

Lars-Göran Bengtsson

Enclosure fires



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Swedish Rescue Services Agency

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Enclosure fires

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Foreword

The aim of this book is to provide a deeper understanding of how fire behaves during enclosure fires. This book has been written primarily with firefighters in mind.

Every year around a hundred people die throughout Sweden as a result of fire, with most dying in house fires. Fire also causes extensive damage to property, with the insurance sector putting an estimated figure of 3.4 billion Swedish kronor (approx. £260 million) on the value of the property destroyed every year. This is why it is important to prevent fire. If considerable resources are channelled into fire prevention this can reduce both the number of deaths and the cost. When a fire breaks out it is vital that it can be tackled at an early stage, taking the appropriate action.

The aim of this book is to help provide a deeper understanding of how fire behaves during enclosure fires. It focuses on understanding the processes involved in an enclosure fire. The main purpose, however, is not to look at how to actually fight this type of fire, by using smoke venting or applying a particular extinguishing medium, for instance, even though appropriate actions like these will be discussed in some sections. When discussing firefighting measures, reference will be made instead to relevant manuals dealing with smoke venting and extinguishing media.

Nor does this book claim to provide an exhaustive insight into this area. For instance, a fire's behaviour in industrial premises is different, compared to in house fires. This book mainly describes fires in smaller areas such as flats or houses. Firefighters need to have basic knowledge about the factors controlling the behaviour of these types of fire. In this situation, as with other operations, there is a great deal of pressure in terms of taking the right course of action. It is also obviously very important to be familiar with and look out for the warning signs which can be picked up during an operation.

During the last 10 years great strides have been made in the research into these areas. This has led to a change in the approach to compartment fires in certain respects. Some of this research provides the basis for this book, along with the practical experience of the local fire service.

The book is intended to provide the basic material for teaching about fire development in Sweden's Rescue Services Agency colleges. This is the group which the book is mainly targeted at. It may also be of interest, however, to people in other professions who encounter problems relating to enclosure fires. I hope that the book will manage to serve this purpose, both in terms of being used as a teacher's guide and as a basic handbook helping to increase the knowledge about fire development.

I am sincerely grateful for all the assistance I received at the various stages in writing this book. There have been contributions from many people, in fact too many for me to name them individually. But I would like to express my heartfelt thanks to them, one and all.

Lars-Göran Bengtsson

Overview

This book assumes that its readers have some basic knowledge about fire theory, for instance, about heat transfer via conduction, convection (heat flow) and radiation. It is also useful to have some knowledge about heat release rate, the combustion process and ignition. (Refer, for example, to Julia Ondrus' book *Brandteori (Fire theory)*.¹)

The chapters in this book follow the stages in a fire's development in chronological order. Most chapters end with a summary. In some chapters there are a number of questions at the end. The purpose of these questions is to allow you to test whether you have understood the content of the chapter. Possible solutions are suggested at the very back of the book.

The first few chapters (1–3) in the book are of a basic nature. The next couple of chapters (4–7) mainly deal with three phenomena: flashover, backdraught and smoke gas explosion. There are also suggestions put forward in terms of appropriate action to take when tackling these phenomena. The book also describes some real-life incidents where the consequences provide real food for thought.

It can sometimes be difficult to differentiate between these phenomena in different situations. Chapter 8 contains, therefore, an in-depth discussion of the grey areas which lie between them.

For readers looking for a more detailed understanding, a number of sample calculations are given. These calculations require a certain level of mathematical knowledge. Complete solutions are provided to the calculations, intended for anyone interested in having a mathematical basis. Only the most important equations are given throughout the text.

Large sections of the book's content, and even its structure, are based on the report *Övertändning, backdraft och brandgas-explosion sett ur räddningstjänstens perspektiv*.² This report can be ordered from the Swedish Rescue Services Agency.

The superscript numbers in the text refer to the bibliography at the end of the book. Any of the works listed in it which are particularly worth recommending are highlighted in **bold**.

Important information also appears in fact boxes.

As the book is written for different professional groups within the fire and rescue service, some chapters go into more detail than others.

These theoretical sections are marked as supplementary information and have a yellow background.



Introduction

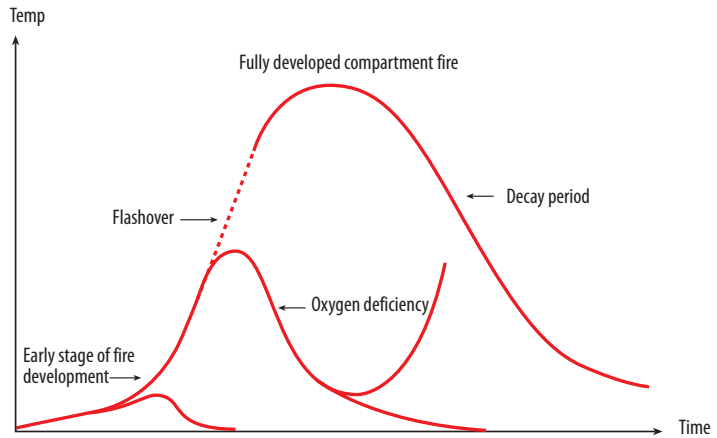
A fire can break out and develop in many different ways. It is impossible to describe and predict every specific type of fire development, but we can provide a general understanding of how a compartment fire develops.

A fire's development is mainly affected by the quantity of combustible material and its arrangement in the fire room. The oxygen supply is another crucial factor. If the compartment where the fire starts is closed its intensity will gradually decrease, which means that the temperature of the smoke gases in the compartment will drop. In some cases, a window may crack, for instance, and the oxygen supply provided as a result will give the fire new impetus. Concepts such as mass loss rate of fuel and heat release rate are important.

We usually use a fire growth curve to describe a fire's development, as shown in Figure 1. This figure is vitally important and will be used in a number of places in the book. The horizontal axis specifies time and the vertical axis the temperature of the smoke gases accumulated under the ceiling – this is assumed to be an average temperature. The figure shows possible paths for the fire's development. The period from ignition to flashover is referred to as the early stage of fire development. We will start by looking at this development.

During the early fire development stage (see Figure 1), the temperature will gradually increase if there is an opening, such as a window or door, in the compartment where the fire starts. This compartment can be a normally furnished apartment. The fire can progress to *flashover*, which means that any combustible surfaces in the area will emit pyrolysis products. The flames produced will completely fill the entire room

Figure 1. Fire growth curve featuring different types of fire behaviour.



space, which will generate very high levels of radiation. A person cannot survive a flashover. Wearing protective clothing allows you to withstand this only for a few seconds. This means that from the point of view of saving lives, one essential task is to prevent the fire from reaching flashover.

In the event of a flashover, the heat released by the fire increases dramatically and the fire can then be very difficult to put out. *This makes the damage much worse.* This is another reason why it is so important to fight the fire so that a flashover does not occur. It is certainly not the case that all fires progress to flashover. In fact, according to statistics from the Swedish Rescue Services Agency, this happens in only a few percent of cases.

After a flashover occurs, it is mainly the access to oxygen which controls the heat release rate. This stage is known as a fully developed compartment fire. This stage in the fire's behaviour is important in terms of the calculations for the building components' bearing and partitioning capabilities.

When all the material in the compartment has been burning for quite a long time, the mass loss rate of fuel and consequently, the heat release rate decreases. This stage is known as the decay period.

The mechanisms which control flashovers, such as flame spread and reradiation from the smoke gas layer, are discussed in detail in chapters 2 and 3. It is very important to learn to recognise the signs of an imminent flashover in order to minimise the risks involved in the fire service's operation. *Recogn-*

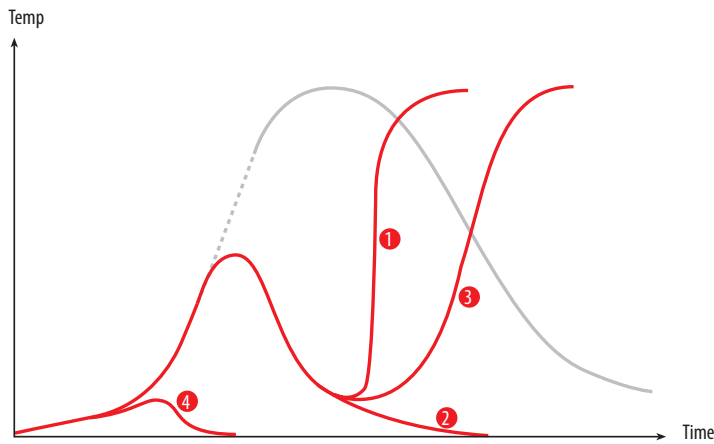


Figure 2. Typical fire behaviour when ventilation control occurs.

nising these signs can be completely crucial to the outcome of the rescue operation.

If there are only leakage paths in a compartment, which is otherwise closed, the fire does not progress to a flashover due to the lack of oxygen. The fire's intensity diminishes before a flashover can occur. This can happen in many different ways, as shown in Figure 2 and is discussed in detail below.

Ventilation control means that the extent of the fire is determined by limiting the amount of oxygen. In many cases the fire will be ventilation controlled when the fire service arrives on the scene. The time it takes for a fire to reach ventilation control varies. Let us take the example of a TV set catching fire. A burning TV set can generate between around 200 and 500 kW. This means that the oxygen in a normal-size room will already be used up 3–6 minutes after the fire has started. After that, the intensity of the fire will diminish and it then usually just smoulders or spontaneously goes out. A large number of the house fires which occur in Sweden are ventilation controlled when the fire service arrives on the scene. But the problems remain as the firefighters open the door to the premises. Air will then rush into the room where the fire is, which may result in the smoke gases in the room igniting. However, this does not happen very often, only in a few percent of all fires (represented by line 3 in Figure 2). If firefighters wearing breathing apparatus take the appropriate action and immediately cool down the smoke gases, the risk of the smoke gases igniting is kept to a minimum.

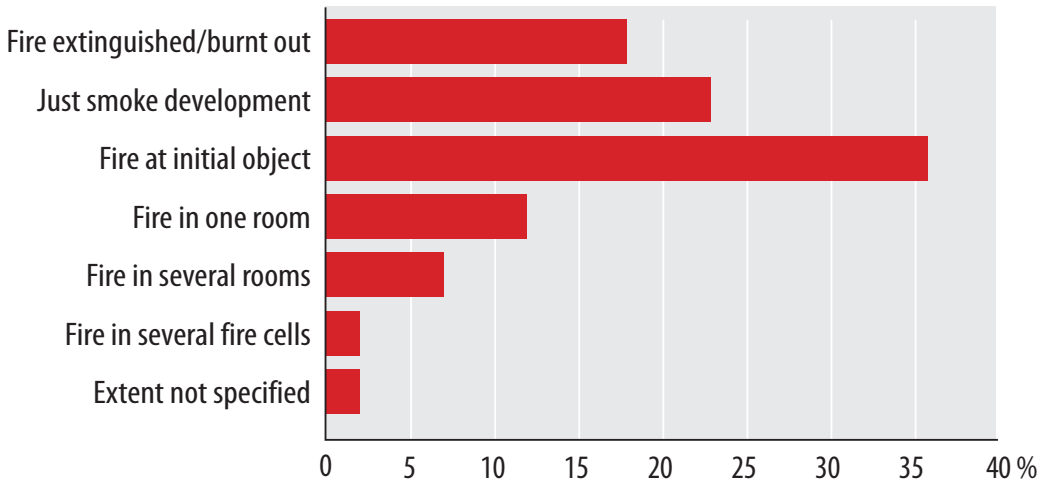


Figure 3. Percentage distribution indicating the extent of a building fire by the time the fire service arrives at the scene. Note that the fire has only spread in a few cases to other rooms when the fire service arrives.

In a few cases, the smoke gases may ignite very quickly and the flames shoot out of the room at a speed of a couple of metres per second. This phenomenon is known as a *backdraught* and is dealt with at great length in Chapter 6. Backdraughts entail major risks, which can even, in some instances, result in firefighters getting killed. This is why it is very important to learn to recognise the signals warning of an imminent backdraught. A backdraught is illustrated by line 1 in Figure 2.

In many apartment fires the impact of the fire is limited to a few objects and there is only slight smoke damage. The fire is often still burning the first object when the fire service arrives.

There are mainly two common scenarios in this case. *In the first scenario*, the fire spontaneously goes out due to a lack of oxygen. It has hardly spread from the initial object. This is indicated by line 2 in Figure 2. The temperature in this case is fairly low, but there can be a lot of smoke in the apartment.

In the other common scenario, the fire is still fuel controlled when the fire service arrives. In this case, air is freely accessible and the fire is controlled by the amount of fuel. Fuel control may be due to the total fire load being small, which means that the fire does not release sufficient heat to cause a flashover. It may also be due to the fact that the fuel arrangement in the compartment, i.e. the combustible objects' locations in relation to each other, means that the fire cannot spread from the initial object.

It is important to be able to understand a fire's behaviour in order to be able to carry out a safe, effective operation.

The apartment may be fairly full of smoke, but the temperature is often fairly low. *This scenario is shown by line 4 in Figure 2.* In order to be able to determine how far a fire will spread, it is important to have a good knowledge about flame spread and ignition.

During 1999 the fire service in Sweden was called out to around 11,000 fires in buildings. Some 6,000 of them were house fires. Statistics show that most fires can be tackled without any major problems. But there are a few fires which involve major risks. It is precisely for these fires that it is important to be properly prepared. You should also remember that situations which are easy for the fire service to handle may be lethal for people who are in the fire room. In many fires people die as a result of smoke gas inhalation.

We have now described a variety of scenarios which could arise in the fire room. This should obviously not be interpreted as meaning that these are the only scenarios which can occur. The reality is much more complicated and the way in which a specific type of fire behaviour develops is controlled by a load of different factors. We have already mentioned a few of them, such as the amount of fuel, the fuel's arrangement and access to air. Other significant factors include the properties of enclosure materials (e.g. walls, glass), especially heat conductivity.

To be able to understand a compartment fire, you need to have a good knowledge of the physical and chemical processes which control a fire's development. This book contains descriptions of these elements, thereby providing a good basis for understanding the different types of fire development and their warning signs.

A fire's behaviour is controlled mainly by the room's geometry, the presence of any openings and their size, the type of fuel and the fuel's arrangement in the room. Other contributory factors include enclosure surfaces' thermal properties, such as density and heating capacity.



How a fire starts

People usually say that “all fires are small to begin with”, which is absolutely true. We will now discuss why some fires remain small and therefore, do not cause any major damage either, as well as what factors cause a fire to grow in size. Two key factors are ignition and flame spread. These will be discussed in more detail.

The diagram shows the temperature in the fire room along the vertical axis and time along the horizontal axis. A fire can develop in many ways, depending on the conditions. The start of the fire, which is the first part of the fire growth curve, is shown in Figure 4.

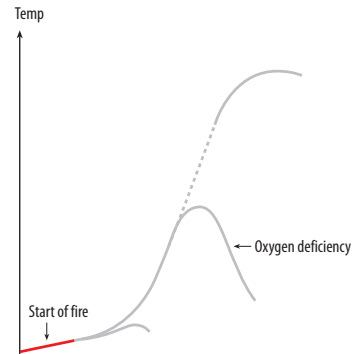


Figure 4. Start of fire.

2.1. Initial fire

When talking about how a fire starts we use the term *fire trigger*. Fire trigger is used to mean the object which has caused the fire. A fire can be triggered by such objects as a hob, radio, TV, candles or an iron. We also speak about the *cause of fire*. The three most common causes are chimneys, fires started deliberately and hobs left unattended. Technical faults are also common.

In the case of fatal fires, bedclothes are the object most frequently involved. This is due to the fact that the most common fire trigger in the case of fatal fires is cigarettes. Other usual causes resulting in people dying include their clothes somehow catching fire.⁴

We will now go through the various stages in a fire’s behaviour in chronological order. The starting point is when an object catches fire. A crucial factor in the fire’s development is



Figure 5. Fire trigger and causes of fire.

In a fuel-controlled fire the heat release rate is controlled by the access to fuel. Ventilation control means that the amount of oxygen controls the heat release rate.

whether the object has sufficient fuel itself or there is some nearby. If the fire does not spread it remains fuel controlled and burns itself out.

When the fire is *fuel controlled* the heat release is controlled by the access to fuel. In this situation, there is therefore sufficient oxygen for all the fuel to be able to combust. On the other hand, when the fire is *ventilation controlled*, it is the amount of oxygen and indirectly, the opening size, which control heat release. The *fuel arrangement* is also crucial to the fire's behaviour. How does the fire then grow? When there is a chance for the fire to spread the heat release rate will increase. The heat from the initial fire will then cause other objects to ignite. Ignition is a vitally important phenomenon, which will be discussed later on in the chapter. The material's flame spread is also very important in terms of how the fire spreads further.

In most cases, the heat release rate from one object is not sufficient for the fire to cause a flashover.

We usually talk about the initial fire as the object which the fire starts with. This may be, for instance, a sofa or a candle on the table (see Figure 7).

Let us start with the initial fire. There are, in theory, two paths which the fire can choose, once it has started. It will either grow or subside.

Scenario 1 (the fire subsides – see Figure 8) is very easy to handle from a tactical point of view. There are often some

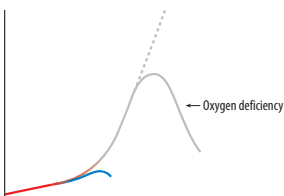


Figure 6. Fire behaviour can develop in two different ways. It can grow or subside.



smoke gases in the compartment, but the actual fire is very easy to extinguish. This situation is very common with house fires in Sweden.

In the case of *scenario 2 (the fire grows – see Figure 9)*, we need to give a bit more thought. Also, as it is interesting to see what happens when the fire spreads further, in the next section we will look at how and in what way the fire will be able to spread during the initial phase.

The fuel's arrangement in the compartment is crucial to the fire's continuing behaviour. Porous and wood-based materials in furnishings contribute to the fire's rapid development. Plastics sometimes cause fires to spread very quickly due to the fact that they drip to form pools of fire on the floor.

We will now look at how the material ignites and flames spread with objects. It is important to understand these processes in order to be able to learn how a fire's intensity increases.

Figure 7. The initial cause of a fire can be, for instance, a desk lamp or a cigarette which ignites a sofa.



Figure 8. The fire does not spread.

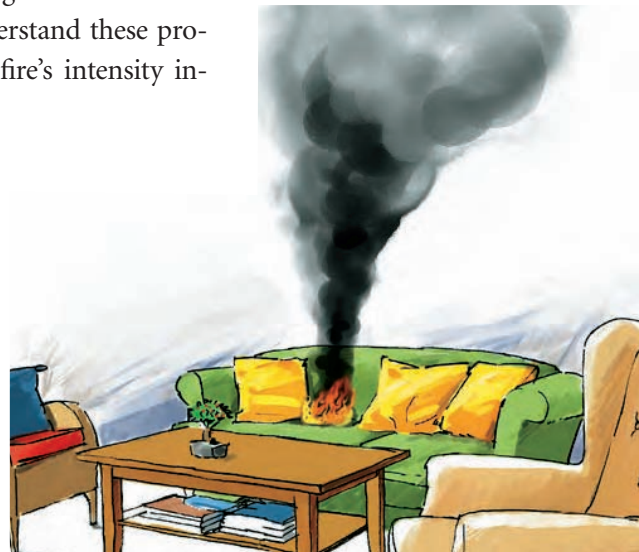


Figure 9. The initial fire in the sofa grows bigger. The fire's area increases.

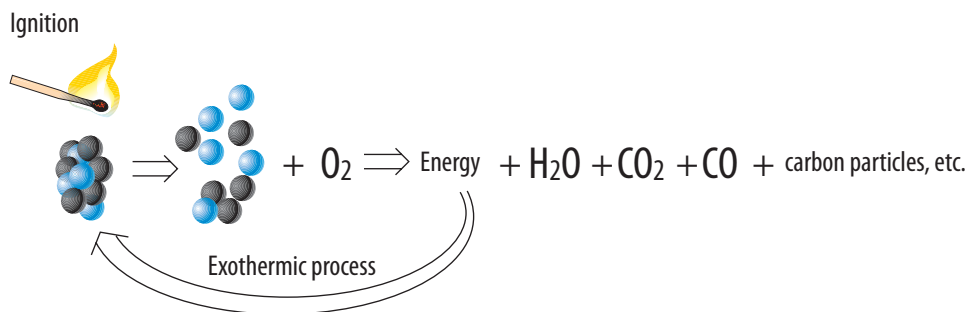


Figure 10.
Combustion process.

2.2 Ignition of solid material

Combustion is a chemical reaction. It involves, to be more precise, a whole series of chemical reactions when the fuel is oxidised. Fuel and oxidising agents react with each other. This releases heat and light. As a result, the chemical process is accompanied by physical effects. Heat is the physical energy which is released during the chemical process. Light is the physical consequence of the fact that there is energy stored in the soot particles, for instance.

Ignition is the first visible sign of combustion. The combustible material may auto-ignite due to the high temperature or it can be ignited by an external source such as a match or spark. In the case of solid materials, there is a critical temperature at which ignition takes place. But this generally varies according to the material which is burning and can therefore not be used as a measure of inflammability. With solid materials, the surface must be heated up to 300–400°C for ignition to occur with a pilot flame. If there is no flame nearby the surface temperature must be higher. Wood needs to reach a surface temperature of 500–600°C before it auto-ignites.⁵

Inflammability in solid materials is estimated using the time it takes for ignition to occur. Ignition takes place when sufficient combustible gases have built up on the solid material's surface for them to be ignited by a small flame.

Materials such as wood or paper (organic polymers) need to emit 2 g/m²s (grams per square metre and second) of combustible gases to be able to ignite. As for plastics (synthetic polymers), which have a high energy content, they need about 1 g/m²s of combustible gases to be able to ignite.

Figure 11 shows what happens on the fuel surface when the

Inflammability in solid materials is estimated using the time it takes for ignition to occur.

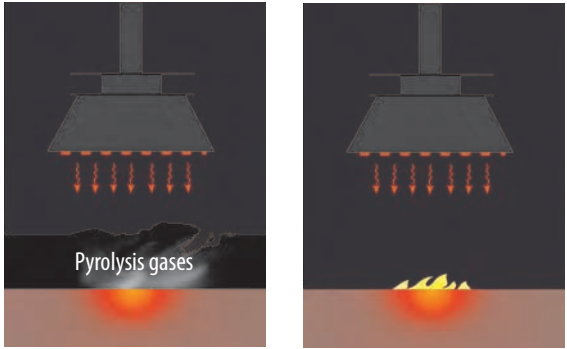


Figure 11. Energy balance on a surface. The figure shows how heat exchange occurs from the object, as well as how thermal conduction takes place through the object.

material is subjected to external radiation (heat radiation). The radiation makes the temperature rise to the level required for the material to pyrolyse. Pyrolysis involves the fuel decomposing. This process requires the external radiation to be at a certain level. If the radiation level is too low the material will never be able to ignite.

Experiments have shown the amount of heat required for a particular material to be able to ignite in proximity to a small flame. This can be measured using a device called a *cone calorimeter*. The material is placed in it under a cone which emits a certain level of radiation. There is a spark generator on top of the sample, continually trying to ignite the material. This is how the time until the material ignites is measured.

Figure 12 shows the radiation intensity (kW/m^2), along with the time it takes to ignite the wood when it is subjected to different processes. Later on in the book, we will explain why radiation levels of around 20 kW/m^2 are so important.

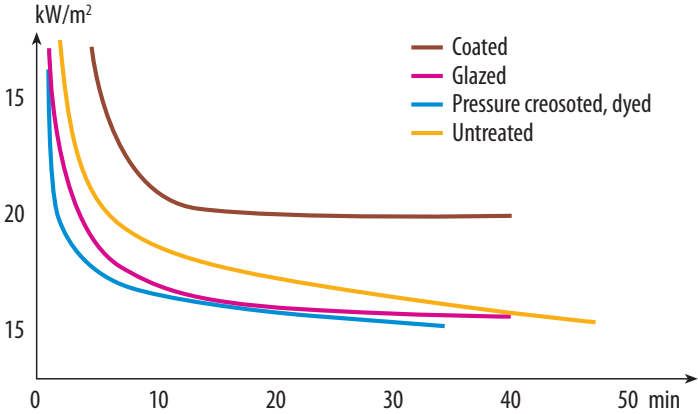


Figure 12. Ignition time as a function of incident radiation.

Surface temperature in solid materials

The surface temperature of a solid material T_s can be calculated using equation 1, which originates from what is known as the general thermal conduction equation. ⁶ This equation has been simplified somewhat, but is still adequate for our purpose.

$$T_s - T_i = \frac{2\dot{q}''}{\pi^{0.5} (k\rho c)^{0.5}} t^{0.5} \quad \text{Equation 1}$$

\dot{q}'' – heat supplied W/m^2 – Radiation energy (in this case, from the fire)

T_s – surface temperature ($^{\circ}\text{C}$) for fuel

T_i – initial temperature ($^{\circ}\text{C}$) of fuel surface (original temperature)

k – thermal conductivity $\text{W/m}^2\text{ }^{\circ}\text{C}$ (a high coefficient means that the material is a good heat conductor)

ρ – density in kg/m^3

c – specific heat capacity in $\text{J/kg } ^{\circ}\text{C}$ (this means the material's ability to store heat)

t – time in seconds

Figure 12 shows that coated pine is ignited only after a very long time has elapsed if the radiation intensity is lower than 20 kW/m^2 . Compared with this, untreated pine ignites in just 7 minutes at the same radiation level. 20 kW/m^2 is equivalent to the level of radiation emitted by a smoke gas layer at a temperature of around 500°C . Inflammability for solid materials can therefore be estimated using the time taken for a certain heat impact to cause ignition to happen.

The surface heats up quickly in a material with a low thermal inertia, $k\rho c$, whereas a material with a high $k\rho c$ value heats up slowly. Table 1 shows the differences in $k\rho c$ (pronounced “kay-row-see”) for various materials.

For instance, we can compare the time it takes for chipboard and wood fibre board to ignite. Both materials are subjected to the same constant level of radiation, 20 kW/m^2 . Chipboard ignites after 180 seconds. But the wood fibre board, which has a much lower $k\rho c$ value, ignites after a considerably shorter time of just 50 seconds. The experiment was carried out using a cone calorimeter. There is therefore a spark generator for igniting the gases in this case.

Ignition time

Ignition time can also be calculated using Equation 2, which is a reformulation of Equation 1. Note that the heat resistance from the surface has been omitted and that the ignition temperature most often lies in the range of 300 °C–400 °C. When the ignition temperature T_{sa} is known the ignition time t_a can be calculated:

$$t_a = \frac{(T_{sa} - T_i)^2}{4(\dot{q}'')^2} k\rho c \times \pi$$

Equation 2

Let us take as an example a fire room where a flashover has occurred. If the temperature in the room is around 600 °C all the surfaces will be affected by radiation in the order of 30 kW/m². If we calculate the length of time it takes to ignite combustible chipboard, for instance, the calculations to be carried out are as follows, assuming that the ignition temperature $T_{sa} = 400$ °C. The $k\rho c$ value is taken from Table 1.

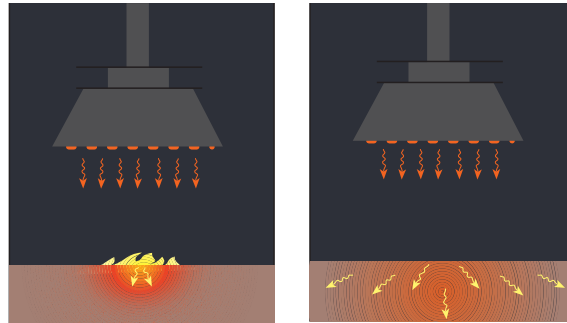
$$t_a = \frac{(400 - 20)^2}{4(30\,000)^2} 120\,000 \times \pi \approx 15 \text{ seconds}$$

This is a rough estimate and must not be regarded as a precise value. In actual fact, the material will heat up at the same time as the surface cools down as a certain amount of heat radiation leaves the surface. If you decide beforehand that the surface should not be heated up beyond a certain temperature, you can calculate the length of time the surface can be subjected to a certain amount of heat, i.e. a certain amount of incident radiation, until it reaches the preset temperature.

Material	k (W/mK)	c (J/kgK)	ρ (kg/m ³)	$k\rho c$ (W ² s/m ⁴ K ²)
Chipboard	0.14	1,400	600	120,000
Wood fibre board	0.05	2,090	300	32,000
Polyurethane	0.034	1,400	30	1,400
Steel	45	460	7,820	160,000,000
Pine tree	0.14	2,850	520	210,000

Table 1. Thermal inertia for different materials.

Figure 13. The heat is blocked at the surface when the material is well insulated. Compare, for instance, wood fibre board (on the left) with chipboard (on the right).



2.3 Flaming combustion and smouldering

A combustion process can actually be divided into flaming combustion and smouldering.

- Flaming combustion (homogeneous oxidation) occurs when fuel and an oxidising agent are in the same state, e.g. two gases.
- Smouldering (heterogeneous oxidation) occurs on the surface when the fuel and oxidising agent are not in the same state, e.g. when the fuel is a solid and the oxidising agent a gas.

The surface of a material with a low thermal inertia, i.e. a low $k\rho c$, heats up quickly as less heat is conducted in the material. A low value means that more heat stays at the surface, which means that the surface reaches the temperature more quickly when there are sufficient combustible gases for ignition, usually between 300°C and 400°C.

Combustion of gases and liquids comes under flaming combustion, whereas solid materials can burn with both types of combustion. We will look at flaming combustion in Chapter 3 and will therefore concentrate on looking at smouldering fires in this section.

Smouldering can occur on the surface or inside a porous material when it has access to oxygen, allowing oxidation to continue. The heat can even remain inside a porous material and support the pyrolysis process until auto-ignition possibly occurs.

The solid carbon layer on the charred residue is a porous material, which commonly smoulders. A smouldering fire most often produces a lot of pyrolysis products which do not oxidise all at once. In a compartment fire the pyrolysis products are emitted by the burning object and accumulate in the upper part of the room without having combusted. The compartment then gradually fills up with smoke gases, which mainly contain carbon monoxide (which is toxic if inhaled).

Smouldering fires can therefore result in people dying.

Smouldering or self-combustion is common in upholstered furniture. The fire starts with the cotton or viscose fabric beginning to smoulder on a layer of polyurethane stuffing, ignited by a cigarette, for instance (see Figure 14).

This type of stuffing material can withstand smouldering very well, without the covering. But in upholstered furniture the various materials combine in such a way that the fabric layer starts to smoulder and it progresses from there. While the fabric is smouldering, the foamed plastic starts to both smoulder and pyrolyse. Pyrolysis from the foamed plastic (the yellow smoke) combines and adds to the fabric's smouldering. The fabric's mass loss rate increases and an increased number of pyrolysis products are released. This results in the entire item of upholstered furniture becoming involved in the fire.

Smouldering fires can often occur inside structures, which then makes them very difficult to get at. In this oxygen-deficient environment you cannot get a flame, but the combustible gases can be transported away and ignite in other places. A smouldering fire burns very slowly, which means that it can go on for a long time.

There are only a few substances that can smoulder. But they are actually quite common. Charcoal is one example. Apart from charcoal, there are also substances which produce carbon on combustion, like wood. It even includes some metals, such as pulverised iron.

2.4 Surface flame spread

When the phrase flame spread is used in this book, it means *the initial flame spread*, i.e. when the fire starts. Obviously, flame spread occurs in the same way in a room which is close to flashover. Flame spread can also occur in a gas layer. The flames start far away from the location where the pyrolysis gases have accumulated.

Flame spread can also be viewed as a series of continuous ignition events. As ignition greatly depends on the thermal inertia of the material, which we mentioned earlier, flame spread will also depend on the material's kpc value.

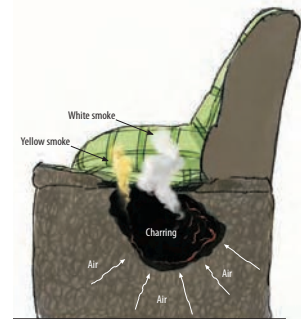


Figure 14.
A smouldering fire in a foamed plastic mattress.

Most cellulose materials form a carbon layer which can smoulder. Even some plastics can smoulder.

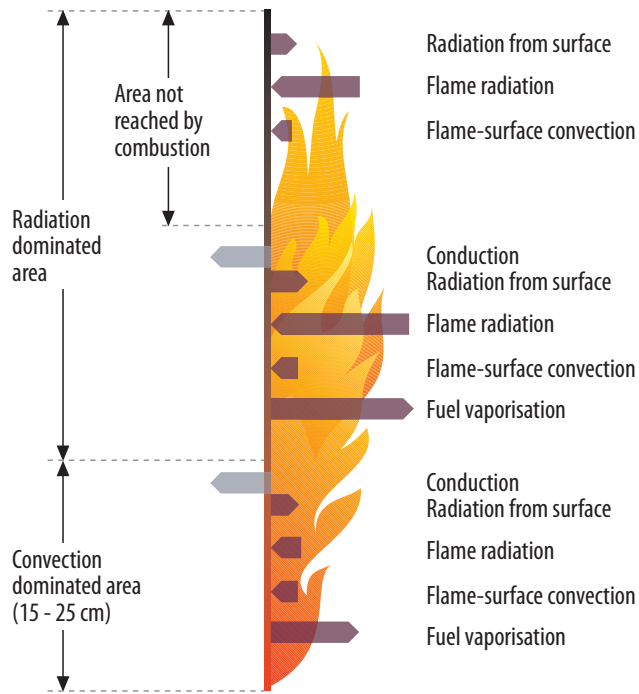


Figure 15. Flame spread on a wall.

As we said earlier, rapid flame spread can contribute to the fire's area increasing, and consequently, to an increase in the heat release rate too. This can gradually lead to a very dangerous situation. It is therefore very important to clarify what factors have an impact on flame spread.

Figure 15 shows what happens on the surface when a wall is on fire. The wall can be split into three sections. The bottom section is dominated by heat transfer to the surface via *convection*. In the middle section, flame radiation is the main factor, which is due to the flame's width increasing with the height. The wider the flame, the more heat transfer occurs via radiation. In the top section, the wall has not ignited yet. In the figure, the length of the arrows corresponds to the size of the various components.

The rate at which the flames spread over the material's surface is mainly dependent on the following:

- the material's thermal inertia, kpc
- the surface's direction
- the surface's geometry
- the surrounding environment.



Figure 16. Flame spread on a light material (on the left) and on a heavy material (on the right).

2.4.1 Thermal inertia $k\rho c$

The flame spread rate depends, to a large extent, on the ignition time, which in turn is heavily dependent on the material's thermal inertia ($k\rho c$), which is a material property. The larger the thermal inertia a material has, the slower the flame spread on its surface.

In the case of solid materials, the *thermal conduction coefficient* (k value) increases most often as the density increases. In most cases, the density determines how quickly flames spread across the surface. This means that the flame spread rate across the surface of a heavy material is usually slower than that across a light material. For instance, in the case of foamed plastics, the flames can spread extremely quickly.

2.4.2 Surface direction

The flame spread rate is mainly upwards. Flame spread rate downwards is much slower, which is due to the fact that the surface does not heat up in the same way. In between, the rate changes according to the surface's gradient.

In the case of vertical flame spread upwards, the height of the flames for many materials, such as wood fibre and chip-board, is roughly twice as large over the same period of time. This means that if it takes 30 seconds for a 25 cm flame to

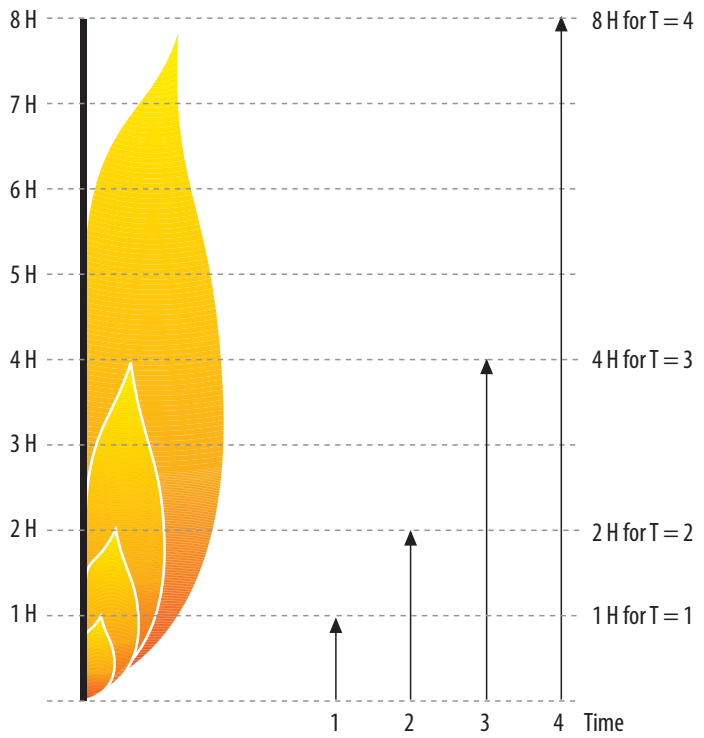


Figure 17. Diagram illustrating fire spread upwards.

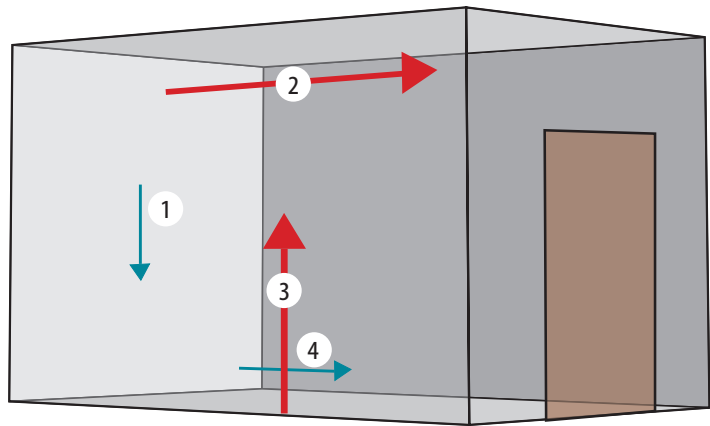
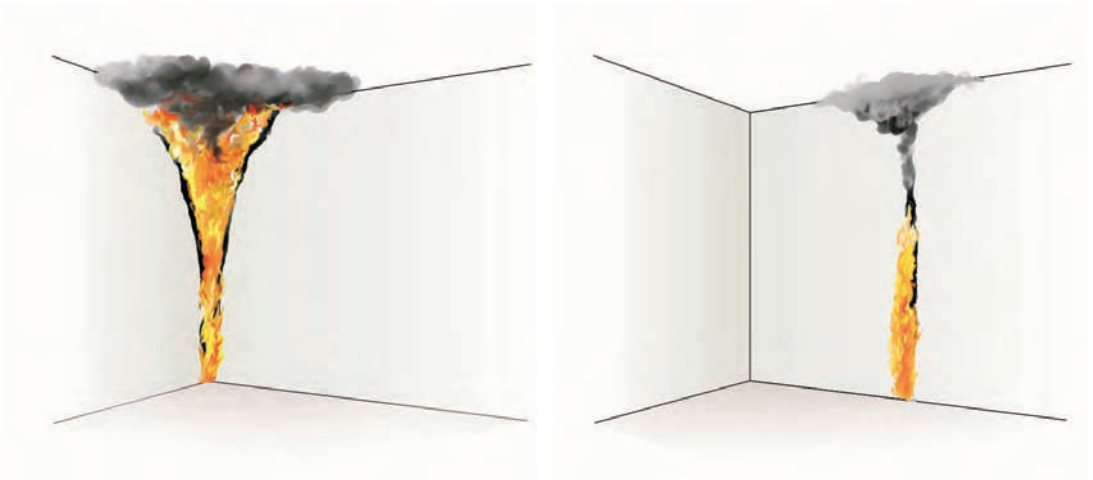


Figure 18. Flame spread in different directions. Vertical flame spread upwards and horizontal spread along the ceiling have the fastest rate.



grow to 50 cm, then a 1 m high flame will grow to 2 m in about the same time, if the wall material is the same. (This value must be regarded as only an approximation.)

The same situation applies to flame spread along the underside of a horizontal surface as in the case of vertical flame spread upwards. In contrast to this, flame spread on the upper part of a horizontal surface or downwards on a vertical surface can be described as “creeping”, as it is slower than flame spread upwards.

2.4.3 Surface geometry

In a corner there is interaction between both burning surfaces, which increases the spread rate. The smaller the angle, the faster the flame spread. This is due to the heat getting trapped in the corner, which then heats up the material. The smoke gases which are forming heat up so that a smaller amount of air is sucked into the plume.

2.4.4 Surrounding environment

When the ambient temperature rises, the flame spread rate increases too. The surface is heated up and the ignition temperature is reached more quickly. The higher the temperature from the start, the faster the flame spread rate will be as well. Another consequence of this is that the higher the temperature a material has from the start, the faster the surface produces sufficient combustible gases.

Figure 19. Interaction in the corner makes the flame spread rate faster, compared with when the flame occurs in the middle of the wall.



Figure 20. Flame spread in every direction.

Let us take as an example of the scenario where a smoke gas layer heats up the ceiling material over a long period of time. By the time the flames have reached up along the wall, the ceiling material is already heated up and the flame spread will be very rapid.

2.5 Summary

Combustion is a chemical reaction process, where fuel oxidation takes place. The first visible sign of combustion is ignition.

When solid materials ignite, flame spread occurs almost at the same time, which can be regarded as a series of ignition events. In the case of solid materials, there is a critical temperature at which ignition takes place. But this is generally irrespective of whatever material is burning and the surface temperature can therefore not be used as a measure of inflammability. With solid materials, the surface must be heated up to between 300 and 400°C for ignition to occur with a pilot flame. If there is no flame close by the surface must reach a temperature of between 500 and 600°C (wood).

Flammability in solid materials is estimated using the time it takes for ignition to occur. The combination of properties represented by k_{pc} refers to the material's thermal inertia and determines how quickly the material's surface heats up. The surface of a material with a low thermal inertia heats up quickly, while the surface of one with a high k_{pc} heats up slowly.

The lower the k_{pc} value a material has, the shorter the ignition time. This means that a porous wood fibre board ignites more quickly than chipboard.

A combustion process can actually be divided into a *flaming fire* and a *smouldering fire*.

A smouldering fire can occur on the surface or inside porous materials where there is access to oxygen.

In the case of many fires which occur, rapid flame spread has been the cause of the serious consequences involved. Flame spread rate is dependent on a number of factors, especially the material's thermal inertia, the surface geometry, the surrounding environment and the surface direction.

The flame spread rate is fairly slow on a surface made of a material with a high thermal inertia (which has, more often than not, a high density). This means that the flame spread across the surface of a heavy material is usually slower than that across a light material.

If the material has been heated up by, for example, a warm surrounding gaseous mass or by radiation from a smoke gas layer, the material can reach its ignition temperature fairly quickly. This means that surfaces which are heated up also lead to faster flame spread than unaffected surfaces.

The direction of the surface and flames are also key factors in the flame spread rate when a fire is spreading. It is mainly vertical flame spread upwards and flame spread along the surface of a ceiling in a compartment, which causes the fire to develop quickly.

In the case of flame spread upwards, where the difference in density and air flow push the flames upwards, the flames from the burning material heat up the part of the material which has not yet started to become pyrolysed.

Flame spread along the ceiling in a compartment can also

cause the fire to develop quickly. There are two reasons for this: firstly, the air flow forces the flames forward and secondly, the ceiling surface has been warmed up considerably by the hot smoke gases which have accumulated in the area of the ceiling.

Horizontal flame spread downwards along the lower section of walls in a compartment occurs at a much slower rate. But in certain cases, when the fire is close to a flashover, flames can spread very quickly downwards due to the surface being heated up via radiation.

We would just like to end by reminding you that this section deals with flame spread involving solid materials. Flame spread with both solid materials and in a smoke gas layer is crucial from the point of view of a fire spreading. Flame spread along the under side of a smoke gas layer is a very common sign indicating that something is changing in the fire room. This flame spread is an important sign for firefighters with breathing apparatus who need to fight the fire. Later on in this book, we will look specifically at flame spread in smoke gas layers.

Test your knowledge!

- 1. Let us assume that the surface of a material is heated up by a heat source. How hot does the surface need to be for the gases which form to be able to ignite?*
- 2. It is a well-known fact that the flame spread rate varies according to the material. Let us compare two materials, such as chipboard and wood fibre board. Which material has the quickest flame spread rate? What does it depend on?*
- 3. What is the abbreviation for thermal inertia? What do the different letters in the abbreviation stand for? Name some materials with a large thermal inertia.*
- 4. What are the different ways in which heat can be transferred? Give some examples from everyday life of each type of heat transfer.*
- 5. Flame spread is a key factor in the acceleration of a fire's development. Name a couple of factors which have an impact on flame spread rate.*

6. *The flame spread rate varies with the direction in which the flames are moving. In which direction(s) do the flames spread fastest? Why is this the case?*
7. *A room is on fire and the temperature in the room is close to 500–600°C. Estimate how long it will take for chipboard to ignite if there is an ignition source. Chipboard is affected directly by this radiation. Hint: use the equation.*
8. *Flame spread is discussed in detail in this book. Why is knowledge about this so important for BA firefighters, for instance?*
9. *Let us assume that a surface is heated up by an external heat source. There is no ignition source. What temperature must the surface reach for the gases to be able to auto-ignite?*
10. *Name some materials whose surfaces have a very rapid flame spread rate.*



Early stage of fire development

Chapter 2 described the physical processes involved in ignition and flame spread. We are now going to describe the chemical processes which play a significant role in the fire's development and enable the fire to spread. The chemical processes involved may be complex, but in many cases, they are easier for firefighters to identify than physical processes.

Some of the key concepts which you need to be familiar with include unburnt gases, premixed flames and diffusion flames. Many of the chemical processes we will be discussing in this chapter obviously occur at other times during a fire's development too.

Let us take a situation where a smoke gas layer is starting to form under the ceiling, while the fire's intensity is continuing to grow. What happens to the smoke gases which accumulate under a ceiling and what can happen in the compartment if the smoke gases start to burn? We are still dealing with the early stage of fire development and the fire's intensity increases due to the fact that the mass loss rate and the accompanying heat release rate are increasing. This early fire development stage is indicated in Figure 21. Ignition and flame spread occur with different objects.

To be able to carry out an operation in the most efficient way possible, it is important to be very familiar with what happens during the early stage of fire development. The processes which occur in the fire room at this stage are highly complex. We are still dealing with a fuel-controlled fire, which means that there is a sufficient volume of oxygen for all the

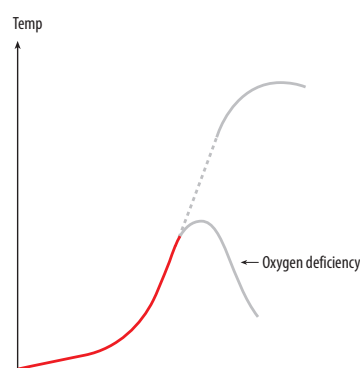


Figure 21. Early stage of fire development when smoke gases are accumulating under the ceiling.

Figure 22. Smoke gases start to accumulate under the ceiling. But the atmosphere in the lower part of the room is still fine for a person to remain there for a short period of time.



Figure 23. The fire has properly spread.



fuel to combust. This is not influenced by whether the room is open or closed, as the amount of oxygen in the room is sufficient for combustion.

This is often the scenario when the fire service arrives at the scene. It is then very important to be able to determine whether the fire is fuel or ventilation controlled, as this will largely influence the type of operation carried out. If the fire is fuel controlled the heat release rate will not increase when the door is opened and you do not need to be concerned about the smoke gases quickly igniting.

3.1 Smoke gases and heat release rate

When the compartment fire grows (as the heat release rate increases), a series of complex processes takes place in the smoke gas layer. In some cases, the smoke gases can ignite. For

this to happen, we need there to be both sufficient fuel and oxygen present, as well as some type of ignition source.

If the smoke gases ignite the fire spreads very quickly and in some cases, the pressure also increases, which affects both people and building structures.

Flames can inflict burns on people. The increase in pressure can affect both people and building structures. In most cases, however, the smoke gases ignite in a quiet and controlled fashion.

3.1.1 Fire plume

When a solid material heats up it starts to emit gases. This process is known as pyrolysis. Pyrolysis usually starts at temperatures in the range from 100 to 250 °C. It is pyrolysis gases which start burning when they are mixed with oxygen. The pyrolysis process involves a chemical decomposition or chemical conversion from complex to simpler constituents. Some of the gases which accumulate at the surface of the fuel will not combust in the flame. These unburnt gases will be accompanied by the plume and will be contained in the smoke gas layer. Figure 24 shows some examples of the types of products to be found in a smoke gas layer.

This is a good point at which to describe the actual plume as, in many ways, it determines the fire's development. A plume most commonly occurs when a diffusion flame spreads across a combustible material.

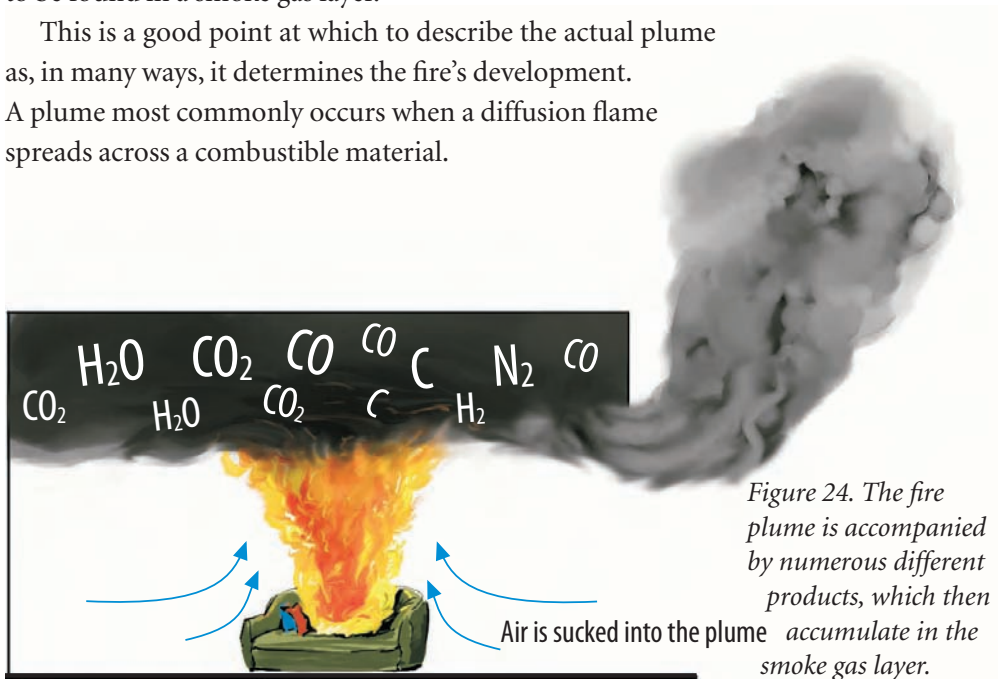


Figure 24. The fire plume is accompanied by numerous different products, which then accumulate in the smoke gas layer.

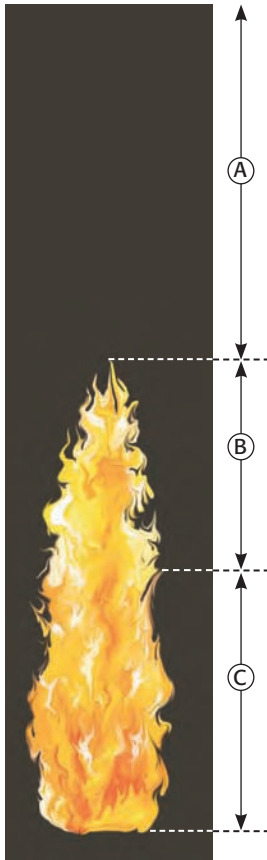


Figure 25. The different sections in a fire plume.
 A: Gas flow plume
 B: Fluctuating flame
 C: Continuous flame

As there are different temperatures in a gaseous mass, a difference in density occurs. The hot part of the gaseous mass, which has a lower density, will rise upwards in relation to the atmosphere, which is the part at a lower temperature and therefore, higher density. This occurs above the source of the fire.

The fire plume is the hot gas flow which forms in and above a natural flame⁷. The fire plume's properties mainly depend on the size of the fire, i.e. the heat release rate a fire generates. These properties influence the fire's continued development in terms, for instance, of how quickly a building is filled with smoke gases and the level of heat impact which surrounding structures have to withstand.

A fire plume can be divided into three sections:

- the section next to the flame base, with the continuous flame
- the section with fluctuating flames
- gas flow above the flame, characterised by a decreasing gas velocity and temperature, i.e. the part which we usually call the "plume".

The temperature and gas velocity within the fire plume are directly dependent on the amount of heat generated by the fire source and the height above the fire source. Mixing with the surrounding air increases the mass flux in the plume. The fire plume's temperature and speed vertically decrease with height.

The smoke gases, which build up during a fire, comprise two constituents⁸. The first constituent, which is considerably more dominant in terms of weight and volume, comprises the air which is "sucked" in or mixed in with the gas flow and remains unaffected by any chemical reactions. This means that the quantity of smoke gases during a fire is generally similar to the quantity of air mixed in with the fire plume. It forms the gas flow which conveys the smoke gases from the fire up to the smoke gas layer, provided that there are openings in the room.

The other constituent contains the decomposition and re-action products which are formed during the fire, specifically, gases (CO_2 , CO , H_2O , CH_4 , etc.) and particles in solid form (soot) or liquid form (such as heavier hydrocarbon com-

Combustion efficiency

Combustion efficiency is usually represented by the letter χ . The maximum amount of energy is obtained if χ is equal to 1.0.

It is the extent of incomplete combustion, which is usually represented as $1 - \chi$, which determines how much potential energy may be left unused in the upper smoke gas layer. When the smoke gases ignite, in some cases, this energy can be converted to heat and increase the radiation in the room. In the case of plastics, χ can be as low as 0.5. When methanol is combusted χ is almost 1.0. This value applies when there is free access to air. If there is only a limited quantity of air χ will be lower, i.e. there will be more unburnt gases in the smoke gas layer.

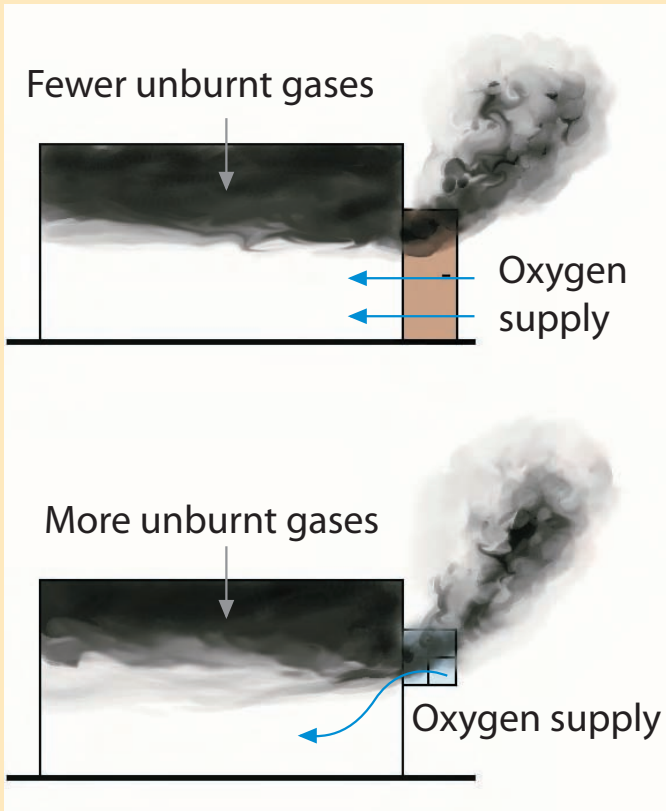


Figure 26. It is the oxygen supply which determines whether unburnt smoke gases are formed from the actual seat of the fire. The smaller the quantity of oxygen being supplied to the room, the larger the quantity of unburnt smoke gases formed.

The production of unburnt gases is crucial to the smoke gas layer being able to ignite. If the unburnt gases accumulated in the smoke gas layer ignite, the radiation levels will rise dramatically in the compartment. This, in turn, causes other materials to ignite. The fire then grows quickly and spreads.

pounds). A more detailed description of the constituents which can be formed during a fire is given in the next section, 3.1.2.

Unburnt smoke gases are always formed if combustion takes place where the oxygen supply is insufficient. But even when the oxygen supply is sufficient for all the fuel to combust, there are always some unburnt smoke gases formed.

The combustible products found in smoke gases originate from:

1. Pyrolysis from materials which are not in contact with the actual seat of the fire. As the temperature is very often high up at ceiling level, combustible ceiling material is usually pyrolysed.
2. Incomplete combustion from the actual seat of the fire.

The more incomplete the combustion is, the more combustible products there are in the smoke gases. The poorer the access to air, the more incomplete the combustion process is. This then increases the likelihood of the smoke gas layer igniting.

You should note that some of the potential energy available in the smoke gas layer is very difficult to extract, even when the smoke gas layer ignites. In the case of soot particles, for instance, the temperature needs to reach $\approx 1000^{\circ}\text{C}$ for the potential energy to be converted to heat.

That explains why we often see black smoke gases streaming out of the fire room, even if the temperature in the room is high. Soot particles can be recognised from their black colour, see Figure 27.

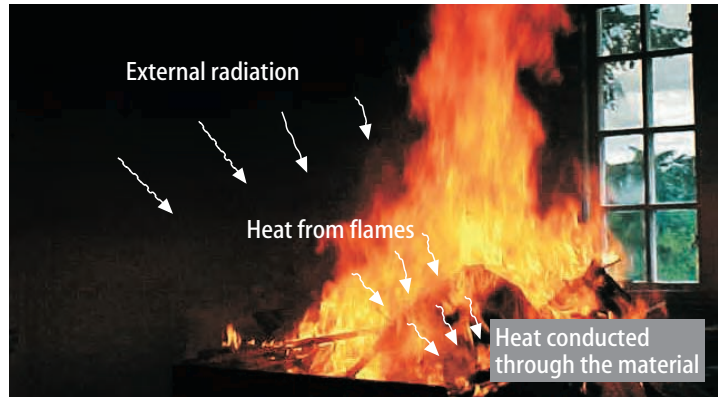
We earlier talked about the heat release rate. The amount of heat energy released during a particular period of time, such a second, is called the heat release rate and is expressed in J/s (joules per second) or W (watts). The heat release rate is a very important concept as it offers us the opportunity to assess the size of a fire, which in turn means that we can work out the scope of the firefighting operation. When working out the scope of a firefighting operation, the fire's heat release rate is compared with the capability offered by different firefighting methods and resources.

The heat release rate from a fuel surface is based on a cer-

Figure 27. (page opposite) Black smoke gases are escaping from the room, accompanied by a lot of potential energy. As we can see, not everything combusts outside either.



Figure 28. Energy balance on a fuel surface.



tain quantity of pyrolysis gases being emitted from the fuel's surface. The mass loss rate is controlled by a number of factors (see Figure 28).

Ventilation has a major impact on combustion efficiency. The less ventilation there is, the lower the combustion efficiency and the more gases accumulate in the smoke gas layer. This means that in an enclosed compartment there is a major risk of there being a lot of unburnt gases. This is also due, of course, to the fact that other surfaces have pyrolysed.

During the last few decades, the shift from using wood-based materials to synthetic polymers has brought about a new situation in the area of fire protection. Certain properties stand out noticeably. For instance, foamed plastics have a low thermal conductivity, k , and a low density, see Table 2.

As a result of this, foamed plastics ignite quickly and lead to rapid flame spread. The possible consequence of this is that the fire progresses to flashover in a very short time. A rapid flashover can also be caused by certain plastics which drip when they burn. The fire spreads very quickly this way and triggers a high heat release rate. The fuel arrangement, therefore, plays a crucial role in determining whether a fire progresses to flashover.

There is also a considerable difference in the technical combustion aspects. The heat of vaporisation ΔH_L , the amount of energy required to vaporise one kilogram of material, can vary a great deal, as can the heat of combustion ΔH_C , which is the amount of energy released when one kilogram of a substance is combusted. The quotient between ΔH_C and

A fire in an apartment can produce a heat release rate of 2–5 MW, compared with, for instance, a match, which can generate 80 W, or a cigarette, just 5 W.

Some release rates for other items include 1–2 MW for a sofa, and a waste paper basket can generate a release rate of between 0.05 and 0.3 MW, depending on its contents.

Heat release rate from a fuel surface

The heat release rate can be calculated using the following formula:

$$\dot{Q} = \dot{m}'' A_f \Delta H_C \chi$$

Equation 3

where \dot{Q} = heat release rate in W

\dot{m}'' = mass loss rate in kg/m²s

A_f = area of fuel surface in m²

ΔH_C = heat of combustion in the case of complete combustion in MJ/kg

χ = combustion efficiency, which measures how efficiently the fuel is used up. 1.0 equals complete combustion, i.e. all the energy is extracted.

You now perform a simple sample calculation. Calculate the heat released from the fire when a heptane pool with a diameter of 1.2 metres is burning. The equation can be used for both solid and liquid fuels.

We need to have the following values (taken from another reference⁵) in the calculations:

$$\Delta H_C = 44.6 \text{ MJ/kg}$$

$$\chi = \text{Assumed to be } 0.7 \text{ (standard value for hydrocarbons)}$$

$$\dot{m}'' = 0.075 \text{ kg/m}^2\text{s}$$

$$A_f = \pi \times D^2/4 = 3.14 \times 1.2 \times 1.2/4 = 1.13 \text{ m}^2$$

This gives a total heat release rate of $0.075 \times 1.13 \times 0.7 \times 44.6 \times 10^6 = 2.6 \text{ MW}$

Equation 3 shows indirectly how much energy can be stored in a smoke gas layer. $1 - \chi$ is the part of the energy accompanied by the fire plume and contained in the smoke gases, which is, in this case, about 1.1 MW.

Material	k (W/mK)	c (J/kgK)	ρ (kg/m ³)	$k\rho c$ (W ² s/m ⁴ K ²)
Chipboard	0.14	1,400	600	120,000
Wood fibre board	0.05	2,090	300	32,000
Polyurethane	0.034	1,400	30	1,400

Table 2. Different $k\rho c$ values for different materials.

Both material properties and ventilation system are crucial factors in the production of unburnt gases, as well as in the extent to which a material represents a fire hazard in a particular situation.

Certain plastics have a high energy content. If the ventilation is poor you can end up with a large number of incomplete products among the smoke gases. When plastics combust, this often produces the conditions which can lead to a flashover occurring.

ΔH_L is known as the combustion value and represents the ratio between the heat released and the heat consumed in vaporising the burning material. The figure corresponding to ΔH_C and ΔH_L indicates how many times more heat is generated than used up during combustion. Solid materials generate around 3–30 times more heat than they use up.

Comparing different materials by comparing their individual properties does not give any indication at all of how they will behave in a real fire. But it is still worthwhile familiarising yourself with the different materials and with the differences between them.

For instance, certain plastics, known as thermoplastics, soften and melt when the temperature is raised. In this situation, these materials behave like a liquid. The radiation heat emitted from the flames in a fire can even cause plastic objects a fairly large distance away from the fire to soften or melt, without them even being directly involved in the fire. The melted material can then ignite through radiation from the fire, burning drips or as a result of a burning object falling on top of the melted material.

The heat of combustion is the amount of heat which can be released from burning material. The amount of heat energy released is expressed in J/kg. The amount of heat which can be released by wood in the case of complete combustion is between 17 and 20 MJ/kg.

There are large differences in the heat of combustion values for plastics. Some generate almost no energy at all. Other plastics, such as thermoplastics, can generate a heat of combustion which is comparable to that of heating oil, at around 40–50 MJ/kg.

3.1.2 Content of unburnt smoke gases

As we have previously mentioned, combustion produces a large number of products. If combustion takes place with a good oxygen supply present this produces large amounts of carbon dioxide and water, which are in themselves not combustible. Numerous other products can also be formed, depending on the accessible oxygen supply and the material's constituents. Some of them are described below.⁵

Carbon monoxide (CO) is the next most common gas which occurs, after carbon dioxide and water, and is very often the main cause of death in fires. This gas is highly combustible and has a broad flammability range. CO is a colourless, odourless gas, which makes it difficult to detect. Carbon monoxide accumulates in large quantities when the ceiling material is made of wood. A content level of 10–15% can be achieved.

The CO content can vary from 0% right up to 15% with certain fuel arrangements. The CO content is critical at 1500 ppm, which is equivalent to 0.15% volume.

CO content % Harmful effect

0.1–0.12	Unpleasant after 1 hour (dizziness, head-aches)
0.15–0.2	Dangerous when inhaled for more than 1 hour (paralysis, loss of consciousness)
0.3	Dangerous when inhaled for 1/2 hour
1.0	Lethal when inhaled for 1 minute

Hydrogen cyanide (HCN) is produced when products such as wool, silk, nylon and polyurethane do not combust completely. This gas is highly combustible and toxic, and can quickly cause death by asphyxiation. It is colourless.

Nitrogen dioxide (NO₂) and other oxides of nitrogen are produced in small quantities from fabrics and in large quantities from materials such as viscose. Nitrogen dioxide causes severe irritation to the lungs and can result in immediate death. It is an odourless gas with, typically brown in colour. Hydrogen cyanide and nitrogen dioxide are often formed at the same time.

Ammonia (NH₃) is produced when materials such as wool, silk and nylon are combusted. The concentration levels are usually low in the case of building fires. Ammonia has a typical odour and causes irritation in low concentrations. But it does not result in death. Ammonia is colourless and is rarely produced in concentrations which would pose a risk to people.

Hydrogen chloride (HCl) is formed during pyrolysis of certain insulating materials for cables, such as PVC, as well as for materials which have been treated with fire retardants and

chlorinated acrylics. Hydrogen chloride is highly corrosive. If it is inhaled it can cause death if you do not leave the area where it is accumulating. Hydrogen chloride is a colourless gas.

Unburnt hydrocarbons are formed when hydrocarbon compounds are combusted. They contain C and H (carbon and hydrogen) in different combinations. They are colourless. There are also pure carbon compounds (C) formed, usually known as soot, at the same time unburnt hydrocarbons are being formed. Soot is made up of carbon particles which are sometimes combined along with some hydrogen. They produce the black streak in the smoke gas. Soot is very often formed in under-ventilated conditions. It is very difficult to extract energy from the carbon particles. Smouldering soot particles give flames their typical yellow colour.

When a fire is burning there are obviously a large number of pyrolysis products formed from material which does not have any direct contact with the centre of the fire. These products may be very pure pyrolysis gases.

3.2 Flames

The smoke gas layer may ignite in many cases. This can occur sometimes with a ventilation-controlled fire and other times, when the fire is fuel controlled. We intend to continue with a look at fuel control, so we will now discuss the type of flames which can arise in this situation. The flame spread rate in smoke gases varies according to what type of flames occur.

In this chapter we are discussing different types of flame. Smoke gases can ignite a little further up on the fire growth curve, see Figure 30. The fire is still fuel controlled. There is still sufficient air for combustion to be able to continue. It is of no consequence whether the room is closed or open, but we are getting close to ventilation control

We mentioned earlier on that smoke gases can ignite if the proportions are right, which can be very dangerous for BA firefighters, for instance. If the smoke gases ignite the radiation heat level will shoot up. This can cause the fire's develop-

Our protective clothing can withstand a high level of heat for a short period of time. RB-90 protective clothing can cope with 1200°C for seven seconds before second degree burns occur. BA firefighters can cope with 200 to 300°C for a couple of minutes.



ment to accelerate, but this is obviously controlled by the access to oxygen as well. During a firefighting operation where breathing apparatus is used, it is important to be aware that smoke gases can change in nature and ignite. It is also important to remember that protective fire clothing can only withstand being subjected to flames for a few seconds.

Flames are usually described as a region where a reaction takes place between fuel and air. More often than not, some type of radiation is usually emitted in this region, frequently in the form of a yellow glare. There are however substances which do not produce a yellow glare, but a blue one instead, such as certain alcohols. The combustion of alcohol is extremely efficient. It results in only a few soot particles being formed and we get a blue glare instead of a yellow one.⁹

Fuel and air must be present for combustion to take place. It is important to remember that, irrespective of whether the fuel is in liquid or solid form, it needs to be converted to a gas to be able to burn. The only exception to this is smouldering fires, which have been looked at earlier in Chapter 2.

If a flame occurs on a fuel surface, like a pool fire, the heat from the flame causes the liquid to vaporise, which is how combustion can continue.

There are two different types of flames: *premixed* and *diffu-*

Figure 29. The fire is starting to approach flashover and the radiation to all the other parts of the fire room is increasing.

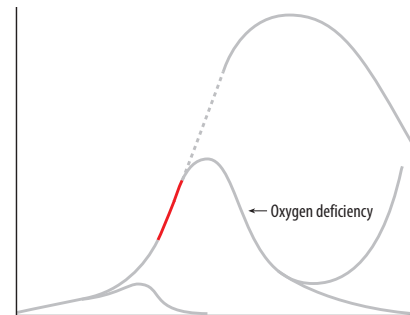


Figure 30. Early stage of fire development, the fire is still fuel controlled.

If smoke gases ignite in an enclosed area it is likely that the fire will become ventilation controlled, if there are no openings available.

sion flames. They both have different properties. To be able to understand the different phenomena which occur in a compartment fire, you also need to understand the properties of flames. A flame is the result of a chemical reaction between fuel and air. A certain amount of energy is required to start the reaction.

Premixed flames occur when the fuel and air are already mixed together and the mixture falls within the flammability range before ignition occurs. An ignition source, such as a spark, is needed to create a flame. In some instances, the gases could ignite without a spark, which is usually called auto-ignition. But it is rare for smoke gases to auto-ignite.

Diffusion flames occur when the fuel and air meet. The fuel and air are therefore not mixed before ignition occurs. Mixing occurs instead through molecular diffusion, which is a fairly slow process, even if the process is accelerated by a high temperature.

Just imagine a can with a small amount of combustible fuel at the bottom of it. The ambient temperature is higher than the liquid's flashpoint, which means that the gases above the liquid's surface are all within the flammability range. If we drop a match in it this can produce a small pop. This is caused by a premixed flame. The flame will then start to spread on the liquid's surface. This is now a diffusion flame.

There are a few examples given below from everyday life intended to provide a better understanding of the different types of flame:¹⁰

1. A candle is a typical example which produces a diffusion flame, with the fuel and air combining in a very thin layer around the wick.
2. A pool fire is an example where both types of flame co-exist. At the time of ignition a premixed flame will quickly spread over the surface. This is then followed by a diffusion flame, which sustains the combustion.
3. A fireball can occur when a cloud of fuel containing a tiny amount of air ignites. The concentration within the cloud

is far too high for a premixed flame to be able to occur. However, there will be a premixed area at the outer edge of the cloud, which is where premixed combustion may occur.

4. If gas leaks from a pipe at high pressure mixing will occur very quickly, which can result in part of the mixture falling within the flammability range. If there is an ignition source a premixed flame occurs.
5. In a smoke gas layer there is often a large amount of fuel and air with a low oxygen content. This means that it is very unlikely that a premixed flame will develop in this layer. A diffusion flame will spread along the under side of the smoke gas layer or higher up in the layer.
6. In some cases, the smoke gases and air mix when air streams into a fire room where combustion has occurred with a lack of oxygen. This can result in a premixed mixture and ignition can then occur quickly.
7. It is possible in a room adjacent to the fire for the smoke gases and air to mix together and fall within the flammability range. If the mixture ignites combustion can occur quickly. A premixed flame occurs and spreads very quickly. This is usually known as a smoke gas explosion.

Depending on how well mixed the smoke gases are, two different types of flames can occur. It is extremely important to be able to differentiate between both types.

We will first of all describe diffusion flames, as they are the most common in a normal compartment fire. We will then look at premixed flames.

3.2.1 Diffusion flames*

A burning candle can be used to explain the basic principles of combustion. The fuel is made up of the melted candle grease in the small liquid pool on the candle. The fuel is sucked up into the wick where it converts to gas form. Candles are a common example of where diffusion flames occur.

There are two different types of flame which can occur when smoke gases ignite: premixed flames and diffusion flames.

*This section is based on Julia Ondrus' book Brandteori (Fire Theory).

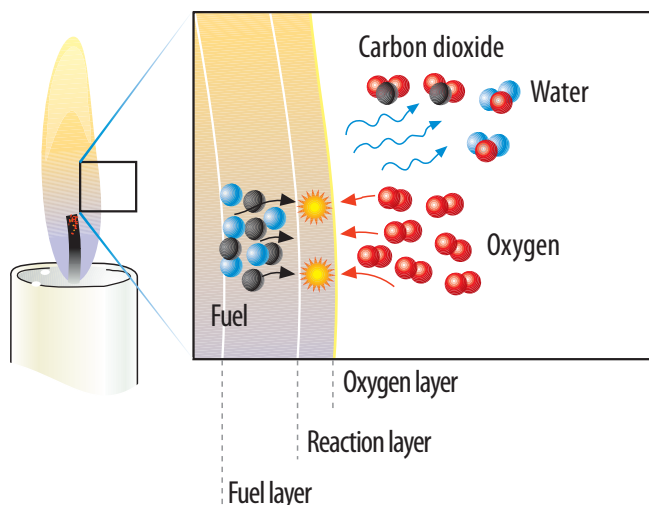


Figure 31. Candle, fuel layer and oxygen-rich layer.

The heat from the flame makes the candle grease melt, but it is not sufficient to vaporise it. The candle grease therefore needs to be moved through the wick to the flame area where the temperature is higher. The complex (long carbon chain) hydrocarbons which the candle grease comprises are broken down to simpler constituents at the centre of the candle's flame.

The fuel molecules are transported to the reaction layer. The reaction layer is sometimes known as the *combustion zone*. This is where the fuel molecules mix with the oxygen molecules from the surrounding air. This transfer process is known as *diffusion* and involves two or more gases mixing.

When the fuel and oxygen have mixed in a certain proportion with each other and are sufficiently hot to ignite, an *exothermic chemical reaction* occurs. "Exothermic" means that something occurs during heat release. This type of reaction releases energy. This energy is used to heat the products formed during the reaction. Oxygen and fuel continue the diffusion process with the reaction layer. A continuous diffusion flame occurs.

The visible, bright part of the flame is produced by heat radiation from the glowing soot particles. When oxidation takes place in the reaction zone mainly carbon oxide compounds (carbon dioxide and carbon monoxide) are produced, along with water and heat. The inner part of the flame, which

is filled with fuel molecules, contains too little oxygen for combustion to be able to take place. The fuel-rich atmosphere is therefore not self-combustible. Combustion takes place, instead, at the periphery, where the fuel and oxygen have diffused into each other. The reaction layer is the place where they are mixed in the right proportion with each other. Fuel and air are very well mixed in this thin layer.

Diffusion flames are usually yellow, which is due to soot forming. Premixed flames do not have the same tendency. It should also be added that there are diffusion flames which do not produce so much soot. They are therefore similar to premixed flames.

Diffusion flames differ in that combustion takes place at roughly the same rate as the fuel gas and oxygen from the air diffuse into each other. Diffusion flames result from a combustion process where fuel molecules are mixed with oxygen through laminar and/or turbulent mixing. This gives rise to laminar and turbulent diffusion flames respectively. Turbulence helps to speed up the mixing process.

Laminar diffusion flames

When a candle burns this produces a typical diffusion flame, where fuel and oxygen from the air flow side by side with each other at low velocity. They mix together laminarly and combustion occurs evenly in the reaction layer. If diffusion takes place slowly the oxygen and fuel need to be mixed for a long time to be able to burn. This is similar to how fire can spread in buildings. A combustible mixture of fuel and oxygen can occur and ignite far away from the original fire source.

Turbulent diffusion flames

The following example is based on a gas burner. If the speed of the fuel is increased the flame will gradually change from being laminar to turbulent. When the rate at which the fuel is flowing out is higher than that at which it is mixing with the oxygen from the air, the mixing process occurs in whirls. This is known as turbulent mixing. In this instance too, mixing with oxygen occurs via diffusion, but the combustion process is uneven and irregular. Even though turbulence causes the

All natural flames are actually diffusion flames, as they are dependent on diffusion. The type of flames which firefighters mainly have to tackle are diffusion flames.



Figure 32. Laminar diffusion flame on the left. Turbulent diffusion flame on the right.

combustion rate to increase, it is much lower for turbulent diffusion flames than for premixed flames.

Turbulent flames have the following main features:

- irregular swirling motion
- rapid diffusion
- thin, irregular reaction layer

Unlike with laminar flames, turbulent flames are often accompanied by sound and rapid changes in appearance. Turbulence can occur in all gaseous media.

Diffusion flames occur in the boundary layer between the fuel and air. This means that we cannot use flammability limits to describe diffusion flames or concepts such as “lean” and “rich”, which are associated with premixed flames.

Turbulent diffusion flames are the type of flames seen in most fires.



Figure 33. Flames on the under side of a smoke gas layer.



Figure 34. A high concentration of fuel high up will gradually cause the flames to reach the under side of the smoke gas layer.

When a smoke gas layer starts to burn the type of flames involved are nearly always diffusion flames.

In the case of a compartment fire, a smoke gas layer which is not homogeneous is formed in many instances. This can be due to the fact, for instance, that there has been a strong pyrolysis effect with the ceiling material. This means that the oxygen content is very low right under the ceiling. The concentration of fuel is not equally distributed either throughout the whole smoke gas layer. The oxygen must then diffuse into the fuel for combustion to be able to occur (see Figure 33).

3.2.2 Premixed flames

We are starting with the assumption that smoke gases have completely filled an area. The gaseous mass is *premixed* and falls within the flammability range. The term “premixed” is used to mean that the fuel is evenly distributed and mixed with air. When the layer starts to burn premixed flames are formed. This section will describe concepts such as flammability limits and burning velocity. We use reaction formulae to describe premixed flames, which is a good way of giving examples of the mixtures.

A smoke gas layer contains different substances in gaseous form, including some which may be combustible. But to be able to provide a simple description of *flammability limits*, we first need to discuss what happens when a gaseous mass comprising only fuel and air ignites (see Figures 35 and 36).



Figure 35. Premixed flames spread in an aquarium. An aquarium is used to demonstrate the flammability ranges for different gases. The most common combination used is liquefied petroleum gas (LPG) and air.



Figure 36. Smoke gases have leaked into an adjacent area. This is a fire scenario in which premixed flames can occur.

Flammability limits

For a premixed gaseous mass to be able to burn, the fuel concentration needs to lie within certain limits, known as *flammability limits*. The range between the lower flammability limit and upper flammability limit is known as the *flammability range*. The size of the flammability range varies according to the substances; different substances have different sizes of flammability range.

Table 3 on the following page indicates the flammability ranges for a number of different gases. The principles applied to the flammability range are the same, irrespective of whether we are looking at a pure gas or pyrolysis gases from a solid substance. The values are measured through experiments. It is also possible to calculate these values and you can refer to page 178 for the whole calculation method.

As you can see from the table, the flammability range varies considerably according to the relevant gas.

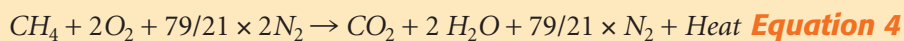
Gases	Lower flammability limit		Upper flammability limit	
	Vol %	g/m ³	Vol %	g/m ³
Carbon monoxide	12.5	157	74	932
Hydrogen gas	4.0	3.6	75	67
Methane	5.0	36	15	126
Ethane	3.0	41	12	190
Propane	2.1	42	9.5	210
Butane	1.8	48	8.4	240
Pentane	1.4	46	7.8	270
Hexane	1.2	47	7.4	310

Table 3. Flammability limits for different gases.¹¹

Stoichiometric combustion

The question arises as to why a substance can only burn between certain flammability limits. In the example below, we are using the simple hydrocarbon, methane. The fact that methane is a pure gas is of no consequence in this instance. It will be shown later that the same situation could apply to a mixture of many different gases, as can be found in an actual smoke gas layer. To begin with, the premixed mass of gas is kept at ambient temperature.

The equation below presupposes stoichiometric combustion of the gaseous mass. This means that only carbon dioxide and water will be formed. All the oxygen is used up in the combustion process, which means in equation 4 below that there are no free oxygen molecules on the right-hand side.



If the mixture is stoichiometric the temperature will be high. This is because the energy released is used to heat a few products. The highest temperature which can be reached is known as the *adiabatic flame temperature* and is indicated by T_f . This is where all the energy released is used to heat the products.

Upper and lower flammability limits

In Table 4 T_f is the adiabatic flame temperature at the lower flammability limit. ΔH_C is the amount of energy converted during combustion of 1 mol of fuel and C_p is the gas's heat capacity. In experiments it has been shown that the products need to reach temperatures of around 1500–1600 K (1300 C) for combustion to be able to continue. This means that the adiabatic flame temperature at the lower flammability limit is around 1500–1600 K.¹¹

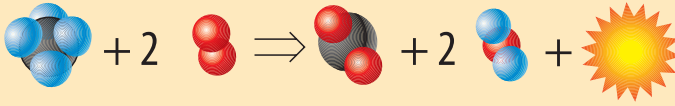


Figure 37. Complete combustion (nitrogen excluded).

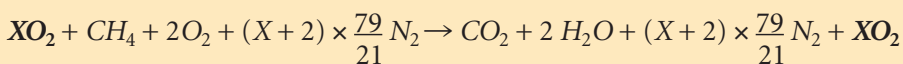
Substance	ΔH_c (kJ/mol)	C_p (J/mol \times K)	T_f (K)
Methane	800	81.3	1600
Carbon monoxide	283	33.2	1600
Carbon dioxide	0	54.3	0
Water	0	41.2	0
Nitrogen	0	32.7	0
Oxygen	0	34.9	0

Table 4. Material data for a number of different substances.¹¹

In the case of a stoichiometric (ideal) mixture, the adiabatic flame temperature is a couple of hundred degrees higher than at the lower flammability limit. It has also been demonstrated at the upper flammability limit that, in theory, the temperature needs to reach 1600 K for combustion to be able to continue.¹¹ It should be added, however, that the adiabatic flame temperature varies somewhat according to the substance. In the following calculations this factor is not, however, taken into consideration.

The equation $\Delta H_c = \Sigma (C_p \times \Delta T)$ can be used to calculate how many degrees (ΔT) a gaseous mass with a heat capacity of ΣC_p heats up by if the energy released in the reaction is ΔH_c . In this instance, it is assumed that all the energy released (ΔH_c) is used to heat the reaction products. Any possible loss to the atmosphere is not taken into consideration, which means that the temperature rise can be described as the adiabatic temperature rise. Adiabatic means that there is no heat loss. Obviously, in reality, heat loss does occur.

When we go to calculate the lower flammability limit, we make the assumption that the products' temperature must reach 1600 K for combustion to be able to continue. Equation 5 below shows an excess of air on both sides.



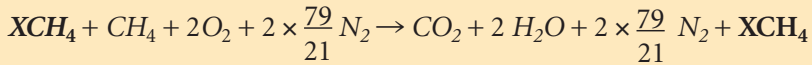
Equation 5

X stands for the excess air. This excess acts as a thermal ballast and absorbs some of the heat generated (the flames cool down).

Equation 5 is a simplified representation compared to what actually happens. In actual fact, there are a large number of stages involved on the way to achieving what is on the right side of the equation. Carbon dioxide and water are not formed until the very last stage in the reaction.

The same method is used for calculating the upper flammability limit. In this case, there is excess fuel. This excess fuel must also be heated up to around 1600 K. In theory, 1600 K has also been shown to apply in the case of the upper flammability limit. This additional fuel can be compared with a thermal ballast and actually has the function of an extinguishing agent. This additional fuel also absorbs energy. In this case, equation 6 is as shown below. We should also add that the reactions are much more complex than shown here, but this simplified expression is used to make it easier to understand. In actual fact, C, CO, C₂ and H₂, for instance, are formed.⁹ In some cases, the process goes through several hundred subreactions before complete combustion is achieved.

X, in this instance, stands for the extra fuel available. The equation is balanced and we add XCH₄ to both sides of the equation to represent an unrestricted number of methane molecules.



Equation 6

Temperature impact on flammability limits

In the sample calculation on page 58, we were dealing with a gaseous mass which was kept at around ambient temperature at the start. The flammability limits change when the temperature of the gaseous mass is raised.

<i>Temperature °C</i>	<i>Lower flammability limit</i>
27	5.7%
127	5.2%
227	4.8%
327	4.3%
427	3.8%

Table 5. Temperature's impact on the lower flammability limit for methane.

The lower flammability limit falls when the temperature is higher. Less energy needs to be released during combustion for the gaseous mass to ignite and burn with a flame. This means indirectly that a smaller amount of fuel is required for combustion to be able to continue.

The temperature is a crucial factor when estimating the risk of a smoke gas layer igniting. The higher the temperature, the more pyrolysis gases have formed, thereby making it easier for the layer to ignite. The fact that the flammability range has widened is more often than not of minor importance.

Flammability limits for gas mixtures

Up until this point we have been discussing one gas or one substance. But a smoke gas layer contains many different gases. The principles for flammability limits apply in the same way to gas mixtures as well.

Pure hydrocarbons, e.g. methane and propane, are special cases. The amount of fuel, specified in g/m^3 , required for the gases to ignite is almost not dependent on the molecular weight. Figure 38 below shows the lower and upper flammability limits for hydrocarbons with different molecular weights. It seems clear that the lower flammability limit is almost constant for most hydrocarbons.

The upper limit, by contrast, varies considerably with the hydrocarbon's molecular weight (see Figure 38).

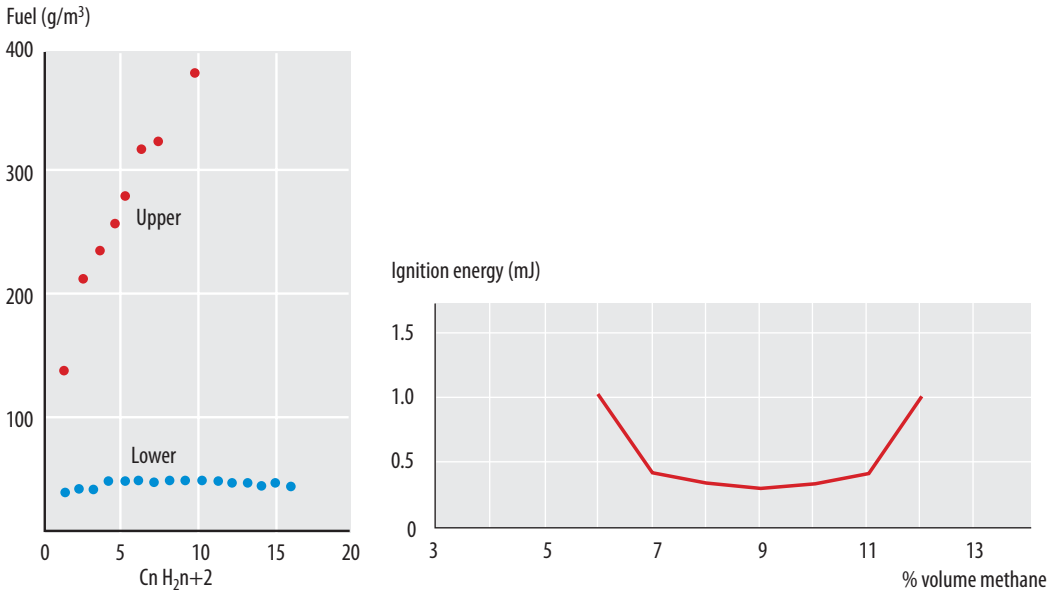


Figure 38 (on left). Flammability limit variation vs. molecular weight: n is a whole number. In the case of methane, $n = 1$.

Figure 39 (on right). Amount of ignition energy required for methane.

For certain substances the stoichiometric point has shifted significantly towards the lower flammability limit. This is due to the fact that air and the relevant fuel may have very different heat capacities (thermal ballast). This means that the flammability limits are affected. This also means, of course, that the substance's energy content is affected. Excess air or fuel can be tolerated only up to a certain level. When this amount of fuel/air is exceeded the temperature drops below 1600 K and the flames go out.

Figure 38 shows that the lower flammability limit is almost constant for most hydrocarbons at around 50 g/m^3 . A smoke gas layer always contains a quantity of different products, so we cannot absolutely confirm that 50 g/m^3 is always a reasonable value. The lower flammability limit may vary from around 50 g/m^3 up to several hundred g/m^3 .

Ignition energy

It is assumed below that there is a gaseous mass within the flammability range. Air and fuel are also available in combustible proportions. A third component, an ignition source, is required for ignition. The amount of energy required to ignite the gaseous mass varies within the flammability range for methane, as shown in Figure 39.

From a stoichiometric point of view, the lowest amount of

energy is required, which can be explained by the fact that the energy supplied will only serve to heat the products, carbon dioxide and water. At the lower flammability limit the energy will also heat the excess air. At the upper flammability limit the energy will partly heat the excess fuel.

It is difficult to estimate the critical spark energy. Generally speaking, the energy from sparks produced when you press a light switch in a room or sparks from a fluorescent tube are sufficient to ignite a gas mixture.

Another type of ignition is spontaneous or auto-ignition. In this case, the combustible medium, e.g. a gas mixture, ignites by means of a spontaneous process. The auto-ignition temperature for the same medium is always higher than the ignition temperature for forced ignition. Auto-ignition is common at temperatures between 500 and 600°C¹. But it is rare for gases to auto-ignite in real-life situations. You will note that we are not touching on auto-ignition in solid materials, as this is partially a different process.

Burning velocity and flame speed

Provided that the gases are premixed, the laminar burning velocity will vary according to where exactly the mixture falls within the flammability range. The laminar burning velocity is the speed which the cold, unburnt gases travel at inside the flame. This concept is rather vague as we cannot “see” this speed.

The flame speed is the speed at which the flame travels.

If the mixture falls near the outer flammability limits the burning velocity will be fairly slow. If the mixture is close to the stoichiometric point combustion will occur more quickly

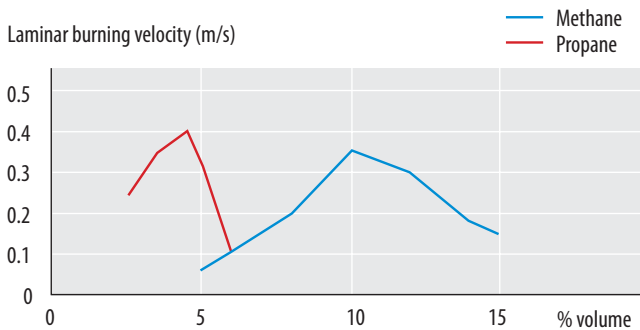


Figure 40. The burning velocity's variation with substance and fuel, estimated as % of volume. As the figure shows, the speed is much lower at the limits.

as more energy is released. It is not the case, however, that the burning velocity will increase, the higher the proportion of fuel in the gaseous mass. It is rather that the burning velocity reaches its highest value when the stoichiometric mixture is roughly achieved and it then drops towards the upper flammability limit.

Figure 40 shows the rate of laminar burning velocity for methane and propane respectively. The burning velocity will affect the build-up of pressure in a room. The nearer to the stoichiometric point, the faster the burning velocity.

If we compare the heat released at the lower flammability limit and when the stoichiometric point is reached, more energy is released in the latter case, as there is a higher percentage of fuel combusted. This means that the burning velocity will be higher with the stoichiometric mixture, compared to at the lower flammability limit.

Similar comparisons can be made between the stoichiometric point and the upper flammability limit. When we get into this upper section of the flammability range, it is the amount of oxygen which determines how much energy can be released.

The richer in energy the gases are, the faster the burning velocity will be. The burning velocity (S_u) is dependent on the energy released.

Some plastics have a high energy value, which means that the smoke gases can contain a lot of potential energy if com-

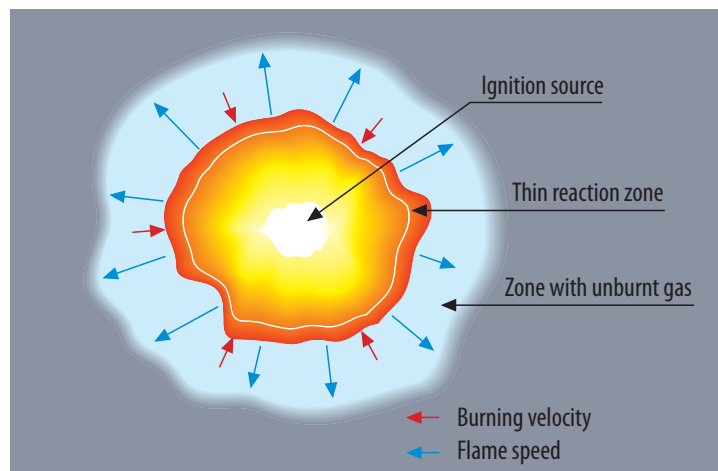


Figure 41. Flame distribution in a premixed gaseous mass.¹²

bustion takes place in under-ventilated conditions. When the smoke gases then ignite, combustion will occur rapidly. This has been discussed in a previous section.

Flame speed or *flame front speed* is the speed at which the thin reaction zone, shown in the figure above, travels through a gaseous mass. This is estimated based on a fixed point, such as the ignition source in Figure 41. Flame speed is related to the laminar burning velocity S_u .

3.2.3 Extinguishing flames

We have now seen that there are different types of flames and that certain gaseous masses can only burn under particular conditions. We have also seen how flames can go out or more accurately, can no longer exist when the ratio between fuel and air is no longer correct. The same applies to the extinguishing process. When we extinguish a fire, we are actually supplying an extinguishing agent (e.g. water), which imposes a thermal load on the flame. This is usually known as the *gas phase effect*. The temperature then drops below the adiabatic flame temperature and the flame goes out.

We can also discuss cooling down the actual fuel surface, when talking about the extinguishing process. This is what happens when we prevent pyrolysis occurring with the actual material. Both extinguishing mechanisms are separate, but still belong together. When we put out the core of the flame in proximity to material we are actually removing the fuel surface's reradiation mechanism, which means that it affects both the gas phase and the fuel surface indirectly too.

In the case of almost all extinguishing agents, the extinguishing effect is achieved by reducing the temperature of the flames or of the surface of the burning material. When powder is used as an extinguishing agent the oxygen content, for instance, is only reduced marginally in the air.¹³

Water is the most commonly used extinguishing agent. Water extinguishes fire by cooling the burning material (surface effect) to a temperature which is so low that the material can no longer emit sufficient combustible gases. Water also extinguishes through the water vapour being heated up and drawing energy from the flames (gas phase effect)¹⁴.

The relation between flame speed and burning velocity

In practice, the flame speed and rate of laminar combustion are never the same. During combustion the flame front pushes ahead due to the expansion of hot gases which occurs and the products are heated behind the reaction zone (see Figure 42). The hot products cannot freely expand, but are confined behind the flame front. Expansion can occur very quickly in some cases!

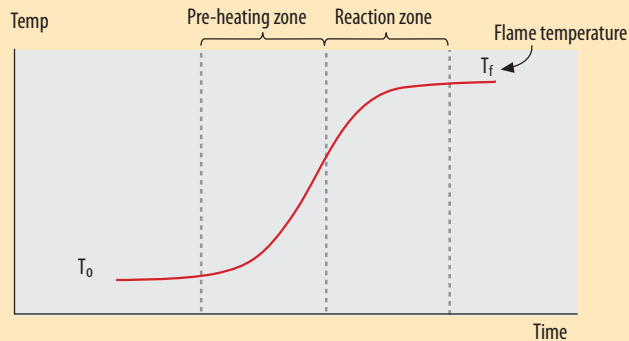


Figure 42. The thin reaction zone shown in Figure 41.

The connection between the flame front speed, S_f , and the rate of laminar combustion, S_u , can be shown in a very simplified equation. The flame front spreads spherically and the hot combustion gases behind the flame front cannot expand freely.

The flow is assumed to be laminar, which gives the following connection:

$$S_f = S_u \times E \quad \text{Equation 7}$$

where E is the expansion factor.

$$E = (T_f/T_i)(N_b/N_u) \quad \text{Equation 8}$$

where T_f = Products' temperature

T_i = Original temperature of unburnt gases

N_b = Sum of the products available after the reaction

N_u = Sum of the reactants available before the reaction

N_b/N_u varies for many gases, but in most cases the quotient is around 1.

We can therefore assume that

$$S_f = S_u \times (T_f/T_i) \quad \text{Equation 9}$$

If turbulence affects the system the flame's surface gets bigger and S_u increases by a factor β . The equation then becomes:

$$S_f = S_u \times \beta \times (T_f/T_i)$$

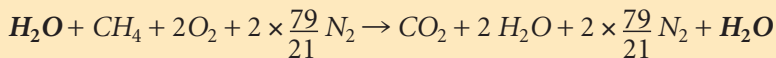
Equation 10

β varies according to the furnishings, openings, etc. or to the use of a fan. The normal value lies between 1 and 5. This makes S_f even higher.

It should be added that T_i is at its highest when the stoichiometric point is reached. This means that the expansion factor too is at its highest when the stoichiometric point is reached, even as high as around 8, but then it can drop to 5–6 at the flammability limits. The expansion factor in the example is based on the gases being at ambient temperature. (As smoke gases are, more often than not, hotter than ambient temperature, the amount of expansion is often lower.)

Extinguishing mechanisms – gas phase effect

The reaction formula in Equation 11 below can be used to describe how a flame goes out. When we extinguish a flame with water we are therefore adding water molecules on both sides of the reaction formula, which means that the flame temperature drops and the flame goes out. The reaction is a complete reaction involving methane (CH_4) and air.



Equation 11

Water (steam) therefore draws energy from the mixture and reduces the temperature to a level where flaming combustion is impossible.

3.3 Pressure conditions in open and closed rooms

This section will deal with pressure conditions in both open and closed rooms. The pressure conditions are instrumental in controlling how smoke gases and air move through the openings which are always found in a building. Naturally, the pressure conditions differ if the room has large openings, compared to if the room is more or less closed. We are still in the early fire development phase. It is actually of no consequence at all in our example whether the fire is fuel or ventila-

tion controlled. This is because the pyrolysis of ceiling materials, for example, can, in any situation, produce high contents of unburnt gases, even if the fire were fuel controlled.

It is of crucial importance to be able to evaluate the pressure conditions in a room. The pressure conditions are very important as they will affect the outcome of our operation, not just with ventilating, but with extinguishing the fire too.

We will focus on the differences in pressure associated with a fire. It is also important to distinguish between pressure differences and absolute pressure. Atmospheric pressure conditions are one thing, whereas the difference in pressure which occurs via openings in a compartment fire is something totally different.

Gases always flow from an area of higher pressure to an area with a lower pressure. The outflow of smoke gases from a fire room and the inflow of air to a fire room are therefore determined by the difference in pressure between the fire room and the surrounding atmosphere.

The unit of measurement for pressure is the Pascal (Pa). Normal atmospheric pressure is usually 101300 Pa or 101.3 kPa. To give you some comparison, a pressure of 1 Pa is equivalent to the pressure exerted by a sheet of paper on the top of a desk. At a pressure of 100 Pa it is difficult to open the door in a room. A pane of glass 1 mm thick, with an area of 1 m² can be cracked with a positive pressure of between 1000 and 5000 Pa, depending on the design and how it is fixed.

It is useful to divide the pressure differences which occur into two categories. The first category is based on the pressure generated by the fire itself. The other is based on the normal differences in pressure which are always associated with a building or between the building and its surroundings, and which can contribute to smoke gases spreading in the event of a fire.

Normal pressure differences can be divided into three types:

- Differences in pressure produced as a result of differences in temperature between outside and inside air
- Differences in pressure produced by the wind's impact
- Differences in pressure produced by mechanical ventilation.

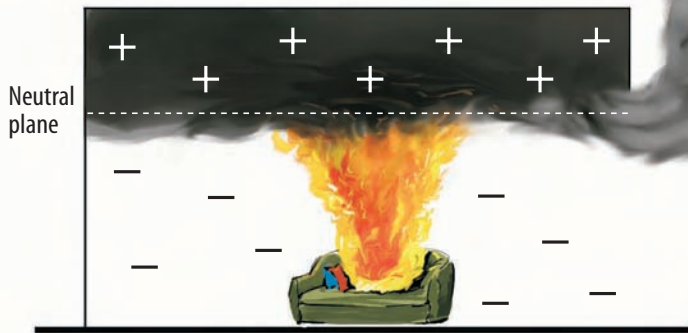


Figure 43. Example of the pressure conditions in a fire room. The room is open.

The differences in pressure generated by the fire can be classified by two types:

- Differences in pressure resulting from thermal expansion being inhibited
- Differences in pressure resulting from the smoke gases' buoyancy.

The relative size of these factors varies according to a building's design and position, external influences, etc. Circumstances can vary enormously both within buildings and between different buildings, as well as over time. But it is natural for the differences in pressure generated by the fire itself to be dominant in proximity to the fire. When the distance from the fire increases and the smoke gases cool down, normal pressure differences are much more dominant.

Differences in pressure cause smoke gases to flow, resulting in them spreading quickly to adjacent parts of the building. This spreading process can occur via vents or openings in the ceiling, floor or walls, along corridors, up (and in some cases down) vertical shafts for staircases, lifts or ventilation as well as via ventilation system ducts.

In this book we are focusing on the differences in pressure generated by the fire. We will discuss these differences in detail and then talk about what the pressure conditions are like in three separate scenarios which we are often faced with when we are at the scene of a fire.

The three scenarios are:

1. Room is closed, or almost completely closed.
2. Room is open, with a door or window open, for instance.
3. Pressure build-up in a room when a gaseous mass ignites.

But we must remember that the other differences in pressure which can arise, for example, caused by the wind, can be of the same magnitude as those generated by the fire. You are recommended to read a more detailed description of the different types of pressure difference.^{7,8,15}

Usually there is a certain amount of leakage in the fire room, which means that the pressure will be seldom more than twenty or thirty Pascal.

3.3.1 Inhibited thermal expansion

When fire breaks out in a compartment which is entirely closed, the pressure will build up. This is a result of the smoke gases being heated, but being prevented from expanding.

Pressure build-up in a closed room

The heat release rate \dot{Q} from a waste paper basket is constant at around 100 kW. Let us make the volume of the room V 60 m³. The starting point for the calculation is that this pressure is the mass and energy balance for a limited control volume. You should note that the release rate \dot{Q} is expressed in kW. We assume an air temperature of 293 K (20°C), ρ_a is the air density and is set to 1.2. C_v is the specific heat capacity at a constant volume, which is set to 0.7.

We use the equation:
$$\frac{(p-p_a)}{p_a} = \frac{\dot{Q}t}{V\rho_a c_v T_a} \quad \text{Equation 12}$$

$$\frac{(p-p_a)}{p_a} = \frac{\dot{Q}t}{V\rho_a c_v T_a} = \frac{(100 \times 1)}{60 \times 1.2 \times 0.7 \times 293} \rightarrow \text{approx. } 700 \text{ Pa}$$

The rise in pressure will then be around 700 Pa/s. After 10 seconds a 1 m² window pane is subjected to a pressure of around 7 kN, which, in real conditions, is more than sufficient for the pane of glass to crack.

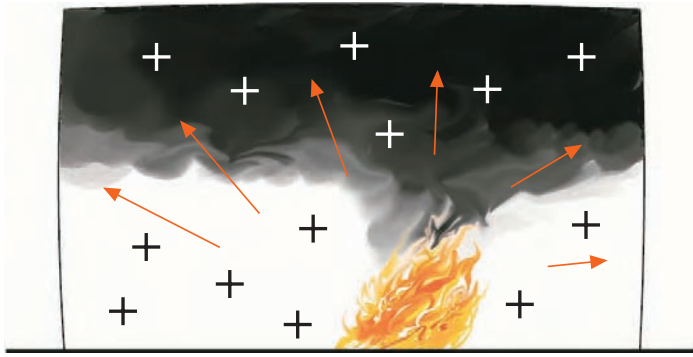


Figure 44. Air/smoke gases heat up, expand and take up more space, which results in an increase in pressure.

Where the differences in temperature are only small or moderate, the pressure generated is small, but in the case of fires where the temperature can reach many hundreds of degrees, the difference in pressure generated by this can have a considerable effect, especially if the fire develops quickly. If the size of the fire is constant the pressure will rise linearly, i.e. it increases linearly over time.

In order to see the magnitude of pressure involved, we can study a fire in a wastepaper basket in a normal office area.

This example is based on a room which is hermetically sealed, i.e. it has no openings at all. In actual fact, the pressure is rarely high enough for window panes to crack. This is because most rooms are not totally seal tight.

There is usually some kind of leakage in the fire room, for instance, in the form of air conditioning or loose seals around windows and doors. This means that the increase in pressure is usually only around 10 to 20 Pascal or so. In some cases, the pressure may perhaps reach a few hundred Pascal.

If there is a 1 m² opening the positive pressure resulting from thermal expansion will be in the order of 0.1 Pa, in other words, very low. This means that the rise in pressure resulting from inhibited thermal expansion can usually be ignored where a fire occurs in a room with normal window openings. Increases in pressure in the order of a few hundred Pascal are common in normal compartment fires.

The rise in pressure resulting from inhibited thermal expansion can usually be ignored where a fire occurs in a room with normal window openings.

Pressure build-up in a room with leakage paths

The brief example below will illustrate this. It is assumed, in this instance, that the leakage path is at floor level (see Figure 45). This means that the air flowing out has the same temperature as the atmosphere. Heat loss from the walls is ignored, as well as the change in the adiabatic work carried out with the increase in pressure.

Let us assume the same situation as in the previous example in a fire room with a volume of 60 m^3 and a fire generating 100 kW . The room is completely closed, apart from a small leakage path, which is 2 cm high and 1 metre wide, therefore 200 cm^2 , which is a realistic example of a leakage area or vent.

We use the equation: $\Delta p = \frac{(\dot{Q}/c_p T_e A_e)^2}{2\rho_e}$ **Equation 13**

where C_p is the specific heat capacity at constant pressure, T_e is the temperature of the gas flowing out, A_e is the leakage area and ρ_e is the density of the gas flowing out.

If we insert the values this gives us:

$$\Delta p = \frac{(\dot{Q}/c_p T_e A_e)^2}{2\rho_e} = \frac{(100/1 \times 293 \times 0.02)^2}{2 \times 1.2} \approx 120 \text{ Pa}$$

The maximum increase in pressure is therefore around 120 Pa , which most window panes can withstand.

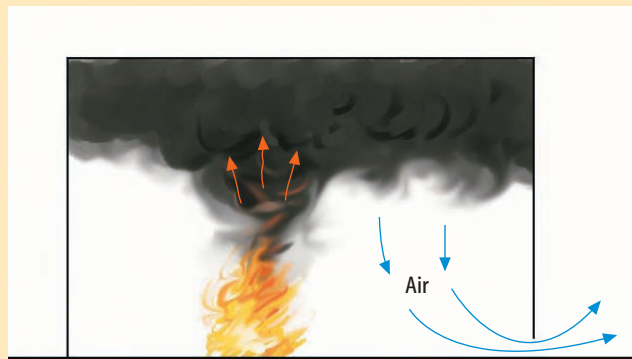
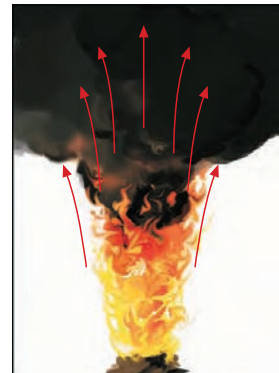
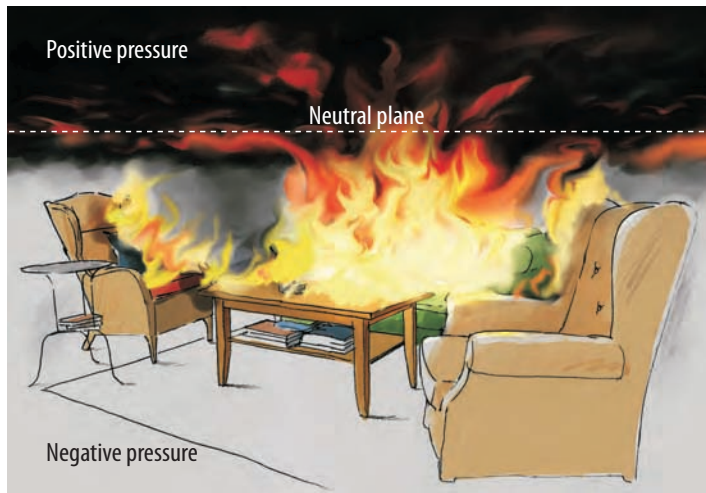


Figure 45.
Leakage path
at floor level.



3.3.2 Thermal buoyancy

In a fire room, the difference in pressure occurs due to the air being heated (smoke gases). The hot gases have a lower density than the unaffected air in the atmosphere and therefore rise upwards in the fire room. We describe this as thermal buoyancy. We then have an upper hot smoke gas layer and lower layer comprising mainly air. The smoke gases' movement upwards may be prevented when they reach the ceiling, but the gases still retain their thermal buoyancy, which affects the difference in pressure via the fire room's openings.

As long as the smoke gases have a higher temperature than the surrounding air and therefore, a lower density, they will continue to rise upwards. As a result of the buoyancy, along with thermal expansion, the smoke gases escape via openings located high up in the room. This can often be clearly seen from the fire room's openings, with fresh air flowing in through the openings lower down and hot smoke gases flowing out via the upper part.

Smoke gases cool down when they are rising upwards, as cold air becomes mixed in the plume. This means that in the case of tall buildings, the smoke gases may not reach the ceiling. Similarly, smoke gases may sink towards the floor when they flow into a corridor and cool down along the ceiling and walls.

Smoke gases flow from a higher pressure environment to a lower pressure one. As a result of the difference in pressure in

Figure 46 (on left). The pressure conditions in a normal room with thermal buoyancy. Positive pressure builds up in the upper part of the room, compared with the outside pressure.

Figure 47 (on right). Hot air is lighter than cold air, just like hot smoke gases, which means it rises upwards (in normal conditions).

Hot gases flow from a higher pressure environment to a lower pressure one.

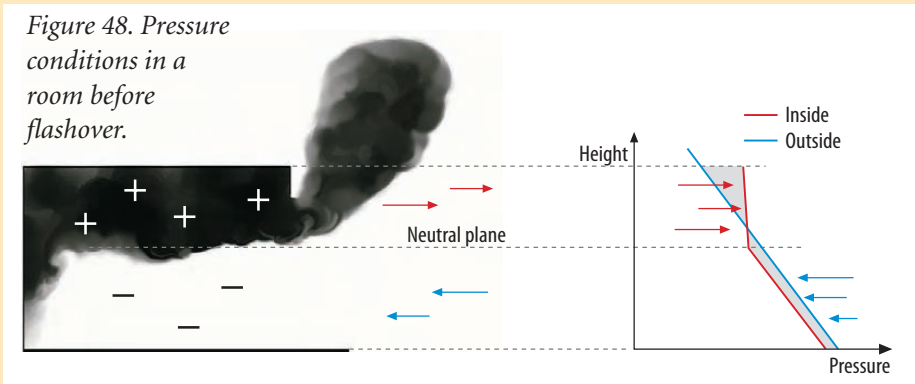
Calculating the thermal pressure difference

We are going to take a fire room with a well-defined smoke gas layer, which has an absolute temperature T_g and will calculate the difference in pressure causing the gas to flow through the opening. The pressure conditions are shown in Figure 48. The difference in pressure is calculated from the neutral plane to the level of the opening at height h

$$\Delta p = (\rho_a - \rho_g)gh$$

Equation 14

where Δp is the pressure difference, ρ_a is the density of the surrounding air, ρ_g is the smoke gases' density, g is the gravitational constant and h is the height from the neutral plane.



To be able to introduce experimentally measured temperatures in equation 14 instead of using the density, which is difficult to measure, the general gas law are used.

$$\rho = \frac{pM}{RT}$$

Equation 15

Insert the values $p = 101.3 \times 10^3 \text{ N/m}^2$
 $M = \text{approx. } 0.029 \text{ kg/mol}$
 $R = 8.31 \text{ J/mol} \times \text{K}$

Using typical values for pressure p , mol mass M , general gas constant R and temperature T , specified in Kelvin, the expression can be simplified to:

$$\rho = \frac{353}{T}$$

Equation 16

This expression can be used as smoke gases have roughly the same physical properties as air. By combining equations 14 and 16 we arrive at equation 17, which can be used to calculate the pressure difference.

$$\Delta p = 353(1/T_a - 1/T_g)gh$$

Equation 17

Let us take a room with a 1 m thick smoke gas layer, calculated from the neutral plane. The smoke gases have a temperature of 200 °C. How big will the thermal pressure difference be?

The pressure difference can be calculated using the expression $\Delta p = \Delta \rho gh$. The density of air at a temperature of 20 °C is 1.2 kg/m³ and 0.75 kg/m³ for smoke gases at a temperature of 200 °C. This gives a difference in density between air and the smoke gases of 1.2 – 0.75 = 0.45 kg/m³.

If the smoke gas layer is calculated on a per meter basis, starting from the neutral plane, i.e. h = 1 m, the pressure difference will be:

$$\Delta p = 0.45 \text{ kg/m}^3 \times 9.81 \text{ N/kg} \times 1 \text{ m} = 4.5 \text{ N/m}^2 = 4.5 \text{ Pa}$$

Therefore, the difference in pressure between the outside and inside air is 4.5 Pa one metre above the neutral plane.

Figure 49 illustrates how the pressure difference varies according to the smoke gases' temperature and the fire layer's thickness. Given that the smoke gas layer in normal premises can be as much as a couple of metres thick, the pressure difference could be as much as 15 Pa at normal room height. This applies therefore when the smoke gases have the opportunity to escape from the room.

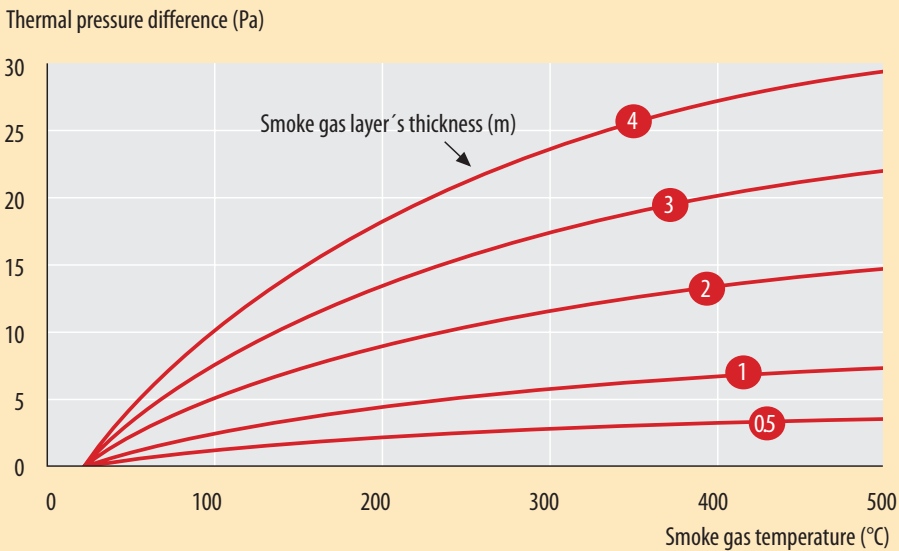


Figure 49. Illustration of how the thermal pressure difference varies with the smoke gases' temperature and the thickness of the smoke gas layer, calculated from the neutral plane.

the upper part of the room, the smoke gases spread through any openings located there. This means that there is positive pressure in the upper part of the room, compared with outside. This results in smoke gases escaping. The pressure difference in the lower part of the room is negative compared with outside. This means that there is a negative pressure and cold air is sucked in through the lower openings. Anywhere between the upper and lower part the pressure difference is zero. This position is known as the height of the neutral plane.

3.3.3 Pressure in a closed or almost completely closed room

As we discussed earlier on, the pressure will depend on how much leakage there is in the room. If the room was completely closed the pressure would be extremely high and would break the window panes, for instance. This does not happen in the case of normal compartment fires. Houses have the usual leakage areas.

We usually calculate the normal value for leakage areas as $1.25 \text{ cm}^2/1 \text{ m}^2$ of enclosure surface.¹⁶ This usually means that the pressure caused by inhibited expansion can reach a maximum of a couple of hundred Pascal, and is very often even lower, in the order of 20–30 Pascal.

The pressure caused by inhibited thermal expansion can reach a couple of hundred Pascal.



Figure 50. Thermal expansion in the room of a house.

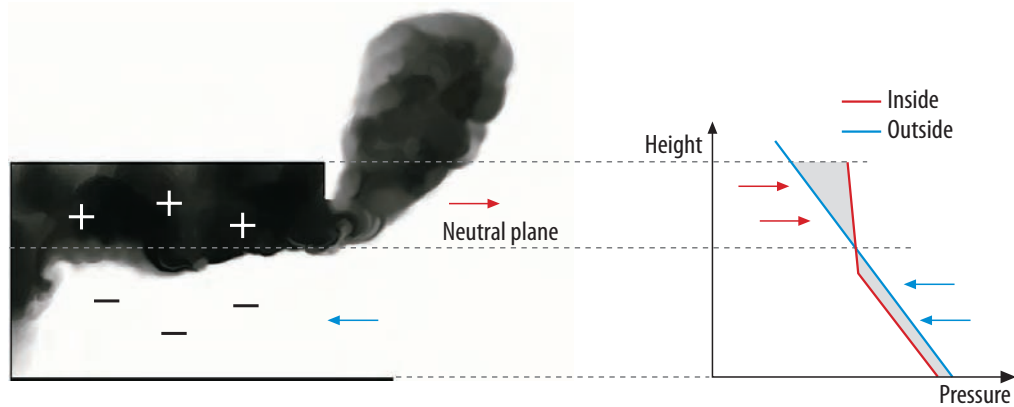
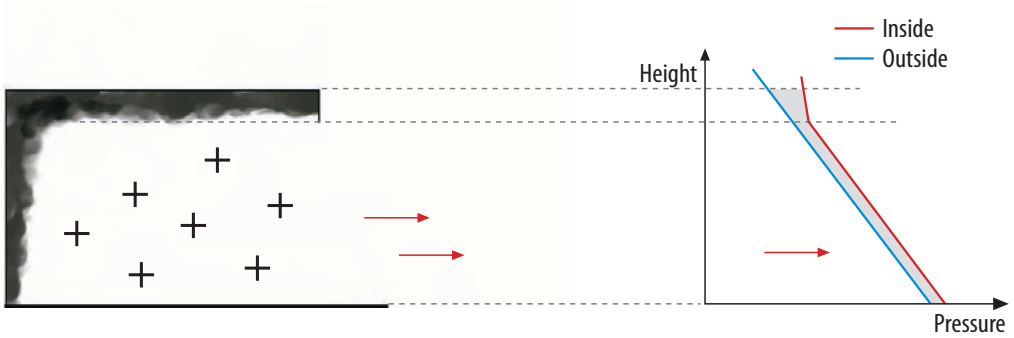


Figure 51 (top). The pressure conditions in a fire room when there is still positive pressure in the whole room can be identified by the “Outside” pressure curve to the left of the “Inside” one. You should note that no smoke gases have escaped from the room up until this point.

Figure 52. The pressure conditions in a fire room with a clear two-zone layer and a clear neutral plane. There is positive pressure above the neutral plane, i.e. the gases are escaping through the room. There is negative pressure underneath the neutral plane, which means that air is flowing into the room.

3.3.4 Pressure in an open room

The development of an enclosure fire usually gives rise to a two-zone layer, with a hot upper smoke gas layer and a cold lower layer of air. The layers usually have a stable formation at a particular distance from the floor. You should note that the pressure curve for outside air has a negative slope, i.e. the atmospheric pressure falls, the higher up in the atmosphere we go.

At the start of the fire there is positive pressure in the whole room. If there is any kind of opening air will squeeze out through the whole opening, which is due to the increase in pressure generated by the fire. The smoke gas layer arrives very

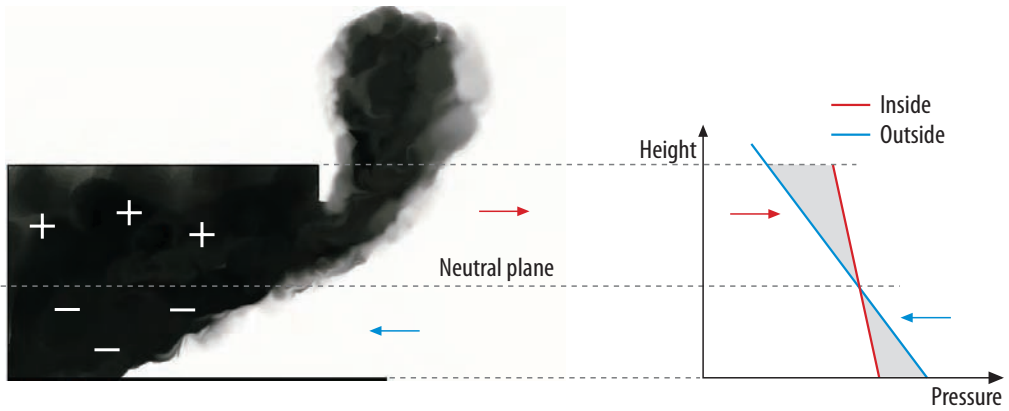


Figure 53. The pressure conditions in the opening to a fire room completely filled with smoke gases or where a flashover has occurred.

quickly down at the bottom edge of the opening and smoke gases start to escape. At the same time, thermal expansion continues to squeeze out cold air, which sustains the positive pressure in the whole room.

As fires are not usually detected until smoke gases have started escaping from the fire room (unless there is a fire detector or automatic fire alarm), it is only then that the fire service is called out. The following two stages are of most interest to firefighters during a fire.

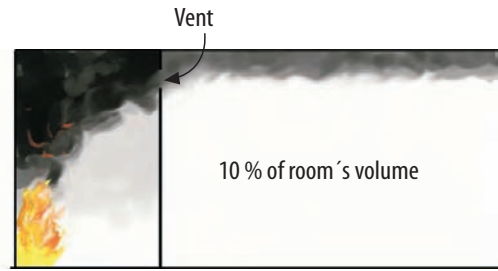
In the first of these two stages (see Figure 52), the flow conditions change so that cold air starts to flow into the fire room and a neutral plane is formed. The height of the neutral plane, i.e. the height where the pressure in the fire room is the same as that in the atmosphere, is shown in the figure.

There is negative pressure under the neutral plane and positive pressure above the neutral plane, compared with the atmosphere. Gas temperature is one of the factors which determines the size of the pressure difference.

A fully developed fire is shown in Figure 53. The compartment is completely filled with smoke gases or a flashover has occurred and the pressure curves are represented by two straight lines. There is negative pressure in the bottom part and positive pressure in the upper part of the compartment.

3.3.5 Pressure build-up in a room when smoke gases ignite

This section is about the pressure which builds up when a gas mixture ignites inside a fairly closed room. *Changes in pressure can occur at different stages in the development of a fire, and not*



just during the early stage of fire development. This section also provides information about how well the parts of a building withstand pressure. Smoke gases can ignite not only in the actual fire room, but also in other areas where smoke gases have escaped to.

The build-up in pressure is due to the gases' volume increasing when they ignite. The increase in volume quickly leads to an increase in pressure.

Differences between premixed and non-premixed gaseous masses

If an explosion occurs in an enclosed room pressure will be generated within the room. This is due to the gaseous mass expanding when the reaction releases energy. If there are no openings or the openings are very small, the pressure will increase in the room. Even if the openings are larger, they are not perhaps large enough to be able to reduce the pressure in the room.

Earlier on in this chapter, we discussed how different gas mixtures ignite. The burning velocity varies according to different factors. If the gaseous mass is premixed the gases will expand very quickly. With a premixed gaseous mass, flames spread at a rate of $\approx 3\text{--}5\text{ m/s}$.¹⁰ Expansion in this case will be faster than with a diffusion flame spreading in the smoke gas layer. We can calculate how much the pressure will increase in the compartment by according to how enclosed it is. The larger the openings, the less the build-up of pressure. You should note that flames spread and pressure increases very quickly, sometimes within a second, when a premixed gaseous mass ignites.

The following example highlights the pressure difference between a premixed flame and a diffusion flame.

Figure 54 (on left). Increase in pressure when gases ignite.

Figure 55 (on right). Smoke gases spreading in the room.

There is assumed to be a certain volume of smoke gas in a compartment (see Figure 55). The gas ignites and the pressure is calculated for different opening areas. The gaseous mass expands between 5 and 8 times when it ignites. This presupposes that the smoke gases are fairly cool from the start. There will be a dramatic increase in pressure if there are no openings in the room. But there is almost always some kind of general leakage.¹⁷

NB: The calculations¹⁸ can only give a rough estimate of the pressure in the room and must in no way be regarded as precise results.

We are now assuming that the gaseous mass is premixed, which means that the flame speed is around 3–5 metres per second. The flames will spread throughout the whole room in about a second. This is obviously a rough assumption, as S_u (the burning velocity) varies considerably according to the type of gas involved and whereabouts within the flammability range the gaseous mass is.

First of all, the gaseous mass is *premixed*.

Figure 56. Pressure build-up if the gaseous mass is premixed before ignition.

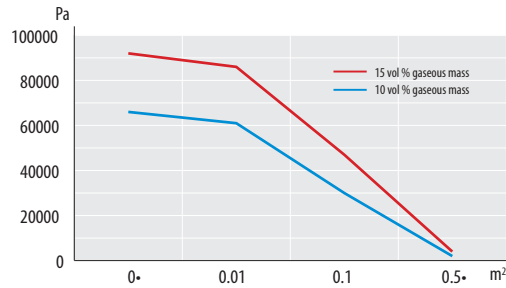
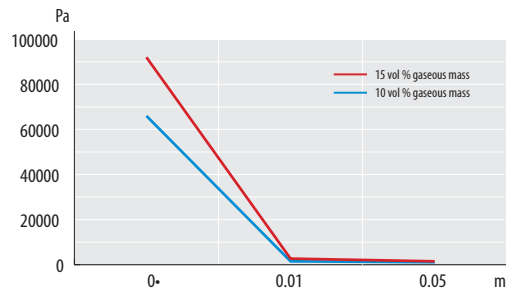


Figure 57. Pressure build-up if the gaseous mass is not premixed before ignition.



The gaseous mass is now burning instead as a *diffusion flame*. It takes a couple of seconds for the gaseous mass to ignite, due to various factors. A rough assumption is made that the gaseous mass will ignite within 5–6 seconds, if the room is 3 metres wide.

The figures above clearly show the difference when the gaseous mass ignites as a premixed mass or as a diffusion flame.

In Figure 57 calculations have not been performed for “large” openings, as it turns out that the increase in pressure is already so low for small openings.

In most fires the gaseous mass is not premixed. If the gaseous mass was premixed doors and windows would be pushed out in normal compartment fires. But this does not actually happen. It is very rare in house fires for doors and windows to crack as a result of the pressure. In Chapters 4, 6 and 7 we will discuss in which situations we can realistically assume that the gaseous mass is premixed. The concept *deflagration* is associated with the ignition of premixed gaseous masses and is often used when talking about fires.

The concept *smoke gas explosion* is often used when talking about fires and means that a large smoke gas volume has been premixed before ignition occurs. The closer the mixture is to the stoichiometric point, the higher the increase in pressure will be. This is because the flame front speed is higher. An *explosion* can be defined as *an exothermic chemical process which, when it takes place at constant volume, results in a sudden, significant increase in pressure*. Occasionally you will hear people talking about the fire spreading like an explosion. This is often incorrect.

Pressure resistance in different building components

Some of the commonest hydrocarbons, e.g. methane and propane, can in stoichiometric mixtures generate pressures of up to 8 bar, if they ignite in a closed room.¹² No building can withstand pressure of this size, unless they are specially designed to do so. Usually the weakest parts in the building will collapse, allowing the gases to escape. This will reduce the pressure build-up. It is still possible, however, for the ventilation areas to be too small, which means that stronger building components can also collapse.

Table 6 (on the following page) shows the level of pressure at which different building components will collapse.¹² The pressure figures given below must be regarded as rough estimates and vary according to the relevant material used and how the experiment has been carried out. The resistance of glass panes, for instance, can vary a lot.

<i>Typical pressure at which various building structures will collapse</i>		
<i>Structure</i>	<i>Pressure (mbar)</i>	<i>Pressure (Pa)</i>
<i>Glass windows</i>	<i>20–70</i>	<i>2000–7000</i>
<i>Room doors</i>	<i>20–30</i>	<i>2000–3000</i>
<i>Lightweight walls (wooden framework and wooden boards)</i>	<i>20–50</i>	<i>2000–5000</i>
<i>Double plasterboard</i>	<i>30–50</i>	<i>3000–5000</i>
<i>10 cm brick wall</i>	<i>200–350</i>	<i>20000–35000</i>

Table 6. Pressure resistance for various structures.

Detonation

In a previous section we discussed how a deflagration can occur when a gaseous mass ignites, resulting in very rapid flame spread in the gases. It is possible for flames to travel even faster, in fact, faster than the speed of sound, in very specific conditions. This is known as a detonation. In a detonation the reaction is caused when the gas and air are mixed as a result of the gases being compressed and heated, which follows after a blast or shock wave.

The shock wave and flame front are linked together and travel through the gas/air mixture at high speed. The speed often reaches the speed of sound. The pressure generated by a detonation is extremely complex and can be as high as 20 bar.¹² This pressure is generated in a matter of milliseconds. When a detonation occurs, the speed and density across the reaction zone decrease while the pressure increases.

Detonations almost never occur along with fires. The detonations which have occurred have taken place when there have been mixtures in narrow pipes where the ratio between the length and diameter of the pipes has been very large. As detonations occur rarely in this area, we will not be discussing this topic any further in this book.

Detonations are most often associated with explosive materials, such as dynamite.

3.4 Summary

In many situations the smoke gas layer will contain unburnt products. The poorer the ventilation, the larger the amount of unburnt gases. As a result of this and in conjunction with a large number of pyrolysis products from material not in proximity to the actual seat of the fire, the smoke gases may ignite.

The energy in the smoke gas layer can be released if fuel and air are in the right proportions, and there is also an ignition source close by. If the energy in the smoke gas layer is released, i.e. if flames occur, the radiation level in the room will rise dramatically.

When the smoke gas layer ignites two types of flames can occur:

- *Diffusion flames, where the oxygen diffuses into the fuel.*
- *Premixed flames, where the fuel and air have mixed prior to ignition.*

Diffusion flames occur in the boundary layer between the fuel and air. In most enclosure fires, what we see are diffusion flames.

During a compartment fire a variety of pressure conditions will control the flow of smoke gases. It is important to be able to recognise pressure conditions as this will effect the type of operation carried out. The pressure generated by fires can be classified by two types:

- Thermal expansion
- Thermal buoyancy.

The pressure difference resulting from inhibited thermal expansion is most often small in normal buildings, as there is always a certain level of leakage.

If the fire room has a large opening the flow will be controlled by thermal buoyancy. The pressure is mostly in the order of 20–30 Pascal, but even this can influence the type of operation carried out.

If a smoke gas layer ignites inside a building a high pressure build-up can occur. If the whole gaseous mass or large parts of it are mixed prior to ignition there will be a considerable in-

crease in pressure, unless the room has openings which are sufficiently large to reduce the pressure inside the room. Only a small amount of the room's total volume is sufficient for the pressure to rise dramatically. The larger the openings, the less the build-up of pressure will be and the more energy the gases contain, the higher the burning velocity.

Scenarios involving premixed gases often cause extremely dangerous situations and there is a very high risk of burns and injuries caused by increased pressure.

If diffusion processes are dominant in the smoke gas layer the level of gas expansion will not be so high and the process is easier to control, which means the increase in pressure in the room will not be as dramatic.

When talking about fires, occasionally the terms *lean* and *rich* are used to describe the smoke gas layer's composition. These concepts assume that the gaseous mass is premixed, which is not the case in most compartment fires.

Test your knowledge!

1. *When can we use the terms "lean" and "rich" when talking about a fire?*
2. *What level of pressure can theoretically build up in a fire room if a premixed gaseous mass ignites?*
3. *Describe the different categories of pressure difference there are. Which are caused by the fire?*
4. *Explain the difference between the various types of flames.*
5. *What speed does a premixed flame front move at?*
6. *What is a deflagration?*
7. *What is a detonation?*
8. *The concepts "fuel control" and "ventilation control" are often used when talking about fires. What is the difference between these concepts? Why is it important to know whether the fire is fuel controlled or ventilation controlled?*
9. *Which products are formed when a fire burns?*
10. *Which substances can you find in a smoke gas layer?*
11. *What factor controls the speed of diffusion flames?*
12. *Describe the pressure conditions in an open room.*
13. *Describe the pressure conditions in a hermetically sealed*

- room and in a fairly closed room (only minor leakages).*
- 14. Which type of flame is dominant in a normal compartment fire?*
 - 15. Windows and doors are usually among the weakest components in a building structure. What pressure is required for these structures to collapse?*
 - 16. What is roughly the size of the pressure difference created in a room due to thermal buoyancy? We are assuming that the room has a ceiling 2.4 metres high.*
 - 17. How does burning material affect the development of a fire? Is it of any consequence at all whether the material burning is made of plastic or wood?*
 - 18. How do you think that the use of double and triple-glazed windows in houses has changed the way in which compartment fires develop?*
 - 19. Balance a reaction formula using propane and air. Explain how it would be possible to indicate the extra oxygen and fuel available when we approach the flammability limits.*
 - 20. Explain why a flame cannot exist outside the flammability range.*



Flashover

This chapter describes the mechanisms which can lead to a flashover occurring. The basic prerequisite is that there is sufficient fuel in relation to the volume of the room. The fire is presented with the opportunity to progress to flashover if there are openings in the room. This chapter also provides a description of what happens in the smoke gas layer during the transition to a fully developed compartment fire. It is particularly interesting to examine the type of flames involved when a flashover occurs.

We are still on the rising gradient of the fire growth curve. Up until this point, we have been describing the fire's behaviour in the early fire development stage. We have not taken into consideration any openings in the fire room, but have assumed that the fire is still fuel controlled. In many respects, we have been in situations which can occur, both if the fire is fuel controlled or ventilation controlled, such as when the smoke gases ignite.

We have now reached a situation where the fire has spread to various objects in the room.

But the fire is still fuel controlled. There is therefore free access to air to allow combustion to continue. The fire can follow various paths. The moment when ventilation control occurs varies according to a number of factors. The description given below does not claim to cover every eventuality, as a fire can develop in many different ways. Figure 58 is therefore a representation, illustrating two basic scenarios: scenario 1 and scenario 2.

We will start by looking at scenario 1. The fire has free access to air/oxygen and continues to develop. The heat increas-

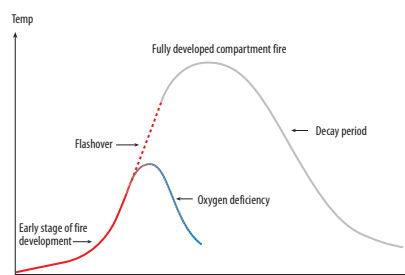


Figure 58. Different fire development paths.

1. The fire can progress to flashover. In this case, the fire room has a good supply of air, which means, theoretically, that there are openings in the room.

2. If a lack of oxygen in the fire room develops the fire's intensity will decrease and the temperature will drop, which may result in the fire spontaneously going out or in it starting to smoulder.

Figure 59. The fire has spread to other objects in the room. Soon the whole room will be involved.



es in the smoke gas layer and the radiation to the lower parts of the room will then start to increase. This process will then be able to accelerate, leading to what is known as a flashover.

Flashovers in buildings sometimes result in people dying, which is why it is important to be familiar with the situations which cause flashovers.

When a fire in its early development progresses to flashover, in theory, it is no longer possible for people in the building to survive. It is therefore very important to tackle the fire before it reaches flashover. A very small percentage of all compartment fires result in flashover. Firefighters must therefore have a basic understanding of the factors which affect the development of a compartment fire, i.e. those factors that lead a fire to flashover.

4.1. Definition of flashover

Flashover has been used as a concept for at least the last 40 years. Its definition has been vague and over the last few years a number of different interpretations of this concept have arisen. Terms such as “rollover”, “lean gas combustion”, “spread-over” and “flameover” have been coined as substitute and/or complementary concepts, but without any agreed structure. Unfortunately, this means that there is a fair amount of scope for misunderstanding. It would be absolutely great if everyone could agree on the same definition (an ISO definition, for in-

stance), which can be used by everyone, anywhere in the world, regardless of whether you work in the fire service, in the insurance sector or in consultancy. If agreement could be reached on the meaning of flashover as a concept there would no longer be any need for so many other terms. The exception to this are the concepts *backdraught* and *smoke gas explosion*, which are described in Chapters 6 and 7.

Many definitions of the flashover concept are very much the same. Some of the most common are given by the international standardisation body ISO and the Fire Research station, a research institute in the UK.

The ISO definition for *flashover* is as follows:¹⁹

The rapid transition to a state of total surface involvement in a fire of combustible materials within an enclosure.

This definition can, however, be expanded in more detail. We have therefore decided to clarify it as follows:

During a compartment fire a stage may be reached where the thermal radiation from the fire, the hot gases and the hot enclosure surfaces cause all combustible surfaces in the fire room to pyrolyse. This sudden and sustained transition of a growing fire to a fully developed fire is flashover.

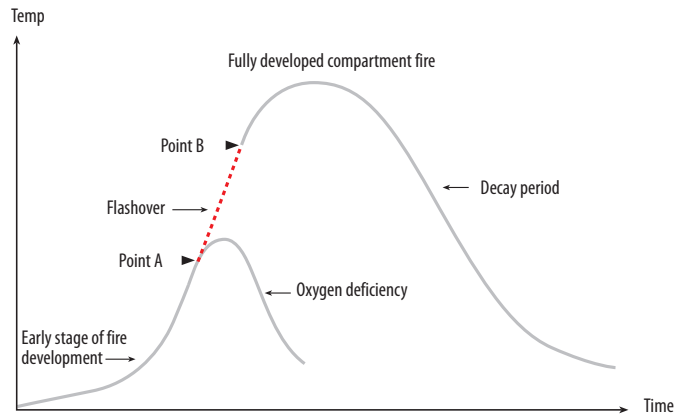
This definition is the same as the one used in the UK, for instance.²⁰ This definition states that a flashover is not classified as a mechanism, but as a *transition period*, which is dependent on a number of individual mechanisms and contributes to the initial fire becoming a fully developed fire. The term “flashover” is used in many countries, including the UK, US, Spain, Japan, New Zealand and Australia.

A flashover always results in a fully developed fire. Point A in Figure 60 may indicate the stage when the flames reach the ceiling in a room. By point B a fully developed fire has been reached.

The period between A and B may, in some particular cases, be very short, even just a few seconds. A flashover can be described as the time taken from the fire being localised until the whole capacity of the room is consumed by flames. Some of

A flashover always results in a fully developed fire.

Figure 60. Flashover occurrence over a period of time.



the factors influencing the length of this period include the room's geometry.

In this description it is assumed that the fire is fuel controlled at the outset, i.e. the room has an opening. When a flashover occurs the fire changes to become ventilation controlled. This can be explained by the fact that all the pyrolysis products which are formed inside the room cannot be burnt in situ due to oxygen deficiency. The unburnt gases will then burn outside the room, which is evident from the appearance of flames.

The heat release required for a flashover to occur in a normal-sized room ($3.6 \times 2.4 \times 2.4$ m³ with a door (0.8×2) m² is in the order of 500–1000 kW (see the calculations later on in the calculations appendix). This can be compared to the heat from a sofa, which releases between 1000 and 2000 kW. Figure 61 presents a sequence of pictures showing how flashover is reached.

4.2 Conditions resulting in flashover

A very large number of the full-scale experiments carried out both in Sweden and other countries have shown that in order for a flashover to be able to occur, the fire needs to exceed a critical level, which is measured in terms of the amount of heat released (kW). This level is mainly dependent on the size of the room, the walls' thermal properties and the ventilation areas. A certain amount of fuel/surface is also required.

As a flashover is a period of time, it is difficult to specify



Figure 61. The stages in the process of a fire progressing to flashover.

precisely the exact moment when it occurs. The criteria used are mainly the temperature in the smoke gas layer and the radiation emitted towards the floor. Results from various experiments show that the outcome can vary hugely. It is difficult to find two independent experts who could pinpoint the exact same time at which a flashover occurred. It is sufficient if you manage to provide an estimate within a 5–10 second difference range. This kind of time difference means that the temperature in the room will be able to change perhaps by 100°C. The rate at which the temperature rises during a flashover is very rapid.

In terms of temperature, the values measured when a flashover occurs vary between 450 and 771 °C, although most values lie between 600 and 700 °C. The radiation values vary from 15 kW/m² to 33 kW/m². Most values, however, are above 20 kW/m². The reason for the variation in these values is obviously also due to the fact that the experiments have been carried out using different fuels and arrangements. Not to mention the fact that those carrying out the experiments do not visually identify a flashover occurring at the same moment in time.

Generally speaking, when the temperature is above 600 °C in the smoke gas layer, most people consider that a flashover has occurred. Similarly, most people consider that a radiation level above 20 kW/m² is sufficient to cause a flashover in a compartment.

Experimental observations have demonstrated that radiation at floor level must reach roughly 20 kW/m² and the temperature under the ceiling about 600 °C (for ceilings around 2.5–3.0 m high) for a flashover to be able to occur. At this stage the radiation levels in the room rise dramatically, which results in pyrolysis increasing as the fuel surface increases. Most of these experiments have been carried out in rooms with openings of different sizes.

4.2.1. Heat release rate

The heat release rate is controlled either by the access to oxygen or the fuel's mass loss rate.

When there is sufficient access to oxygen and the size of the fire is controlled by the fuel's mass loss rate, this fire, as has

Heat release rate required for a flashover to occur

Data has been correlated from over 100 experimental fires for varying room sizes.²¹ These experiments have formed the basis for equation 18 below. This equation can be used to determine the amount of fuel burnt up when the fire progresses to flashover. The heat release rate required for a flashover to occur can be described using the following formula:

$$\dot{Q}_{fo} = 610 (h_k A_T A_w \sqrt{H})^{0.5} \quad \text{Equation 18}$$

where \dot{Q}_{fo} – heat release rate required to trigger a flashover (kW)
 h_k – heat transfer coefficient (kW/m²K), which specifies the amount of heat absorbed by the enclosure surfaces
 A_T – internal enclosure area in room (m²)
 A_w – ventilation opening's area (m²)
 H – ventilation opening's height (m)

Equation 18 has been produced for a normal-size room. But it has also proved to be valid for significantly larger rooms. Many different types of fuel have been tested, including wood, plastic and various gases. Both windows and doors have been used as openings. The material which the walls and ceiling are made of have had a wide variety of properties.

However, this equation does have certain limitations. It only applies to fuel-controlled fires and when the source of the fire is not located close to any wall. If it was located close to a wall the coefficients in the equation would be different. The equation applies to temperatures between around 20 and 700 °C⁷. There is a sample calculation on page 181, which shows the scope of application for this equation. The equation is often used for scoping purposes.

The fully developed fire is ventilation controlled, which means that equation 18 cannot be applied at this stage. When the fire is ventilation controlled the heat release rate, in particular, is limited in the room by the amount of air flowing in through the opening. This amount is calculated using equation 19. When a flashover has definitely taken place we can use equation 19 to estimate the actual heat release rate.

In actual fact, all the air which flows into the room is not used for combustion. Consequently, the amount of energy released is not as much as equation 19 gives, but the approximation must be regarded as being adequate for our purpose.

$$\dot{m}_a = 0.5 A_w \sqrt{H} \quad \text{Equation 19}$$

where \dot{m}_a (kg/s) is the mass flow of the incoming air, A_w (m²) is the opening's area and H (m) is the opening's height. (cont. on next page →)

The amount of energy released when the oxygen in 1 kg of air fully reacts with fuel is about 3 MJ/kg. A standard door opening of $2 \times 1 \text{ m}^2$ can produce a heat release rate of 4.2 MW, assuming that all the oxygen is fully combusted. Any extra fuel available will burn outside the room.

Another important point to note is that some of it burns outside the room. Using the equation we can calculate the maximum amount of heat released inside the room.

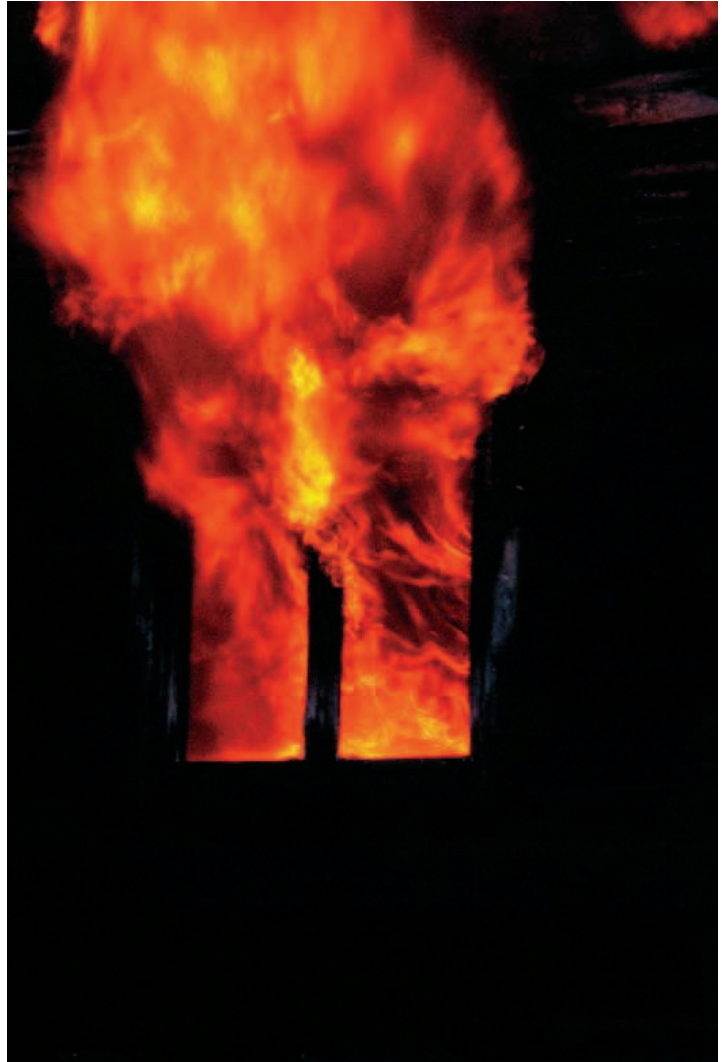


Figure 62. In this instance, the fire is ventilation controlled. Heat is released partially inside the room and partially outside of it.

Relationship between heat release rate and mass loss rate

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

Equation 20

where ΔH_c – heat of combustion (J/kg)

χ – combustion efficiency

\dot{m} – mass loss rate (kg/s)

been previously mentioned, is fuel controlled. When there is limited access to oxygen and the heat release rate is affected by this, this type of fire is described as ventilation controlled.

The heat release rate is related to the available equipment and what you manage to extinguish. Just to give you a comparison, firefighters can more or less manage to tackle a fire with a heat release rate of 15–20 MW. This is a higher release rate than in a normal house fire.²² The ability to extinguish the fire is obviously dependent on accessibility and the individual ability of the firefighters.

The heat release rate required for a flashover to occur can be converted to a mass loss rate (the amount of pyrolysis from the fuel), using equation 20.¹¹

4.2.2 Increasing the mass loss rate

In this section we will discuss the processes which contribute to an increase in the mass loss rate and indirectly, in the heat release rate, allowing a flashover to occur.

Figure 63 illustrates the thermal balance on a fuel surface. In this instance, we are assuming that we have an object on the floor. This is obviously not completely indicative of a standard compartment fire, but we will use this figure to make it easier to understand the mechanisms involved.

There is a big difference between, for instance, a piece of furniture burning outside in the open air and inside a room, where there is an impact from radiation emitted by the flames and walls, as well as from smoke gases. Reradiation increases and then the fuel emits more pyrolysis gases and the heat released by the fire increases.

We have therefore noticed that a particular heat release rate

is required in the form of a mass loss rate. The mass loss rate is controlled by:

1. *Flame spread and ignition (the area of the initial fire increases)*
2. *Higher intensity of combustion on a particular fuel surface.*

These two mechanisms are each then dependent on three processes closely linked to one another, specifically:

\dot{q}''_{loss} (the energy produced by the fuel, but not used for vaporisation)

\dot{q}''_{f} (heat from the flame)

\dot{q}''_{ext} (radiation from the surrounding area)

\dot{q}''_{loss}

When a fire is at the start of its development, a large amount of the energy transferred to the fuel is used to raise the temperature of the fuel rather than for generating fumes from the surface. Burning thermoplastic provides an example of this: it will not reach its maximum mass loss rate until a large amount of the material has melted to form a pool fire. This process uses up a lot of energy. After a while, however, the fuel and its underlying surfaces will have excess heat and \dot{q}''_{loss} will drop. According to equation 21, the mass loss rate will then increase.

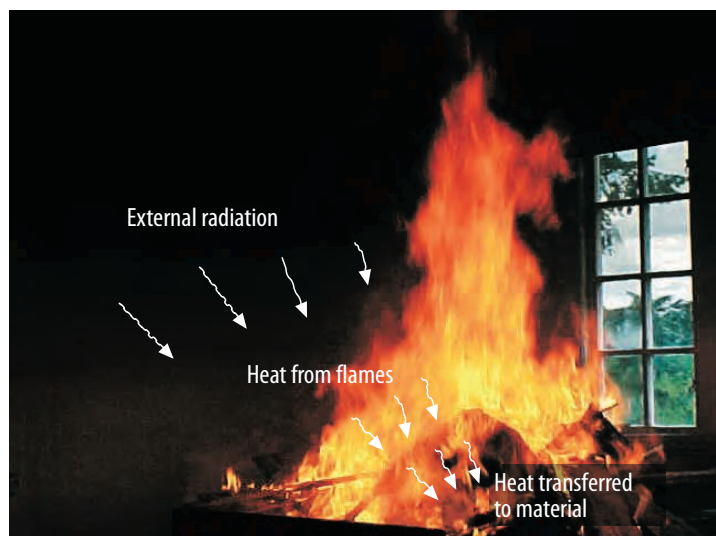


Figure 63. Thermal balance on a fuel surface.

Thermal balance on a fuel surface

The thermal balance on a fuel surface can be described using equation 21.¹¹

$$\dot{m} = \frac{\dot{q}''_f + \dot{q}''_{ext} - \dot{q}''_{loss}}{L_v} A$$

Equation 21

where \dot{m} is the mass loss rate in g/s, \dot{q}''_f is the heat transfer from the flame to the burning surface (kW/m²) and A is the fuel area in m². \dot{q}''_{ext} is the radiation from the fuel surface (kW/m²) from the hot enclosure surfaces, e.g. walls, ceiling and smoke gas layer.

\dot{q}''_{loss} corresponds to the energy transferred to the material without it being used directly to vaporise the fuel. Once the material has become saturated, the value will drop. L_v (kJ/g) is the heat of vaporisation, i.e. the amount of heat required to emit 1 g of gas from the fuel's surface. The heat of vaporisation is often assumed to be a material constant but in the case of many materials, is dependent on the material's temperature.

\dot{q}''_f

The heat from the flame (initial fire) partly causes the material to vaporise during the initial fire and partly heats the material outside this. This results in flame spread and an increased fuel surface. The flame spread rate depends, to a large extent, on which materials are mixed together, but perhaps even more so on the fuel arrangement around the initial fire. For example, flames will spread much more quickly along a vertical surface, compared with a horizontal one.

When the material has actually ignited a flammable wall lining will make the flames spread very quickly and produce extended flames under the ceiling. The radiation levels in the room will then jump dramatically. This often happens immediately before a flashover occurs in the room (see Figure 64).

You should note that we started off discussing a material's flame spread at floor level, but the principle determining the increase in the mass loss rate is obviously the same, wherever the material is located. Flame spread can cause a flashover to occur as the heat release rate is increasing. This is shown in Figure 64.

In a number of high-profile incidents during the last few

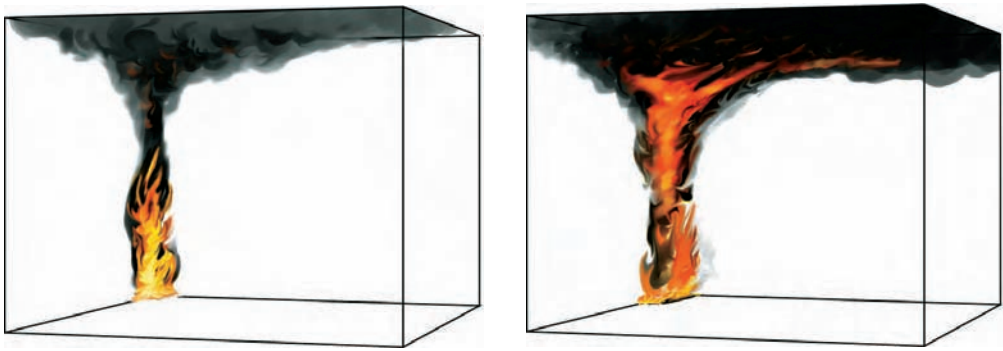


Figure 64. Flame spread under the ceiling.

years, fires have developed very rapidly. Some examples of this include the King's Cross underground station in London where many people lost their lives and the fire at the Stardust Club discotheque in Dublin²³. In these cases, the flame spread process was absolutely crucial to the tragic course of events.

$$\dot{q}''_{ext}$$

The mass loss rate of a material which is already burning in a room increases when the heat radiation level increases from the upper parts of the room. Based on the values measured, the mass loss rate can increase many times over when materials are affected by external radiation²⁴. The size of that increase depends on the specific material involved.

In a compartment fire the smoke gases build up under the ceiling. The upper part of the room is therefore filled with smoke gases, provided that the gases do not escape out any available openings. The enclosed smoke gases and hot upper surfaces generate heat radiation affecting both the fuel and other flammable surfaces. This helps to increase the mass loss rate further on surfaces which are already burning, as well as to heat any other potential fuel. This increases flame size, which, in turn, raises the temperature, which then increases the amount of reradiation, and so on.

The external radiation will also help to accelerate the flame spread process. If there is sufficient fuel in the fire room this will result in an accelerating process.

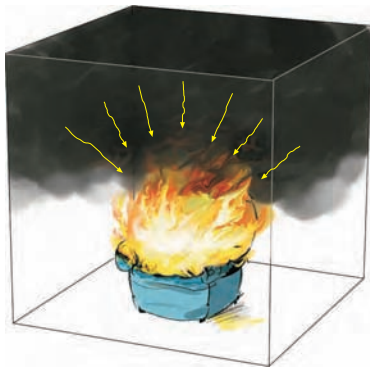


Figure 65. An armchair which is affected by radiation releases more heat.

4.3 Processes taking place in the smoke gas layer

The combustion of the smoke gas layer is a typical stage in the flashover process. The smoke gas layer usually ignites immediately before a flashover takes place.

We discussed flames in smoke gases earlier on and noted that they were diffusion flames. This is because the smoke gases do not have the time to mix together before they ignite, as the whole time is “consumed” by the ongoing fire. For this reason, it is not possible for any major amounts of premixed gases to accumulate.

If the smoke gas layer contains unburnt smoke gases this can result in combustion, which can then lead to a significant rise in the level of external radiation.

The unburnt smoke gases accumulate when the oxygen supply is not sufficient. But even when there is sufficient oxygen, a certain amount of unburnt smoke gases always accumulate. The less oxygen there is, the more unburnt gases there are. In these situations there are also a lot of pyrolysis products, mainly from the flammable ceiling material.

When the flames grow in size, a stage is reached where the top of the flames penetrate the smoke gas layer and touch the ceiling. The situation is critical when the top of the flames reach the ceiling. When the flames spread along the ceiling a large amount of radiation is emitted to the surfaces in the lower part of the room. When the smoke gas temperature under the ceiling has reached about 600°C the flashover process may start.²⁵

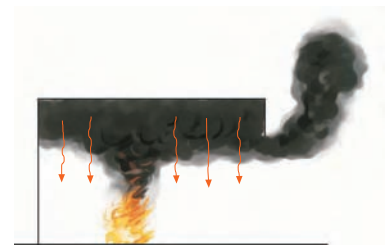


Figure 66. In this case, we are assuming that there is only fuel at floor level. This can make the description simpler.

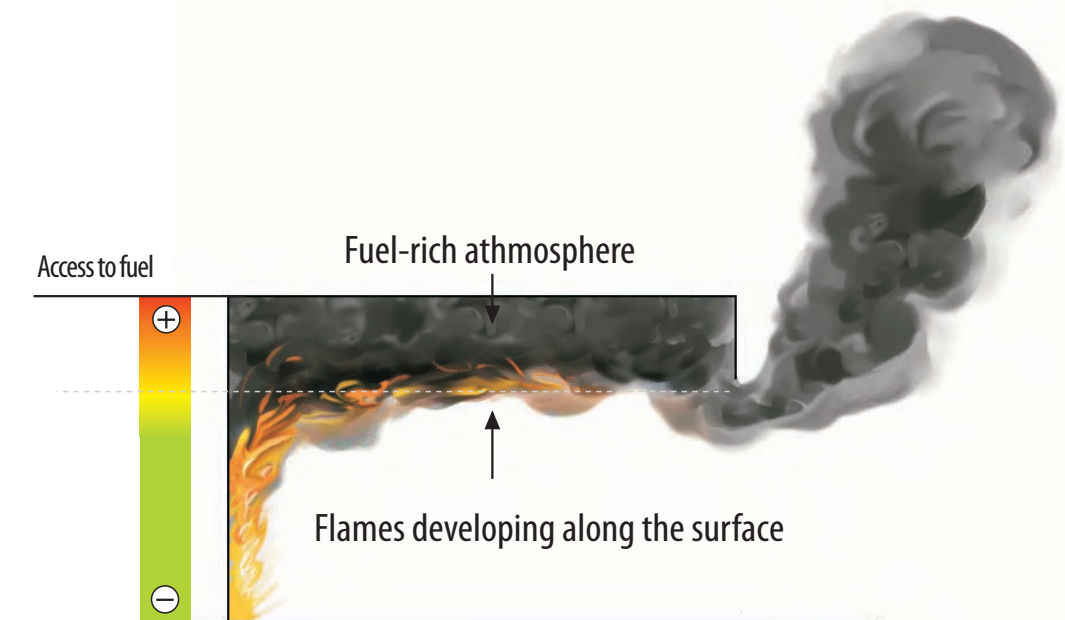


Figure 67. Fire's development along the under side of the smoke gas layer.

When the smoke gas layer sinks, this reduces the oxygen supply to the upper part of the flames and the combustion process becomes less efficient. The smoke gas layer's temperature also increases as the hotter air penetrates the plume. When the combustion process then increases, as a result of a higher level of reradiation, a large part of the flames will penetrate the smoke gas layer whose content will now comprise large amounts of unburnt gases. At the same time, the amount of oxygen will decrease until the layer is completely expended.

As the fire develops on the surface, the under side of the smoke gas layer becomes unstable with a burning gaseous mass (with temperatures of 800–1000 °C). This encourages the hot gases and air to mix in the smoke gas layer (see Figure 67).

This increases the radiation level considerably, which causes the mass loss rate to increase. This is the stage right before the whole compartment is involved in the fire.

The above discussion is based on there being sufficient fuel for the mass loss rate to increase, as well as free access to air.

The more fuel there is in the smoke gas layer, the greater the likelihood that the flames will burn along the under side of the layer. This has been observed in many practical instances. But it is still difficult to make a generalisation in saying that flames always burn along the underside of the smoke gas layer.²⁶

Another crucial factor can be how the fuel is arranged in the fire room. This will control the air flow in the room. If the ceiling's outer layer is flammable a fuel-rich mixture will form right next to the ceiling, which will increase the likelihood of the flames burning along the under side of the layer. It is also difficult to notice where the flames are exactly in the room, as the thick smoke gases make it hard to see the flames.

It is not so important to know exactly where the flames can occur. The firefighters will still understand what is happening due to the heat.

4.4 Risk assessment

It is important to be able to assess the level of risk in certain situations during rescue operations. Firefighters safety must, under no circumstances, be jeopardised. BA firefighters are particularly vulnerable, as they often work in a dangerous environment and their job is to look for people in smoke-filled areas.

Conditions can change dramatically, in just a few seconds. It is therefore vitally important that BA firefighters and other crew members working outside the building are very familiar with the signs indicating a flashover may soon occur. Sometimes you need to be able to act immediately.

The colour of the smoke gases is often used as one of these signs. But this is not enough. To have a definite idea of when a flashover is imminent, you have to be able to weigh up together a number of different indicators.

4.4.1 Smoke gases' colour

The colour of smoke gases does not give enough indication as to how imminent a flashover is. This is because there is not really a definite connection between the colour and how dangerous the situation is.

In many cases, the smoke gases' colour depends on whether the fire shows flames or is smouldering. Some of the following smoke gases are described as dangerous in the specialist literature²⁰:

- thick, dense black smoke gas: this often forms when hydrocarbons are burning and contains soot, which

The radiation level will increase when the smoke gas layer ignites, wherever the flames are.

It is important to differentiate between premixed flames and diffusion flames. During the normal flashover period, diffusion flames are the type of flames seen, which means that in most cases, the fire's development can be controlled. This is based on the assumption that the room is roughly the same size as one in a normal apartment.

produces the typical colour. The more under-ventilated the fire is, the more unburnt products are produced.

- rapid colour changes with smoke gases from thick, dense and black to yellow or greyish yellow.
- yellow smoke gases, produced by polymers containing nitrates and sulphur (e.g. tyre material).
- thick billowing clouds of yellow smoke gas.
- white cold smoke gas e.g. from smouldering foam rubber.

The signs indicating that a flashover is imminent must be assessed according to the specific situation. The focus should not be put on a single indicator, for instance, the colour of the smoke gases. On the other hand, if you weigh up a number of indicators together you will obtain a good idea as to when a flashover is imminent.

These are just some of the examples of what the colour of smoke gases can apparently indicate. As the density and colour of the smoke gases also depend on the type of material burning, we therefore need to find out as well about both the fire room's contents and geometry. As smoke gases sometimes need to be examined at night time in different types of street lighting or using other light sources, this presents even more problems when using colour to obtain a sufficiently good idea of the fire's cause.

One example indicating that you cannot regard the smoke gases' colour as a sure sign is the explosion at the Chatham Dockyard in London.²⁷ A smouldering fire in some foamed rubber mattresses filled the entire building with flammable pyrolysis products. An explosion occurred when an attempt was made to ventilate the building. The smoke gases were understood to be cold and were white in colour. The conclusion was made, therefore, that they were not dangerous. In fact, two firefighters died.

Foamed rubber mattresses are made from natural rubber. This rubber is usually also known as *latex*. *Foamed plastic* is made from *polyurethane*, a manufactured rubber. Polyurethane is commonly used in mattresses, whereas foamed rubber is seldom used, but it can be. Foamed rubber has more of a tendency to smoulder, whereas polyurethane is more likely to burn with a flame. Polyurethane can certainly emit grey smoke gases as well in some cases, but these gases are not as cool as with foamed rubber.

The risk from fires involving plastics, with explosive smoke gases building up, is greatest when foamed rubber is present. Ignition sources, such as cigarettes, which do not burst into



Figure 68. White smoke gases are definitely not harmless. In this case, the fuel is some type of wooden boards fitted at ceiling level. The colour of the smoke gases is largely dependent on whether the fire is smouldering or burning with a flame.

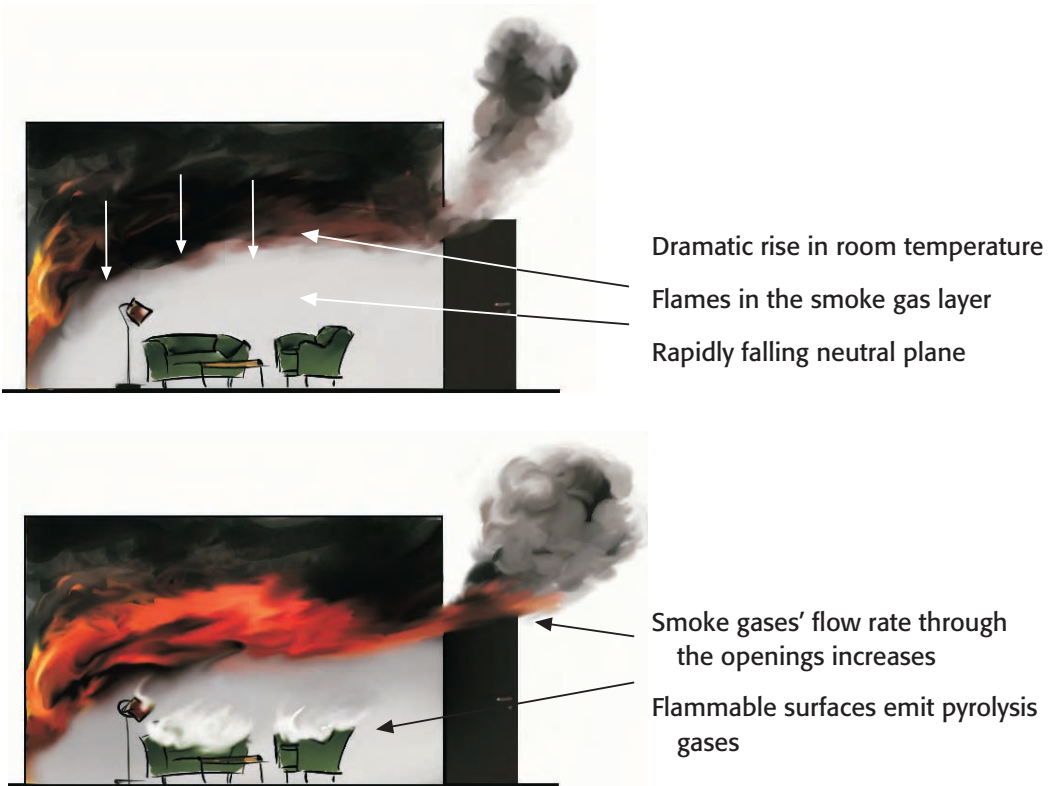


Figure 69. Different signs indicating an imminent flashover.

flames, can cause smouldering fires, which emit cool grey smoke gases. It is easy to misinterpret these smoke gases.²⁸

The amount of foamed rubber in houses is not usually enough to be able to reach the concentrations required to cause an explosion.

There are other materials too, which, in certain ventilation conditions, can emit greyish-white pyrolysis gases (see Figure 68, for instance). The colour is often determined by whether the fire is smouldering or burning with a flame.

4.4.2 Signs indicating an imminent flashover

Room temperature is a crucial factor in the progression to flashover. A list is provided below of some of the signs which can be used to predict a flashover. In some cases the colour of the smoke gases or any change in their colour is added to the listed points.

- The room temperature rises dramatically. It seems as if the fire is speeding up. When the temperature rises the difference in pressure between the room and its

White smoke gases are definitely not harmless.



Figure 70. The fire is localised in the corner. There is still no indication that the fire's development is going to accelerate.

Figure 71. Twenty seconds later. The fire is now fully developed and the temperature in the whole room is above 500°C.

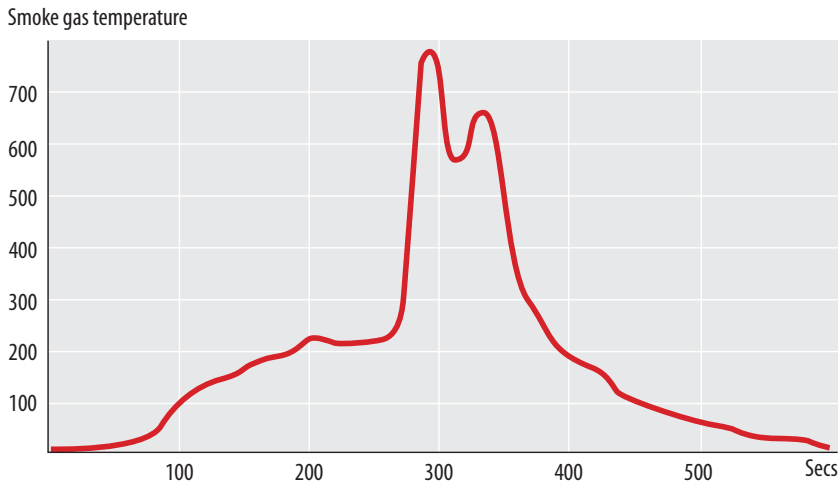


Figure 72. Temperature curve for the experiment. Flashover occurs very quickly. Efforts to extinguish the fire started at the 350-second mark.

- surroundings increases too. The neutral plane’s position in the opening, i.e. the position where the pressure difference is zero, will fall quickly downwards.
- Flames start to appear at the top of the smoke gas layer.
 - As the temperature is rising, the flow rate of the smoke gases through the openings will also increase. It is easier for crew outside the building to notice this.
 - All flammable surfaces emit pyrolysis gases, as a result of the dramatic increase in the radiation level in the room. Objects in the room are giving off smoke.
 - Flames start to spread along the ceiling. There are two possible causes of this: the ceiling material is flammable, which causes the flames to spread along the ceiling or the flames from the fire are longer than the height of the ceiling. The flames are then forced to “bend” to find oxygen for combustion. In both these situations with the flames spreading along the ceiling, a significant level of reradiation occurs in all parts of the room, which means that more fuel can be pyrolysed.

The transition from a localised fire to one involving the room’s entire capacity will occur very quickly in certain conditions. According to observations during full-scale experiments, the period from when the situation goes from being calm until a flashover occurs in the room can be very short, at around 15–20 seconds.²⁹

This means that it is difficult to make an exact assessment as to whether a flashover is imminent or not. The rate of a fire's development obviously is largely dependent on the type of fuel involved and the fuel arrangement. It often takes time for the walls to heat up and the fire often develops fairly slowly up until that point. Fire service staff need to be very observant.

4.4.3 Course of action

It is vitally important to try to extinguish the fire before a flashover occurs, as the chances of saving lives, property and the surroundings are much better in this case. Obviously, the risks involved must be assessed in relation to what can be achieved by the operation.

As we discussed earlier on, a fire's development can sometimes accelerate quite unexpectedly, which can lead to problems, especially in the case of long access routes. Alarm points can only withstand a flashover for a small number of seconds. This means that communication between the firefighter commander and their crews is extremely vital.

It is also important to remember that a normal nozzle cannot cope with fires with a heat release rate in excess of 15–20 MW.³⁰ This figure is larger than the amount of heat released in a normal apartment fire, but apartment fires where a lot of window panes have been broken get close to this level. It is possible to estimate the heat release rate for ventilation-controlled fires, using the size of the openings.

4.5 Summary

The following definition of flashover is used in Sweden:

During a compartment fire a stage may be reached where the thermal radiation from the fire, the hot gases and the hot enclosure surfaces cause all combustible surfaces in the fire room to pyrolyse. This sudden and sustained transition of a growing fire to a fully developed fire is flashover.

Flashovers occur in premises where there is good access to a supply of air during a particular stage of development. The room can have any kind of opening. The definition makes it

clear that we need to reach the stage of a fully developed fire before we can say that a flashover has occurred. A certain heat release rate is required, which corresponds to a particular mass loss rate.

The mass loss rate is affected by the radiation from the flames, the hot smoke gases and the hot walls. When a flashover occurs, the fire most often changes from being a fuel-controlled to a ventilation-controlled fire.

The smoke gas layer often ignites immediately before a flashover. This causes instability, which means that the fuel and air mix together and combust.

This process is controlled by a diffusion flame. It is therefore not possible to use terms such as “lean” and “rich” to describe a flashover. Premixed flames do not feature at all in a flashover.

A flashover can occur within a few seconds. This is why it is so important that firefighters are well informed about what a flashover is and about the conditions causing it. This can also help to prevent an imminent flashover. This is particularly important when you are in larger premises or when the access routes are long.

Signs indicating a potential flashover are linked with the rise in temperature which occurs. The common signs are as follows:

- Flames start to appear at the top of the smoke gas layer
- The smoke gases’ flow rate through openings increases
- The neutral plane’s position is changed.

The colour or change in colour of smoke gases can only be used as a sign if there is sufficient background information about the fire.

Test your knowledge!

1. *What type of flames is present when a flashover occurs?*
2. *What kind of temperature is reached during a flashover?*
3. *A flashover is described as a period. How long is this period?*
4. *What mechanisms are crucial to a flashover occurring?*
5. *What kind of protection can be provided against a*

flashover?

6. *What signs are present to indicate a flashover?*
7. *Statistically speaking, flashovers are a fairly rare occurrence. Why is this the case?*
8. *What is the percentage of house fires in Sweden which progress to flashover?*
9. *Compare two compartments, one containing mineral wool and the other concrete in their enclosure structures. Which compartment requires the most fuel for a flashover to occur?*

Fire in the Stardust Club in Dublin

This example illustrates how crucial the flame spread process is in determining whether a flashover occurs or not.

A fire broke out at the Stardust Club, a discotheque located in Dublin, in 1981, which developed unusually quickly. The fire involved a platform area measuring $17 \times 10 \text{ m}^2$, see Figure 73. The fire started on the platform area marked “A” on Figure 73.²³

The platform area sloped upwards towards the back wall, which was 2.4 m high. This platform, which happened to be empty, was partially separated from the main part of the dance floor by a large blind (see Figure 74). The western part of the platform had rows of seats which were 0.9 m wide. The seats were made of polyurethane with a PVC cover. The row right at the back was placed tightly against the back wall.

The back wall had a flammable lining and the ceiling comprised incombustible mineral wool. The fire started in the very back row (see position Z in Figure 74). It spread quickly along the row. People outside in the large hall noticed that there was a small fire in the area. The flames spread quickly along the back wall, and then the fire developed extremely rapidly. Within a few seconds the fire had involved the whole platform area and a flashover occurred. Smoke gases and flames spread across the large dance area.

The Fire Research Station in the UK reconstructed the fire, which showed, amongst other things, that when a seat ignited this generated radiation levels of around 100 kW/m^2 along its entire length against the back wall.

The combination of the combustible seats and combustible wall lining produced a heat release rate of 800 kW/m in the back part of the room. This caused the flames to spread upwards along the ceiling, which then generated high radiation levels on the seats in front. One unexpected incident during the experiments was that the heat radiation from the flames right in front of the back wall rose to $100 - 200 \text{ kW/m}^2$, which is a huge level.

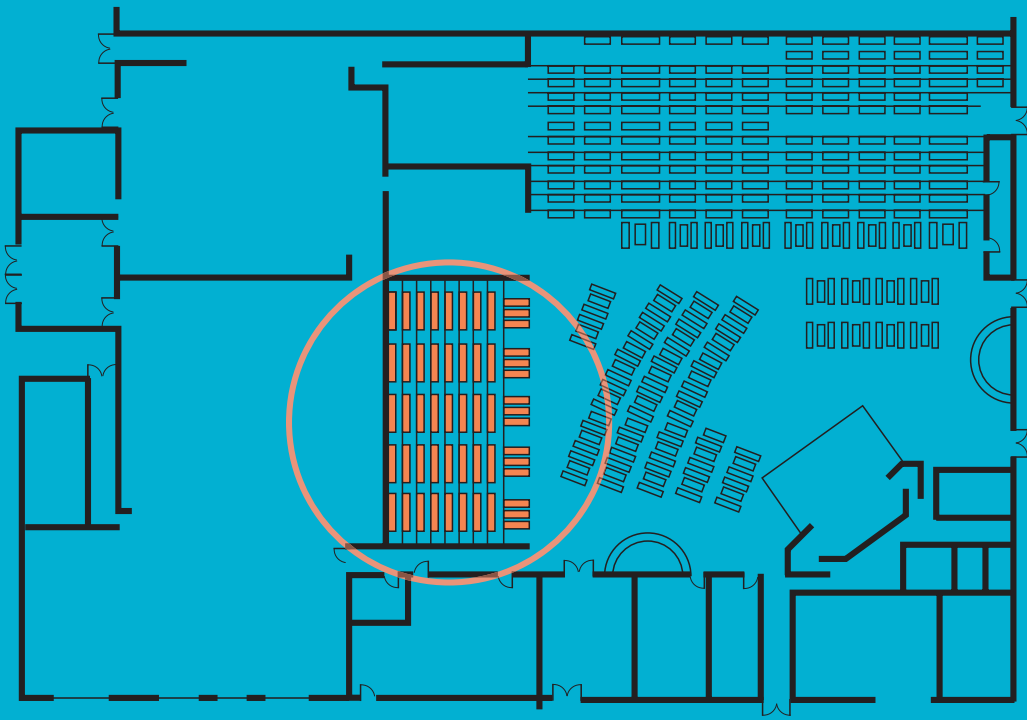


Figure 73 (above).
Discotheque ground plan.

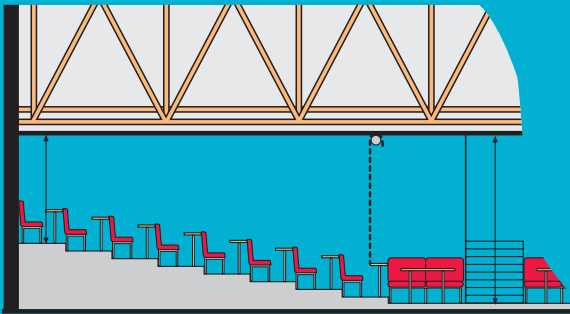


Figure 74 (left). Cross-section drawing of the platform area.

As a result, the top of the seats in front were exposed to a heat radiation of 60 kW/m^2 . This amount of radiation is sufficient to cause the seats to ignite within a few seconds. This meant that a flashover occurred in the premises very quickly.

It is worth pointing out in connection with this that the ceiling collapsed and brought part of the roof with it. This helped to reduce the impact exerted by the heat and smoke gases. 49 people died in this tragic accident, but the figure would have definitely been higher if the ceiling had not collapsed.



Fully developed compartment fire and decay period

A flashover results in a fully developed compartment fire. During a fully developed compartment fire some of the combustion will take place outside the compartment. This is actually due to the fact that the fire is ventilation controlled, which means that it produces an excess of combustible gases. As a result of this, flames will escape out through the building's openings.

A fully developed compartment fire can last for a long time, even several hours sometimes, mainly depending on the amount of fuel there is in the compartment. Temperatures of 800–900°C are common. As long as there is fuel available in the compartment and access to oxygen for combustion, the temperature will remain at that level.

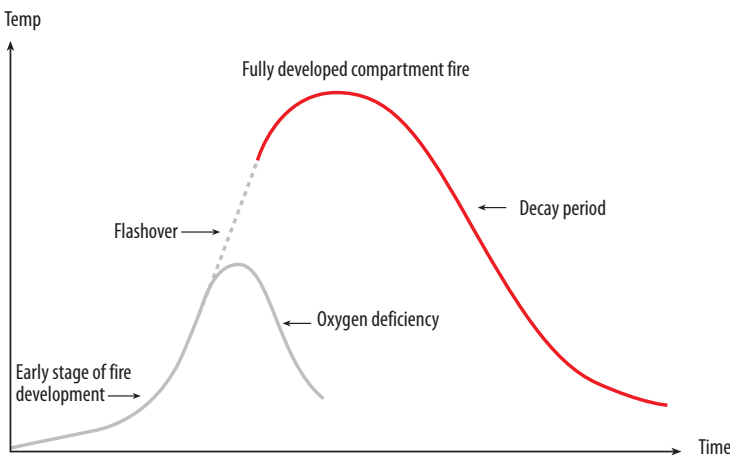


Figure 75. Smoke gas temperature during the fire's various stages.



There have been very high demands imposed for a long time requiring buildings to have structural elements with sufficient load bearing capacity to withstand fire. According to the available statistics, human fatalities and injuries in a fire are very rarely due to the building's structure collapsing. There are very good reasons for imposing these high demands, especially in the case of buildings which cannot be totally evacuated during a fire. It is also important for firefighters to be able to rely on the structure's bearing capability. The bearing structure is built differently, according to the type of building. It is usual to classify buildings in terms of ability to withstand a fire for up to several hours.

Other factors affecting a fully developed fire in a compartment include:

- the amount and type of combustible material
- the density, shape and arrangement of the material
- the amount of air available
- the size and geometry of the compartment
- the properties of the structure surrounding the compartment.

The decay period can last a long time and it is very common, in this instance, for the fire to return to being fuel controlled. During this stage, smouldering fires are very common.

The structural material often loses some of its strength as a result of the heat's impact. This can lead to the building collapsing, either locally or completely.

Materials made from steel are very sensitive to heat and lose half of their strength at 500 °C. Concrete retains around 75% of its strength at 500 °C.¹ The size of wooden structures is reduced as a result of combustion and a carbon layer is formed. Wooden beams become thinner, which makes them weaker. The smaller the cross-section means the less strength they have.

Figure 76 (opposite page). A fully developed fire. Part of the combustion takes place outside the room.



Fire development in a room with limited ventilation

In this chapter we will be discussing how fires develop in rooms with limited ventilation. If there is an oxygen deficiency the fire will not progress to a flashover, but rather its intensity will decrease. The temperature falls as the level of combustion decreases. The fuel surfaces cool down slowly, which means that there are still large amounts of pyrolysis gases accumulating. We will not go beyond point B shown in the figure, which is actually a requirement for a flashover to be able to occur. This is a common scenario with fires in a closed room, where there are no openings created, for instance, through a window breaking. The fire's development follows the path of the dotted line in Figure 77.

We now have a situation where there may be a large amount of unburnt smoke gases in the compartment. At the same time, the oxygen concentration is low. A number of different events may occur when the fire service arrives at the scene. We will discuss four different development scenarios for the fire, some of which are more common than others. These four scenarios are: 1. The fire has spontaneously gone out, 2. The fire resumes its development, 3. The smoke gases auto-ignite, 4. A backdraught occurs.

Before any of these scenarios can occur, pulsations may occur in the fire's development. Consequently, we will first describe the pulsations and then discuss the four development scenarios.

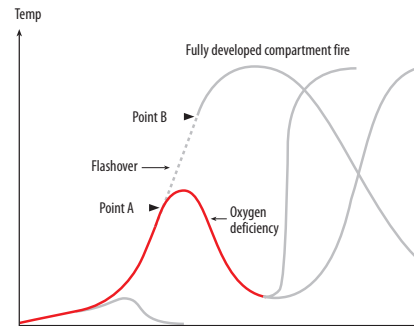


Figure 77. The development of the fire when the amount of oxygen restricts the heat release rate.

- Four fire development scenarios:**
1. The fire has spontaneously gone out
 2. The fire resumes its development
 3. The smoke gases auto-ignite
 4. A backdraught occurs.

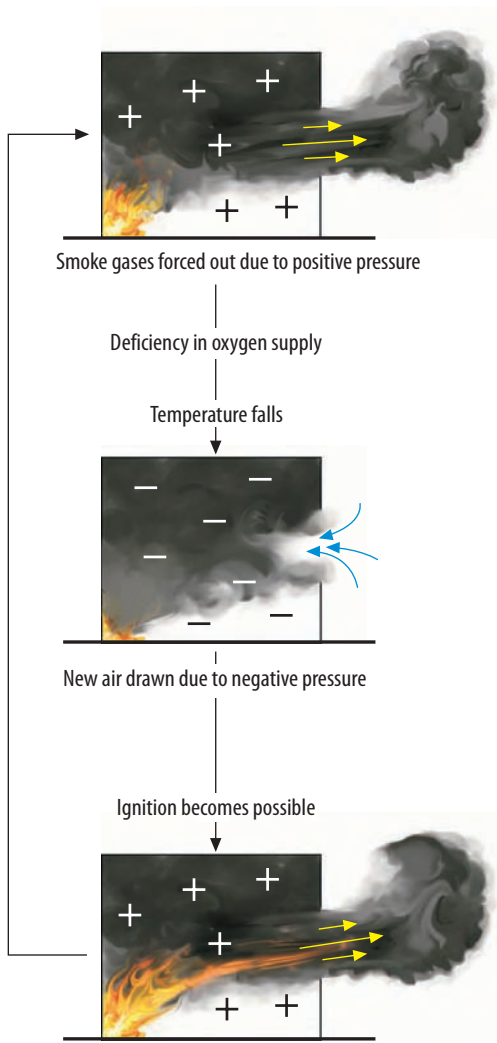


Figure 78.
Fire pulsating.

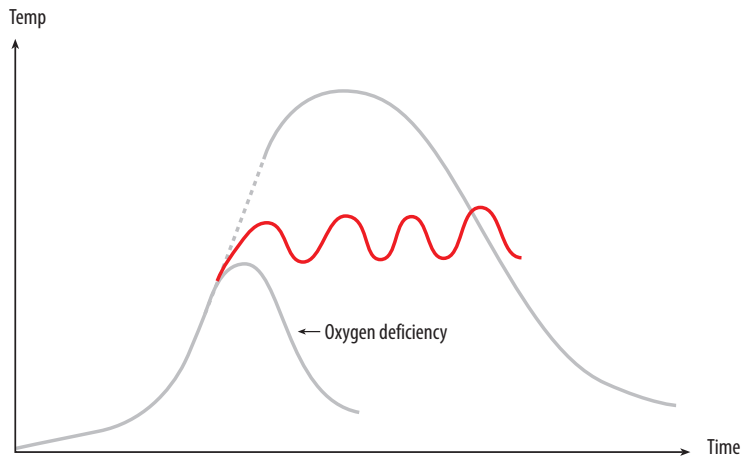


Figure 79. Pulsations
drawn on fire
development curve.

6.1 Pulsations

In a ventilation-controlled fire the heat release rate is limited by the amount of oxygen flowing into the compartment. This can sometimes cause the fire to “draw breath”. Pulsations start as a result of the heat release rate falling due to the limited amount of oxygen. When the temperature drops the volume of gas in the fire room will also drop, thereby creating a certain amount of negative pressure. Air can be drawn into the fire room again and when the oxygen reacts with the combustible gases, combustion occurs.

When the smoke gases ignite the volume increases, which generates positive pressure. Smoke gases are then forced out through the available openings. This causes a lack of oxygen again, which limits the release rate, thereby triggering the next pulsation. Fire pulsations are shown in Figure 79.

It is difficult to determine in which situations a fire may start to pulsate. One of the factors causing pulsations is the size of the openings in relation to the heat released.

6.2 Fire has spontaneously gone out

If the fire continues burning in an oxygen-deficient environment it is very likely that gradually, it will spontaneously go out or start smouldering. This probably happens before the temperature in the fire room has risen sufficiently to trigger significant pyrolysis of other fuel surfaces in the room. If the fuel surface is also limited the chances of the gaseous mass being able to ignite will be low.

When the temperature drops the pressure will also fall in the fire room, which means that so many smoke gases will not be forced out. As a result, it can take a long time for the fire to be detected.

This situation is very common in apartment fires. Often the apartments are affected by quite extensive smoke damage, but there are very often no problems at all in extinguishing the fire.

In this situation too, the conditions in the fire room will be very dangerous for people. The smoke gases contain a number of hazardous substances, such as carbon monoxide, which can mean that someone who is asleep will not wake up when the

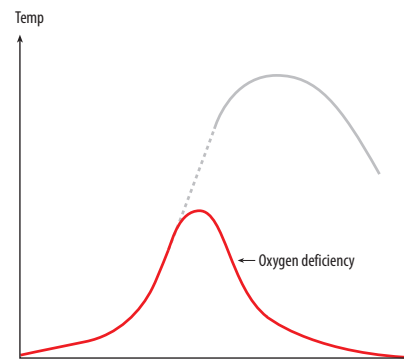


Figure 80. The fire has spontaneously gone out due to oxygen deficiency.



Figure 81 (above).
The fire is about to spontaneously go out in a closed room. The smoke gases sink down above the seat of the fire. The only clear visibility is at floor level.

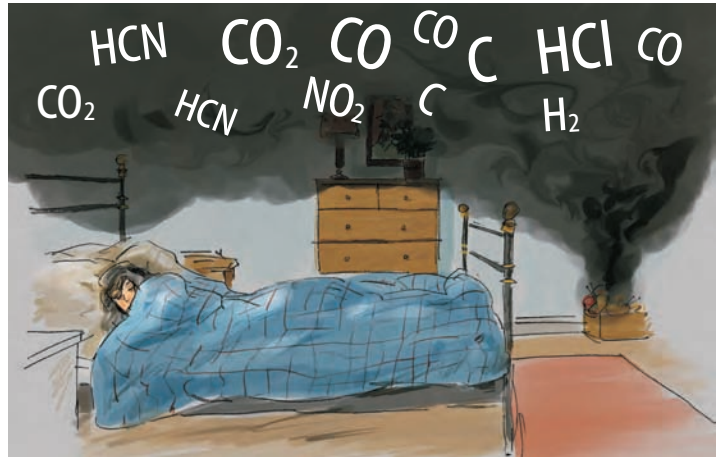


Figure 82 (right).
The smoke gases contain a number of toxic products.

fire is burning. In this situation fire detectors are vital. They can really save lives.

Figure 83 shows the result of a compartment fire. The fire starts in a closed room. As you can see, the fire becomes ventilation controlled after about 300 seconds, when the temperature and heat release rate start to drop.

The temperature falls quickly and pyrolysis of the material stops fairly rapidly. In this instance, there are not enough combustible gases available for the smoke gases to be able to ignite. But people without any breathing apparatus can still die in the room due to the toxic smoke gases. When the door

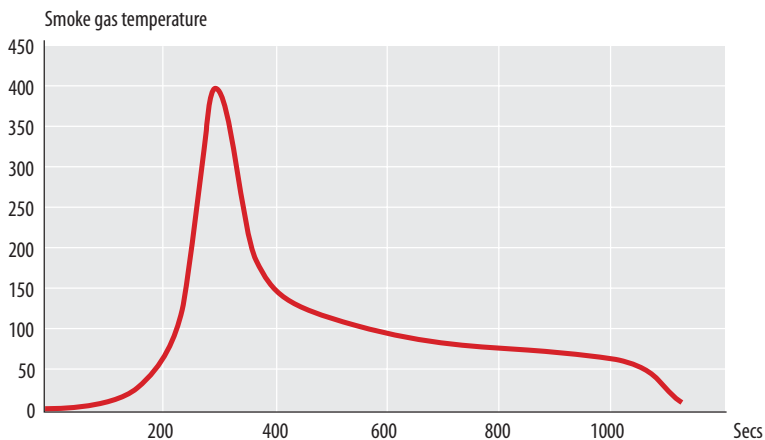


Figure 83. Temperature in a closed room.

to the room is opened the smoke gases can escape, but the gases are fairly cold and do not ignite, which makes the fire easy to extinguish.

6.3 Fire resumes its development

We now have a situation where the fire has managed to spread to a number of other objects before the oxygen becomes deficient. The heat impact in the fire room has been considerable. Smoke gases have filled up the fire room, containing a large amount of unburnt gases. This means that the fire has the opportunity to grow into a fully developed fire if it is supplied with air again.

Now let us assume that the BA firefighters open the door to the house or a window breaks with the heat. As a result of this, the smoke gases will escape out of the top part of the opening, while air will flow in through the bottom part of the opening and the neutral plane will rise. The stream of air will stoke up the flames in the initial fire again and the fire will grow. The flames then reach the smoke gas layer and a flame front spreads throughout the room.

This scenario is a continuation of the fire’s interrupted development. Its growth is much the same as when a fire develops and progresses to flashover in a room which has already had an opening right from when the fire started. Figure 85 (on the following page) illustrates this process.

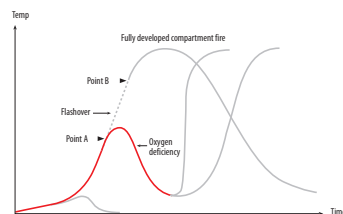


Figure 84. The fire resumes its development resumes and becomes a fully developed fire.



Figure 85. The fire resumes its development. The door is opened and the smoke gases escape. After a while you can see flames up under the ceiling and soon flames can be seen throughout the whole room.

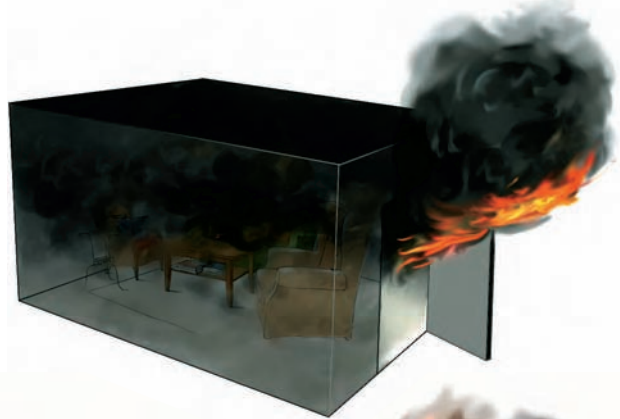


Figure 86. The smoke gases auto-ignite when they come into contact with air.



The fire often develops quietly as the flames which occur are diffusion flames. The fire resumes its interrupted development and progresses to flashover if there are sufficient oxygen and fuel available.

6.4 Smoke gases auto-ignite

In rare cases, the smoke gases may auto-ignite, for instance, if a door is opened. The smoke gases need to be at a high temperature for this to happen. Temperatures usually have to be between 500 and 600 °C.

The oxygen-deficient room contains smoke gases which have a temperature in excess of the thermal ignition point, usually above 500–600 °C.

When the smoke gases have been allowed to escape through an opening, which may have occurred when the BA firefighters entered the room, the smoke gases will mix with the air (oxygen). As the temperature of the gases is above the thermal ignition point, the air/fuel mix will auto-ignite and burn outside the room.

When the air flows into the room and mixes with the escaping smoke gases, it will then be possible to see how the fire gradually grows in the room. In this case, the flames involved are diffusion flames. This scenario is actually a continuation of the early fire development stage, which was interrupted due to the deficiency of oxygen. The fire can now progress to a fully developed compartment fire, provided that the opening

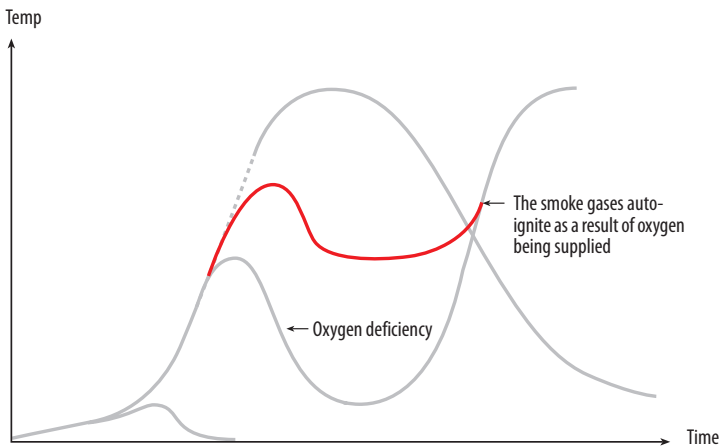


Figure 87. The temperature of the smoke gases is higher than normal in this case.

is sufficiently big. A fire's progress can accelerate to become a fully developed compartment fire (see Figure 87).

This situation most often arises when there is a smaller opening in the room. The fire is supplied with oxygen through the opening, which is positioned so that the escape of smoke gases is limited. There is an example of this in an apartment fire when smoke gases escape through a cracked pane at the back of the building. When the door to the stairwell is then opened the gases may be hot and auto-ignite.

If you then close the door of the room tight after seeing the smoke gases auto-ignite outside the door, the flames will disappear as the oxygen is burnt up.

You can sometimes see smoke gases auto-ignite when an attempt is made to ventilate an attic fire. The smoke gases then ignite immediately on contact with the air. This is obviously assuming that the fire is ventilation controlled.

It can be difficult to assess whether the smoke gases auto-ignite in the opening or whether the flames originate from inside the room.

6.5 Backdraught

This section provides a definition of what a backdraught is. A description is also provided of the scenario which typically occurs if air flows in when an opening is made. This section also describes the conditions which cause a backdraught to occur and the signs indicating an imminent backdraught.

In some cases, smoke gases can ignite very quickly. This is usually known as a backdraught. The ignition process can be so powerful that you do not even have time to react. A backdraught is a highly dangerous phenomenon, which can catch firefighters unawares. This is why it is very important to be able to identify situations which can result in a backdraught.

A backdraught can occur in the following circumstances. A fire has been ventilation controlled. A large amount of unburnt gases have accumulated in the fire room. When the door is opened air flows in. The current of air forms a premixed gas mixture—premixed area. The location of the ignition source has a crucial role to play. It is the location which determines

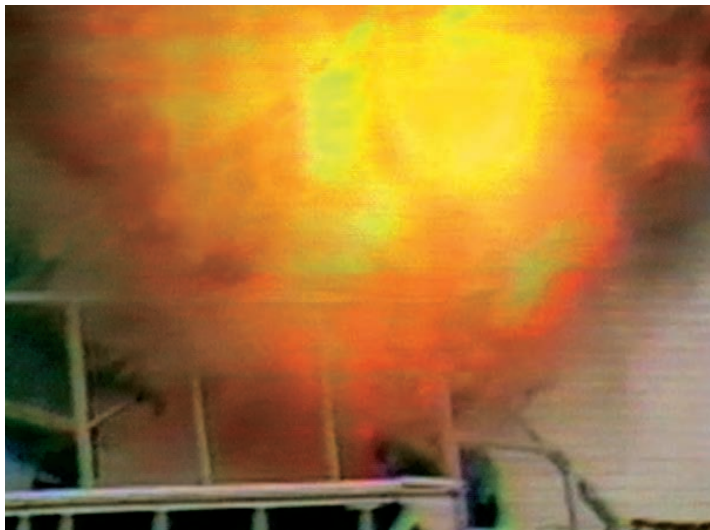
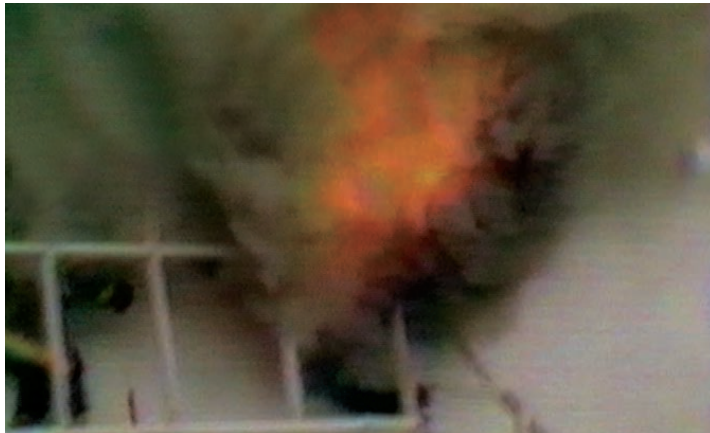
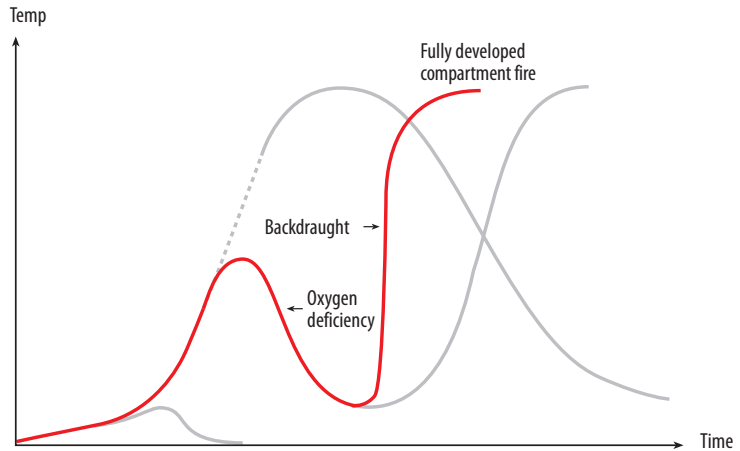


Figure 88. The firefighter has deliberately broken the pane to vent out the smoke gases. When the air flows in the smoke gases ignite and a fire ball shoots out of the opening.

Figure 89. A backdraught entails a rapid increase in temperature and pressure.



the amount of smoke gases which will be premixed before ignition occurs.

Diffusion and premixed flames occur. In the premixed area, which is created between the fuel-rich smoke gas layer and the incoming air, a premixed flame can spread very quickly. The hot pyrolysis products push downwards behind the flame and mix with the air-rich layer. This creates diffusion flames. As you can see, combustion and expansion occur quickly in the fire room, which means that the smoke gases which do not ignite in the fire room shoot out and ignite outside. As a backdraught involves a rapid, powerful expansion of smoke gases, this results in a fire ball outside the opening. A backdraught can lead to the stage of a fully developed compartment fire, but sometimes it results in the room being emptied of smoke gases, leaving just small fire cores or smouldering fires.

The air supply is the key factor resulting in a backdraught.

6.5.1 Definition of backdraught

Backdraught, as a phenomenon, has still not yet been defined by international standard organisations. But the definitions of this phenomenon which are used internationally (e.g. by the NFPA, FRS and IFE) are all similar. The term “backdraught” is used in many countries, including the US, the UK, Japan and New Zealand.

The Fire Research Station (FRS) has suggested the following definition:

*Limited ventilation can lead to a fire producing smoke gases containing significant proportions of unburnt gases. If these accumulate then the admission of air when an opening is made to the compartment can lead to a sudden deflagration, moving through the apartment and out of the opening. This deflagration is known as a “backdraught”.*²⁰

The National Fire Protection Association (NFPA) has the following definition:

*Backdraft is the burning of heated gaseous products of combustion when oxygen is introduced into an environment that has a depleted supply of oxygen due to fire. This burning often occurs with explosive force.*²⁰

The Institute of Fire Engineers (IFE) proposes the following:

*An explosion of greater or lesser degree, caused by the inrush of fresh air from any source or cause, into a burning building, in which combustion has been taking place in a shortage of air.*²⁰

The definitions are similar and it is not really very important which one is used. In some definitions the word “explosive” is used, which indicates an explosion could take place. But this does not necessarily need to be the case; a backdraught often occurs in a fairly quiet way.

We use our own definition in Sweden, based on the others. This states:

A backdraught is the combustion of unburnt smoke gases, which can occur when air is introduced into a room where the oxygen content is significantly reduced due to the fire. Combustion can then occur more or less rapidly.

A backdraught presupposes that a certain part of the content is premixed, otherwise the incident is not classified as a backdraught.³¹

A backdraught includes the following features:

- Unburnt gases accumulate
- An air-rich current
- There is a well-mixed area of unburnt gases and air
- An ignition source ignites the gases in the well-mixed area
- A turbulent deflagration occurs in the room
- A fire ball is ejected out of the room.

A backdraught can occur when the fire is ventilation controlled at a very early stage, for instance, if the room is closed from the outset or if there are only limited openings (see Figure 89).

When the oxygen level drops the temperature in the room falls too. If the door to the room is then opened the smoke gases can ignite and cause a backdraught (see Figure 89). When a backdraught has occurred the whole room can be involved in flames, thereby resulting in a fully developed compartment fire. A backdraught can cause significant damage in the area outside, as there can be a very high pressure build-up there.

6.5.2 A typical backdraught scenario

A fire breaks out in a room. Combustion takes place either as flaming combustion or a smouldering fire. The room has a limited vent opening, e.g. normal leakage paths. The fire grows until the level of oxygen in the room becomes restricted. During the same period, a hot smoke gas layer will have formed beneath the ceiling and it sinks downwards. As the smoke gas layer grows, the air, which is being drawn into the top part of the fire's plume, will contain ever-increasing quantities of unburnt gases and an ever-decreasing proportion of oxygen.

This process results in incomplete combustion. As the heat release rate falls due to oxygen deficiency, the unburnt gases accumulate in the hot smoke gas layer. Then, the fire will either continue to smoulder or spontaneously go out, depending on the amount of fuel available and the size of the ventilation opening.

As time goes on, the concentration of unburnt gases will increase. This produces a fuel-rich atmosphere in the room. The type of fuel plays a crucial role in determining the amount of gases which will have accumulated. Some materials emit pyrolysis products more easily than others.

A door or window is then opened in the room. This can happen, for instance, when firefighters enter an apartment or a window cracks. The hot smoke gases escape through the opening and air will be sucked in through the bottom part of the opening (see Figure 91).

This inflow of cold air is known as a *gravity current*.³² When

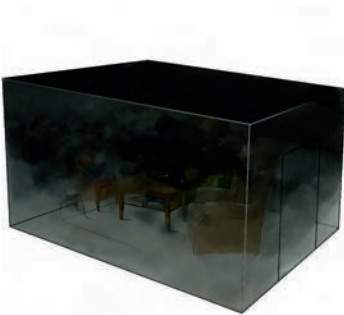


Figure 90. The picture shows a ventilation-controlled fire, which has returned to being a smouldering fire. Unburnt smoke gases accumulate.

the air enters the room it mixes with the fuel-rich gases and a premixed gaseous mass accumulates in a particular area. The turbulent motion takes place on the top side of the air current or through the turbulence generated when there is an object, such as furniture, in the current's path.

Figure 93 below shows the turbulent mixing process which takes place along with the air current. This mixing process produces a mixture which may fall within the flammability range when the pyrolysis products are diluted.

If the smoke gases are actually inside the flammability range and there is an ignition source present, e.g. a flame, glowing particles or an electric spark, the mixture will ignite.

Figure 92 shows how the flames spread along the mixed area.

It is the flames which cause the smoke gases to rapidly expand, pushing the rest of the fuel, at very high speed, out through the opening, where the unburnt gases mix with fresh air. When the flames spread in the premixed layer this results in ignition and in an immediate increase in pressure. This causes a fireball, which is a very typical feature of a backdraught. The more unburnt gases there are, the larger the fire ball formed.

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.³³

In a backdraught some of the flames are premixed flames, which means that the course of events will be rapid.

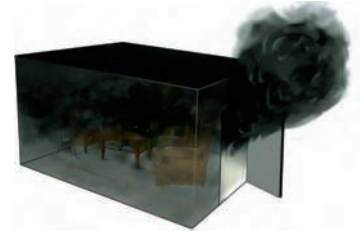


Figure 91. Air flows in and smoke gases escape.

A backdraught occurs in situations where the fire is ventilation controlled at a very early stage.



Figure 92. Premixed area ignites, which corresponds to the dark area.

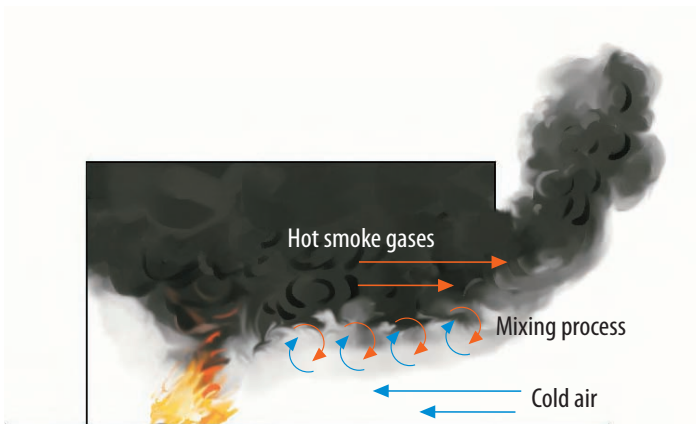


Figure 93. An ideal representation of gravity current in a room.

The current which results in smoke gases mixing with air is completely crucial to the course of events. For this reason, we will now take a look at what controls the current in the room.

6.5.3 Gravity current

As was mentioned earlier, cold air will flow into the room when it is opened. The hot smoke gases then escape and, as the current is controlled by gravity, this produces a mixture which falls within the flammability range.

The rate at which the air flows in depends on a number of factors, including the following:

- Size of the room (how long does it take for the air to flow into the room?)
- Room's type of openings (different types of opening produce different mixing processes)
- Density difference (controls the air current's speed)
- Height of ceiling (produces different levels of gravity in a low and high-ceiling room)
- Turbulence (may be caused, for instance, by a firefighter standing in the open doorway).

Figure 94 is only for qualitative purposes, taken for a computer simulation.³⁴ The first sequence is taken when the air current is on its way into the room and the other picture is taken when the air current has reached the back wall. Blue represents air and red the smoke gases. Green and yellow are mixed in any proportion and could represent a combustible area.

The mixing process will take place as a result of the turbulence generated when the air current flows into the room. *Obviously, the area between the fuel-rich layer and the air current is where the mixture is best.*

If the air current reaches the back wall the mixed region will be much bigger. In a nutshell, we can say that any kind of delay may be very dangerous.

If the current is able to reflect against the back wall the premixed area will increase considerably. This factor must be taken into account when entering an apartment. Any delay may be very dangerous.

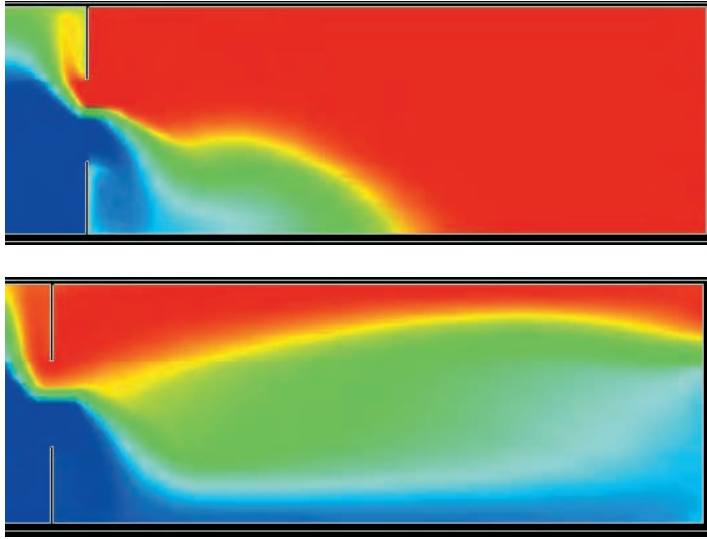


Figure 94. In this instance, the opening is a window. The pictures show that a much larger part of the flames are premixed when the air current has reached the back wall and is on its way back out again.³⁴

To get some idea of how long it takes for an air current to flow into a room, it is useful to be familiar with some standard values. Air current speeds in the order of $\approx 1\text{--}2$ m/s can be regarded as one of these standard values. The speed can be calculated using a single equation, which is described on page 182.

The higher the temperature the smoke gases have, the quicker the air current flows into the room.

A firefighter opens the door, crawls into the apartment and then closes the door behind him. In most cases, the air current he has allowed in is enough to create a flammable mixture inside the room. *It is very important to know what happens when you open a door to a burning room.*

The higher the smoke gases' temperature, the quicker the air current moves in the room.

Smoke gas temperature (°C)	v (m/s)
150	1.1
300	1.6
500	2.2

Table 7. The air current's speed at different temperatures (approximate values). These values are influenced by a number of factors, including the room's height and the type of opening.

The current is generated in the room when the air flow passes the edges of the opening. This produces turbulence. Similarly, turbulence is generated when there is a lot of furniture in a room or when you are actually crawling around inside a room or if you are using a fan, for instance. This is not to say that

fans should not be used. You should just take special care and be aware of the risks when using a fan.

We will now continue with a discussion about the ignition of the gaseous mass. To do this, it is important to be familiar with how smoke gases mix.

6.5.4 Ignition of premixed area

The following description assumes that a room is opened after a little while. When the room is opened air enters and mixes with the fuel-rich smoke gases in the room. There needs to be an ignition source in the premixed area for ignition to be able to occur. Ignition can occur at various times during the process. There will be mixed areas in different places and at different times.

1. When the air current is on its way into the room.
2. When the air current is going to leave the room.
3. With a very long delay after the air current has left the room.

The premixed areas in these different scenarios will be of different sizes, which means that when ignition occurs the backdraught will have different levels of power. The ignition source in the figures below is located right inside the room along the back wall. In reality, the ignition source can obviously be located anywhere in the room.

1. When the air current is on its way into the room

If ignition occurs when the air current is on its way into the room a premixed flame will occur in the boundary layer, see Figure 95. You should note that the pictures only give a rough representation of what happens. As was the case earlier, the yellow and green represent some type of premixed area.

When the premixed gases ignite this produces a turbulent combustion area behind the premixed flames (see Figure 96). This region is created as the hot products rise and force down the unburnt smoke gases. The gases come into contact with the air-rich layer and combust. Expansion pushes the rest of the smoke gases out through the opening. This is what produces the typical fire ball.³²

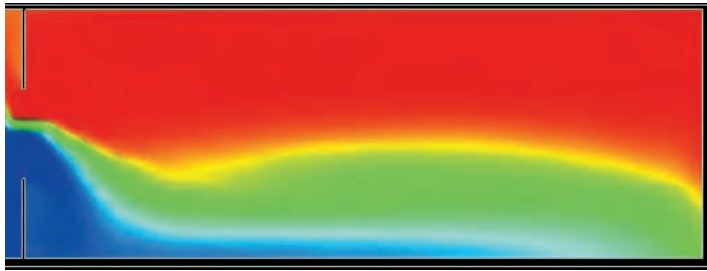


Figure 95. The air current has just reached the back wall. The premixed area is large.



Figure 96. This shows the different types of flames developing. In the under side a premixed flame can be seen and a diffusion flame against the back wall.

The larger the premixed proportion in the volume of gases when ignition occurs, the faster the process will be. Premixed flames and diffusion flames have major differences in terms of rates of combustion. In this example, the ignition source is located in the premixed area, which is a prerequisite for ignition.

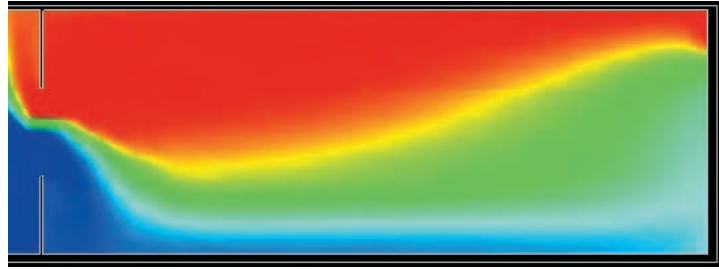
In many real-life cases, the ignition source is very low down in the fire room, e.g. with smouldering fires. The ignition source is often the initial fire, which flares up.

2. When the air current is going to leave the room

If ignition does not occur until the air current has reflected off the back wall the premixed area will be very large (see Figure 97).

If the gas mixture ignites the flames will spread in a more spherical formation and there will be a larger increase in pressure due to a larger proportion of the gaseous mass being

Figure 97. A larger part is premixed when the air current reaches the back wall, almost half the volume of the room.



premixed. The smaller the opening in the room, the larger the increase in pressure in the room. Figure 98 shows how the flames spread.³²

This expansion will result in a large fire ball outside the room. The size of the fire ball depends on the amount of unburnt gases which have accumulated in the room.

3. With a very long delay after the air current has left the room

When the incoming air current has mixed with the fuel-rich gases, bounced off the back wall and then left the room, the lower part of the room will be filled almost solely with pure air. This means that there may still be combustible gases above the doorframe in the room (see Figure 101).

When ignition occurs the flames will spread up to the height of the doorframe. When the volume of combustible gases is smaller the heat release rate will not be as large. But it is important to note that in larger, and especially high premises, there may be larger quantities of combustible gases. There are major risks associated with this.

The delay may only last a few minutes. Figure 102 shows how the flames spread up to the height of the doorframe and how the remaining gases are ejected from the room and burn as a small fire ball. In this experiment, therefore, the ignition source has been placed high up in the room.

If there is a large distance between the door's upper edge and the ceiling a large quantity of gases can mix there and with serious consequences, even if the environment lower down in the room is fine. This has happened a few times in Sweden.

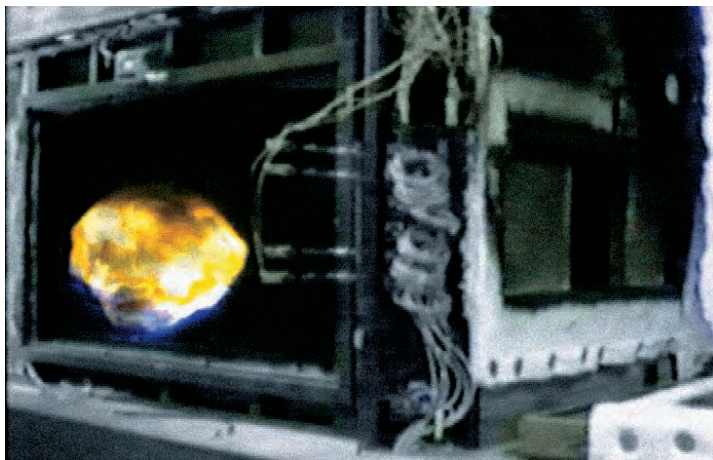


Figure 98. This shows the flames spreading out in a more spherical formation when ignition occurs with the air current being reflected.



Figures 99 and 100. The fire ball formed due to the expansion of the smoke gases.

Figure 101. There are still combustible gases right at the top of the room.

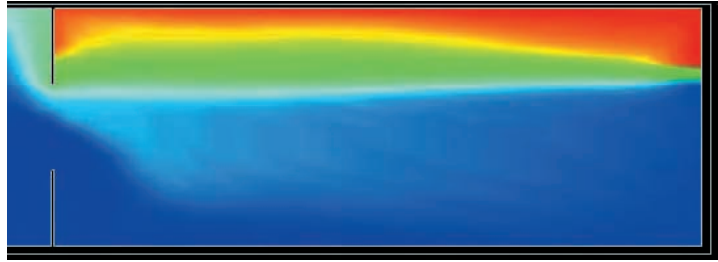


Figure 102. The flames spread up to the height of the door opening. Further down in the room there are no combustible gases.



If we compare the three scenarios we can see that the highest increase in pressure occurred, at the time of ignition, when the air current is going to leave the room. This is because the size of the premixed area is biggest in this instance. The smaller the opening, the larger the pressure.

You should note that the position of the ignition source obviously controls the resulting development path. In the figures above, the ignition source has been placed right at the back of the room, a bit away from the floor. If the ignition source was located anywhere else the fire would obviously not develop in the same way. It is important to be aware of this when discussing different backdraught scenarios. The ignition source must be in the combustible area, exactly at the right time. The likelihood of this happening is fairly small.

This is one of the reasons why we do not come across backdraughts very often.

6.5.5 Conditions resulting in a backdraught

It is difficult to specify exactly the conditions which create a backdraught. We can, however, indicate some of the factors which are a prerequisite to a backdraught occurring.

The fact that backdraughts do not occur very often is because we are good at cooling down the smoke gases with water and there is seldom a large enough amount of combustible gases and an ignition source present at the same time. Generally speaking, it is difficult to achieve the large quantities of fuel which are required.

The following factors have an influence on whether a backdraught will occur:

- *Presence of an ignition source.* There needs to be an ignition source within the combustible area. Usually the most combustible area is the boundary layer between the fuel-rich smoke gas layer and the incoming air. In many cases ignition sources can be very low down in the room. This is perhaps the main reason why backdraughts are not a very common occurrence.
- *Fuel's arrangement (and type of fuel).* The higher up in the room the fuel is located, the more combustible pyrolysis products will accumulate there.^{35,36} The obvious requirement, of course, is that there is sufficient fuel in the room so that the gas concentration required to cause a backdraught can be achieved.
- *Openings' location/size (original openings).* The lower down the opening is, the smaller the proportion of pyrolysis products which disappear through the opening. If the opening is too small it is likely that the fire will spontaneously go out. If it is too large the fire will progress immediately to flashover. The opening needs to be sufficiently large. You should note that this applies to the opening in the room at the time the fire starts, in other words, not the opening made as a result of entry during a rescue operation.

Fires in saunas can cause a backdraught.



Figure 103. Sauna. A common scenario which can cause a backdraught.

- *Insulation in the room.* The better insulated the room is, the higher the temperature rises in it. The temperature can also be maintained for a long time, even if the fire has almost spontaneously gone out. A large quantity of unburnt products accumulate, especially if the fuel is located high up in the room. The lower the fuel's pyrolysis temperature, the easier it is to reach the concentration required for a backdraught to be able to occur. The fuel concentration needs to be very high.³⁷

In the case of fires in saunas, most of these factors occur. The fuel is certainly located high up in the room. The room is well insulated, which means that the temperature is maintained for a long time. An opening at the lower edge of the door can often allow a small amount of oxygen into the fire room. There is obviously a sufficient content of unburnt gases in sauna fires.



Figure 104. Smoke gases are escaping out of a building, but there are no flames visible. The fire officer in charge reflects on what he can do.

6.6 Risk assessment

There are obviously risks involved with tackling a ventilation-controlled fire. These situations can be very risky and unfortunately, it is not always easy to detect the warning signs. It is difficult to know what will happen before we enter the room. But the more warning signs there are indicating a backdraught, the higher the chance that this has occurred. If the signs are not very clear some of the other scenarios may occur.

At this point, we need to refer back to the section on flashovers, where we discussed the colour of smoke gases in detail. The smoke gases' colour can sometimes be used as an indicator of an imminent backdraught. But the smoke gases' colour cannot be used as the only indicator. If this is combined with a number of other indicators, we can get a clear idea as to whether there is any danger of a backdraught occurring. The crucial factor with regard to backdraughts is air.

A number of signs indicating an imminent backdraught are described below.

6.6.1 Warning signs

It is important to carry out thorough risk assessments, both before and during an ongoing operation. The indicators below, taken together, should be regarded as warning signs for

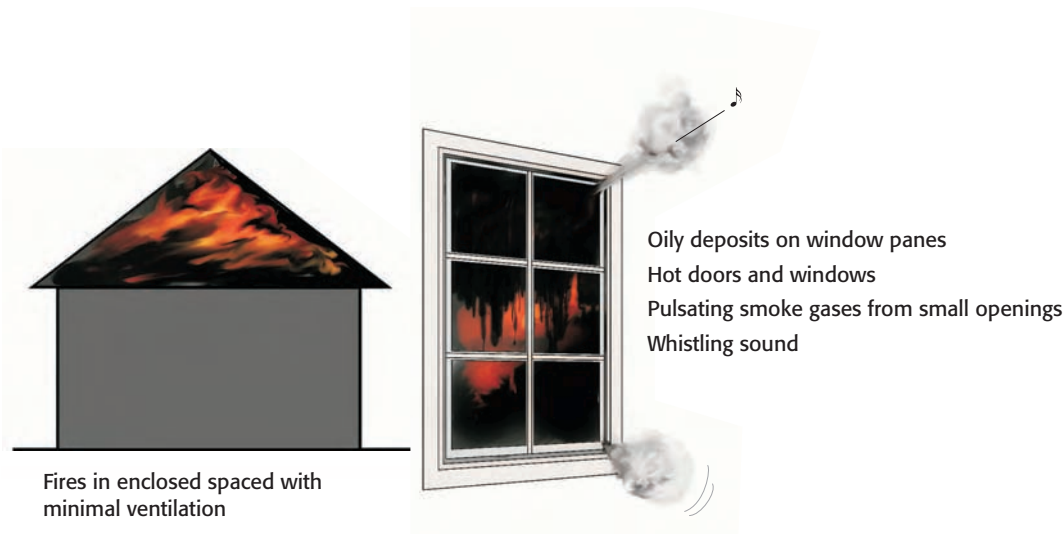


Figure 105. Backdraught warning signs.

The smoke gases' colour is not a definite warning signal.

an imminent backdraught. It is simply not enough at all to consider the smoke gases' colour as the only warning signal. Before a firefighter opens the door to the fire room, the following points need to be taken into consideration:

- Fires in enclosed spaces with minimal ventilation, for instance, closed rooms or spaces under the roof.
- Oily deposits on window panes, which is a sign that pyrolysis products have condensed on cold surfaces. A sign of an under-ventilated fire.
- Hot doors and windows, indicating that the fire has been burning a while, perhaps with limited ventilation.
- Pulsating smoke gases from small openings in the room, which are a sign of under-ventilated conditions. When the air enters the room combustion takes place, which means that the oxygen runs out as the temperature rises. Then the temperature falls slowly and when the pressure has dropped slightly the air can be sucked into the room.
- A whistling sound in openings, which may be related to the fire pulsating.

In those cases where the decision is made to enter, the firefighter must be on the lookout for the following signs, particularly at the moment when he has opened the door to the fire room and looks into the room. These signs, along with the others, can provide warning signs for an imminent backdraught.



- an orange glow or a fire which is not visible can indicate that the fire has been burning a long time with a lack of oxygen.
- smoke gases drawn back through the opening, indicating that an air current has entered the room. Hot smoke gases will leave the room, perhaps through another opening and replacement air will be drawn in through the opening. It may seem as if the smoke gases are being drawn towards the fire.
- The neutral plane is close to the floor.
- A whistling sound may occur due to air being drawn in through small openings at high speed. Unfortunately, a backdraught may have already occurred and those people standing at the opening may be seriously injured, even fatally.

Figure 106. The fire officer in charge must assess the risks in relation to what can be achieved by the operation.

6.6.2 Course of action

It is very important for us to assess the risks thoroughly. Each person involved is responsible for their own safety and should think carefully about some of the following questions:

Figure 107. The smoke gases are streaming out from an attic fire.



1. How airtight is the structure? Are there any leaks at floor level? Is the room well insulated?
2. What stage is the fire at? Fuel controlled or ventilation controlled? How long has the fire been burning for?
3. Where is the fire having the biggest impact? Where could there be ignition sources? Where should we ventilate?
4. How big is the fire load? The quantity of combustible material available and its arrangement can determine the quantity of combustible gases. What type of material are we dealing with?
5. Where is the air inflow coming from during an operation? Has much turbulence been generated? Turbulence can affect the fire's development.

It is obviously important to think about and take stock of the risks associated with the approach you choose.³⁸ As it actually says in § 11 of AFS 1995:1 (Swedish Working Environment Authority's regulations), *The fire officer in charge must ensure that the risks which firefighters are exposed to are reasonable, taking into account what the operation can achieve.*

If it is felt that the risks are too great in relation to the operation's objective, we may be forced to adopt defensive tactics.

If there is a risk of a backdraught occurring it is best to ventilate the room directly out to the open air, if possible.

Ventilation must be done as high up as possible to force out any unburnt smoke gases. As there is a build-up of positive pressure, it is important that there is a “clear path” out for any backdraught which occurs. Otherwise, there can be a very large increase in pressure. A backdraught is a very short event. This means that firefighters wearing the appropriate protective clothing have a good chance of coping, even if they are caught unawares by an ignition.

You can also try to cool down the smoke gases. The best way to do this is without opening the room, for instance, by using piercing nozzle or a cutting extinguisher.

The piercing nozzle option comes in two versions: *piercing nozzle attack* and *piercing nozzle containment*. You proceed with this option as follows. First of all, you make a hole in the structure. You then insert the piercing nozzle. Given that, with this extinguishing method, you are not opening any doors and windows or piercing a large hole, this prevents any additional excess air reaching the fire, which could make the fire more intense. The piercing nozzle is dispensed at around 70 l/min. at a pressure of 8 bar. Piercing nozzle is a good method to use in the case of attic fires, for instance, when the fire still has not yet broken through the ceiling (see Figure 108).

The *cutting extinguisher* is a device which is under development in Sweden. Cutting extinguishers have the unique ability to penetrate walls and outer layers, along with efficiently extinguishing fires. These are features which are considerably valuable during a firefighting operation. The water droplets coming through the jet reduce the temperature more effectively than a standard mist nozzle.³⁹

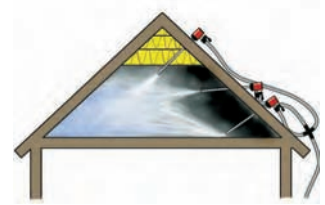


Figure 108.
Piercing nozzle.



Figure 109. Hand-held lance version of cutting extinguisher.



Figure 110. The fixed lance version of the cutting fire extinguisher.

There are two types of cutting extinguisher available. The first type which has been produced is fixed to the outside of the hydraulic platform cage. With this version, a pressure of 200 bar is applied with a flow of about 40–50 litre/min. The second version is a hand-held lance and operates at a pressure of 300 bar and flow of around 30 litre/min.

In some cases a rapid internal operation may need to be carried out from inside, e.g. in a life-saving situation. Sometimes you need to open a room. In these scenarios there are two alternative approaches:

1. Open the door quickly. Cool down. Close the door quickly. Repeat this procedure until the temperature and pressure in the room have dropped. You should note that if the door is opened just for a couple of seconds this is enough for too much air to get in, which could cause a backdraught.
2. The BA firefighters crawl in and close the door behind themselves as quickly as possible and cool down the smoke gases. This method can entail major risks for the firefighters. It is important not to get caught in the open doorway. Apart from the risks being greater, it also helps to generate more turbulence.



Figure 111. Positive pressure fan.

In some cases a positive pressure fan can be used for ventilation-controlled fires. But there is still a great risk of the heat of the fire increasing as air can enter the room.

Fans should be used with great caution in a backdraught situation. Fans generate powerful turbulence, which can cause the smoke gases to mix, making them ignitable. The smoke gases must be cooled down before ventilation. Otherwise, there is a great risk that they will ignite. Using a fan can also cause smoke gases to be quickly removed from a room. You need to assess whether fans should be used on a case-by-case basis. There is no definite answer on which choice to make.

Fans should be used with great caution in the case of ventilation-controlled fires.

6.7 Summary

We have seen that there are at least four different scenarios which can occur, where we face a ventilation-controlled situation and air is being supplied to the fire room: 1. The fire spontaneously goes out, 2. The fire resumes its development, 3. The smoke gases auto-ignite, 4. A backdraught occurs.

Scenarios 1 and 2 are the most common, but scenario 4 is by far the most dangerous. This is why it has been described in the most detail.

A backdraught occurs when a quantity of unburnt gases have accumulated in the smoke gas layer. If a door is opened, for instance, a current of air will be sucked into the fire room. This creates a well-mixed area, which can ignite if there is any ignition source present. This then creates a flame front, which spreads out through the opening, producing a fire ball. This process can be said, therefore, to go through the following stages:

Four fire scenarios:
1. The fire has spontaneously gone out
2. The fire resumes its development
3. The smoke gases auto-ignite
4. A backdraught occurs

- Accumulation of unburnt smoke gases.
- Inflow of air current.
- Mixing of air and smoke gases.
- Ignition of premixed area.
- Turbulent deflagration.
- Creation of fire ball outside the fire room.

The premixed region is roughly just as large for a door opening as for a window opening. The mixing process occurs when the current passes by a sharp edge on its way into the room. The mixing process can also occur if BA firefighters are standing in the open doorway.

If the air current reaches the back wall the premixed area will become much larger. If ignition occurs in this situation there will be a much larger increase in pressure than if ignition occurs when the air current is on its way into the room.

A third scenario arises if the air current has left the room a long time before ignition occurs. In this case, there may still be combustible gases above the doorframe. In most cases, ignition will not cause any powerful backdraught, which is quite simply due to the fact that the combustible gaseous mass is so small. In larger premises, particularly where the distance be-

tween the ceiling and the top edge of the opening is large, the volume can be much bigger. The situation may seem to be calm and the firefighters can go far into the room without noticing that there are still any smoke gases. But when ignition occurs the consequences will be serious.

A backdraught is a short event, unlike a flashover. The key factor determining whether a backdraught occurs is the air supply. In the case of a flashover, temperature is the key factor, as it means that the radiation level is rising in the room.

Both premixed and diffusion flames are present in a backdraught. In the premixed area which is created between the fuel-rich smoke gas layer and the incoming air, a premixed flame can spread very quickly. The hot pyrolysis products are pushing downwards behind the flame and are mixing with the air-rich layer. This creates diffusion flames. There is a huge difference between the combustion rate of a premixed flame and that of a diffusion flame.

The more the smoke gases are premixed, the quicker they will escape out through the opening. This means that a backdraught will be more powerful if ignition occurs when the air current has bounced off the back wall and is moving towards the opening. The smaller the opening, the larger the increase in pressure.

The boundaries between a flashover and a backdraught may be blurred in many cases. They must be determined on a case-by-case basis. Let us take the following example. *A compartment fire has been burning for a long time. Unburnt gases have accumulated in the room. The door to the room is opened. It takes about 20–30 seconds before you can see any flame inside the room. When the flames come out through the opening they are travelling at a low speed and no fire ball is formed outside the room. Is this a backdraught or a normal transition to a fully developed fire?*

Obviously, there is a boundary between a flashover and a backdraught in any situation, but it is not always easy to identify. This is described in Chapter 8.

A backdraught is a rare occurrence. This is because very high concentrations of fuel are needed for a backdraught to be able

to occur. If a backdraught occurs this is due to some of the following factors:

- the presence of an ignition source
- the fuel's arrangement
- the location/size of the openings
- insulation in the room.

The signs indicating an imminent backdraught are mainly pulsating smoke gases from small openings and no visible sign of a fire.

In many actual cases where a backdraught has occurred, the consequences of the incidents have been serious. This can often be explained by the fact that it is difficult to detect the warning signs for a backdraught.^{40, 41}

Test your knowledge!

1. *What type of flames is involved in a backdraught?*
2. *A backdraught involves a number of stages. What are these?*
3. *According to the statistics, backdraughts occur very seldom. Why is this the case?*
4. *What are the signs indicating a backdraught?*
5. *Does a backdraught occur due to ventilation control or fuel control?*
6. *How can you protect yourself against a backdraught?*
7. *What tactics can you use?*
8. *Does a backdraught always result in a fully developed fire?*
9. *What are the conditions required for a backdraught to be able to occur?*
10. *Name some of the types of premises where you think a backdraught might occur.*
11. *Sometimes you can see a fire pulsating. Explain what is going on in this instance.*
12. *What aspects should you look at when carrying out a risk assessment before an operation?*
13. *You open the door to an apartment where a ventilation-controlled fire has been burning for a while. What are the different scenarios you might expect to occur?*
14. *Which of these scenarios do you think is the most common?*

15. *When you open the door to an apartment the gases autoignite immediately. Is this usual? Why is this the case?*
16. *Explain how a ventilation-controlled fire can result in a flashover.*
17. *What determines the size of a fire ball when a backdraught occurs?*
18. *How is it that a flame can escape at a rate of 15–20 m/s when a backdraught occurs, while flames usually move much more slowly?*
19. *Can a fire burning a single object be dangerous from the point of view of a backdraught occurring?*

Fire at 62 Watts Street

The New York fire service received a call on 24 March 1994 to say that smoke was coming out of a chimney on a three-storey house in Manhattan, New York.⁴² The building contained four apartments, with one on each floor. All the apartments could be accessed from a common stairwell, apart from the apartment at basement level, which had a separate entrance. The building, which dated from the end of the 19th century, but had been recently renovated, was considered to be very exclusive. Figure 112 shows a sketch of the building.

When the fire service arrived at the scene, with three fire engines and two ladder engines, smoke was coming from the chimney, but there were no other visible signs of any fire burning. The firefighters were instructed to open the roof hatch at the top of the stairwell and two crews of firefighters with breathing apparatus were instructed to enter the apartments on the ground and first floor respectively using the same stairwell. The crew on the ground floor opened the apartment door and noticed air being drawn in to the apartment. This was followed by a hot outgoing current of air, which caused a backdraught with flames reaching from the door right out into the stairwell. The flames then stretched from the ground floor even right up through the roof hatch in the stairwell and lasted six and a half minutes. The crew on the ground floor managed to duck and get themselves back out through the stairwell. The crew on the first floor did not have any escape route and the three firefighters perished in this backdraught.

This example illustrates that caution is required, even during operations which, on the surface, seem to be routine and familiar. There may be factors involved which mean that the operation will have devastating consequences if the usual measures are taken in wrong situations.

Where did all the fuel come from that was able to sustain the flames for so long? A sketch of the ground floor is shown in Figure 113.

The apartment owner had left home at around 6.30 AM. He had placed a bin liner on the gas hob, which was switched off. But it was probably the cooker's pilot flame which ignited the bin liner. The fire then spread

to a couple of bottles of alcohol, then to the wooden floor and some other combustible materials. The doors and windows were closed, so the only source of combustion air was in the living room through the chimney to the open fireplace. It was from this chimney that the smoke and sparks were detected, about an hour after the owner had left the apartment. At the start, the chimney acted as a channel for decreasing the pressure and after a while, smoke started billowing out.

This meant that the fire burnt for a long time in extremely under-ventilated conditions. This type of combustion produces a quantity of unburnt gases in the form of carbon monoxide and other gases. Studies show that when the door to the apartment is opened this causes the air and the hot unburnt smoke gases to mix, which can combust. It is unusual, however, for so much fuel to be accumulated, as in this case.

The National Institute of Standards and Technology (NIST) in the US carried out a computer simulation of the fire. The data input was based partly on information from firefighters and partly on the measurements taken at the scene of the fire. It was possible to recreate the situation using simulations and it clearly showed that such a large quantity of unburnt smoke gases had accumulated in the room that the flame could burn for six and a half minutes.

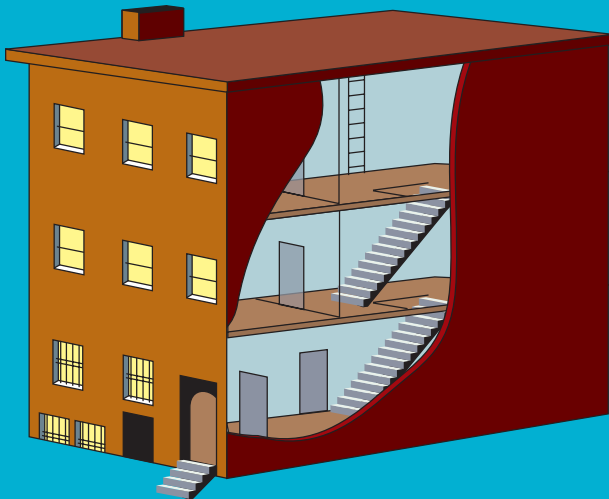
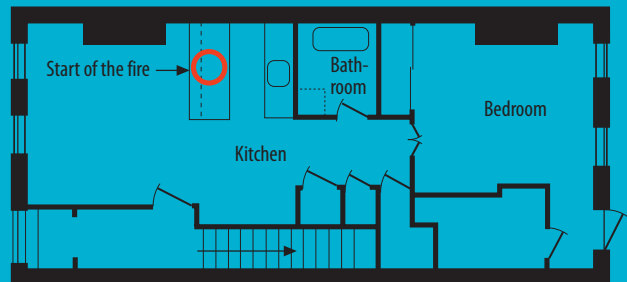


Figure 112. Building at 62 Watts Street. The fire was on the ground floor and the firefighters who died were on the first floor.

Figure 113. Plan drawing of the ground floor apartment in the building at 62 Watts Street.





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Smoke gas explosion

Throughout the book we have followed the development of an enclosure fire using a diagram where different scenarios can be identified. The diagram only shows, however, what is happening in the actual fire room and not the conditions in adjacent rooms. Smoke gas explosions most often occur in adjacent rooms. In this chapter we will discuss what situations can result in a smoke gas explosion. We will also discuss how a smoke gas explosion can be defined and the size of the pressure which can be generated.

A backdraught can cause a significant increase in pressure if the ventilation openings in the room are small. A flashover, on the other hand, does not cause any particularly major increase in pressure. The prerequisite for a backdraught is that the ventilation conditions change during the course of the fire's development. The larger the proportion of the gaseous mass that is premixed before ignition occurs, the larger the increase in pressure will be. Usually there is only a small amount of the gaseous mass premixed in a backdraught scenario.

In some situations the smoke gases may mix very well with air before they ignite. This scenario is the most common in rooms adjacent to the fire room and where there is almost no



Figure 114. The smoke gases have leaked into the adjacent room and are ignited by a shooting flame.

opening available. As, in this instance, the pressure in the room cannot be relieved if ignition does occur, the resulting deflagration is very powerful. It can destroy the entire structure of a building. This phenomenon is known as a smoke gas explosion. Smoke gas explosions can also occur in the fire room, but this is less frequent.

7.1 Definition of a smoke gas explosion

The concept of a smoke gas explosion is not defined as an ISO standard. This concept is used, however, in many countries and the definitions for it which exist are very similar. We are using the following definition in this book:

When smoke gases leak into an area adjacent to the fire room, they may mix very well with air. This mixture can expand into the whole or parts of the volume and fall within the flammability range. If the mixture ignites the pressure may increase significantly. This is known as a smoke gas explosion.

It is important to emphasise that a smoke gas explosion is a deflagration, and not a detonation. It can therefore be classed the same as an explosion. We discussed the terms “deflagration” and “detonation” earlier on in Chapter 3. A smoke gas explosion occurs without any opening in the room being modified. For a backdraught to occur, the ventilation conditions in the room need to change during the fire’s development. Obviously, the boundaries between the two concepts may be blurred in certain cases. We will return to this issue in Chapter 8.

7.2 Conditions required for a smoke gas explosion

The risk of a smoke gas explosion is greatest in rooms adjacent to the fire room. The gaseous mass can be well premixed in these rooms. The only factor missing from causing the gaseous mass to ignite is an ignition source. The resulting heat release and flame spread occur in a well premixed gaseous mass, which causes the gases to expand much more significantly than in the case of a flashover and backdraught. The

ignition source required to ignite a premixed gaseous mass can be very small (see Chapter 3).

There is an alternative scenario for a smoke gas explosion, which can possibly occur in the fire room. If there is only a small opening in the fire room, i.e. if the opening is not big enough to cause a flashover in the fire room, the fire will continue to burn with a depleted supply of oxygen. This will cause a large quantity of unburnt smoke gases to accumulate in the fire room. The fire in the room may even seem to spontaneously go out. If the temperature remains high in the room a lot of unburnt gases can accumulate in the smoke gas layer, especially if there is a lot of combustible material at the top of the room. If the room is well insulated the temperature can remain high for a long time.³⁵

This may seem harmless, but after a long time the room starts to cool down and air is sucked in. The fuel-rich atmosphere combines with the air. The oxygen content rises to around 10% of the volume, which is roughly the amount needed for the gases to be able to combust. The gases in the room have now mixed very well, but they do not ignite as there is no ignition source present. The ignition source, e.g. embers that fly up from the initial fire, can appear later and ignite a more or less premixed gaseous mass.³⁶ This will cause a powerful smoke gas explosion.

The chance of the ignition source appearing when the gaseous mass is premixed must be considered, however, as being small. It is difficult to predict smoke gas explosions, which means it is also difficult to guard against them. They occur only a few times a year in Sweden. Unfortunately, they are so dangerous that they can have fatal consequences.⁴⁰

7.2.1 Factors affecting the power of a smoke gas explosion

Size of ventilation opening(s)

The larger the opening, the easier it is for the pressure to drop in the room. If the room is almost completely closed the pressure will be much higher if the gaseous mass ignites. Theoretically, the pressure could reach as much as eight bar in a totally closed room.

Premixed proportion in room volume

The larger the premixed proportion in the room volume, the greater the increase in pressure. It only requires a small volume percentage of the smoke gases to be premixed for the pressure to become very high, see Chapter 3 earlier on.

Building components' pressure resistance

The weakest building component collapses first, after which the pressure will decrease. If the building was entirely closed and the building components could cope with the increases in pressure, the pressure could reach as much as 8 bar.¹² In most buildings, however, there is, for example, a window, which means that the increase in pressure is very often moderate. The table below indicates the approximate values for the amount of pressure various building components can withstand:

<i>Typical pressure at which various building structures will collapse</i>		
<i>Structure</i>	<i>Pressure (mbar)</i>	<i>Pressure (Pa)</i>
<i>Glass windows</i>	<i>20–70</i>	<i>2000–7000</i>
<i>Room doors</i>	<i>20–30</i>	<i>2000–3000</i>
<i>Lightweight walls</i> <i>(wooden framework and wooden boards)</i>	<i>20–50</i>	<i>2000–5000</i>
<i>Double plasterboard</i>	<i>30–50</i>	<i>3000–5000</i>
<i>10 cm brick wall</i>	<i>200–350</i>	<i>20000–35000</i>

Table 8. Pressure resistance for various structures.¹²

Burning velocity (Su)

The higher the burning velocity, the faster the expansion. The rate depends on the substance involved in the combustion and also varies according to where the gaseous mass ignites in relation to the stoichiometric point. The burning velocity is highest when the stoichiometric point is reached. There is a common misconception that the mixture must be very close to the stoichiometric point to achieve large increases in pressure. But the pressure will be very high, even when the gas mixture is close to the flammability limits. The burning veloc-

ity is also affected by turbulence in the room. The higher the turbulence, the higher the burning velocity. Turbulence is affected, for instance, by the furniture in the room or by the firefighters' movements.

Expansion factor

The higher the final temperature the products reach during the combustion process, the more they expand. The more they expand, the greater the increase in pressure. The products' temperature depends partly on the substance involved in combustion and partly on the point within the flammability range at which the mixture ignites.

7.3 Risk assessment

7.3.1 Signs indicating an imminent smoke gas explosion

Unfortunately, it is very difficult to predict a smoke gas explosion. This can then mean that completely unsuitable actions are taken. As a result, a smoke gas explosion can also have serious consequences. When the risk assessment is carried out the following points should be borne in mind:

- Are there any concealed spaces? If there are, it is possible for smoke gases to accumulate there. Concealed spaces are common between the roof and under-roof and with sloping roofs.
- Is the actual structure combustible? If this is the case, you can assume that the material on “the other side of the wall” can pyrolyse when the heat is transferred through the structure. This obviously applies to objects close to the wall.
- Are the conduits badly designed? In this case, you can assume that smoke gases can easily leak from the fire cell boundaries, which otherwise seem intact.

The signs in this case point more to preventive maintenance. Badly designed conduits must be rectified very early on. In some cases, it is possible to install a sprinkler system or detectors, which will detect when smoke gases accumulate, not just in the fire room, but in adjacent rooms too.

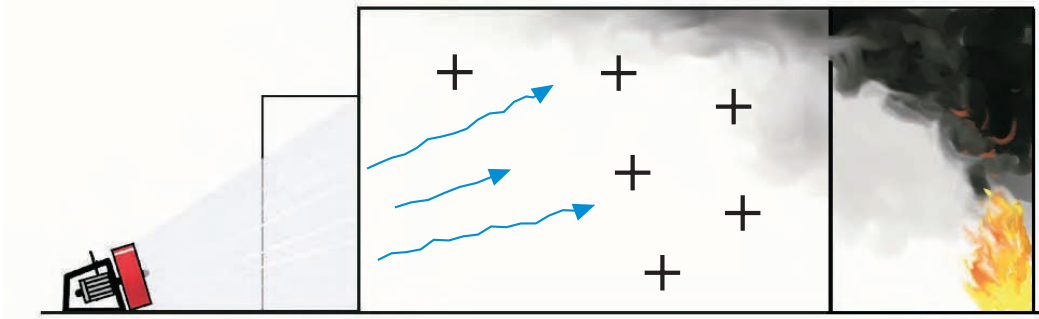


Figure 115. It is important to ventilate the adjacent area at an early stage or to exert positive pressure on the area.

7.3.2 Course of action

If smoke gases have already accumulated in the adjacent area the situation is very difficult to resolve. At first, it is very difficult to neutralise the effect of the gases by spraying fine particles of water on them. The smoke gases may well be fairly cool, which makes it very difficult to vaporise the water. The fact is that they are still dangerous because the temperature does not have any influence in this case.

If we decide to ventilate the area we must be careful not to cause any sparks, as this is the most dangerous factor of all. This can be difficult if we have to pierce a hole to let the smoke gases out. In other cases, it is perhaps not possible to ventilate the area easily, which means that we are facing an even more difficult situation.

The overall conclusion must be, therefore, that the easiest solution is to prevent the build-up of smoke gases through preventive maintenance, as well as to ventilate the area at an early stage before any smoke gases have managed to accumulate within the flammability range. The prerequisite for this, of course, is to call the fire service early so that they can arrive quickly at the scene.

At the scene of the fire it may be important to get hold of people who are familiar with the building. If we can get access to a good plan drawing at an early stage this will facilitate our job immensely.

Sometimes we can perhaps manage to exert pressure on the area before smoke gases accumulate. But there needs to be a small level of leakage, otherwise it will be difficult to do this.

7.4 Summary

A smoke gas explosion occurs when a premixed gaseous mass ignites in a room or area. This most commonly occurs in an area in proximity to the fire room. The smoke gases are able to mix well here. This phenomenon is mainly controlled by premixed flames. Smoke gas explosions can also occur in the fire room, but this is less frequent.

There are a number of factors which determine the magni-

tude of the increase in pressure caused by a smoke gas explosion, including the following:

- size of ventilation opening(s)
- premixed proportion in room volume
- building components' pressure resistance
- burning velocity (S_u)
- expansion factor.

We should also add that if we compare the increase in pressure caused there is no clear boundary between a smoke gas explosion and a backdraught. But one of the conditions for a backdraught to occur is that a ventilation opening has been modified. Typical features of a smoke gas explosion include the fact that the smoke gases are premixed, which can therefore result in a very large pressure increase. During a flashover, by contrast, the diffusion process is in control.

When flammable liquids leak, large quantities of premixed gases can accumulate, which can cause a considerable increase in pressure if they ignite. This depends on the liquids' flashpoint.

It goes without saying that the same scenario can occur even when flammable liquids are not mixed. The only difference is that smoke gases contain a load of particles which act as thermal ballast, which means that the burning velocity decreases somewhat.

In many cases, it can be difficult to identify the signs indicating an imminent smoke gas explosion. This is mainly to do with technical building aspects, e.g. the design of the conduits, whether the fire cell boundaries are intact and whether there are any concealed spaces. Detectors or sprinkler systems can help to prevent a smoke gas explosion. Actions which can be taken at the scene may include ventilating or reducing the pressure in an area before combustible smoke gases accumulate.

Test your knowledge!

1. *Why do smoke gas explosions occur so seldom?*
2. *Which factors determine how powerful a smoke gas explosion will be?*
3. *Which flames are involved in a smoke gas explosion?*
4. *Does the gaseous mass need to use up the whole volume to generate high pressure?*
5. *Theoretically, how high can the pressure reach in a smoke gas explosion?*
6. *In practice, how high can the pressure reach in a smoke gas explosion?*
7. *Why is it unlikely for a smoke gas explosion to occur in the fire room?*
8. *What are the signs indicating an imminent smoke gas explosion?*
9. *What should we do to prevent a smoke gas explosion in an area?*
10. *Which preventive fire protection measures can prevent smoke gas explosions?*

Explosion at the Grand Hotel in Helsingborg

Smoke gas explosions do not occur very often, as a rule. But this was the cause of the incident which took place at the Grand Hotel in Helsingborg.

At 20.39 on 12 January 1995, the Helsingborg fire service department received an automatic fire alarm call from the Grand Hotel. A few minutes later, an emergency call was also received from the hotel. Staff thought they could smell smoke coming from the conference area. When the fire crew arrived at the scene of the incident a few minutes after the alarm, a powerful explosion was heard. Large window panes in the building were shattered and splinters of glass fell out on to the road. This showed that a powerful pressure wave had been generated. An investigation carried out afterwards showed that the fire started in a sauna, which was located in the middle of the first floor. The sauna was adjacent to a hotel corridor (see Figure 116). The hotel corridor was about 25 metres long.

The fire had been caused by an electrical fault and had probably been burning for a long time before the automatic fire alarm went off. The sauna was separated from the corridor by double plasterboard, which managed to contain the fire. But the smoke gas was able to leak out to a space between the under-roof and ordinary ceiling. This space was above the hotel corridor (see Figure 117).

The space was 2.2 metres wide and 1.2 metres high and also contained ventilation shafts. As already mentioned, the hotel corridor was about 25 metres long, which meant that smoke gases were able to accumulate in a large volume. The smoke gases were able to mix very well with the air in this space as there was no ignition source present during the initial stages. The mixture then reached the flammability range and ignited.

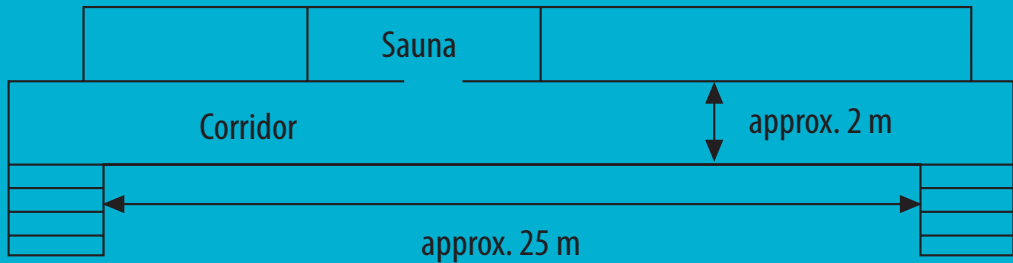


Figure 116 (above).
Plan drawing of first floor (NB: not drawn to scale)

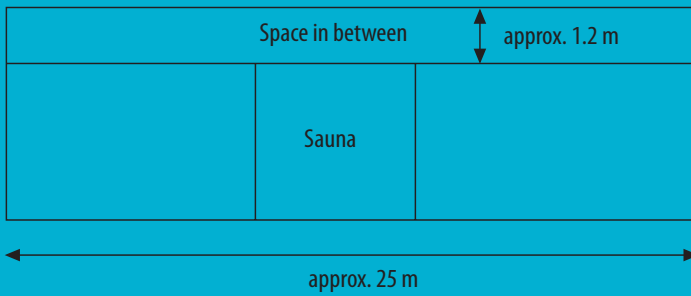


Figure 117. Cross-section drawing of sauna (NB: not drawn to scale)

The ignition source could possibly have been a shooting flame from the sauna.

When the gases ignited this caused a powerful smoke gas explosion and generated a positive pressure estimated at between 50 and 250 mbar. This caused glass splinters to become embedded in walls, doors to burst open, window panes were blown out on to the street and large sections of the under-roof collapsed. This type of combustion, i.e. when a considerable volume of smoke gases ignite within the flammability range, generates a huge increase in pressure. The closer the mixture is to the stoichiometric point, the larger the increase in pressure when ignition occurs.

Five people were injured during this smoke gas explosion, but none of them seriously. There were 32 people in total in the hotel when the incident occurred.



Grey areas between the various phenomena

We have described up until now some of the phenomena which can occur in a compartment fire. We pointed out earlier on that a fire can develop in different ways. In reality, we sometimes encounter situations which lie between different phenomena. We are going to describe below five scenarios where it can be very difficult to differentiate between the various phenomena.

8.1 Differentiating between flashover and backdraught

A flashover occurs when there is good access to an air supply and there is a certain amount of fuel. A backdraught originates in a totally different way and occurs when there is a limited air flow in a building/room, which means that combustion continues with a limited oxygen supply. This then leads to the accumulation of a quantity of unburnt gases, which can ignite at a later stage when air is supplied.

So, why should it be so difficult to differentiate between these scenarios? We are assuming that we are dealing with a ventilation-controlled fire where a door or window is opened and air flows in.

We note immediately that there will be no powerful backdraught unless the flames are coming out through the opening slowly. This scenario was earlier described as when “the fire resumes its development”, which is exactly what is happening. If we had a slightly bigger area with premixed smoke

What is important is to understand the various processes involved, but obviously, it is just as important to use standard terminology.

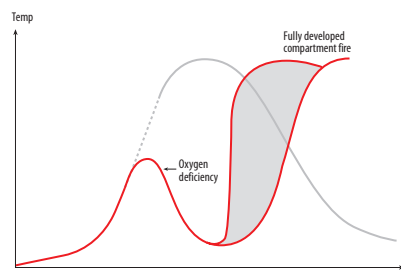


Figure 118. Grey area.V

gases the flames would come out through the opening more quickly.

It goes without saying then that we are now faced with a type of grey area, where the amount of premixed smoke gas controls how quickly the fire will develop. Are we looking at a backdraught or a continuation of a fire's interrupted development? Of course, we have to assess the situation on a case-by-case basis. This is shown in Figure 118.

8.2 Differentiating between smoke gases auto-igniting in the opening and a backdraught

The scenario where the smoke gases auto-ignite occurs when the smoke gases have a temperature which is higher than the thermal ignition point. In some cases when this happens, it can cause turbulence, which spreads throughout the room, with considerable force too, which may result in a small-scale backdraught. This is rare, but has occurred in some situations. This scenario obviously lies in the same grey area, but is based on the fire growth curve which is at a higher initial temperature than earlier (see Figure 118).

8.3 Differentiating between smoke gases auto-igniting and a fire resuming its development

It can be difficult to identify the situation where smoke gases are auto-igniting in the opening. Sometimes it seems as if flames are appearing there, but they may have actually originated from far inside the room. This then makes it difficult to decide whether the smoke gases are auto-igniting or the fire is resuming its development.

8.4 Differentiating between a backdraught and a smoke gas explosion

A backdraught and a smoke gas explosion originate in totally different ways. A backdraught occurs in a room where the ventilation conditions have changed. This may be, for instance, a room where the panes are cracking, allowing air in, which can

result in ignition. A smoke gas explosion, on the other hand, occurs most often in an area adjacent to the fire room.

Generally speaking, a backdraught causes less pressure to build up than a smoke gas explosion. A backdraught requires the ventilation conditions to change, which, in itself, helps to ease the pressure. In the chapter on smoke gas explosions, we also discussed the fact that a smoke gas explosion can occur in the fire room, but that this is a rare occurrence. This is because there is very often an ignition source, which consumes the combustible gaseous mass as soon as it is formed. As a rule, the size of the combustible gaseous mass formed is not sufficiently large.

We need to try and get some idea of the extent to which ignition is dependent on whether the ventilation opening has changed or not. If the situation has arisen due to a change in ventilation we are dealing with a backdraught.

8.5 Differentiating between a flashover and a smoke gas explosion

Both these scenarios are the simplest to differentiate between, as a flashover involves diffusion flames, whereas premixed flames are involved in a smoke gas explosion.

8.6 Summary

To sum up, we can say that it is important to understand the processes which control how fire-related phenomena occur so that we can realise what has actually taken place. The terms used, of course, also are fundamentally important, as in situations requiring quick, appropriate action, there is no room for any misunderstanding.

Generally speaking, it is difficult to differentiate between the various phenomena which have the same type of flame involved. For instance, diffusion flames are involved in a flashover, whereas both premixed and diffusion flames are involved in a backdraught. This can make it difficult to distinguish between them. On the other hand, if we compare a flashover with a smoke gas explosion, where premixed flames are involved, it is much easier to differentiate between these.

Sauna fire in Kiruna

This incident took place on 5 October 1999.⁴³ The Kiruna fire service received an emergency call to attend a sauna fire at the Malmfälten high school. One minute after this, the fire engine left the station, there was also the automatic alarm from the high school itself. The firefighters noted at the scene that the stairwell by the sauna was filled with white, light smoke.

Firefighters with breathing apparatus entered the building to go down to the basement via the stairwell and extinguish the fire. They first did a search from the pool room to the sauna to make sure there was nobody left in the building and then proceeded towards the sauna. They did not notice the temperature at the door being any higher, however, they could hear a crackling noise coming from the sauna. When the BA firefighters opened the sauna door they felt a very strong inward pull through the door opening. A moment later, a bluish flame shot out from the sauna. The smoke gases outside the sauna ignited and a bang was heard, all within a fraction of a second.

The officer in charge was paying out the hose when he heard

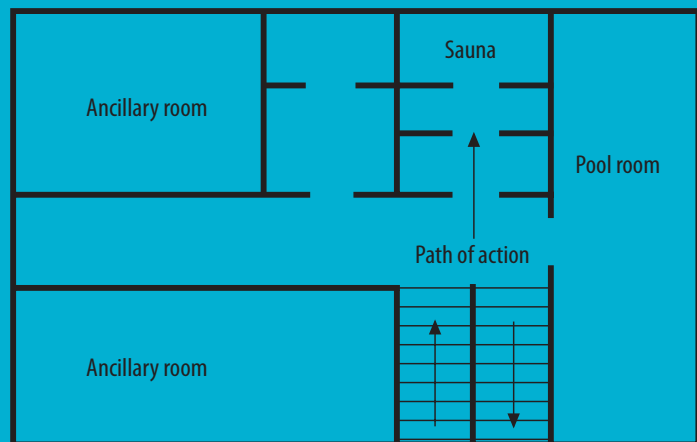


Figure 119. Plan drawing of the basement level. Note that the stairwell is open and leads up to entrance level.

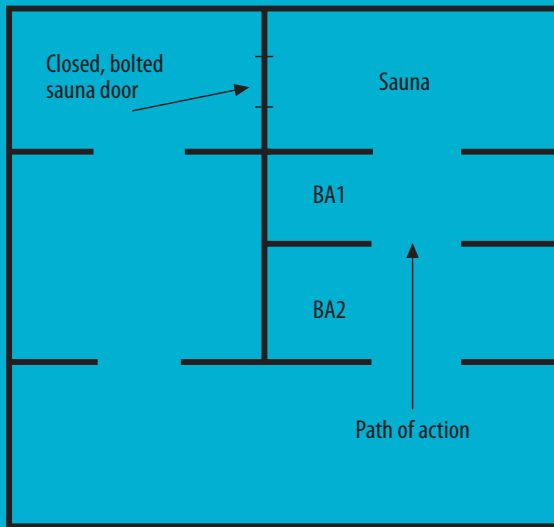


Figure 120. A detailed drawing of the sauna. The path of action is directly down from the stairwell right to the sauna. You should note that a search was carried out in the ancillary rooms first.

a loud bang. He saw a board come flying out, heard glass shatter and smoke was streaming out through the main entrance. Unperturbed, he made contact with the BA firefighters. They responded immediately, saying that that were in no danger. In the areas adjacent to the stairwell on the ground floor, parts of the under-roof had collapsed. This occurred even though the stairwell formed its own fire cell and so, was separated from the adjacent rooms.

The worst damage was right at the top of the stairwell where a section of glass had shattered, as well as a locked door had been blown out and parts of the doorframe had broken loose. Apart from the fact that large areas of the building were filled with smoke, the damage was limited to the actual sauna itself, which was totally gutted.

The likely course of events was as follows. The fire had been burning in the sauna for a long time and a large amount of the heat and smoke gases had remained there. But the smoke gases managed to escape, including to the stairwell, but the temperature was not high enough to trigger the heat detectors. The smoke gases in the stairwell also mixed with the air and reached the flammability range. When the BA firefighters opened the door to the sauna there was a fuel-rich atmosphere in the sauna room. The bluish flame which shot out from the sauna ignited the smoke gases outside. The actual development of the fire was not as intense in the basement area as higher up in the stairwell. This is where the worst damage was sustained.

Glossary

- Adiabatic flame temperature** If all the energy released during combustion is used to heat the products formed during combustion, the temperature which is reached is known as the adiabatic flame temperature. This is the highest temperature which can be reached. But the adiabatic flame temperature is rarely achieved in reality, as some of the energy is lost during combustion.
- Backdraught** Restricted ventilation during the development of a fire can lead to the formation of a large quantity of unburnt gases. If an opening suddenly appears the incoming air can mix with the smoke gases, forming a combustible mixture anywhere in the room. If there is an ignition source of any kind present, e.g. embers, this will cause the gaseous mass to ignite, which will then accelerate the combustion process considerably. When the volume of gas expands this causes the rest of the unburnt gases to be pushed out through the opening, producing a fire ball outside the opening. This phenomenon occurs seldom, but can be extremely dangerous.
- Burning velocity** Burning velocity is used to describe the speed at which a flame moves in a gaseous mass. The unit used is m/s.
- Combustion efficiency** A substance which burns rarely releases all its energy, even when there is a good oxygen supply available. Some of it remains unconsumed in the plume, which conveys the smoke gases to the ceiling. The poorer the supply of oxygen, the more unburnt gases are produced.
- Decay period** The decay period is the period after a fully developed compartment fire. At this stage, the temperature starts to fall as the fuel starts to get used up. The fire is fuel controlled.
- Deflagration** The term “deflagration” is used to describe flame spread in a premixed gaseous mass. During a fire the flame front moves at a speed of around 3–5 m/s. A smoke gas explosion is therefore a deflagration.
- Detonation** Detonation relates to a combustion scenario whereby flames travel very quickly, sometimes even faster than sound. The shock wave and flame front are linked together and travel through the gas/air mixture at high speed. In reality, detonations are caused by solid explosive substances and not by gas mixtures.

Diffusion flame	A diffusion flame occurs when the fuel and air are not mixed with each other at the moment of ignition. Fuel and air diffuse into each other, creating a combustible area in the boundary layer between them. Candles are an everyday example of this.
Early stage of fire development	This is the period from when the fire starts until a flashover occurs. During this period the fire can spread from the initial object and people who are in the building are at major risk of getting injured.
Expansion factor	When a gas mixture ignites, the temperature can rise by a factor of 8. This causes the volume to expand by the same magnitude.
Explosion	An exothermic chemical process which, when it happens at a constant volume, generates a sudden, significant increase in pressure.
Flammability range	This is the range within which gas/air mixtures can ignite.
Flashover	A flashover is a transition period from when the fire is burning locally until the whole room is involved in the fire. A flashover occurs when the fire's heat release rate exceeds a particular critical level. Factors contributing to the increase in the fire's heat release rate include flame spread over combustible surfaces and reradiation from the hot smoke gas layer. A flashover marks the transition from the early fire development stage to a fully developed compartment fire.
Fuel control	After ignition and at the start of a fire's development, the fire is described as fuel controlled as there is sufficient air for combustion and the fire's development is controlled entirely by the fuel's properties and arrangement. A fire can also be fuel controlled at a later stage in its development.
Fully developed compartment fire	This stage is reached when a flashover occurs. In this instance, the fire is ventilation controlled and it is usual for smoke gas temperatures to reach the order of 800–900 °C. Flames spread via the building's openings. This means that part of the combustion process takes place outside the compartment.
Heat release rate	When a material combusts heat will be released. The heat released is measured in watts (J/s).

- Heat of combustion, ΔH_c** This measures the amount of energy the material releases when it burns. The unit used is MJ/kg or kJ/g.
- Heat of vaporisation, ΔH_v (sometimes L_v)** The heat of vaporisation is the amount of heat required to produce 1 g gas from the fuel surface.
- Laminar flow** There are two different types of flow. This is evident when, for instance, smoke flows up and out of a narrow chimney. First of all, the smoke moves in a parallel layer without mixing. But at a certain distance from the outlet the flow type changes and smoke particles move in irregular paths, in a swirling motion. The layered type of flow is known as laminar and the irregular as turbulent. The word “laminar” is taken from the Latin word “lamina”, meaning plate, board, and “turbulent” is taken from the Latin word “turbulentur”, meaning disturbed or tempestuous.
- Mass loss rate** The mass loss rate is the speed at which pyrolysis occurs from a material, sometimes also known as the rate of pyrolysis. This is often measured in the unit g/m²s.
- Premixed flames** A premixed flame occurs when the fuel and air are well mixed with each other before ignition occurs.
- Pulsation** Pulsations occur occasionally when the fire is entering a ventilation-controlled stage. If there is an opening in the room the fire can have access to air to allow combustion to take place. As a result of this, positive pressure builds up in the room and the temperature rises. The fire subsides due to oxygen deficiency and the temperature falls as new air can be drawn into the room.
- Pyrolysis** Pyrolysis is a chemical decomposition process or other chemical conversion from complex to simpler constituents, caused by the effect of heat.
- Smoke gas explosion** When unburnt smoke gases leak into an area adjacent to the fire room they can mix very well with air to produce a combustible mixture. If there is an ignition source available or one becomes available some other way, the smoke gases can ignite, with an extremely devastating effect. As a rule, this phenomenon occurs seldom.

- Stoichiometry (ideal mixture)** When there is exactly the amount of air required to burn the fuel completely this is known as the stoichiometric point. In this instance, only carbon dioxide and water are produced. This happens extremely rarely in practice.
- Turbulence factor** When flames spread the area of the flames will increase and they are then broken up, which means that the area of the flame front will get bigger. This results in an increase in the burning velocity.
- Turbulent flow** There are two different types of flow. This is evident when, for instance, smoke flows up and out of a narrow chimney. First of all, the smoke moves in a parallel layer without mixing. But at a certain distance from the outlet the flow type changes and smoke particles move in irregular paths, in a swirling motion. The layered type of flow is known as laminar and the irregular as turbulent. The word “laminar” is taken from the Latin word “lamina”, meaning plate, board, and “turbulent” is taken from the Latin word “turbulentur”, meaning disturbed or tempestuous.
- Unburnt gases** If the fire continues with a depleted oxygen supply unburnt gases will accumulate. Unburnt gases always accumulate, even if there is good access to an air supply. The unburnt gases contain potential energy and may be released at a later stage and cause the temperature to rise.
- Ventilation control** As the fire grows it may become ventilation controlled when there is no longer sufficient oxygen to combust the pyrolysis gases formed. The fire’s heat release rate is then controlled completely by the amount of air which is available, in which case the fire is described as being ventilation controlled.

Suggested solutions to test questions

Chapter 2

1. Usually in the order of 300–400 °C
2. The flames will spread quickest in wood fibre board as the thermal inertia is less for this material. This material's surface will then heat up more quickly.
3. kpc. k stands for heat conductivity, ρ stands for density and c for heat capacity. Steel and pine wood have high values.
4. Through conduction, convection and radiation. With conduction, a material conducts heat through its structure. For instance, steel is a very good conductor of heat, which means that in vehicle fires, for example, any material coming into contact with the steel structure can ignite. With convection, heat is transferred from hot smoke gases, for instance, to a heat detector. With radiation, adjacent buildings can be ignited when they are subjected to high levels of radiation.
5. The flame spread rate is mainly affected by the material's thermal inertia, the surface's direction, the surface's geometry, as well as by the material being pre-heated.
6. When flame spread occurs vertically upwards and flames spread along the ceiling. This is due to the surfaces being considerably pre-heated.
7. The calculation is in Chapter 2. It takes roughly 5–15 seconds.
8. Flame spread can cause the heat release rate to increase dramatically in just a few seconds. BA firefighters must be prepared to take the appropriate action quickly, if a flashover is imminent.
9. Usually around 500–600 °C.
10. Plastic materials with a low thermal inertia, e.g. polyurethane. Porous wood fibre boards are another example.

Chapter 3

1. “Lean” and “rich” can be used to describe a gaseous mass which is premixed.
2. About 8 bar.

3. This is usually split into normal pressure differences and pressure differences caused by the fire. Normal pressure differences are caused by the wind, air conditioning and temperature differences between outside and inside air. Pressure differences created by the fire are inhibited thermal expansion and thermal buoyancy.
4. Premixed flames occur when fuel and air are premixed before ignition occurs, whereas diffusion flames occur when fuel and air are not premixed when ignition occurs.
5. A premixed flame front can travel at around 3–5 m/s.
6. A deflagration is when flames spread in a premixed gaseous mass.
7. A detonation is when flames spread in a premixed gaseous mass where a shock wave is associated with the flame front, which can produce very high pressure and speeds.
8. When the fire is fuel controlled the heat release rate is controlled by the fuel. In ventilation-controlled fires the heat release rate is controlled by the size of the openings. It is very important to know whether the fire is fuel or ventilation controlled, for instance, when you are using a fan. It is then possible to predict the consequences resulting from supplying air.
9. A number of products are formed during a fire, including carbon dioxide and water, which are the most common. When the combustion efficiency drops unburnt gases such as carbon monoxide and unburnt hydrocarbons are produced.
10. You can obviously find the products specified in the answer to question 9, as well as a quantity of air, associated with the plume.
11. The rate is controlled by the speed at which the molecules diffuse into each other. This rate increases with temperature, for instance.
12. In an open room there will be positive pressure at the top of the room, which results in smoke gases leaking out. In the bottom part of the room there is negative pressure, which causes air to get sucked in.

13. In a closed room there will be positive pressure in the entire room because of thermal expansion. But as soon as there is less leakage the increase in pressure due to thermal expansion will fall and the pressure conditions will appear the same as for an open room.
14. During a normal compartment fire diffusion flames dominate.
15. In the order of 2000–7000 Pascal.
16. About 15–20 Pascal. It depends on how hot the smoke gases are.
17. The material releases a certain amount of heat energy during combustion and in some cases, it can drip and spread the fire. The flame spread occurs at different rates, depending on the specific material.
18. In many cases, the window panes are still intact by the time the fire service arrives at the scene. This means that the fire may have entered a ventilation-controlled process.
19. The additional oxygen can be included on both sides using the symbol X. The additional fuel can be included on both sides in the same way. The equation is balanced with 5 oxygen molecules. The products will be 3 carbon dioxide and 4 water molecules. Propane contains 3 carbon and 8 hydrogen atoms.
20. The flame will not be able to exist outside the flammability range, as the thermal ballast is too great. This means that the energy released is not sufficient to heat all the products, allowing combustion to continue.

Chapter 4

1. A flashover is controlled by diffusion flames.
2. About 500–1000 °C.
3. The period varies depending on a number of conditions, including the room's geometry. Sometimes this period can take just a few seconds.
4. Mainly reradiation from the smoke gas layer and flame spread on different surfaces.

5. The main protection against a flashover is to be able to predict when a flashover is imminent. You need to have a good knowledge of a fire's development to do this. It is very important to know what the signs are. At a more practical level, it involves reducing the smoke gases' temperature so that the reradiation level and heat release rate will not be too high.
6. The reference literature mentions some of the following signs: change in the smoke gas layer's position, the speed at which the smoke gases leave the room, pyrolysis from the various fuel packages and flames in the smoke gas layer. The smoke gases' colour or a change in colour may also be used, but with a certain degree of caution.
7. In many cases, the fire does not spread from the initial object and as a result, the heat release from the fire is not sufficient to cause a flashover. In some situations the fire is ventilation controlled and the heat release rate is limited before the progression to flashover is reached.
8. Just a few percent.
9. In the premises where concrete is used in the enclosure structure. This is because more energy disappears through conduction.

Chapter 6

1. Both premixed and diffusion flames are involved in a backdraught.
2. Unburnt smoke gases accumulate, air flows in, the gases and air mix, they ignite with some kind of ignition source, a turbulent deflagration occurs and a fire ball appears outside the room.
3. The conditions required for a backdraught to occur are very particular. The chances of an ignition source being present at the very moment the premixed area forms in the compartment are very low.
4. Pulsations from small openings around doorframes, for instance, hot doors and windows, no visible sign of a fire and a whistling sound around openings.
5. A backdraught occurs when the fire has been ventilation controlled for a while.

6. By cooling down the smoke gases before they ignite or by ventilating the smoke gases out before you enter the room. There are many options for doing this. Wearing suitable protective clothing is vital in these situations.
7. The best tactic is to try to cool down the smoke gases before you draw too much air in.
8. No. It depends on the radiation levels and the types of material which are close by.
9. There must be a high concentration of unburnt smoke gases. These can accumulate if the building is well insulated, there is a great deal of combustible material at the top of the room, if there are fewer leakage areas right down at the bottom of the room and if an ignition source can appear.
10. It is common in sauna fires.
11. When combustion takes place in a fairly enclosed room positive pressure will build up, which causes smoke gases to be pushed out through the openings. The oxygen content also drops and the flame goes out. After a while the temperature falls, which creates negative pressure and fresh air can then be drawn into the room. Ignition is possible again after this. It is very difficult to predict whether a fire will pulsate or not.
12. Think about at which stage the fire is at, the length of time it has been burning, then weigh up the risks and compare with the possible outcome of the operation.
13. A backdraught has occurred, the fire resumes its development, the fire may have spontaneously gone out or the smoke gases auto-ignite in the door opening.
14. The fire has spontaneously gone out or the fire resumes its development and the fire becomes more intense.
15. This is not common. This phenomenon occurs as the smoke gases' temperature is higher than the auto-ignition temperature. The gases ignite on direct contact with the air.
16. If the fire is ventilation controlled, when we open the door, the fire receives new impetus and its development can then resume.

17. The quantity of unburnt gases which are in the room and the mixture. The larger the proportion of premixed smoke gases, the higher the pressure.
18. This is because positive pressure builds up in the fire room.
19. Probably not, but you can never be completely sure.

Chapter 7

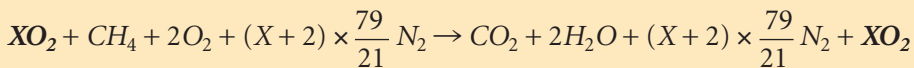
1. Many factors need to coincide at the same time. There needs to be a combustible mixture in an adjacent area, not to mention an ignition source as well.
2. The proportion of the premixed volume, the building components' pressure resistance and the size of the ventilation openings.
3. Premixed flames.
4. No. Only a small proportion of the gaseous mass is sufficient.
5. About 8 bar of pressure, if the room is entirely closed.
6. The pressure is no higher than the pressure which builds up when the weakest structure collapses. Then the pressure drops.
7. It would be very rare for such a large quantity of premixed gases to be able to accumulate in the actual fire room as there is very often an ignition source constantly present.
8. Unfortunately, extremely few. They are often linked with the preventive aspects. Sometimes you might realise that the conduits are poorly insulated and think about where there might be any concealed spaces. Smoke gas explosions often occur in rooms which people did not know even existed.
9. If it is possible to adjust the pressure in the room before there is time for dangerous concentrations to accumulate.
10. Check that the fire cell boundaries are intact. Detectors or sprinkler systems can also help to prevent a smoke gas explosion.

Sample calculations

Flammability limits

Sample calculation: Lower flammability limit

We start with the stoichiometric reaction for methane. An unknown number of mols of oxygen gas are added to both sides. The energy released will be used to heat a number of extra products, compared with at the stoichiometric point. X is released and the proportion of methane in the mixture is calculated. The following reaction formula is used:



Methane releases 800 KJ/mol and C_p for the incoming products is taken from Table 4 on page 57.

The equation $\Delta H_c = \Sigma (C_p \times \Delta T)$ is used, where ΔT is the difference between the adiabatic flame temperature and the initial temperature. The initial temperature is set to 300 K and the adiabatic flame temperature is assumed to be 1600 K.

$$\frac{800000}{(1600-300)} = 54.3 + 2 \times 41.2 + X \times 34.9 + X \times \frac{79}{21} 32.7 + 2 \times \frac{79}{21} \times 32.7$$

The equation gives $X = 1.47$ and using this, we can calculate the proportion of methane in the mixture, i.e. the number of mols CH_4 shared with the total number of mols of reactants.

$$\frac{1}{1.47 + 1 + 2 + (1.47 + 2) \frac{79}{21}} = 5.7\% \text{ volume}$$

According to the result of the equation, 5.7% of the reactants are methane. The lower flammability limit for methane is therefore 5.7%. This is converted to g/m^3 using the density for methane gas. The equation will then be:

$$16/29 \times 1.2 = 0.65 \text{ kg/m}^3$$

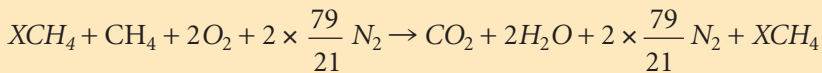
This will then give the mass as $0.65 \times 0.05 \approx 35 \text{ g/m}^3$.

You should bear in mind that this calculation is based on an initial temperature of 300 K and the chemical reaction has been simplified. In some tables the data is based on another temperature, but particularly in experiments where the correct reaction formula is used indirectly.

Sample calculation: Upper flammability limit

Methane releases 800 KJ/mol and C_p for the incoming products is taken from Table 4.

The equation $\Delta H_c = \Sigma (C_p \times \Delta T)$ is used, where ΔT is the difference between the adiabatic flame temperature and the initial temperature. The initial temperature is set to 300 K and the adiabatic flame temperature is set to 1973 K, which is somewhat higher than normal.¹¹ The reaction formula is as follows:



$$\frac{800000}{(1973 - 300)} = 54.3 + 2 \times 41.2 + X \times 34.9 + \times 2.33 + 2 \times \frac{79}{21} 32.7$$

The equation gives $X = 1.17$ and using this, we can calculate the proportion of methane in the mixture.

$$\frac{1.17 + 1}{1.17 + 1 + 2 + (2)\frac{79}{21}} = 18\% \text{ volume}$$

According to the result of the equation, 18% of the reactants are methane. 18% is converted to g/m^3 using the density for methane gas. The equation will then be:

$$16/29 \times 1.2 = 0.65 \text{ kg/m}^3$$

This will then give the mass as $0.65 \times 0.18 = 117 \text{ g/m}^3$.

You should bear in mind that this calculation is based on an initial temperature of 300 K and the reaction formula has been simplified. In some tables the data is based on another temperature, but particularly in experiments where the correct reaction formula is used indirectly.

Sample calculation: Temperature impact on lower flammability limit

We will start with a sample calculation where the lower flammability limit for methane has been calculated. The initial temperature, T_0 , is changed in the calculations and replaced by 500 K. Calculations are very approximate, but provide a rough estimate of the temperature's effect on the lower flammability limit.

The equation $\Delta H_c = \Sigma (C_p \times \Delta T)$ is used, where ΔT is the difference between the adiabatic flame temperature and the initial temperature. The initial temperature is set to 500 K. The reaction formula is the one used earlier (see Sample calculation: lower flammability limit).

$$\frac{800000}{(1600 - 500)} = 54.3 + 2 \times 41.2 + X \times 34.9 + X \times \frac{79}{21} \times 32.7 + 2 \times \frac{79}{21} \times 32.7$$

The equation gives $X = 2.18$ and using this, we can calculate the proportion of methane in the mixture.

$$\frac{1}{2.18 + 1 + 2 + (2.18 + 2) \frac{79}{21}} = 4.8\% \text{ volume}$$

According to the result of the equation, 4.8% of the reactants are methane. This can be compared with the result for the lower flammability limit calculation from the earlier example, 5.7%, where the initial temperature was assumed to be 300 K.

If the temperature continues to rise, in theory, even small amounts of fuel will be combustible. The upper flammability limit's variation with temperature can be calculated using the same method.

Flashover

Sample calculation: Heat release rate required for a flashover

Let us take a room measuring 3.6 m × 2.4 m × 2.4 m. The opening is in the form of a door 0.8 m wide and 2 m high. The enclosure material is lightweight concrete. Calculate the heat release rate required for the fire in the room to progress to flashover.



To start with, h_k is calculated. For fairly short periods of time h_k is determined by $h_k = (kpc/t)^{0.5}$, where kpc represents the material's properties and t is the time from when the fire started. kpc for lightweight concrete is roughly 75000 W²s/m⁴K². The time is assumed to be 10 minutes. We can assume that the fire service has arrived by that point.

h_k is calculated using the expression $\sqrt{kpc/t}$ and will equal 0.0112 kW/m²K.

The values are entered in the equation:

$$\dot{Q}_{fo} = 610(h_k A_T A_W \sqrt{H})^{0.5}$$

This gives: $\dot{Q}_{fo} = 610 (0.0112 \times 44.48 \times 1.6 \times 2^{0.5})^{0.5} = 650 \text{ kW}$

This can be compared to a sofa, which releases between 1 and 2 MW. The heat release required is therefore much less than this.

If we had calculated instead the heat release rate required to cause a flashover after 2–3 minutes, it would be much higher. You can even try by varying the time (t) in the expression for h_k .

Backdraught

Sample calculation: The speed of the incoming air current

The room has the dimensions $2.4 \times 2.4 \times 6 \text{ m}^3$ and the opening is wide, roughly a third of the room's height, i.e. 0.8 metres. The opening is about 2.2 metres wide. The smoke gas temperature is about 150°C . This gives a rough smoke gas density of 0.84 kg/m^3 . The air density is about 1.2 kg/m^3 , representing β .

$$\beta = (1.2 - 0.84)/0.84 \approx 0.42$$

v^* is obtained from reference 32. This value is connected to the size of the opening in relation to its geometry, in this case, the wide opening.

$v^* = v/(g \times h \times \beta)^{0.5}$, which gives:

$$v = 0.35 \times (9.81 \times 2.4 \times 0.42)^{0.5} \approx 1 \text{ m/s}$$

Based on the equation above, this gives a speed of about 1 m/s, which visually seems to be a good approximation. It is important not to use this result as an exact value, but just as an approximation. You should also note on this subject that it can take a number of seconds for a combustible mixture to reach the ignition source, if it is placed far inside the room.

The above equation is also useful for applying to the outgoing air current and it is important to mention that it can take many seconds for the air current, which has reflected against the back wall, to reach the door opening again. In this case, the mixture in the room may be very well mixed and ignition can result in a very rapid heat release rate with fatal consequences.

List of quantities

$$t_a = \frac{(T_{sa} - T_i)^2}{4(\dot{q}'')^2} k\rho c \times \pi$$

$$T_s - T_i = \frac{2\dot{q}''}{\pi^{0.5}} \frac{t^{0.5}}{(k\rho c)^{0.5}}$$

- T_{sa} – surface temperature at the moment of ignition (°C)
 t_a – time to ignition (s)
 \dot{q}'' – heat supplied W/m² – Radiation energy (In this case, from the fire)
 T_s – temperature on surface (°C) of fuel
 T_i – initial temperature (°C) on fuel surface
 (original temperature)
 k – heat conductivity W/m °C – A high value means that the material easily conducts heat
 ρ – density in kg/m³
 c – specific heat capacity in J/kg °C – Means ability of material to store heat
 t – time in seconds (s)

$$\dot{Q} = \dot{m}'' A_f \Delta H_c \chi$$

- \dot{Q} – heat release rate in W
 \dot{m}'' – mass loss rate in kg/m²s or g/m²s
 A_f – size of fuel surface in m²
 ΔH_c – heat of combustion in the event of complete combustion in J/kg
 χ – combustion efficiency controlling how effectively the fuel is consumed (indeterminate)

$$\Delta H_c = \Sigma (C_p \times \Delta T)$$

- ΔT – temperature difference (°C)
 C_p – gases' heat capacity (J/mol × K)
 ΔH_c – heat of combustion in the event of complete combustion (MJ/kg or kJ/g)

$$S_f = S_u \times E \text{ (m/s)}$$

- E – expansion factor (indeterminate)
 S_u – rate of laminar burning velocity (m/s)
 S_f – flame speed (m/s)

$$E = (T_f/T_i)(N_b/N_u)$$

T_f – temperature of products (K)

T_i – original temperature (K)

N_b – sum of the products available after the reaction

N_u – sum of the reactants available before the reaction

$$S_f = S_u \times (T_f/T_i)$$

$$S_f = S_u \times \beta \times (T_f/T_i)$$

β – turbulence factor (indeterminate value)

$$\Delta p = (\rho_a - \rho_g) gh$$

Δp – pressure difference in Pa

g – gravitational constant (m/s^2)

h – height (m)

ρ_a – density of the surrounding gas (kg/m^3)

ρ_g – density of gases (kg/m^3)

$$\rho = \frac{pM}{RT}$$

M – molecular weight (kg/kmol or g/mol)

R – 8.31 (J/molK)

T – temperature (K) NB: do not use C° in the equation.

p – pressure (Pa)

$$\Delta p = 353(1/T_a - 1/T_g) gh$$

353 – constant

T_a – ambient temperature (K)

T_g – temperature of gases (K)

$$\frac{(p - p_a)}{p_a} = \frac{\dot{Q}t}{V\rho_a c_v T_a}$$

\dot{Q} – heat release rate (W)

V – room volume (m^3)

P_a – normal pressure (Pa)

P – pressure created (Pa)

t – time (s)

T_a – temperature (K)

- ρ_a – density of normal air (kg/m³)
 c_v – specific heat capacity at constant volume (J/kgK)

$$\Delta p = \frac{(\dot{Q}/c_p T_e A_e)^2}{2\rho_e}$$

- \dot{Q} – heat release rate (W)
 C_p – specific heat capacity at constant pressure (J/kgK)
 ρ_e – density of outflowing gas (kg/m³)
 T_e – temperature of outflowing gas (K)
 A_e – leakage area (m²)

$$\dot{Q}_{f0} = 610(h_k A_T A_W \sqrt{H})^{0.5}$$

- \dot{Q}_{f0} – the heat release rate required to trigger a flashover (kW)
 h_k – heat transfer coefficient (kW/m²K), which specifies the amount of heat conducted in enclosure structures
 A_T – internal enclosure area in room (m²)
 A_W – ventilation opening area (m²)
 H – height of ventilation opening (m)
 610 – constant produced via regression

$$\dot{m}_a = 0,5 A_w \sqrt{H}$$

- \dot{m}_a – mass flux of the inflowing air (kg/s)
 A_w – opening area (m²)
 H – height of opening (m)

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

- \dot{Q} – heat release rate (W)
 ΔH_c – heat of combustion (MJ/kg or kJ/g)
 χ – combustion efficiency (indeterminate)
 \dot{m} – mass loss rate (kg/s)

$$\dot{m} = \frac{\dot{q}''_f + \dot{q}''_{ext} - \dot{q}''_{loss}}{L_v} A$$

- \dot{q}''_{loss} – heat loss from the fuel surface (kW/m²)
 \dot{q}''_{ext} – radiation from surrounding areas (kW/m²)
 \dot{q}''_f – heat transfer from flame (kW/m²)
 \dot{m} – mass loss rate in g/s
 A – fuel area in m²
 L_v – heat of vaporisation (kJ/g)

$v^* = v/(g \times h \times \beta)^{0.5}$, which gives:

v – air current speed (m/s)

v^* – indeterminate Froude coefficient

h – height of room (m)

g – gravity (m/s²)

β – difference in density between the media (indeterminate)

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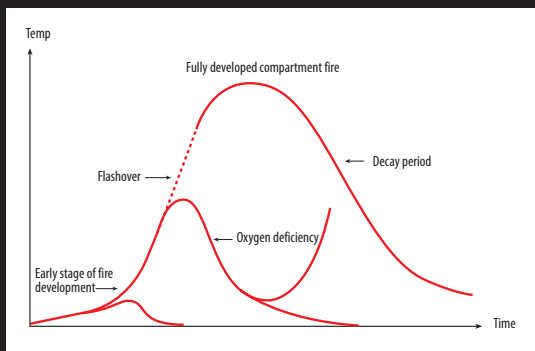
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**Approximate conversion values
for rough calculation:**

1 MPa = 10 bar
1 kPa = 100 mm water column
1 Pa = 0,1 mm water column
1 bar = 0,1 MPa = 100 kPa
1 mm water column = 10 Pa

KNOWLEDGE about fire development, the spread of smoke gases, pressure conditions and risk assessment may be crucial to the outcome of a firefighting operation. Basic knowledge about the factors which control the fire's development is a must for fire service staff. It is also important to be familiar with and on the lookout for the warning signs which can be observed during an operation.

Enclosure fires brings together the experience acquired by the district fire service and the research in the form of experiments and theoretical studies on the subject. With this book the Swedish Rescue Services Agency wants to contribute to a deeper understanding about fire development in the case of enclosure fires. Firefighting measures, such as applying an extinguishing agent, fire ventilation, etc. are discussed in detail in several sections, but the book focuses very much on acquiring an understanding of the processes which control enclosure fires.

This book is primarily intended to be used by the Swedish Rescue Services Agency in its training activities, but is also suitable for active firefighters and anyone else who may be interested.



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