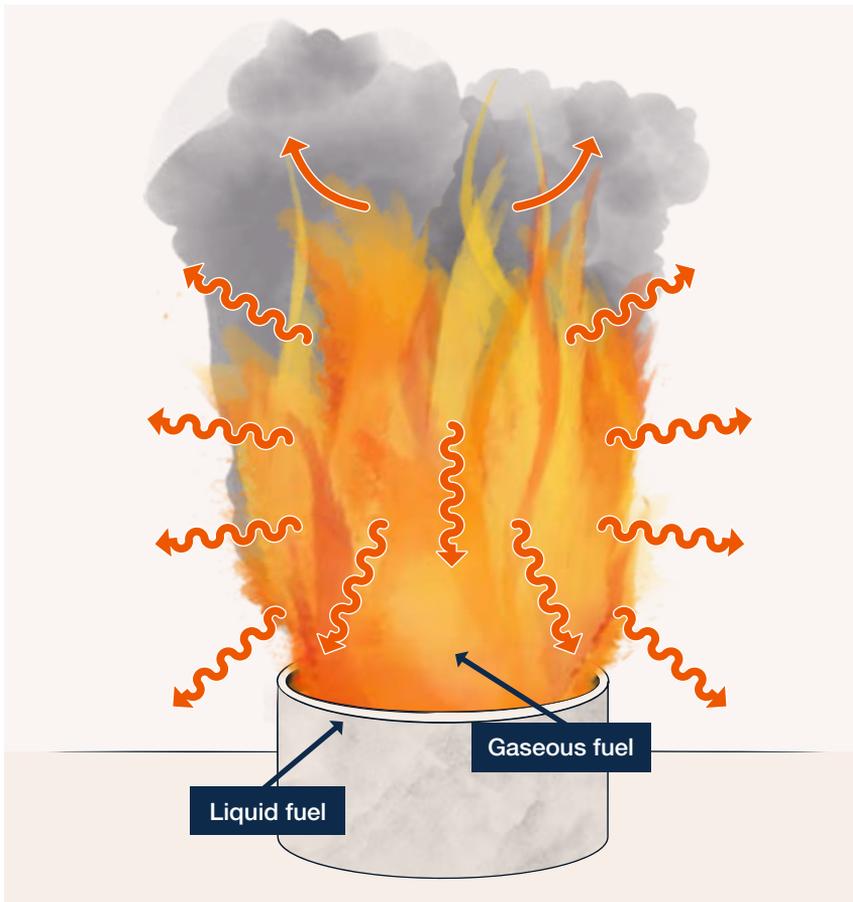
**Figure 20.** A candle is a simple example of a very complex chemical process



Combustion is both a physical and a chemical phenomenon. These are interactive, that is, dependent on each other. Interaction also occurs between the fuel and the environment. In order for combustion to start and eventually become self-sustaining, it is therefore necessary to supply heat energy to a mixture of fuel (in gaseous form) and oxygen in a certain ratio to each other. In the candle, combustion takes place precisely in the area of the flame where the mixture between oxygen and fuel gas is just right. There is no oxygen inside the flame, so no combustion takes place there.

The ignition source provides an initial supply of heat energy (ignition energy). Once combustion has started, additional heat energy is needed for the process to continue and become self-sustaining. Since combustion and fire are normally exothermic processes, i.e., heat energy is developed, the heat energy from the combustion itself will keep the combustion process going. The heat energy is returned to the combustion partly by radiation from the flame, partly by re-radiation from heated surfaces and hot combustion products (fire gases).

**Figure 21.** Parts of the heat energy developed in a fire is returned to the fire so that the combustion process can continue



## Pyrolysis

Pyrolysis is a type of chemical reaction that is an essential part of fire and combustion, especially in fires in buildings. It is a process where a substance is heated and decomposed without any actual combustion taking place, that is, there is essentially no oxidation of fuel. Pyrolysis breaks down a material and produces a variety of different substances. These normally consist of volatile gases, gaseous oils that can be condensed and a residue in solid form. The volatile gases include water vapour, carbon monoxide, methane and other lighter hydrocarbons (compounds between carbon and hydrogen) as well as heavier organic compounds such as tar and other heavier hydrocarbons. These volatile substances are released in gaseous form. The remaining solid residue consists mainly of carbon, but there may also be some liquid substances that remain. Pyrolysis is the thermal decomposition of a material.

Pyrolysis differs from gasification. Pyrolysis forms other substances and chemical compounds than those found in the original material. Gasification, on the other hand, does not form any such other substances. There is no breakdown of the material, but the substances simply change form to gas. Pyrolysis also involves a phase transition, but through thermal decomposition. In most cases, the material then goes directly from solid phase to gas phase, without first becoming a liquid. An exception may be certain plastics, mainly so-called thermoplastics, which first melt and then pyrolyse, but even plastics in solid form can be thermally decomposed and form flammable gases without first melting. This depends, among other things, on how much heat energy is supplied and how quickly the heat energy is supplied, but also on the properties of the plastic.

### Pyrolysis

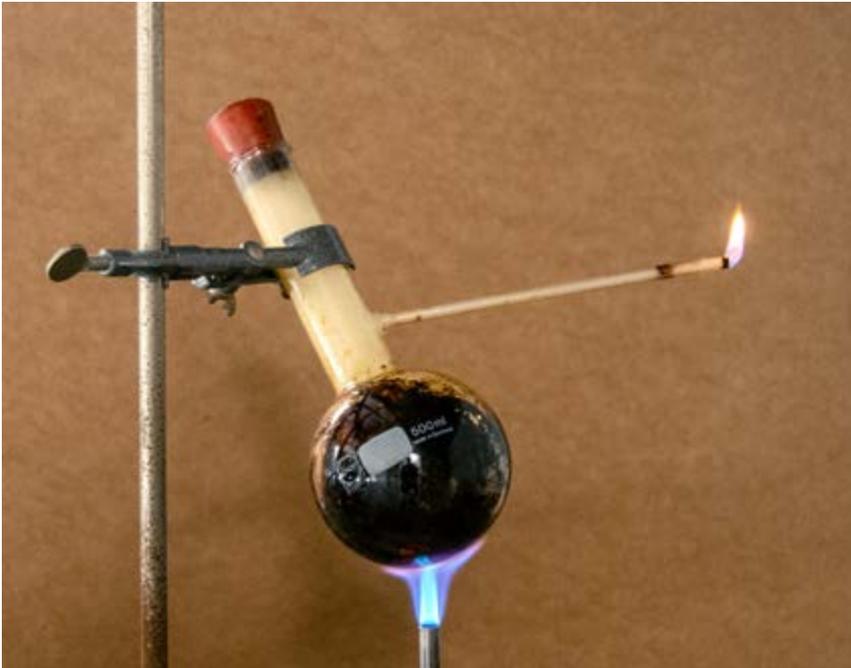
A chemical decomposition or other chemical transformation from complex to simpler constituents, caused by heat.

The volatile gases that are released are usually flammable, which means that the combustion gases formed during pyrolysis are flammable. The different substances and the exact composition of what is formed during pyrolysis are determined, among other things, by factors such as the properties and composition of the original material, temperature, pressure and, not least, the availability of oxygen (air). Pyrolysis that occurs under good air supply can produce completely different combustion gases than pyrolysis that occurs in, for example, ventilation-controlled fires, where there is a lack of air. Such a ventilation-controlled fire is often more difficult to handle for the fire service than a fuel-controlled fire, which have full access to air, among other things because of the combustion gases that are formed when there is a lack of air.

In order for combustion and fire in a solid object to occur, pyrolysis needs to occur. The solid simply needs to become a combustible gas, which pyrolysis gives rise to. An exception may be stearin or wax, which is in a solid phase at room temperature, but which melts when heated and then gasifies. It is then the gasified stearin (or wax) that burns, but there is a significant difference between gasification and pyrolysis.



During pyrolysis, solids break down and form flammable gases. Photo: Stefan Svensson.



Dry distillation of wood is a simple example of pyrolysis. Photo: Stefan Svensson.

Unlike a phase transformation, for example from solid to liquid, pyrolysis is not reversible, meaning it cannot go back in the opposite direction. Once a substance has been pyrolysed, its chemical composition cannot be changed to return it to its original phase or composition.

Pyrolysis is the fundamental explanation for many fire events. The fuel gas that develops during pyrolysis, i.e., the broken down, gasified and volatile part of the material, mixes with oxygen from the air and burns in the flame itself.

Pyrolysis also explains why objects far away from the fire can be ignited by radiant heat alone. The radiation from a fire is absorbed by and heats the object to the temperature at which pyrolysis can start. If the temperature rises further, the ignition temperature of most of the pyrolysis gases can be reached.

Sometimes, when an object is on fire, you can see flames that “lift” and burn high in the air, separated from the burning object. This is when pyrolysis products are lifted by the hot air current and gradually burn (oxidise) as they come into contact with oxygen. Closest to the object that is pyrolysing, there is too little oxygen for combustion to occur.



Thermal radiation from the flames causes surfaces, such as floor and walls, to pyrolyze. Photo: Stefan Svensson.

Fire gases normally consist largely of pyrolysis gases, i.e., a fuel that has been broken down and turned into combustible gases. The pyrolysis of a fuel is of great importance for how a fire develops and spreads in buildings and for how the resulting fire gases affect people, property and the environment.



# Chapter 5

# Fire physics

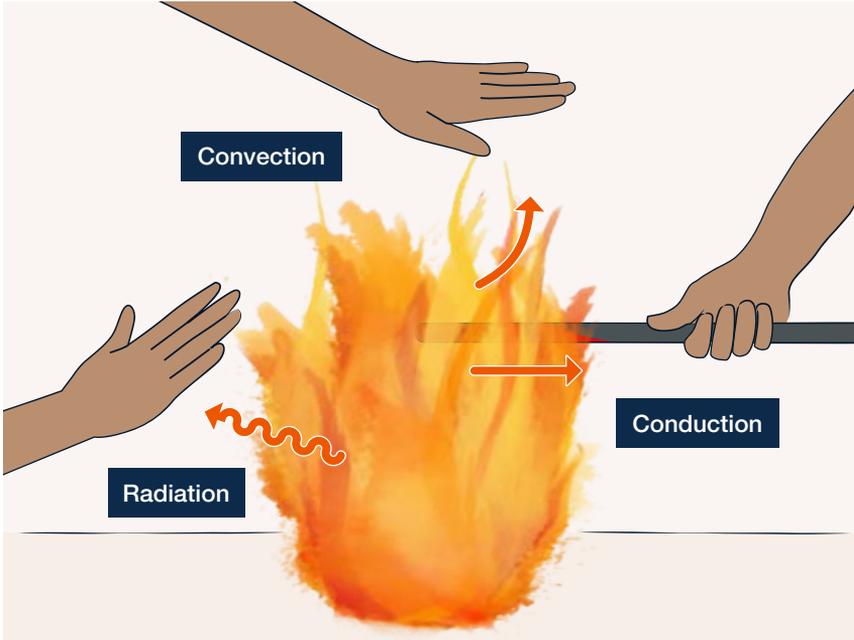
Fire physics is a specialised area of physics that includes the physics of fire and combustion. Much of what is covered in this section is not unique to fires. For example, heat transfer is an important factor to consider when designing buildings, since we want buildings to be as energy efficient as possible while maintaining a comfortable indoor climate. However, in this book, the starting point is fire in buildings.

## Transportation of heat and heat transfer

Transportation of heat and heat transfer involve the transport of thermal energy between different parts of a medium or material, or between different media or materials. Heat can only be transferred spontaneously from something hotter to something colder. Something that is cold “contains” less energy than something that is hot, so the energy can only be transported in one direction, from the hot to the cold. Transportation of heat and heat transfer are fundamental to the onset and spread of fires.

Heat can be transferred in three ways – by conduction, convection and thermal radiation. Conduction mainly occurs in solid materials or between solid materials. Convection occurs due to the movement of a liquid or a gas. In convection, at least one of the materials through which heat is transferred is always between a liquid or a gas. The other material from or to which heat is transferred can be a solid material, such as a wall, or a liquid, such as water. Thermal radiation occurs regardless of whether the phase of the media is gas, liquid or solid. However, within a solid material or between two solid materials that are in direct contact with each other, heat is transferred by conduction. Thermal radiation does not require a transporting medium, heat can be transferred through a vacuum, just like other electromagnetic radiation.

**Figure 22.** Heat transfer can occur through conduction, convection and thermal radiation



In the event of a fire in a building, the dominant mode of transport varies, depending on, among other things, how long the fire has been going on (time) and where in the room or building you are. This will be discussed in more detail later.

## Conduction

In solids, heat is transferred mainly by conduction. In liquids, heat transfer also occurs to some extent by conduction. The movement of molecules is transferred directly from molecule to molecule. If you place your hand on a hot metal object, thermal energy (molecular motion) is transferred from the metal to your hand. As the energy is transferred, the molecules move faster, which causes the temperature of your hand to increase. Heat is conducted from a hotter object to a colder one or from the hotter part of an object to the colder part.

**Figure 23.** Transportation of heat into and within materials occurs through conduction



The ability of a material to transfer heat is called conductivity or thermal conductivity. In physics, this ability is usually described by the thermal conductivity, which is denoted by the Greek letter  $\lambda$  (lambda) or by the letter  $k$ .

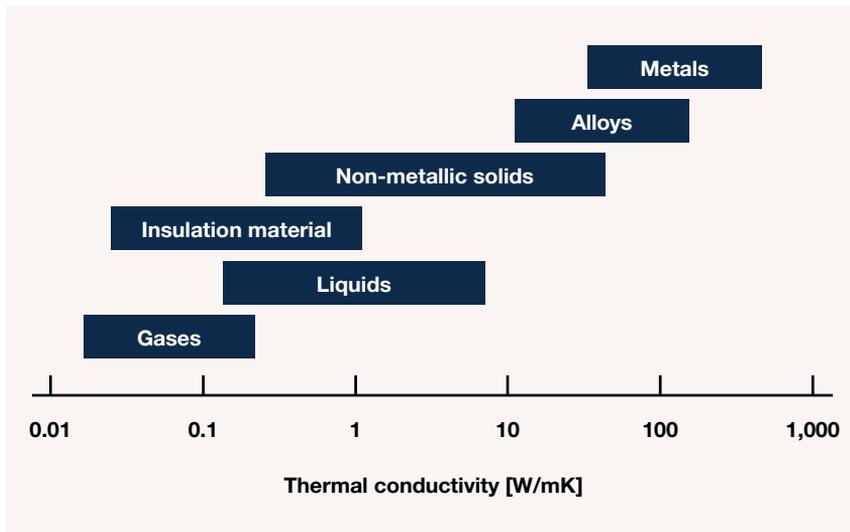
Materials with high thermal conductivity are good conductors of heat: they transfer heat well. They are often also good conductors of electricity, meaning they conduct electricity well (but there are exceptions). Such materials have strong bonds between the molecules and allow more heat energy to pass through than materials with slightly looser bonds. This is because molecules with strong bonds can more easily transfer their motion to each other.

A material that does not conduct heat particularly well has a lower thermal conductivity and thus a higher thermal resistance, i.e., a higher resistance to heat transfer. On the surface of such materials, the temperature can increase rapidly, because the heat is not conducted further. This affects how a fire spreads in a room, because a low thermal conductivity of the wall material means that the heat from the fire is not conducted further into the walls at any greater speed. The surface of the material then heats up faster, pyrolysis starts earlier and the fire can spread faster than if the walls had a higher thermal conductivity. The temperature in the room also increases faster and can ultimately be higher, compared to a room where the wall material has a high thermal conductivity.

**Table 1.** Thermal conductivity of some common materials

Material	Thermal conductivity [W/mK]
Silver	427
Copper	387
Gold	315
Aluminum	238
Brass	111
Iron	46
Brick	0.69
Plaster	0.48
Wood (pine)	0.14
Concrete	1.7
Glass	1
Cell plastic	0.037
Air	0.026

**Figure 24.** How thermal conductivity of different types of materials relates to each other



A simple example of thermal conductivity and thermal resistance is if you first place your hand, which is warmer than the surroundings, on a wooden surface that is as warm as the surroundings. Then you place it on a metal surface, also as warm as the surroundings. The metal and the wood are equally warm, and yet the metal surface feels much colder than the wooden surface. The explanation is that metal is a very good conductor of heat. It conducts heat away from the hand, and the hand then gets a lower temperature. The wooden surface feels warmer because it does not conduct away as much heat. Metal has a high thermal conductivity and a low thermal resistance, while wood has a lower thermal conductivity and a higher thermal resistance. For example, we prefer wooden floors to metal floors in our homes.

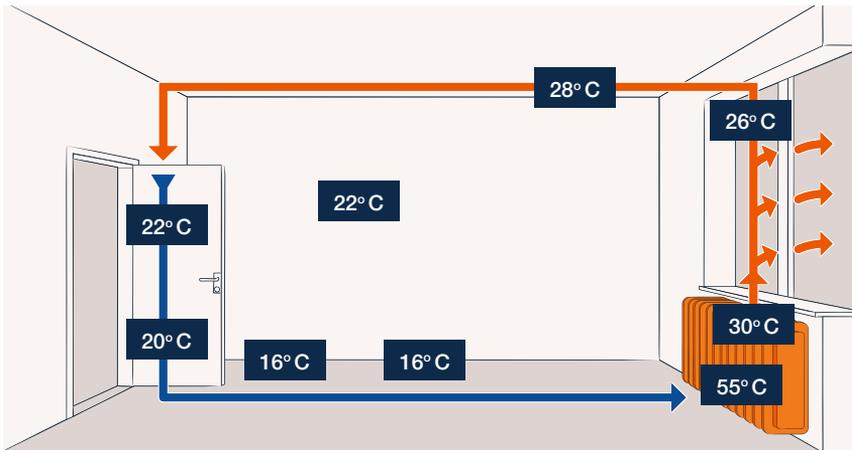
A steel beam that runs from a fire room through a wall to another room can cause a fire on the other side of the wall. Steel has a high thermal conductivity and therefore conducts the heat to the other room. For a certain time, the surface of the beam remains quite cold because the heat is conducted away from the surface, but gradually the entire mass of the beam heats up. Then the surface can become so hot that it ignites flammable material that it is in contact with on the other side of the wall.

## Convection

Flowing substances, gases as well as liquids, can transfer heat as they flow. The flowing substance, for example water or air, can heat up a colder solid or liquid substance along its path, or vice versa: the flowing substance can be heated by a warmer solid or liquid substance that it flows through or past. This transfer of heat is called convection.

Convection, i.e., heat transfer through flow, plays a major role in the spread of fire. Approximately 70 percent of the energy released in a fire is transferred through convection, mainly through the hot gases produced during combustion and flowing upwards. On their way upwards, these hot gases mix with cooler air from the surroundings. The cold air is heated and follows the upward flow.

**Figure 25.** Heat transfer between a gas/liquid and a solid/liquid occurs through convection



If the rising stream of hot gases encounters a ceiling, this stream of gases will be deflected and flow along the underside of the ceiling. Heat is then transferred, via convection, from the hot gas to the ceiling.

**Table 2.** Typical values for convection

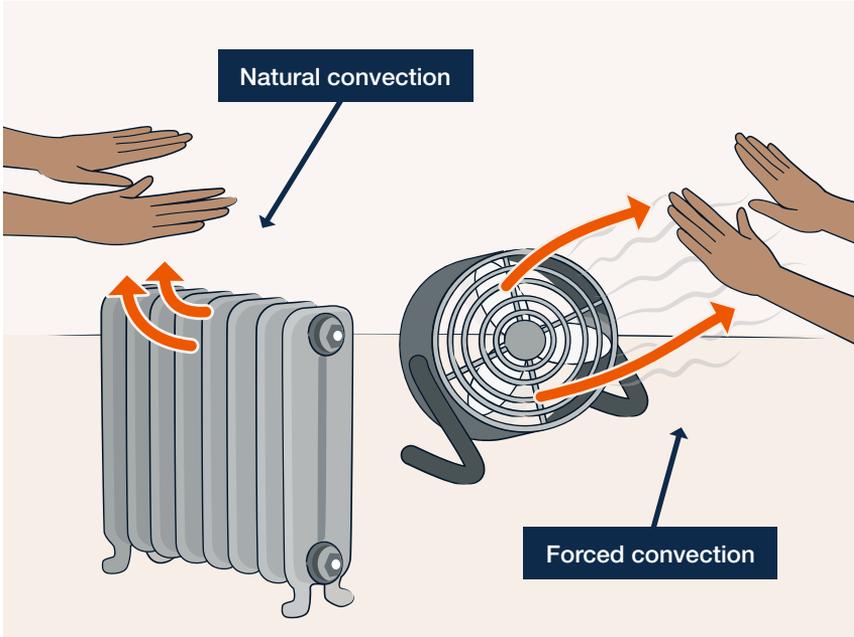
Media	Type of convection	Heat transfer coefficient, $h$ [ $\text{W}/\text{m}^2\text{K}$ ]
Air	Natural	3–12
	Forced	10–150
Water	Natural	200–1,200
	Forced	3,000–7,000

How much heat is transferred by convection can be described using the term “heat transfer coefficient”. The heat transfer coefficient depends, among other things, on the temperature difference between the media and on their thermal conductivity. However, the heat transfer coefficient also depends on the velocity of the flowing gas, and a distinction is normally made between natural convection and forced convection.

### Natural and forced convection

Natural convection is the type of heat transfer where the movements in the liquid or gas are not created by any external influence such as a pump, fan, wind, fire or the like. It is only differences in temperature and thus differences in density that create movements in the liquid or gas. Hot air and hot fire gases rise upwards, because they are lighter than cold air and cold fire gases. This heat transfer that occurs through movements created by density differences is called natural convection.

**Figure 26.** Natural/forced convection



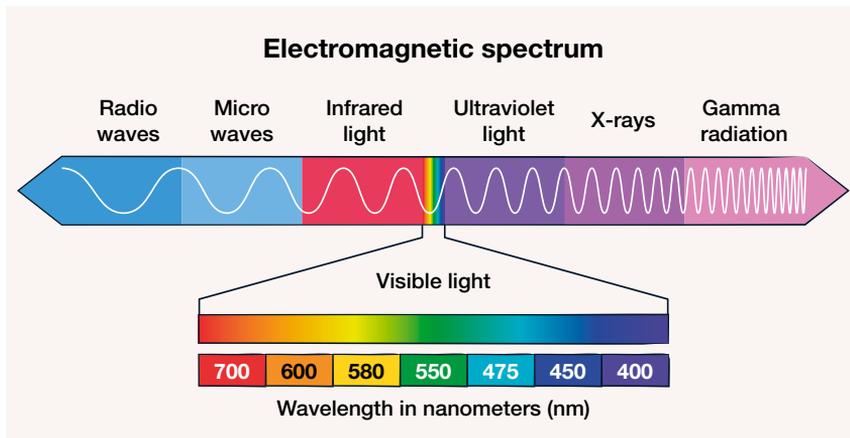
Forced convection is the opposite of natural convection. It can be caused by, for example, wind, a fan or pump, i.e., movements in the liquid or gas that are created by more than just differences in density. In forced convection, the transfer of heat, convection, can be much greater than in natural convection. For example, a strong wind against a building where there is a fire can affect the development and spread of the fire even inside the building. Also, wind against a building affects pressure differences between different sides of the building and allows more air to be supplied to the fire.

## Thermal radiation

In the event of a fire, we can feel the heat from a distance with our hand, and we could do so even if there was a vacuum between the fire and the hand. Compare this to the heat we feel from the sun. The transportation of thermal energy thus occurs without the heat passing through a medium or material. The heat is transferred directly from hot surfaces or from the flames in a fire, through electromagnetic radiation.

Electromagnetic radiation is a wave motion that propagates in time and space. The most important property of electromagnetic radiation is its frequency or wavelength. Frequency means how fast the wave motion is, and wavelength means how far it is between two wave peaks. These are like two sides of the same coin: high frequency gives short wavelengths while low frequency gives long wavelengths. Electromagnetic radiation occurs in a wide spectrum of wavelengths. The part of the radiation that we perceive as light is only a very small part of all the possible wavelengths, or frequencies, that the radiation can have.

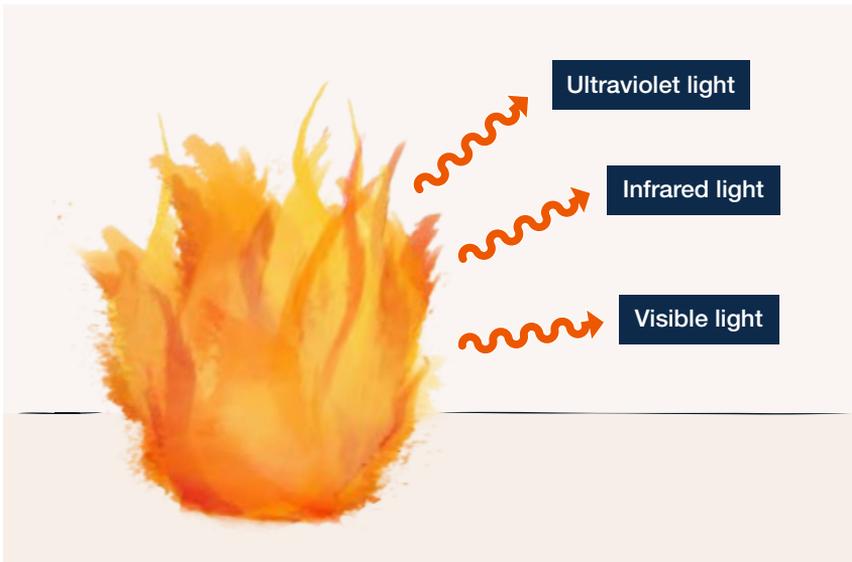
**Figure 27.** Electromagnetic radiation can have a variety of wavelengths



Radioactive radiation is at one end of the radiation spectrum. It is a form of electromagnetic radiation that has a high frequency and a very short wavelength. The energy content of radioactive radiation is therefore very high. Radio waves are at the other end of the spectrum and have a low frequency but a long wavelength. The energy content of radio waves is therefore very low.

A fire emits electromagnetic radiation in a broad wavelength spectrum, which mainly consists of infrared light, visible light and ultraviolet light. Some wavelengths are visible, others are not. The visible range lies between ultraviolet radiation (short waves) and infrared radiation (longer waves). The transportation of heat that occurs in a fire through radiation occurs for the most part within the frequencies that we call infrared radiation. Objects that have been heated, for example due to a fire, then also emit electromagnetic radiation, primarily in the form of infrared radiation.

**Figure 28.** A fire emits electromagnetic radiation in a broad wavelength spectrum



The electromagnetic radiation emitted from a fire consists mainly of infrared light, visible light and ultraviolet light.

A flame is actually a hot mass with a “surface” from which heat radiates (thermal radiation). A flame consists largely of hot soot particles that emit heat in the form of thermal radiation. The “stronger” the flame, the more radiant heat it emits. By strong we mean that the flame contains a large amount of soot particles and that it is high, deep or wide. It is from these particles in the flame that the heat is transferred by thermal radiation.

Flames from, for example, burning alcohol contain few soot particles and therefore emit relatively little visible radiation. Note that even fuels that emit more or less invisible flames, due to the few soot particles in the combustion products, can emit large amounts of infrared thermal radiation. Such flames can also heat up surrounding surfaces.

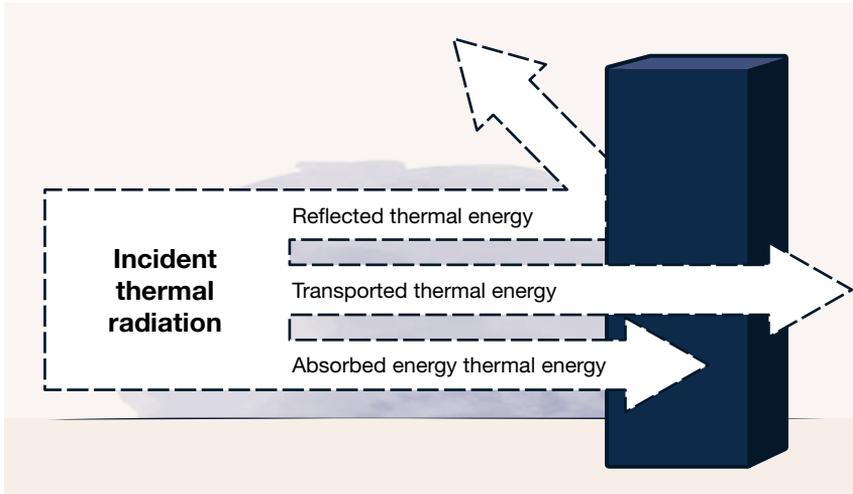
Thermal radiation is measured in  $\text{kW}/\text{m}^2$ , that is, how much energy hits a surface per unit of time.



The larger the flame, the more thermal radiation from the flame. Photo: Peter Lundgren.

When thermal radiation reaches a surface, the energy is split up. Some is reflected, some is absorbed (“sucked up”) and some is transmitted (let through). All the parts together are always equal to the original energy (according to the first law of thermodynamics, which states that energy cannot be created or destroyed, only transformed from one form to another).

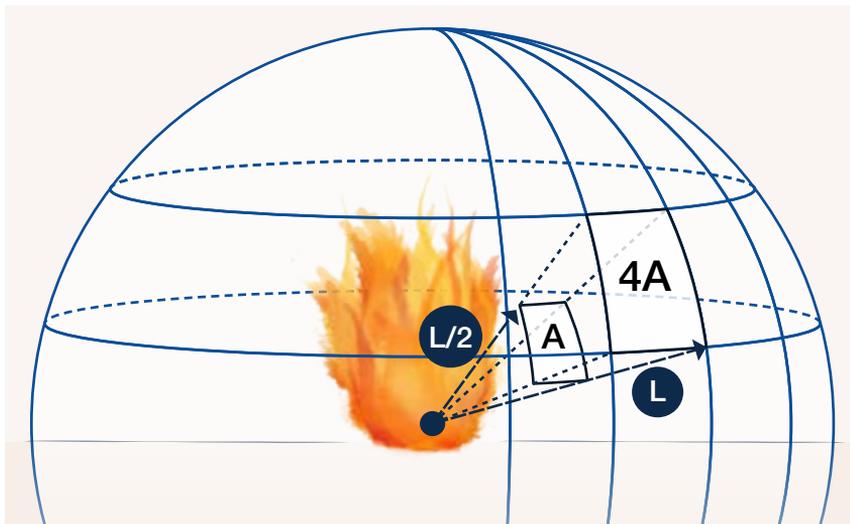
**Figure 29.** When thermal radiation reaches a surface (an object), a division of the energy occurs



The radiation incident on an object is divided into reflected radiation, transmitted radiation and absorbed radiation.

From a fire (a radiation source), heat spreads in all directions, through thermal radiation. The further away from the fire, the less the radiant heat affects people or objects. This means that only a limited amount of heat falls on a surface further away from the fire. Imagine that the radiation source is a point in the middle of a sphere. The surface of the sphere is irradiated by the radiation source from the inside, and the radius of the sphere is the surface's distance from the radiation source. Since the inner surface of the sphere increases with the square of the distance, the incident radiant heat to the surface (the inside of the sphere) decreases sharply with distance (i.e., with the square of the distance). The energy coming from the radiant source becomes much smaller when it is distributed over each unit area of the inner surface of the sphere. The radiant heat that reaches each small part of the inside of the sphere is only a fraction of the total radiant heat (energy) from the fire. The area that is “visible” at a certain angle from the centre of the sphere becomes larger the larger the sphere. The amount of thermal radiation that hits each such area then becomes smaller (it must be distributed over a larger area), even though the total amount of thermal radiation coming from the radiation source is the same.

**Figure 30.** Thermal radiation decreases with the square of the distance between the source and the irradiated object



At twice the distance from the radiation source, the surface area is 4 times as large. Then the amount of radiation that hits this surface is only a quarter. The radiation is "spread out" over a larger surface area and will then be lower.

Different materials emit different amounts of thermal radiation. This is referred to as the emissivity of the surface, or material.

The emissivity of the surface of a material describes how efficiently the surface emits energy as thermal radiation. As mentioned, this can consist of both visible radiation (light) and infrared radiation, which is not visible to the human eye. Some of the thermal radiation from very hot objects can be visible to the eye, for example from a red-hot iron rod.

**Table 3.** Some examples of levels of thermal radiation

Thermal radiation	kW/m <sup>2</sup>
A sunny summer day	1
Pain after a few seconds	3–5
During flashover in a room	20–25

The emissivity of a surface depends on its chemical composition and geometric structure. Emissivity is given between 0 and 1. The value indicates the ratio of the thermal radiation from a given surface to the thermal radiation from an ideal black surface at the same temperature. The surface of a perfect black body has an emissivity of 1. It emits thermal radiation at about 448 watts per square metre at room temperature (298.15 K). All real objects have an emissivity less than 1 and emit thermal radiation with correspondingly lower energy.

Dark surfaces emit more heat radiation than light surfaces. Polished metal surfaces also reflect most of the incident heat radiation and do not heat up as easily. This also has an impact on what we can see in a thermal camera.



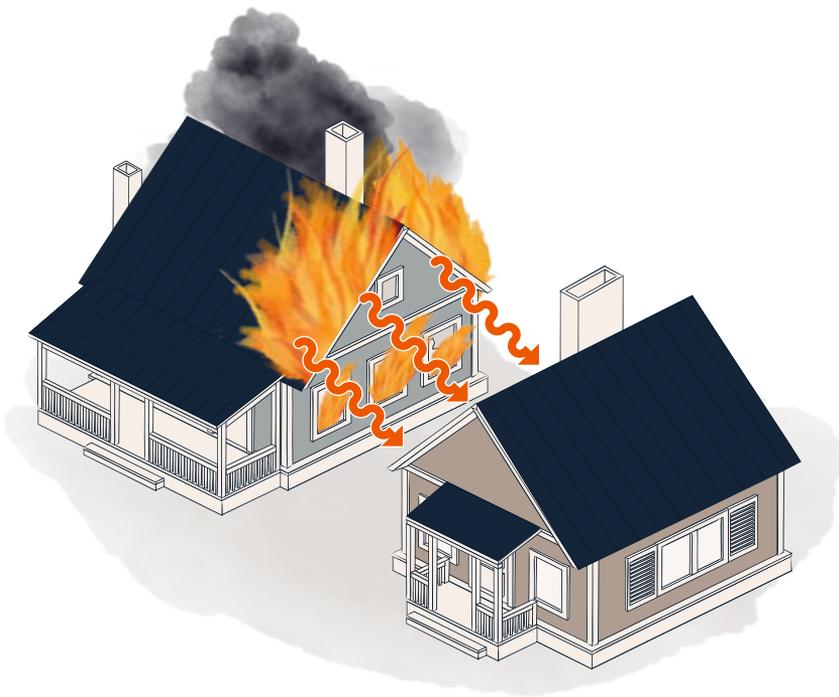
Different materials can have different emissivity and are therefore perceived differently in, for example, a thermal camera. Photo: Stefan Svensson.

The thermal radiation that comes from an object or from another radiation source, for example a fire, thus depends on the distance from the radiation source and on the nature of the surface, but also on the angle to the radiation source.

Thermal radiation can contribute to the spread of fire over large distances, for example between buildings. The risk of fire spreading between buildings depends on factors such as the distance between the buildings, the size of window openings, the properties of the wall materials and, of course, the size of the fire. Building regulations set requirements for how this risk should be managed, for example, requirements for a certain minimum distance between buildings and certain technical measures.

The thermal radiation from flames depends on the temperature of the flames, the properties of the flames (including the amount of soot), the size of the flames (height and width) and the distance to the flames.

**Figure 31.** Fire can spread between buildings due to thermal radiation



## Fuel and properties of fuel

Fuel in this context refers to almost all the materials we have around us, at least those that are combustible. Even non-combustible materials have the properties described in this section, apart from the fact that they do not burn, but otherwise, such materials also have mass, volume, strength properties, etc. Even non-combustible materials are affected by fire and high temperatures, since their properties can change in a similar way to combustible materials. Non-combustible materials can, of course, also affect the development of the fire, for example through re-radiation from heated surfaces.

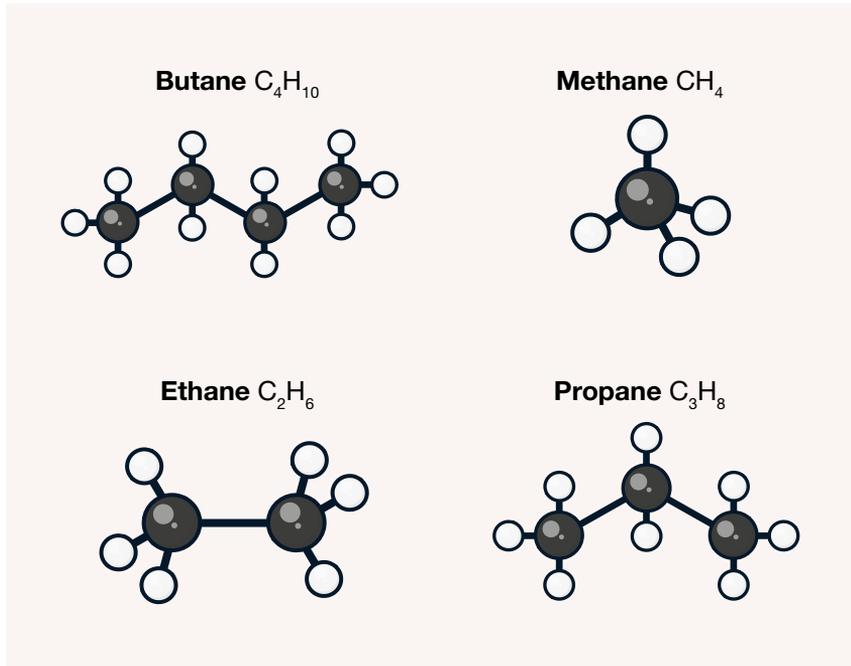


Most materials in our homes are fuel. Photo: Johnér Bildbyrå.

All matter is made up of atoms which in turn are combined into molecules, some very simple and others more complex. Most fuels are made up of more or less complex molecules. In many cases, fuels are also mixtures of a large number of different types of molecules, that is, different substances. Materials that we often perceive as relatively simple in everyday life, such as wood, actually consist of a variety of such mixed substances. When such a material is exposed to heat and begins to pyrolyse, these substances decompose. If the material is also

composed of a variety of different compounds (of different types of molecules), the gases formed during pyrolysis can become extremely complex, and even if the various individual gases formed have a relatively simple molecular structure, the mixture of pyrolysis gases can make the fire gases both flammable and toxic.

**Figure 32.** Different materials are made up of more or less complex molecules



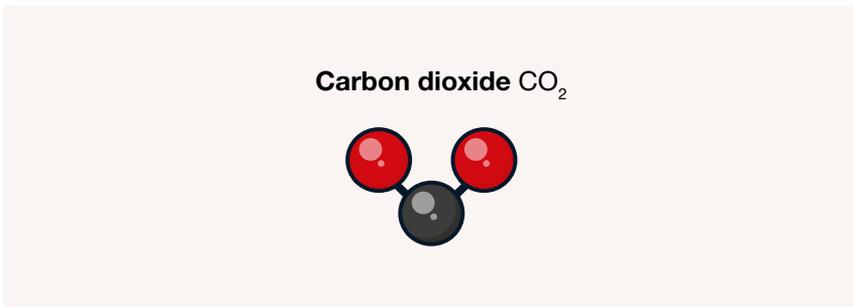
Most fuels are composed of a large number of different molecules, that is, different substances or compounds. Fire gases also consist of a large number of different compounds.

Hydrogen occurs in almost all fuels. The hydrogen atoms are then normally combined with other substances in molecules that strive to form, among other things, water through oxidation. The result is that quite large amounts of water vapour are formed during combustion. Water is a very stable molecule compared to the gases of which it is composed (hydrogen and oxygen) and also compared to a number of other pyrolysis products and combustion products. During the combustion of substances containing hydrogen, a reaction occurs in which a lot of heat is released, that is, a heat-producing (exothermic) reaction.

It is this heat that is necessary for continued combustion and that becomes both noticeable and dangerous in the event of a fire.

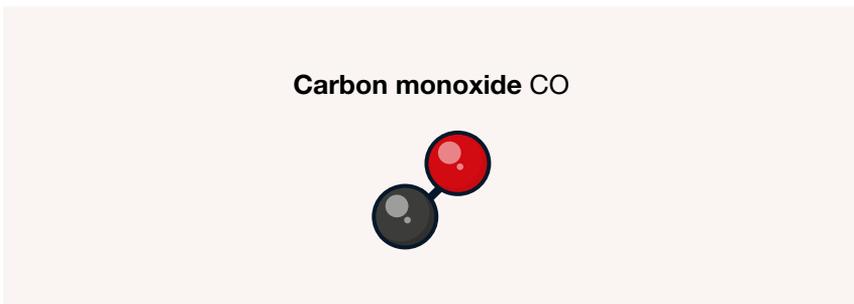
Another element of particular interest in connection with combustion is carbon (C). Carbon is also present in almost all fuels and forms the basis of molecules in so-called organic compounds, which are often combustible materials.

**Figure 33.** During complete combustion (oxidation) of coal, carbon dioxide is formed



Carbon dioxide CO<sub>2</sub> is produced when organic materials (containing carbon) are burned. Carbon dioxide is harmless but displaces oxygen and therefore has a suffocating effect. Since the gas is already oxidised, it can be used for fire extinguishing.

**Figure 34.** Incomplete combustion (oxidation) of carbon produces carbon monoxide



Incomplete combustion of coal produces carbon monoxide instead. Carbon monoxide is a known toxic gas. The most important reason is that it binds to red blood cells approximately 250 times more strongly than oxygen does. This significantly impairs the ability of blood cells to transport oxygen. Carbon monoxide is always formed when combustion has limited access to oxygen, which is normally the case in most fires and especially in building fires.

We then have the combustion of hydrogen and oxygen, which forms water, and the combustion of carbon and oxygen, which then forms carbon dioxide and carbon monoxide. These reactions are fundamental to the final combustion products.

Most fuels contain a large amount of carbon and hydrogen, in a variety of compounds, and therefore produce large amounts of water, carbon dioxide and carbon monoxide.

Another substance that is normally found in large quantities in most fuels is nitrogen (N). Nitrogen does not “burn”, that is, it does not contribute to combustion and therefore does not contribute to any heat-releasing (exothermic) reaction. However, nitrogen can still be part of the chemical reactions that occur during combustion. Nitrogen can then form a long series of gases, many of which are toxic, even though nitrogen itself is harmless.

Sulphur can also be found in various compounds, such as certain plastics. When sulphur oxidises, sulphur dioxide (SO<sub>2</sub>) or sulphur oxide (SO) is formed, which are very toxic gases. There are also many other substances in fuels. In connection with combustion, these can react with oxygen or hydrogen and form fire gases that can be both toxic and flammable.

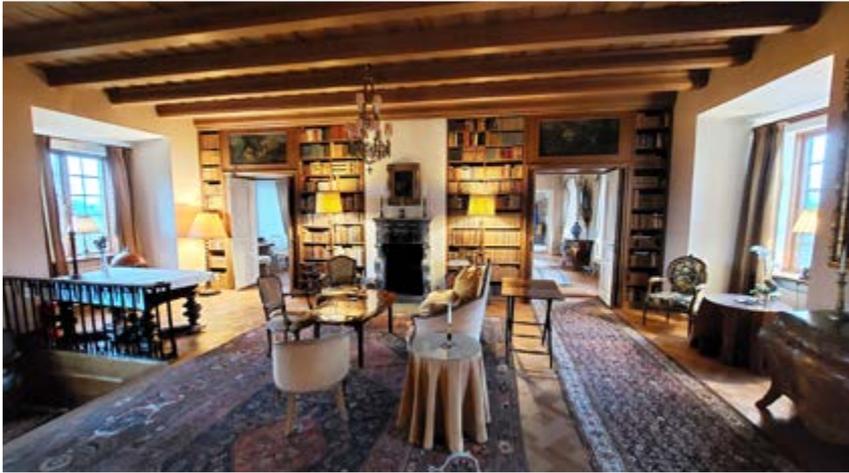
Many fuels, such as wood, also contain a large number of inorganic compounds, that is, compounds that do not contain carbon. These inorganic compounds often remain after combustion in the form of ash, but they can also contribute to the combustion process or otherwise create combustion products that are also included in the fire gases. These combustion products can also be combustible.



Fuels can be in gaseous, liquid or solid form. Photo: Stefan Svensson.

Fuels can be in gaseous, liquid or solid form, but regardless of the form the fuel is in, the fuel must be in gaseous form in order to burn. This means that a liquid must vapourise before it can catch fire. A solid material must either melt and then vapourise, such as stearin, or it must be pyrolysed, that is, exposed to heat and broken down so that flammable gases are formed from the solid. There are a few important exceptions, such as coal, which burns in the solid phase without first becoming gasified.

Over time, the fuels available in buildings and other facilities have changed in nature. What previously consisted of natural materials has increasingly come to contain plastic, both in our homes and in our workplaces. In addition, design, building materials and construction methods have changed. This affects and has changed the nature of fires in buildings over time. In a somewhat simplified way, it can be said that fires tend to develop and spread much faster today than they did in the mid-20th century. Many older buildings are not always dimensioned for the interior materials (fuels) we have today in our homes and workplaces. This can mean that fires in older buildings where modern materials burn can develop and spread faster than in newer buildings.



The fuels available in buildings have changed in nature over time and today we have a lot of plastic in our homes. Photo (top): Stefan Svensson. Photo (bottom): Johnér Bildbyrå.

Different materials have different properties, and it is not as simple as fuels being either combustible or non-combustible. Both non-combustible and combustible objects and surfaces in a room have a major impact on the development and spread of a fire, and we often use non-combustible building materials that can be greatly affected by a fire, such as steel and concrete.

Materials can be characterised by their density, thermal conductivity, heat capacity, thermal inertia and heat of combustion, among other things. Also, the shape, distribution and location of the fuel in the room or building will affect the fire.

## Density

Density is a measure of a substance's mass per unit volume. The higher the density of a substance, the greater the mass per unit volume. Density thus directly affects the weight of the substance. Sometimes the expression specific gravity is used as a synonym for density, but in scientific contexts their meanings can differ significantly. The greater the density of a substance, the heavier we perceive the substance. In most cases, we indicate density in kilograms per cubic metres,  $\text{kg/m}^3$ . Density is also described with the Greek letter  $\rho$  (rho).

**Table 4.** Examples of density for some common materials, at room temperature

Material	Density, $\rho$ [ $\text{kg/m}^3$ ]
Steel	7,820
Polypropylene	900
Wood (pine)	520
Plasterboard	720
Particleboard	600
Fiberboard	300
Polyurethane	30

For porous and powdery materials, such as sand, a distinction is made between compact density and bulk density. Compact density is the “actual” density of the material, that is, when the space between the particles is removed. Bulk density is the density of the porous material, including the voids. You also need to keep track of what is between the grains in powdery materials.

## Density

A measure of a substance's density, that is, a substance's mass per unit volume. The higher the density of a substance, the greater the mass per unit volume. Density is given in  $\text{kg/m}^3$ .

Wood and other materials that are naturally moist, that is, contain a greater or lesser amount of water, shrink when they dry or are exposed to heat, for example in a fire. For such materials, the density is affected by both the moisture content and how much the material shrinks. For wooden materials, the density is usually given as the mass of the dry substance divided by the moist volume (the volume before drying has taken place). This measurement is usually called the dry-wet density (dry material in the raw or moist volume).

Density can vary enormously between different substances. For example, iron has a density of approximately  $7,800 \text{ kg/m}^3$ , while air has a density of  $1.2 \text{ kg/m}^3$  (at  $25 \text{ }^\circ\text{C}$ ). The naturally occurring substance with the highest density is osmium,  $22,610 \text{ kg/m}^3$ . Density is affected by the temperature of the substance, since the volume changes when the temperature changes. The density of a substance affects how the substance reacts and behaves in a fire or when exposed to heat. If we look only at the property of density, a combustible material with a low density generally ignites faster than a combustible material with a high density. It also spreads fire more quickly. A material with a high density can absorb more energy than a material with low density.

Density also affects the thermal conductivity of the substance.

## Thermal conductivity

Thermal conductivity (or conductivity only) is the property of a material to conduct heat. The thermal conductivity of a material is given in watts per metre and kelvin,  $\text{W/mK}$ , and is normally described by the letter  $k$  or by the Greek letter  $\lambda$  (lambda). The lambda value of a material is also referred to as the thermal conductivity of the material.

**Table 5.** Thermal conductivity of some different materials, at room temperature

Material	Conductivity, k [W/mK]
Steel	45
Polypropylene	0.19
Wood (pine)	0.14
Plasterboard	0.25
Particleboard	0.14
Fiberboard	0.05
Polyurethane	0.034

The thermal conductivity of a substance affects how the substance reacts and behaves in a fire or when exposed to heat. For a material with high thermal conductivity, heat is conducted away more quickly so that the surface of the material heats up more slowly. This means that ignition and spread of fire in materials with high thermal conductivity generally occurs more slowly than in materials with low thermal conductivity.

### Thermal conductivity

The ability of a material to conduct heat. Also called conductivity or specific thermal conductivity. The thermal conductivity of a material is expressed in watts per meter and kelvin, W/mK, and is normally denoted by the letter k or by the Greek letter  $\lambda$  (lambda).

At the same time, a material with high thermal conductivity can conduct heat to the other side of the material, so that ignition can occur there if the material there touches a combustible material, even if the material that conducts heat is not combustible (for example, steel).

Thermal conductivity also states that the amount of heat energy that passes through a material per unit time is proportional to the area through which the heat passes. This means that the larger the area, the more heat energy can flow through. The amount of heat that is conducted through a material is also proportional to the temperature difference between the cold and hot sides. This means that the greater the temperature difference between the two sides of the material, the more heat energy can flow through. The amount of heat that is conducted through a material is also inversely proportional to the material thickness. This means that the thicker a material is, the less heat energy can flow through per unit time. For materials with high thermal conductivity, the heat flow can be greater than for a material with low thermal conductivity.

A material with high density normally also has high thermal conductivity, while low density normally means low thermal conductivity.

## Heat capacity

Heat capacity (or specific heat capacity) is a measure of the amount of energy that corresponds to a certain temperature change of an object or gas. The unit of specific heat capacity is joule per kilogram and kelvin, J/kgK, and is denoted by  $c$ . It can also be said that heat capacity indicates the ability of a substance to store thermal energy.

### Heat capacity

A measure of the amount of energy that corresponds to a certain temperature change in an object or gas. Heat capacity is given in joules per kelvin, J/K, but usually heat capacity is given per mass, J/kgK, and is then referred to as specific heat capacity. Specific heat capacity is indicated by the letter  $c$ .

The specific heat capacity of a substance describes how much energy is required to raise the temperature of one kilogram of the substance by one degree kelvin (or Celsius). The specific heat capacity of an object depends on the object's mass (density), the substances it is composed of, and the prevailing temperature and pressure.

**Table 6.** Specific heat capacity of some different materials, at room temperature

Material	Specific heat capacity, $c$ [J/kgK]
Steel	460
Polypropylene	1,900
Wood (pine)	2,850
Plasterboard	960
Particleboard	1,400
Fiberboard	2,090
Polyurethane	1,400

A material with a high heat capacity requires more energy to heat up than a material with a low heat capacity. In the event of a fire, this can mean that it takes longer for a material with a high heat capacity to ignite than a material with a low heat capacity.

### Thermal inertia, $k\rho c$

The properties of a material during ignition and fire are complex. In addition to heat capacity, thermal conductivity and density must also be considered. Normally, it is the combination of these three that is interesting in describing how a material behaves during a fire.

Different materials can have different abilities to absorb and retain heat, regardless of whether the heat transfer occurs through conduction, convection or thermal radiation. The ability of materials to absorb heat affects several stages in a fire. This ability is called heat absorption capacity or, preferably, thermal inertia. It consists of the product of the following three parameters:

- Thermal conductivity –  $k$  eller  $\lambda$  (lambda)
- density –  $\rho$  (raw)
- specific heat capacity –  $c$ .

The designation for thermal inertia is  $k\rho c$  (which is pronounced kay-raw-c). Depending on the material's thermal inertia, different materials heat up at different speeds. This affects how fire spreads in an object, in a room and in a building.

**Table 7.** Thermal inertia of some different materials

Material	Thermal inertia, $k\rho c$ [ $W^2s/m^4K^2$ ]
Steel	161,874,000
Polypropylene	324,900
Wood (pine)	207,480
Plasterboard	172,800
Particleboard	117,600
Fiberboard	31,350
Polyurethane	1,428

### Thermal inertia

The ability of a material to absorb heat. Also called thermal inertia. It is the product of the following three properties:

- thermal conductivity –  $k$  or  $\lambda$  (lambda)
- density –  $\rho$  (raw)
- specific heat capacity –  $c$ .

The designation for thermal inertia is  $k\rho c$  (which is pronounced k-raw-c). Thermal inertia is given in  $\text{W}^2\text{s}/\text{m}^4\text{K}^2$ .

Imagine a room with particleboard walls. In the middle of one of the walls is a steel column. A fire starts in the room, and both the wall and the steel column are at the same distance from the fire. The specific heat capacity of the steel column is lower than that of the particleboard and should therefore heat up faster than the particleboard. Nevertheless, it does not do this, and the steel column remains cold for quite a long time. This is because steel has a higher thermal conductivity than particleboard and heat is conducted faster into the steel than into the particleboard. Instead, the surface of the particleboard quickly heats up to its ignition temperature and can then participate in the fire. The steel column continues to heat up, but the heat is conducted away. It can therefore eventually cause ignition of combustible material on the other side of the wall or higher up in the building.

Initially, the heat is conducted away from the surface of the steel column, and it remains cold. The particle board, on the other hand, does not conduct away as much heat at the same time, even though it needs more energy for heating. It stores heat at the surface. The explanation is the difference in the thermal inertia. The density is higher for steel than for particle board. The thermal conductivity is also higher for steel than for particle board. The three properties multiplied by each other ( $k\rho c$ ), give a significantly higher value for steel columns than for particle board.



In a steel container, which is often used in fire service exercises, fire spreads in different ways than in a real furnished room, because the thermal inertia of walls and ceiling is different. Photo: Stefan Svensson.

Materials with low thermal inertia absorb little heat. The heat is not conducted into the material but stays at the surface, that is why they feel warm to the touch. The surface heats up quickly, and the material burns well, provided that it is combustible. Metals generally have a higher thermal inertia; the heat is conducted away from the surface and they therefore feel colder. The surface remains cold for a long time and the material burns poorly.

For a combustible material, the higher the thermal inertia, the longer it takes to heat up the surface. This affects how fire spreads in the material: flame spread over the surface is slower. The faster the surface heats up, the faster the flame spread and the faster the fire spreads in the room. The thickness of the material also affects heating. A thinner material heats up faster than a thick one, because there is a smaller amount of mass to be heated.

## Heat of combustion

Heat of combustion is a term that indicates how much energy can be developed when burning a certain amount of a fuel. This is also called the calorific value of the fuel. In connection with combustion and fire, it is used to indicate the potential energy of the substance, in the form of chemically bound energy. Heat of combustion is an important property of fuels, as it indicates their energy content, and can vary greatly between different fuels.

The heat of combustion of a fuel tells us how much potential energy the material “contains” per unit weight. It is given in joules per kilogram, J/kg, or more often in MJ/kg (million joules per kg) because the amount of potential energy is often very large.

For example, wood has a heat of combustion of approximately 16–20 MJ/kg, while acetone has 30 MJ/kg and polypropylene 43 MJ/kg. The fact that wood has a range, unlike many other fuels, is partly because wood is not a homogeneous material (it consists of several different substances), and partly because the heat of combustion varies between different types of wood. In addition, wood can have different amounts of moisture in it, which also affects the heat of combustion.

**Table 8.** Examples of heat of combustion for some different materials

Material	Heat of combustion [MJ/kg]
Wood	16–20
Cellulosic materials (cotton, paper, paper, etc.)	20
Polyvinyl chloride (PVC)	20
Ethanol	30
Polyester	30
Rubber tires	32
Polypropylene	43
Petrol	45

The heat of combustion of a material affects the amount of energy that is developed in a fire, and thus also the fire's rate of heat release. In general, it can be said that materials with a high heat of combustion also provide a high rate of heat release, but not necessarily. It should be noted, however, that in a fire, not all of the energy specified by the heat of combustion is released, normally only 70–80 percent with good access to air. The rest of the energy remains in the residual products or is released as unburned gases. In fire gases, there can thus be a lot of potential energy left, which contributes to the combustibility of the fire gases and consequently also to the spread of the fire.

### Heat of combustion, $\Delta H_c$

A measure of how much energy a material can theoretically release when it burns, that is, how much energy the material “contains.” The unit is MJ/kg or kJ/g.

Natural materials often have a heat of combustion of around 15 – 20 MJ/kg. For many synthetic materials, i.e., plastics of various types, the heat of combustion is around 35 – 40 MJ/kg. This means that many modern interior materials have much more energy content compared to the natural materials that were more common as interior materials in the past.

When there is more energy that can be released, the fire progresses faster. Over the past half century, the time to flashover in a normal room has decreased from around half an hour to just a few minutes. The trend continues. In a battery, the energy is stored even more densely, and the fire progression in a battery fire can proceed even faster. Fires in larger batteries have been shown to be able to cause a room fire to flashover in as little as a fraction of a minute.

Consequently, more energy is released in a fire in modern materials than in older materials at the same time, which means that the development and spread of fires in buildings is often faster today. In addition, fire gases from modern materials often have higher flammability, meaning they can be relatively flammable and thus spread fire both further and faster.

The building regulations are based on the energy content of building materials when dimensioning fire protection. The concept used is "fire load", which means fire energy per floor area within a certain space, in MJ/m<sup>2</sup>.

### **Unburned gases**

Pyrolysis gases that have not been burned. The poorer the oxygen supply, the more unburned fire gases are formed. The unburned gases contain potential energy that can be released at a later stage and cause a temperature increase.

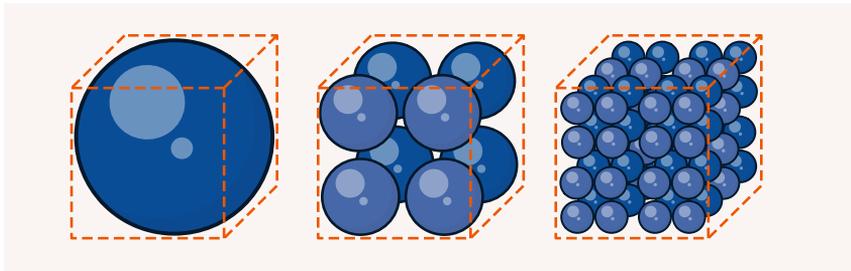
The heat of combustion is actually a rather poor measure of how “flammable” a substance or material is, but it can give us an idea of the energy that can potentially be developed in a fire and thus also how this can affect, for example, a building. A building that contains materials with a high heat of combustion has, for example, the potential to create fire gases that are

more energy-rich than a building where the heat of combustion is lower, and fire gases that contain more energy increase the risk of fire spreading. However, the heat of combustion does not actually say anything about how flammable or combustible the material or fire gases are.

## Fuel distribution

How the fuel is distributed also affects how fires develop and spread. Distribution here refers to whether the fuel is in gaseous form, as liquid particles or as solid particles. The smaller a droplet or particle is, the larger the particle's surface area will be in relation to its volume, and the smaller a particle is, the less it weighs. If we atomise a certain amount of a material, smaller droplets or particles will give us larger surfaces, which provides increased opportunities for exposure to, for example, heat.

**Figure 35.** Small particles have a larger surface area relative to their volume than large particles



A small particle heats up faster than a large one, and it therefore gasifies or pyrolyses faster. In addition, the reaction surface becomes larger, that is, the surface that, for example, the oxygen in the air has access to becomes larger. Small combustible particles ignite and burn faster than large ones. Gases burn the fastest, where the molecules are “separately”.

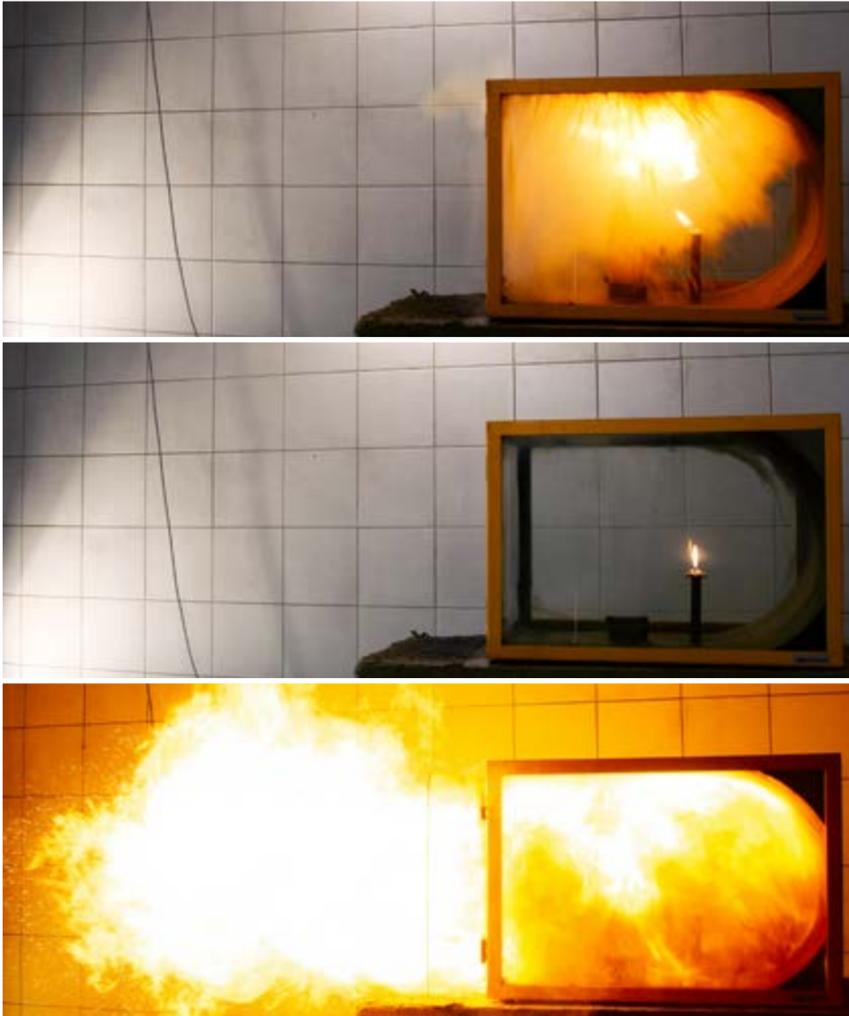
This can mean that, for example, a solid material that is difficult to ignite or even non-combustible can become combustible if it is finely divided enough, that is, the material is made into very small particles. An example might be that iron in the form of steel wool is combustible. Even an oil with low flammability, such as hydraulic oil, becomes highly flammable when it is atomized and, in spray form, hits a surface that is hotter than the ignition temperature.



Metal is also flammable, especially if it is finely divided. Photo: Stefan Svensson.

Finely divided fuel, even materials that are normally considered non-combustible, can cause problems, for example in the form of dust explosions. Dust explosions can have a devastating effect and lead to both personal injury and major material damage. They can occur when a combustible dust or powder swirls up and forms a dust cloud, which is then ignited by, for example, a spark, a flame or a hot surface.

Flammable materials, both solids and liquids and gases, often have distinct characteristics in relation to fire. When it comes to dust and other finely divided fuels, it is not so simple. Most organic materials such as wood, flour, sugar, dye and plastic can create an explosive atmosphere, as can some inorganic materials such as metals. A very finely divided fuel burns in almost the same way as a combustible gas.



Dust explosions can occur when finely divided and often airborne material ignites.  
Photo: Stefan Svensson.

In the industry, large quantities of materials are handled that, when finely divided, can cause dust explosions. Examples of such materials are wood, flour, sugar, paint, plastic and metals. People who handle metal dust are often unaware that metal dust can be flammable or become so finely divided that it can cause a dust explosion.

The activities where there is the highest risk of dust explosions include:

- sawmills – drying and sawing of wood
- carpentry factories, furniture factories – wood dust
- heating plants – pellet burning
- industrial painting – sanding and blasting produce paint residue and dust
- powder coating – paint powder that is applied to metal surfaces using static electricity and burned in ovens.

But the fuel does not have to be very small particles for the ratio between surface area and volume (and weight) to change. An example is when we are going to light a fire in a stove. It makes it easier if we divide the firewood into smaller pieces so that more surface area is exposed to the heat from the flame. In addition, smaller pieces of fuel heat up faster, which makes it easier to ignite.

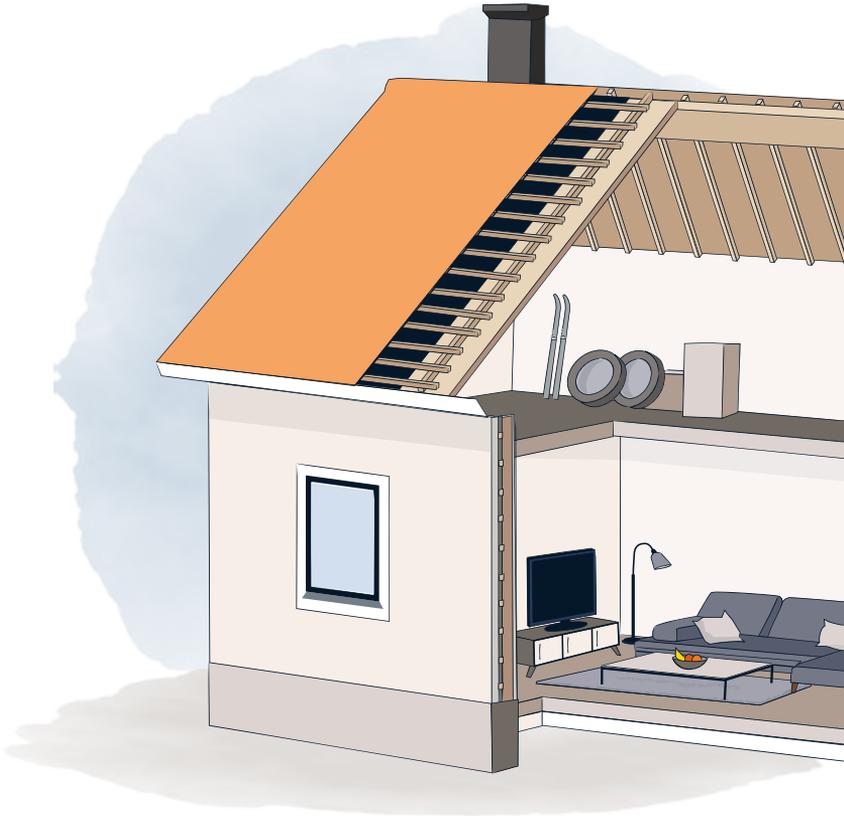
How the fuel is distributed also involves how objects are placed in a room, in relation to surrounding walls and ceiling surfaces. This aspect of fuel distribution will be discussed later.

## **Other material properties**

In buildings, we use a variety of different types of materials, for different things. A lot of it is furniture and other furnishings that we take with us when we move in or out of the building, as well as clothes and other items that we have in our homes. Many of these items and materials act as fuel in a fire.

But the building itself often consists of fuel or materials that are not necessarily flammable but are still affected when the building is on fire. We then talk about building materials or structural materials. Examples of such materials are brick, concrete and steel. When energy is supplied to these materials, the molecular movement in the materials increases, the load-bearing capacity changes and the materials can also deform.

**Figure 36.** Both the interior and the building itself normally consist of a variety of combustible materials



The load-bearing capacity of a material is about how much weight the material can support. How a material deforms is about how the material changes shape when exposed to heat.

The time it takes from the start of heating until the material properties change throughout the material depends on the material's thermal conductivity and heat capacity. The change is faster in metals and slower in poor thermal conductors such as wood and concrete.

The different properties of a material often affect each other. For example, the load-bearing capacity decreases if a material deforms and becomes more brittle.

## Load-bearing capacity

In general, the strength of all materials decreases when exposed to high temperatures. Reduced load-bearing capacity can then lead to local collapse, progressive collapse or the collapse of an entire building. How far this goes depends on, among other things, how long a fire has been going on, how it spreads, how big it is, how high the temperature is or has been and, not least, what materials the building is made of.

Steel materials are very sensitive to heat. At around 500 °C, steel loses about half of its strength. At this temperature, steel can only support half the load it can support at room temperature. At around 700 °C, the load-bearing capacity is almost non-existent; then the steel cannot even support its own weight, even though steel does not melt until a much higher temperature. At the same time, the dimensions of the material of course affect how quickly it heats up. Just because the surface is very hot, it does not necessarily mean that the entire material has the same temperature. The thermal conductivity of the material thus affects its load-bearing capacity.

The load-bearing capacity at different temperatures varies for different metals. Light metals, such as aluminum, lose most of their load-bearing capacity already at 400 °C.



Steel loses half of its strength at around 500 °C. Photo: Stefan Svensson.

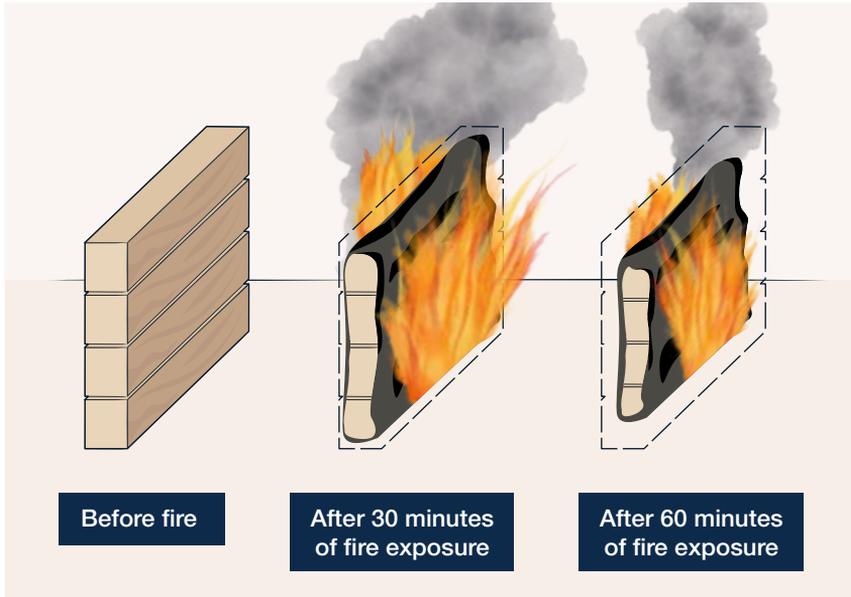
In the metal industry, steel as well as other metals are sometimes heat treated to increase strength, known as hardening. This usually requires that both heating and cooling occur in a controlled manner and within certain temperature ranges.

Ceramic materials, stone materials, concrete and glass often crack when exposed to high temperatures, and then have a reduced strength. The cracking is due to the low tensile strength of these materials. When one side is heated, it expands. If the other side is cold, the expansion creates a stress in the material that can cause it to crack. The same thing happens if a material is heated and cooled quickly. It then shrinks, which can lead to cracking. However, there are also ceramic materials that resist high temperatures. The problem with many materials is often the joints, where movements occur so that cracks occur and the strength decreases. The same can be true with a brick wall. The bricks are fired at high temperatures and therefore resist fire quite well, while the joints have much lower strength.

Concrete retains approximately 75 percent of its strength at 500 °C and approximately 25–50 percent at 800 °C. Note that the thermal inertia will also affect the strength. So even if the temperature in a burning room is above 800 °C, this does not necessarily mean that the concrete in the walls will lose strength, as it will take a certain amount of time to heat up the concrete. The same applies to other construction materials. Heating a material takes time, which affects the strength. The strength of concrete is also affected by so-called spalling, which is the gradual peeling and pushing away of the concrete surface, largely due to the moisture content and movement (expansion) of the concrete. Or spalling occurs because the underlying iron reinforcement is heated. Iron expands more from heat than concrete and can then spall off the entire cover layer.

Wooden structures are reduced in size through combustion and carbon growth, meaning that the wood in, for example, a beam is gradually burned and the beam becomes weaker. A reduced cross-section means reduced durability and thus a weaker wooden beam. However, wooden structures exposed to heat are a complex area because there is also a certain amount of heat conduction into the material. This also affects the strength, in addition to the cross-section decreasing. In addition, wooden structures are combustible, and can thus contribute to the course of the fire. Also, composite wooden structures can fall apart and expose new or more wood surface, which also affects the course of the fire.

**Figure 37.** Wood loses strength mainly because the cross-sectional area becomes smaller when the wood burns



When wood burns, the material pyrolyzes and is burned. Solid material gradually disappears and the cross-sectional area becomes smaller.

Plastic materials can be affected by both low and high temperatures, but this varies greatly between different types of plastic. The type of plastic that is included in the group of thermoplastics is normally very affected by heat. Several thermoplastics melt at fairly low temperatures (around 110 °C), and after prolonged exposure to heat they can melt as low as 80 °C. Polyethylene and polypropylene, two very common plastics, are thermoplastics. Heat radiation from a fire can cause plastic objects at a relatively large distance from the fire to soften or melt without directly participating in the fire. The low melting point can also cause thermoplastics to melt and participate in the fire in the form of a liquid. This poses a risk of further spread, as the melted and possibly burning plastic can flow away over long distances. Some thermoplastics behave in principle like flammable liquids, that is, they melt and then evaporate and burn. A product with similar properties is roofing felt, where bitumen can melt, flow away and spread the fire in the event of a fire. Bitumen is a binder made from crude oil. Thermoplastics can also pyrolyse after they melt, contributing to the build-up of flammable gases inside a space.



Thermoplastics can melt, start to burn and flow long distances, thereby contributing to the spread of fire. Photo: Stefan Svensson.

Another type of plastic is thermoset plastics. These do not normally melt but pyrolyse and char, much like wood. The breakdown of thermoset plastics due to heat occurs through decomposition without prior softening. For several types of thermoset plastics, the tensile strength drops to 50 percent of the original at 70–200 °C. Thermoset plastics are often used together with some form of reinforcement, such as glass fibre or carbon fibre, which, of course, affects the strength in the event of a fire. Such reinforcement also affects the thermal inertia of the plastic. In the event of a fire, the plastic reinforcement can give rise to hazardous dust with very small particles. The reinforcement can also be flammable, which means that it participates in the fire process if exposed.

## Deformation

Deformation means a change in the shape or size of a material. One reason may be that the material is exposed to a high load, that is, that it supports a lot of weight. When materials are exposed to elevated temperatures, their properties change so that they can deform in different ways than at room temperature. In general, it can be said that materials become less brittle at elevated temperatures, but there are important exceptions such as concrete and plaster. This means, for example, that a steel beam does not break in the same way as at room temperature, but rather bends.



Deformation of beams that have been exposed to high temperatures. Photo: Johnér Bildbyrå.

All materials weigh something and can therefore deform even if they do not support any additional load. If deformation persists after unloading, this is called plastic deformation. If, on the other hand, the material regains its shape after unloading, this is called elastic deformation. In a fire situation, most materials deform plastically.

One type of deformation that can be of great importance in a fire is expansion. Almost all materials expand when the temperature increases, but the amount of expansion varies greatly between different materials. The ability of a material to expand can be described by a coefficient of thermal expansion (or simply coefficient of expansion), which indicates the relative change in length at a certain temperature change. The unit for the coefficient of thermal expansion is metres per metre and kelvin,  $\text{m/m/K}$ . For practical reasons, however,  $\text{mm/m/}^\circ\text{C}$  is most often used, i.e., millimetres per metre and  $^\circ\text{C}$ , i.e., how many millimetres the material expands per metre of its length and for each  $^\circ\text{C}$  change in temperature. Coefficient of thermal expansion is denoted by  $\alpha$  (alpha).

The coefficient of thermal expansion also varies with temperature.

**Table 9.** Examples of materials and their coefficient of linear expansion

Material	$10^{-3}$ mm/m/K
Aluminum	23
Concrete (dry)	9–14
Glass	3–10
Gold	14
Ice	50
Iron	11–20
Carbon (graphite)	2
Copper	17
Magnesium	26
Plexiglass	70–100
Porcelain	2–5
Stainless steel	18
Silver	19
Wood (along the grain)	5–9

The value shows how many millimeters a material expands per kelvin and per meter of length of the material.

### Coefficient of linear expansion

A measure of how much a material expands when heated.  
The unit is usually mm/m/K.

For some materials, the coefficient of linear expansion is different in different directions. This applies to composite materials and other so-called anisotropic materials, i.e., materials that have different properties in different directions, such as composite materials (composite materials).

Almost all materials have a positive coefficient of expansion, i.e., they expand if the temperature increases. An important exception is water, the volume of which decreases between freezing point and 4 °C. Water's density is thus greatest at 4 °C.

In the event of a fire, the linear expansion of a material can affect, among other things, the strength of a building. For example, a steel beam that becomes longer may well push away other building parts and thereby cause a collapse.

The relative volume change is given by the coefficient of volumetric expansion, which is approximately three times the coefficient of linear expansion. The unit of volumetric expansion is, therefore, cubic metres per cubic metre and kelvin,  $\text{m}^3/\text{m}^3/\text{K}$ .

## Combustion efficiency

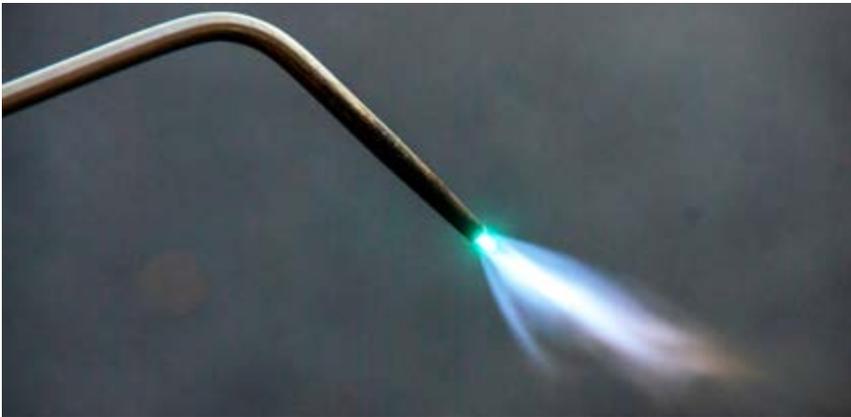
Combustion efficiency is a measure of how efficient a combustion is, i.e., how efficiently a fuel is consumed or how efficient the chemical reaction is. In a fire, combustion efficiency is rarely complete, i.e., it is not 100 percent. In a fire, therefore, a large amount of unburned substances is often formed.

### Combustion efficiency

A substance that burns rarely releases all its energy even if the oxygen supply is good. Some of the energy remains chemically bound in the form of unburned products. The poorer the oxygen supply, the more unburned gases are produced. The combustion efficiency is denoted by  $\chi$  and is given as a percentage of the total amount of available potential energy, from 1–0.

In a welding flame, the aim is to achieve as complete combustion as possible, so that the flame temperature is as high as possible. This can be achieved by adjusting the mixture between fuel gas (acetylene) and oxygen so that a so-called stoichiometric mixture is obtained, i.e., a “perfect” mixture between the gases, where the atoms are equal in the chemical reactions that take place.

Incineration plants are also designed to achieve the highest possible combustion efficiency. In such a plant, we want to be able to achieve the most efficient combustion process possible, for economic reasons but also for environmental reasons. The end product should ideally be carbon dioxide, water and solid residues that can be easily disposed of, often metal oxides.



In a welding flame, you want complete combustion, so that the temperature is as high as possible. Photo: Stefan Svensson.

When burning in a candle with free access to the oxygen in the air, the combustion efficiency is approximately 0.7, which means that approximately 70 percent of the chemically bound energy is released. For a fire in a sofa in a room fire, the combustion efficiency can be significantly lower, since the air supply as well as the surrounding surfaces and materials affect the combustion.

The fact that chemically bound energy has not been released means that it remains partly in the fire residues but above all in the fire gases. Fire gases are therefore fuel.

Combustion efficiency is usually indicated by the Greek letter  $\chi$  (pronounced "chi") and is dimensionless, meaning it has no unit.

## Flammability limits and flammability range

For something to burn (or be burned), fuel, oxygen and heat are required. The fuel must normally be in gaseous form in order to mix with the oxygen in the air, and for the fuel to become gaseous, it must either be pyrolysed or gasified.

In order for a mixture of fuel gas and oxygen to burn, the concentration of each gas must also be within certain limits, known as the flammability limits. If the mixture is outside these limits, combustion cannot occur. The mixture must simply be "just right". The lower flammability limit describes the minimum concentration of fuel gas required for ignition. Correspondingly, the upper flammability limit tells us how high the concentration of fuel gas can be to produce a combustible mixture. The area between the lower and upper flammability limits is called the flammability range. Flammability limits and flammability range are applicable to premixed flames. These concepts are only exceptionally applicable to fires in buildings.

**Table 10.** Flammability range for some different flammable gases

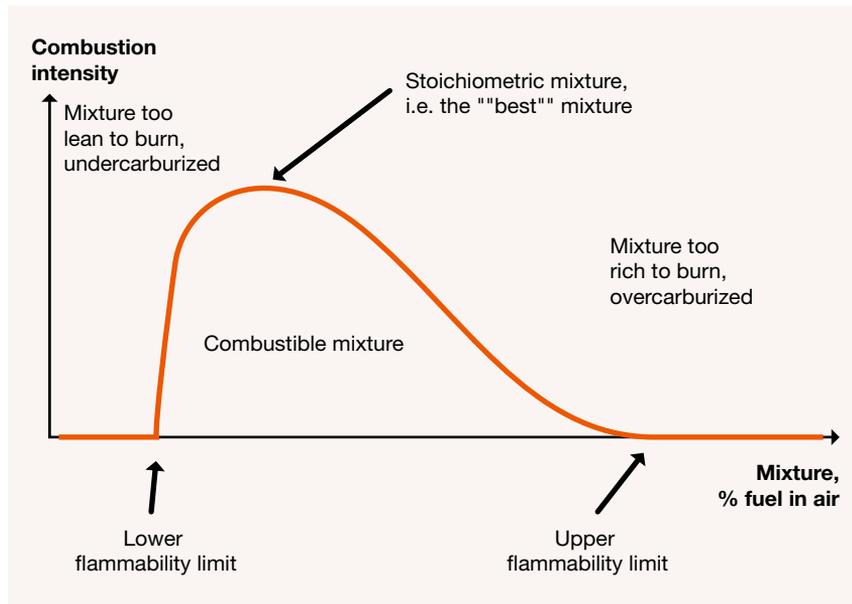
Substance	Lower limit (vol %)	Upper limit (vol %)
Carbon monoxide (CO)	11	74
Ethanol (vapors of $C_2H_5OH$ )	3.1	19
Ethylene oxide ( $C_2H_4O$ )	2.6	100
Hydrogen ( $H_2$ )	4	77
LPG (95 % propane, 5 % buthane)	2	10
Natural gas (mainly $CH_4$ )	4	15
Vapors of petrol	1	8

If the gas mixture is below the lower flammability limit, the mixture is said to be too lean. If the gas mixture is above the upper flammability limit, the mixture is said to be too rich. If the mixture is “perfect,” that is, ideal for combustion, the mixture is said to be stoichiometric.

## Stoichiometry

A condition where there is just enough oxygen to completely burn the fuel. Can also be called an ideal mixture.

**Figure 38.** Lean, rich and stoichiometric mixture



The size of the flammability range depends on both the substance and the temperature, and varies considerably depending on the substance in question.

At higher temperatures, the lower flammability limit drops, and the flammability range becomes larger. Less energy is then required for the gas to ignite and burn with a flame. This also means that a smaller amount of fuel is needed for combustion to continue at the lower flammability limit.

Most hydrocarbons, i.e., various chemical compounds where carbon and hydrogen are the main ingredients, have a lower flammability limit of around 1–5 volume percent and an upper limit of 5–20 volume percent. For the vast majority, the lower limit is around 5 volume percent, which corresponds to around 50 g/m<sup>3</sup>. The upper limit, however, varies greatly depending on the hydrocarbon.

There are other substances with a much larger flammability range. Hydrogen and carbon monoxide are the clearest examples – around 4–77 volume percent and around 11–74 volume percent, respectively. Hydrocarbons with chemically bound oxygen also have a larger flammability range than hydrocarbons that do not have chemically bound oxygen.

### **Flammability range**

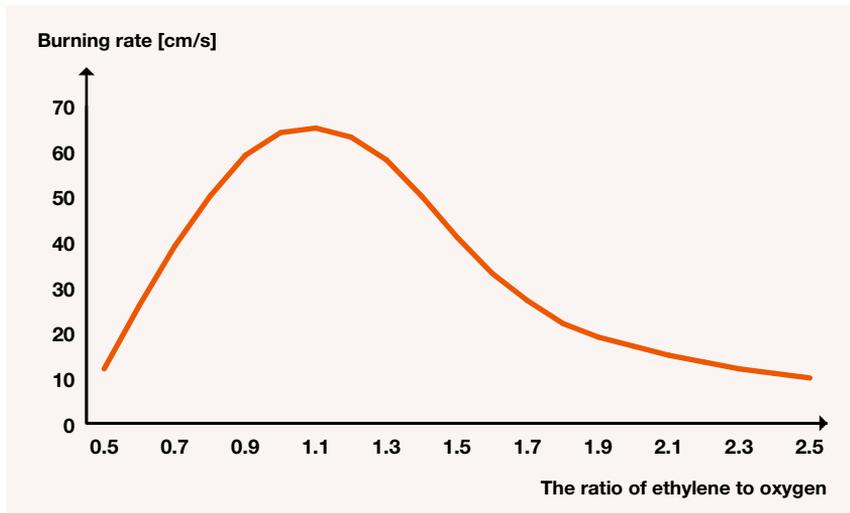
The concentration at which a gas and air mixture can ignite. The flammability range is limited by the lower and upper flammability limits of the gas.

The principles of flammability limits also apply to gas mixtures. However, it is more difficult to specify the flammability range for gas mixtures, as it varies depending on the mixing ratio. One can also speak of flammability limits for mixtures of dust and air.

Fire gases also have a flammability range. However, for fire gases, it is practically impossible to specify limit values for the flammability range, since fire gases in the vast majority of cases consist of both several different substances and unknown concentrations of these substances. The particles that are normally present in fire gases also affect the flammability range. In addition, the temperature of the fire gases that are formed varies greatly. In some cases, the flammability range is larger,

in other cases smaller, depending, for example, on whether the particles are combustible or not, their size and their quantity. There are also no practical possibilities to measure the content of fire gases in the event of a fire in a building. Fire gases can also have different compositions in different parts of a building.

**Figure 39.** The combustion rate changes with the concentration of combustible gas



Stoichiometric mixtures give the highest combustion rate, meaning that the chemical reactions occur fastest when the mixture is ideal.

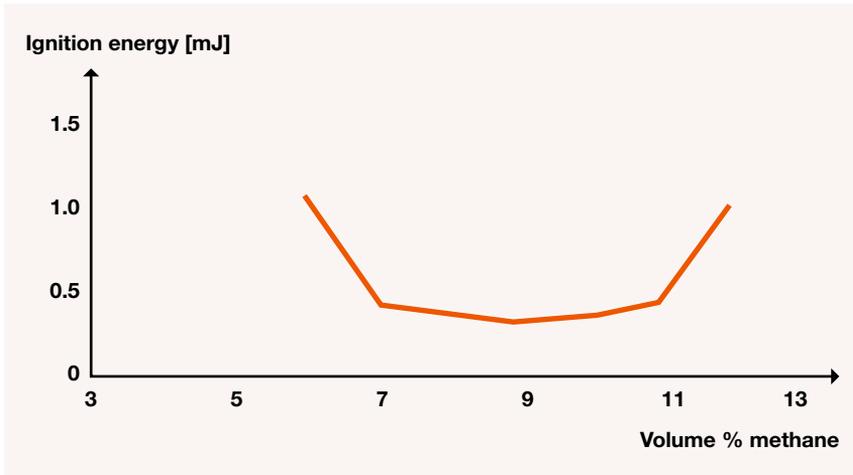
## Ignition energy

In addition to requiring a mixture of combustible gases and air that is within the flammability range, an ignition source that can supply a certain minimum amount of energy is also required. The energy required for ignition is called the ignition energy or activation energy.

At stoichiometry, the ignition energy is lowest, since there is then no excess air or fuel that needs to be heated.. At the lower flammability limit, the energy is also used to heat excess air. At the upper flammability limit, the energy is also used to heat excess fuel. Therefore, near the flammability limits, the ignition energy increases.

In some cases, a small spark from, for example, a switch can be enough to ignite a gas mixture. However, to ignite fire gases, more ignition energy is normally required than that.

**Figure 40.** The ignition energy of a gas mixture is lowest at a stoichiometric mixture



Another type of ignition is spontaneous ignition, also called self-ignition. In this case, the combustible substance, for example a gas mixture, ignites without the addition of heat from, for example, a spark or flame. For the same substance, the self-ignition temperature is always higher than the ignition temperature when ignited by forced ignition with, for example, a flame. Self-ignition usually occurs at temperatures between 500 and 600 °C. However, it is rare for gases to self-ignite in real situations, as this requires a correct mixing ratio.

When it comes to the ignition of fire gases, it can often be difficult in practical contexts to determine whether the fire gases ignite spontaneously or through an ignition source. This can be the case, for example, if we open a door to a fire room and a large amount of fire gases flows out and ignites. It may then appear that the fire gases ignite spontaneously due to high temperatures and contact with the oxygen in the air, but it could just as well be that there is an ignition source just inside the door.

## Mass loss rate

During combustion and fire, a number of chemical reactions take place. The chemically bound energy in the fuel is converted into heat and light and into other chemically bound energy in the combustion products. As a consequence of these chemical reactions, the fuel is converted so that some of it is released as combustion products in gaseous, liquid or solid form while some of it becomes a remaining residue. Consequently, the mass of the initial fuel changes during combustion, and some of the fuel mass is converted (through evaporation or pyrolysis) into gas that is completely or partially burned.

### Mass loss rate

The rate at which a substance evaporates or pyrolysis occurs from a material. Mass loss rate is given in  $\text{g/m}^2\text{s}$ .

This change in the mass of the fuel during a fire is called mass loss rate. It can be stated as mass flow per unit of time, normally in kilograms per second,  $\text{kg/s}$ , or grams per second,  $\text{g/s}$ . However, it is most often stated as mass flow per unit of area and per unit of time: kilograms or grams per square metre and second,  $\text{kg/m}^2\text{s}$  or  $\text{g/m}^2\text{s}$ . In particular, for flammable liquids, the mass loss rate can be assumed to be a property of a material, although the size and shape of the vessel also have an effect. There is a lot of research on this, and in calculations it is possible to compensate for the size and shape of the vessel. However, the larger the vessel, the less important it is for the mass loss rate.

Sometimes a distinction is also made between burning rate and mass loss rate, since not all of the fuel normally participates in the combustion, even if the mass is converted, for example, from solid to gaseous form. For fuels that burn with unlimited access to air, however, mass loss rate and burning rate can be assumed to be synonymous.

**Table 11.** Mass loss rate for some different types of liquids and materials

Substance	Mass loss rate [g/m <sup>2</sup> s]
Ethanol	15
Methanol	17
Polypropylene	18
Polystyrene	34
Kerosene	39
Acetone	41
Petrol	55

The size of the mass loss rate, that is, how quickly a fuel decreases in weight during combustion, depends partly on the material. It is thus a material property, but the mass loss rate also depends on surrounding factors. If the fire is in a room, the thermal radiation from ceiling and wall surfaces will increase the mass loss rate. The number of openings in the room and their size can also affect the mass loss rate. Fewer or smaller openings mean that the airflow to the fire is reduced, and that a larger proportion of the energy released remains in the room, which means that the mass loss rate can increase. A fire in a room is thus a fairly complex phenomenon, where both the properties of the fuel and the geometry and other properties of the room have an impact. The thermal inertia of the surfaces in the room is an example of such properties that can affect the fire.

## Rate of heat release

The amount of energy released over a period in time is called rate of heat release or heat release rate. Rate of heat release is expressed in joules per second (J/s) or watts (W). We recognize this, for example, from lighting where the "size" of a lamp is described in watts. Note that brightness is measured in candela and luminous flux in lumens. In this case, it is about how much energy per unit of time (joules per second) the lightbulb consumes. Anyone who has ever bought a lamp for their home probably knows approximately how much light a lamp marked 20 W provides. In the context of fire, 1 joule per second (1 W) is a very small amount of released energy. We therefore usually instead state rate of heat release in thousands or even millions, that is, in kilowatts (kW) or megawatts (MW). A thousand joules per second is thus the same as 1 kW (a thousand watts), and a million joules per second is correspondingly 1MW (one million watts).

### Rate of heat release

The heat generated when a material is burning. The heat generated is measured in watts (J/s). Rate of heat release is denoted by  $\dot{q}$ . Also expressed as heat release rate.

The amount of heat a fire generates is called its heat release rate. It is difficult to say exactly how large the heat release rate is in a specific fire, since most fires are not constant but change in size over time. However, it is possible to give some simple guidelines so that one can get an idea of how large the heat release rate is for a certain size of fire. Note that when specifying heat release rate for a fire in this way, it is normally the maximum heat output that is referred to. For liquids, it is primarily the size of the surface that determines rate of heat release. The larger the liquid surface, the greater the rate of heat release. If the surface of the liquid is constant, the rate of heat release is also constant. Even for solid materials, the size of the surface will affect the rate of heat release.

**Table 12.** Examples of maximum rate of heat release of different materials and objects

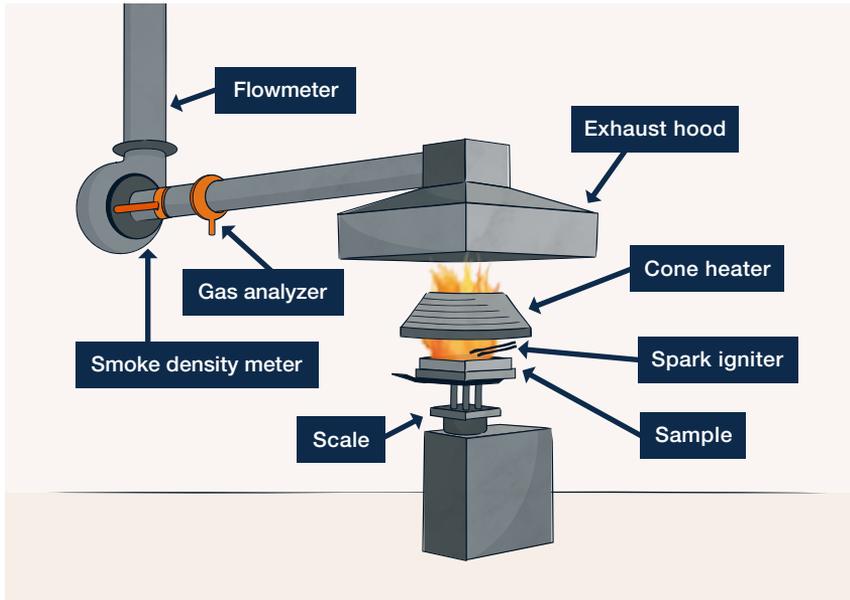
Object/fuel	Maximum rate of heat release
Led lamp	1–10 W
Light bulb	40–100 W
Wastebasket	40–100 kW
Chair with seat cushion	200–500 kW
Armchair with upholstery	500–1,500 kW
Sofa with upholstery	1,000–3,000 kW
1 m <sup>2</sup> gasoline fire	2.5 MW
3 m high stack of wooden pallets	7 MW
2 m <sup>2</sup> plastic cups, 4.9 m high	30–40 MW

The rate of heat release that can be specified for certain types of objects applies provided that the object burns freely with free access to air. If the object burns inside a room, the rate of heat release is also affected by, among other things, the location in the room, the size of the room, whether there are other objects in the room and, not least, how many and large openings there are to the room.

The rate of heat release from a fire is always difficult to assess, and we cannot measure it during a firefighting operation. However, if one can somewhat estimate how large the rate of heat release is, one can in some cases also make a rough assessment of, for example, how much extinguishing water is needed or how large exhaust air openings are needed for fire ventilation.

The rate of heat release in fire tests can be measured either by measuring the mass loss rate with a scale or by measuring how much oxygen the fire has consumed. The energy developed per kilogram of oxygen consumed is approximately the same for most fuels, 13 MJ/kg.

**Figure 41.** Measurement of heat release rate can be done in a laboratory using a so-called cone calorimeter



The energy developed per kilogram of oxygen is approximately the same for most fuels, approximately 13 MJ/kg. The combustion gases are collected in the cone calorimeter, the oxygen content and the amount of combustion gases are measured. From this, the rate of heat release can be calculated. The time to ignition and mass loss rate are also measured. In addition, the amount of soot formed and other types of gases, such as carbon dioxide, can be measured.

## Temperature

Most of us are used to measuring temperature, for example, so that we know how to dress when we go outside, but temperature is more complex than it seems at first glance. Heat and temperature should not be confused. The difference is that heat is a quantity of energy, while temperature is a state, a measure of heating or a level achieved through heating. In addition, perceived temperature can differ significantly from actual temperature, since factors such as wind and humidity have a large impact. For example, a sauna where the temperature is 80 °C and the humidity is 40 percent can be experienced as much hotter than a sauna where the temperature is 100 °C and the humidity is only 10 percent.

Temperature is a measure of how much and how quickly something heats up or cools down, that is, in principle, a measure of the speed of movement of atoms and molecules. When heat energy is added to a substance, the speed of movement of atoms and molecules increases and the temperature rises (temperature is a measure of heating or a level achieved by heating). If the heat is removed for some reason, the speed of movement decreases and the temperature drops.

The lowest possible temperature means that no movement occurs in the molecules. This occurs at  $-273\text{ }^{\circ}\text{C}$  (absolute zero), which is the starting point for the absolute temperature scale given in kelvin (K). Scale divisions in the kelvin scale are the same size as in the Celsius scale, and a degree difference in Celsius is the same size as a degree difference in kelvin. Conversion from  $^{\circ}\text{C}$  to kelvin is then  $T_{\text{kelvin}} = T_{\text{Celsius}} + 273$ .

In England and the USA, the temperature scale is used according to Fahrenheit ( $^{\circ}\text{F}$ ). Each  $^{\circ}\text{F}$  is approximately twice  $^{\circ}\text{C}$ . The freezing point is  $0\text{ }^{\circ}\text{C} = 32\text{ }^{\circ}\text{F}$  and the boiling point is  $100\text{ }^{\circ}\text{C} = 212\text{ }^{\circ}\text{F}$ . A conversion can be done using these formulas:

$$^{\circ}\text{F} = 1.8 * ^{\circ}\text{C} + 32$$

$$^{\circ}\text{C} = 0.55 * ^{\circ}\text{F} - 32$$

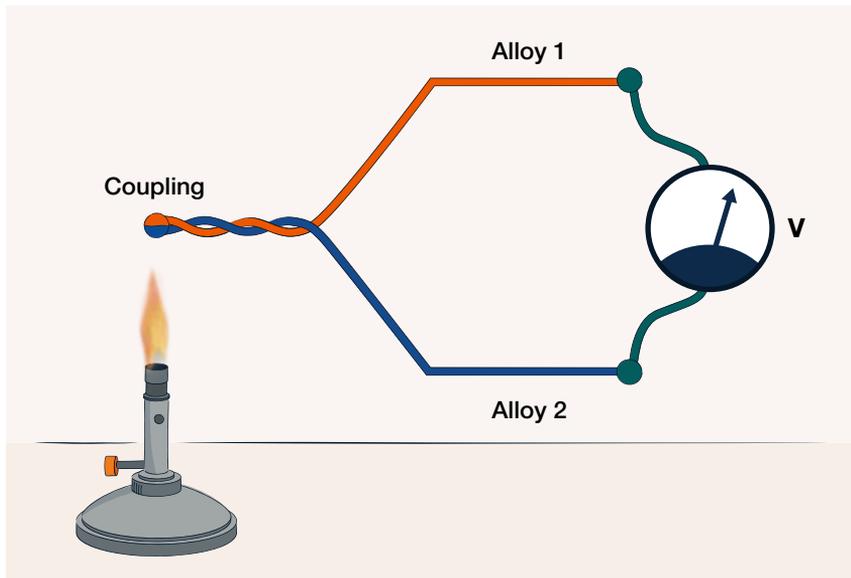
**Table 13.** Conversion between different measures of temperature

	Kelvin, K	Celsius, $^{\circ}\text{C}$	Fahrenheit, $^{\circ}\text{F}$
Absolute zero	0	-273.15	-459.67
The freezing point of water	273.15	0	32
Human body temperature	310.15	37	98.6
Boiling point of water	373.15	100	212

Measuring temperature is based on the zeroth law of thermodynamics. It states that two bodies in thermal contact with each other assume the same temperature because heat energy in the warmer body flows to the cooler body.

Measuring temperature can be perceived as easy, but it can be difficult to know what you have measured or to get measurements that are relevant. For example, if you use a regular thermometer to measure the air temperature in a room, it is not actually the temperature of the air that you are measuring, but the temperature of the thermometer. A thermometer also has the properties described earlier, such as density, thermal conductivity and heat capacity. In addition, the heat transfer coefficient is affected by whether it is natural or forced convection and whether the heat transfer occurs by conduction between two materials. For a regular outdoor thermometer, this is of very little importance. However, for measurements in a fire context, where the temperature can vary by several hundred degrees in a few seconds, the measuring equipment has a very large impact on the accuracy of the result.

**Figure 42.** When measuring temperature in a fire context, so-called thermocouples are used



A thermocouple consists of two interconnected wires of different metal alloys. In the junction, a small electromotive force, a voltage, is created, which is temperature dependent. This is called the Seebeck effect.

# Chapter 6

# Fire and flames

Combustion of most gases, liquids and solids occurs by flame combustion in the gas phase. Some solid materials, such as coal, can be burned in the solid phase in air. In a few substances, especially explosives, fuel and oxidiser are already present together. Such substances are completely burned in the solid phase.

A combustion process can be divided into flaming combustion and smouldering fire. Flaming combustion (also called homogeneous oxidation or homogeneous combustion) occurs when both fuel and oxidiser are in the gas phase. In most fires, the oxygen in the air is the oxidiser while pyrolysis gases are the fuel. An example of such combustion is the candle. Gasified wax from the candle breaks down and burns with a luminous flame, where the fuel mixes with the oxygen in the air.

Smouldering fire (which can also be called heterogeneous oxidation or heterogeneous combustion) occurs at the surface of a solid-phase fuel. The most common example is charcoal which we use for barbeque, which is in the solid phase and reacts with the oxygen in the air, which is in the gas phase. The result in this example is a smouldering fire on which we can have a barbeque on. The trick is to achieve as good a smouldering fire as possible. In fires in buildings, smouldering fires can be difficult to handle, not least if they are hidden inside walls or floors.

## Ignition

The first visible sign of combustion is ignition. The combustible substance, for example a gas mixture, is ignited by a source, such as a match or a spark. The heat is then supplied from outside. In such cases, it is called piloted ignition, i.e., ignition is piloted by a small flame or a spark.

In order for ignition to occur, the fuel must be heated so that it either begins to pyrolyse (solid materials) or gasify (liquids). The fuel must then also reach its ignition temperature. Ignition of a material depends, among other things, on the ignition source, since different ignition sources can have different temperatures and ignition energies and thus different properties with regard to heat transfer. For a combustible material, the higher the thermal inertia, the longer it takes to heat up the surface. This affects the time to ignition. The faster the surface is heated, the faster the material can reach its ignition temperature and ignite. In addition, a certain minimum amount of pyrolysis gases or gasified liquid is required for ignition to occur.

## **Piloted ignition**

Piloted ignition, or forced ignition, is when a material is ignited by a spark or flame. The ignition temperature during forced ignition is also called the flash point of the substance. The flash point is most often mentioned in connection with flammable liquids, which are classified according to their flash point. Liquids with a low flash point ignite at a relatively low temperature and are therefore considered more flammable than liquids that ignite at a higher temperature. They must first be heated to their ignition temperature. This means that liquids with a high flash point take longer to ignite and are therefore less flammable in terms of flammability. Note that there may be other factors that affect or can describe the flammability of a flammable liquid, such as the vapour pressure of the liquid. A low vapour pressure causes the liquid to vapourise at a low temperature, while a high vapour pressure requires a higher temperature for the liquid to vapourise.

For most solid materials, the ignition temperature during forced ignition is between 300 °C and 500 °C. This is a consequence of the fact that the complex molecules of the solid materials usually must first decompose into simpler components (pyrolysis) before they can ignite.

The oxidation in the gas mixture occurs at approximately the same temperature, but heating the material to this temperature takes different amounts of time for different materials. This means that we cannot assess the hazard of solid materials by their flash point but by the time to ignition, given that the material is exposed to a certain amount of heat.

## Spontaneous ignition

Another type of ignition is spontaneous ignition or self-ignition. In this case, the combustible material, for example a gas mixture, ignites through a spontaneous, internal heat-emitting (exothermic) chemical or biological process.

Simple examples where self-ignition can occur are cloth rags soaked in raw linseed oil and large piles of wood chips.

Self-ignition is actually a series of chemical chain reactions. Since the speed of these chemical reactions increases with rising temperature, the heat that is developed during combustion and that is added to or remains in the material becomes important for the continued chemical reactions.

If the reactions occur at a moderate rate, a moderate amount of heat is developed. If this heat is constantly transferred to the surroundings, combustion cannot accelerate and lead to spontaneous ignition. However, if for some reason the heat cannot be transferred to the surroundings, the temperature increases to the self-ignition temperature and ignition occurs. This can happen, for example, if the reactions start in the middle of a peat pile, where the surrounding peat is a good insulating material. In such cases, combustion can proceed. This type of spontaneous combustion usually occurs when finely divided or powdered organic material such as peat, sawdust, or coal dust is stored in large quantities and where biological processes cause heat to develop. The larger the storage volume, the more heat can remain in the material, and the risk of spontaneous combustion increases.

The sensitivity to ignition (flammability) of various combustible substances and materials is characterised by the lowest temperature at which the material can ignite. For one and the same material, the spontaneous ignition temperature is always higher than the ignition temperature in the event of forced ignition. The difference can be several hundred degrees.

## Flaming combustion

What is often characteristic of fire is the flames that arise. This is what we see from the fire. In a fire (or combustion), in addition to heat, light is also produced, which we then perceive as the flames from the fire.



What is often characteristic of a fire are the flames that arise. Photo: Stefan Svensson.

Flames can be described as the place where a reaction between fuel and air takes place. This place usually emits thermal radiation, radiation in the form of visible light and also radiation with wavelengths that the human eye cannot see, such as ultraviolet and especially infrared radiation. The yellow or orange-red light from flames is largely due to the soot particles that form and glow in the flame. However, there are fuels that do not give rise to yellow or orange-red flames, the most common example being certain alcohols. The combustion of alcohol is very efficient, which means that only a very small number of soot particles are formed. We then get blue or almost invisible flames instead of yellow. The radiation from such a fire can still be high, but not in the visible range.

### **Adiabatic flame temperature**

The temperature that results from combustion under ideal conditions where no heat or mechanical energy is exchanged with the surroundings. It is the theoretically highest possible temperature.

Flaming combustion can only occur if there is a certain amount of oxygen available. Air normally contains about 21 percent oxygen. If the oxygen content drops to about 10 – 12 percent, flame combustion can no longer occur (at normal air pressure and about 20 °C). If the oxygen content is reduced from 21 percent, the flames simply become smaller and smaller until they cease completely at about 10 – 12 percent oxygen. However, smouldering can continue at lower oxygen levels than that.

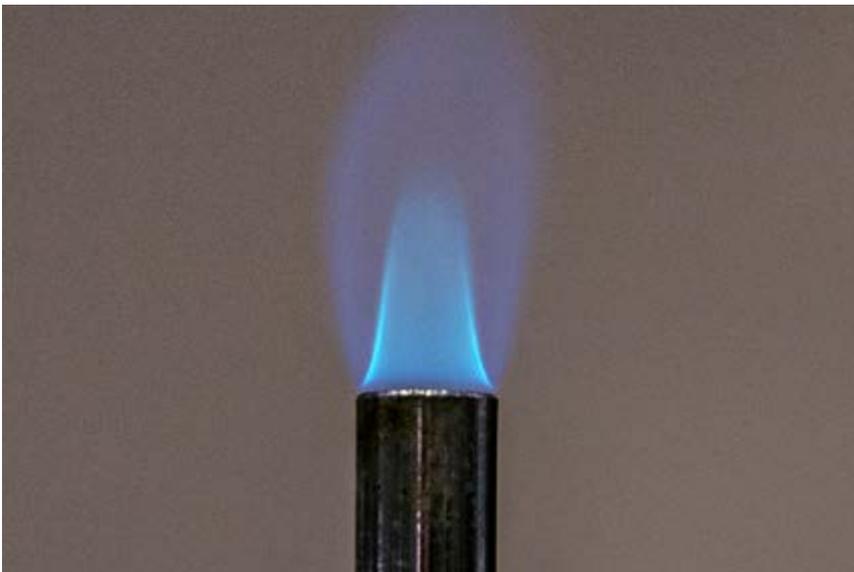
There are two different types of flames, premixed flames and diffusion flames. These have slightly different properties.

## Premixed flames

Premixed flames occur when gaseous fuel and air are mixed at a concentration within the flammability range. Thus, there is already a ratio between the amount of fuel and oxygen that is sufficient for combustion to occur. A common example of a premixed flame is in a welding nozzle. For example, a mixture of acetylene and oxygen is used for welding, contained in two separate containers. These two gases are mixed in the welding nozzle and when this gas mixture is ignited, a premixed flame occurs. By regulating the ratio between the amount of oxygen and combustible gas, the temperature of the flame can be adjusted, within certain limits.

### Premixed flames

A flame that occurs when gaseous fuel and air are well mixed with each other before ignition occurs.



A premixed flame. Photo: Stefan Svensson.

Premixed flames can also occur in a building fire, but this requires special conditions and is relatively uncommon. This will be discussed later, primarily in the section on backdraft and fire gas explosion.

## Diffusion flames

Diffusion flames occur when combustion takes place as fuel and air meet. The fuel and air are not mixed before combustion occurs. Instead, the mixing occurs through molecular diffusion during the combustion itself. This is a relatively slow process, although it is accelerated by high temperature.

An example of a diffusion flame is when a candle burns. The heat from the flame causes the stearin to melt and then be drawn into the wick. The temperature further up the wick is higher than further down, which causes the stearin to gasify while the long carbon chains that make up the stearin are broken down into simpler components in the centre of the candle flame. If you look closely at a candle, you can see a dark, flameless area closest to the wick. Here, the amount of fuel gas is too high for it to burn. The gas mixture is too rich. In this area, the fuel gas (stearin) is also broken down so that combustion can occur more easily.



A candle is an example of a diffusion flame. Photo: Stefan Svensson.

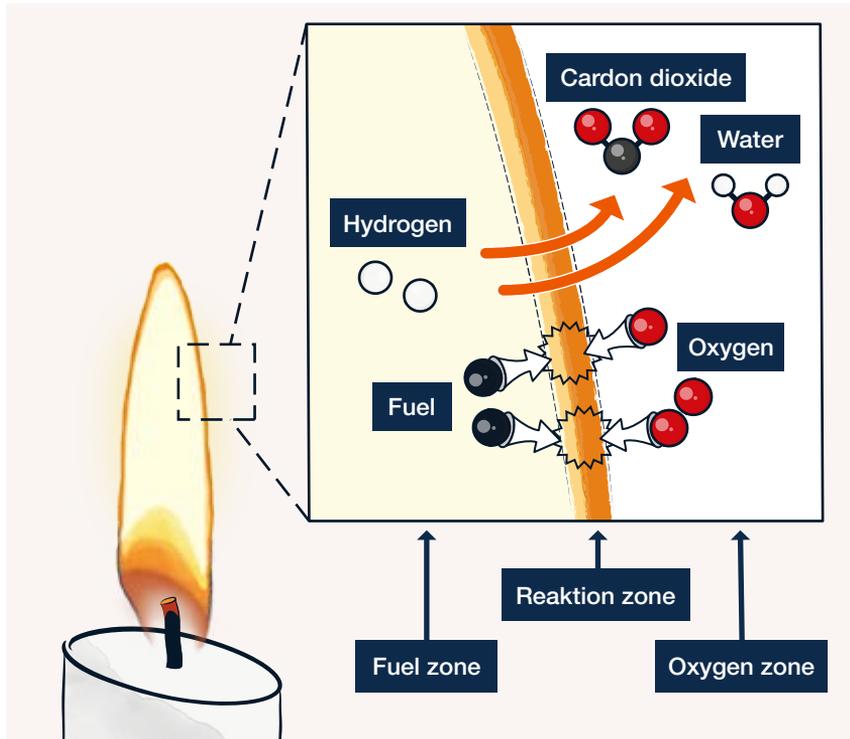
The fuel molecules, consisting of the gasified and partially decomposed stearin, then flow to the place where the actual combustion takes place. This place is called the combustion zone or reaction layer. This is where the fuel molecules mix with oxygen molecules from the surrounding air. The transport process where two or more gases mix in this way is called diffusion. The gases diffuse into each other.

### **Diffusion flame**

The flame that occurs if the fuel and air are not mixed together when ignition occurs. Mixing occurs instead during the actual combustion. Fuel and air diffuse into each other, and a combustible region is formed at the boundary between them. The flame from a candle is a common example.

An exothermic chemical reaction occurs when the fuel and oxygen are mixed in a certain proportion to each other and are burned. Such a reaction releases energy. The energy is used to heat the products formed in the reaction. The oxygen and fuel continue the diffusion process towards the reaction layer. A continuous diffusion flame is created.

**Figure 43.** In a diffusion flame, fuel gas and oxygen are mixed in connection with the reaction itself



Diffusion is a natural process in which particles move from an area of high concentration to an area of low concentration until they are evenly distributed. In a diffusion flame, fuel molecules diffuse from the fuel zone, which has a high concentration of fuel molecules, and oxygen molecules from the oxygen zone, which has a high concentration of oxygen molecules, into the reaction zone where combustion occurs.

The visible luminous part of the flame consists of thermal radiation from glowing soot particles. During oxidation in the reaction zone, carbon dioxide, carbon monoxide, water and heat are mainly formed (in the example with stearin). The inner part of the flame, which is filled with fuel molecules, contains too little oxygen for combustion to take place there. Combustion instead takes place at the edge of this area, where fuel and oxygen diffuse into each other.

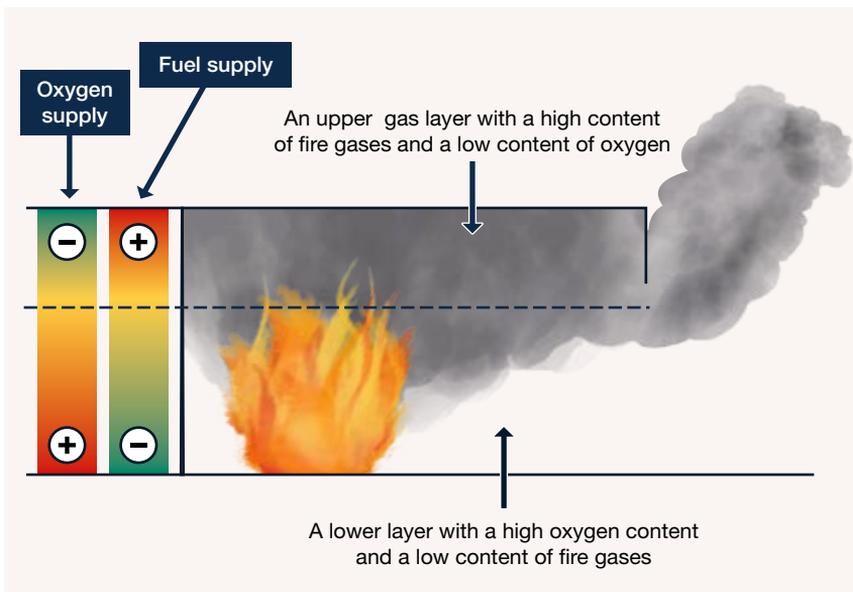
The combustion efficiency is lower in a diffusion flame than in a corresponding premixed flame. The fact that combustion is not complete results in the formation of soot particles. These soot particles have the

same temperature as the flame, and they emit electromagnetic radiation, including in the visible light spectrum: the flame becomes yellow/orange. It can be added that there are diffusion flames that do not soot as much, for example the flames during the combustion of certain alcohols. They therefore resemble premixed flames in appearance.

The diffusion flame occurs in the boundary layer between fuel and air, where the mixing ratio is “just right”. Closest to the fuel surface, the fuel concentration is 100 percent, and next to the flame it is 0 percent. Therefore, flammability limits cannot be used to describe a diffusion flame.

Fires in buildings almost always involve diffusion flames. The fire gases that accumulate in a room during a fire often have different compositions or concentrations of substances in different parts of the room. This can be due, for example, to the fact that there has been a strong pyrolysis of the ceiling material or that objects in the room are pyrolysing. This is, of course, also due to the fact that hot fire gases rise upwards. The oxygen content is then very low just below the ceiling. The fuel concentration is then not evenly distributed throughout the room. The oxygen must diffuse into the fuel in order for combustion to occur, which normally occurs on the underside of the fire gases.

**Figure 44.** The concentration of fuel gas in a fire room



Diffusion flames are characterised by combustion occurring at approximately the same rate as the fuel gas and oxygen from the air diffuse into each other, since combustion in principle occurs as the gases mix. A diffusion flame is the result of a combustion process in which fuel molecules mix with oxygen through mixing that can be laminar (side by side) or turbulent (swirling). This results in So-called laminar and turbulent diffusion flames. Turbulence accelerates the mixing process, and the flames then take on a slightly different character.

### **Laminar diffusion flames**

When a candle burns, a typical laminar diffusion flame occurs, where fuel and oxygen from the air flow side by side at low speed. The mixing occurs laminarily, and combustion in the reaction layer becomes even. If diffusion occurs slowly, the oxygen and fuel need to mix for a longer time in order to burn. We call such flames laminar diffusion flames.



Laminar diffusion flame. Photo: Stefan Svensson.

In a building fire, laminar diffusion flames occur primarily during the initial fire and possibly also during the early stages of the growth phase.

The fire is then small, the velocity of pyrolysis gases or the vapourised fuel is low, and the velocity of the air flowing into the fire is also low. Later in the fire process, laminar diffusion flames are uncommon.

### **Turbulent diffusion flames**

If the velocity of the pyrolysis gases or the vapourised fuel increases, the flames gradually change from being laminar to turbulent. When the velocity of the fuel gas becomes higher than the mixing rate of oxygen from the air, mixing occurs in eddies. This is called turbulent mixing. The mixing of oxygen also occurs here by diffusion, but the combustion becomes uneven and irregular. Although turbulence increases the combustion velocity, the combustion velocity of a turbulent diffusion flame is much lower than that of a premixed flame.

Turbulent diffusion flames are what we normally see in fires in buildings.



Turbulent diffusion flame. Photo: Stefan Svensson.

Turbulent flames are characterised by:

- irregular swirling motion
- rapid diffusion
- thin and irregular reaction layer.

Turbulent flames are often characterised by noise and rapid changes in appearance, that is, turbulent flames “flutter,” unlike laminar flames.

## Smouldering combustion

A combustion in the form of smouldering occurs at the surface of a fuel, where the fuel is in the solid phase and the oxidiser in the gas phase. Thus, it is only in solid materials that smouldering combustion can occur. In a room fire, the oxygen in the air is the oxidiser.

A smouldering fire can also occur inside a porous material where there is a limited supply of oxygen, but sufficient for the oxidation (combustion) to continue. Inside such a porous material, the heat can also remain and maintain the pyrolysis process, until a possible spontaneous ignition occurs or the combustion ceases.



Incandescent (smouldering) fire. Photo: Stefan Svensson.

A smouldering fire can produce a lot of pyrolysis products that do not oxidise or participate in the combustion process directly, or where the oxidation is incomplete. This happens especially inside porous materials. These products can collect in the upper part of the room without being burned. Since the smouldering fire occurs with limited air supply, large amounts of carbon monoxide are formed. If a smouldering fire is allowed to continue, the pyrolysis gases can eventually ignite. This increases the risk of the fire spreading to adjacent spaces. Such problems can arise, for example, in connection with subsequent extinguishing. Remaining smouldering fires produce pyrolysis gases that collect in hidden spaces. These can ignite if the amount of incompletely burned pyrolysis gases becomes sufficient and there is an ignition source. If these incompletely burned pyrolysis gases are mixed well with air before ignition, a so-called fire gas explosion can occur.

Smouldering fires are common in fires in upholstered furniture, such as mattresses, armchairs and sofas. The fire occurs, for example, when pieces of cotton or viscose fabric on a polyurethane padding substrate begin to smoulder, perhaps due to a dropped cigarette or due to radiant heat from another burning object.

Smouldering fires can also occur inside structures, for example in insulation materials or wooden materials, and are then very difficult to access. Such an environment quickly becomes oxygen-poor due to the combustion, so that no flame can arise. The flammable gases are instead transported away and can be ignited elsewhere. A smouldering fire burns very slowly and can therefore last for a long time. There are many cases where smouldering fires have lasted for a long time and eventually ignited and caused total damage to the building, due to extensive spread and ignition of fire gases. Smouldering fires can simply be difficult to deal with.



Smoldering fires inside structures are difficult to detect. For example, when a wall is broken open to access a smoldering fire, there is a risk of flame combustion occurring or the fire spreading as air is supplied. Photo: Stefan Svensson.

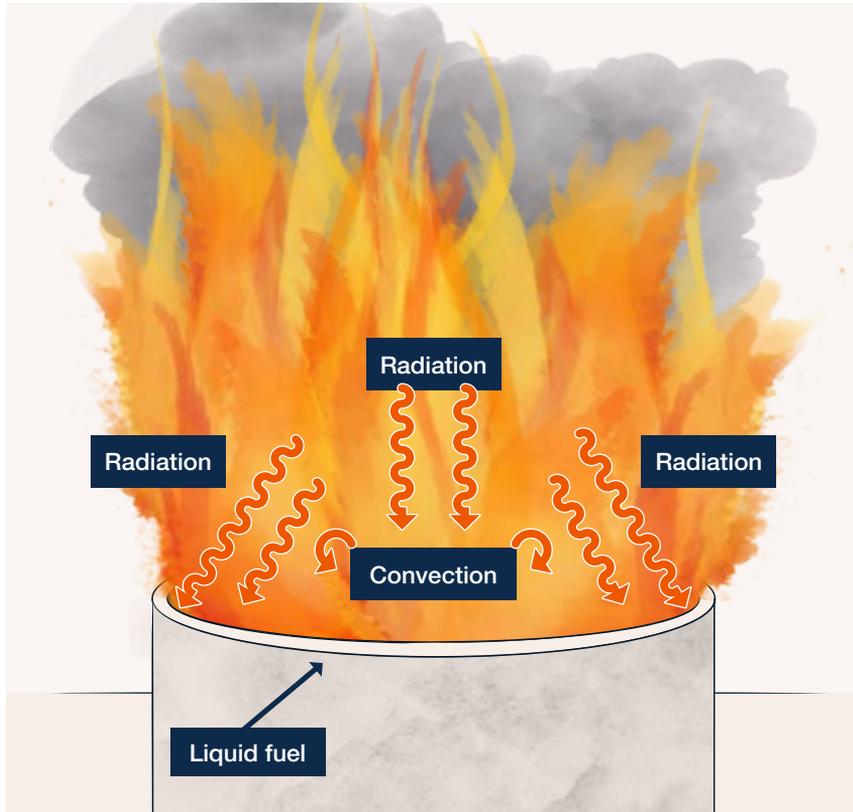
There are relatively few substances that burn with embers, but these substances are common. Charcoal is an example. In addition to coal, this also applies to substances that release carbon when burned, such as wood. Buildings often contain a large amount of wood, both in interior decoration and in building materials. This is why ember fires often occur, which can cause major problems during rescue operations. Ember fires can also occur in some metals, including finely divided iron or steel wool, but this is unusual in fires in buildings.

## Flame spread

Flame spread is an important process in a fire, especially when a fire in a single object develops into a room fire. Flame spread can occur on the surface of materials but also in the combustion products (fire gases) that are formed during a fire. Flame spread in such combustion products can occur far from the location where the pyrolysis gases were formed. Flame spread in fire gases will be discussed in more detail later.

Flame spread on materials can be seen as a series of continuous ignition events, where the material gradually ignites. Since ignition is strongly dependent on the previously described thermal inertia ( $k\rho c$ ) of the material, flame spread also depends on material properties. Flames spread by transferring heat from the fire back to the fuel, both the fuel that is already burning and that which is not yet burning. This heat transport occurs primarily through convection and thermal radiation. Which dominates depends, among other things, on the size of the fire and the amount of fire gases at a certain time. Heat can also be transported into a material, through conduction. This can also affect flame spread, but since conduction occurs more slowly than radiation and convection, it also affects flame spread more slowly.

**Figure 45.** Heat transfer from the fire back to the fuel



Heat transfer from the flames to the fuel occurs primarily through radiation, but at the surface some transfer also occurs through convection.

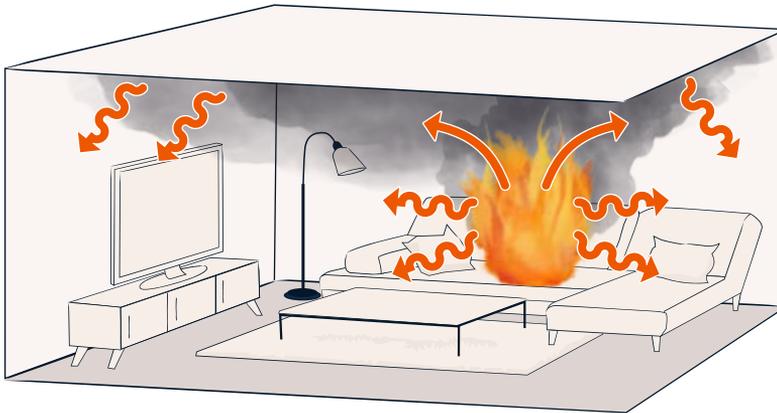
Rapid flame spread contributes to increasing the surface area of the fire and thus the rate of heat release. The fire simply becomes larger as more and more fuel participates in the combustion. This also means that, among other things, heat radiation gradually increases, which further increases the rate of flame spread.

The speed at which the flame spreads over the surface of a material is mainly dependent on:

- the thermal inertia of the material,  $k\rho c$
- the orientation of the surface
- the geometry of the surface
- the surrounding environment.

Flame spread can be said to be the movement of a flame front over the surface of a combustible material. Together with heat radiation and convection, flame spread is usually the dominant mechanism when a fire develops and spreads. When flame spreads over a surface, the fire (flames) can be seen as a traveling ignition front. The flame front acts both as a heat source – it heats the combustible material in front of the flame front to the ignition temperature – and as an ignition source. How quickly the flames spread over a surface of a solid material is determined by chemical and physical material factors as well as by surrounding factors. Such material factors include the properties and conditions of the material, such as initial temperature, thickness, thermal properties, density, geometry, surface orientation and direction of flame spread. Environmental factors that affect flame spread include atmospheric composition, pressure and temperature, heat flow from external sources, and air velocity. Moreover, the higher the temperature in a room, the higher the velocity of the gases in the room.

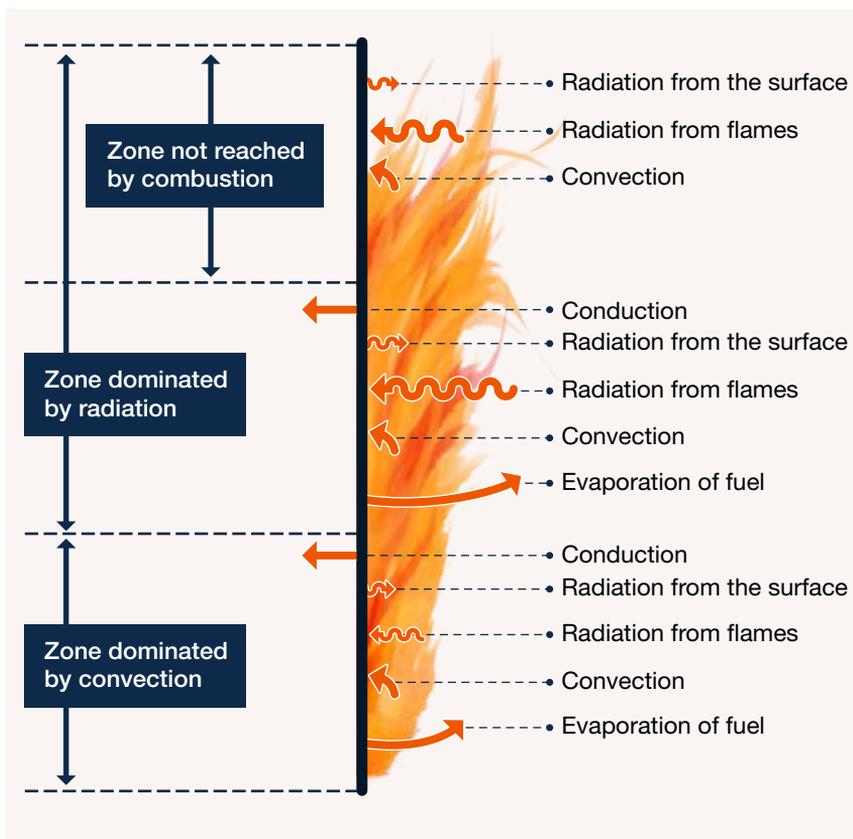
**Figure 46.** Heat transfer from an initial fire to the other surfaces of the room occurs in several ways



Closest to the initial fire, heat transfer occurs primarily through radiation from the flames. Towards the ceiling, heat transfer occurs largely through convection but also through radiation. The fire gases will also heat other surfaces in the room through radiation.

Flames spread more slowly on a combustible material with a high thermal inertia than on a material with a low thermal inertia. High thermal inertia means that heat is more easily conducted away from the surface, at least initially. However, note that the thickness of the material also has an effect, since a thinner material heats up faster than a thicker one. In a building, the fuel, both surrounding surfaces and objects, is often composed of several different types of materials with different thicknesses. This further complicates the flame spread process.

**Figure 47.** Flame spread over a wall

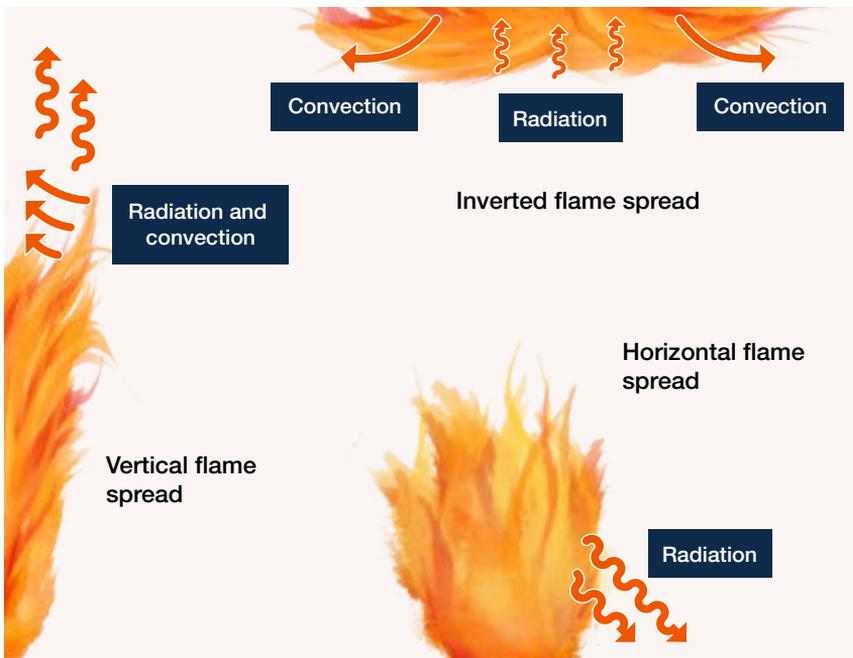


The length of the arrows corresponds to the size of the components. At the bottom, heat transfer is dominated by convection. Further up, radiation from the flames dominates. Above the flames, heat transfer occurs primarily by convection from the hot gases formed during combustion.

When a fire spreads upwards along a wall, the wall can be divided into three zones. The lowest one is heated primarily by convection. In the middle one, the heat radiation from the flame contributes most to the heating. This is because the thickness of the flame increases with height. The thicker the flame, the greater the proportion of heat transfer occurs by thermal radiation. In the top zone, the wall has not yet ignited, but the wall is heated by convection from the hot combustion products from the burning surfaces.

If the surface over which flame spread occurs has a geometry other than vertical, heat transport occurs in other ways, with varying degrees of heat radiation, convection and conduction.

**Figure 48.** Flame spread over surfaces with different geometries



When the flame spreads upwards, heat transfer occurs through radiation and convection. When the flame spreads horizontally, heat transfer occurs through radiation. For example, under a roof, heat transfer during flame spread occurs primarily through convection.

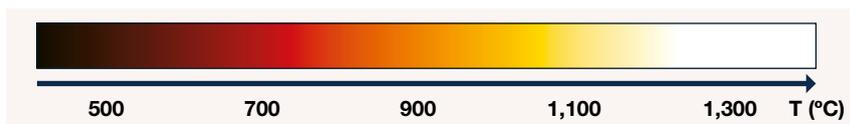
A simple rule of thumb says that a fire in a building spreads downwards in hours, sideways in minutes and upwards in seconds.

## The colour of flames

Flames can appear in different colours. In some cases, the colour can give us information about the properties of the fuel or even what type of fuel it is or under what conditions the fuel is burned.

A certain amount of soot is always formed during combustion. The soot is solid particles and, depending on their temperature, they emit different amounts of heat radiation. At about 550 °C they begin to emit heat radiation in the visible light spectrum. The particles begin to emit red light. If the combustion is better, the temperature becomes higher and heat radiation begins to be emitted as orange and yellow light, as in a candle. Then the temperature is about 800 °C. With even better combustion, light is emitted in the entire visible spectrum and the flame becomes white, for example, like in a welding flame. The temperature is then up to 1200 °C.

**Figure 49.** Approximate flame colors at different temperatures

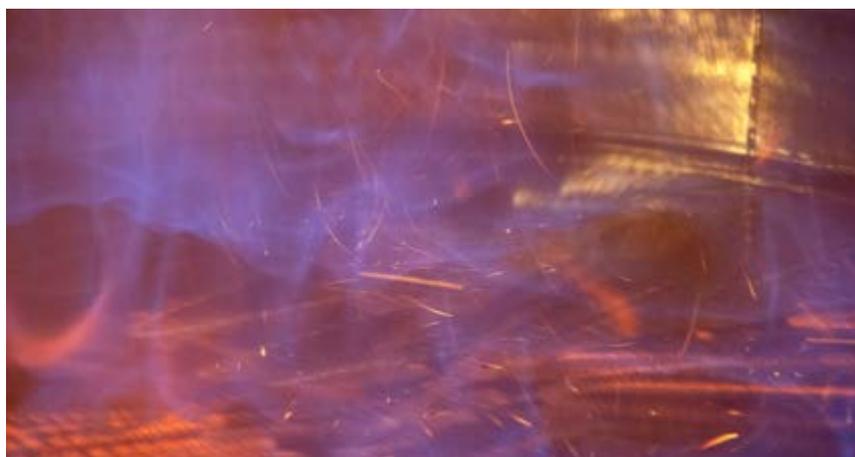
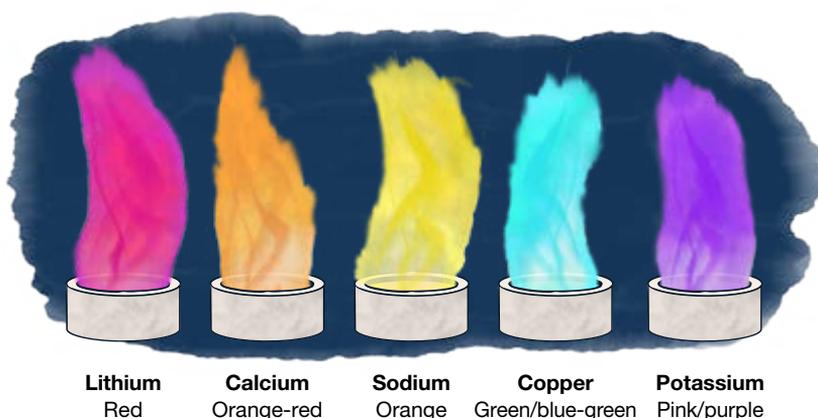


**Table 14.** Approximate temperatures and flame colors

Color	Temperature [°C]
Pale red	500
Blood red	600
Red	700
Cherry	750
Light red	800
Salmon-colored	850
Dark orange	900
Orange	950
Lemon	1,000
Light yellow	1,100
White	1,200

The fact that flames can have different colours is because they emit electromagnetic radiation with different wavelengths. When a substance is heated, the electrons in the outermost electron shells of the atoms absorb energy that they use to “jump up” to a higher shell (the electrons are excited). This is not a stable state, so the electrons fall back to their ordinary electron shell. The substance's unique amount of energy is then emitted in the form of electromagnetic radiation. Metal ions give typical colours to flames. Sodium gives yellow flames, strontium gives red flames and copper gives green flames. Chlorine also makes flames green. This is used, for example, in fireworks to achieve different effects.

**Figure 50.** Different substances can give different colors to flames



Flames can be of different colors. For example, methanol produces blue or almost invisible flames. Photo: Stefan Svensson.

Flames that are barely visible or that burn with only very weak blue flames may be due to the fuel being an alcohol. The combustion efficiency is then very good, so that the combustion products consist almost exclusively of carbon dioxide and water. However, alcohols can also burn with yellow flames that also produce a lot of soot (black fire gases). This can be the case, for example, if the fire is very large, so that a large part of the combustion takes place with an air deficit. In this case, the combustion efficiency is low, and large amounts of unburned products and soot are formed.

In addition to the properties of the fuel, the conditions under which combustion occurs will also affect the colour of the flames.

## Flammable liquids and gases

Combustible liquids burn in a slightly different way than solids. A solid usually needs to pyrolyse for a fire to start and continue. For a liquid, it is sufficient for it to gasify, that is, to change its state from liquid to gas. A flammable liquid also decomposes, but this only happens in the gas phase. The combustion of liquids is therefore more similar to the combustion of gases than it is to the combustion of solids. Depending on the properties and state of the fuel gas, the combustion (fire) can occur in different ways.

For a liquid, it is primarily the size of the liquid surface that determines the size of the fire, while the depth of the liquid pool determines how long it will burn.



A liquid fire in the open air is fuel-controlled, while a liquid fire in a room can become ventilation-controlled just like a solid fuel fire. Photo: Peter Wemmert.

The flammability of liquids depends on how easily they evaporate. Flammability can be described using two temperatures – flash point and thermal ignition point. Flash point is the temperature at which a liquid can be ignited by a flame. The gas concentration at the liquid surface is then above the lower flammability limit of the substance. The thermal ignition point is the temperature at which the liquid ignites spontaneously without any ignition source.

Substances with a low flash point can have a high thermal ignition point. However, substances with a low flash point can also have a low thermal ignition point and there is no simple relationship. The flash point of gasoline is below  $-30\text{ }^{\circ}\text{C}$  and the thermal ignition point is around  $400\text{ }^{\circ}\text{C}$ . For diesel, the flash point is above  $55\text{ }^{\circ}\text{C}$ , while the thermal ignition point is only  $220\text{ }^{\circ}\text{C}$ .

A flammable liquid can also be described by its burning rate. This property is substance-dependent and more or less constant for the same substance. The size of the liquid pool also has some influence. If the liquid is in a vessel, the surrounding material in the walls of the vessel will have some influence, but the larger the puddle, the less influence the vessel has. An exception may be if the edges of the vessel are very high, that is, if the edge protrudes very much above the liquid surface. In such cases, the vessel can have a significant impact on the liquid fire. This happens partly because the edge of the vessel becomes very hot, and partly because the air supply to the fire is affected. If the walls of the vessel are hot, it will also be more difficult to extinguish the fire. If the walls of the vessel are very high, it may also be difficult to reach the fuel surface with extinguishing agent.

**Figure 51.** If you know the mass loss rate, you can calculate the rate of heat release

$$\dot{Q} = \dot{m} \cdot \Delta H_c \cdot \chi$$

$\dot{Q}$	Rate of heat release [MW]
$\dot{m}$	Mass loss rate [kg/s]
$\Delta H_c$	Heat of combustion [MJ/kg]
$\chi$	Combustion efficiency [-]

When a liquid burns in a room, the walls of the room, among other things, will affect the rate of heat release. The hotter the room, the higher the rate of heat release. However, fires in liquids are affected somewhat less than fires in solid materials.

A larger amount of solid material in the vicinity of a burning liquid can affect the liquid fire even if the solid material is non-combustible. The solid material heats up and reradiates large amounts of heat energy to the liquid. The fire then becomes more difficult to extinguish, because in addition to extinguishing the liquid fire itself, the solid material must also be cooled. This may be the case, for example, in tanker accidents and cistern fires, where the metal in the container quickly becomes very hot. Even if the liquid fire is then extinguished, metal parts that have a higher temperature than the fuel's thermal ignition point will cause the fuel to reignite. If it is then difficult to cool the metal, the liquid fire will be difficult to extinguish.

The same applies to a gas. For a combustible gas flowing out of, for example, a pipe, the so-called source strength will largely determine the size of the fire. Source strength means how many liters or kilograms of fuel gas flow out per second. The duration of the fire is then determined by how long the emission continues. If the gas stops flowing out, the fire goes out. The rate of heat release is determined by the source strength, that is, the outflow of the combustible gas. If the source strength decreases, the rate of heat release also decreases. If the fire is extinguished but the gas continues to flow out, a cloud of combustible gases is formed.

A gas cloud can behave somewhat differently when it is ignited. If the gas cloud is well mixed with air, an explosion or a premixed flame can occur. Then the combustion process proceeds very quickly. An explosion is often accompanied by a pressure wave and a sound effect. This will be discussed in more detail later. If the gas cloud is not pre-mixed with air, a diffusion flame occurs. However, the combustion process in such a situation can cause the turbulence to become severe and the mixing of air to increase rapidly. In this case, even such a non-pre-mixed gas cloud can give rise to premixed flames.

## Combustion products and fire gases

When there is a fire, gaseous combustion products are always formed. In addition to being normally hot, they are also toxic and can be flammable. They also often react easily with various materials and cause consequential damage such as corrosion. When these combustion products rise upwards, they mix with air and form fire gases. When fire gases spread in a room or further in a building, the fire gases will heat up objects and surfaces through convection and thermal radiation. How much these objects and surfaces are heated depends, among other things, on the temperature of the fire gases. The content and velocity of the gases can also be important. For example, forced convection provides higher heat transfer than natural convection. Fire gases are therefore important and have a very large impact on how fires develop and spread in buildings.

The fire gases formed during fires consist of two components:

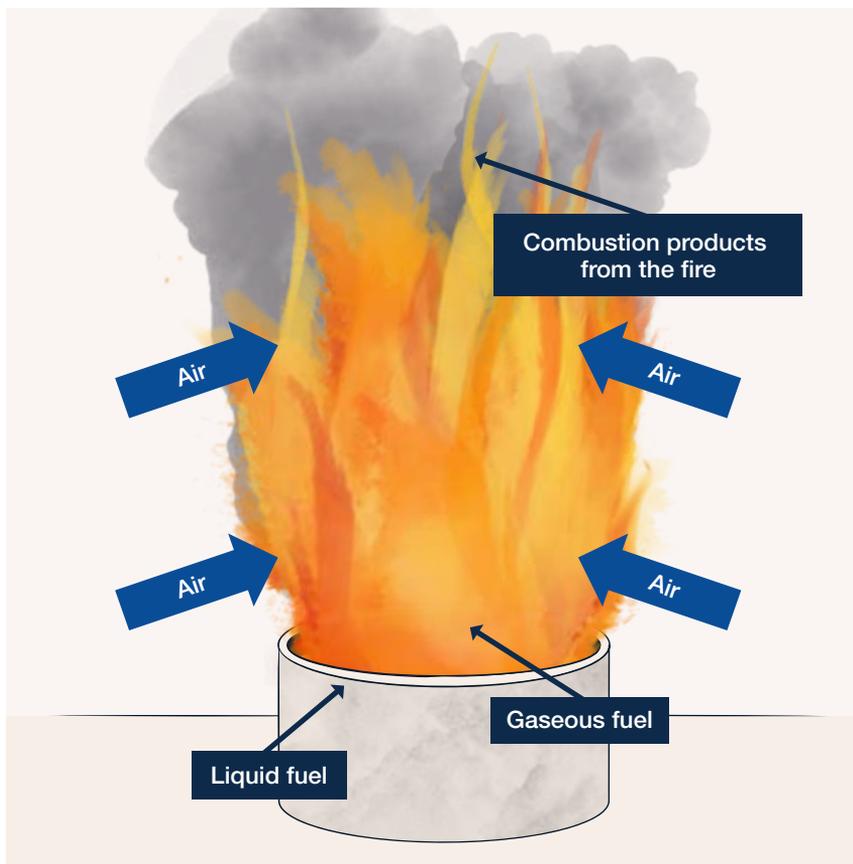
- air (including excess nitrogen from used air)
- combustion products, such as carbon dioxide, carbon monoxide and soot, but also a wide range of other compounds, including solid products and liquid particles.

The term “fire gases” is therefore misleading, since the combustion products consist of gases, liquids and solid products. However, the largest component of fire gases is air that does not participate in the combustion. It is heated by the fire but is relatively unaffected by the chemical reactions that occur in the fire. Some of the air in the building will participate in and affect the combustion process itself. However, air can also be supplied from outside, which can have a major impact on how the fire will develop and spread.

The second component consists of the combustion products that are formed during the fire and mix with the air. These include gases such as carbon dioxide, carbon monoxide, nitrogen oxides, hydrogen sulfide, water vapour and hydrogen cyanide. There are also particles in solid form (soot) or in liquid form, for example heavier hydrocarbon compounds, that is, compounds that mainly consist of the elements carbon and hydrogen. This second component is small in both weight and volume, compared to the air contained in the fire gases. The physical properties

of fire gases are largely similar to the properties of air. Therefore, flows of fire gases can be treated as a flow of heated air in both calculations and tactical assessments of fires. One advantage is that we can usually see the fire gases. Fire gases flow in the same way as air even if the production of fire gas is large or if they contain a lot of particles and therefore have low transparency. The air that is supplied to the fire gases and heated is still many times larger than the other contents, but we must also take into account the temperature and flammability (energy content) of the fire gases, as this contributes to the spread of the fire. In addition, the amount, type and properties of the particles in the fire gases will be decisive, among other things, for how much thermal radiation the fire gases emit towards surrounding surfaces and objects.

**Figure 52.** Fire gases consist of combustion products from the fire and air



The exact composition of the fire gases is determined, among other things, by the conditions prevailing during the fire – partly the composition and properties of the fuel, and partly the amount of air available for combustion. The composition therefore changes depending on the conditions prevailing at each individual time, and it varies over time. If the availability of air (oxygen) during combustion is low, the fire gases will largely consist of unburned products from the fire. If, on the other hand, the availability of air is good, the fire gases will consist of a smaller proportion of combustible products. This may still be sufficient to make the fire gases combustible.

The composition of the fire gases is also affected by the temperature in the flames. The temperature in a fire room is in turn affected by the availability of air, and thus also by the ventilation measures that the rescue services may take. A room fire is thus a very complex process when it comes to which substances are present in the fire gases and how much of these substances there are.

The content and chemical composition of the fuel also affect the composition of the fire gases. For example, materials containing nitrogen, such as polyurethane foam, produce nitrous gases, while materials containing sulphur produce sulphur dioxide.

Fire gases are often white, grey, yellowish-brown or black. The reason for this is that they contain particles that refract light. Transparent liquid particles refract light in a way that produces white fire gases. However, the appearance does not provide any information about whether the transparent liquid is water or a flammable liquid. The blacker the fire gases, the greater the amount of soot. Yellowish-brown fire gases can come from a pyrolysis process, but high levels of nitrous gases can also produce such a colour. The colour of the fire gases is a poor indicator of how toxic or flammable the fire gases are.

How a fire develops is affected both by the fire gases and by substances that do not normally directly participate in combustion, such as nitrogen. For example, heat will be used to heat such substances. The substances then act as a so-called thermal ballast, which lowers the temperature and suppresses the fire. Almost all extinguishing agents also act as thermal ballast, since the extinguishing agent absorbs heat. If the extinguishing agent causes the temperature to drop sufficiently, the flames will go out.

Depending on, among other things, the ratio between fuel and air, different combustion products and different quantities of these combustion products are formed. The fire gases can also have different colours, depending on the properties of the fuel and the conditions under which the combustion has taken place.

Fire gases have different properties depending on their composition:

- Fire gases can be opaque and thus limit our vision.
- Fire gases can be flammable, even if they are completely transparent.
- Fire gases are generally toxic and affect people, animals and the environment in both the short and long term.
- Fire gases can be reactive and thus destroy furnishings, tools or other equipment.
- Fire gases can be hot.

How a fire spreads in a building is primarily affected by the combustibility of the fire gases, their temperature, the amount of particles and the properties of the particles (size, flammability, etc.).

It is difficult to assess how combustible fire gases are. In fires in buildings, combustion is almost always incomplete, since it takes place with limited oxygen supply (ventilation-controlled fires). When there is a lack of oxygen, combustion products are formed that are more or less combustible and can therefore start to burn under certain circumstances. These combustion products form part of the fire gases and collect in the fire gas layer that forms closest to the ceiling of the room or building. Carbon monoxide is an example of such a combustible gas that is formed in room fires. The flammability range for carbon monoxide is between 11 and 74 percent at room temperature, but this range increases at higher temperatures. The mixture of other gases and the particles that are formed in room fires also affect both the flammability range and the ignitability. Therefore, the flammability of fire gases is extremely complex. The flammability of fire gases cannot be simply equated with the flammability of an individual gas. The flammability range of fire gases will vary from case to case, and in practice cannot be determined precisely.



Fire gases can be hot and flammable. Photo: Stefan Svensson.

Depending on the types and amount of particles contained in the fire gases, flammability can increase or decrease. For example, certain types of particles can reduce flammability. This can happen because the particles act as a kind of thermal load, which means that more energy is required to raise the temperature. Other types of particles can instead increase flammability by helping to raise the temperature or maintain the temperature for a longer period of time. This can also happen because the particles themselves are flammable. In addition, the size of the particles affects flammability. Small particles have a larger surface area in relation to their volume. This leads to more molecules of the particles being exposed to the environment, which increases the potential for them to react and contribute to the chemical reactions.

## Example

On the night of October 9, 1986, the fire station in Täby received an alarm from a hardware store. The building was divided into two sections, separated by fire protection class A60 (steel joists with double plasterboard on both sides and non-combustible sealing on the floor, walls and inside the ceiling). The smaller section contained a retail section, while the larger section contained a sales section for private consumers and a sales section for professionals.

The fire had started in the sales section for private consumers. As part of the extinguishing work, a BA-team consisting of two firefighters was tasked with checking the sectioned wall section between the retail section and the rest of the building. When the work began, white smoke plumes could be observed, and visibility inside the retail section was considered relatively good. To control the spread of the fire, the team broke open a door between the retail section and the sales section for professionals. When this happened, it was announced that a fire was heading towards the smoke divers, and they were ordered by the team leader (on the outside) to close the door.

Somewhat later, the BA-team announced that “it’s getting hot in here”. They were then ordered to go outside. On the way out, something that has been assessed as a fire gas explosion occurred, followed by strong flames that shot out through the entrance to the shop section.

Attempts were made to rescue the two firefighters, but unfortunately their lives could not be saved.

The fire in the sales section for professionals was probably ventilation-controlled. Large quantities of flammable combustion products spread to the shop section through a sliding door that was open and had not been identified. When the quantity of combustion products became sufficient in the shop section, these ignited in an explosion-like manner.

In the example, it is therefore fire gases that have leaked into the shop section and ignited. (Investigation Report No. 3:1987, Committee (Kn 1981:02) for the investigation of serious accidents/ Utredningsrapport Nr 3:1987, Kommittén (Kn 1981:02) för undersökning av allvariga olyckshändelser).

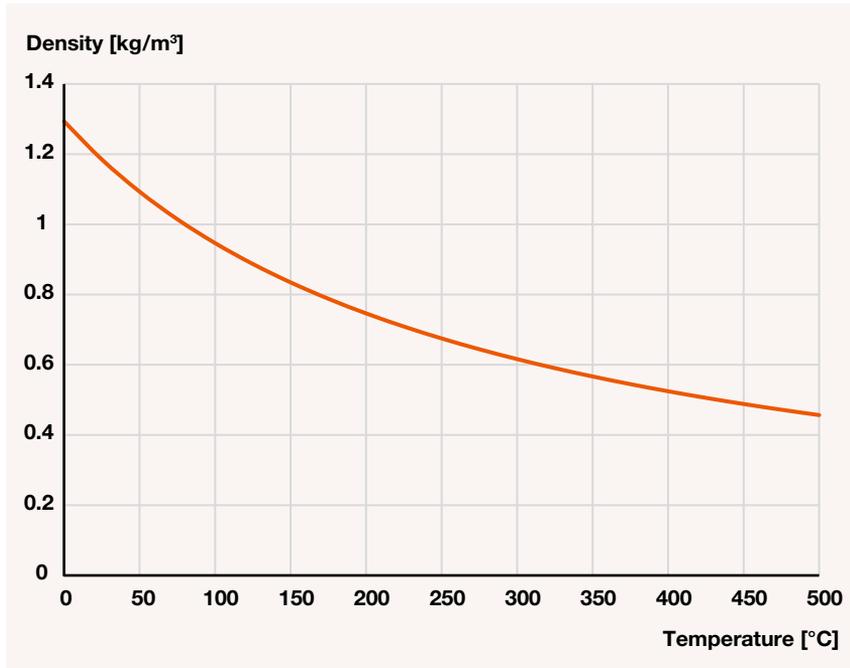
Even completely transparent fire gases can be flammable and dangerous. Carbon monoxide is an example of an invisible but flammable gas. We never know the exact composition of fire gases, and therefore also their exact properties. Accordingly, it is very difficult to determine the flammability of fire gases based on transparency. When there is a risk of large quantities of transparent fire gases being formed, rescue workers should use full protective equipment including breathing apparatus. There should also be immediate access to extinguishing agents.

Fire gases are usually hot, which also affects in a variety of ways. Above all, it gives us the basic mechanisms for the spread of fire gases and fire, primarily thermal lift which causes the fire gases to flow upwards. The thermal lift of fire gases is simply about the fact that the density of fire gases decreases as the temperature increases. This is because the hotter the fire gases are, the faster the molecules that make up the fire gases move and the more space the fire gases need. The fire gases expand (thermal expansion), they take up more space so that the density decreases, and thus the fire gases rise upwards.

Air at 20 °C has a density of 1.2 kg/m<sup>3</sup>. Air and fire gases at a temperature of 300 °C have a density of 0.6 kg/m<sup>3</sup>. If the temperature is 500 °C, the density of the fire gases is 0.45 kg/m<sup>3</sup>. The density differences quickly become large even with relatively small temperature increases.



The hotter the fire gases, the lower the density. Photo: Pavel Koubek.

**Figure 53.** Temperature and density of fire gases

Hot fire gases can contribute to the spread of fire even at great distances from the fire, as the fire gases flow further into a building or inside a structure. The heat in the fire gases is also a major contributor to, among other things, flashover in rooms. This occurs primarily through heat radiation from the fire gases towards surfaces and objects in the room, but also through convection, that is, the heat transfer that occurs when the gases flow past surfaces or objects.

Fire gases are a mixture of combustion products from the fire and air that flows into the plume and mixes with the combustion products. If combustion occurs with a good supply of oxygen, large amounts of carbon dioxide and water are created, which are not in themselves flammable. Depending on the available oxygen and the components of the material, a number of other products can also be formed. Combustion efficiency is normally quite poor in fires. This means that the fuel is not completely broken down during combustion. Instead, a large amount of residual products are formed, both in solid form and in gaseous and liquid form.

Carbon monoxide (CO) is the most common gas besides carbon dioxide (CO<sub>2</sub>) and water. It is usually the primary cause of death when people die in fires. Carbon monoxide is flammable and has a wide flammability range. The gas has neither colour nor odour, which makes it difficult to detect. However, fire gases generally have a strong odour, and the odour of other compounds in the fire gases can help us detect the dangerous carbon monoxide, even if the fire gases are more or less transparent. Carbon monoxide is formed in large quantities, especially when the air supply to the fire is limited. Concentrations of 10–15 percent can be achieved.

Hydrogen cyanide (HCN) is produced during the incomplete combustion of products such as wool, silk, nylon and polyurethane. The gas is flammable, and it is a poison that quickly leads to death by blocking cellular respiration so the cells cannot absorb oxygen. Hydrogen cyanide is also colourless, and thus invisible in a similar way to carbon monoxide.

A large number of unburned hydrocarbons is also formed when hydrocarbon compounds are burned, such as various types of plastic. Such substances contain carbon and hydrogen in various compounds. At the same time as unburned hydrocarbons are formed, pure carbon compounds (C) are also formed. They are called soot and are the black part of the fire gases. The soot consists of carbon particles that combine to form larger particles. The lower the combustion efficiency, the more soot is formed. However, there are also fuels that produce large amounts of soot at high combustion efficiency. It is also glowing soot particles that give flames their characteristic yellow colour. Note that soot can also consist of substances other than carbon compounds, such as heavy metals or partially unburned products from the fuel.

The colour of fire gases does not really say anything about flammability, toxicity, transparency or temperature. However, in general, the following can be said about fire gases based on their colour:

- Black fire gases are often formed during the combustion of hydrocarbons and contain large amounts of soot, which gives the characteristic colour.
- The more underventilated the fire is, the more unburned products are formed. This can produce large amounts of soot.

- Yellowish fire gases can be caused by nitrate- and sulphur-containing polymers, such as tires and similar.
- Whitish fire gases can come from smouldering fires in, for example, foam rubber, but it can also be caused by large amounts of water vapour.

To assess the “danger” of fire gases, one needs to make a combined assessment of the flammability, toxicity, transparency and temperature of the fire gases. To do this, in addition to the colour of the fire gases, one also needs to take into account, among other things, the flow rate of the fire gases and, not least, changes that occur over time. However, this is very difficult – in some cases impossible.

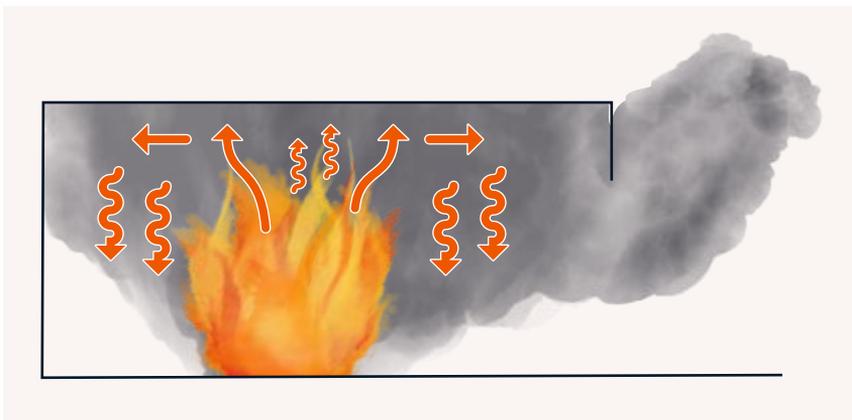


To assess the danger of fire gases, in addition to the color of the fire gases, it is also necessary to take into account, among other things, flow rate and the changes that occur over time. Photo: Åsa Brorsson.

In addition to being toxic and flammable, fire gases will primarily affect the environment through heat transfer. Fire gases normally have a higher temperature than the surrounding air and surrounding surfaces. This means that when hot fire gases flow past surfaces with a lower temperature, energy is transferred from the fire gases to the surfaces by convection.

A typical surface that is exposed to a lot of heat energy through convection is the ceiling of a burning building. Energy will also be transferred through thermal radiation, partly to the surfaces that the fire gases flow past, and partly to other surfaces and objects in the room. The hotter the fire gases are, the greater the proportion of energy that is transferred through thermal radiation.

**Figure 54.** Heat transfer from fire gases is of great importance for the spread and development of fires



Heat transfer to the ceiling and the upper parts of the walls occurs through convection and radiation. Heat transfer to the floor and other surfaces below the fire gases occurs primarily through radiation from flames and fire gases.

This means that the fire gases can affect surfaces and objects at great distances from the initial fire. The more fire gases and the hotter they are, the more the fire gases affect other surfaces and objects and the longer the distance they can be affected. This is especially true if the fire gases remain inside a building. Fire gases that can be vented out reduce the risk of fire spreading. Venting out fire gases naturally also has other advantages, such as reducing toxicity and reactivity inside the building and improving visibility.

The amount of fire gases produced will, of course, be of great importance, but the size of the spaces also determines how much they are affected by the fire gases. In a large room, the heat transfer is generally less, since there are more surfaces to be heated. The fire gases must simply be distributed over more surface area. The distance to objects in the room

also becomes greater, the larger the space. Consequently, the fire gases will affect a smaller room or space more than a larger one. In so-called structural fires, even small amounts of fire gases can contribute significantly to the spread of a fire, since spaces within the structure of buildings (walls, floors, etc.) are normally small.

## Deflagration, detonation and explosion

Three terms that are particularly used in the context of rapid fire events are deflagration, detonation and explosion.

### Explosion

An exothermic chemical process that, when occurring at constant volume, gives rise to a sudden and significant increase in pressure. The term is often used to describe when something ignites rapidly and creates pressure, often with an accompanying sound effect, an audible bang. An explosion is thus a rapid process that releases energy and gives rise to a pressure wave.

In a somewhat simplified way, one can say that explosion is the general term, which is generally used when something ignites rapidly and creates pressure. Also often with an associated sound effect, a loud bang. An explosion is thus a rapid process that releases energy and gives rise to a pressure wave. In the case of fires in buildings, this is normally not the case, but there are exceptions, such as in the case of so-called backdraft or fire gas explosion.

### Deflagration

Combustion where the reaction zone spreads slower than the speed of sound, for example a fire gas explosion. In a room fire, the flame front moves at a speed of approximately 3–5 m/s.

A deflagration can be said to be a rapid combustion where the combustion speed is below the speed of sound (approximately 340 m/s at room temperature and normal air pressure). The combustion speed can be high, energy is released but there is no significant pressure. Deflagrations can occur during a fire in a building, for example when premixed gas masses ignite and give rise to premixed flames. A deflagration can also give rise to sound, but in this case it is mainly the noise from the turbulence of the flames.

### **Detonation**

In a detonation, the reaction zone expands faster than the speed of sound. The process creates a shock wave and a loud bang. Detonations normally occur in solid explosives.

A detonation is then in a sense the opposite of deflagration – the combustion speed is higher than the speed of sound, and the detonation creates quite a lot of pressure and a bang. Most often, detonation occurs in solid materials (explosives), since it is normally only in solid materials that the combustion speed can be high enough to create a detonation. Note that the combustion speed in solid materials (explosives) is normally very high, up to several thousand metres per second.



Detonations occur primarily in solid materials. Photo: Johnér Bildbyrå.

Deflagration is the desired combustion process in, for example, an internal combustion engine, a rocket engine or a firearm. These can be damaged if a detonation occurs. Detonation is the desired process for explosives in, for example, mining.

# Chapter 7

# Enclosure fires

Everything that has been discussed so far is important for how a fire develops in an enclosure (a room), and eventually spreads to several rooms or to the rest of the building. In the following discussion, the starting point will be that the so-called initial fire, that is, the first fire that occurs, is relatively small. If no measures are taken, it grows larger, to encompass the entire room and ultimately the entire building. A fire that is already large in the initial stage will develop somewhat differently. An example would be if a large liquid spill ignites inside the building, but the basic factors that affect the development and spread of the fire are, of course, the same. It can happen that a flammable liquid leaks into a room and then ignites. Such a fire can develop very quickly. If the liquid has a low vapour pressure and thus evaporates at a low temperature, there may also be a flammable gas cloud in the room. This can produce explosion-like effects when ignited.

A room fire is always complex, as there are a number of factors that interact. For example, the availability of air in the room will affect how quickly the fire grows. At the same time, a lack of air supply to the fire in the room can cause more unburned fire gases to be produced. This increases the risk of the fire gases igniting, and also increases the heat radiation from the fire gases back towards the fire. Thus, there are factors that can both increase and decrease the development and spread of the fire at the same time.

## Fire in an object

We assume that we have a combustible object that is completely free in a large room or outdoors. When a fire occurs in this object, a number of things happen at the same time. The molecules that the fuel consists of are exposed to heat energy, and will then begin to break down and form combustible gases (pyrolysis). At the same time, the chemically bound energy in the fuel will be converted into heat energy and light as well as other chemically bound energy in the combustion products that are formed. Some of these combustion products will “go up in smoke”, that is, they mix with air and form fire gases. The remaining combustion products will remain in solid form. The heat energy that is developed will be transported back to the fuel to some extent so that it continues to burn. This heat transport back to the fuel occurs mainly through heat radiation from the flames towards the surface of the fuel. However, the majority of the developed heat energy will be transported away through the hot gases that are produced and rise. On their way up, these hot gases mix with the surrounding cooler air. This cooler air is then heated by convection and rises upwards together with the combustion products from the fire.

The combustion products together with the air that is mixed in form fire gases. These have a major impact on how fires spread in rooms and buildings. This is because fire gases can spread long distances and heat surfaces and objects through both heat radiation and convection.



The initial fire heats up the fuel that is not yet burning, so that flame spread in the fuel can occur. Photo: Stefan Svensson.

Depending on the shape or appearance of the fuel, convection can play a crucial role in heating fuel that has not yet ignited. For example, if it is a combustible board standing on its edge, the hot fire gases will flow upwards along the surface and heat the material by convection even when the flames are very small. At that stage, heat transfer by thermal radiation is still small.

As the flames grow, thermal radiation will increase, eventually becoming the dominant mechanism for heat transport to the part of the disc that is not yet burning.

If the adjacent fuel is not heated sufficiently for the fire to spread, it will eventually go out. A fire in the open air is considerably less complex and relatively easy to describe, since only the properties of the fuel and the availability of fuel affect the development and spread of the fire. However, if the object in which it is burning is located in a room, the process becomes more complex. Let us therefore assume in the following discussion that the initial fire, with its associated fuel, is located inside a room.

Batteries are one type of object that can pose a particular problem. Battery fires are a type of so-called high-energy fire. High-energy fires release a remarkably large amount of (heat) energy and can be caused by the properties of the fuel or by the oxygen source (air). There is no set definition of how much energy is required for something to be considered a high-energy fire, as it is not an officially recognised term (ISO, NFPA).



Battery fires can cause major problems. Photo: PerOla Malmqvist.

Battery fires have become increasingly common in recent years. This is partly due to the fact that batteries are found in more and more objects, and partly because product development is constantly increasing the amount of energy that a battery can store. In batteries, oxygen is chemically bound inside the components of the battery. If the battery is charged and therefore contains a large amount of energy, a battery fire can sustain itself for a long time. After all, there is then both fuel and oxygen and heat in the battery itself. Battery fires are also difficult to extinguish, since it is difficult to get into batteries and cool the burning surfaces. It has also been shown that battery fires develop large amounts of toxic fire gases in a short time and that they can give rise to flames under high pressure and with high temperatures.

If such battery fires occur indoors, this of course causes major problems, partly because of the fire gases that are produced, and partly because of the high temperatures that the flames can reach. In addition, battery fires can develop very quickly.

## Fuel control and ventilation control

A fire requires fuel and air to start and develop. The availability of fuel, as well as its properties, shape, appearance and location in the room, are important components that affect how the fire will initially develop. Moreover, the amount of air that the fire has access to is also often crucial for how the fire develops and spreads in a room and further in a building. We can categorise a fire in a room as fuel controlled or ventilation controlled. This is a simplified but functional division, which we can greatly benefit from in rescue operations. The final results of the operations can be greatly affected by how we handle the fire based on whether it is fuel controlled or ventilation controlled.

A fuel-controlled fire is a fire whose course is mainly controlled and affected by the properties of the fuel. A typical example is a fire in a garbage container that stands alone in the open. Note, however, that there may be areas in the fire where the access to oxygen in the air is limited, for example inside the fire itself. Such a fire is still classified as fuel-controlled, since the fire itself has free access to oxygen in the air. The fact that there are areas inside the fuel is about the shape and appearance of the fuel, not the fire's access to oxygen.

### Fuel control

A fuel controlled fire is controlled and influenced primarily by the amount, distribution and properties of the fuel. After ignition and during the early stages of the fire, the fire is normally fuel controlled. There is then sufficient air for combustion, and the development of the fire is controlled by the properties of the fuel and its location. A fire can also be fuel controlled at a later stage of the fire, during the cooling phase.



A fuel-controlled fire is a fire whose development is mainly controlled and influenced by the properties of the fuel. Photo: Stefan Svensson.

Even inside a room or other space, a fire can be fuel controlled. This is the case, for example, if the space is large in relation to the fire or if the fire is small in relation to the size of the space. Another example is if there are large or many openings to the space, so that fire gases can flow freely out of the space and air can flow freely in. However, if the fire no longer has free access to the oxygen in the air, the fire becomes ventilation controlled. This happens when the oxygen content drops below 21 percent.

A ventilation-controlled fire is thus a fire whose course is mainly controlled and influenced by the availability of oxygen in the air. In the case of a room fire, it is to a large extent the number of openings to the room and their size that control and influence the development of the fire. The distance between the fire and the opening or openings can also be of decisive importance.



A ventilation-controlled fire is a fire whose development is mainly controlled and influenced by the availability of oxygen. Photo: Stefan Svensson.

In a closed room, the fire “consumes” the oxygen in the air through the chemical reactions that occur, so that the oxygen content in the room drops. The oxygen participates in the combustion process and forms new compounds together with the combustible gases from the fuel. The fire then decreases in intensity. The flames become smaller and smaller as the content of freely available oxygen in the room decreases. If the room continues to be closed, the oxygen content drops to a level where flame combustion can no longer occur. This level is approximately 10–12 percent. The combustion process then continues, but then as an ember fire.



In practice, the degree of ventilation control is affected by how many and how large the openings are to the room where the fire is. Photo: Åsa Brorsson.

Even the ember fire consumes oxygen through the chemical reactions that occur during combustion. If the ember fire is allowed to continue and the room is still closed, the ember fire will eventually cease at an oxygen content of approximately 6–8 percent. The fire will self-extinguish. However, when the flame combustion ceases, we usually say that the fire will self-extinguish. The expression “self-extinguish” is therefore not entirely unambiguous.

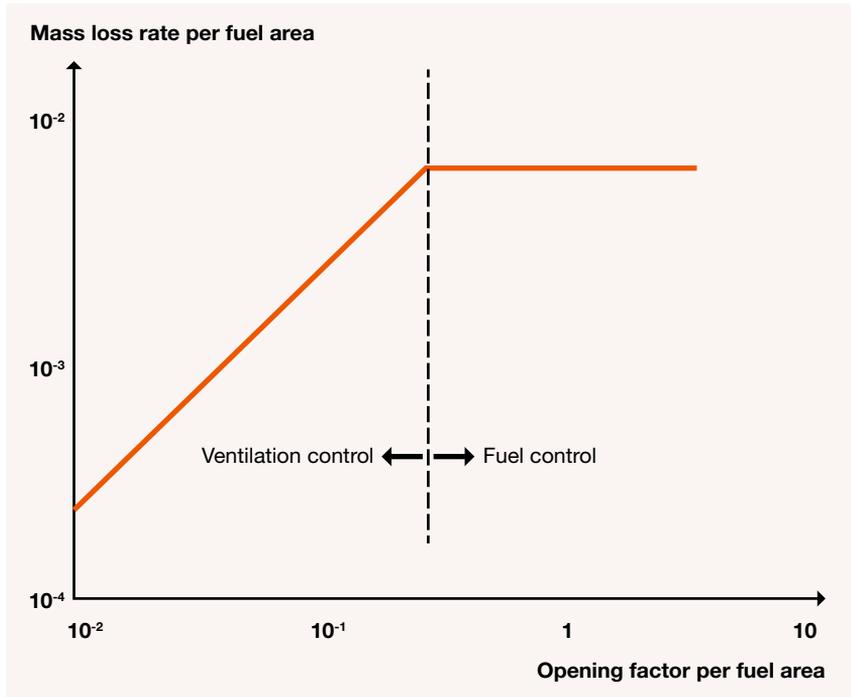
### **Ventilation control**

A condition where a fire is primarily controlled and affected by the amount of available air. In practice, this means that it is the number and size of openings in the room that are crucial to the development of the fire.

The oxygen content of the air is normally around 21 percent. As soon as the oxygen content drops below this level, the fire becomes ventilation controlled to some extent. Especially in small spaces, the temperature

can remain high. Pyrolysis can then continue, provided that there is enough fuel in the space and at least a small supply of air. The fire then becomes more and more ventilation controlled, while unburned combustion products (pyrolysis gases) continue to be produced in the space.

**Figure 55.** The relationship between mass loss rate and opening factor (after Harmathy, 1972)



The diagram shows that a fuel-controlled fire always has full access to air, while a ventilation-controlled fire can have a varying degree of access to air, but always less than the normal oxygen content of the air (approximately 21 percent).

A fuel-controlled fire has full access to air. In other words, there is about 21 percent oxygen in the incoming air, but normally the oxygen content begins to drop when a fire occurs in closed rooms of so-called ordinary size, such as a kitchen or bedroom, and then the fire becomes ventilation controlled. A fire can be ventilation controlled to varying degrees. The fire becomes more and more ventilation controlled as the oxygen content in the air drops. If the fire has been going on for a long time or if the space is very small, we sometimes speak of a heavily ventilation-controlled fire.

A fire can occur with a deficit of air. This does not necessarily mean that the fire is ventilation-controlled. An open-air fire is normally fuel-controlled. However, if the fire is very large, a large part of the combustion will occur with a deficit of air because the oxygen in the air cannot reach the interior of the fuel. Ventilation-control may occur for fires that are enclosed in some kind of space, such as a room. It is then the size and number of openings that determine whether the fire is ventilation-controlled or fuel-controlled. However, an open-air fire is normally considered fuel-controlled, even if the combustion efficiency is low due to poor air supply to the interior of the fire.

### Opening factor

The term opening factor is used to describe the ventilation conditions in a room. The opening factor gives us a relationship between the size of the openings, their height and the size of the room. The smaller the opening factor, the smaller the fire required for it to be ventilation controlled. The opening factor has also been shown to have a major impact on, among other things, the temperature in the fire room.

**Figure 56.** The opening factor can be used to describe the ventilation conditions in a room

$$\text{Opening factor} = \frac{A_0 \sqrt{H_0}}{A_t}$$

**A<sub>0</sub>** Area of opening

**H<sub>0</sub>** Height of opening

**A<sub>t</sub>** Surrounding area of the enclosure

The opening factor is used, among other things, to dimension the load-bearing structure of buildings. It can be used to calculate maximum temperatures in a fire compartment. The smaller the opening factor, the lower the temperature in the fire compartment. The temperature in a fire compartment is important for how long a building structure can withstand fire before the structure collapses.

Calculating the opening factor is particularly simple for a single room with only one opening. In cases where there are several openings to the room, the total opening area and an average value of the height of the openings can be used. However, the more openings there are or if they have different heights, the more uncertain the result will be.

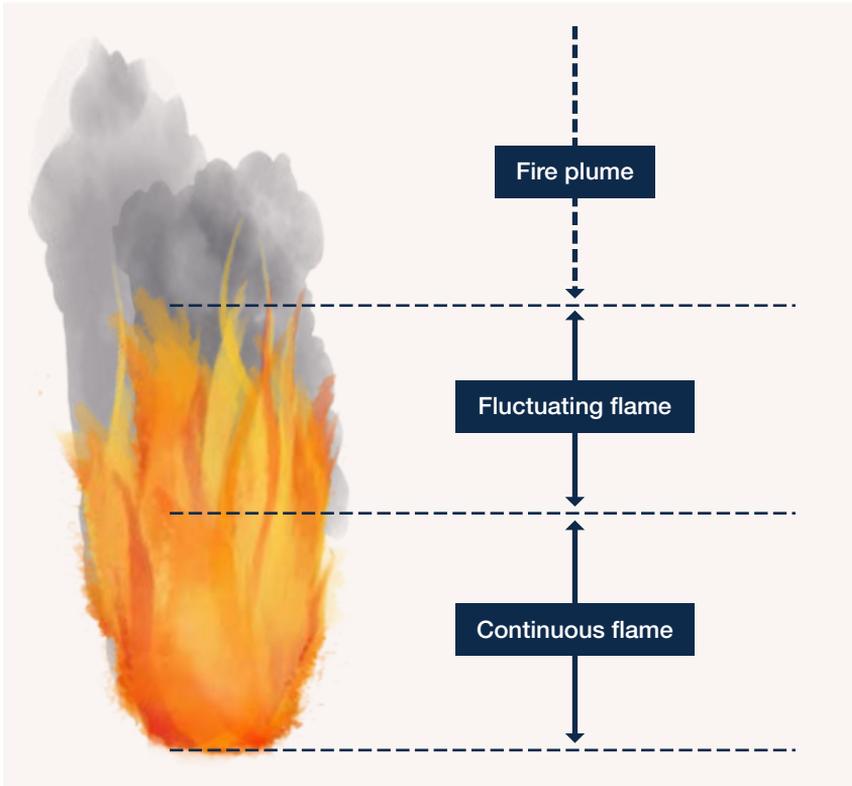
## Fire plume

The fire plume is the hot gas stream that forms in and above a flame. The properties of the fire plume are primarily dependent on the size of the fire, that is, the heat output a fire develops. In a fire room, the fire plume can be divided into three areas:

- the area near the flame base, with the continuous flame
- the area with uneven flame (we usually say that flames “flutter”)
- the gas stream above the flame, characterised by gas velocity and temperature decreasing with height.

It is primarily the gas stream above the flame that is meant when we speak of fire plumes. This part constitutes the largest part of the fire plume.

**Figure 57.** The fire plume is the fire gases that flow upwards and are directly connected to the fire



The temperature and gas velocity inside the fire plume are directly dependent on how much heat the fire source emits and the height above the fire source. The mixing of ambient air increases the mass flow in the plume, that is, the amount of combustion products and air. The temperature and velocity of the fire plume decrease with height. A candle affects the air flow about one metre above the flame. For a large fire in, for example, a warehouse, the fire plume can be a couple of kilometres high, before the fire gases have diluted and cooled and disappear with the wind.

## The initial fire and the early stages of fire

Let us now return to a fire in a space. A fire starts in an initial (starting) object. It could be a sofa, cooking oil in a pan on a stove, a computer or some other object. The cause of the fire will not be further elucidated in this book, but the starting point is that some form of energy conversion occurs that results in heat generation and fire. It could be kinetic energy that produces friction, which in turn produces heat. It could also be electrical energy that produces heat energy, for example due to a short circuit. With a starting object and a cause of fire, the fire has started and we have an initial fire.



When a fire occurs in an object in a room, this is usually referred to as an initial fire.  
Photo: Johnér Bildbyrå.

The heat generated during ignition gives rise to a fire, provided that there is sufficient fuel that is combustible and sufficiently flammable. The continued development of the fire is also determined by the presence of additional fuel in the vicinity of the initial fire. If not, the fire can self-extinguish as the fuel runs out. It must therefore be possible for a flame to spread. This can occur either through pyrolysis in more or less continuous fuels, by the flames of the initial fire heating up nearby objects so that they ignite, or by the fire gases that are formed igniting.

If the fire gases are produced and accumulated in sufficient quantities, with a certain minimum temperature and with a certain combustible content, the fire can spread via the fire gases.

The properties of the surrounding surfaces also affect whether and how the initial fire spreads. For ceiling and wall materials with low thermal inertia, the heating of the surfaces, and thus also the heat radiation from these back to the initial fire, can initially be higher. The initial fire then grows faster than if the ceiling and wall materials had a high thermal inertia.



The early stages of the fire. Photo: Stefan Svensson.

The fire gases affect the further development of the fire in the room, as they heat up surrounding surfaces. The heating occurs partly through convection when the hot fire gases flow past surfaces in the room, for example a ceiling, and partly through heat radiation towards the ceiling, walls and objects in the room, such as furniture and other furnishings. The hotter the fire gases become, the more heat transfer occurs through heat radiation, and the more particles (soot) the fire gases contain, the more heat transfer occurs through heat radiation. For completely transparent fire gases, heat transfer occurs largely through convection. Heat transfer also occurs through heat radiation outside the visible range of the electromagnetic spectrum, mainly through IR radiation (radiation in the infrared spectrum).

### **The early stages of the fire**

The period from the start of a room fire until flashover occurs. During this period, the fire is normally limited to one or a few objects in the room.

The properties of the fuel also affect the early course of the fire through, among other things, the amount and type of fire gases produced. Porous and fibrous materials, such as wood, cloth and foam plastic, can contribute to a faster development because such materials often pyrolyse faster and with lower radiation exposure. Some plastics can also contribute to a faster development and a faster spread of the fire. This is because they can melt, drip onto other materials or form puddles of fire that can even run away. The radiant heat emitted from flames during a fire can also cause plastic objects at a relatively large distance from the fire to soften or melt and also to begin to pyrolyse, without directly participating in the fire. The molten material can then be ignited by heat radiation from the fire, by burning droplets, or by a burning object falling into the molten material. In this way, molten plastic behaves somewhat like a flammable liquid.

As previously described, some fuels produce more unburned pyrolysis gases or larger amounts of combustion gases than others. For example, methanol produces both smaller amounts of unburned gases and smaller amounts of soot than a burning car tire. However, if the combustion occurs with poor air supply, the initial fire can quickly become ventilation controlled, so that combustion efficiency becomes very poor. In such cases, large amounts of unburned combustion products can be produced from most types of fuel.



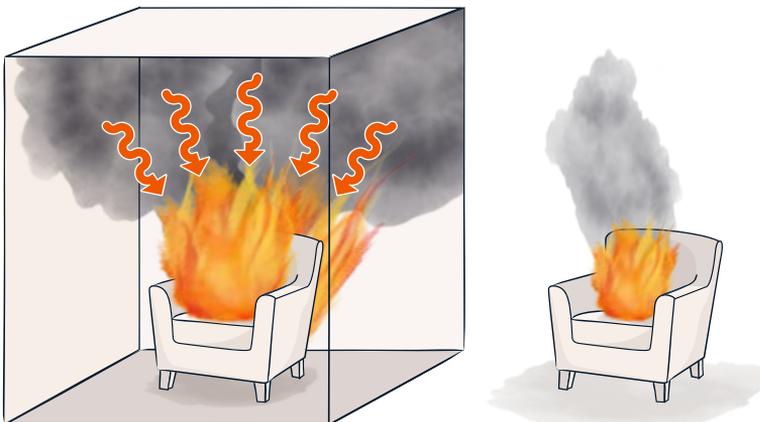
Porous materials with lower thermal inertia are affected more quickly by a fire and may therefore ignite faster. The wooden frame of the armchair, which has a higher thermal inertia, ignites more slowly. In the picture, the wooden frame is almost unaffected, as more energy is required for it to pyrolyze. Photo: Stefan Svensson.

The shape, appearance and location of the fuel in the room affect the spread of fire. A fire in a chipboard that is lying flat on a floor and ignites in the middle will spread slowly outwards. The flame spreads slowly across the material, since heat transfer mainly occurs through heat radiation and there is a large distance between the flame and the surface. The parts of the chipboard that are not yet burning are then affected almost exclusively by heat radiation from the flames. If the chipboard is instead standing up, the flame spreads across the board more quickly. This is because both

the fire gases formed and the flames heat up the surfaces above, through convection and heat radiation. If the flames are closer to a surface, the heat radiation to the surface is much greater. The flame spreads across the board most quickly if it is on the ceiling, with a fire on the underside. How much radiation hits a surface depends on the distance to the object from which the radiation comes. The fire grows larger faster, which means that the entire room and other objects in the room heat up faster. The spread of fire in the room, to other objects, also occurs faster.

The location of the fuel in the room also affects the course of the fire. For example, if a burning armchair is next to a wall, the wall heats up faster than if the armchair is in the middle of the room. This happens partly through convection when the fire gases flow past the wall, and partly through heat radiation from the fire. As the wall heats up, it will radiate back onto the armchair. The armchair, including the parts of it that are not yet burning, heat up faster and pyrolysis increases. The fire then increases in intensity faster, meaning that the rate of heat release increases faster. In addition, the wall can also start to pyrolyse and contribute to the growth and spread of the fire. Even a non-combustible wall made of concrete or plaster normally has a combustible surface layer in the form of wallpaper or paint. Such a thin layer can be sufficient for flame spread to occur over the surface.

**Figure 58.** The location of the fuel in the room affects the development and spread of the fire



In the figure on the left, the fire is affected partly by radiation from the flames and partly by radiation from the fire gases and from hot roof surfaces. In the figure on the right, the fire is affected only by the flames.

If the fuel is placed against a wall, the wall restricts the flow of air to the fire. When less air is mixed in, the reactions in the flame proceed more slowly, and the temperature of the fire gases does not drop as much with height. The flame then stretches out and becomes higher. In addition, combustion is limited due to the reduced air supply. The flame becomes higher so that combustion can be more complete. This means that heat radiation towards the wall increases faster, and that heat radiation towards other surfaces and objects in the room becomes greater (because the flame becomes larger and the fire gases hotter). The surfaces and objects in the room heat up faster, and the fire can then also spread faster in the room. If the fire is in a corner, the air supply is further restricted, with the consequence that the flames become even higher.



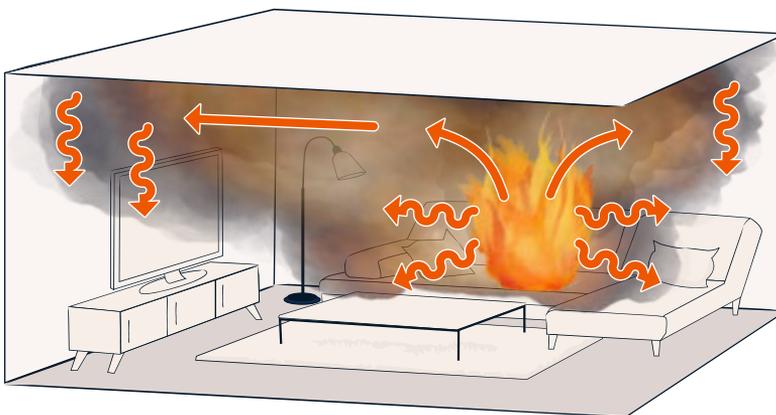
Flames in a corner will be higher than in the middle of a wall or in the middle of a room.  
Photo: Stefan Svensson.

As the initial fire progresses and spreads in the room, more fire gases are also formed. Note that the initial fire is normally fuel controlled, even if the room is completely closed and provided that the fire does not grow too quickly. There is still enough oxygen in the room, that is, approximately 21 percent. This changes when the oxygen content in the room begins to drop. How quickly the oxygen content drops depends, among other things, on the size of the room and on how quickly the fire grows, that is, how quickly the rate of heat release increases.

The fire gases formed from the initial fire rise towards the ceiling, because they are hot and have a lower density than the surrounding air in the room. They hit the ceiling and spread. The spread of these initial fire gases under a ceiling is sometimes called a ceiling jet. It is the ceiling jet that should normally activate smoke alarms, smoke detectors and sprinklers. Gradually, a so-called fire gas layer is formed closest to the ceiling in the room, that is, a layer of hot fire gases. The fire gas storage tank gradually fills up and the underside sinks towards the floor.

This layer of smoke gas contributes to the heating of all surfaces in the room, including walls, ceilings and loose objects in the room. The heat transfer from the smoke gases to such surfaces occurs partly through convection, that is, the hot smoke gases flow past colder surfaces. This heat transfer occurs primarily towards the ceiling, but also towards those parts of the room walls that are encountered by smoke gases. As the layer of smoke gas fills up, the smoke gases will affect the walls of the room further and further down. The heat transfer from the smoke gas layer also occurs through thermal radiation. This then affects all surfaces that are exposed to the smoke gases. The closer an object is to the smoke gases, the more heat energy is transferred through thermal radiation, and the hotter the smoke gases become, the more heat is transferred to surfaces and objects in the room, through both convection and thermal radiation.

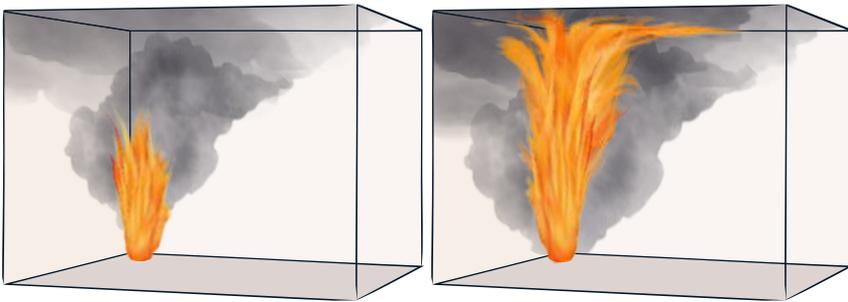
**Figure 59.** The fire gases rise upwards, spread under the ceiling and heat up the surfaces of the room



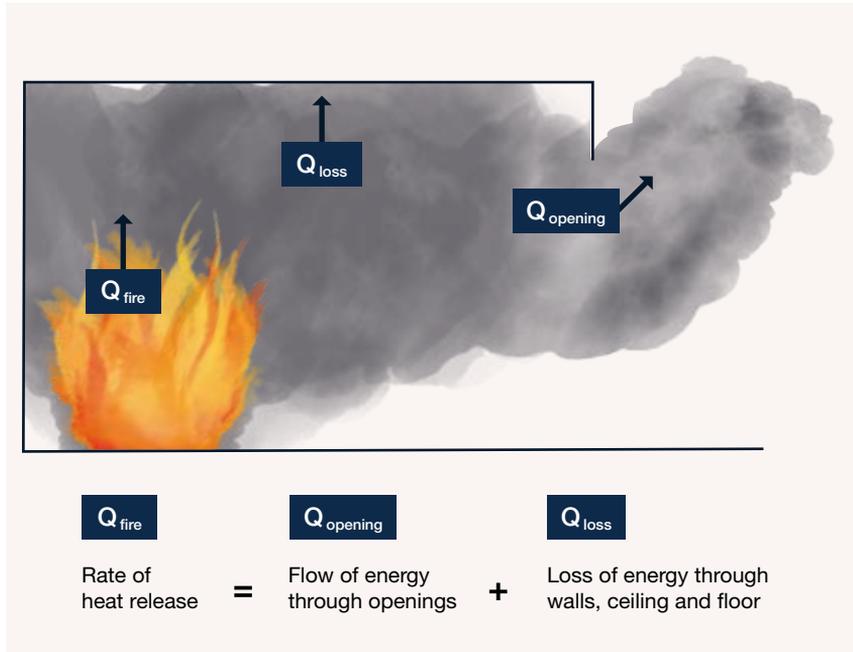
During the early stages of a fire, heat transfer to the ceiling occurs primarily through convection. Heat transfer to other surfaces in the room occurs primarily through radiation from the fire gases. The higher the temperature of the fire gases, the more heat transfer occurs through radiation.

The most important thing in this process is thermal radiation. Both from heat conduction and convection, heat transport is proportional to the temperature difference: a small increase in temperature gives a small increase in heat transport. With thermal radiation, it is different. It increases with the temperature raised to the power of four, which means that even a small increase in temperature gives a sharp increase in thermal radiation.

**Figure 60.** When the flames reach the ceiling, they bend and follow the ceiling



When the flames reach the ceiling, they bend and follow the ceiling. This causes the heat radiation from the flames to increase towards the ceiling, the floor and the upper parts of the walls. The heating of the room surfaces then occurs more quickly, the pyrolysis of combustible materials increases, and the fire now begins to spread more rapidly.

**Figure 61.** Energy balance for a room fire

Since energy can neither be created nor destroyed, there must always be a balance in the room, a balance between both energy and mass. The energy that is developed when the fuel burns will heat up the surrounding surfaces of the room (ceiling, walls and floor). At the same time, the energy flows out of the room with the fire gases that are formed in the fire. In addition, a certain amount of energy is returned back to the fuel, so that the fire can continue. The sum of the energy that flows out of the room, the energy that is transferred to surfaces and objects and the energy that is returned to the fire in the room, corresponds to the energy developed by the fire. The mass in the room is the same. The fire gases that flow out of the room must be replaced by air that flows in. Energy and mass in the room must always be in balance. These two mechanisms are the main causes of, among other things, the flow of fire gases in and out of a building.

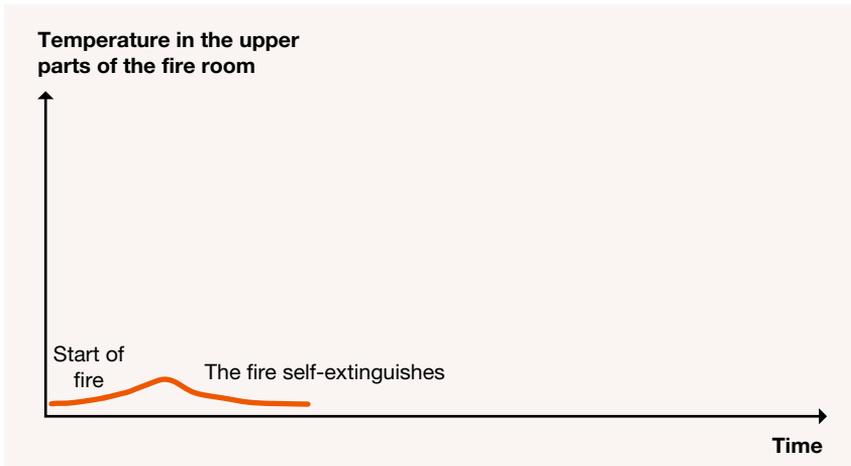
## The continued course of the fire

Generally, the initial fire can develop in three different ways:

1. **The fire extinguishes itself.**

This can happen if there is not enough fuel in the room, if there are too large distances between different fuels, if not enough fire gases are formed or if the room is completely closed so that the oxygen content drops below approximately 10–12 percent. Note, however, that even if the fire extinguishes itself, the fire gases produced can be sufficient to kill a person.

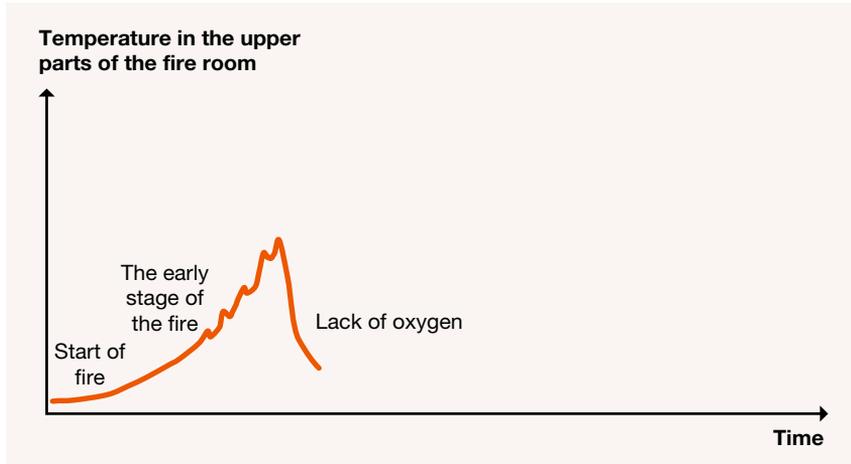
**Figure 62.** The fire self-extinguishes



2. **The fire decreases significantly in intensity, but continues to burn.**

This can happen if there are insufficient ventilation openings to the room (windows, doors, etc.) so that only a limited amount of air can flow into the fire. The fire can then continue for a very long time and possibly continue to produce large amounts of pyrolysis gases. This type of fire can lead to, among other things, so-called backdraft, which will be discussed later, but it can also happen that the fire resumes its course if a door or window is opened or if a window breaks as a result of the heat from the fire. The development of the fire can then proceed very quickly, since there is a large amount of unburned fire gases and there may be a lot of heat in the room. This is sometimes referred to as a ventilation-induced flashover.

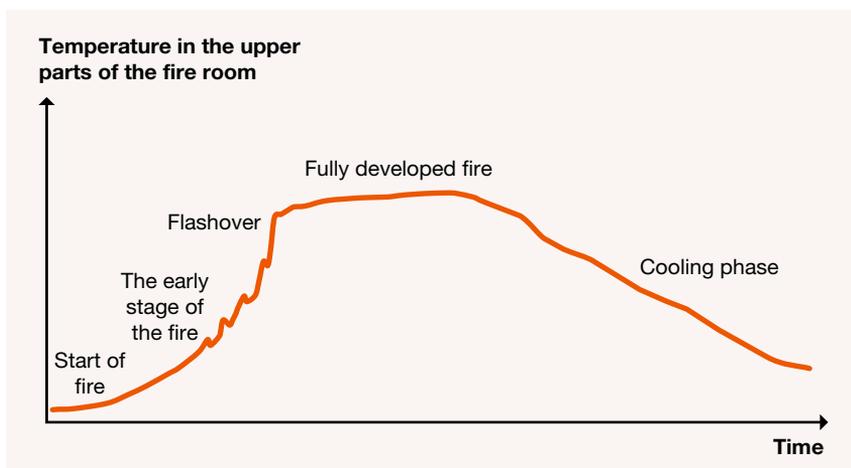
**Figure 63.** The fire is greatly reduced in intensity, but continues to burn



3. **The fire process transitions to a flashover, which results in a fully developed room fire.**

This can happen if there is enough fuel (objects or flammable surfaces) in the room, if fire spread between these objects can occur and there are enough ventilation openings so that air can flow in. This is a basic scenario that is relatively easy to explain and describe.

**Figure 64.** The fire progresses to a flashover, resulting in a fully developed room fire



Case 2 and case 3 are quite similar, and the differences between them can often be difficult to define. The major difference may be the rate of fire spread, since the surfaces and objects in the room will probably be more heated in case 2 than in case 3. It can be difficult to distinguish in practice between different types of rapid fire progression, especially when it is fire gases that are ignited. The differences are often subtle, while definitions and explanations are based on well-controlled experiments in laboratory environments.

If there is still enough air in the room, surfaces and objects in the room will eventually become so hot and produce so much pyrolysis gases that they will ignite in a relatively short period of time. This is especially facilitated if there are one or more openings through which air can flow in.

We have then reached the stage in the fire called flashover, that is, case 3 in the description above. The other two cases will be discussed in more detail later.

## **Flashover**

If the initial fire is allowed to continue and has sufficient oxygen to grow, a stage will occur where the radiation from the fire, the hot gases and the hot surfaces cause all combustible surfaces in the fire compartment to pyrolyse and ignite. This stage of rapidly increasing fire is called flashover, and it is closely related to the early fire progression and the fully developed fire.

Time 2:11



Enclosure fires

Time 2:14



Time 2:17



Time 2:19



During a room fire, the thermal radiation from the fire, the hot gases and the hot surfaces may cause all combustible surfaces in the fire compartment to pyrolyze and ignite. This sudden and continuous transition stage of increasing fire is called flashover. The time shown is given in minutes and seconds from ignition.  
Photo: Lars Axelsson.

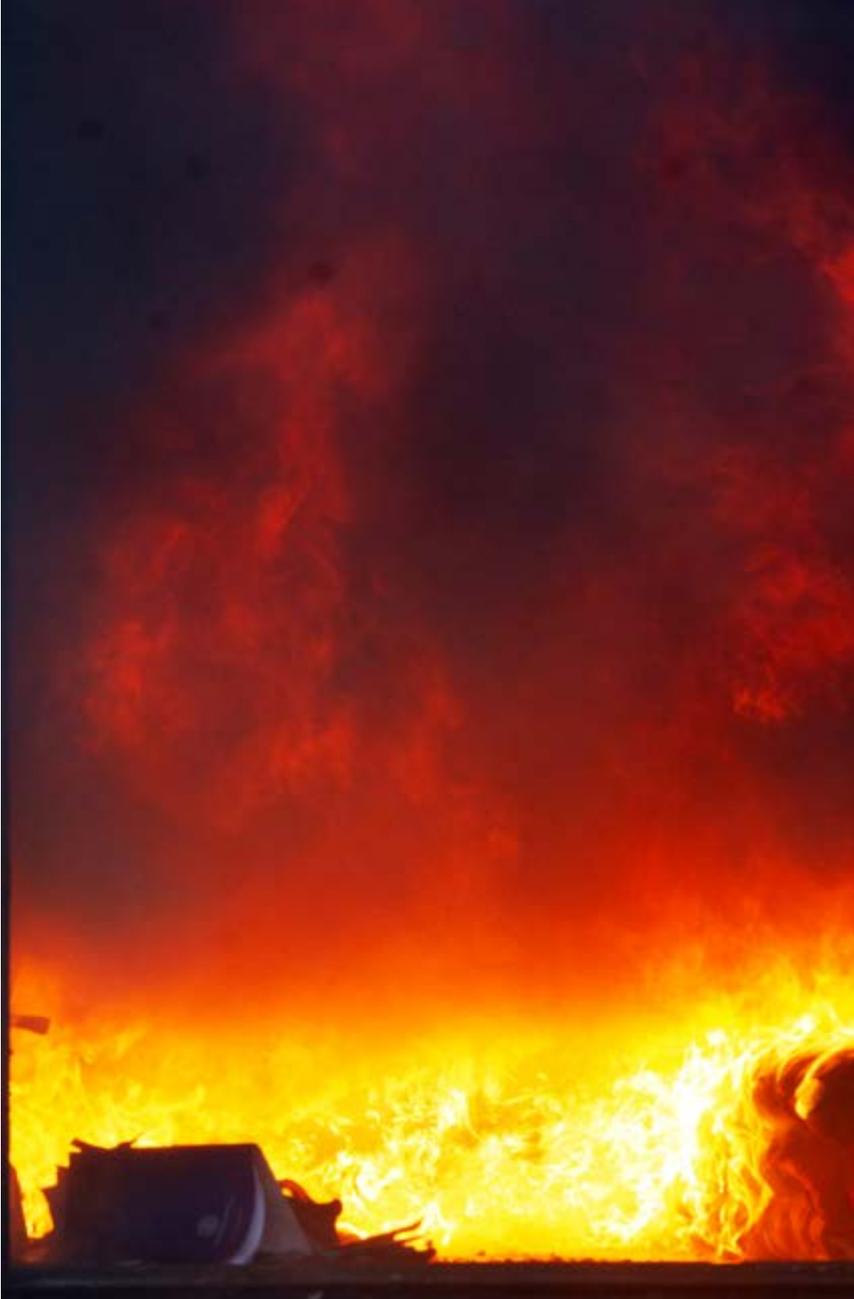
When the flashover occurs, the fire changes from being fuel controlled to being ventilation controlled. If it was ventilation controlled before the flashover, it changes to a higher degree of ventilation control. There is now no longer enough air in the room for all the pyrolysed fuel to burn. Of course, some flame combustion can still occur inside the room, depending on how much air can flow into the room. The temperature in the room is still very high, which means that large amounts of pyrolysis gases continue to be produced. The flame combustion of these gases takes place largely outside the room, even though the basic chemical reactions for combustion take place inside the room.

### **Flashover**

A stage in a room fire where the thermal radiation from the fire, the hot gases and the hot enclosing surfaces cause all combustible surfaces in the fire compartment to pyrolyse and ignite. This sudden and continuous transition stage of increasing fire is called flashover.

A clear sign that flashover is occurring or has occurred is that the fire gases flowing out through openings ignite. It will then burn with strong flames out through the openings of the room (doors and windows). It is then no longer possible to survive inside the room, partly because of the temperature, partly because of the large amount of combustion products (pyrolysis gases).

Flashover is thus not a special phenomenon, but rather a transitional period. The fire changes from being fuel controlled and burning only in one or a few objects to becoming ventilation controlled (to a high degree) and involving all combustible surfaces in the room. After flashover, a large part of the flame combustion takes place outside the room, since there is not enough oxygen in the room for complete combustion to occur. On the other hand, the temperature is often high, and extensive pyrolysis takes place inside the room.



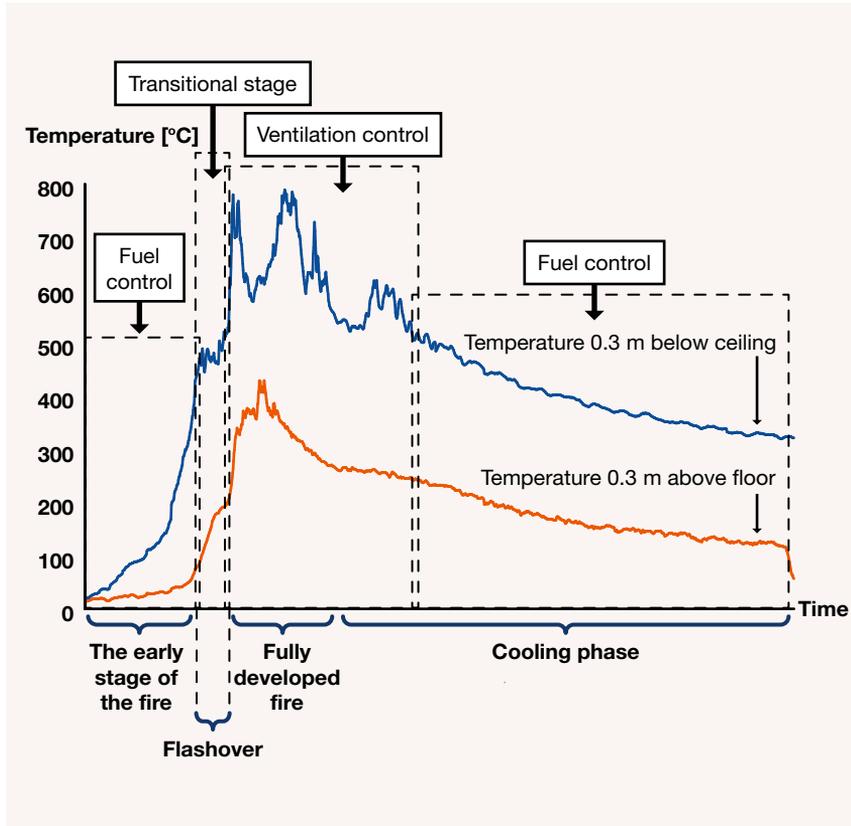
A flashover is a transitional stage from the fire being fuel-controlled to the fire becoming ventilation-controlled. Photo: Stefan Svensson.

This description assumes that the fire is initially and during growth fuel controlled, that is, that there is sufficient access to air in the room. When the flashover occurs, the fire becomes ventilation controlled. The unburned gases then burn outside the room, which is visible in the form of flames through openings.

In order for a flashover to occur, the initial fire must be able to grow large enough and have a sufficiently high rate of heat release, so that extensive pyrolysis of the room's surfaces can occur. This rate of heat release depends, among other things, on the size of the room, the thermal properties of the walls and the ventilation area. A sufficient amount of fuel and fuel surface are required to produce this rate of heat release. Often, the rate of heat release is large enough to cause a flashover in homes or offices, but it happens that the initial fire instead goes out due to a lack of fuel.

Since flashover is a stage, it is difficult to specify a precisely defined time for when it occurs or how long this stage is. The criteria used are primarily the temperature in the fire gas layer and the thermal radiation to the floor, something we do not have the opportunity to measure in connection with fire and rescue operations. However, the speed at which the temperature increases during the flashover period can be very high. In a few seconds, the temperature can increase by several hundred degrees.

Generally, it is said that when the temperature is above approximately 600 °C in the upper gas layer, a flashover has occurred. Similarly, it is said that when the radiation level towards the floor exceeds approximately 20 kW/m<sup>2</sup>, a flashover has occurred (for normal ceiling heights, approximately 2.5 m). However, the clearest criterion for a flashover is that flames are pushing out through openings. Note that flames can also push out through openings for other reasons, for example, that there is a burning sofa right inside a window. It can then be easy to make an incorrect assessment of the situation.

**Figure 65.** Example of how temperature develops in a fire room

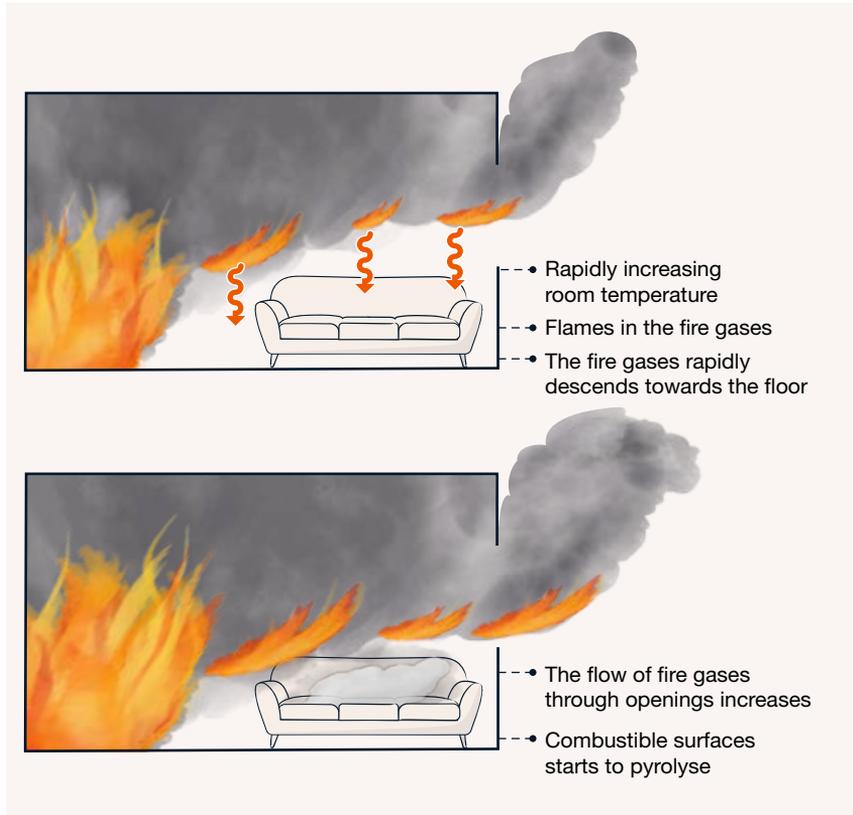
The definition of flashover is largely based on experiments in controlled environments, although there is also a large amount of experience that says the same thing. In real cases, it can be difficult to determine when a flashover occurs and what the process looks like. The definition has been somewhat vague in order to be directly used in practical contexts, and as a consequence of this, different interpretations of what flashover means have arisen. Often, these interpretations have arisen when observing the phenomenon in combination with a lack of knowledge about the basic factors that control and influence the development of fire in rooms. Expressions such as rollover, lean flashover, spreadover and flame-over have been used, especially internationally, to replace or supplement the word flashover, without any unified structure. This indicates that flashover is a phenomenon that can be difficult to identify and understand.

We therefore need to have good knowledge about the factors that influence how a fire develops in rooms in order to be able to make good assessments in connection with fire and rescue operations.

There are thus a number of explanations and descriptions of the phenomenon of flashover, most of which are largely based on experiments under controlled conditions. In general, it can be said that a flashover is characterised by:

- a transition from a local fire in one or a few objects to all combustible surfaces in the room being involved in the fire
- a transition from the fire being fuel controlled to ventilation controlled
- fire gases that are suddenly lowered towards the floor and increase both the thermal radiation towards the objects and surfaces in the room and the convection towards the upper parts of the room
- a sudden ignition of and flame spread in the fire gases that have collected in the upper part of the room, with a sharp increase in thermal radiation towards the surfaces of the room as a result.

The last two characteristics are important to remember, as they indicate that the combustion gases are an important component for flashover to occur. A fuel that does not produce any large amounts of combustion gases rarely leads to flashover in the space. With flames in the combustion gases, a rapid increase in temperature occurs. It is this increase in temperature that provides the driving force in the flashover process. When the temperature in the combustion gases increases from, for example, 300 °C to 600 °C, this means an increase by a factor 2. At the same time, the thermal radiation from the combustion gases increases with temperature raised to the power of four, which is a very large increase in thermal radiation.

**Figure 66.** Signs of impending flashover

A flashover always leads to a fully developed room fire, and the fully developed room fire is consequently ventilation controlled.

## The fully developed room fire

After a flashover has occurred, all objects and surfaces in the room are involved in the fire. The temperature is high, the fire is ventilation controlled, flames break out through openings and large amounts of pyrolysis gases are formed inside the room. The fire is now fully developed. During this stage, a large part of the flame combustion takes place outside the room. This is because the fire is ventilation controlled at the same time as the fire produces an excess of combustible gases.



A fully developed room fire is ventilation controlled. Photo: Åsa Brorsson.

Since the fire is ventilation controlled, not all of the pyrolysed fuel inside the fire room is combusted. A large part burns on the outside after being mixed with more air there: flames push out through the openings of the room. The fully developed room fire can last for a long time, sometimes for several hours, largely depending on the amount of fuel in the room. This also assumes that the construction surrounding the fire room does not give way. Temperatures of 800–900 °C are common, but the temperature depends on the size and number of openings. Opening factor can be used to describe ventilation-controlled fires. It provides a measure of the size of the openings in relation to the enclosed area of the room. The opening factor also affects the mass loss rate in the room and also provides a measure of rate of heat release. As long as there is fuel in the room and oxygen is available for combustion, the temperature remains at this level. If the opening factor is known, it is possible to approximately calculate the rate of heat release in the room.

At this stage, there is normally no possibility of survival in the room. Even with adequate protective equipment, it is not possible to survive for any length of time, in practice only a few seconds. During a fully developed room fire, the thermal radiation from the fire towards the surrounding surfaces of the room is very high. The thermal radiation then comes mainly from the hot and sometimes burning fire gases that are formed in the room, but also from any flames in the space. When the surfaces in the room are heated due to thermal radiation, the heat is conducted into the walls, ceiling and floor construction. In some cases, the heat conduction through walls, ceiling and floor can be so strong that the fire spreads to combustible material on the other side.

### **Fully developed fire**

A stage that occurs after flashover has been reached. The fire is then ventilation controlled. Flames come out through the building's openings. A large part of the combustion takes place outside the room.

When the fire is fully developed, the load-bearing capacity of the building can become a problem. The longer the fire is allowed to continue, the greater the risk that the building's load-bearing parts will collapse. The heat that is conducted into the structure affects the materials in the structure. The load-bearing capacity of buildings is designed to withstand fire for a certain period of time. The load-bearing structure is dimensioned differently depending on the type of building. It is common to classify buildings as being able to withstand fire for up to several hours, but depending on the nature of the fire, this time can be considerably shorter. However, it is unusual for buildings to collapse completely. However, more or less local collapses can occur, steel beams can be distorted or roofs can collapse.



The longer the fire is allowed to continue, the greater the risk that the building's load-bearing parts will collapse. Photo: Åsa Brorsson.

The fully developed fire in a room is affected by, among other things:

- fuel
  - quantity, type, density, shape and location
  
- oxygen
  - size, shape and number of any opening
  
- heat transport and heat transfer
  - which in turn is affected by the shape of the room, the size of the room surfaces and the thermal properties.

The fully developed fire continues as long as there is fuel available. When the fuel starts to run out, the fire enters the so-called cooling phase. The fire then becomes fuel controlled again, as more air can flow into the room than is required to burn the combustible gases that are formed. Note, however, that for now we are assuming that only one room is burning and that this room does not collapse due to the fire.

## The cooling phase

When the fuel in the room starts to run out, the fire enters the so-called cooling phase. The fire then becomes fuel-controlled again. If the fire is not extinguished, the cooling phase can last for a long time, often several days. During this stage, smouldering fires are very common.

However, the reality is more complex. It is rare for a room fire to reach the cooling phase, as it has most likely spread to other parts of the building by then and the building has more or less collapsed. Such processes also lead to cooling in themselves, but the fire compartment is then no longer intact and we can no longer speak of a room fire.

### Cooling phase

The period after a fully developed room fire, when the temperature drops and the fire once again becomes fuel controlled.

If the fire service has made an effort and extinguished the fire, there can be no talk of a cooling phase either. From a scientific perspective, the description of the fire's cooling phase is based on the fact that the fire is allowed to develop and spread completely without human intervention, that it does not spread outside the initial fire room and that the room is intact. If the fire spreads to several rooms, a cooling phase may also occur, but this case is also based on the fact that the fire does not spread outside these rooms and that these rooms are intact.



The fire's cooling phase is based on the fire developing and spreading completely without human intervention, but the fire does not spread outside the initial fire compartment.  
Photo: Stefan Svensson.

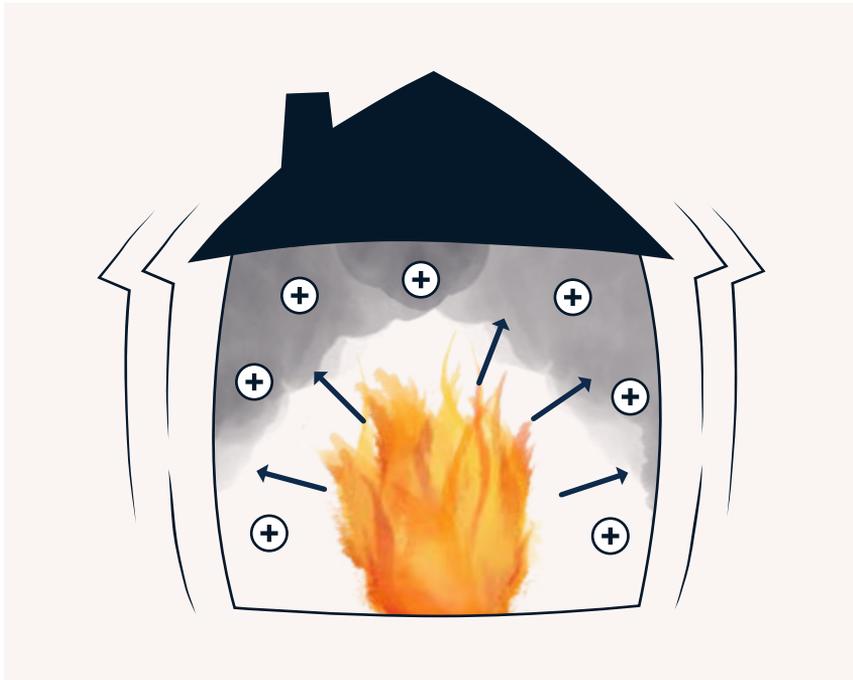
Even if the fire has spread to the entire building so that it has burned down to the ground, one could speak of a kind of cooling phase. The fuel is then running out, but the fire has gone from being a room fire (or a fire in a building) to being a fire in the open, roughly like a fire in a single object. The term cooling phase cannot then be used in the same way as for a room fire.

## Pressure in fire rooms

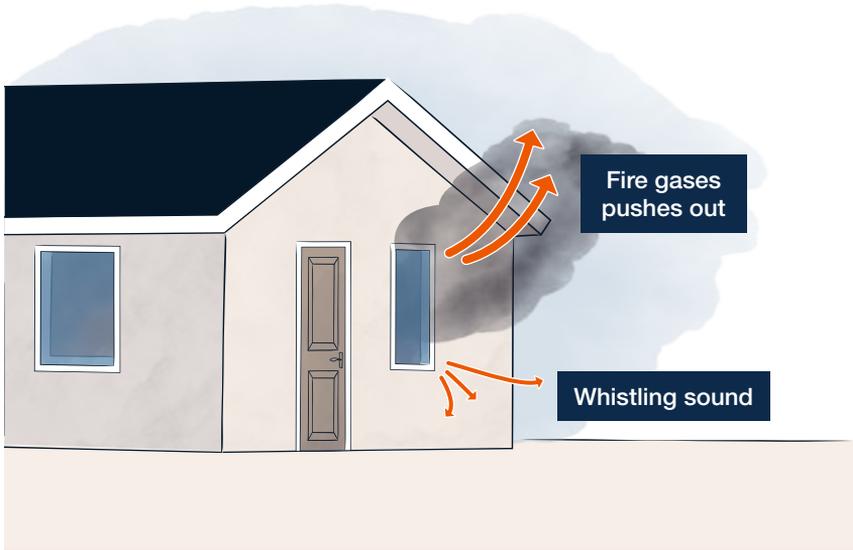
During combustion, energy is released. This energy causes the temperature to increase, that is, the molecules move faster. The molecules then need more space, which means, among other things, that the hot fire gases take up more space the hotter they become. The fire gases expand. In addition, they then become lighter than the surrounding (colder) air, which causes the fire gases to rise upwards. The density of hot air (and hot fire gases) is lower than that of cold air.

In a fire in a completely closed room, an overpressure builds up as a result of the air heating up and expanding. There does not have to be a fire for such thermal expansion to occur, but in spaces without a fire, the pressure build-up is small. In a fire, where the temperature can reach many hundreds of degrees, however, this pressure difference can have a considerable impact, especially if the fire develops and grows quickly. If a fire occurs in a completely closed room, there is also no exchange of gases or particles (mass) with the surroundings.

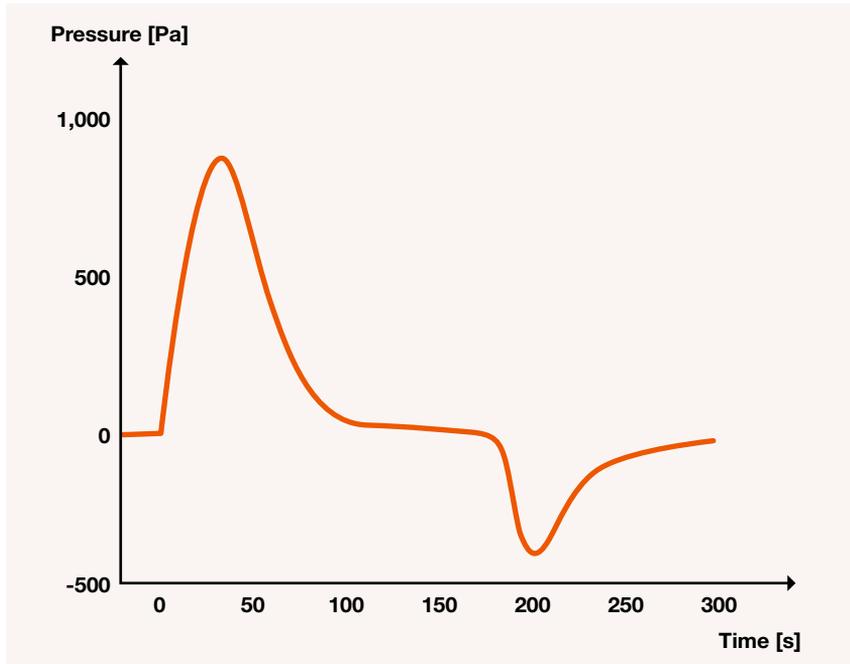
**Figure 67.** In the event of a fire in a completely closed room, pressure builds up



**Figure 68.** External signs of thermal expansion



There is usually some air leakage in the fire room, for example in the form of comfort ventilation or leaks around windows and doors or in other structural details. Since a fire in a room normally grows, the pressure is gradually equalised due to leaks and leakage. The pressure increase is therefore only in the order of a few Pascals, if there is any pressure increase in the room at all. This depends largely on the size of the openings in relation to the rate of fire growth, but time also plays a role, as pressure equalisation occurs over time. If there are no openings at all or if the openings are very small, the pressure in the room or building can briefly be several hundred Pascals.

**Figure 69.** Example of pressure build-up in a completely closed fire apartment

Immediately after ignition, the pressure rises rapidly. The pressure is then equalized due to the leakage surfaces that are normally found at windows and doors and via ventilation. When the fire becomes ventilation-controlled, the intensity of the fire decreases, the temperature drops and the pressure becomes negative so that air is sucked in.

Source: Rein, 2007

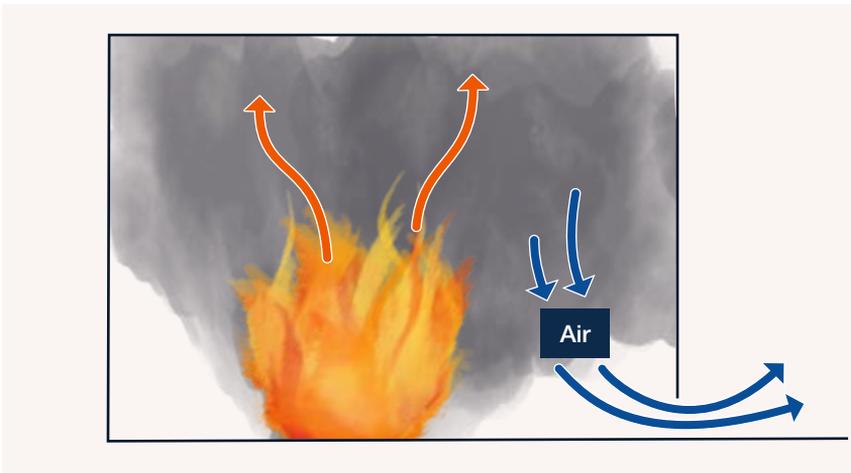
The pressure can increase sharply and rapidly in the room. This may be because the fire is growing rapidly or because it is already relatively large in the early stages of the fire, for example if a spilled flammable liquid is ignited. This pressure increase is at most directly proportional to the increase in temperature. Even in this case, the pressure is equalised relatively quickly in practice.

If the room has an opening, the pressure that arises will be equalised even faster. How quickly the equalisation occurs depends, among other things, on the size of the opening. It may also partly depend on how far from the fire there is an opening. This is mainly relevant in very large buildings or if the building has several rooms that connect the primary fire room with the opening to the outside. In that case, it will instead be the openings between these rooms that will be decisive for how quickly the pressure in

the fire room and other rooms is equalised. Each such opening or connection between the rooms will involve a restriction of the flow, and there will be a loss of pressure when gases flow through the opening.

In a room that has a small opening in relation to the size of the room, the pressure in the room can be relatively high for a long time. The same can happen in a room where the fire is growing quickly. From the outside, this can be seen by fire gases clearly flowing out through openings, possibly under a certain pressure (that is, the speed or flow is perceived as “high” or “large” in some sense). If we try to close a door to a fire room, we can often also perceive the door as difficult to close. This is because the temperature in the room is high and the fire gases expand. Once the door is closed, we can often observe that the pressure in the room drops because we have then limited the air supply, with the result that the fire effect decreases, the temperature drops and the pressure decreases, because the fire gases decrease in volume as the temperature drops.

**Figure 70.** In a fire room with leaky surfaces, the pressure will equalize



This can also result in the pressure dropping when the temperature drops in a relatively tight room or in a relatively tight building. This could happen, for example, when the fire becomes ventilation controlled after a growth period due to a lack of oxygen, so that its rate of heat release decreases and the temperature consequently drops. If this is the case, it is not entirely obvious that it will be visible from the outside that there is a fire in the room. Since the temperature and thus the pressure in the

building drops, air will flow into the building through any leakage surfaces. Then no fire gases will necessarily be visible from the outside, even if there is still an ongoing ventilation-controlled fire in the building. Eventually, the pressure will have been equalised by air flowing in. This addition of air can cause the fire to grow again, the temperature and thus also the pressure to increase and fire gases to be forced out. This pulsating effect can continue for a long time and lead to a heavily ventilation-controlled fire in a space where the temperature is still high. If the space is opened up, a so-called backdraft can occur.

What is described above is the pressure that arises as a result of thermal expansion in closed rooms or in a closed building. Even if pressure arises in the building as a result of a fire, this will normally be equalised relatively quickly, due to the building's natural leakage surfaces.

Let us now assume instead that we have a room with a relatively large opening in relation to the size of the room. For example, it could be a standard bedroom with dimensions of 5×3 m, a ceiling height of 2.5 m and a door of size 2×0.8 m. A small fire occurs in this room. 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 that occurs. Therefore, no pressure will arise in the room, or a very small pressure. The pressure is simply equalised over time.

Most buildings consist of several rooms that are connected. There, pressure differences can arise between different rooms or spaces in the building. For example, if a door is closed or if the openings between rooms are very small, a higher pressure may arise on the side of the door where the fire is. When there are different pressures in different parts of a building, the flow of fire gases will occur from the higher pressure to the lower. Pressure differences constantly strive to equalise.

Fires in closed or almost closed buildings or rooms create pressure differences due to prevented thermal expansion, that is, the hot fire gases cannot expand. During a fire, combustion products are formed that can contribute to an increased pressure, but these are such small quantities that they can be ignored. In fires with high rate of heat release, fires that grow quickly, or in buildings where the openings are relatively small, the pressure differences together can become considerable and contribute to the spread of fire gases. The spread then always occurs from higher pressure to lower pressure.

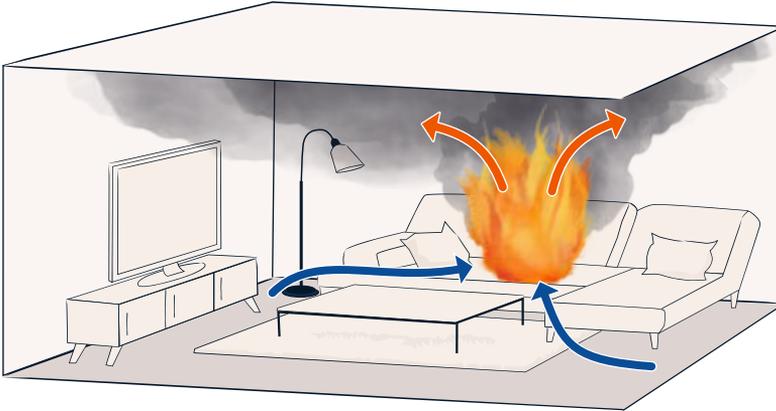
If the boundary of a fire compartment is deficient or if the structure is weakened, for example due to fire effects, the pressure differences can cause the fire cell boundary or the structure to weaken further. This happens in particular in the case of very intense or rapid fire progression or at high temperatures. Special phenomena such as backdraft and fire gas explosion can cause building components to fail. These phenomena will be discussed later. However, the failure of building components is more often due to direct heat from the fire, through heat radiation, convection or conduction.

## **The flow of fire gases**

Since fire gases consist mostly of air, it can be assumed that the density of fire gases is approximately the same as that of air and changes in a similar way to air. The density of air at 20 °C is approximately 1.2 kg/m<sup>3</sup>. Air and thus also fire gases at a temperature of 300 °C have a density of 0.6 kg/m<sup>3</sup>. If the temperature is 500 °C, the density of the fire gases is 0.45 kg/m<sup>3</sup>. The density differences quickly become large even with relatively small temperature increases.

The lower density of the hot fire gases causes them to rise upwards and form a fire gas layer that collects under the ceiling. How thick this fire gas layer becomes and how much it increases in volume depends, among other things, on the volume of the space, the height of the openings, the size and growth rate of the fire and the properties of the fuel. When the fire gases reach the top of the door, they will flow out of the room and into the next room or into the open air.

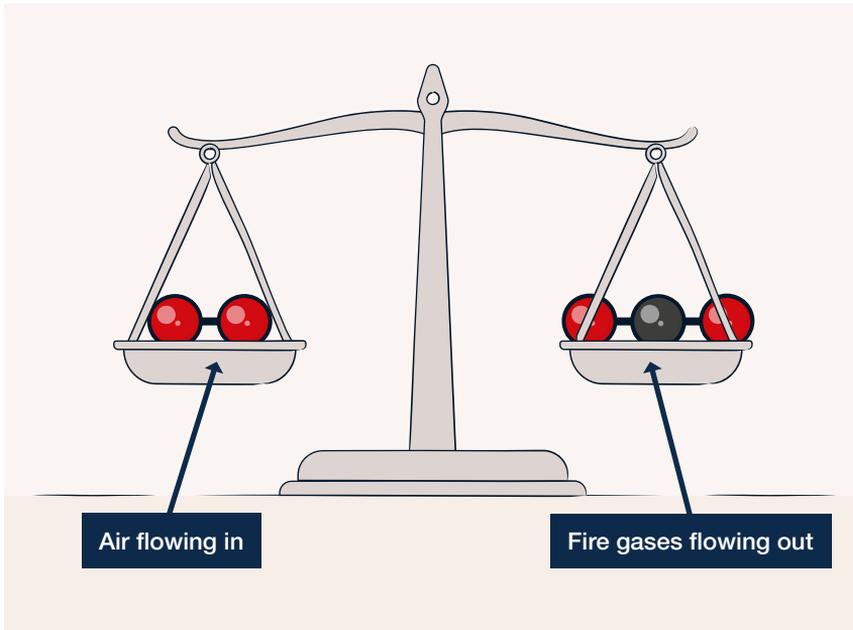
**Figure 71.** The hot fire gases rise upwards from the fire and collect under the ceiling



Since the room is open, either directly to the outside or to one or more other rooms that are open to the outside, no greater pressure will arise in any part of the room or rooms. This, of course, assumes that the opening or openings are large enough so that the outflow of fire gases is not restricted. Instead, it is largely the lower density of the fire gases, the thermal lift, that gives rise to a flow of fire gases out of the room and a flow of air into the room. The fire becomes, so to speak, an engine that, by supplying energy, drives the fire gases upwards and forces air to be sucked into the room and up into the plume, but the thermal expansion and the addition of mass to the fire gases during combustion will also contribute to the flow of fire gases.

The fire gases that are formed simply have to go somewhere, that is, upwards and outwards from the fire. As a direct consequence, air will also flow into the room to replace what is flowing out. This inflow of air normally occurs at floor level, because the cold air flowing in has a higher density than the warm fire gases flowing out. The fact that air flows in when fire gases flow out is based on the principle of conservation of mass. The amount of fire gases that flow out, as a result of thermal buoyancy, must be replaced by a corresponding amount of air flowing in.

**Figure 72.** The principle of conservation of mass



The principle of conservation of mass states that the amount that flows out must be replaced by the corresponding amount that flows in. Note that there are also combustion products from the fuel, which also flow out.

In principle, no pressure is formed in the room, provided that the room is open, either directly to the outside or to one or more other rooms that are open to the outside. Instead, differences in density are largely the driving force that causes a flow of fire gases, both inside the room and out of the room or building. The fire gas layer that forms inside the

room, and possibly also in adjoining rooms, is then also formed as a direct result of differences in density (the thermal lift). The dividing line between the upper fire gas layer and the lower (more or less fire gas-free) air layer is a clear temperature boundary and thus also a boundary between higher and lower density. It is often possible to feel a clear difference in temperature between the upper and lower layers with your hand, even during the early stages of a fire.

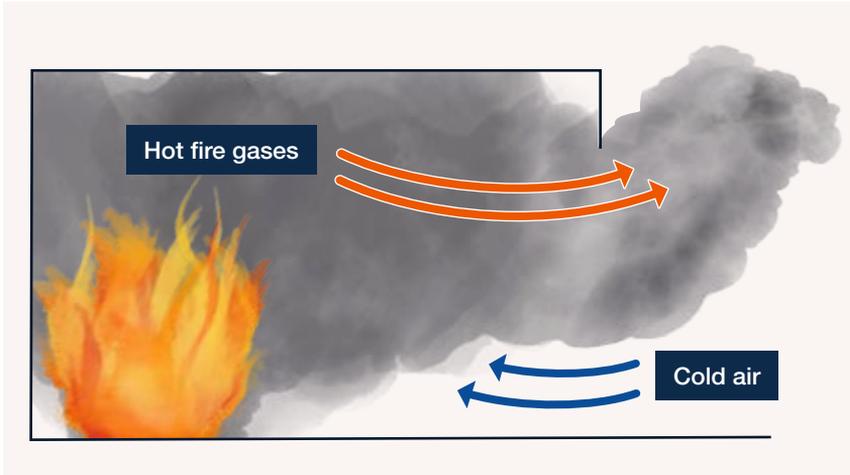
This dividing line is also called the neutral plane, neutral layer or zero plane. It is not a boundary between different pressures in the room: the room has the same pressure everywhere, provided that it is not a very large or otherwise complex room.

The neutral plane that occurs in a fire room is largely due to differences in temperature and density. This so-called neutral plane can be said to be a thermal discontinuity, that is, a “jump” in temperature and often a noticeable boundary between the hot fire gases and the colder air mass below the fire gases. Note, however, that the pressure in the room is the same everywhere.

As a consequence of the density difference (which gives rise to a thermal discontinuity) and the law of conservation of mass, fire gases will flow out of the room above the neutral plane and fresh air will flow in below. The fire gases that flow out through the upper parts of the openings must be replaced by fresh air that flows in through the lower parts of the openings, as a consequence of the law of conservation of mass.

Similarly to the energy balance of a fire room, the law of conservation of mass (also called the principle of conservation of mass) states that the mass in a closed system is constant. This principle means, among other things, that there must always be a balance between the mass flowing out of a room and the mass flowing in. The fire gases flowing out of the room must therefore be replaced by air flowing in. Energy and mass in the room must always be in balance.

**Figure 73.** Fire gases flowing out are replaced by fresh air flowing in

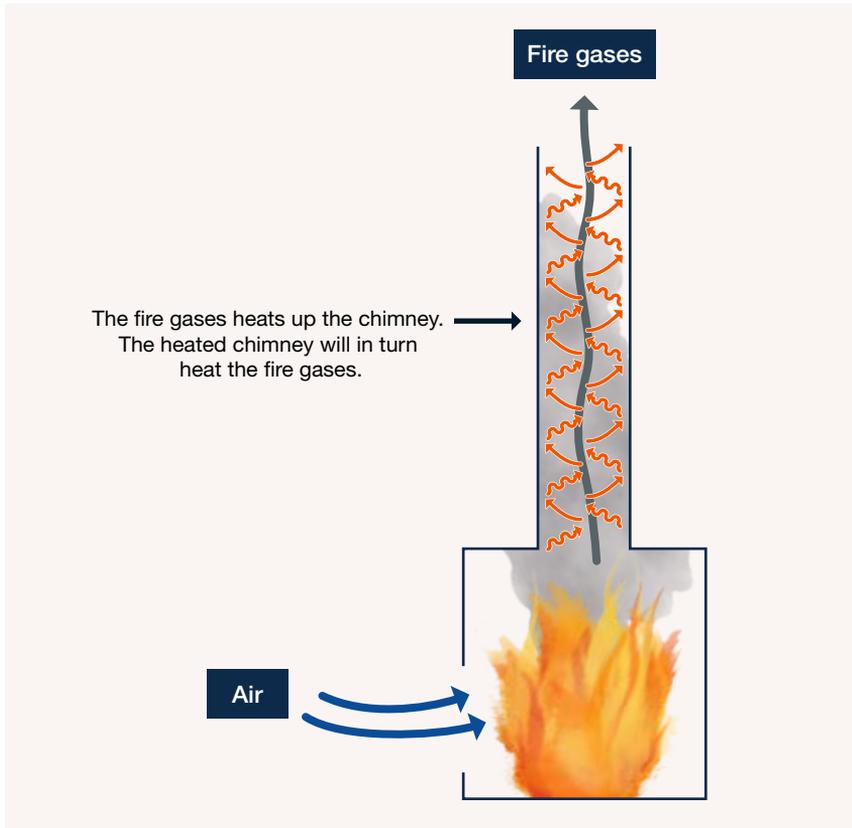


In the event of a room fire, hot fire gases will flow out through the upper part of the opening, and fresh air will flow in through the lower part of the opening.

## Flow of fire gases in tall buildings

In shafts, especially in tall buildings, something called the stack effect can occur. The hot fire gases from the fire have a lower density and rise upwards in the shaft (stairwell, elevator shaft, installation shaft or similar). If there is an opening both at the top and at the bottom (which is often the case, in the form of leakage surfaces), this means that fire gases flow out at the top and air flows in at the bottom, as a direct consequence of the principle of conservation of mass. If the shaft is high, there can be large temperature and density differences between ground and ceiling level. Then the flow in the shaft will also be large. If the area of the shaft is also relatively small, the speed of the flowing fire gases can be high.

A chimney is based on this principle. There, the supply air opening at the bottom is normally larger than the exhaust air opening at the top. In a stove, you can regulate the air inflow by changing the size of the supply air opening, and thereby also control the fire's rate of heat release.

**Figure 74.** Stack effect

The stack effect means that the fire gases heat up the chimney. The heated chimney will in turn heat up the fire gases. This causes the velocity in the chimney to be high and fresh air to flow in at the bottom, increasing the fire's rate of heat release.

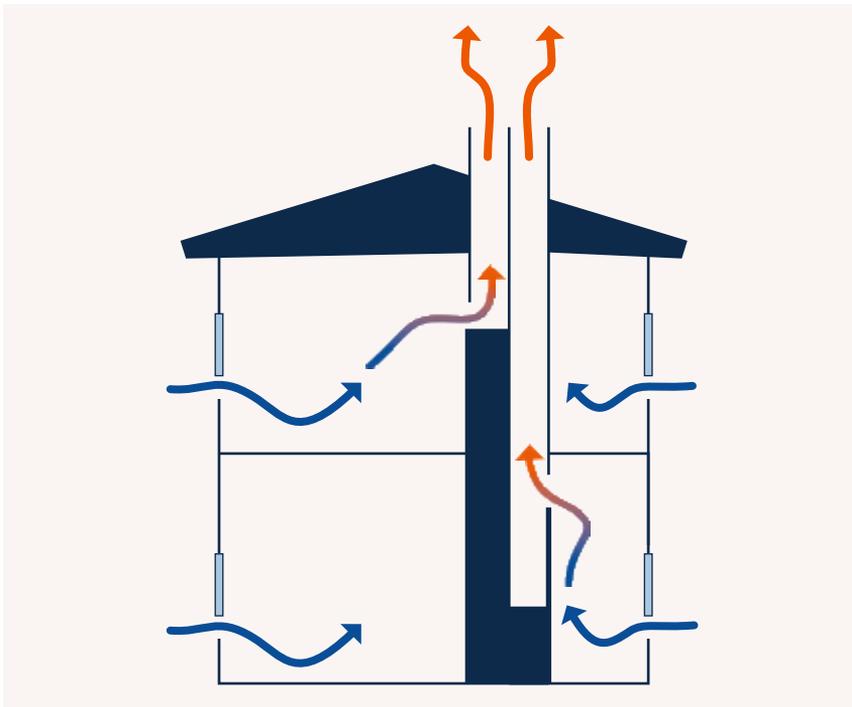
The walls of the shaft shield against further air intrusion. This means that the fire plume is not cooled down but retains its high temperature. The lifting force is then large and the velocity high. At the same time, this means that air is supplied to the fire at a higher speed at the lower opening and that the fire becomes more intense. And the higher the shaft, the greater the driving force in the flow. If there is combustible material in the shaft, the process will escalate further. As the process of the fire escalates, the temperature of the upwardly flowing fire gases rises and the speed increases further.

High speed of the upwardly flowing fire gases can cause large amounts of fire gases to flow upwards in the building. The speed can also contribute to greater convective heat transfer to the walls of the shaft. As the walls of the shaft heat up, the speed of the gas flow in the shaft can increase further. In addition, the air that flows into the bottom of the building can then also gain high speed, which contributes to the fire's rate of heat release increasing faster than it would otherwise have done. If the rate of heat release increases, the production of combustion gases increases further, the convective heat transfer increases further and so on.

Stack effects also occur in lower buildings, provided that there is a height difference between the inlet opening and the exhaust opening, but they become particularly noticeable in tall buildings or the higher the shaft is.

In older buildings, the stack effect is often used to achieve comfort ventilation.

**Figure 75.** Comfort ventilation in older buildings is based on the stack effect



This type of natural ventilation is based on the stack effect. The heated air flows out through ventilation ducts, which causes fresh air to flow in through the building's leaks.

## **Fire progression in enclosed spaces**

A fuel-controlled fire, with full access to air, is relatively easy to predict. The process often follows a clear “scheme”. The spread often occurs through heat radiation from the flames, upwards or to the sides, and is limited by, among other things, the amount, type and location of the fuel. A ventilation-controlled fire is more difficult to predict, but there are normally a number of basic processes that such a fire follows.

It should be borne in mind that these different possible processes are rarely as pure as they may appear in the literature. Definitions and descriptions of these processes are based on standardised conditions or from conditions that can be recreated, for example, in experiments in a laboratory environment. In reality, different phenomena can overlap. It can also be difficult to determine, for example, whether the ignition of fire gases or objects occurs spontaneously or due to an ignition source. However, knowledge and understanding of the basic mechanisms and the defined phenomena still give us better opportunities to assess the situation in the event of a fire in a building.

## **Fire progression in rooms with limited ventilation**

Most buildings are relatively airtight, although there may be some leakage areas, for example around doors and windows. In a somewhat simplified way, it can also be said that the total size of the leakage areas is proportional to the size of the room or building. A large building thus has larger leakage areas. In addition, there is often also comfort ventilation, which means that air is constantly supplied to the building. However, the air supplied via leakage areas and comfort ventilation is rarely sufficient for the fire to grow really large. It is completely out of the question that the fire would grow into a fully developed room fire if the room is completely closed. Such a development normally requires that windows or doors are open or broken.

This means that most fires that the emergency services arrive at are ventilation-controlled to a greater or lesser degree (see earlier discussion on ventilation control). The response force normally needs to open doors or windows to access the fire, with the result that air is supplied to the fire. However, this can often be managed by adding extinguishing agent either before or in conjunction with the opening of doors or windows.

In a room or building where the air supply to the fire is insufficient, combustion will decrease and the temperature will drop. However, the cooling of the fuel surfaces is slow, which means that large amounts of pyrolysis gases are still formed.

We then have a situation where there may be high concentrations of unburned fire gases in the room at the same time as the oxygen concentration may be low or very low. A number of different events may occur when the rescue service arrives at the scene. The further development can occur in a number of ways, some of which are typical of:

- the fire self-extinguishes
- pulsations occur
- the fire process resumes
- the fire gases self-ignite
- backdraft occurs.



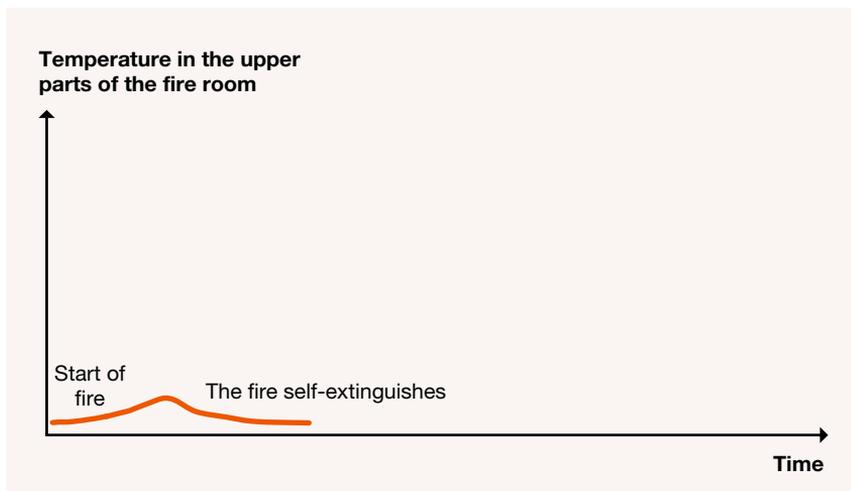
Fire progression in rooms with limited ventilation. Photo: Åsa Brorsson.

### The fire self-extinguishes

If the fire continues under controlled ventilation conditions, it may eventually self-extinguish or become a smouldering fire. This will probably happen before the temperature in the fire compartment has increased enough to cause severe pyrolysis of other fuel surfaces in the room. The fire may be limited to a single object or may not spread for other reasons.

When combustion in the room decreases, the temperature will also drop and the pressure in the fire compartment will decrease. Not as much fire gases are then expelled, and it may take a long time before the fire is discovered. This situation is not entirely uncommon in apartment fires, for example if a fire starts on the stove.

**Figure 76.** The fire self-extinguishes



The apartment can then suffer quite extensive smoke damage, but extinguishing the fire is usually not a major problem. Even in such a situation, the conditions in the fire room or apartment can be very dangerous for people. The fire gases contain a number of toxic substances, such as carbon monoxide, which prevents sleeping people from waking up when there is a fire. Smoke alarms are vital in this situation. They really save lives.

When the door to the space is opened, the fire gases can flow out, but the gases do not ignite because they are relatively cold. The fire is easy to extinguish.

## Pulsations

In a ventilation-controlled fire, the fire's rate of heat release is limited by the amount of oxygen that enters the room. This sometimes leads to the fire "breathing". This means that air is sucked in and causes a temporary increase in combustion and that combustion then decreases again. A kind of back and forth movement occurs that we call pulsations. A prerequisite is that there are one or more small openings to the room – door cracks or similar. The pulsations begin with the rate of heat release decreasing due to the limited amount of oxygen in the room. As a consequence of this, the temperature drops, which causes the gas volume in the fire room to decrease (the fire gases contract). A certain negative pressure is formed. Air can be sucked into the fire room again, and when the oxygen reacts with the combustible gases, combustion occurs.

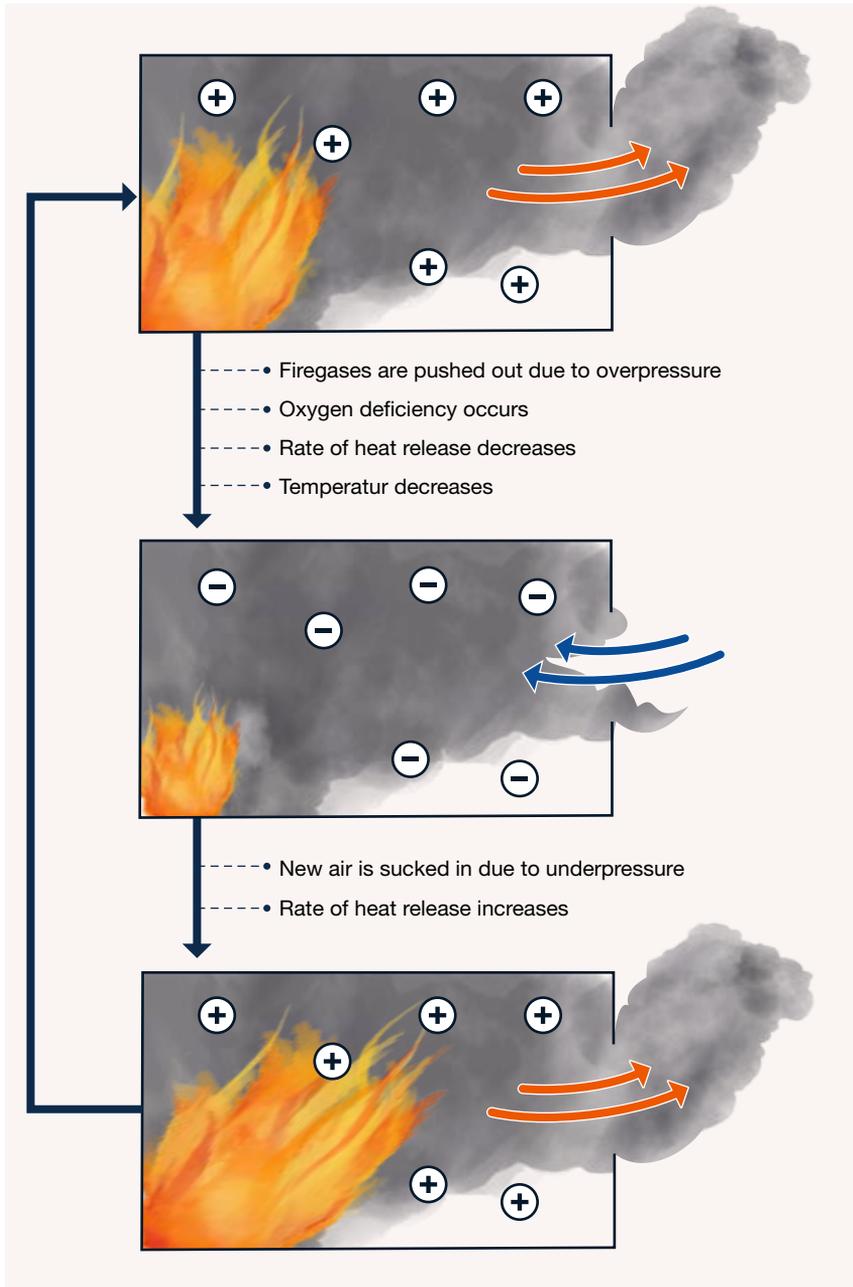
The combustion increases again, the temperature rises, the volume of the fire gases increases, which results in an overpressure. Fire gases are then forced out through the existing openings. This again leads to a lack of oxygen, which limits the rate of heat release. The next pulsation picks up speed. The size and length of the pulsations depend, among other things, on the size of the openings in relation to the rate of heat release. It is difficult to determine in which situations the fire can start to pulsate.

### Pulsation

Alternating negative and positive pressure, which sometimes occurs when the fire is ventilation controlled. If there is an opening in the space, the fire can gain access to air so that combustion can take place. This in turn leads to the formation of an excess pressure in the room and a rise in temperature. The fire decreases due to a lack of oxygen and the temperature gradually drops. New air can then be sucked into the room and the process is repeated.

The phenomenon is unstable. Often, the variations in the flow lead to, for example, a pane of glass breaking and the fire restarting.

Figure 77. A pulsating fire



### The fire process resumes

In a room with limited ventilation, the fire process can resume when air is supplied, for example if a door is opened or a window is broken. This can be the case, for example, if the fire has spread to a number of other objects before a lack of oxygen occurs. There has been a large thermal impact in the fire room. The room has been filled with fire gases, which contain a lot of unburned gases. However, the fire gases are not hot enough or in a large enough quantity for, for example, a backdraft to occur. This means instead that the fire has the opportunity to grow into a fully developed fire if air is supplied again. The scenario is a continuation of the fire process being interrupted as a result of the limited ventilation. The growth is similar to that which occurs when a fire develops and leads to a flashover in a room that already has an opening at the start of the fire. However, in the closed room, the process has been delayed.

If a door to the room is opened, fire gases will flow out through the upper part of the opening, as a result of the thermal lift and thermal expansion. At the same time, air flows in through the lower part of the opening, as a result of the principle of conservation of mass. The air flow causes the initial fire to flare up again and the fire to grow. The flames reach the fire gas layer, and a flame front moves out through the room.

**Figure 78.** The fire resumes



The process is often calm, since the flames that arise are diffusion flames. It can still be somewhat faster than if the fire is allowed to develop completely freely. This is because the surfaces in the room are already heated. The interrupted fire process is resumed, develops into flashover and a fully developed room fire, provided that there is enough oxygen and fuel (that is, if the opening is large enough).

However, the process assumes that the degree of ventilation control is relatively low, that the temperature in the space is relatively low and that excessive amounts of hot pyrolysis gases have not yet been produced. However, this is difficult to determine in advance.

### **The fire gases self-ignite**

Due to limited ventilation and ventilation control, a large amount of pyrolysis gases with high temperature may have been formed. If a door is suddenly opened or a window breaks, the fire gases can self-ignite. However, for this to happen, the temperature of the fire gases usually needs to be up to 500–600 °C, that is, above the thermal ignition point of the fire gases.

When the fire gases flow out through, for example, a door that the rescue service has opened, the fire gases mix with air. The fire gases self-ignite and burn outside the space.

Since the fire is ventilation-controlled and maintains a high temperature, the only thing needed is the oxygen in the air. This case is actually a continuation of the early fire process, which was interrupted due to the lack of oxygen and became ventilation-controlled. The fire thus goes more or less directly from this early fire process to a fully developed fire. Here, one cannot really speak of any flashover occurring in the same way as when the fire process grows in the manner described earlier. The process is similar but can proceed more quickly, since the ceiling and wall surfaces are now more heated than in cases where the fire is allowed to grow unhindered.

**Figure 79.** The fire gases ignite spontaneously upon contact with air



This situation can occur when there is a small opening in the space. The opening supplies the fire with oxygen and is positioned so that the outflow of fire gases is limited. An example could be an apartment fire, where fire gases flow out through a window that is cracked or ajar. When the door to the stairwell is then opened, the gases can be very hot and ignite spontaneously.

Spontaneous ignition of fire gases can also occur when attempting to ventilate an attic fire. The fire gases then ignite directly upon contact with the air, provided that the fire is ventilation-controlled. This is often the case with attic fires because attics are relatively dense and because there may be large amounts of fuel.

However, it can be difficult to perceive from the outside whether the fire gases ignite spontaneously in the opening or whether the flames originate from the interior of the room.

## Backdraft

An unusual phenomenon that can pose a great risk to emergency personnel is the so-called backdraft. The element of surprise can be great, with such a rapid and powerful ignition of fire gases that there is no time to react. It is therefore very important to be able to identify the situations that can lead to backdraft and what it can look like when there is a risk of backdraft.

A backdraft can be described as follows: A fire in a room has been going on for a long time and has been heavily ventilation controlled. A lot of unburned gases have collected in the fire room. When a door is opened, air flows in. When the incoming air meets the outgoing fire gases, a premixed gas mass is created – a premixed zone. When this gas mixture reaches an ignition source, often in the form of the initial fire, the gas mixture ignites. In the premixed zone, between the fuel-rich fire gas layer and the incoming air, a premixed flame spreads very quickly. In front of this flame, the hot pyrolysis products are pressed downwards and mixed with the air-rich layer. This causes a diffusion flame. This then results in rapid combustion and expansion of the fire gases in the fire chamber. The fire gases that do not ignite inside the fire chamber are pressed out and ignited outside the chamber. Since an incipient backdraft causes the fire gases to expand rapidly and strongly, the result is a mushroom-shaped fireball outside the opening.



A backdraft often results in a mushroom-shaped fireball outside the opening. Photo: Hans Loo.

The location of the ignition source plays a crucial role here. The location in relation to the opening (door) determines how much fire gases are premixed before ignition occurs. In a backdraft, both diffusion flames and premixed flames occur. A backdraft normally leads to a fully developed room fire, but it can also lead to the space being emptied of fire gases, and only small fire centres or smouldering fires remain in the room. The properties of the fire gases are an important part of the possibility of a backdraft occurring.

A backdraft includes the following elements:

- Unburned gases accumulate as a result of a ventilation-controlled fire.
- An opening is created and fresh air flows in.
- A premixed region of unburned gases and air is created as fresh air flows in and fire gases flow out.
- An ignition source ignites the gases in the premixed region.
- The temperature and volume of the ignited gases increase up to eight times.
- Unburned fire gases are forced out of the room and ignite in the form of a fireball.

Backdraft can occur when the fire has been going on for so long that it has become heavily ventilated and there are at the same time enough openings for pyrolysis to continue and a relatively high temperature in the space. A backdraft can be preceded by pulsations.

**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. The combustion can then occur rapidly.

Backdraft can cause significant damage inside and outside the space because the pressure build-up can be very high. High pressure and significant damage occur especially if the backdraft occurs far into a building where several rooms are connected to each other. In such cases, large amounts of fire gases may have had time to be premixed before they ignite.



When a door is opened, air flows in and mixes with the fire gases. The mixture ignites inside the room, and the flames are pushed out through the opening. The time shown is given in seconds and hundredths of a second from when the door is opened. Photo: Stefan Svensson.

It is difficult to specify the exact conditions required to create a backdraft, but there are a few factors that are essential:

- An ignition source is required that is located in the combustible region of the fire gases.
- A certain minimum amount of fuel is required in the space. The closer the fuel is to the fire or to hot fire gases, the more pyrolysis products will be formed.
- The lower the opening is, the smaller the proportion of pyrolysis products can escape. If the opening is too small, the fire is likely to self-extinguish, and if it is too large, the fire will grow to direct ignition.
- The better insulated the room is, the higher the temperature can be and the longer the heat is maintained in the space.
- The lower the pyrolysis temperature of the fuel, the more combustible products can be formed.

There are also a number of warning signs that a backdraft may occur:

- fires in enclosed spaces where ventilation is minimal, such as closed rooms or attics
- oily deposits on window glass, which is a sign of pyrolysis products condensing on cold surfaces and a sign of a ventilation-controlled fire
- warm doors and windows, which indicate that the fire has been going on for a long time
- pulsating fire gases from small openings in the room
- whistling sounds in openings, which can be related to the pulsations of the fire
- the neutral layer is close to the floor.

The inflow of fresh air when, for example, a door is opened is called gravity flow. As the air moves into the room, it mixes with the fire gases. A premixed gas mass is formed in a certain zone, normally in the layer where the air and the fire gases meet. The mixture will ignite if the fire gases are within the flammability range when they encounter an ignition source, such as a flame, glowing particles or an electric spark.

The ignition of the premixed zone causes a rapid expansion of the fire gases. This forces the remaining fire gases out through the opening at very high speed, and outside there the unburned gases mix with fresh air. As the flame spreads in the premixed layer, the ignition causes an immediate increase in pressure. This results in a fireball, which is very characteristic to a backdraft. The more unburned fire gases, the larger the fireball.

The concentration of combustible substances must be high for the mixture to fall within the flammability range when the fuel-rich gases are diluted with air. In a backdraft, the flames are partially premixed flames, which means that the sequence of events is rapid.

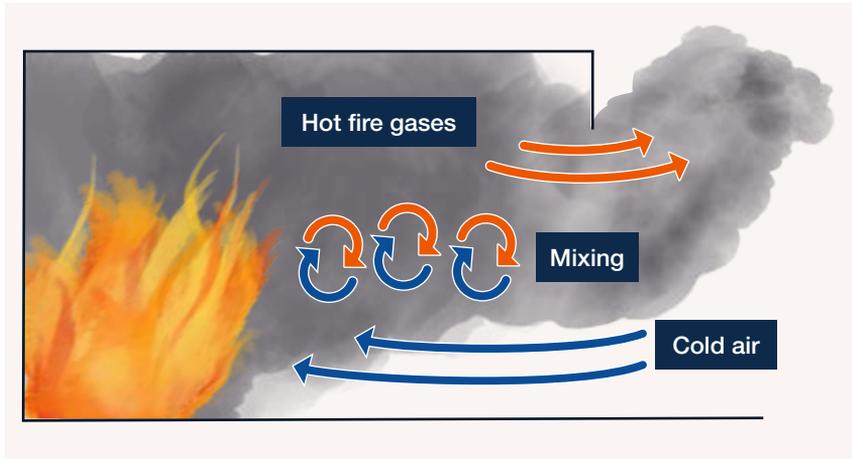
How much fire gases are mixed with air and how quickly the mixing occurs depends, among other things, on:

- the temperature of the escaping fire gases
- the speed of the incoming air
- the size of the room (area and ceiling height)
- the size and location of the openings
- the distance from the opening to the ignition source.

If the incoming air “bounces” against the back wall, the premixed area will increase in size.

When and how the premixed gases ignite is also important. The longer it takes from the creation of an opening to the premixed zone hitting an ignition source, the larger the premixed zone can become, resulting in a faster or more violent process.

The properties of the surrounding surfaces will also affect the risk of backdraft. If the ceiling or wall surfaces have a high thermal inertia, more heat will be conducted away through the walls and ceiling. It may then take longer for the conditions that can cause backdraft to occur. Steel, for example, has a high thermal inertia. However, once steel ceilings and walls have been heated, they can contribute to the production of pyrolysis gases by transferring more heat (through thermal radiation) back to the fuel.

**Figure 80.** Gravity current

When the door is opened, hot fire gases flow out through the upper part of the opening. Fresh air flows in through the lower part of the opening. In the boundary zone between the hot fire gases and the fresh air, they mix, making the mixture flammable.

If the fire compartment is far inside a building, so that there is additional space between the fire compartment and the door that opens, it will take longer for the air flowing in to reach the fire compartment. Since the distance is longer, more fire gases will also be mixed with the incoming air (that is, the gravity-driven flow and mixing). There is also a risk that a backdraft will be more violent and powerful. This is because the ignited gas mass must be transported a longer distance before it reaches the open air. There is more mixing, the pressure has time to build up more and there is also more fire gases that can be ignited because the volume is larger.

## Fire gas explosion

In some situations, the fire gases can mix well with the air before they ignite. This normally occurs in spaces adjacent to the fire compartment, and where there are no other openings or only very small openings. Since the space is then unable to relieve pressure in the event of an ignition, the ignition and the pressure increase that follows can be very strong, so strong that it can destroy entire building structures. This phenomenon is called a fire gas explosion.

A fire gas explosion is a deflagration, not a detonation. The speed of the moving combustion zone is lower than the speed of sound. A fire gas explosion occurs without any opening in the room changing, while a backdraft requires that the ventilation conditions in the room change during the course of the fire. This is a major difference between the two phenomena.

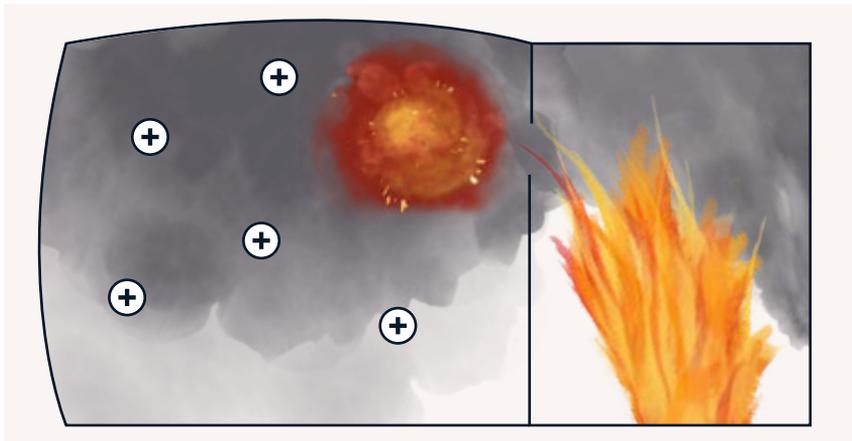
### Fire gas explosion

When the fire gases leak into spaces adjacent to the fire room, they can mix very well with the air. This mixture can fill all or part of the volume and be within the flammability range. If the mixture ignites, the pressure increase can be very strong. This is called a fire gas explosion.

The risk of a fire gas explosion is greatest in rooms adjacent to the fire compartment. In such spaces, the mixture may be pre-mixed if fire gases have leaked in for a long time. The fire gases may then have cooled down and mixed with the fresh air in the space, and the mixture has thus ended up within the flammability range. The only thing missing for the ignition of the gas mixture is an ignition source. When the gas mixture ignites, the flame spread occur in a pre-mixed gas mass, which leads to the gases expanding much more strongly than in flashovers and backdrafts. Only a very small ignition source is needed to ignite a pre-mixed gas mass.

A fire gas explosion may also occur in a fire compartment. If there is only a small opening in the fire compartment and it is not enough to cause a flashover, the fire will continue under oxygen deficiency. This leads to a large amount of unburned fire gases accumulating in the fire compartment. The fire in the room may self-extinguish or decrease to a smoldering fire. If the temperature in the room is still high, a lot of unburned gases can accumulate. If the room is well insulated, the temperature can remain high for a long time.

**Figure 81.** Fire gas explosion



Fire gases that leak into adjacent spaces can mix well with air. This mixture can then end up in the flammability range. If the mixture ignites, this can lead to a fire gas explosion.

When the fire goes out and the temperature therefore begins to drop, the pressure drops and air is sucked in. The air mixes with the fire gases, and the concentration of the mixture can end up in the flammability range. The gases in the room may now be mixed very well, but they do not ignite because there is no longer an ignition source. However, an ignition source can occur later, for example by embers flickering up from the initial fire. This can ignite a more or less pre-mixed gas mass. The fire gas explosion becomes powerful.

The entire room does not need to be filled with a premixed gas mass for a fire gas explosion to occur. It is sufficient for a small part of the room to have a premixed gas mass that ignites. This may be sufficient for building components to be destroyed or pushed out.

### Expansion factor

When a premixed gas mixture is ignited, the temperature rises, which also causes the volume to increase. The expansion factor is greatest at stoichiometry, up to about 8.

Factors that affect the force of a fire gas explosion include the following:

- **Rate of heat release**  
The higher the rate of heat release, the faster the expansion. The rate depends on which substances participate in the combustion. It also varies depending on where the ignition of the gas mixture occurs in relation to stoichiometry.
- **Expansion factor**  
The higher the final temperature the products reach in the combustion process, the more they expand. The more they expand, the greater the pressure increase. The temperature of the products depends partly on which substance participates in the combustion, and partly on where within the flammability range the mixture is ignited.
- **Proportion of premixed volume**  
The larger part of the room volume that is premixed, the more the pressure increases. It is enough for a few volume percent of the fire gases to be premixed for the pressure to be very high.
- **Pressure resistance of building components**  
The weakest building component gives way first, after which the pressure will decrease. For example, most buildings have windows, which means that the pressure increase is usually moderate.
- **Size of the openings**  
The larger the openings that can be when building parts give way, the easier it is to depressurise the room. If the room is almost completely closed during the entire process, the pressure will be very high when the gas mixture ignites.

**Table 15.** Pressure resistance of building components

Construction component	Pressure [Pa]
Glass window	2,000–7,000
Interior doors	2,000–3,000
Interior walls	2,000–5,000
Double layer of plasterboard	3,000–5,000
Brickwall	20,000–35,000

When it comes to the pressure increase that occurs, there is no sharp boundary between a fire gas explosion, backdraft or when fire gases self-ignite (for example in an opening). Backdraft, however, requires that some ventilation opening be changed. A characteristic of a fire gas explosion is that the fire gases are pre-mixed and that the pressure increase can therefore be very large. During a flashover or a backdraft, however, it is the diffusion process that controls, i.e., how the fire gases mix with air in connection with ignition.

The characteristics of an imminent fire gas explosion can in many cases be difficult to perceive. They largely have to do with building technical measures, for example how penetrations are made, whether the fire cell boundaries are intact and whether there are hidden spaces. Detectors or sprinklers can help prevent fire gas explosions. Since fire gases can in some cases be completely transparent, it is not always possible to determine the risk of a fire gas explosion by identifying fire gas-filled spaces, and even if there are large amounts of fire gases in a space, it is not possible to determine the flammability of these fire gases.

### **Flashover, backdraft or fire gas explosion?**

In a laboratory environment or other controlled conditions, it is often relatively easy to distinguish between a flashover, backdraft, fire gas explosion and spontaneous combustion of fire gases. In reality, it can be very difficult or even impossible. The boundary between these different phenomena is fluid.

Flashover occurs due to the availability of good air and a certain amount of fuel. Backdrafts have a completely different origin and occur when there is a limited air flow into the building or room, which means that combustion takes place with a limited oxygen supply. A quantity of unburned gases is then formed, which can ignite at a later stage when air is supplied.

The situation where the fire gases spontaneously ignite occurs when the fire gases have a temperature that is higher than the thermal ignition point. In some cases, when this happens, turbulence is created that spreads into the room and stirs vigorously, which can lead to a backdraft of a smaller size. Sometimes it looks as if the flames are arising in the opening, but they could very well originate further into the room. It can therefore be difficult to determine whether the fire gases are self-igniting or if the fire process is restarting.

Backdraft and fire gas explosion have completely different origins. Backdraft occurs in a room where the ventilation conditions have changed. For example, it could be a room where the windows are cracked and air is let in, which causes air to flow in and mix and then ignite. Fire gas explosion usually occurs in a space that borders the fire room and where the fire gases have been well mixed with air.

In general, it can be said that a backdraft leads to a lower pressure build-up than a fire gas explosion. Backdraft requires that the ventilation conditions change and that this in itself acts as pressure relief.

Distinguishing between flashover and fire gas explosion is easiest, since flashover involves diffusion flames while fire gas explosion involves premixed flames. It is therefore very unlikely that these situations will be confused.

### Example

In mid-February 2024, a fire broke out during the construction phase of Oceana at Liseberg in Gothenburg. The fire started outside next to a water slide, and large amounts of fire gases were formed that spread into an adjoining building.

Relatively early in the process, a fire gas explosion occurred that pushed out large parts of the building's walls. Two firefighters and a construction worker narrowly escaped the fire gas explosion. Unfortunately, a construction worker who did not have time to evacuate died due to the large amounts of fire gases that quickly flowed into the building.

The heat from the fire in the water slide probably caused large amounts of unburned pyrolysis gases to develop and flow into the building via the water slide, which led up to the top of the adjoining building. The gases accumulated in the building and were ignited by the flames from the initial fire.

The fire gas explosion was very powerful.

(Statens haverikommission, SHK 2025:05)

## Liquid fires in enclosed spaces

A liquid burns somewhat differently than solid objects. Provided that the liquid is flammable, it does not need to be pyrolysed, that is, broken down chemically, in order for flammable gases to form. It is enough for the liquid to evaporate for it to ignite. It is then the evaporation of the liquid and its flashpoint that largely determines how the fire develops and spreads.

A significant difference between a “normal” initial fire and when a larger amount of spilled liquid ignites in a room is that the initial fire can become large already upon ignition. It is then the size of the vessel or puddle that determines the size of the initial fire, since the mass burning is relatively constant for flammable liquids. If a vessel or puddle is large, the fire in

the space can become ventilation-controlled much faster than a more “normal” growing fire in fibrous material or plastic. If the space is closed or has only small or few openings, the pressure increase in the room can be very large even at the time of ignition.

A liquid fire is more sensitive to insufficient air supply. A liquid cannot be pyrolysed, and a liquid cannot smoulder. Therefore, the fire will go out when the oxygen content in the space has dropped below approximately 10–12 percent. The fire can also go out relatively abruptly, unlike in a solid material where the rate of heat release decreases gradually. The rate of heat release can also decrease gradually to a certain extent in liquid fires under limited air supply. The fact that a liquid fire goes out abruptly can in turn mean that flammable liquid continues to degas even after the fire has gone out. How much evaporates depends on the flashpoint of the flammable liquid and the temperature in the space, on the floor or in the vessel where the liquid is stored. There is a certain similarity here with the accumulation of combustible gases (pyrolysis gases) from a solid fuel.



Liquid fire in room. Photo: Stefan Svensson.

The vapour from some liquids is heavier than air, which is a big difference from the smoke from a solid fuel. Instead of rising and accumulating under the ceiling, the vapour from some flammable liquids can collect at the floor. This happens in particular if the liquid fire extinguishes itself but the liquid continues to evaporate. A simple and common example of such a liquid is gasoline. The flash point of gasoline is also as low as  $-30\text{ }^{\circ}\text{C}$ . Note, however, that the vapours can rise upwards if they are hot and therefore have a lower density than the surrounding air.

If the vapours from a flammable liquid ignite in a space, the fire process can be very similar to a smoke explosion or an explosion in other gases such as natural gas or LPG. This can be a big problem if the liquid has largely evaporated before ignition occurs.

### **Example**

One night in the fall of 2017, the fire department in Helsingborg received a call to a fire in a building on the sixth floor of an apartment building. On arrival, there were building parts on the ground below the building and it was burning with open flames from both sides of the building. The railing to the walkway outside the apartment had been moved outwards and the outer walls on both sides of the apartment had been pushed out. The investigation afterwards showed that it was probably petrol vapours in the apartment that had ignited. The amount of petrol leaked was unclear, but it was most likely only a few litres that had evaporated. The force of the rapid process that occurred was sufficient to push out the walls.

(Olycksundersökning, brand och explosion i byggnad, 2027-09-19, Helsingborg. Räddningstjänsten Skåne Nordväst. 2018)

# Chapter 8

# Fires in buildings

So far, fires in single rooms have largely been addressed, but from a fire and rescue service perspective, a fire in a single room is rarely a major problem. If we can reach the fire, it can also be extinguished in most cases. It is then mainly a matter of the amount of extinguishing agent and how quickly this can be applied, that is, the flow of extinguishing agent. Even if the room is in an apartment, the apartment is normally separated from other apartments and spaces in the building for a certain period of time in terms of fire protection. Even in an apartment fire, the fire itself is often limited to a single room, but the fire gases affect the entire apartment and can also affect, for example, the stairwell. And there is also a risk of fire spreading via windows to the facade or to an attic.

However, the fact that rooms are in buildings makes the work of the fire and rescue service more complex. We rarely know the layout of the building where the fire is. In buildings, fires can also spread further through, for example, walls, ceilings or floors, and the rooms can be large in terms of both floor area and ceiling height. There is also a risk that the building will collapse completely or partially.

The basic mechanisms for the spread and development of fire are, of course, also valid in buildings as such. However, in order to be able to manage fires that have begun to spread in a building, we must have good knowledge of the conditions the building provides for the course of the fire.

## Buildings

A building is defined in the Planning and Building Act (2010:900) as “a permanent structure consisting of a roof or of a roof and walls and which is permanently located on land or wholly or partly underground or is permanently located in a certain place in water and is intended to be constructed so that people can live in it”.

Neither a tent, a construction hut or a caravan is a structure that is permanently located. They are therefore normally not considered buildings in the sense of the law, but even in this type of structure, a fire will behave based on the conditions that the structure and its contents provide. This also applies to road tunnels, wind turbines and other more or less complex facilities.



Different types of buildings. Photo: Stefan Svensson samt Johnér Bildbyrå.

The term construction also includes facilities in the form of fixed building structures (on land or water) that are not intended for people to live in. The focus of this book, however, is on buildings, that is, buildings that people normally stay in more or less permanently – homes, offices, hospitals and the like.

The basics of fire in buildings are, of course, also valid for other types of construction, but fires can develop very differently in them. Road

tunnels, wind turbines and large industries are examples of constructions where fire can have a large impact on human safety as well as on the functioning of society. Fires in this type of construction will not be treated explicitly in this book. For such constructions, reference is made to other literature. There is a wealth of research on, among other things, the development and spread of fires and fire gases in tunnels, for example.

The requirements for building technical fire protection have a long history, and are constantly changing, but the basic principles of fire development and spread are the same, regardless of how the building or structure is designed or when the building was constructed.

## **Building types and building constructions**

There are many different building types, which can accommodate a variety of different types of activities. A simple division of different building types can be industries, offices, theaters, residences, hotels and healthcare buildings.

These different building types affect a fire in a building in different ways. For the initial fire and the early course of the fire, the differences between different building types are small. However, the building type can have a great impact on flashover, the fully developed room fire and the continued spread of fire to several rooms, in large rooms, fires in structures and in tall buildings.

In a somewhat simplified way, it can be said that the larger a building is, the more difficult it is to describe and predict the development of a fire. Aggravating circumstances include a large number of rooms, large rooms and the height of the building. The activities and contents of the building also matter. There are quickly many parameters that affect the course and spread of a fire. In the context of firefighting operations, we often talk about complex buildings. In a somewhat simplified way, it can be said that fires become more complex if they are not located at ground level. The higher up in a building or the further down below ground level, the more complex the conditions become from a fire and rescue services perspective.

Building design is about how to dimension and design a building and what types of building materials are used. Building design often focuses on how should design a building based on the loads the building is expected to be exposed to, including fire. There are quite extensive regulations for how buildings can or should be designed. Essential technical properties that require design work include:

- load-bearing capacity, stability and durability
- safety in the event of fire
- protection with regard to hygiene, health and the environment
- safety in use
- protection against noise
- energy conservation and thermal insulation.



One of several essential technical requirements for buildings is safety in the event of fire.  
Photo: Stefan Svensson.

Protection against fire, its origin and spread, is a property requirement that has existed for quite some time, and there are buildings that are over a hundred years old where clear technical measures have been introduced to protect against fire. Examples are so-called fire walls and non-combustible roof coverings. Older buildings often have surprisingly good protection against the spread of fire inside and outside the property. Such measures that are built into buildings in advance are collectively known as structural fire protection.

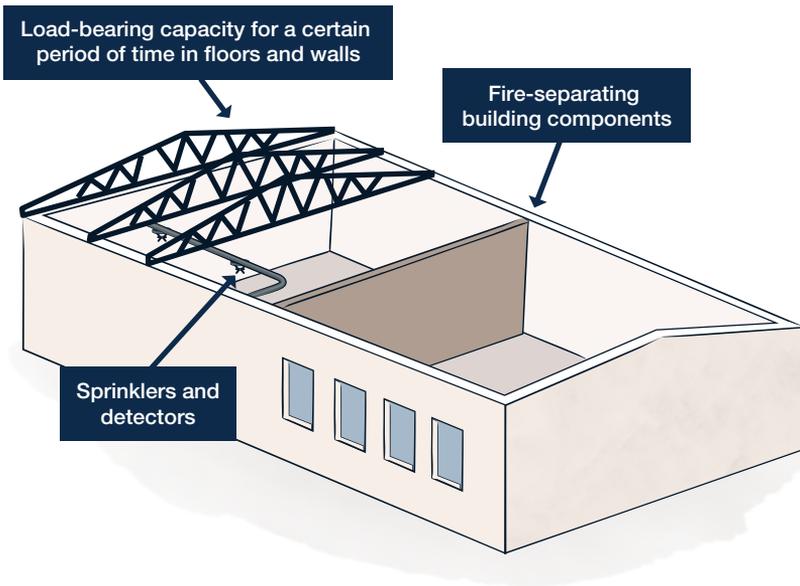
## **Fire protection in buildings**

Fire protection in buildings usually refers to the technical solutions that are built into buildings and that aim to prevent fire from starting and spreading inside and outside the building. In a fire and rescue operation against a fire in a building, functioning fire protection in buildings is often crucial to the end result, regardless of how knowledgeable and well-organised the fire and rescue service is. However, it is often required that the fire and rescue service actively do something to ensure that the fire protection measures in buildings can function as intended.

How the fire protection is designed in a building has an impact on how a fire can spread, both in one room and to several rooms or to other buildings. The requirements that building legislation places on, for example, the choice of materials, are set based on the aim of preventing or limiting the start and spread of fire.

Society places a number of demands on fire protection in buildings, but this protection varies greatly between different buildings. The measures that have been built in and the protection against fire they provide depend, among other things, on when the building was constructed, the type of building and the activities that take place in the building.

**Figure 82.** Examples of fire protection measures in buildings



Fire protection in buildings refers to the technical solutions that are built into buildings and that aim to prevent the onset and spread of fire inside and outside the building.

The requirements depend on a number of factors. In order to achieve the right level of fire protection, buildings are divided into activity classes, from 0 to 5 with subclasses. There are 12 activity classes in total. The division depends on:

- If people can be expected to be aware of the layout of the building
- If people can be expected to be awake
- If people can be expected to evacuate on their own
- If there is a high risk of fire.

Buildings are also divided into building classes based on the protection requirement, from building class 0 to building class 3. This division takes into account probable fire progression, potential consequences of a fire and the complexity of the building.

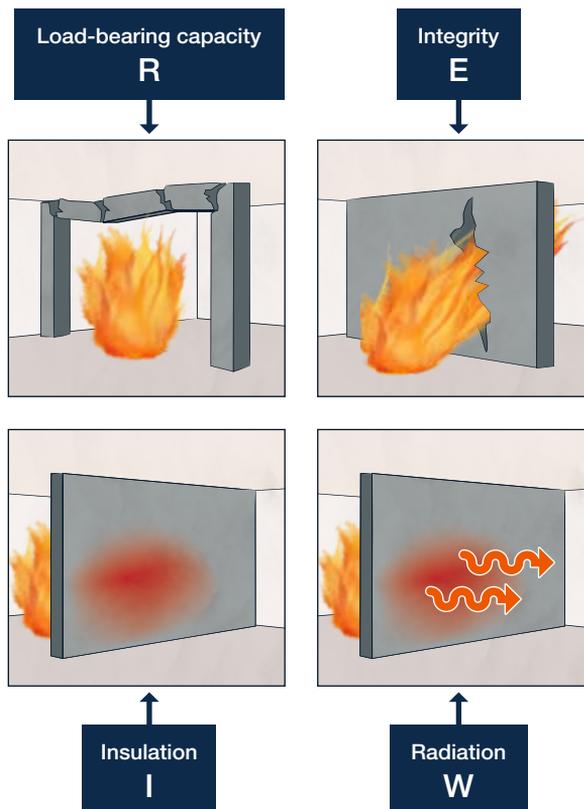
Based on the building's activity class and building class, a variety of different requirements are placed on the building components used in the building. These building components are tested and classified based

on very specific test methods with certain criteria for the fire protection requirement levels. Testing and classification are based on the following main classes for fire resistance:

- R – load-bearing capacity in the event of fire
- E – integrity, that is, tightness against fire and fire gases
- I – insulation, that is, limitation of temperature on the side not exposed to fire
- W – protection against thermal radiation, that is, limitation of thermal radiation from the side not exposed to fire.

There is also an additional class for resistance to mechanical impact after fire, M.

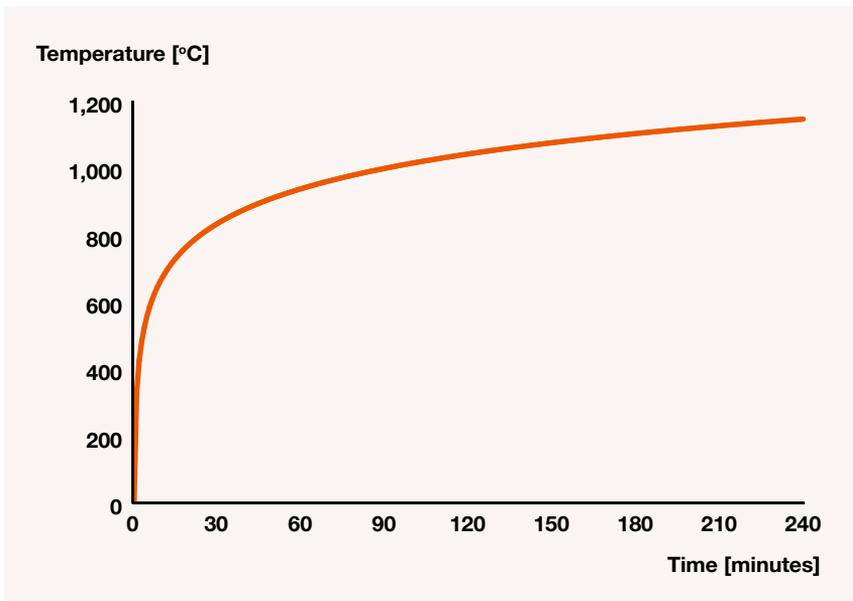
**Figure 83.** Fire protection requirements are set for load-bearing capacity, integrity, insulation and protection against radiation



The classification specifies how long the building components should be able to maintain a certain function. These functions can then be combined. The property of fire resistance is always combined with a specific time. A building component that is classified as RE60 must have a load-bearing capacity and integrity that lasts for at least 60 minutes in connection with testing. Note, however, that the temperature to which the building component is exposed during testing is not necessarily the same as the temperature to which the building component can be exposed in an actual fire.

In addition, a number of class designations are used for materials, cladding and surface layers. Note that there are generally no corresponding requirements for furnishings or other objects we have in our homes, such as furniture, clothing and the like. A fire usually starts in this type of object.

**Figure 84.** Temperature development over time for the fire that a building component is exposed to during certain testing



Building components are tested based on their function, and the requirements can be different in different buildings. There can thus be large differences between buildings in terms of, for example, the thermal inertia of the materials used, even if the constituent building components meet the applicable requirements. As we have seen in previous chapters, the design and size of buildings will also affect how fires develop and spread.

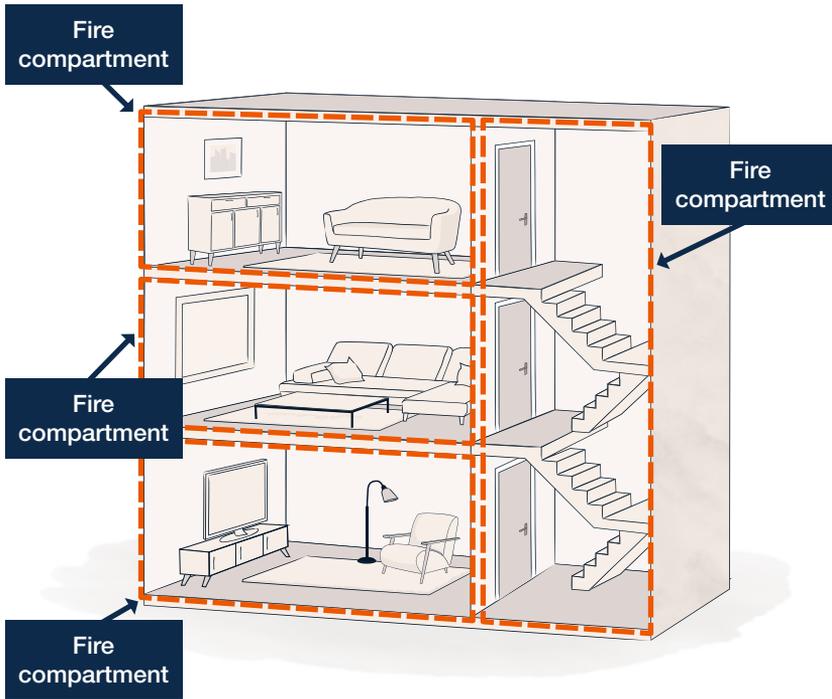
There are a number of requirements that must be met for building fire protection. Only some of them will be described here, based on the fact that they are particularly important for the course and spread of fires. For more detailed descriptions of structural fire protection, reference is made to other literature.

## **Fire compartments**

Fire compartments play a central role in fire protection in buildings. A fire compartment is a defined space in a building that must withstand fire for a certain period of time. Generally, different activities in a building should be in separate fire compartments. In an apartment building, each apartment is usually its own fire compartment. With current building regulations, the apartment's floor, walls and ceiling must be able to withstand a complete fire process, which is tested with a so-called standard fire for 60 minutes. The aim is for the fire to subside or be extinguished during that time, and thus not spread to the next fire compartment. This requirement was introduced in 1960 but was already the practice before that. Many older buildings are also divided into fire compartments according to activities.

In principle, a single-family house is a fire compartment, but then distance is used instead as a protective measure. There should normally be at least four metres from the building to the property boundary and, consequently, eight meters between buildings. If the distance is shorter, additional measures are often required to prevent fire from spreading from one building to another within a certain period of time. For example, it may be that there are no windows in the facade or that the outer wall has a certain fire rating.

**Figure 85.** A fire compartment is a defined space in a building that must resist fire for a certain period of time



Generally, different activities in a building should be in separate fire compartments.

Fire compartments are very useful and valuable during firefighting operations, for example to effectively limit the spread of fire. Spread between fire compartments usually occurs where there is some type of gap. This can, for example, happen through windows via the facade to another fire compartment or when ventilation ducts, cables or drain pipes pass through the fire compartment boundary. Such penetrations must, of course, also meet the same requirements as the rest of the fire compartment, but for practical reasons it can be difficult to make this function completely satisfactory. Spread to other fire compartments can also occur if the fire is allowed to continue unaffected for a long time.

## Firewalls

A firewall should be able to contain a fire without the intervention of the fire and rescue service and should withstand the mechanical impact of the fire for a certain period of time. It should also be easily identifiable by firefighting personnel. Generally, firewalls are usually located between properties or between buildings/spaces where there may be particularly flammable activities or goods. What usually characterises firewalls is that they rise a bit above the roof. This makes them easy to identify from the outside of the building.

In older buildings, firewalls are often easy to identify because they are a relatively thick brick wall that rises approximately 10–20 cm above the roofs. When creating boundary lines for fires in buildings, it is often appropriate to make the boundary line adjacent to a firewall. If this is not possible, fire compartments can be useful, but these are more difficult to identify and do not have the same resistance as firewalls.



Example of a firewall that protrudes above the roof at the property boundary.  
Photo: Stefan Svensson.

## Fire section

A fire section is a separate part of a building within which a fire can develop without spreading to other parts of the building or other buildings. The fire section must be separated from the rest of the building by firewalls and floors or equivalent so that the spread of fire within and between buildings is limited.

The difference between a fire section and a fire compartment is that a fire section must be separated from the building by firewalls and floors to limit the spread of fire within or between buildings. A fire compartment does not need to have a firewall as a separating structure, but it is sufficient that it meets a certain fire protection class, for example EI60. A fire section thus has higher protection against the spread of fire than a fire compartment.

## Fire load

Fire load is a term often used to describe the “flammability” of a room or a building – its potential contribution to a fire. Fire load is the basis for how fire protection in buildings is designed, especially with regard to load-bearing capacity. Fire load tells us how much potential energy there is in the building.

The Swedish National Board of Housing, Building and Planning define fire load as fire energy per floor area within a certain space, expressed in MJ/m<sup>2</sup>. Fire load is the total amount of energy that can be burned in a complete fire event in relation to the floor area of the space in question. The space is normally equivalent to a fire compartment.

A distinction is made between permanent and variable fire load. The design fire load is the total amount of permanent and variable fire load in the fire compartment. Permanent fire load are combustible building components whose quantity and combustion behaviour do not vary over time, or only vary negligibly. Examples of permanent fire loads are combustible building materials including the load-bearing structure, insulation, surface layers, cladding and permanently installed technical equipment. Variable fire loads are combustible materials that can vary in quantity and combustion behaviour over time. Examples of variable fire loads are inventory, movable equipment, furniture and other loose furnishings.

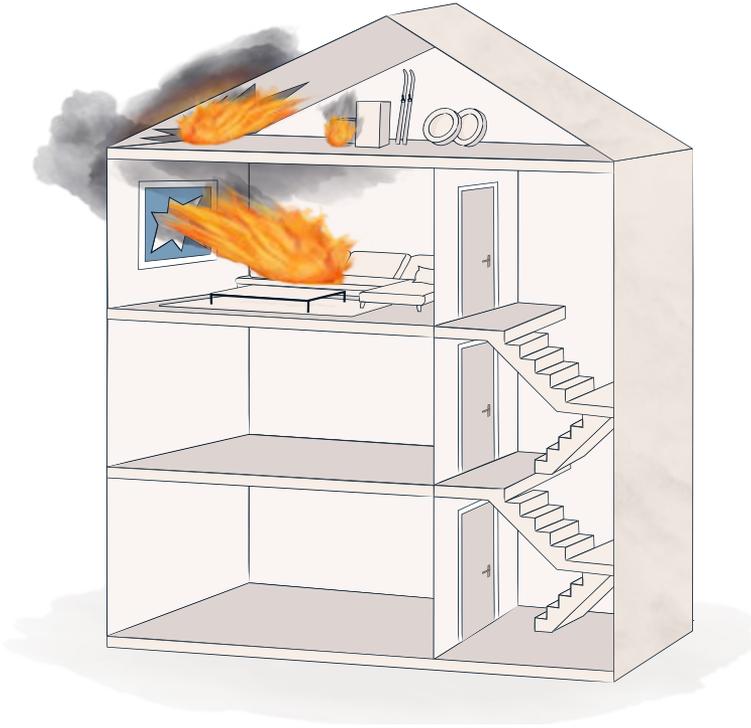
**Table 16.** Example of variable fire load used as a basis for dimensioning fire protection in some different types of buildings or businesses

Activity	Variable fire load [MJ/m <sup>2</sup> ]
Concrete industry	50
Cinema, restaurant and theater	
Office	600
Garage	
Schools	
Malls and shopping centers	1,200
Archives	
Library	1,600
Warehouse	

## Fire in several rooms

Fire and fire spread in multiple rooms is more complex than in a single room, for several reasons. The basic mechanisms work in exactly the same way. For example, the properties of surrounding surfaces, including walls, ceilings, floors and objects, will affect the further spread in the same way as in a single room. One of these properties is the thermal inertia of different materials, regardless of whether the materials are combustible or not. Openings will also affect the process. One difference is that now there are not only openings to the outside, where fresh air can flow in and fire gases can flow out. Now openings between connecting rooms will also affect how the fire and fire gases spread. Each such opening limits how much air and fire gases can flow between the different rooms.

**Figure 86.** Despite fire protection measures in a building, a fire can spread between fire compartments

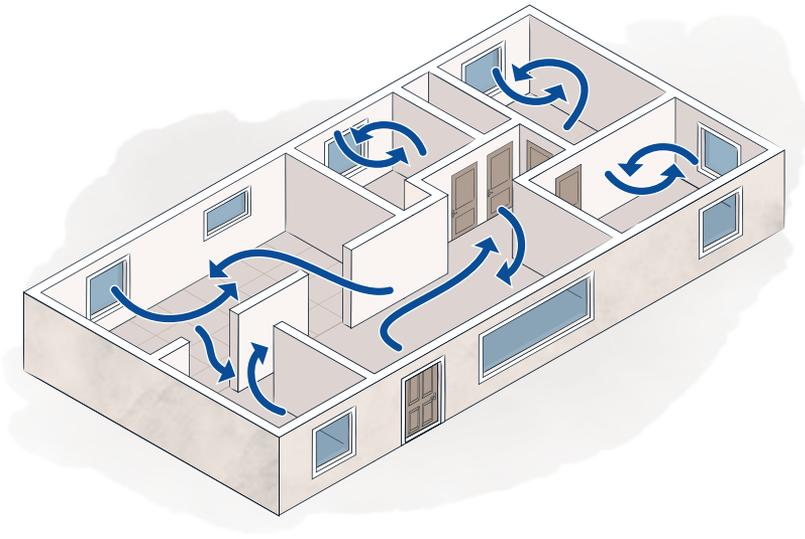


A fire that spreads to several rooms or to several different activities in a building quickly becomes extremely complex, as there are many more parameters that affect the course of the fire.

The number of rooms affects the course of the fire by increasing the overall volume with more rooms. If there are many or large rooms that are connected to each other, the large air volume means that the fire can continue to be fuel controlled for a longer time or that the degree of ventilation control increases more slowly than in a single room. If there is an opening to the outside in a connected room that is far from the original fire room, the incoming air and the outgoing fire gases will have a longer path to be transported. The flow will then take longer. At the same time, fire gases will accumulate in the connected rooms, which will heat up all surfaces that the fire gases encounter, through convection and heat radiation.

This can mean that the degree of ventilation control will be different in different rooms in a building. A fire that involves several rooms can be fuel controlled in a room that is open directly to the outside and at the same time heavily ventilation controlled in a room that is located further into the building. Nevertheless, overall, for the entire building, the fire should then be considered ventilation controlled.

**Figure 87.** Several interconnected rooms contain more air



Several rooms that are connected to each other mean that there is more air available, and that both air and fire gases have longer distances to flow.

Quite early after a fire in a room starts, that is, an initial fire, it will also begin to affect the rooms connected to the first fire room. The fire gases that are formed will eventually flow out of the fire room and heat up first and foremost the ceiling surfaces in adjacent rooms through convection. At the beginning, the temperature of the fire gases is relatively low and the amount of heat that is transferred is small, but gradually, the fire gases become hotter and hotter, and an increasing amount of fire gases flows out to adjacent rooms.

The more fire gases that are produced and spread to connected spaces, the more heat will be transferred to the ceiling surfaces through convection and heat radiation. Moreover, the hotter the fire gases are and the more fire gases that are produced, the more of the transfer will take place via heat radiation. Partly towards the ceiling, partly towards the upper parts of the walls and also towards objects and other surfaces in adjacent rooms.

Even though the room where the fire occurs quickly becomes hot, the temperature in adjacent rooms can in some cases be considerably lower for a relatively long time. However, if fire gases flow out of the room and into adjacent rooms, these will heat up the surfaces in the adjacent rooms.

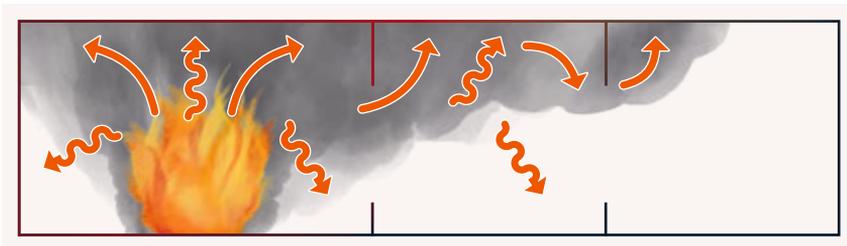


Fire gases and flames from the first fire room will heat up surfaces and objects in adjoining rooms. Photo: Stefan Svensson.

When the fire in the room of origin eventually reaches flashover, adjacent rooms are already heated. This means that the spread of fire to and in these rooms will then be faster, provided that there is enough oxygen in the rooms. Otherwise, the fire will become increasingly ventilation controlled and the rate of heat release will decrease, in the same way as for an individual room.

If the adjacent rooms become sufficiently heated, these will also begin to contribute to the production of fire gases. The more or larger the rooms that are adjacent to each other, the more surfaces and more objects there are that can contribute to the development and spread of the fire. This occurs primarily because more pyrolysis gases can be produced. The larger the fire grows in the room of origin and the more heated the adjacent rooms become, the more oxygen will be consumed in the rooms. If there are then no further openings from the outside to these adjacent rooms, the degree of ventilation control can be higher than if only one room had burned without any adjacent rooms.

**Figure 88.** Several interconnected rooms create different conditions for the fire



A fully developed fire can spread more quickly to other rooms, as these are already heated by the fire gases spreading from the original fire room.

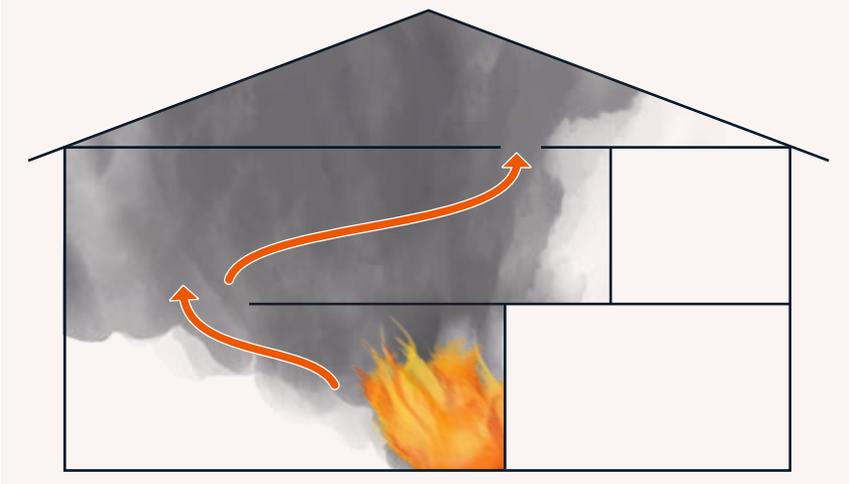
The more rooms involved in the fire, the greater the total rate of heat release can be, because there is normally more fuel available. At the same time, the rate of heat release, just as in the case of a single room, will be limited by the available amount of air, that is, the number and size of the openings. Here too, the opening factor plays a role. How much air can flow into the fire is crucial for the size and growth rate of the fire, regardless of how many rooms there are in the building.

If several rooms are involved in the fire, the fire can last longer, because there may then be more fuel available. As a consequence, the risk of spread through surrounding surfaces increases, that is, the fire spreading to the building structure, to other fire compartment or to other buildings. More rooms that are adjacent to each other also normally mean that there are more openings (doors and windows). This also means an increased risk of spread, to even more rooms or to the facade. Consequently, the risk of the fire spreading to several floors also increases.

Many single-family houses have two floors that are in open connection to each other and sometimes also to a basement floor. There, fire gases will also spread upwards in the building due to the thermal buoyancy. If we assume that the fire starts on the ground floor or in the basement, the fire gases will rise upwards. Upper floors may then heat up more and faster than parts of the floor where the fire started (but not faster than the fire room and the surfaces the fire gases encounter on their way up in the building). The fire gases that flow upwards in the building heat up the surfaces and objects they pass through, through convection and thermal radiation. At the same time, more air will be mixed into the fire gases on their way up in the building, which means that the temperature of the fire gases that reach the upper floors will be somewhat lower. However, the amount of fire gases becomes larger because more air can mix with the combustion products when they flow over a longer distance. A fire normally becomes worse if several floors are involved. This is one reason why fire cells are normally only allowed to cover two floors in height (unless it's a single family house).

As a consequence, surfaces and objects on the upper floors can begin to pyrolyse. The fire can then quickly spread upwards in the building, if the temperature of both fire gases and surfaces and objects becomes high enough.

**Figure 89.** Several interconnected floors create different conditions for the fire



In the event of a fire on the ground floor of a two-story house, the fire gases spread upwards in the building and also heat up the upper floor, as well as the surfaces that the fire gases flow past.

If the fire starts on the upper floor, initially only the upper floor will be heated. The fire gases will not flow down to the lower floor until the upper floor has been completely filled with fire gases (assuming there are no other influencing factors, such as external wind conditions). Fire gases can only flow downwards if the density is higher than the surrounding air. This can result in a fully developed room fire in one or more rooms on the upper floor, while the ground floor is relatively unaffected by both heat and fire gases.



A fire on an upper floor does not necessarily spread very quickly to the lower floors.  
Photo: Lars Axelsson.

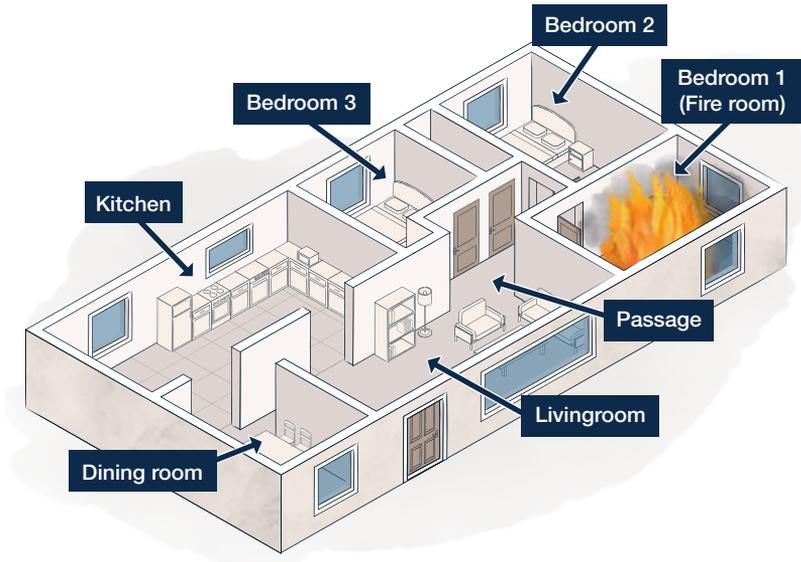
A fire involving several connected rooms normally produces a higher rate of heat release, but even in this case, it is to a large extent the number and size of the openings (the opening factor) that affects the size of the fire. The fact that there are several openings distributed over several rooms can, for example, mean that there is a fully developed fire in several rooms at the same time and that flames break out through several openings. Since buildings often have openings in several directions, the wind can affect the air supply to the fire. Note that a small opening factor does not limit the fire if there are openings that are affected by wind conditions. If the wind blows in through an opening, the fire will, of course, have access to more air.



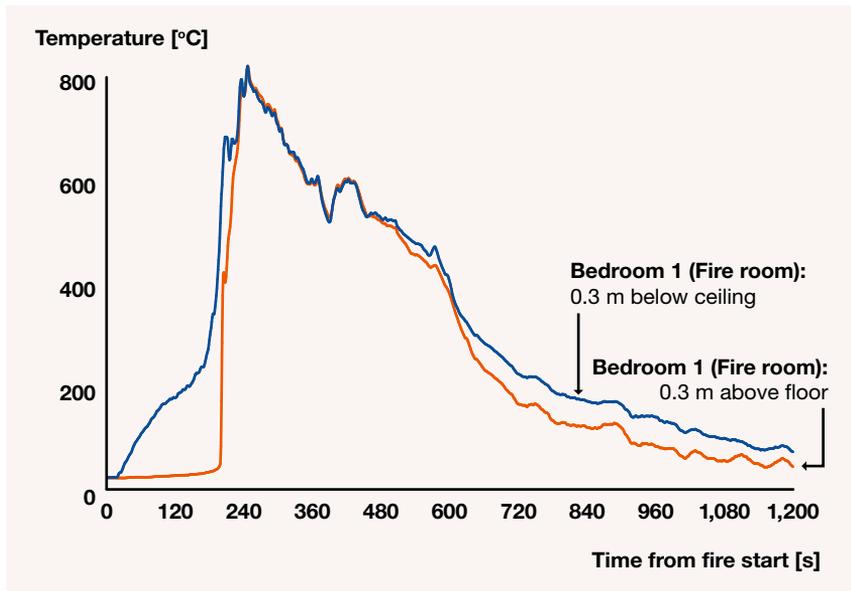
A fully developed fire in several rooms can cause flames to shoot out through several openings simultaneously. Photo: Peter Lundgren.

Let us look at an example, taken from full-scale experiments conducted in the USA (Madrzykowski & Weinschenk, 2019). The building used for the experiment was a furnished single-storey single-family house. It should be noted that there are some differences in building design between the USA and Europe, but these differences did not affect the course of the fire to any great extent during the time the experiments were running. If the fire had spread to the building's structure (walls or trusses), the differences would have become more obvious. The building had equipment installed to measure temperature, among other things, and the experiments were filmed with cameras mounted inside the different rooms. All doors and windows to the surroundings were closed and no extinguishing was done.

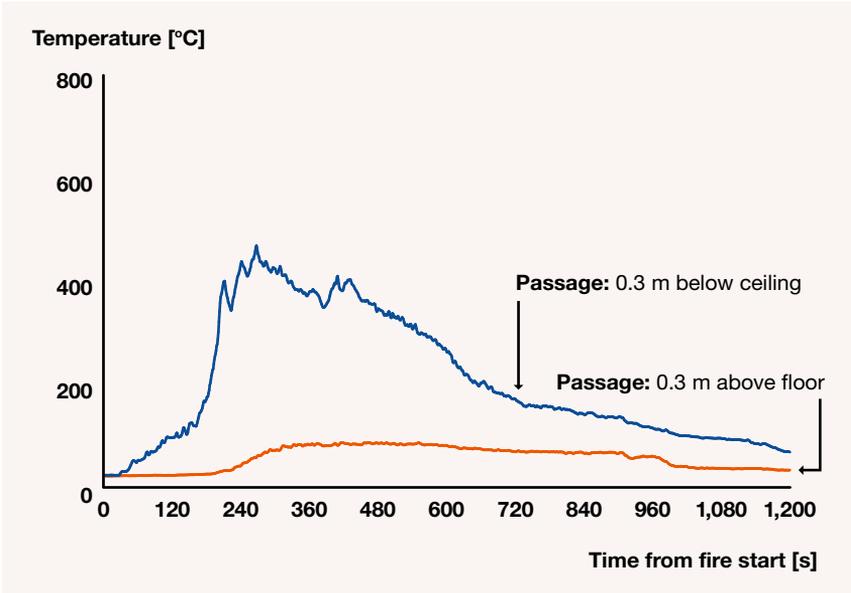
**Figure 90.** Overview of experimental building, all openings closed



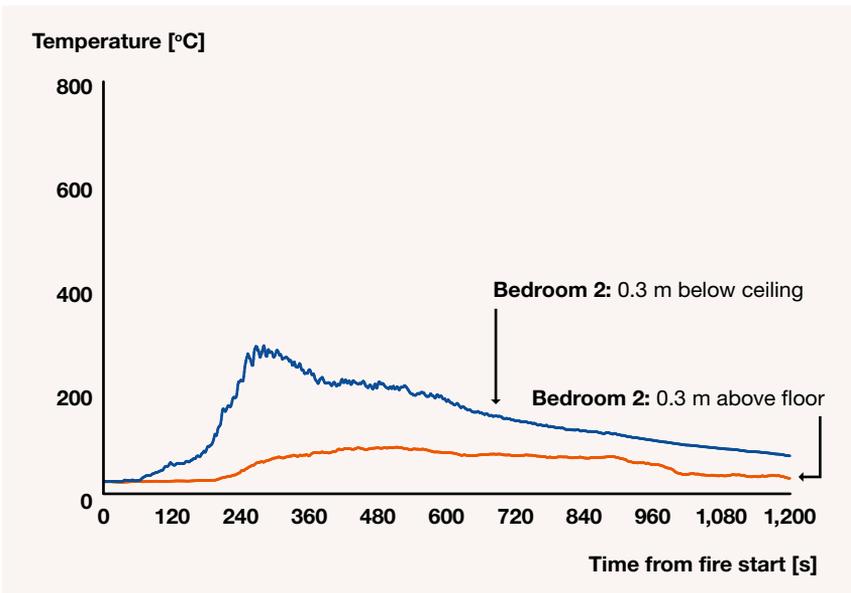
**Figure 91.** Temperature in bedroom 1 (fire room)



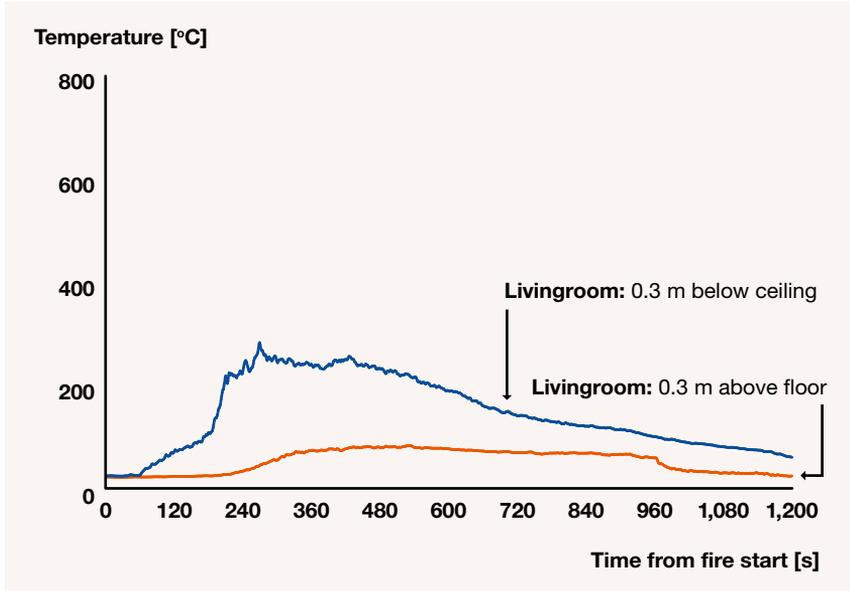
**Figure 92.** Temperature in passage (outside the fire room)



**Figure 93.** Temperature in bedroom 2



**Figure 94.** Living room temperature



**Figure 95.** Temperature in kitchen

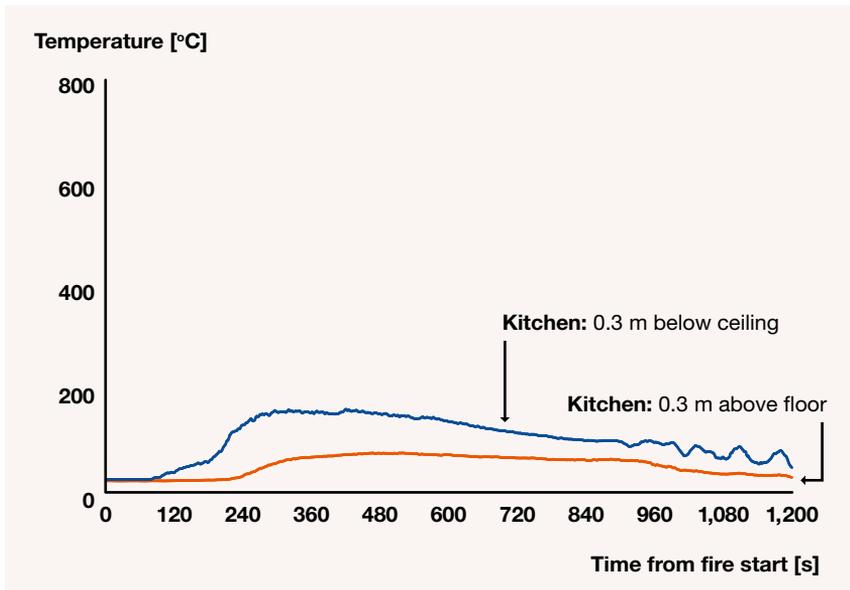
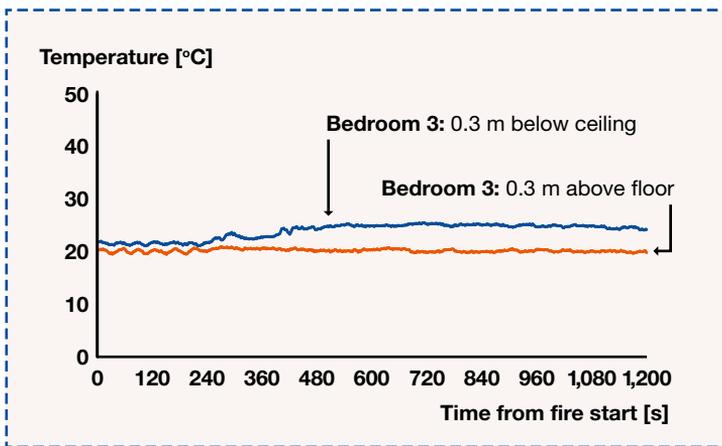
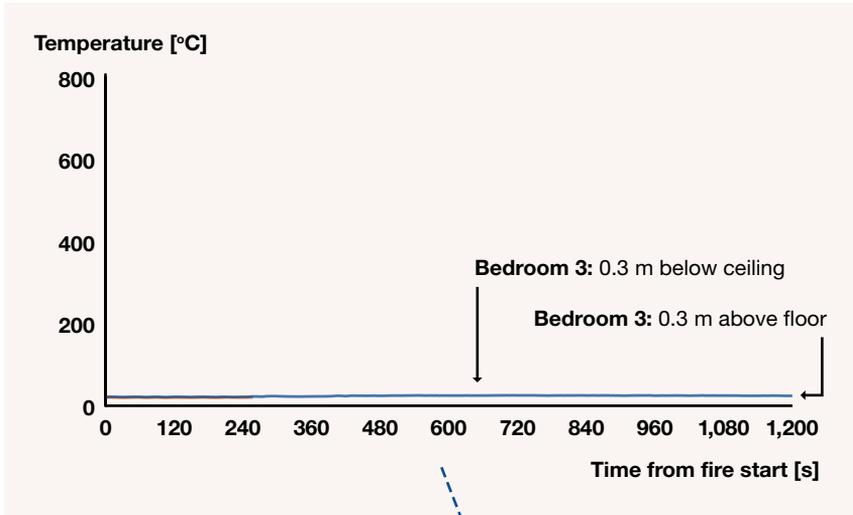


Figure 96. Temperature in bedroom 3



Zoomed in version. Note that the diagram has a different temperature range.

It is clear that the hot fire gases spread from the room of origin, that is, the room where the fire started, to other rooms. You can also see how the fire gases cool down, because the temperature of the fire gases is lower the further from the fire room. The difference is greatest closest to the ceiling. You can also see a time lag for the temperature increase between the different rooms. It simply takes longer for the fire gases to flow to and heat up the rooms that are furthest from the room of origin.

The temperature varies with height and it is warmer closer to the ceiling. The reason is the thermal lift: hot fire gases have a low density and rise upwards. These vertical temperature differences become greater the higher the ceiling height in the room. In general, ceiling surfaces and the upper parts of walls will heat up first and most.

There are also horizontal temperature differences. The greater the distance from the fire, the lower the temperature. Even in the same room there are horizontal temperature differences. These temperature differences are greater the larger the area of the room.

The temperature in bedroom 3 is almost not affected at all, because the door to the bedroom was closed. Measurements of oxygen content showed that the environment in the room was almost unaffected. This shows that even a simple interior door can stop the spread of fire and fire gases for a relatively long time. The possibility of survival behind such a door is therefore good.

In the example, in the room of origin a flashover occurs after just under four minutes. Note that there is no flashover in any of the other rooms. This is due, among other things, to the fact that the fire quickly becomes ventilation controlled because all windows and doors to the surroundings are closed. In this experiment, no extinguishing takes place; the fire is allowed to burn out and self-extinguish.

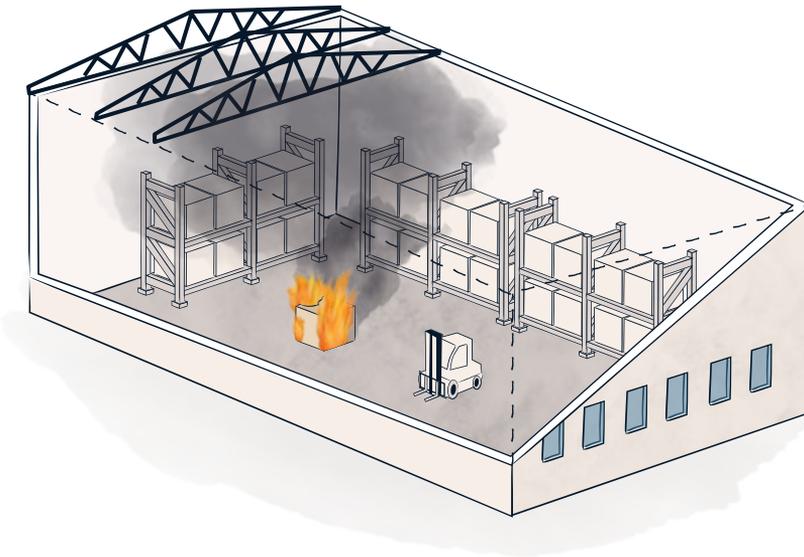
If the front door or any window had been opened or remained open during the process, the fire would have progressed more quickly. It would also have probably spread in the direction of the opening and more rooms would have been involved in the fire itself. Most likely, the temperature would also have become higher, due to the increased air supply. In addition, surrounding wind conditions could have affected the course of the fire.

If a room fire continues for a long time, if the temperature is high or if the room's wall or ceiling materials are deficient, a structural fire may occur. A structural fire is a fire that spreads to the building's structural elements and to the cavities that are normally found in, for example, walls and floors.

## Fire in large enclosures

In large enclosures, such as public premises or industrial buildings, the exchange between the fire, the fire gases, the surrounding surfaces and objects in the room takes place in a slightly different way, compared to smaller and normal-sized rooms, such as a kitchen or a bedroom. The heat transport in the room and the heat return to the fire are different.

**Figure 97.** Large rooms create different conditions for a fire to develop and spread



In large rooms, it is less likely that a flashover will occur in the same way as in normal-sized rooms (such as a kitchen or a bedroom in a single-story house).

Rooms can be large because the floor area is large. The fire usually behaves differently when the floor area is larger than approximately  $150 \text{ m}^2$ . The course and spread of the fire then differs somewhat from the course of a room fire as previously described. The rooms can also be large because they have high ceilings. In principle, anything that is higher than normal living spaces can be considered high ceilings, that is, higher than approximately 3 m. The larger the floor area or the higher the ceiling height, the greater the differences compared to normal living spaces.

A larger floor area has an impact, among other things, by creating greater distances, both between walls and between objects (fuels) in the room. It will also take longer for the fire gases to collect, since it is a larger volume that must be filled. This affects the heat transfer, both back to the fire and towards the ceiling and wall surfaces in the space. Heat radiation is strongly distance-dependent. In a larger space, the radiation from flames or from fire gases will therefore affect objects such as the floor, walls and ceiling less. The surfaces will heat up more slowly. It may then take longer for them to start pyrolysing and contribute to the production and spread of fire gases and to the course of the fire.

The ceiling height affects the fact that it will take longer to fill the room with fire gases. On the way up the fire gases will also mix in more air, which causes the temperature of the gases to drop. The fire gases that are formed should simply be distributed over a larger volume. This can partly mean that the temperature of the fire gases will be lower (or increase more slowly), and partly that the heat transfer from the fire gases to surrounding surfaces (ceiling and walls) will be lower or slower (through convection). The speed of the fire gases' movement in the room can also be lower, which also contributes to lower heat transfer, and if the temperature is lower, the thermal radiation from the fire gases will also be lower.



Large rooms may have higher ceilings or greater distances between surfaces than normal-sized rooms. Photo: Johnér Bildbyrå.

In large rooms there is also more air available. It may therefore take longer for the fire to become ventilation controlled, or the degree of ventilation control increases more slowly. In very large premises the fire may remain fuel controlled for a long time, even if it grows very large.

In large rooms, the phenomenon of flashover cannot always be used to describe the development of the fire over time. As a result of the greater distances between the surfaces of the room, the stage is not always reached where the thermal radiation from the fire, the hot gases and the hot surrounding surfaces cause all combustible surfaces in the fire room to pyrolyse and ignite. The fire may become large, but does not spread to the entire space, at least not as quickly as in a smaller or normal-sized room. The spread of fire simply occurs in other ways in large rooms. In some cases, one can speak of a local flashover of the room. In this case, a certain part of the room can be considered flashover, in a similar way to a flashover in a room of a more normal size. In that part of the room, everything combustible is then covered by the fire, but not the rest of the space.

Note that there is a difference between the terms flashover and a flashed over fire. Flashover is a stage in the development of a room fire – between the initial fire and the fully developed room fire. We have an flashed over fire after the flashover has occurred and all combustible material is covered by the fire. The fully developed fire can thus be said to be an flashed over fire. Sometimes the term “flashed over” is also used for fires in the open air. For example, a flashed over car means that the entire car is on fire, but this has nothing to do with the flashover of a room.

In large rooms there will also be more pronounced differences in temperature between different parts of the room. Vertically there will be greater differences in temperature between floor level and ceiling level than for the corresponding fire in a smaller room. This is mainly due to the thermal lift, but also to the heat radiation from hot fire gases towards the surfaces in the space.

Horizontally, there will be correspondingly greater differences in temperature the greater the distance to the fire. This is partly due to the fact that thermal radiation is strongly distance-dependent. The closer you are to the fire, the more the thermal radiation from the fire will affect

you, but it is also due to the fact that the temperature of the fire gases is lower the further away you are from the fire. When the fire gases flow past ceiling and wall surfaces, heat transport occurs through convection, and the temperature of the fire gases then drops. More ambient air is also mixed in when the fire gases have a longer distance to flow. This also causes the temperature of the fire gases to drop, and the lower the temperature of the fire gases, the less heat radiation they give rise to.

### **Example**

Late in the evening of November 30, 1991, the fire and rescue service in Västerås received an automatic fire alarm from ABB Relay AB. The building was constructed of a non-combustible construction with external dimensions of 109×168 m and a room height that varied between 6 and 7 metres. The largest room, where the fire broke out, was approximately 6,500 m<sup>2</sup>. The fire probably started in a machine for washing freshly soldered circuit boards, due to overheating in a faulty circuit breaker.

The fire spread to the roof of the building, where the asphalt in the roof covering melted and ran down through the internal drain pipes, which then also melted. The fire became very intense, as a result of the plastic casings of the machines, the asphalt, the drain pipes and a large amount of cables.

The damage to the building was extensive, due to the large amounts of fire gases that were formed. The actual fire damage was fairly limited to the area closest to the initial fire, partly because of the size of the premises, and partly because the fire and rescue service managed to limit the fire to this area. The high ceiling height and the distance between machines and other furnishings probably meant that the fire could not spread faster than the fire service had time to limit the fire damage.

(Statens haverikommission. Brand den 30 november 1991 i ABB Relay AB:s lokaler i Västerås, U län. Rapport O 1991:1)

## Travelling fires

The description of a flashover process works for normal-sized rooms in homes and similar spaces, that is, rooms that are smaller than approximately 150 m<sup>2</sup>. Note that this is not an exact limit but rather serves more as a guideline. In larger spaces than this or if the room is far from square, for example in a corridor, flashover does not occur in the same way. In such spaces, something that can be called a “travelling fire” occurs instead. In travelling fires, the flame spreads over surfaces much more slowly than in the case of flashover, even though it occurs indoors. However, a travelling fire requires that there is sufficient combustible material in the space and that these combustible materials are more or less connected, so that flame spread over the surfaces can occur. However, even in the case of travelling fires, the fire gases will be of great importance. The fire gases heat the surfaces in front of the fire (through convection and thermal radiation), which causes combustible surfaces to begin to pyrolyse in front of the fire.

If the floor area in the room is large, what we call flashover usually does not occur, that is, the more or less sudden transition stage from a fire in one or a few objects to a fire that encompasses the entire room. The room is simply too large for the initial fire and the fire gases that are formed to be able to affect the other surfaces or objects in the room to the extent required for a flashover. The circumstances are not such that a layer of fire gases can build up so hot that a flashover can occur. The fire gases are cooled against the ceiling, more cold air is mixed in, etc. If there are large amounts of combustible material in the room, a flashover can in itself occur, leading to a fully developed room fire, but the larger the space, the less likely it is that a flashover will occur in the same way as in a more normal room, that is, that the entire room is covered by the fire.

**Figure 98.** Travelling fire

In the event of a travelling fire, flame spread over surfaces occurs much more slowly than in the event of a flashover.

Note that the term "travelling fires" is well established in forest and bush fires, where it is used to describe how and in what type of fuel the vegetation fire spreads. What is common for travelling fires indoors and outdoors is that the fire spreads at a certain speed (or a speed range) over a surface. In the case of a travelling fire indoors, other surfaces and objects in the space will, of course, also contribute to the spread of the fire. It can also have its primary spread along the floor, while the ceiling surfaces are only covered secondarily.

In the event of a flashover, the fire spreads in the room at speeds of the order of 2–6 m/s, but higher speeds than this have also been reported. In the case of a running fire, the spread rate is more likely to be around 20–50 mm/s or 15–25 m<sup>2</sup>/min or even less. In addition to the properties of the fuel, the location and distribution of the fuel in the room will also affect the rate of spread. The fire spread is therefore relatively slow. This is an important difference between a flashover and a travelling fire indoors: a flashover occurs rapidly in a room so that everything combustible in the space is covered within a relatively short period of time, while a travelling fire is a fire spread phenomenon. The fire, or rather the fire front, moves through the space at a certain speed, a certain distance or over a certain area (Grimwood 2018).

The phenomenon occurs, for example, in office landscapes with open floor plans and public buildings with large open areas. It is also necessary that there is enough fuel for a fire to spread. However, the fuel is normally located in the lower part of the room and not in the form of ceiling material. This means that not as much fuel is exposed to direct flame impact. The ceiling height is important; it affects how fire gases fill the

room and how re-radiation occurs from both fire gases and flames towards primarily ceiling surfaces. However, since the floor area is large or long, the flames from the initial fire will not affect other objects or surfaces in the room in the same way as in normal-sized rooms (<150 m<sup>2</sup>), simply because there is often greater distance between furniture and other objects in rooms with a larger floor area.

In rooms with high ceilings, fire does not spread in the same way as in rooms with more normal ceiling heights. In many cases, the fire will then remain local in the space for a relatively long time. However, this depends largely on which fuels are present in the space and how these relate to each other. In some cases, so-called running fires can occur in rooms with high ceilings, that is, the fire does not reach ignition but spreads gradually in the space.

## Wind-drive fires

Wind-driven fires can occur due to high-speed air flows. The flow of air is primarily caused by external wind conditions, usually in combination with broken windows or incorrect use of positive pressure ventilation (fans). If air blows into a fire compartment at high speed, this can cause complex fire processes with rapid growth or rapid spread. The air flow can turn the most modest fire into an inferno. There are several examples where firefighting personnel have been injured or died as a direct result of so-called wind-driven fires, although not in Sweden. This has primarily occurred in fires in high-rise buildings, which become more exposed to wind the higher up the building. However, wind-driven fires can also occur at ground level, since it is mainly the surrounding wind conditions that affect, not primarily the design of the building or the room fire as such. However, structural fire protection requirements for, for example, windows in high-rise buildings can reduce the risk of wind-driven fires.

### Wind-driven fire

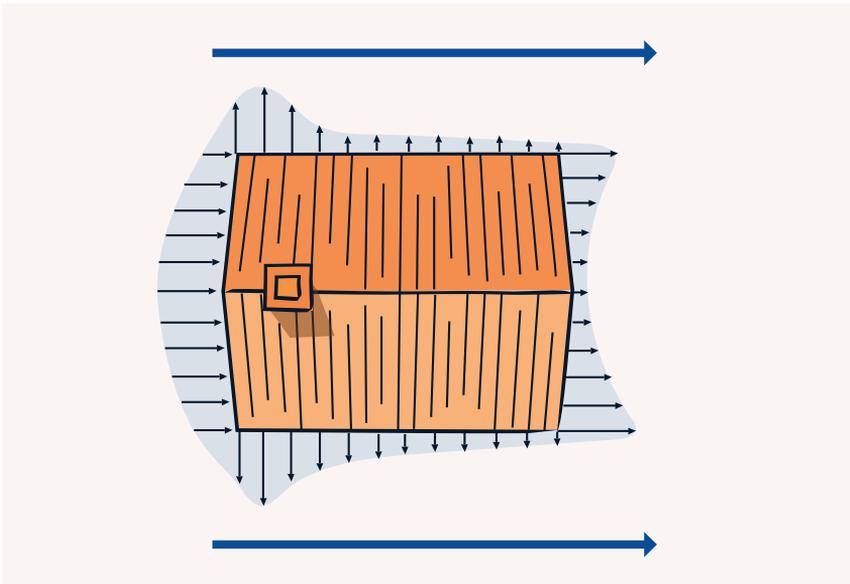
A fire in a building where ambient wind conditions cause abnormal fire growth, rapid spread rates, or high temperatures, due to openings on both the windward and leeward sides of the building.

The term “wind-driven fire” has become a commonly used term for fires in buildings that are strongly affected by ambient wind. For ease of presentation and understanding, a wind-driven fire can be defined as a fire in a building where ambient wind conditions cause abnormal fire growth, high rates of spread, or high temperatures, due to openings on both the windward and leeward sides of the building.

Wind is caused by pressure and temperature differences at the Earth’s surface and in the atmosphere and can be described as the flow of gases on a large scale. Wind is measured in a number of different ways, but metres per second (m/s) are commonly used.

When wind hits an object, such as a wall, pressure is created against the wall (an overpressure, that is, a positive pressure). However, the wind simultaneously creates a negative pressure on the opposite side of the object. Wind also creates a negative pressure on flat roofs and on wall surfaces perpendicular to the wind direction. On a gable roof, the pressure over the surfaces varies, both on the windward and leeward sides, depending on the angle of the roof.

**Figure 99.** Wind pressure around a building



Wind creates a positive pressure (an overpressure) on the windward side and a negative pressure on the leeward side of a building. Negative pressure is created on sides perpendicular to the wind.

As a consequence of this, a wind blowing against a wall where there is an open window will also create an overpressure inside the room. If the room has no other openings, the pressure will rise in direct proportion to the wind speed. However, if there is also a window on the other side of the building, that is, on the leeward side, the air that is forced in on the windward side will flow through the building and out the other side. Compare this to what we commonly call crosswinds, that is, when we open several doors or windows on different sides of a building on a windy day.

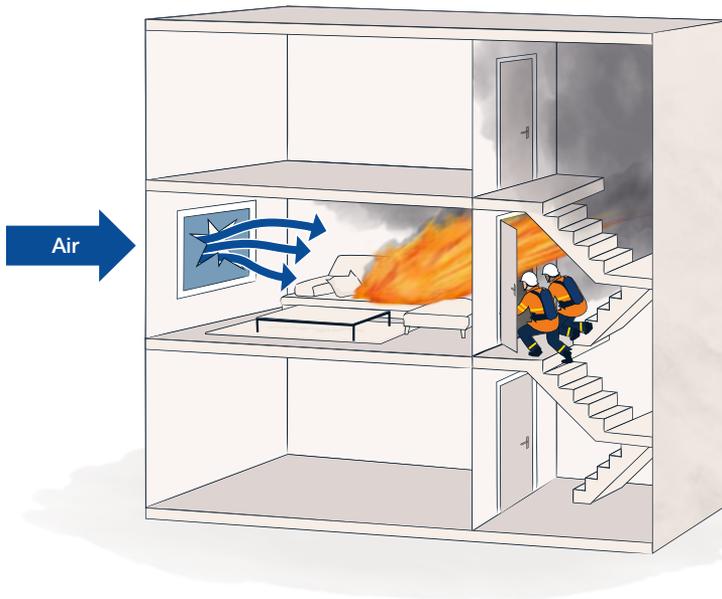
Air flowing through an opening of a certain size will have a certain velocity and flow rate. If there is no wind at all towards the opening, only a limited amount of air can flow through the opening. The flow rate through the opening then depends mainly on the temperature difference (density difference) between the air inside the opening and the air outside. If there is a fire in a room inside the opening, the velocity will increase as the temperature in the room increases.

Let us now imagine a room where a fire has broken out. There are large amounts of combustible material in the room, so that the fire can continue for a long time. There is only one opening to the room, in the form of a window. As the fire grows, the inflow of air and the outflow of fire gases increase. After a while, the fire has grown so large that it begins to become ventilation controlled. The size of the opening is then no longer sufficient for air to flow in sufficient quantities to the fire in the room.

Now let's imagine that the wind is blowing directly at the window. Since there is only one opening to the room, the pressure will increase, both against the building and inside the room. The fact that the pressure inside the room increases is largely due to the pressure against the window preventing the fire gases from flowing out of the room. At the same time, the wind pressure forces air into the building, and in extreme situations, strong pulsations can occur in the opening. The combustion inside the room continues. When the pressure from the combustion becomes greater than the wind pressure, flames and fire gases will be pushed out through the window. The pressure in the room decreases and the wind pushes the combustion back into the room. This is repeated so that pulsations occur.

If a door on the leeward side is now opened, the wind pushing against the building will force fire gases out through the new opening, while air flows in through the window on the windward side. The opening on the windward side does not have to be to the fire room, but can be in another space that is connected to the fire room.

**Figure 100.** Wind-driven fire



Openings on the windward side of a building can cause the fire to grow rapidly and be pushed into the building towards emergency personnel.

If a lot of air flows in to the fire, the fire can spread rapidly and strongly. The consequence can be that the fire spreads inside the building at great speed and with a rapidly increasing rate of heat release. The fire has then become wind-driven, that is, its course and development are mainly controlled and influenced by the surrounding wind.

It is similar to blowing on embers or small, modest flames to start a stove: the increased air supply increases the combustion rate. If the original fire creates large amounts of pyrolysis gases, that is, combustible combustion products, these can ignite on the leeward side of the fire. The process can be very violent.

If the fire room only has one window on the windward side, important information can be obtained by observing the behaviour of the flames at the window. If the flames “pulse” out through the window, it is a sign that the fire is strongly influenced by the wind. If a door to the fire room is then opened, so that a flow occurs from the window on the windward side, through the fire room and out through the open door on the leeward side, fire gases and fire can spread at great speed. A wind-driven fire has then occurred.

A wind-driven fire means that hot fire gases or flames flow horizontally out of the fire room, from the windward side of the building towards the leeward side of the building. For wind-driven fires to occur, the fire must be in a flow path. In other words, the fire must be between the supply air opening, where the wind blows in, and the exhaust air opening, where fire gases can flow out. Without such a flow path, a wind-driven fire in the building cannot occur.

### **Example**

Early in the morning of December 18, 1998, several units in New York were called to a fire on the tenth floor of a nursing home. While the forces searched the other floors and pulled hoses into the stairwells and corridors, three of the firefighters headed for the burning apartment. There, the door was ajar, allowing large amounts of fire gases to escape into the connecting corridor. They probably made their way to the burning apartment and opened the door to begin extinguishing the fire. The fire was at this time fully developed, and a strong wind was blowing towards the building and into an open window in the burning apartment.

When the firefighters opened the door, a flow occurred due to the wind against the open window, which caused fire gases and flames to be pushed straight towards the group. The heat was extreme. All three died in the corridor outside the burning apartment, without any opportunity to get out of there or even get water on the fire. The fire spread very quickly because of the wind against the window.

(Norman, J., Extreme Wind Driven Fireproof Multiple Dwelling Fires. With New York Firefighters (WNYF), New York, NY, 1st/2007)

## Chimney fires

A type of fire that is fairly common is a so called chimney fire. Such a chimney fire occurs when tar and soot that have collected in a chimney ignite. This can, due to the stack effect, lead to extremely high temperatures and damage to the chimney or the spread of fire gases or fire to the rest of the building. In addition to the fact that heat conduction through the chimney can ignite adjacent building parts, cracks can cause fire gases and flames to spread throughout the building.

In a brick chimney, the joints between bricks are the weak point and it is not certain that they will withstand the high temperature. Cracks can also occur due to expansion when the chimney is heated. This can be several centimeters at the top and the higher the chimney, the longer the expansion. Floors and other things that are attached to the chimney do not follow the expansion and this movement can cause cracks to occur.



A chimney fire can produce flames that rise high above the chimney top. The risk of spreading to the building's structure is very high. Photo: Johnér Bildbyrå.

There can be several causes to chimney fires. For example, using damp or insufficiently dry wood can lead to incomplete combustion. The fire gases then become colder and tar condense and stick to the inside of the chimney. It can also be due to poor air supply, which means that combustion efficiency is low and larger amounts of tar are formed, which condenses on the inside of the chimney. When the amount of tar or soot has become large enough, this can ignite and a chimney fire occurs.

Burning a lot and "hard" for a long time, causing the chimney to over-heat, can also lead to the fire spreading outside of the chimney to nearby building parts due to heat conduction.

If the chimney is not completely blocked, a sign of a chimney fire may be a loud, rumbling or roaring sound from the chimney. This is due to the stack effect, i.e. the speed in the chimney is high due to the large temperature difference. Another sign may be sparks, flames or thick, black smoke coming from the top of the chimney.

The best way to suppress a chimney fire is to keep the temperature down by restricting the air supply at the bottom, i.e. to ensure that the fire is heavily ventilation controlled and burns at a low intensity. Applying extinguishing agents can crack the chimney and make the situation worse.

## **Structural fires**

A situation that complicates fires in buildings is so-called structural fires. This is a term used when the fire spreads to the structural elements of the building. The fuel is then no longer only the contents of the building, but to a large extent combustible structural parts such as wooden beams, cables, insulation and the like. Such a structural fire can start as a room fire and then spread to the structure, but a structural fire can also start inside, for example, walls or floors, where there are often cavities of various kinds. Such cavities are often not visible and can be difficult to detect. This makes it difficult to deal with structural fires. Hard work or some ingenuity is often required when extinguishing.

For the continued presentation of structural fires, the following definition is used: A structural fire is a fire in hidden spaces or on surfaces with limited accessibility, often with exposed combustible surfaces such as building materials and installations, and which are not normally used for, for example, storage or occupancy (Svensson, 2020). It is therefore mainly the structure and its parts that are themselves the fuel of the fire. Both the shape and size of such hidden spaces are often very different compared to ordinary rooms, which affects the spread of both fire gases and fire. In addition to the fact that the spaces can have a small volume, they can be elongated, have low ceilings, contain sloping surfaces, etc. In addition, accessibility to such spaces is often poor. It can be difficult

for the fire service to extinguish structural fires. Partly because they are hidden and therefore difficult to find, and partly because it can be difficult to access such fires even if they have been found.

### **Structural fire**

A structural fire is a fire in hidden spaces or areas with limited accessibility, often with exposed combustible surfaces such as building materials and installations, and which are not normally used for, for example, storage or occupancy.

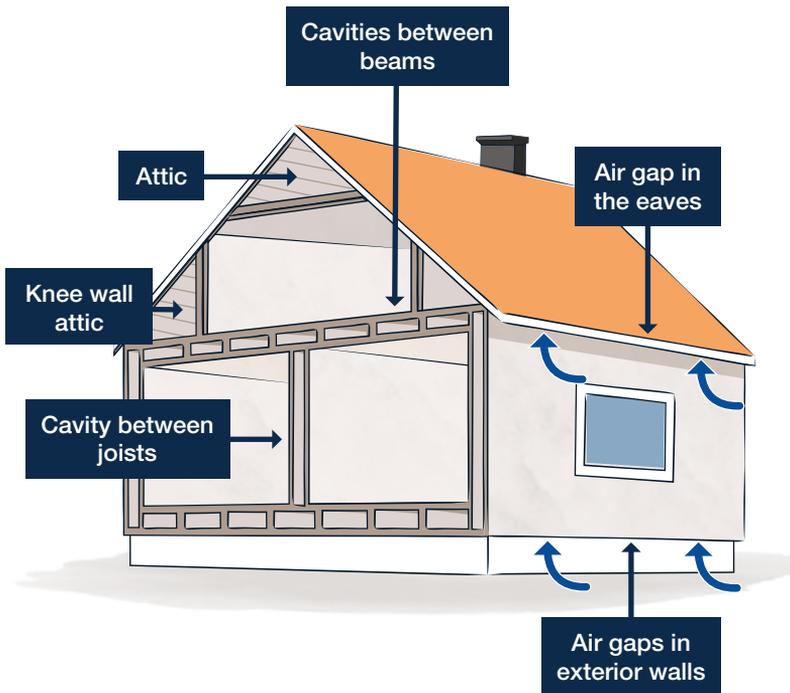
Examples of hidden spaces where structural fire can occur or spread include:

- smaller cavities such as
  - air gaps in facades, eaves or insulated ceilings/roofs
  - structural cavities in building components, which occur, for example, in trapezoidal sheet metal, renovations or joists
  - cavities that arise as a result of fire, for example due to melting insulation
  - cavities caused by pests
  - voids in uninsulated interior walls
  - cavities between building elements
  - cavities between building modules
- larger cavities such as
  - uninsulated attic spaces
  - crawl spaces
- larger vertical cavities such as
  - shafts.

Such spaces can pose particular problems with regard to both fire spread and the response of the fire service.

Please note that there is no clear definition of what constitutes a structural fire. Rather, we use the general term structural fire to describe various firefighting problems that can primarily be attributed to difficult accessibility. For example, a fire in an installation culvert can in many ways behave like a structural fire due to its difficult accessibility, even though it is technically defined as a room fire. A fire in an attic can also develop in a similar way and be defined as a structural fire, regardless of whether it is easily accessible or not. A regular attic with storage spaces for an apartment building is not difficult to access, but a fire there still has much in common with structural fires. Such attics can, for example, contain large amounts of combustible material, including both the structure and what is stored in the storage spaces, while being large and having a complex design.

**Figure 101.** Buildings typically contain a variety of cavities





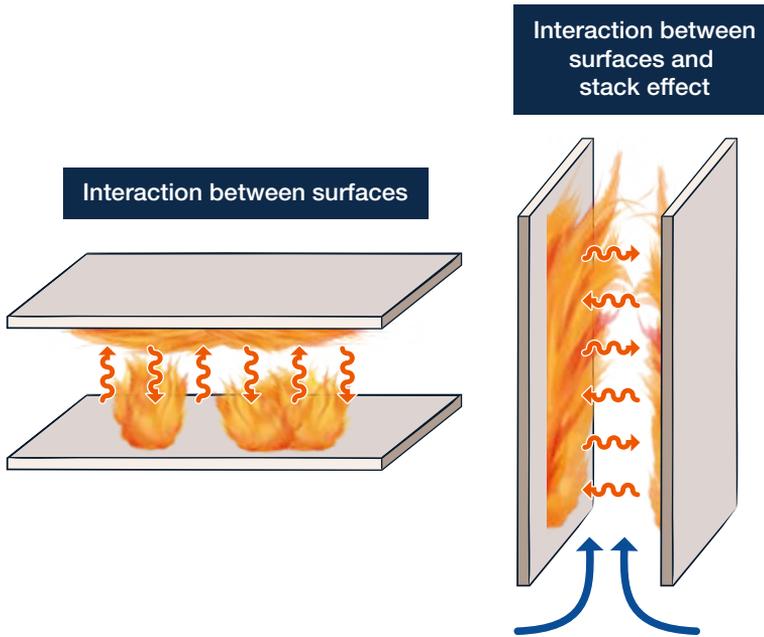
Certain types of buildings and their construction methods can increase the problem of structural fires. Photo: Stefan Svensson.

## Fire behaviour in structural fires

The mechanisms that control and influence fires and their spread in structural fires are, of course, the same as in other fires in buildings. This applies, for example, to how different types of materials affect and are affected. The differences compared to ordinary rooms are partly the size and geometric design, and partly how combustible materials are exposed. What is characteristic of structural fires is above all that it is the structural parts of the building that are the fuel. The latter also means, among other things, that the greater the proportion of combustible materials a building is constructed of, the greater the risk of fire spreading, and if the building's structure becomes involved in the fire, the risk of collapse increases because the load-bearing capacity may be reduced.

The geometric differences can include a short distance between opposing surfaces, small volumes, high or wide volumes, complex shapes, etc. Moreover, structural fires are often difficult to detect and access for extinguishing. The problem is complex, and there are several different mechanisms that play a role and influence simultaneously.

**Figure 102.** Fire behavior in structural fires

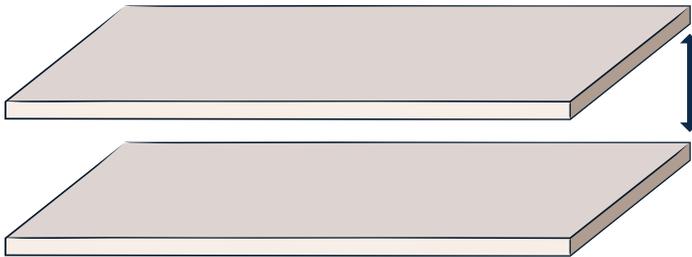


Fire behavior in structural fires is affected more by geometric differences in relation to ordinary rooms, among other things. If the distance between surfaces is small, the surfaces will affect each other so that the spread of fire occurs at a faster rate.

The smaller the distance between opposing surfaces, the greater the interaction between the surfaces can be. If we assume that fire gases have spread to a space with a small distance between the wall surfaces, the surfaces will be heated by convection. As the wall surfaces heat up, the thermal radiation between the surfaces will increase, and the smaller the distance between the opposing wall surfaces, the faster the heating will occur due to the thermal radiation between the opposing wall surfaces. As the temperature increases in the space, the hot fire gases will rise faster and faster. The gas velocity in the space becomes higher, convection increases, the surfaces become hotter, the thermal radiation between the surfaces increases, pyrolysis increases, the speed of the gases (and eventually the flames) increases even more and so on. Consequently, a fire in a space with a small distance between opposing surfaces can

spread extremely quickly. This, combined with the fact that the fire is hidden, that is, occurs inside a structure behind wall panels or similar, makes the fire very difficult for the fire and rescue service to handle. Note, however, that the smaller the distance between two opposing surfaces, the greater the flow losses, which slows down the process. Heat losses also increase the closer two surfaces are to each other. A certain minimum distance is required for a flame to pass, known as the “quenching distance”. This distance varies depending on the properties of the fuel and the surrounding surfaces.

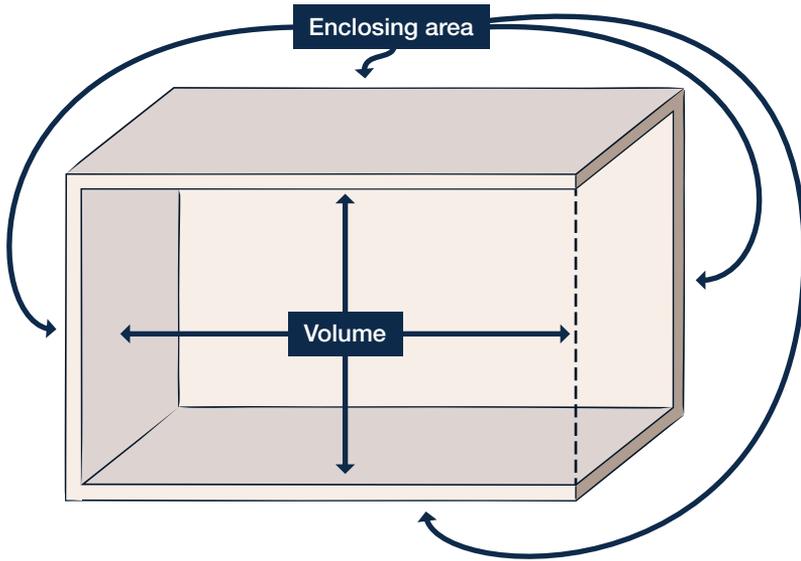
**Figure 103.** The distance between surfaces affects the spread of fire



The smaller the distance between opposing surfaces, the greater the interaction – heat exchange – between the surfaces.

The smaller the volume of a space, the larger the enclosed area in relation to the volume. This means that there will be relatively more surfaces that are heated. If the structure consists of combustible material, such as wood, more fuel will be exposed to fire or fire gases, relatively speaking, and the smaller the volume, the faster the fire can become ventilation controlled.

**Figure 104.** The volume of the space affects the spread of the fire



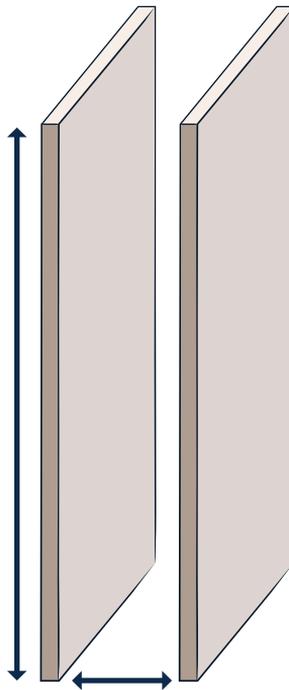
The smaller the volume of space, the larger the enclosed area will be in relation to the volume.

A fire or fire gases that spread into high narrow spaces (similar to a chimney) will give a greater temperature difference between the lower and upper parts of the space the higher the space is. The hot fire gases from the fire have a lower density and rise upwards in the shaft. If there are openings both at the top and bottom of the space, fire gases will flow out at the top and air will flow in at the bottom, as a direct consequence of the principle of conservation of mass. If the space, for example an air gap in a facade, is high, this can also mean that the flow in the air gap is large. If then the area of the air gap is small, the speed of the flowing fire gases can be high, resulting in rapid fire spread. We call this the stack effect, but it is also related to the short distance between opposing surfaces.

The stack effect becomes noticeable because air cannot be mixed into the fire plume from the side, unlike when burning in the open air. The plume does not cool down, but rather retains its temperature and lifting force.

The speed of the upward-flowing fire gases can be high. This results in a higher convective heat transfer to the walls of the shaft, and as the walls of the shaft heat up, the heat from the walls can contribute to a further increase in the speed of the gas flow in the shaft. Since air can flow in at the bottom, the fire's rate of heat release increases faster than it would otherwise have done. The temperature, and consequently also the density difference, can then become very high, and as the rate of heat release increases, the production of fire gases increases further, the convective heat transfer increases further and so on.

**Figure 105.** The height of the space affects the spread of the fire



The higher and narrower a space is, to a certain limit, the greater the upward velocity of the gases in the space. The distance between the sides of the space has a great impact on the velocity.

The production of fire gases and the spread of fire in buildings depend to a large extent on whether a fire is fuel controlled or ventilation controlled. This also applies to structural fires, even though the volumes or surfaces there have a different shape than “normal” rooms. Overall, the fire gases and thus also the fire have completely different conditions for spread if the fire is ventilation controlled. If the space where the fire is burning has a small volume, the fire can become ventilation controlled much faster than in a normal room, especially if the space has large amounts of combustible material (construction materials or installations).

Structural fires can also be difficult to find and identify for firefighting personnel. Even if you have access to a thermal imager (an infrared camera), it takes a certain amount of time for the heat to spread through the structure. How quickly the heat is conducted through the structure depends, among other things, on how it is designed and what materials are included. This means that what is visible in the thermal camera on the outside of, for example, a wall structure is already “history”. The fire may have spread far from the place where the thermal camera indicates heat on the outside of the structure. Note that the thermal camera is not an X-ray camera: it only shows how much thermal radiation is emitted from the surface of what you are looking at, not what it looks like behind it.

What is visible in the thermal imager may also be traces of gases that have flowed through the structure, either cold air that has flowed in or warm fire gases that have flowed out. These gas streams can provide clues to where the fire’s supply and exhaust air openings are, but do not necessarily indicate where the fire source itself is.

When the fire and rescue service opens up a structure to access the fire, there is a risk of adding air to a heavily ventilation-controlled fire. This can increase the rate of spread and cause the fire to spread uncontrolled.



A thermal imaging camera is a valuable tool for finding hidden structural fires, but it can provide incorrect information because the heat conduction through, for example, a wall takes some time. The image shows a modular multi-family building with fire spread between the modules. Photo: Christer Björkman.

## Different types of structural fires

In order to effectively manage structural fires, it is important to understand the mechanisms behind them. It is also possible to distinguish a number of typical examples of structural fires, where the mechanisms affect in different ways. Some such examples are:

- facade fires
- fires in trusses, walls and crawl spaces
- attic fires
- fires in modular buildings.

## Facade fires

Facades have proven to be a particular problem, as they often contain air gaps to protect against moisture. Although the amount of combustible material in such air gaps may be minimal, it can be sufficient to cause a fire to spread rapidly inside a facade. The combination of the mechanisms described above means that fire and fire gases can spread particularly quickly in facades. This is especially the case in tall buildings, although in some cases there should be structural fire protection devices to reduce the risk of fire spreading in facades.



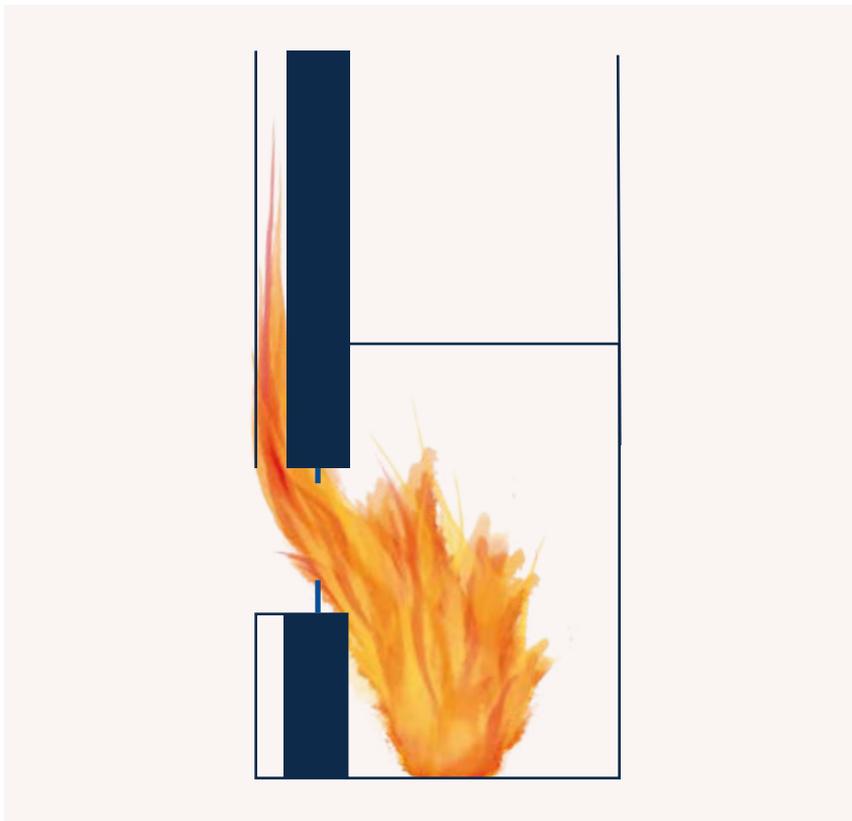
Facade fires can cause major problems due to the rapid spread of fire.  
Photo: Johnér Bildbyrå.

A facade fire is a type of structural fire that does not necessarily meet the definition in the introduction to this section, but the problem is similar. A facade fire can be described as a fire in a space or rather on surfaces with limited accessibility, often with exposed combustible surfaces such as building materials and installations. A facade can also contain hidden spaces, for example in the form of air gaps, but not necessarily. Cavities can also form during a fire, for example in foam plastic that shrinks when exposed to heat. If a fire occurs inside or outside a facade, the upward spread can occur very quickly. If the

spread occurs inside cavities in the facade, the spread can occur faster than if the spread only occurs on the outside of the facade. This is due to the so-called stack effect, which has a major impact on the upward spread rate of the fire. The fire can also spread into the building from the outside or from cavities in the facade, possibly to several floors at the same time.

Facade fires spread rapidly upwards. In some cases even very quickly, so quickly that the facade of a building with many floors can be involved in the fire before the fire and rescue services are even alerted to the incident. If the structure contains, for example, cellular plastic, burning drops of molten plastic can also flow downwards. The fire then spreads rapidly downwards, unless fire-separating parts in the structure stop the process.

**Figure 106.** Facades often contain air gaps where fire can spread



In addition to the problems with the mechanisms that control the spread of structural fires, accessibility for the fire and rescue service becomes another complicating aspect. Facade fires can, for example, be difficult to reach due to the height of the facade. Facades can also be long/wide, which also limits accessibility. In a somewhat simplified way, it can be said that in this type of fire, the fire service cannot reach the fire with extinguishing agents, even if the fire is not hidden. Fires in high facades must be extinguished by other means than from the ground or from high-altitude vehicles. Both radiation from facade fires and falling building parts can also limit accessibility for the firefighting personnel.

The same problem also applies to roof surfaces, the outside of the eaves, etc. The fire is not necessarily hidden, but it may be difficult to access, and the risk of continued and rapid fire spread is high.

### **Fires in trusses, walls and crawl spaces**

Inside trusses, walls and crawl spaces, the distance between opposing surfaces can be very small. This can, for example, apply to the distance between the “floor” and the “ceiling” inside a cavity in a truss or the distance between the inner sides of a wall. This means that stack effects can occur inside walls, in a similar way to facade fires. If two opposing and heated surfaces are close to each other, the thermal radiation between the surfaces will also contribute to further and faster heating. Inside trusses and walls, the surrounding surfaces can also be large in relation to the volume. The smaller the volume in a space, the larger the surrounding area, relatively speaking. This means that more surface area is heated, in relation to the volume of the space. Spaces with limited accessibility can also collect a lot of dust, dirt and other particles, which can contribute to both fire gas production and fire spread. Finely divided fuel is more flammable than solid fuel. In addition, flammable insulation can further increase the risk of fire starting and spreading inside the floors and walls.



Fires inside walls and floors can sometimes be seen by flames or fire gases escaping at great velocity. Photo: Stefan Svensson.

In addition to air gaps in walls, there may be cavities in an uninsulated interior wall or in a truss. Cavities can also be present if such a wall or truss is insulated. In some cases, it may be enough for a cavity to have an area of just a few square centimetres, or even less, to cause problems in the event of a fire.



Fire in trusses. Photo: Christer Björkman.

There are also cavities for installation reasons. Examples of such installations are cable routing and pipe routing for water, sewage and ventilation. Such installations must be fire-resistant insulated or otherwise protected against the spread of fire through a number of construction measures. Despite this, these cable routing and pipe routing themselves create cavities. If the installations are made of plastic, there is a risk that they will melt. This makes the penetrations larger, while melted and burning plastic can spread the fire by flowing over long distances. If the fire spreads to such installation cavities, for example shafts, the fire can quickly spread over long distances.

Cavities can also be the result of carelessness during construction or renovation. Especially in older buildings, there may also be passages created by voles and mice. These, in combination with flammable insulation in such older houses, can cause the fire to spread very quickly.

Installation cavities can be vertical or horizontal. If they are vertical, the thermal buoyancy can cause stack effects, which can then spread fire and fire gases quickly and far. If the smaller cavities are horizontal, the spread is likely to be slower, but since the cavities are hidden, spread can occur to unexpected places. If the air supply in such cavities is poor, the spread can occur in the form of smouldering fires. These are even more difficult to find with, for example, thermal imaging cameras, since the temperature is relatively low. If a hole is made in connection with extinguishing, air is supplied, and the smouldering fire can then turn into a blazing fire. In combination with, for example, stack effects, this increases the speed of spread. The consequence of a hole can be that the fire spreads to the entire building, resulting in total damage.

The consequences of structural fires can be that the production of fire gases and the spread of fire accelerate much faster than in fires in spaces of more normal dimensions, that is, ordinary rooms. If the volume of the space is also relatively small, a lot of fire gases can accumulate in relation to the available fuel, which further increases the heat transfer to fuel that has not yet ignited.



Fires inside structures can spread long distances and cause extensive damage.  
Photo: Stefan Svensson.

The starting point should be that a fire in a cavity inside the floor and walls is ventilation controlled. Such a fire can cause major problems if the hole is made without other measures being taken at the same time. When the hole is made, air is supplied, which can contribute to the spread of the fire. The problem with smaller cavities is that they can be difficult to identify, and it can be difficult to determine how far such cavities extend. We simply do not know where they go.

Since the production of fire gases can be large in relation to the size or shape of the space, the oxygen concentration is limited more quickly. This means that the fire can become ventilation controlled more quickly, and as previously described, it is particularly with strong ventilation control that a number of problems can arise when making holes in order to ventilate the fire gases or to access and extinguish the fire. If the space is high and narrow, ventilation measures in the form of making holes can result in a stack effect, which can quickly spread both fire and fire gases over long distances.

In shafts, the problem is mainly that when a hole is made or a fire is burned through, stack effects occur early on. If this happens inside a shaft (or in a chimney) with a cross-sectional area that is small in relation to the height of the shaft, there can be high speeds of the hot air flowing upwards. The result is that the fire gases flow upwards at high speed, and that convection becomes greater, that is, the heat flow from the hot gas into the walls of the shaft. This in turn has the consequence that the fire can spread faster upwards in the shaft, since the surfaces are heated up faster by the hot fire gases flowing upwards.

In shafts, glowing material can also fall down and spread the fire to the floors below. An unknown shaft can thus cause the fire to spread to both the basement and the attic at the same time, which can give the fire and rescue service an unpleasant surprise. Plastic, for example in the form of foam plastic insulation, can melt, burn and thus spread the fire long distances inside structures.

### **Attic fires**

An attic can often be compared to a living space, but there are some significant differences. The differences lie primarily in the fact that they are spaces where people do not normally stay and that the design is different compared to, for example, a living space. Uninsulated attics that are used as storage often have exposed wooden surfaces, that is, the inside of the roof. Attic spaces can also contain large amounts of flammable material that residents of the property store. The fire load is often high and the space can be very dry.

Attic fires can quickly become ventilation controlled due to the amount of exposed flammable material in attics in relation to the volume of the space. A ventilation-controlled fire lacks air, so any attempt to open up the space will add air to the fire. This can in turn cause the fire to spread quickly and uncontrollably, if no other measures are taken.

Attic spaces that are not used as storage can be difficult to access, and often the ceiling height is low. Attics are often also used for the building's ventilation systems, there may also be a variety of other installations. Through the building's ventilation system, the space is then also connected to the rest of the building, which creates a risk of fire and fire gases spreading from the attic to the other spaces in the building.

However, there are requirements that ventilation systems should generally protect against the spread of fire and fire gases, corresponding to the requirements for separation capacity that apply to, for example, a fire compartment. However, the details of these requirements vary, including between different types of buildings.



Attic fires can often cause major problems to deal with. Photo: Stefan Svensson.

In this context, roof fires can also be mentioned. Many roof structures in larger buildings, such as warehouses and industries, often contain flammable cellular plastic insulation and flammable roofing material. The roofs can have been rebuilt, which means that they can contain large amounts of flammable material. Roof surfaces are often both large and difficult to access from the ground. In addition, both the plastic in the insulation material and the binder bitumen from roofing felt melt at low temperatures. In the event of a roof fire, burning plastic and bitumen can drip and flow downwards into the building. If the roof is constructed of so-called trapezoidal sheet metal, there may be a number of cavities where burning or liquid bitumen or insulation material can quickly spread the fire over long distances or large areas.

### **Fires in modular buildings**

In recent years, so-called multi-storey modular buildings have become increasingly common. However, modular buildings have been around for a long time for small houses and single-family homes. A modular

building is simply a building that is constructed with prefabricated modules that are lifted into place, much like building blocks, on a pre-made foundation. Since a single-family home is normally its own fire compartment, this construction method does not pose a major problem in terms of spread in the event of a fire. However, if the modules are built together, especially at height, in order to create, for example, multi-family buildings, each apartment must be its own fire compartment. Due to the design of the modules, a number of problems related to structural fire can arise that mean that the protection of the fire cells is not maintained in the way intended.

When the modules are assembled and stacked on top of each other, natural cavities arise due to the construction; often there is exposed combustible material here, and if the modules are assembled on several floors, such cavities can extend the entire height of the building. These cavities must be sealed in the joints, both vertically and laterally. However, there are examples where the seals were not designed or made in a good way during construction. The more modules that are built together, the more cavities can arise and the more opportunities there are for the fire to spread. It becomes especially sensitive if electrical installations are installed in these spaces. This is partly due to the risk that a fire can start in the installation, and partly because such installations require penetrations and increase the amount of combustible material.

The spread of fire and fire gases in such cavities is affected by all of the mechanisms described previously.



Modular homes can pose significant risks of structural fire and spread to large parts of the building. Photo: Sofie Bergström.

### Example

Late on Christmas Eve afternoon 2008, the fire department in Umeå received a call about a fire in an apartment building. A pan of oil had caught fire in the kitchen of an apartment on the top floor. The fire department was quickly on site and extinguished the fire. After this, an extensive check of the walls and trusses was carried out, and the kitchen cabinets were dismantled for further investigations using a thermal imaging camera. The smoke duct was also examined and there was nothing to indicate that the fire was still burning or that there would be any embers left. An hour and a half later, the operation was completed and the fire department returned to the station.

Approximately eight hours later, the fire department received a new call to the same address. It later turned out that the attic insulation, which consisted of wood chips, had begun to glow due to heat conduction from the smoke duct in combination with deficiencies in the insulation of the smoke duct. The smouldering fire continued for many hours and had finally grown large enough and developed enough heat and combustion products for a fire to start in the attic.

Despite a well-executed fire and rescue operation and thorough investigation work by the fire service after the first alarm, a smouldering fire could start in the attic. Note in particular the very long time that passed from the kitchen fire to the attic fire, which indicates that initially only a very small amount of wood chips was involved. Probably so little that it would have been very difficult to detect regardless of the investigation method.

Fire spread inside structures and hidden spaces is often very difficult to detect, not least because the process can be very slow and initially extremely limited.

(Lundqvist, M. In-depth accident investigation: Fire in building Geografigränd 2 A-J in Umeå 2008-12-24 Fire Service response report 2008/888-889.)

# Chapter 9

# Models and training facilities for fire

In order to be able to handle fires in buildings safely and effectively, training and practice are essential. Although fires in buildings only account for about 10 percent of the incidents or missions that the fire and rescue service handles, there is a high expectation that such incidents can be handled professionally and with good precision. To be able to do this, we need to create different types of models and training devices, so that we gain a higher understanding of how fires develop and spread in buildings. Such models and training devices must be able to reflect real conditions during fires in buildings. This applies to both simple models to demonstrate how different types of materials react when exposed to heat, as well as more complex training devices where firefighting practice takes place.



Models are simplifications of reality, where much is lost during the process of simplification. Photo: Åsa Brorsson.

It is difficult to deal with reality in all its complexity. Instead, we often need to create models of reality. The purpose of these models is, among other things, to reduce this complexity in order to increase the possibilities for understanding. The models are thus simplifications of reality. In this simplification process, something is lost. No matter how we construct these models, they will be more or less incorrect, but we do not always know in what way they are wrong.

Our training devices are models, that is, simplifications of reality. When such training devices are to be created, there are a number of challenges. On the one hand, safety must be high, so that unnecessary damage does not occur to people, property or the environment. On the other hand, they must provide as realistic a picture as possible of how a fire develops and spreads.

Regardless of the materials used in such educational devices, they will be affected by the energy generated by fire. Even materials that are non-combustible will be affected by this energy. Examples of materials that we use for different types of models and educational devices are brick, concrete, steel, wood or plastic. When energy is added to these materials, the molecular movement in the materials increases, the load-bearing capacity changes, and the materials can also deform.

Different materials have different properties that affect how a fire develops and spreads in a building, including educational facilities. As described earlier, the thermal inertia of a material is an important property in the event of a fire. The thermal inertia is the product of a material's:

- thermal conductivity –  $k$  eller  $\lambda$  (lambda)
- density –  $\rho$  (raw)
- specific heat capacity –  $c$ .

The designation for thermal inertia is  $k\rho c$  (which is pronounced kå-rå-ce). Depending on the thermal inertia of different materials, they heat up at different speeds, which affects the spread of fire in an object, in a room and in a building. This can be of great importance for how we conduct training and exercises in different types of training devices or models.

For example, we can compare the properties of a training facility built of steel, such as a steel container, with the properties of plasterboard, which is a common wall covering material in our homes and workplaces. Steel has a higher density, higher thermal conductivity, lower heat capacity and higher thermal inertia than plasterboard.

A fire in a steel container will therefore be affected by its surroundings, the steel in the walls, in a different way than a fire in a regular living room with plasterboard walls. For example, a steel wall will conduct heat away more effectively than a plasterboard wall. The thickness of the wall also has an effect. A thinner material heats up faster than a thick one, since there is a smaller amount of mass to be heated. The walls of a steel container are normally quite thin, compared to a plasterboard wall or a wall in a residential building. Walls in real houses are also normally composed of several different materials and can be very thick. This means that training and practice in a steel container can give an incorrect picture of how a fire develops and spreads in buildings.

There are also requirements for both the work environment and the environment outside the training facility. The work environment must be safe for both instructors and students. This means that it is not normally possible to choose fuels that correspond to the materials we have in our homes or workplaces. For environmental reasons, we cannot choose just any fuels, as we need to minimise the environmental impact of fire drills. The properties of the fuels used in training facilities are therefore different from the materials we normally have in our homes.

In a normal home, there is a lot of plastic in our interior design materials and in all the things we surround ourselves with, but in educational facilities, we often use wood-based materials, not least for environmental reasons. The differences between plastic and wood are large. For example, the heat of combustion for plastic (about 43 MJ/kg for polypropylene) is more than twice as much as for wood (about 18 MJ/kg). This means that more than twice as much energy can be developed in a home as in an educational facility, even if the weight of the fuel is the same.

Fire gases often consist largely of soot. In addition to transparency, this soot will also affect the reflection towards surfaces and objects in a room, which in turn affects the spread of fire. The amount and properties of soot formed during combustion vary between different types of fuels. For example, the combustion of polyurethane develops more than ten times more soot than wood. The amount of soot formed also depends on the temperature and thus also on the opening factor. A smaller opening factor and thus lower temperature gives rise to more soot. Other components in fire gases also vary greatly between different fuels and different temperatures. During training and exercises, all of these components, with varying properties and amounts, will affect both the work environment and the surrounding environment and not least how fire develops and spreads in training devices.

Creating complex environments for training and practice for educational purposes is extremely difficult. Some examples of such environments are:

- high stairwells
  - stairwells filled with fire gases
  - spread of fire gases to several apartments connected to the stairwell
  - fire spread in stairwells
  
- shopping malls
  - long attack routes filled with flammable fire gases
  - large amounts of fuel and the properties of these fuels
  - several floors
  
- underground facilities
  - multi-storey parking garages
  - vehicle fires, both fossil-fuelled and electric vehicles

- industries and warehouses
  - long penetration routes filled with flammable fire gases
  - high ceilings and storage in high pallet racks
  
- older buildings
  - flammable structures
  - inadequate structural fire protection
  - conversions and extensions that have created cavities.

All such environments, and more, are difficult to recreate for several reasons, but this is the type of environment that the fire and rescue service encounter in connection with firefighting operations. At the same time, knowledge and understanding of the mechanisms and phenomena described in this book are important for managing fires in this type of environment.

We often use different types of models to demonstrate and show different phenomena or processes related to fire. These models can be scaled down versions of a reality, that is, smaller in size. Note that even educational devices are a kind of models of reality, but the phenomena that we are trying to show cannot be scaled down geometrically. Depending on which phenomenon or processes you want to demonstrate and show, you have to take into account how scaling can happen.

**Figure 107.** Examples of how various fire-related phenomena can be scaled down

Rate of heat release [kW]	$\dot{Q}_F = \dot{Q}_M \times \left( \frac{L_F}{L_M} \right)^{5/2}$
Velocity [m/s]	$u_F = u_M \times \left( \frac{L_F}{L_M} \right)^{1/2}$
Time [s]	$t_F = t_M \times \left( \frac{L_F}{L_M} \right)^{1/2}$
Energy [kJ]	$E_F = E_M \times \left( \frac{L_F}{L_M} \right)^3 \times \frac{\Delta H_{c,M}}{\Delta H_{c,F}}$
Mass [kg]	$m_F = m_M \times \left( \frac{L_F}{L_M} \right)^3$
Temperature [K]	$T_F = T_M$

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*Index F = full scale      Index M = model scale*

For example, if a model of a building has a scale of 1:10, this means that:

- the rate of heat release is scaled down by a factor of 316
- the velocity of the gases is scaled down by a factor of 3.16
- the time is scaled down by a factor of 3.16
- the energy is scaled down by a factor of 1,000 (provided that the corresponding type of fuel is used)
- the mass is scaled down by a factor of 1,000
- while the temperature is not scaled down at all.

This means that it is rarely possible to create a single model that can be used for several different types of demonstrations.

It is simply difficult to design a model or training device to behave realistically like a real building. For example, it is not normally possible to construct a single model or training device that exhibits all the characteristics of a real building. Therefore, different training devices may be required to demonstrate the different phenomena and characteristics that a real fire may exhibit. It is also necessary to choose the fuel with care.

There are a number of pedagogical challenges to ensure that those being trained do not get an incorrect picture of how fires develop and spread in buildings. In addition, people and technical systems present in the building can interact with the fire and create additional dynamics. This places high demands on instructors and teachers, both in terms of content and pedagogically.

**Some final words**

# Some final words

Fire, and especially fires in buildings, is more complex than most people realise or understand. The development and spread of a fire depends on the objects that are burning, the material the objects are made of, how they are designed, and more. However, it is not just the fuel, i.e., the object or material that is burning, that affects how a fire develops. The fire is also affected by the context in which it is located, in this case the building, including the objects and materials in the building, which can be both flammable and non-flammable, but that's not all. Surrounding conditions also affect the fire, i.e., things outside the building, including the weather and wind, and if there are other objects or buildings near the building where the fire starts, the fire can also spread there.

But regardless of whether it is a single object that is burning or if the entire building is involved in the fire, it is still basic physics and chemistry that govern and influence how the fire will spread and develop.

Firefighters must be able to safely handle fires in buildings, regardless of their role, function or task, and in doing so, it is crucial to have good knowledge and a good understanding of the factors that control and influence the development and spread of fire.

The hope is that this book describes and explains the basic knowledge required. There is, of course, even more to delve into, and the reference list at the end of the book can be a good basis for further knowledge acquisition.

The development of knowledge does not stand still either; we are constantly learning more about fire and how fires in buildings develop, and not least how the rescue services can handle the fires that arise in different ways. We must therefore constantly learn new things and question the knowledge we already have. We must not stop learning new things.

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# **Appendix 1**

# Measures, quantities and units

In order to be able to compare, describe and explain different properties and phenomena, we need a common language for these properties or phenomena.

The property or phenomenon of an object that can be measured or calculated can be expressed in mathematical terms, that is, in numbers, and is then called a quantity. Among the basic quantities we find, for example, length, mass, time and temperature.

When we measure these properties or quantities, we indicate the measurement value using units. A unit is a fixed value of a quantity. These values and units have been established by agreements and are used by all countries that have accepted the agreements.

Quantities and units have also been assigned certain specific designations (symbols). Sometimes letters from the Greek alphabet are used, sometimes Latin (our usual) letters. Designations for units are given as SI symbols (see table below). SI is an abbreviation for *Système International d'Unités*, which is the international system of units of measurement. The seven base units in the SI system are

- length – metre (m)
- mass – kilogram (kg)
- time – second (s)
- electrical current – ampere (A)
- temperature – kelvin (K)
- luminous intensity – candela (cd)
- amount of substance – mole.

It is important to specify both units and quantities with the correct designation, otherwise it can cause great confusion.

**Table 17.** Quantities, designations and units

Quantity	Designation	Unit	Designation
<b>Space and time</b>			
length	l	metre	m
thickness	$\Delta$	metre	m
diameter	d	metre	m
area	A	square metre	m <sup>2</sup>
volume	V	cubic metre	m <sup>3</sup>
time	t	second	s
speed	v	metre per second	m/s
acceleration	A	metre per second square	m/s <sup>2</sup>
<b>Energy and power</b>			
energy	E	joule	J
power	$\rho$	watt	W
<b>Mechanics</b>			
mass	M	kilogram	kg
density	$\rho$	kilogram per cubic metre	kg/m <sup>3</sup>
volumity	$v=1/\rho$	cubic metre per kilogram	m <sup>3</sup> /kg
force	F	newton	N
work	W	joule	J

Quantity	Designation	Unit	Designation
mass flow		kilogram per second	kg/s
mass flow per unit of area		kilogram per square metre and second	kg/m <sup>2</sup> s
flow		cubic metre per second	m <sup>3</sup> /s
pressure	p	pascal	Pa
<b>Heat</b>			
absolut temperature	T	kelvin	K
celsius temperature	$\theta$	degrees Celsius	°C
temperatur difference	$\Delta T, \Delta \theta$	kelvin	K
coefficient of linear expansion	$\alpha$	per kelvin	K <sup>-1</sup>
volumetric expansion coefficient	$\gamma$	per kelvin	K <sup>-1</sup>
heat	Q	joule	J
specific heat	q	joule per kilogram	J/kg
rate of heat release	P	watt	W
conductivity	$\lambda$	watt per metre kelvin	W/mK
heat transfer coefficient	$\alpha$	watt per square metre and kelvin	W/m <sup>2</sup> K
specific heat capacity	c	joule per kilogram kelvin	J/kgK
heat of vapourisation	l	joule per kilogram	J/kg
melting heat	l	joule per kilogram	J/kg

Dimensionless quantities are those quantities that can be expressed only by measurement numbers (numerical values without units). They have the unit 1 (one). The unit is usually not written out. For example, efficiency can be expressed as 0.8, which expresses the quotient of two power values, or as 80 percent. Both expressions mean that the output power is 80 hundredths of the input power.

1 percent means 1 hundredth and can be written as 0.01 without a unit.

So-called derived units can be built by combining base units and supplementary units according to physical or geometric relationships between the quantities.

**Table 18.** Examples of derived units

Quantity	Unit	Designation
area	square metre	m <sup>2</sup>
volume	cubic metre	m <sup>3</sup>
density	kilogram per cubic metre	kg/m <sup>3</sup>
force	newton or kilogram metre per second square	N, kgm/s <sup>2</sup>
pressure	pascal or newton per square metre	Pa, N/m <sup>2</sup>
energy	joule or newton-metre	J, Nm
speed	metre per second	m/s
acceleration	metre per second square	m/s <sup>2</sup>
rate of heat release	watt or joule per second	W, J/s
Celsius temperatur	degrees Celsius	°C
kelvin temperatur, absolute temperatur	kelvin	K

A multiple unit is a unit formed by multiplying a unit by a certain numerical factor (prefix), usually a power of 10 (i.e., multiplied by a factor of 10, 100, 1,000, and so on). The prefix indicates that the unit has been multiplied by a certain power of ten. If the unit W (watt) is multiplied by the power of ten 3, which is equal to 1,000, the prefix k (kilo) and the multiple unit kW (kilowatt), i.e., 1,000 W, are given priority.

The prefixes 3, 6, 9, and so on are prioritized (multiples of 3), and powers like 2, 4, 5, 7, and so on are avoided.

**Table 19.** Examples of prefixes

Prefix	Designation	Power of ten	Meaning
giga	G	$10^9$	1 billion
mega	M	$10^6$	1 million
kilo	k	$10^3$	1 thousand
milli	m	$10^{-3}$	1 thousandth
mikro	$\mu$	$10^{-6}$	1 millionth

Note that some multiple units are abbreviated with a capital letter, others with a lowercase letter. These should not be confused, as they are symbols for different concepts and mean completely different things. A capital M means mega, a small m means milli (note that "m" also can stand for the unit "metre" but is then a quantity for length). Multiplication of the units is expressed by writing the units together, for example Nm (newton metre). Division of the units can be expressed as m/s or ms<sup>-1</sup>.

There are also a number of older units that are still used to some extent in other parts of the world. These include

- length: inch, foot, yard, mile
- temperature: Fahrenheit
- energy: british thermal unit (BTU)
- mass: pound, ounce.



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