Stefan Särdqvist

Water and other extinguishing agents

RÄDDNINGS VERKET
Swedish Rescue Services Agency

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Foreword

Swedish firefighting personnel of all ranks have used this book since the Swedish edition was released in 2001. It deals with practical matters, e.g. how to run a trailer pump, and theoretical matters, e.g. the fire point theory. Most readers are therefore not interested in all the pages, but if you are devoted to any aspect of firefighting, you will find the book rewarding.

Some parts, in particular the descriptions of equipment are biased towards what is common in Sweden. Also, many of the references are in Swedish. Nevertheless, the theoretic foundation is universal and internationally applicable. It is based on international science and therefore most of the references are in English.

This book is partly based on Göran Holmstedt's compendium Extinguishing Agents and Extinguishing Effects (1998), which is used on the fire engineer course at Lund University. The Foam Guide (1993) by Mats Rosander and Krister Giselsson, and Fire Water Supply (1999) have also been important sources of information; both published by the Swedish Rescue Services Agency.

Not wanting to name or forget anyone, I'll just say thank you to everyone who has contributed with ideas and who has read, commented, and expressed opinions about the book during its various stages of production. It is hoped that the reader will overlook the delay in the translation process.
Stefan Särdqvist

Introduction

The mandate of the fire and rescue service is laid down in law. The Swedish Rescue Services Act states that the fire and rescue service must prevent or limit damage. It does not specify that the service must put out fires, but that it must minimise damage. This means that the fire and rescue service must not cause greater damage through its firefighting operations than the fire itself would have caused. The law also states that the fire and rescue service must be structured and organised in such a way that it can act effectively. Careful planning of firefighting tactics will result in the right method being chosen. There are many methods available, with different outcomes in terms of personal injury and damage to property and the environment. Each method needs different personnel, materials and extinguishing agents.

The methods used by fire and rescue services are based on technical developments and on local traditions which vary between one country and another, between one part of a country and another and between large and small communities.

There are often several different ways of achieving the same results. One obvious example is how water is taken from a fire engine to a firefighter. This can be done by means of a semi-rigid hose on a hose reel connected to a high-pressure pump. It can be done by using a pre-connected, double-rolled small diameter hose with a low-pressure pump. It can also be done by using a large diameter hose from a hose basket, connecting it to a dividing breeching and then to a small diameter hose. All these three methods will provide the firefighter with water for his nozzle. Different systems have different advantages and disadvantages. For example, some systems are fast and others are robust or cheap. Systems are chosen on the basis of the relative importance of their advantages and disadvantages. The variety of solutions available is the reason why this book sometimes describes different ways of achieving the same results.

A fire in a block of flats is one of the many situations that can confront the fire and rescue service.

THE CONTENT AND STRUCTURE OF THE BOOK

This book describes extinguishing agents and their use. The book is intended primarily for emergency personnel in the fire service, which means that it is written largely from the perspective of the fire service. The book deals mainly with extinguishing fires in organic materials, as this is the most common type of firefighting operation. It primarily covers fires in urban environments and in buildings. It does not deal with forest fires. Automatic suppression systems are covered to the extent that they affect the fire service. For information on more advanced systems and on the design of systems see the references to other literature.

The main message of the book is that it is possible to analyse which of the available methods is most suitable for use at each fire. It is also possible to estimate the demand for extinguishing agents, personnel and materiel.

The major part of the book deals with different technical systems and components. A deliberate decision has been made not to name specific products or to cover aspects such as reliability, maintenance and cost-effectiveness.

The introduction is followed by a chapter which deals with the choice of extinguishing agent and places this choice in a broader context. This chapter also covers portable fire extinguishers.

After this come four chapters which deal with the different types of extinguishing agents: water, foam, powder and gas. The structure of these four chapters is very similar. They begin with a description of the physical properties of the extinguishing agent. This is followed by a description of how the extinguishing agent is stored and of the equipment needed to bring it to the fire. The following section of these chapters describes how and for what purpose the extinguishing agent can be used and the size of the systems involved. Each chapter ends with a description of the harm which the extinguishing agent can cause to people and the damage it can cause to the environment and to property. The size of the four chapters reflects the extent to which each extinguishing agent is used. The chapter about water is the largest, while the chapter on foam is smaller and those on powder and gases very short.

The chapter on the theory of extinguishing fires covers the reasons why different types of fires go out. The starting point of this chapter is the two types of flames: premixed flames and diffusion flames. A distinction is also made between flames that interact with the fuel surface and those that do not.

At the end of the book is an extensive bibliography. In the text, cross-references to the bibliography are shown in brackets, for example (Särdqvist 2000) or Särdqvist (2000). The purpose of the bibliography is to allow readers to go back to the source material and find out more about a specific subject. Information from other sources may contradict what is written here and printing errors may also occur. For these reasons it must be possible for anyone who wants to investigate what lies behind the information to return to the original references.

The bibliography is followed by a list of quantities and the index. The list of quantities gives all the quantities and units used in the book. At different times, different units have been used to describe the same quantity. This book uses the SI system because this requires the least effort in calculations and reduces the risk of errors. Other units are used in older works and in books written in other countries, for example to measure pressure. On the back jacket flap is a conversion table which is intended to make it easier to convert one unit to another.

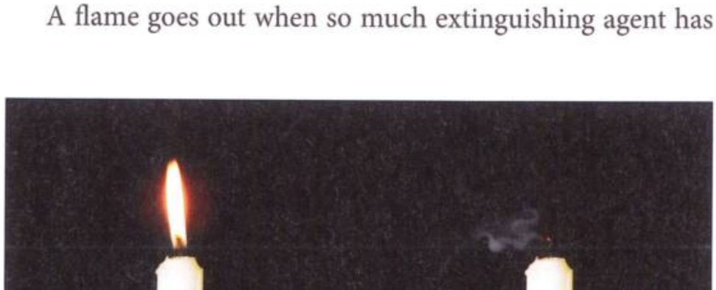
Overview of firefighting operations

1.1 The smaller the particles of the extinguishing agent, the larger the surface area which comes into contact with the flames. If the sides of the small cubes are 1 cm long, the surface area of the large cube is 24 cm^2, while the total surface area of all the small cubes is 48 cm^2. When the size of the droplets or grains is halved, the surface area doubles.

The most common reason for a fire going out is that the temperature of the flames falls too low. This is referred to as the thermal extinguishing effect. When water is sprayed onto the surface of burning wood, the fire goes out because the flames cannot maintain a sufficiently high temperature. This, in its turn, is due to the fact that the concentration of pyrolysis gases falls and that energy is used to vaporise the water, rather than to decompose and vaporise the fuel.

Spraying an extinguishing agent onto a burning mass of gas also results in a thermal extinguishing mechanism taking effect. In this case it concerns the heat balance in the flames themselves where the chemical reaction takes place. The extinguishing agent, for example droplets of water or grains of powder, must be heated to the same temperature as the flames. This uses so much energy that the flames are extinguished. The smaller the droplets or grains are, the more effective the heat transfer.

A flame goes out when so much extinguishing agent has



1.2 Combustion involves a fuel reacting with oxygen to release heat. Extinguishing involves heat losses in the flames becoming so great that the combustion process stops.

been applied that the reaction velocity falls below the minimum level needed to maintain the combustion process. Some specific extinguishing agents take part in the chemical reactions in the flames with the result that the radical content becomes too low. In this case the extinguishing agent is said to have a chemical effect. This method of extinguishing fires is sometimes referred to as inhibition.

Fires are suppressed by means of cooling

The fire triangle is sometimes used to describe the components needed to start a fire. The fire triangle has three sides: fuel, oxygen and heat. In some cases an uninhibited chain reaction is added to the triangle to turn it into a four-sided tetrahedron. However, this approach is far too simple to explain why fires go out. It describes the ingredients needed for combustion, but not the mechanisms which cause fires to occur or to be extinguished. For this reason, the fire triangle cannot be used in discussions about extinguishing fires.

It is only necessary to remove part of the fuel, oxygen or heat to extinguish a fire. The effects of different measures are interconnected and vary a great deal. If water is sprayed onto a burning surface, the surface temperature falls and the production amount of pyrolysis gases is reduced. As a result the fuel concentration in the flames decreases and less heat is generated. At the same time the oxygen concentration falls because of the steam which is produced. Spraying water on the surface of fuel therefore has an impact on all three sides of the fire triangle. However, the fundamental principle behind the fire going out is that not enough heat is released to maintain the temperature of the flames.

The fire triangle describes the components involved in combustion but does not help to explain why a flame goes out. Most often flames go out because too little energy is released to maintain the temperature of the flames.

Sometimes the fire triangle can also be misleading. Extinguishing the burning surface of a fluid with a carbon dioxide extinguisher primarily has a thermal effect. The oxygen concentration certainly falls, but the most important extinguishing effect is that the carbon dioxide must be heated to the same temperature as the flames. This uses so much energy that the flames are extinguished.

DIFFERING TIMESCALES

The reactions between the fuel and the oxygen take place at a molecular level. This is a question of chemistry. The movement of the fuel, oxygen and combustion gases are on the other hand a physical phenomena. The chemical reactions normally take place quickly in relation to the velocity with which the gases are transported within the flames. The chemical timescale, which depends on the reaction rate, is therefore short in comparison with the mechanical timescale which is governed by gravity.

In the case of fires which are about to go out, for example because an extinguishing agent has been applied, the temperature of the flames falls and the reactions become slower. The time needed for the chemical process therefore increases. The extinguishing agent cools the flames and the reactions are slowed down. When the chemical timescale is as long as the mechanical timescale, the flames become increasingly unstable and finally go out altogether. The flames are extinguished when the movement of gas out of the flames is faster than the reaction velocity.

The fact that the movement of gas and therefore the combustion process is controlled by gravity becomes evident when the gravitational force changes. The limits of combustibility and inerting depend on gravity i.e. the mechanical timescale. Normal variations in gravity do not have any impact, but the effects become clearer at the low G forces which occur during space travel and the high G forces which are generated in a centrifuge.

1.3 The burning material can be moved away to make extinguishing the fire easier.

SEPARATION

Separation does not involve applying an extinguishing agent to the fire. Instead the fire's fuel supply is cut off. This is basically a defensive approach, because it is not aimed primarily at extinguishing the fire. Instead it means accepting that the materials which form part of the fire will continue to burn, but preventing further fuel from becoming involved.

Separation is not an extinguishing agent, nor is it purely an extinguishing method. If a building is overcome by flames and

1.4 In olden times fire hooks were used to pull burning objects out of fires or to rescue valuable items.

is emitting powerful radiant heat in the direction of a caravan which is parked nearby, separation involves moving the caravan away. This will probably use fewer resources than continuously dousing the caravan with water. It is likely that it will be quicker to move the caravan away than to protect it with a sheet of foam. Using a sheet of foam is also an extinguishing method which in some respects involves separation. Which extinguishing method is being used when a smoke vent is opened in a burning industrial building and flashover is prevented by allowing the accumulated smoke to escape?

Separation is an excellent first resort, for example in the case of fires involving gas leaks. Burning gas from a broken pipe can be extinguished using powder or a water fog, for example. Unfortunately the gas will continue to escape and may accumulate, resulting in an increased risk. A better approach is to cut off the gas supply and allow the flames to go out of their own accord.

The simplest method of handling fires in storage areas is generally to separate the seat of the fire from the unaffected fuel mechanically. In the case of large fires, separation is often the means by which the fire is actually brought under control.

During the post-war period large quantities of grain were stockpiled throughout Sweden. One day one of the supervisors of the grain store in Nässjö, Bror Larsson, smelled smoke. The store was large, 40 x 80 m, and after searching for some time he located the problem. The mountain of grain had

It is important to have the right tools for any task and there is no single tool which can saw, hammer in nails and put in screws. In the same way there is no single universal fire extinguishing method which suits all types of fire.

become too high in one place when the store was filled, and had engulfed a light bulb. For safety's sake Larsson informed the fire service, before digging out the bulb. The officer in charge misjudged the situation and a few minutes later three fire engines arrived with sirens blaring. The firefighters began setting out their hoses with the aim of using water to put out the fire. Fortunately the operation was stopped and as a result the affected grain could be carried out in tin buckets. Four buckets of grain were spoiled but the rest of the store, around 5000 tonnes, was saved from the firefighting operation.

The choice of extinguishing method

Just as a painter has a range of colours on his palette, so the fire service has a number of different extinguishing methods and techniques at its disposal for fighting fires. In every situation it is important to choose the best solution in order to cause as little damage as possible and use the least possible effort. This will result in the best cost-benefit ratio. It is important to consider which type of operation will result in the least overall damage. By studying different fire extinguishing agents and methods it is possible to evaluate the advantages and disadvantages of the different systems. However, it is not a new approach in itself which will produce improved results. The new approach must also be logical and appropriate.

Firefighters must have had extensive practice in the methods used in operations. They must also be able to handle equipment which is rarely used.

It is worth remembering that all fires will go out sooner or later and that there is unfortunately no multi-purpose method which is right for all situations. Using a water spray to put out a fire manually is the best solution for most fires, but by no means all.

Regardless of which method the firefighters use, they must have practiced it carefully beforehand. All the personnel involved in an operation must be fully familiar with the equipment and the methods being used. This applies in particular to equipment and methods which are rarely used, where firefighters do not have the opportunity to acquire enough experience from using them in real-life situations.

1.6 The firefighter finds it difficult to reach the fire in the rolls of paper using water. The build up of smoke may gradually force him to retreat.

1.7 Low-expansion foam runs down between the rolls and reaches the fire more effectively. As a result the fire is extinguished more quickly.

1.8 A built-in fire extinguishing system is an even better solution, primarily because of the position of the nozzles above the fire.

In the case of fire in the roof area of a 1960s block of flats, with concrete beams between the attic and the top-floor flat, the least damage can often be caused by not extinguishing the fire. The structure is allowed to burn, but the risk of the fire spreading must be taken into account. For example the base of the roof may burn and collapse, and therefore hoses must be in position round the whole building. The beams and the remainder of the building must be checked to ensure that the fire does not spread through gaps in the beams and other structures. The firefighters must be ready to put out the fire if this is deemed necessary, using foam, for example.

The table overleaf gives a summary of the different types of situation and the applicability of different extinguishing methods. The information in the table should not be regarded as hard and fast rules, as the most appropriate method always depends on the individual situation.

In real-life situations there are always other facts to be taken into consideration which may mean that the assessment of the situation can change. The table should therefore be regarded as a basis for discussions about the advantages and disadvantages of different extinguishing agents.

This type of table can be inappropriate or even dangerous if it is used incorrectly. A table appears to provide a categorical solution, but the conclusions only apply in a few clearly defined situations. In the same way it is impossible to produce a completely comprehensive checklist. If you look carefully at the contents of the table, you will soon find that the operational situations are not particularly well defined and that it is easy to identify situations where you would make quite different recommendations.

The aim of the table is to attempt to help readers to create their own picture of the advantages and disadvantages of different extinguishing agents. This will allow readers to make their own assessments in each individual situation and to draw their own conclusions about the most appropriate solution in the situation with which they are faced.

The second paragraph on this page is so important that it bears repeating. There are no definitive truths.

The table gives a summary of the different types of situation and the applicability of different extinguishing methods. The information in the table should not be regarded as hard and fast rules, as the most appropriate method always depends on the individual situation. In real-life situations there are always other facts to be taken into consideration which may mean that the assessment of the situation can change. The table should therefore be regarded as a basis for discussions about the advantages and disadvantages of different extinguishing agents.

Operational situation	Water jet	Water spray	Water fog	Low-expansion foam	Medium-expansion foam	High-expansion foam	Powder[1]	Gaseous extinguishing agents[1]	Separation etc[2]
Preventing solid material from catching fire	***	****	****	*****	***	***	**	**	*****
Extinguishing deep-seated smouldering fires in enclosed material	*	*	**	*	**	***	**	***	****
Extinguishing smouldering fires in open material	***	****	***	****	***	**	**	**	****
Extinguishing a fire in leaking gas	**	**	***	**	**	**	***	**	*****
Preventing an enclosed mass of gas from igniting	*	**	***	**	**	***	**	****	****
Extinguishing a fire with flames and embers which is hard to access	*	**	***	**	***	****	**	***	*****
Extinguishing a fire with flames and embers which is easy to access	***	*****	*****	*****	****	***	*****	**	***
Extinguishing a fire in a pool of flammable liquid	*	*	***	*****	*****	***	***	***	***
Extinguishing a fire in electrical equipment indoors	*	*	***	*	**	***	***	****	**
Extinguishing a fire in electrical equipment outdoors	*	*	***	***	**	**	***	**	**
Extinguishing a metal fire	***	**	**	**	**	**	****	**	***

1.9 A rough assessment of the situations in which various extinguishing agents are appropriate as part of a fire service operation.

Extinguishing agents with an excellent effect are indicated with *****. There is then a sliding scale which goes down to *. This means that the extinguishing agent has little effect or can even make the situation worse.

1. The properties vary depending on the chemical composition.

2. Separation can include, for example, turning off a gas tap, moving a car or taking other measures which involve controlling the fuel supply.

"Some years ago the Stockholm Fire Brigade was called out again and again to fires in the cooker hood in a restaurant kitchen. We put the fires out, as we had been taught, using carbon dioxide. As the story continually repeated itself, I finally got fed up with it and told the firefighters to use powder. And it did the trick. The fires stopped as if by magic. And that all happened in the 1950s." (Bergström, 2001)

A general analysis can be made in the same way when deciding on the size of automatic fire extinguishing systems. Some of the aspects of the assessment can include the price, the weight and the space needed for the different types of system (Olausson, 2000). Different facts have a different impact on the assessment, depending on whether the system is intended to protect a modern fighter jet or a medieval castle. The information in this table, which covers the remaining aspects, should not be regarded as hard and fast rules, as the most appropriate solution depends on the individual situation.

1.10 Other aspects must also be assessed when choosing an extinguishing agent for firefighting.

Other aspects	Low-expansion foam	Medium-expansion foam	High-expansion foam	Water jet	Water spray	Water fog	Powder[1]	Gaseous extinguishing agents[1]	Separation etc.
Personal injury caused by extinguishing agent	****	****	***	*****	*****	****	****	***	***
Property damage caused by extinguishing agent	**	***	****	*	***	****	*	*****	*****
Environmental damage caused by extinguishing agent	**	***	****	*	***	****	****	***	****
Visibility	*****	****	*	*****	****	**	*	***	***
Range	*****	***	**	*****	****	**	****	***	***
Use of personnel	***	****	*****	***	****	****	****	*****	****
Use of equipment	**	**	***	**	***	****	****	*	**
Consumption of extinguishing agent	**	***	****	****	*****	****	***	*	*****

The classification is the same as in the previous table, with ***** indicating the best option and * the worst.
1. The properties vary depending on the chemical composition.

1.11 A small fire needs only a small amount of extinguishing agent. Large fires need large amounts of extinguishing agent.

OPTIMISING THE APPLICATION OF EXTINGUISHING AGENTS

It is obvious that a small fire will require a small amount of extinguishing agent and that a large fire will require more. In addition fires grow in size over time. Therefore either a small quantity of resources is needed at an early stage or a larger quantity later in the development of the fire. The difference between the early and late stages of a fire can be as little as a few minutes.

The time needed to extinguish a fire depends on the application rate of the extinguishing agent. See the figure on page 21. If the application rate is too small, the fire will not be extinguished. If the application rate is increased, the fire will eventually go out. The minimum flow needed to extinguish the fire is referred to as the critical application rate. Unfortunately at the critical application rate an almost infinite amount of time will be required to extinguish the fire.

The more extinguishing agent which is applied to the fire, the faster the fire will be put out. If the application rate is increased too much, some of the extinguishing agent will not be used.

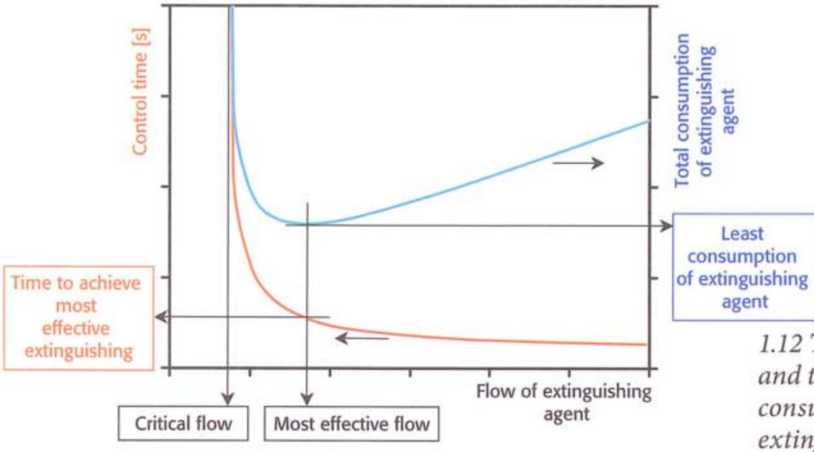
The fundamental link between the extinguishing time and the application rate remains the same, regardless of the extinguishing agent used, for example water, foam or powder. At a certain lowest application rate, the extinguishing time can extend into infinity as shown in the figure on the next page. Therefore it is the extinguishing situation which determines the critical application rate.

However, it is not only the application rate which is of interest, but also the total consumption of extinguishing agent. If the application rate is multiplied by the extinguishing time, this gives the total consumption of extinguishing agent. The curve showing the total consumption of extinguishing agent has an interesting appearance. When the flow is close to the critical application rate, the total volume is large. This is because it takes a long time to extinguish the fire. However, in the case of large flows and overkill situations, the total volume is also large. This is because so much extinguishing agent is applied to the fire that some of the extinguishing agent is not used effectively. The minimum total volume lies somewhere between these two extremes. The minimum total volume can be referred to as the optimum application rate.

The curve showing the total quantity of extinguishing agent takes the form of a fish hook. This is because, however large the flow of the agent, it still takes a certain amount of time to extinguish the fire. The shorter the overall time, the larger the proportion of the time is spent putting the extinguishing agent in place. This will always take a certain amount of time and in many cases is not related to the total amount of extinguishing agent.

The total consumption of the extinguishing agent will be at a minimum and the extinguishing agent will be used most effectively when the actual application rate is somewhere between two to four times the critical application rate. A larger quantity of extinguishing agent is needed when the application rate is increased. This results on the one hand in the cost of the firefighting operation being higher and on the other hand to direct damage being caused by the extinguishing agent, for example in the form of water damage.

The flow rate being referred to here is the amount which actually reaches the fire. The range of the equipment is often limited and the firefighter therefore has to move close to the



1.12 The control time and the total consumption of extinguishing agent vary depending on the application rate.

fire to extinguish it, which in some cases is not possible. This aspect must be taken into account when designing a a system. The effectiveness of the extinguishing agent is therefore limited and only part of the extinguishing agent will be used effectively, because of problems in applying it. There are examples of firefighting operations which had almost no effect at all, simply because the firefighter could not get close to the fire. The fire burns out of its own accord and this takes a long time. The most obvious example of this is probably fires in tunnels (Bergqvist, 2000).

In many situations it is impossible to assess how big a fire will become. Experience from a number of large fires shows that it is better to attack the fire aggressively from the beginning and send resources back unused at a later stage, than to fall behind and be forced to wait for additional resources to arrive. In addition the delay between ordering resources and them becoming available can be a problem.

It is even better to assess the resources needed for a fire in a specific building in advance. A thorough evaluation in advance of the amount of resources needed, when the necessary technical information can be obtained, is significantly better than an assessment carried out in the heat of the moment.

THE ELEMENTS OF A FIREFIGHTING OPERATION

Firefighting operations can be broken down into different elements and each of these can be described separately. All the elements together form a complete firefighting operation. An assessment can be carried out of what should be done and which resources are needed for each element of the operation.

It is a good idea to find out in advance, for example, how much time is needed before a trailer pump begins to emit water or before a high-expansion foam unit begins to produce foam. It is also a good idea to practice tasks in advance, which provides feedback for the fire brigade's exercise programme.

The water supply is often a central function of firefighting operations. (Melin et al., 1998 a)

Level 1 may imply that 1 person, with access to 1 fire engine, can provide the firefighting entry point with water within 60 seconds and then ensure a constant water supply from a hydrant.

Level 2 may imply that 1 person with a water tender can provide a water supply within 60 s and be able to supply on average 300 l/min at a distance of up to 5 km from a hydrant.

Level 3 may imply that 2 people with access to a hose tender and a trailer pump can connect to a static water supply and supply water within 120 s, and lay out 600 m of single hose or 300 m of double hose within 20 minutes.

Level 4 may imply that 3 people with two hose tenders and trailer pumps can supply 600 l of water per minute using a relay pumping system at a distance of 1200 m from the water supply within 40 minutes or supply 1800 l/min at a distance of 1000 m from a static water supply using a 110 mm hose and trailer pump. (Melin et al., 1998 b)

This approach also formed the basis for the structure of the Swedish civil defence organisation. Each group had a clear statement of what it was required to do and the resources available to it. (Handbok BRAND, 1986)

Each civil defence fire group consisted of the group leader, deputy group leader and six firefighters who had at their disposal a class 1 or class 2 trailer pump, a 500 l water tank and two vehicles with trailers. Each group also had 950 m of 76 mm hose, 400 m of 63 mm hose and 600 m of 38 mm hose.

The fittings consisted of 3 breechings and 4 small and 3 large nozzles. Two BA sets, an ice drill, two stretchers and two first-aid kits rounded off the group's equipment. This would allow the fire group to begin fighting the fire as soon as it arrived at the scene of the incident using water it had brought with it and within 15 minutes of arrival to provide its own water from a water supply up to 600 m from the site of the fire. The group would also be able to set up a 100 m long containment line up to 400 m from the water supply and be able to fight spot fires 600 m from the water supply. The group would also be able to carry out operations in enclosed spaces, provide first aid and transport casualties to the assembly point.

A so-called water group consisted of four people. Their equipment included two hose tenders and a trailer pump. They had 1000 m of 110 mm hose and 300 m of 76 mm hose. Their remaining equipment consisted of 3 breechings for 110 mm hose, two radios, one floodlight and an ice drill. This would allow the water group to begin relay pumping with two fire groups within 15 minutes of arrival. Within 8 hours the group would be able to refill a 400 m^3 emergency water supply from another water supply a maximum of 1000 m away. The group would also be able to provide first aid for the injured.

These examples show the types of task a crew has to handle regardless of the type of fire. If this reasoning is taken further, the capacity of the crew can be related to the size of the fire. The size of the fire can be expressed, for example, in terms of the heat release rate (MW) or of the quantity of fuel which burns in specific period of time (g/s). This can be related to the quantity of extinguishing agent needed. This gives an indication of the amount of resources required for fires of different sizes. This in turn provides a better basis for assessing the size of an operational crew and the resources required in the case of fires in different types of building.

PLANNING FIREFIGHTING OPERATIONS

When a firefighting operation starts, the incident commander must have a plan for how he intends the operation to work. In some cases this is an unspoken plan, often because the situa-

1.13 The first step towards ensuring a reliable, long-term water supply is normally to connect a hose to a hydrant.

tion is familiar and the crew is using a tried-and-tested routine. Sometimes improvisation is needed to achieve the best results, but in these cases it is worth remembering that there must be a plan in place before you can deviate from it.

The fire service's tasks include planning for future assignments. This involves making preparations to ensure that every fire is tackled in the best possible way, taking into account the requirements of the fire and the skills of the fire service. If a crew is mentally prepared for different situations, the operation is likely to have a better outcome.

It is possible to identify possible or probable fire scenarios for particular premises, groups of premises or buildings. The intensity and development of the fire can be assessed using different engineering models. There are methods which describe how the heat release rate of a fire develops and how this influences, for example, the temperature in the fire room or the radiation into neighbouring buildings.

If the size and the consequences of the fire are known, the fire service can plan its countermeasures. There are two starting points for this planning process. On the one hand the planning process increases the knowledge available about how different fire protection systems work. This knowledge is important in situations where, for example, the firefighters must choose whether to open smoke vents or not. On the other hand the planning process also allows possible fire scenarios and countermeasures to be identified. This means that the most effective methods can be used, but also that cases where the fire service's capability is insufficient can be highlighted. (Särdqvist, 1996)

If fire service personnel do not understand how the fire protection system is intended to work in a building, they will not be able to use the system correctly.

When the fire service becomes involved, the fire has already broken out. However, it is worth noting that every building and premises has a passive and/or active fire protection system. The fire service must be able to use these systems.

A fire is burning fiercely inside a small industrial building and the smoke vents in the roof have been opened. If a water monitor is set up to spray water through the openings, the smoke will cool down and the amount of gas being released will be reduced. In tactical terms this can be a good or a bad move, but it is important to know that in this case the two measures counteract each other.

By reviewing the different methods available to the fire service, it is possible to identify those measures which will help the firefighters to achieve their objective. In addition it is possible to identify the method which will allow the objective to be achieved using the minimum staff, materials and extinguishing agent.

The pre-fire plan is an important document which summarises this work. The pre-planning involves studying all the fire protection systems in each specific building. However, it is worth pointing out that the simpler the plan is, the fewer things there are to go wrong. You should never produce a plan that is so complicated that it is not possible to explain it to those responsible for implementing it. In addition the plan should not be so comprehensive that no one can update it.

REVIEWING THE OPERATION

The time that is needed to bring a fire under control varies depending on the application of extinguishing agent. If the operation does not have any effect within a very short period of time, the extinguishing agent, the application rate and/or the application method is not correct. Only a few minutes are needed to

"The first five minutes of an operation will determine the following five hours."

review whether the operation is successful or not. This is true regardless of the extinguishing agent being used, provided that the operation is basically offensive in nature. The control time is almost constant for all fires which can be extinguished and when the application of extinguishing agent reaches the critical level the control time increases dramatically.

If the structure and size of the operation are correct, then its effects will be seen immediately. If no clear effects are seen, the firefighters need to consider whether they have chosen the right extinguishing agent, application method and application rate. If nothing decisive has happened within half an hour, then the method used or the size of the operation are definitely wrong!

This reasoning applies to operations with an offensive objective, where the aim is to extinguish the fire. Defensive operations, where the objective is to prevent the fire spreading, but not to attempt to extinguish it, are more time-consuming. In these cases the fire must be preventing from spreading until it dies out because of a lack of fuel.

Studies of major fires show that the incident command was not always aware of the progress of the spread and the extent of the fire (Särdqvist, 1998). This means that the context in which the firefighting operations took place was not clear. If the conditions of the fire are not known, the fire service operation will not produce the best possible results. If the size of the fire is not known, it is not possible to decide on the size of the operation needed to combat it. (Svensson, 1999)

There are unfortunately several examples of operations where the fire service worked for hours to put out a fire and where a change of extinguishing agent or extinguishing method brought the fire under control in an hour or so. In these cases the operation should have been reviewed at a much earlier stage in order to keep unnecessary damage and costs to a minimum.

Even though large fires cause problems for the fire service, the majority of fires are extinguished when they are still small or very small. Much can be achieved if there are people nearby who can start extinguishing the fire.

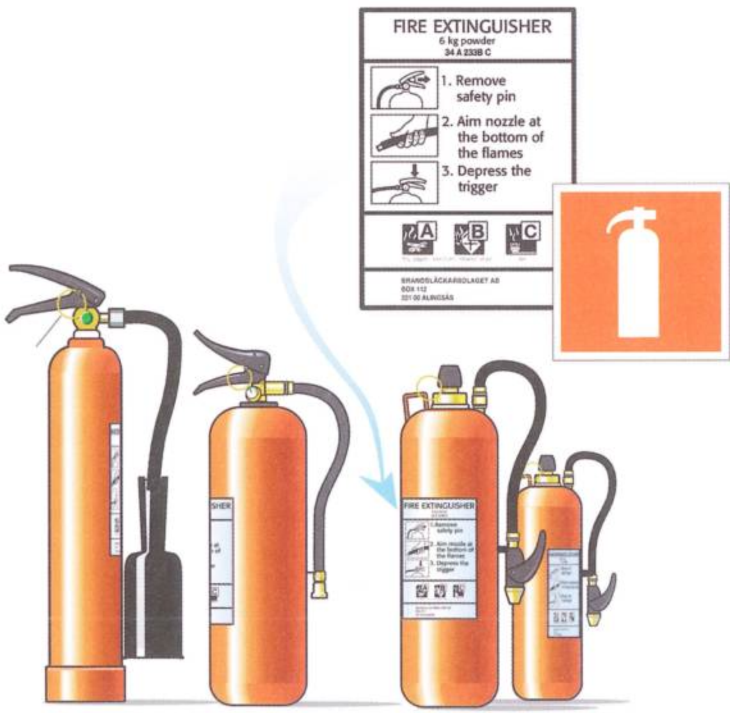
Portable fire extinguishers

Fire extinguishers are designed to allow a quick response to fires which have not yet grown too large. They are therefore intended to be used by members of the general public without the need for specific protective equipment. Fire extinguishers must therefore not be so unwieldy and heavy that people in the vicinity are not able to use them. A fire extinguisher containing 12 kg of extinguishing agent may be the ideal piece of equipment in a fire engine, but it is far too heavy for most other locations.

THE CHOICE OF EXTINGUISHER

Powder has the best extinguishing effect per kilogram of extinguishing agent. A 6 kg powder extinguisher is therefore more powerful than a foam or carbon dioxide extinguisher containing the same weight of extinguishing agent.

The choice of a portable extinguisher must always be based on its intended location. Powder extinguishers are the least sensitive to frost and are therefore the first choice of extin-



1.14 The most common types of portable fire extinguishers: 5 kg carbon dioxide, 9 l foam and 9 and 6 kg powder. The labels on the fire extinguishers are standardised and contain information about the type and quantity of extinguishing agent, the class of the extinguisher and instructions etc. Symbols make the extinguisher easier to use for anyone who cannot read the instructions. The location of portable fire extinguishers is indicated using a standardised sign.

guisher for an outdoor location. Other factors, such as the size of the fire, the extinguishing capacity, the weight, the risk of accidentally setting off the extinguisher, cleanliness and sensitivity to wind, also have an impact on the choice of the type and size of fire extinguisher. Recommendations on which type of extinguisher best suits a particular situation can be obtained from a range of different sources, depending on the field of business. In Sweden guidelines are available from the Work Environment Authority, the Consumer Agency, the Rescue Services Agency, the Maritime Administration and the Road Administration, as well as from insurance companies, fire and rescue services and firefighting equipment dealers.

The recommendations vary depending on the source and have different levels of detail. A 6 kg powder extinguisher or a 9 l foam extinguisher is normally suitable for most buildings, including homes, hotels, offices, care institutions etc. The three most important factors for deciding whether powder or foam is best are that powder creates a lot of dust and is hard to clean up, that powder has the best extinguishing effect and that foam has a more predictable effect for ordinary people. The significance of these three factors varies depending on the position of the extinguisher and on who gives the recommendations. For example, in cultural buildings foam extinguishers are preferable.

In a restaurant kitchen a 5 kg carbon dioxide extinguisher should be used. In boiler rooms, garages and similar locations a 9 kg powder extinguisher may be needed, and in high-risk environments more powerful equipment may be advisable. Carbon dioxide is generally the best choice for electrical cabinets. An extinguisher with at least 2 kg of powder is suitable for small vehicles. The majority of large vehicles, including forestry and agricultural machinery, should have a 6 kg powder extinguisher. In some cases more than one extinguisher is needed. (Handbrandsläckare, 1998)

POSITIONING AND MAINTENANCE

The normal recommendation is for a maximum distance of 25 m between fire extinguishers and for at least one fire extinguisher on each floor of public buildings and workplaces.

In addition fire extinguishers must be placed next to specific risk areas.

Fire extinguishers should also be positioned close to entrances or exits. Then, there is always an escape route behind you and it is possible to stop the extinguishing efforts and evacuate if the fire spreads too quickly. Additionally, the extinguishers are also close at hand in the case of a fire in empty premises which is discovered, for example, because someone smells smoke.

A portable fire extinguisher should always be placed so that it can be used in the case of fire. It must have a clearly visible position and a standardised sign to identify it. The sign should make it possible to see the location of the fire extinguisher even if there are people in the way. Indoor fire extinguishers should be hung on the wall, but not so high that they cannot easily be lifted off the wall. There are specific mountings for fitting extinguishers in vehicles etc. to ensure that they are positioned where they are needed and where they are easily accessible. If necessary the extinguisher can be placed in an extinguisher cabinet.

In addition fire extinguishers must be checked and maintained, and the intended users must have practice and training in using them.

As part of the monthly checks the owner should make sure, for example, that the fire extinguisher:

- is in the correct position in the building
- has a sign which can be clearly seen
- has the right contents and is the right size for its position
- has a wall mounting which is firmly fixed to the wall and which makes the extinguisher easy to lift down
- has no external damage or rust
- has a safety seal
- has a manometer which shows the correct pressure
- has clear instructions for use.

Servicing and maintaining fire extinguishers requires expert knowledge and must therefore be carried out by specialist firefighting equipment companies. Staff in large companies may have the necessary skills, in the same way as the fire service, which in some cases handles the servicing and maintenance of local authority fire extinguishers. The normal inspection interval is one year and a check can be made to ensure that the inspection process is working correctly as part of the fire inspection. A particular audit inspection is needed for some pressurised containers, such as carbon dioxide fire extinguishers and propellant gas containers.

THE DESIGN OF PORTABLE FIRE EXTINGUISHERS

A portable fire extinguisher which complies with the relevant standards is red in colour and is labelled with the type and quantity of the extinguishing agent and the class, amongst other things. Fire extinguishers are available with most types of extinguishing agent with the exception of some gaseous agents. Extinguishers have a standard design and the majority of the specifications below concerning the design and testing of extinguishers are taken from the European standard EN 3, 1996.

Some portable fire extinguishers are pressurised and some are not. Pressurised extinguishers are pressurised as part of the filling process. They often have a pressure gauge which indicates the pressure level. Pressurised extinguishers are the most common type and are the only possible type for gaseous extinguishing agents. Extinguishers which use powder or liquid-based extinguishing agents are obtainable in non-pressurised form. Inside these extinguishers is a small container with propellant gas. This container is opened when the extinguisher is used. The propellant gas is usually carbon dioxide or nitrogen. Non-pressurised foam extinguishers may have the foam concentrate and the water in separate containers. When the system is put under pressure, the foam concentrate container empties and the concentrate mixes with the water. The advantage of this is that it extends the storage period of the foam.

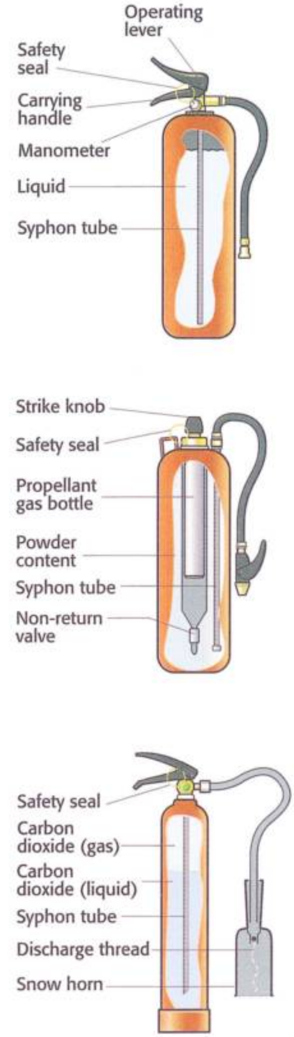
The control valve on fire extinguishers normally consists of a squeeze grip or a push button. Squeeze grips occur most commonly on pressurised extinguishers and are always used in combination with gaseous extinguishing agents. Non-pressurised extinguishers have a strike knob, which punctures the membrane covering the propellant gas bottle and activates the extinguisher. Then a squeeze grip or push button is used to control the flow.

Fire extinguishers have a safety seal in order to prevent them from being set off accidentally. It must be possible to remove the safety seal easily without using tools, and this must be a different process from that used to activate the extinguisher. The seal can consist of a thin wire or something similar, which indicates whether or not the extinguisher has been used.

The size of portable fire extinguishers is normally specified in terms of the quantity of extinguishing agent. Powder extinguishers normally come in 2, 6, 9 and 12 kg sizes. Carbon dioxide extinguishers normally have 2 or 5 kg of extinguishing agent. Halon extinguishers are very seldom used for environmental reasons. Water-based and foam extinguishers come in 2, 3, 6 and 9 l sizes.

The design of the extinguishers differs slightly depending on the type of extinguishing agent. The container of carbon dioxide fire extinguishers differs most from the other types as it is designed to withstand significantly higher pressure than the others. The extinguishers also differ in other details, such as the nozzle. The nozzle of foam extinguishers is often shaped like a small shower head and carbon dioxide extinguishers have a snow horn.

In order to ensure that extinguishers can be put to effective use before they are empty, a minimum discharge time has been specified. Normally the discharge time is much longer than the minimum, around half a minute for larger extinguishers. A good quality extinguisher should have as steady a flow of extinguishing agent as possible and a long effective operating period.



1.15 Cut-away diagrams of a pressurised foam extinguisher, a non-pressurised powder extinguisher and a carbon dioxide extinguisher.

FIRE CLASSIFICATIONS

As a result of the properties of different fuels, different extinguishing agents are needed for different types of fire. Fires can be divided into different classes, depending on the properties of the fuel. The classes specified in EN 3 are A, B, C and D.

Class A includes fires in solid materials, primarily organic substances, such as wood, textiles, paper and many types of plastic. A characteristic feature of these materials is that they normally form embers when they burn. A normal fire therefore consists of both flames and embers.

1.16 The symbols for the three most common classes of fire.

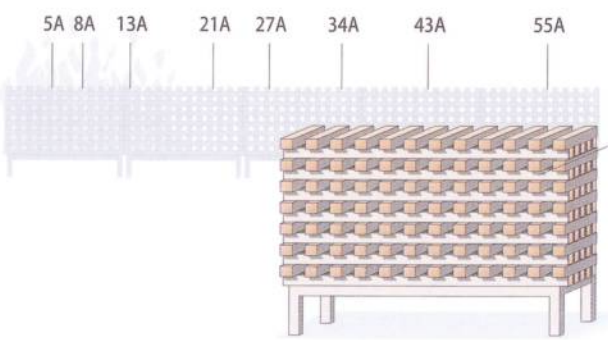
Class B includes fires in liquids and solid materials which can take on a liquid form. Examples of these substances are oil, petrol and alcohol. These are substances which burn with flames but without embers. The temperature of the surface of the fuel never rises above the boiling point of the fuel.

Class C includes gas fires, for example propane or natural gas. These substances also burn with flames but without embers. With gaseous fuels there is no link between combustion and the vaporisation of the fuel. This is an important contrast to classes A and B.

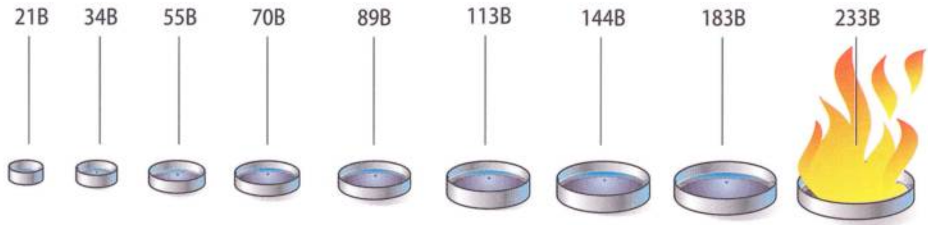
Class D includes fires in metals and metal alloys. The most common fuels in this group are magnesium, aluminium, sodium and potassium.

In some cases fires in live electrical equipment fall into a separate class. Sometimes, but not in EN 3, this type of fire is referred to as a class E fire. Equipment with electrical cables, such as televisions, computers etc. falls into this group. In many cases fires in this type of equipment are easier to manage if the power supply is disconnected, which means that most of these fires belong to class A instead.

It is important to remember how different materials burn. An extinguishing agent which is only effective in the gas phase will provide poor protection against a class B fire reigniting. The reason for this is that there is almost always a flammable mixture of fuel vapours and air above the surface of the fuel. In a similar way an extinguishing agent which only has a surface effect will not extinguish a class C fire.



1.17 Test fire for testing portable fire extinguishers against class A fires. The test fire for class A fires comes in the following lengths: 0.5, 0.8, 1.3, 2.1, 2.7, 3.4, 4.3 and 5.5 m. With a few exceptions each length is the sum of the two previous lengths.



CLASSIFICATION OF PORTABLE FIRE EXTINGUISHERS

1.18 Test fire for testing portable fire extinguishers on class B fires. The square of the radius of the test fires is 21, 34, 55, 70, 89, 113, 144, 183 and 233 dm^2. This value can be multiplied by pi to give the size of the fire in dm^2.

Portable fire extinguishers are classified in accordance with EN 3. The classification numbers are largely incomprehensible to the uninitiated. They are based on the size of test fire which the extinguisher can handle.

Fire extinguishers are classified for class A fires, that is fires in solid materials, by extinguishing a specific stack of pieces of wood. The stack consists of 14 layers of wood with a 39 mm square cross-section. The width of the stack is 0.5 m and the

Extinguishing agent	Quantity in [kg] or [l]	Class A fire	Class B fire
Powder	1	5A*	21B
Powder	2	8A*	34B
Powder	3	13A*	55B
Powder	4	13A*	70B
Powder	6	21A*	113B
Powder	9	27A*	144B
Powder	12	43A*	233B
Water/foam	2	5A	34B
Water/foam	3	5A	55B
Water/foam	6	8A	113B
Water/foam	9	13A	183B
Carbon dioxide	2	–	21B
Carbon dioxide	5	–	55B

* applies only to powder extinguishers classified for class A fires.

1.19 The table shows the smallest fire which can be used to test each type of extinguisher, in order to prevent unsuitable fire extinguishers from being classified. However, a good quality extinguisher must be able to handle a significantly higher class. A 6 kg powder extinguisher, for example, can handle classes 43A and 233B.

class is equivalent to the length in metres. For example a 13A test fire is 13 dm long. The stack of wood is lit from below with a heptane fire which burns for a specific period of time. The extinguisher is classified according to whether the operator can put out the fire within five minutes (seven minutes for 27A fires and larger). After the fire has been extinguished, no flames should be visible for a period of three minutes. The results from this type of test are unfortunately dependent on the operator and vary depending on who carries out the test.

The classification for class B fires, that is fires with a fuel in liquid form, is based on the same standard and involves putting out a fire in a circular pool of heptane on a water bed. Heptane is a non-polar liquid. Therefore there is no guarantee that a foam extinguisher tested to class B will extinguish fires in alcohol or other polar liquids. The number of the test fire indicates the square of the radius of the fire measured in decimetres. Fire 70B is a circle with a radius of 0.84 m and a surface area of 2.20 m^2. The fire is put out manually in the same way as for class A fires and the results are therefore also dependent on the operator.

For class C fires there are no classifications for testing portable fire extinguishers.

Portable fire extinguishers with water-based extinguishing agents are tested on fires in electrical equipment. If the extinguisher does not meet the requirements, this must be specified on the extinguisher. Electrical conductivity is measured by pointing the jet of liquid from the extinguisher at a live plate and measuring the current running through the jet.

Powder fire extinguishers are also tested to ensure that the powder does not compress and make the extinguisher unusable. There are also several requirements relating to the technical design of fire extinguishers, for example frost and corrosion resistance, the strength needed to activate the extinguisher, the strength needed to break the safety seal, mechanical resistance and the accuracy of the pressure reading etc. See EN 3, 1996.

Water

Water has properties which make it the most important extinguishing agent, regardless of whether the fire is being put out by members of the public, by the fire service or by an active fire extinguishing system. No other extinguishing agent is available in such large quantities and at such a low price as water. It is easy to transport and to apply to the fire. Because it vaporises, water has good extinguishing properties.

The behaviour of water in a firefighting context is described by Herterich (1960). For a more general description of water, refer to an encyclopedia.

Physical properties

Water has interesting physical properties from a firefighting perspective. Its freezing point and boiling point are such that it occurs naturally in solid, liquid and gaseous form. It has a high vaporisation heat, 2260 kJ/kg, and it is a challenge for firefighters to make the best possible use of this property. The surface tension of 73 mN/m between water at a temperature of 18°C and the air will be of interest when we come to discuss additives.

Freezing point	0	°C
Boiling point	100	°C
Specific heat capacity of ice	2.09	kJ/kgK
Specific heat capacity of liquid at 15°C	4.18	kJ/kgK
Specific heat capacity of gas at 700°C	2.0	kJ/kgK
Fusion heat	334	kJ/kg
Vaporisation heat	2260	kJ/kg
Surface tension at 18°C (liquid-air)	73	mN/m

2.1 Water's most important physical properties.

Temperature [°C]	Density [kg/m³]	Dynamic viscosity [Ns/m²]	Kinematic viskosity [m²/s]	Steam pressure [k…
0	999.87	$1.780 \cdot 10^{-3}$	$1.785 \cdot 10^{-6}$	0.61
5	999.99	$1.518 \cdot 10^{-3}$	$1.518 \cdot 10^{-6}$	0.87
10	999.73	$1.307 \cdot 10^{-3}$	$1.306 \cdot 10^{-6}$	1.23
15	999.13	$1.139 \cdot 10^{-3}$	$1.139 \cdot 10^{-6}$	1.70
20	998.23	$1.002 \cdot 10^{-3}$	$1.003 \cdot 10^{-6}$	2.34
25	997.07	$0.890 \cdot 10^{-3}$	$0.893 \cdot 10^{-6}$	3.17
30	995.67	$0.798 \cdot 10^{-3}$	$0.800 \cdot 10^{-6}$	4.24
40	992.24	$0.653 \cdot 10^{-3}$	$0.658 \cdot 10^{-6}$	7.38
50	988.07	$0.547 \cdot 10^{-3}$	$0.553 \cdot 10^{-6}$	12.33
60	983.24	$0.466 \cdot 10^{-3}$	$0.474 \cdot 10^{-6}$	19.92
70	977.81	$0.404 \cdot 10^{-3}$	$0.413 \cdot 10^{-6}$	31.16
80	971.83	$0.352 \cdot 10^{-3}$	$0.364 \cdot 10^{-6}$	47.34
90	965.34	$0.315 \cdot 10^{-3}$	$0.326 \cdot 10^{-6}$	70.10
100	958.38	$0.282 \cdot 10^{-3}$	$0.294 \cdot 10^{-6}$	101.33

2.2 Some of these properties vary depending on the temperature. Density: CRC (1986) page F-10. Other figures: Vennard & Street (1982)

PRESSURE

Pressure is measured either as an absolute figure or as the difference when compared to a reference pressure, normal atmospheric pressure. This is similar to temperature which is measured either in Kelvin as an absolute temperature or in relation to the freezing point of water in Celsius.

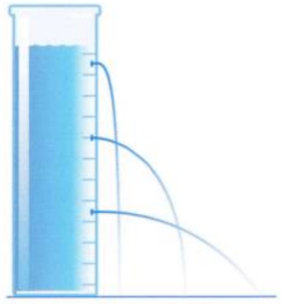
In the case of water supplies for firefighting relative pressure is used almost exclusively. This describes how much higher or lower the pressure is than atmospheric pressure. Pressure gauges are calibrated to show a reading of zero at normal air pressure. If there is a risk of confusion, it must be clearly stated whether positive pressure or absolute pressure is meant.

1 Pa corresponds to the pressure exerted on the surface of a table by a piece of paper. Atmospheric pressure is 0.101 MPa. This corresponds to the pressure from a column of water 10 m high.

Pressure applies in all directions and this can be illustrated using the example of a fire hose. If the pressure is raised, the flow will increase which means that the pressure has increased along the length of the hose. In addition the hose becomes harder. The pressure is also having an effect across the width of the hose.

If two different-shaped containers are filled with liquid to the same level, they will contain different amounts of liquid and weigh different amounts. However the pressure on the base of the two containers will be the same, because the level of the liquid is the same. This is referred to as the hydrostatic paradox.

If a 1 m long, vertical tube with a cross-sectional area of 0.01 m^2 is given a base and filled with water it will hold 10 kg of water. The water will exert a force of 9.81 N/kg · 10 kg = 98.1 N on the base of the tube. This force will be the same across the whole of the base, which is therefore subjected to a pressure of 9810 N/m^2, or 9810 Pa when the pressure is expressed as the force per unit of area. If we then take the example of a swimming pool which is 1 m deep and has an area of 100 m^2, the force exerted on the bottom of the pool will be 981,000 N. This force is distributed across the whole of the bottom, which means that the pressure is the same: 9810 Pa. In other words, the pressure at a specific depth below an open water surface is the same regardless of whether the water is in a lake, a pipe or a water tank.



2.3 The larger the distance between the surface of the water and the hole, the higher the pressure and the larger the quantity of water which runs out.

COMPRESSIBILITY

Liquids, in contrast to gases, cannot normally be compressed. If a liquid is subjected to increased pressure, its volume remains largely unchanged. This property is exploited in hydraulic systems. When making calculations concerning water for firefighting, it can be assumed that the density of the water will remain the same regardless of the pressure. Therefore the volume flow rate remains constant throughout the whole hose system. The water which is put in at one end comes out at the other.

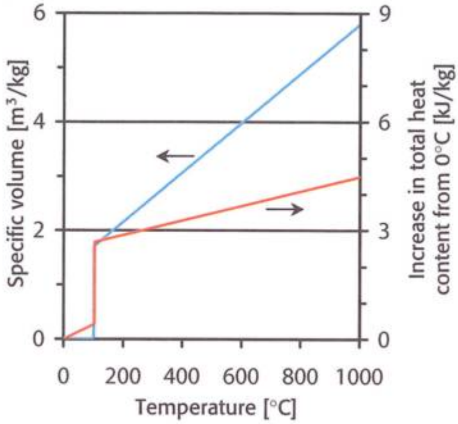
DENSITY

Density is a measure of mass per unit of volume. It can be expressed as:

$$\rho = \frac{m}{V}$$

ρ [kg/m^3] density
m [kg] mass
V [m^3] volyme

Density varies slightly depending on the temperature. Water is at its most dense (1000 kg/m^3) at 3.98°C. At room temperature water density falls to 998 kg/m^3 and at 100°C to 958 kg/m^3 (CRC, 1996 F-4). The density of water is also influenced by its composition. The salt in sea water gives it a slightly higher density than fresh water. For the purposes of calculations the differences in the density of water are normally negligible.



2.4 Two important physical properties of water in a firefighting context are the variations in its energy content (right) and volume (left) as the temperature changes.

The fact that the density of water is at its highest at 4°C means that the volume of a certain quantity of water is at its lowest at this temperature. If the temperature falls, the volume increases. When water freezes its volume increases further. As water cannot be compressed either in its liquid or solid form, the pressure exerted by the water increases. Water which remains in a fire hose will stretch the hose slightly. Water which is left in a pump will burst the pump when it freezes, as metal is not elastic enough. In the same way a car radiator without antifreeze will burst when it freezes, as will a glass beer bottle in a freezer.

VISCOSITY

When water flows through a hose, the velocity of the water is highest in the middle and decreases towards the sides. The water closest to the side of the hose is stationary. Different fluids have different levels of viscosity and therefore different velocity profiles in a hose. Viscosity can be described as the resistance of a fluid to deformation.

There are two different types of viscosity. Dynamic viscosity is the dynamic connection between the force which is applied to a liquid and the movement which this force gives rise to. Kinematic viscosity is the dynamic viscosity expressed in relation to the density of the substance.

$$\upsilon = \frac{\mu}{\rho}$$

υ [m^2/s] kinematic viscosity
μ [Ns/m^2] dynamic viscosity
ρ [kg/m^3] density

HYDRAULICS

In most firefighting operations the water supply does not pose any problems. However there are two main situations where problems with the water supply do arise. One of these is a fire on a farm or an industrial site where the volume of water available is limited. If the firefighters attack the fire vigorously in its early stages, this will use a lot of water. There is then the risk that the water will run out before a continuous flow of water has been set up. The second situation concerns forest fires, where the hose system quickly becomes confusing and too many nozzles, single hoses that are too long and too few pumps result in the water supply being cut off to some nozzles.

Hydraulics, which is a well-established engineering discipline, involves transporting water through hose systems. As a result there are a number of textbooks which cover this subject. It is not only the fire service which has an interest in how fluids behave. See, for example, Vennard & Street (1982), Featherstone & Nalluri (1995) and Titus (1995).

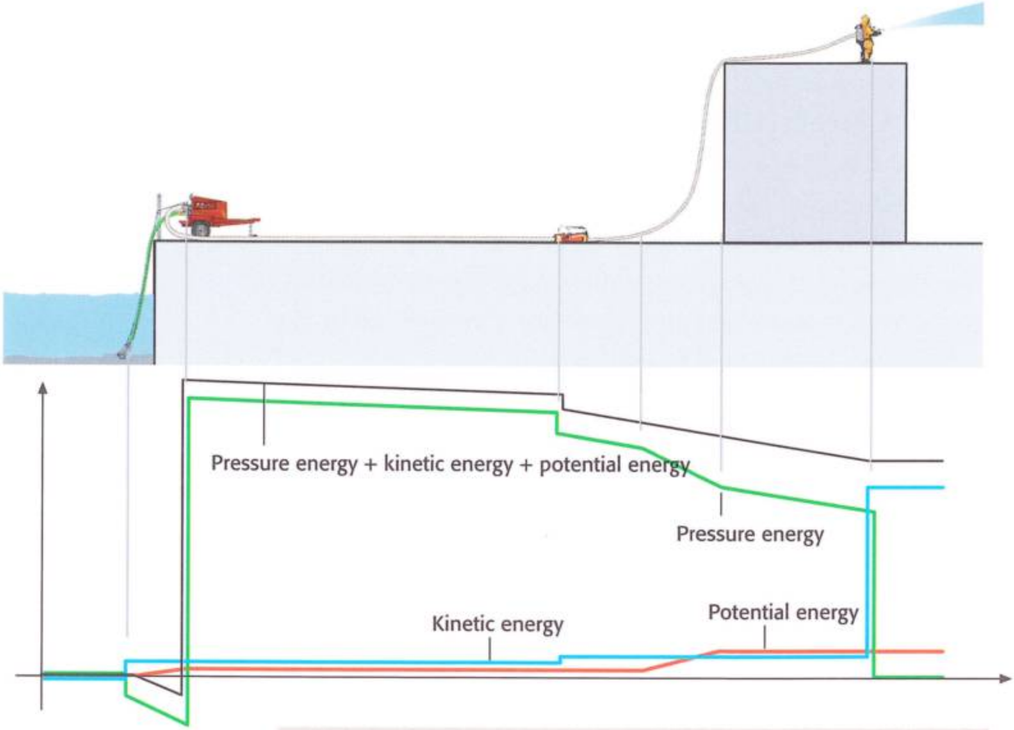
A large part of the problem relating to water flow and pressure can be avoided by using pressure gauges and/or flow meters. If a pump has a flow meter fitted, the pump operator can set the pressure of the pump so that the required flow is produced in the nozzle. If the flow is correct, the nozzle pressure will also be correct.

Pressure gauges are easy to use and are an excellent means of investigating pressure losses in experimental conditions. A short, wide hose which is smooth on the inside and having a small flow of water will have small pressure losses. On the other hand a long and narrow hose which is rough on the inside and with a large flow of water will have large pressure losses.

THE RELATIONSHIP BETWEEN PRESSURE ENERGY, KINETIC ENERGY AND POTENTIAL ENERGY

A large part of hydraulics theory is based on the statement that energy and matter are indestructible. This means that the total energy and the total matter in a system are always constant. The fact that the total matter is constant means that the same amount of water flows out of one end of a hose as is pumped in at the other.

In hydraulic calculations energy is usually expressed in the form of pressure energy, kinetic energy or potential energy. These three forms of energy can all be represented by the same unit, the Pascal.



2.5 The energy lines illustrate the connection between the different forms of energy.

Pressure energy: p

Kinetic energy: $\frac{\rho v^2}{2}$

Potential energy: ρgz

p [Pa] pressure
ρ [kg/m^3] density
v [m/s] velocity
g [m/s^2 or N/kg] gravitational constant 9.81
z [m] height
K [Pa] quantity of energy

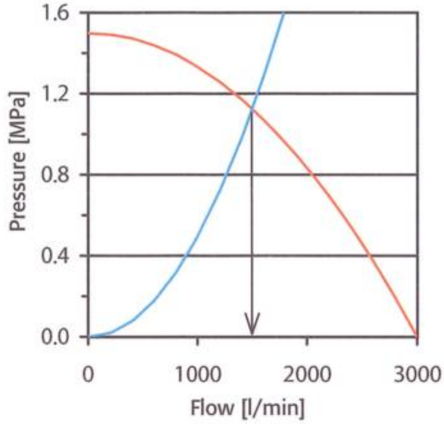
In the 18th century Bernoulli discovered that the total of the pressure energy, kinetic energy and potential energy is constant for an ideal fluid.

$$p + \frac{\rho v^2}{2} + \rho gz = K$$

The equation applies to all points in a system of pipes or hoses. Therefore energy cannot disappear, but it can be converted into a different form of energy. Other energy forms include heat or chemically stored energy. As water in a hose system generally has the same temperature and the same chemical composition throughout the system, these forms of energy are generally constant in a firefighting context.
However, in reality flow losses occur and a small amount of energy is converted into heat. The energy content at point 1 in a system is the same as the energy content at point 2.

$$p_1 + \frac{\rho v_1^2}{2} + \rho g z_1 = p_2 + \frac{\rho v_2^2}{2} + \rho g z_2 + p_f$$

p_f [Pa] pressure loss



2.6 Adding up the total losses in the hose and nozzle produces a system curve (blue). This intersects the pump curve (red) at a point which represents the actual flow in the system.

The flow in a fire hose is determined by the extent of the pressure losses in the system. Pressure losses occur in all pipes which fluids flow through, which means that pressure energy is converted into heat. The extent of the pressure loss is governed, for example, by the length and diameter of the hose and by how smooth it is inside. Local losses can also occur, for example where there are couplings, valves or kinks in the hose. In addition all these losses increase significantly as the flow in the hose increases.

It is possible to create a diagram showing how much pressure a pump can produce at different flow rates. In the same way a diagram can be produced showing the total pressure losses in a hose system at different flow rates. The point where the two curves intersect always represents a state of equilibrium.

ENERGY AS HEIGHT

Dividing each term by the density of the fluid and the gravitational constant results in energy expressed as a height in metres. The total of the pressure energy, kinetic energy and potential energy is still constant, but is expressed here in metres.

$$\frac{p}{\rho g}+\frac{v^2}{2g}+z=H$$

H [m] quantity of energy

This is the background to the pressure units mmHg (millimetres of mercury) and mWc (metres of water column). These forms of energy can also be referred to as pressure height, kinetic height and geometric height.

The water mains network and fire hydrants

All the water used in extinguishing fires is stored in some kind of container. For example, it can be stored in a static water supply, a public water tower, a sprinkler tank, an emergency water supply, a fire service water tender or a portable fire extinguisher. A system of pipes and hoses is used to take the water from the container to the place where it will be used. Information about reservoirs and hydrants, in other words the locations where the fire service can obtain water for firefighting, can be found in the local authority's fire and rescue service plan.

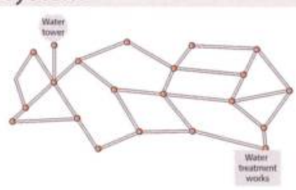
The public water supply system consists of a network of water mains, distribution pipes and service pipes. The water mains run from the water treatment works and reservoirs to residential and industrial areas. The distribution pipes take the water to the customers. Service pipes carry the water on the last stage of its journey from the distribution pipes into each property. The size of the pipes determines their capacity, in just the same way as for fire hoses.

The central part of the water supply network generally takes the form of a grid system with at least two routes connecting any two points in the system. The peripheral areas of the network often consist of a branch system. A branch system has a tree structure in which each point in the system is supplied from a single source.

Sprinkler systems have a similar structure with pipes that branch out into a tree structure. To enable the use of pipes that are as small as possible and therefore to reduce the installation costs, the ends of the pipes are often connected together to form loops.

Fire hoses can also have either a tree, linear or loop structure. The tree system is used when water is taken from one source and a large number of nozzles are used. In order to ensure that the nozzle pressure is the same for all nozzles, it is best if the system is symmetrical, which means that all nozzles supplied by a single pump are of the same type and are connected to hoses of equal length. A line structure consists of a few nozzles supplied from one water source. While fighting the fire the system can be extended by adding supply hoses and moving the attack hoses forwards. A loop structure involves laying a hose in a circle round the fire. It does not matter where on the loop the attack hoses or the water supply is connected. The reliability of the system can be increased by connecting hoses together so that the system can be supplied from more than one source, either by using a cross-supply system or a loop.

The differences between grid and branch systems are the same for the public fire hydrant network, a sprinkler system or a fire service hose system. Often a combination of a grid and a branch structure is used in the water mains network, sprinkler systems and fire hose systems.

Grid system	Branch system
	
If a pipe or another component is damaged, part of the system can be closed off without interrupting the water supply to the remainder of the system.	If a pipe or another component is damaged, the entire system downstream of the component is affected.
If necessary water can be kept circulating throughout the system without any being taken out.	Water can remain stationary in the pipes.
The capacity of the system is larger because the flow can be distributed amongst a large number of pipes.	
The system is more confusing and it is hard to determine how the flow and the pressure are distributed through the system.	The system is easily understood and the pressure and flow can easily be determined.

2.7 Different types of systems for distributing water have different advantages and disadvantages.

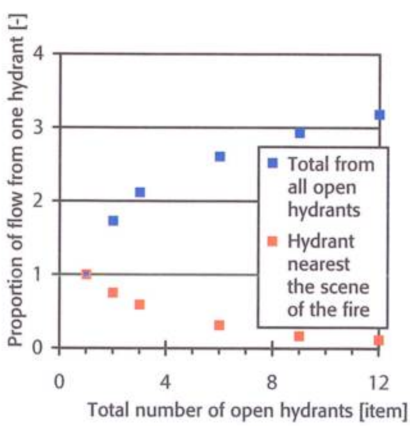
FIRE HYDRANTS

The most common way for a fire service to ensure that it has a continuous water supply is to connect its hoses to the public water mains network. A water supply map is an invaluable tool for identifying where water can be obtained, and there should be copy of the map in every fire engine. A good water supply map will show the location of the nearest hydrant and its pressure and capacity both during peak and low consumption periods. If more accurate data is not available, a classification can be of great help, for example class A for hydrants with a flow greater than 900 l/min and class B for hydrants with a lower flow. The map should also show the location of the next hydrant in case the first hydrant is not working or cannot supply enough water. It should also indicate where the pipes run in case so much water is needed that another water main must be used.

However, it is important to be aware that the specified flow will only be obtained if other hydrants are closed. If one hydrant is open and the next one is also opened, the flow will not be doubled. In practice the total flow will increase by just over 50% when the second hydrant is used. If the third nearest hydrant is opened, the increase in the flow will be even smaller. At the same time the flow from the first hydrant will fall. (Nyberg, 1978)

Even without obvious signs of fire on arrival, the firefighter responsible for the water supply must locate the nearest hydrant.

The water supply map must show all the possible water sources. As no one knows where the next large fire will occur, this should include the public network of hydrants, private industrial networks and static water supplies. The map should be more than a simple map of fire hydrants.



2.8 When several fire hydrants are used, the additional amount of water available is reduced. This example is based on free-flowing hydrants without heads. In reality the change in the flow is not as extreme if additional hydrants are opened.

Many hydrants have a capacity of between 1500 and 2500 l/min. On the edges of the network, for example in residential areas, the capacity may be significantly lower, down to as little as 600 l/min. This applies in particular to so-called flushing hydrants, which are used to flush out the pipes and are therefore at the edges of the network. In these areas the pipes often have a diameter of only 50 mm.

In other places, for example in the vicinity of a refinery, there may be hydrants with a very high flow. These are sometimes called super hydrants. In order to allow the fire service to take large quantities of water from the public network, the service pipes must be connected to mains pipes at least 200 mm in diameter, the reservoir must have sufficient volume and the water treatment works sufficient capacity to supply large amounts of water over a long period (VAV P76, 1997). If this is not the case, then a dedicated permanent firefighting network can be set up which is supplied directly from a static water supply. However, these systems tend to be less reliable because they are only used infrequently.

2.9 In Sweden the same type of hydrant head is used for all hydrants. In other countries, such as Iceland, fixed hydrant heads of different sizes are used. The size of the head relates to the capacity of the hydrant. There it is clear whether the hydrant can supply a large or a small quantity of water.

The pressure in fire hydrants also varies. Normally the highest operational pressure is 0.7 MPa. When a large amount of water is taken from a hydrant the pressure falls, sometimes as low as 0.15 MPa.

At industrial sites it is not uncommon for companies to set up their own water systems for firefighting on the premises. Sometimes this is a requirement from a local authority before a company can occupy a site. These systems can be of different types, but it is important that the fire service is aware of their structure and of what is needed to access the water. More water is often needed for a firefighting operation than for normal operation. For this reason there may be a bypass coupling for the water meter which reduces flow losses and increases capacity. It is the responsibility of the fire service to open this valve if fire hydrants on an industrial site are being used and to ensure that it is closed and sealed when the operation is completed.

Fire hydrants should preferably be positioned next to the road, ideally on the pavement and near to a junction. This ensures that they are not in the way and that the traffic is not

2.10 Hydrant with a hose connected.

obstructed while they are in use. At the same time they are fully accessible, both for filling water tenders being used in a shuttle service and for use with hoses which are taken directly from the hydrant to the scene of the fire.

In Sweden the location of fire hydrants is indicated by a hydrant flag or a sign 2.2 m above ground level and a maximum of ten metres from the fire hydrant (VAV P76, 1997). The sign shows the direction of and distance to the hydrant. Using this information it is possible to locate the hydrant cover, if the hydrant is covered with snow. The hydrant key can be used as a ruler. Keys are normally 1.2 m long and have 0.5 m and 1.0 markings on the handle. By knocking on the ground with a hydrant key and listening to the sound it makes, it is possible to find the hydrant cover.

Fire hydrants normally contain water which must be flushed out before the hydrant is used. Once all the discoloured water has been washed out, the hydrant head can be fitted.

Connecting to a ground hydrant:

1. Prize off the cast iron cover using the point of the hydrant key.
2. Open the bottom valve and flush the hydrant until fresh water appears.
3. Close the bottom valve and fit the hydrant head. In the

case of hydrant heads with a screw fitting, the key can be placed between the valves on the head and used carefully as a lever.

4. With the valves on the hydrant head closed, open the bottom valve fully and then close it a quarter turn. The hydrant is now pressurised and ready for use. The key should be left behind if the hydrant needs to be closed.

2.11 Hydrant head and key.

Hydrant connections vary from city to city. Each city has adapters to fit its own hydrants.

A hydrant head consists of a standpipe with two large diameter hose outlets, each of which has a screw valve. Hydrant heads are normally cast in a light metal alloy. In order to make the best use of the water available, hoses should be connected to both outlets.

The hydrant must be closed after use. If it does not seal properly, there may be debris in the valve, which must be flushed out. If this does not help, the gasket may need to be changed. In winter the hydrant may need to be emptied before the cover can be put back in place.

Where there is a risk of hydrants freezing, it may be preferable to mount them on a wall and/or to install a heating element. Hydrants may also be mounted on walls for easy accessibility or because of the position of water pipes, for example on industrial sites.

No hydrant head is needed for a wall-mounted hydrant. The supply hose simply needs to be connected to it. However a specific key is required to open the wall cabinet.

In accordance with VAV P76 (1997), fire hydrant inspections can include:

1. Checking accessibility, signs and directions.
2. Checking the cover and fittings.
3. Checking the opening and closing valve.
4. Checking that there are no leaks.
5. Checking the drainage and any drain holes.
6. Pumping dry if necessary.
7. In winter checking that snow has been cleared and that the heating element, if there is one, is functioning.

	Type of building	Recommended flow [l/min]
Residential area etc. including service facilities	Detached, terraced and semi-detached houses, together with blocks of flats with less than 4 floors	600
– " –	Other residential buildings	1200
Industrial and similar areas from a firefighting perspective	Fire-resistant buildings with no stocks of flammable materials	600
– " –	Fire-resistant buildings with no large stocks of flammable materials	1200
– " –	Heavy fire load, for example carpentry workshops and timber yards	2400
– " –	Exceptional fire load, for example oil processing plants	> 2400

2.12 Water requirements for firefighting in a conventional system (VAV P38, 1979).

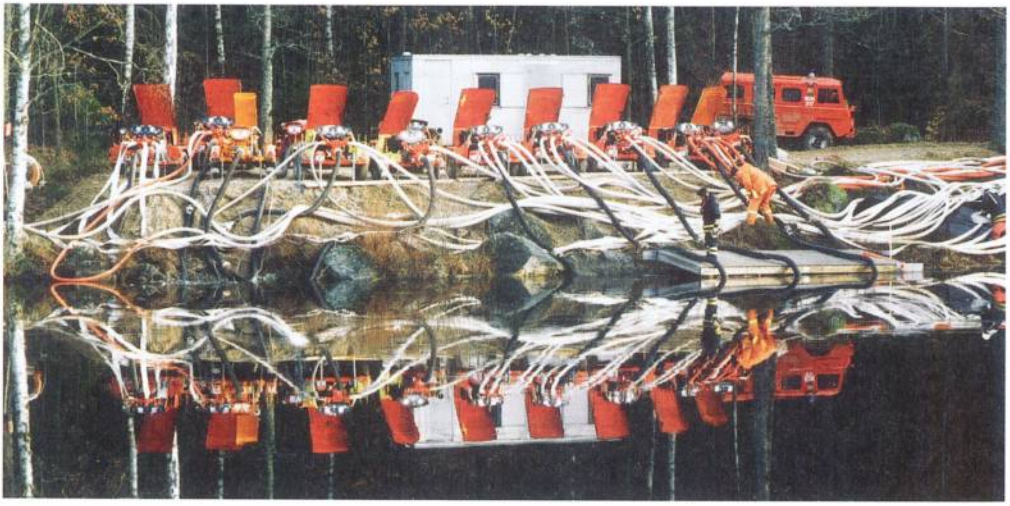
THE CONVENTIONAL SYSTEM AND THE ALTERNATIVE SYSTEM

The conventional system involves using hoses and booster pumps to take water directly from fire hydrants. In this system the hydrants must be a maximum of 100 m apart. However, this distance can be increased to 150 m in areas where there are one-family and two-family houses. The size of the conventional system is based on the fact that the fire service does not bring significant quantities of water to the scene of a fire.

The alternative system also includes using the water tenders which most local fire services in Sweden have. With one or more water tenders operating a shuttle service the same flow of water can be maintained. If the water is supplied using water tenders, the distance between the furthest built-up area and the fire hydrant must not be more than 1000 m. The flow must be at least 900 l/min. The main argument for the alternative system is a financial one. The conventional system requires a very large number of fire hydrants which involves significant installation and maintenance costs (Mattsson, 1994).

STATIC WATER SUPPLIES

Using a static water supply near the scene of the fire as a source of water is often an excellent solution. Lakes, rivers,



2.13 *Taking water from a static water supply at the water treatment works in Karlshamn using trailer pumps was a temporary solution when a Hazmat accident prevented the normal water supply from being used.*

streams and ponds generally contain sufficient quantities for use in extinguishing smaller fires. Swimming pools can also be used where appropriate. However, springs have such small volumes of water that they can rarely be used.

If water can be taken from a static water supply, suitable sites must be investigated in advance and marked on the water supply map. If necessary, sites for portable or trailer pumps can be set up. For special buildings a fixed suction hose can be installed which the pump can be connected to.

Salt water is sometimes the most easily accessible type of water and it is an excellent extinguishing agent. However, it can cause damage to pumps and fittings, which means that they must be carefully rinsed out. Salt water also damages vegetation.

If a water treatment works is out of action for any reason, the network of hydrants will be unusable. In this case the fire service must be prepared to fetch water from another source. A combination of static water supplies and water tenders is the obvious choice in most cases.

However, it is not always possible to take water from static water supplies. A water tender without a suction hose and a pump primer will not be able to do this. A suitable pump must also be taken to the incident.

A variant of a static water supply is a mobile water tank. These are normally made of rubber or plastic fabrics. Diffe-

2.14 Water tenders running a shuttle service can be used to ensure a reliable water supply.

rent types are available, including self-supporting pools and pools with frames. Depending on the purpose for which they will be used, they come in different sizes and can hold tens of cubic metres of water. The self-supporting pools in particular are relatively light in weight. This means that they do not need to be near a road and therefore provide an excellent temporary water supply. They simply need a level, relatively smooth surface where they can be set up.

SUPPLYING WATER USING WATER TENDERS

In some situations the fire service is faced with a choice of transporting water to the scene of the fire using hoses or water tenders. If the water and the fire are around 500 m or more apart, it starts to become worth using water tenders rather than hoses, although this may depend on the local conditions. The decisive factors include the water consumption, transport capacity and, not least, how long the operation is expected to last.

It is important that the vehicles running the shuttle service are able to take a circular route. If many vehicles are being used, the logistics must be carefully planned, in particular if the road leading to the scene of the fire is narrow. It may be appropriate to ask the police to set up a one-way system on the narrow roads around the fire.

The water can be discharged from hoses directly into the firefighting network at the scene of the fire. The water system starts with a collecting breeching at the discharge point which the water tenders can be connected to in turn. The major disadvantage is that several water tenders are needed for continuous operation. In addition the water tenders take a long time to empty. One advantage is that the water tenders' pumps can be used at the scene of the fire.

An alternative to using a collecting breeching is to bring a tank to the scene of the fire. The tank must have the same volume as the tenders which are operating the shuttle service and can either consist of a vehicle or a tank with trailer pump to suck out the water. The tank must be positioned where the water can easily be discharged and as close to the scene of the fire as possible. This means that the supply hoses will be short. As a result the pressure losses will be small and only a small quantity of water will be needed to fill the hoses. This system probably offers a more reliable water supply than using a collecting breeching, but in both cases the logistics must be carefully thought out in order to guarantee the availability of the water.

The tank system needs more resources than a hose system in situations where a large flow is needed over a long period. On the other hand the start-up time is short, which means that the fire can be tackled more quickly.

The water tenders also function as a buffer at the scene of the fire. The firefighting operation can therefore start with a relatively large flow in a short time before water needs to be taken from hydrants.

THE CAPACITY OF WATER TENDERS IN SHUTTLE OPERATIONS

The capacity of a shuttle system using water tenders can be determined by dividing the volume of the vehicle's tank by the time it takes to do one lap of the transport route. (Sjölin, 1977)

$$q = \frac{V}{t}$$

q [l/min] continuous transport capacity
V [l] tank volume
t [min] time needed for one lap of the transport route

The time needed for one lap of the transport route is the total time needed for the journey to the water supply, connecting and filling the tank, the journey back to the scene of the fire, connecting and emptying the tank. The times can be measured or estimated.

$$t = t_{journey} + t_{conn} + \frac{V}{q_{fill}} + t_{journey} + t_{conn} + \frac{V}{q_{empty}}$$

q_{fill} [l/min] filling rate

q_{empty} [l/min] emptying rate

$t_{journey}$ [min] journey time in one direction, distance divided by speed

t_{conn} [min] time needed for connecting and disconnecting when filling and emptying the tank

The calculation applies to one water tender. If more than one vehicle is being used, the flows must be added together.

A water tender with a 10,000 litre tank is running a shuttle service to fill another water tender close to the scene of a fire. The journey time for the 6 km loop at an average speed of 40 km/h is 9 minutes. Filling the tender from a hydrant takes 5 minutes and discharging the water takes 10 minutes. The connection time is 2 minutes in each direction, which makes 4 minutes in total. In this case the possible flow is: q = 10,000 / (9 + 5 + 10 + 4) = 360 l/min.

If both water tenders are used and discharge the water into a collecting breeching, the water can only be used at such a rate that the other tender has time to return before the one at the scene of the fire is empty. The water in each tank must last for 9 + 5 + 4 = 18 min and the possible flow is 550 l/min.

WATER SUPPLIES FOR SPRINKLER SYSTEMS

For sprinkler systems computer software is generally used to calculate the drop in pressure, pipe sizes and pump requirements etc. If the public water mains network or booster pumps do not have sufficient capacity for a sprinkler system, water must be stored in tanks (VAV P37, 1980).

In some buildings the mains network supplies both the sprinkler system and manual firefighting. In this case it is important for firefighters to know how much water they can take out without affecting the sprinkler system.

Fire pumps

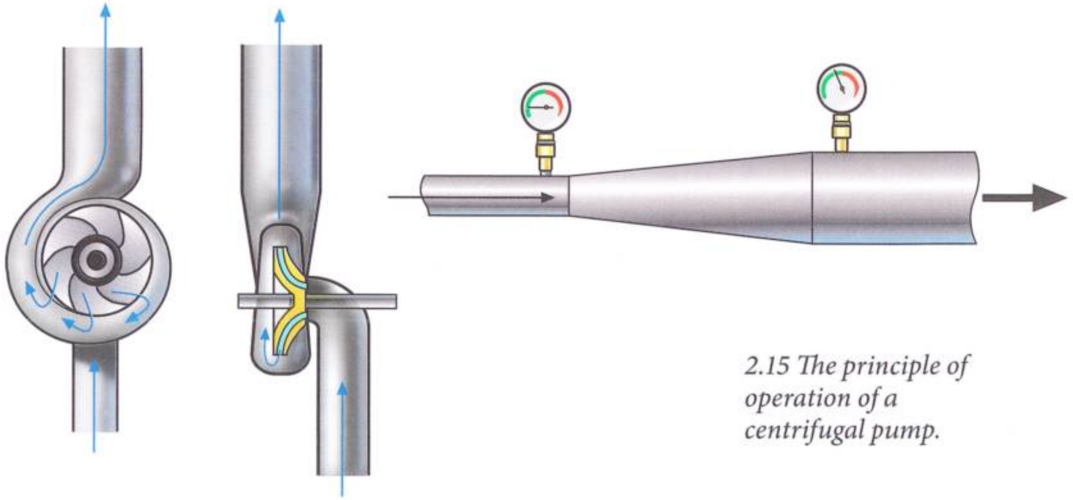
There are flow losses in all hose systems. In order to compensate for these energy losses, additional energy must be supplied. Energy is also needed to overcome the difference in height between the reservoir and the nozzle and to provide the required pressure at the nozzle. Pumps are used to supply the energy.

The development of powerful pumps made a major contribution to the effectiveness of the fire service. Almost 150 years ago Lindgren (1864) stated that "the most important thing is a powerful pump equipped with hoses of a suitable length".

There are several different types of pump. The first fire pumps were plunger pumps, which belong to the family of displacement pumps. They can produce very high pressure, but not a particularly high flow rate. Plunger pumps were ideal for manual operation. They could also be powered by a steam engine because of its forward and backward movement.

Since the introduction of motorised vehicles in the fire service, the majority of pumps used to extinguish fires are centrifugal. This type of pump is well suited to the rotary movement of electric motors and internal combustion engines. The advantage of centrifugal pumps is that the flow is not forced. Instead there is an open connection through the pump. As a result these pumps can be run with a closed valve and will generate pressure in the nozzle even when it is closed.

The two main components of the centrifugal pump are



2.15 The principle of operation of a centrifugal pump.

2.16 It can be mentioned that the epaulettes of British fire officers show a stylised impeller.

the housing and the impeller. The impeller is mounted on a shaft which is connected to an engine via a clutch. When the impeller rotates, it pushes the water outwards and a negative pressure forms in the centre of the impeller where the suction hose is connected. This allows water to flow into the pump and balance the pressure. The impeller is sometimes referred to as the runner.

There is a volute around the impeller which means that the space between the impeller and the housing gradually increases. This allows the water to be transferred to a diffusor. The water flows from an area where it is moving at high speed into the diffusor which has a larger cross section. The water slows down and its kinetic energy is to large extent transformed into pressure energy. The water is collected and taken through a pipe to the pressure outlet.

The capacity of a pump is determined by the design of the impeller. In centrifugal or radial pumps the water leaves the impeller radially, at right angles to the shaft. This produces a significant increase in pressure in comparison to pumps in which the water moves along the pump shaft or diagonally to it. This is why this type of pump is the most common in the fire service. However the increase in pressure takes place at the expense of the flow.

There are drain valves at the lowest points of the pump to

2.17 Different types of mobile pumps for extinguishing fires: manual plunger pump, steam-powered plunger pump, engine-driven centrifugal pump and vehicle-mounted, engine-driven centrifugal pump for low and high pressure.

2.18 Control panel for a trailer pump including a vacuum gauge and manometer. Note the sign with the conversion factors for different units of pressure.

allow it to be drained after use at freezing temperatures. One of these points is at the bottom of the volute.

Pumps with only one impeller are the most common type in use in the fire service. The output pressure is higher if two or more impellers are positioned one after another. A pump with two impellers one after the other is called a two-stage pump. The impellers can also be positioned parallel to one another. Multi-stage parallel pumps are also available.

A combined high-pressure and low-pressure pump consists of several impellers, sometimes as many as four, connected in series. The water can either be taken out after the first stage of the pump where it will have low pressure but a high flow rate, or after the last stage where the pressure is high but the flow rate is reduced. For firefighting purposes a high-pressure pump is a pump with an output pressure above 2 MPa.

The manometer shows the pump's output pressure. The vacuum gauge shows the pump's input pressure. The pressure is positive if the water is taken from a hydrant or another pump and negative if the water is taken from a static water supply. If a pump is not designed to take water from a static water supply, it often has no vacuum gauge. The speed of the engine is a measurement of the load that it is subjected to. Some pumps have a rev counter which shows the engine speed. In the case of trailer pumps it is often easiest to listen to the sound the engine is making.

There is normally a net on the pump inlet which prevents large pieces of debris from damaging the pump. If the pump gradually or suddenly starts to pump out a smaller quantity of water, the net may be clogged. This often happens when water is taken from a static water supply.

TYPES OF PUMP

The majority of pumps used by the fire service are vehicle-mounted. Almost all fire engines and water tenders are equipped with pumps. The design of the pump is determined primarily by the options for connecting pipes to and from the pump and by the transfer of power between the engine and

2.19 A fire engine equipped with a pump with a high-pressure hose reel and low-pressure outlet, together with equipment for mixing foam. Note that the pump has a flow meter. With a feeder pump, it can also take water from a static water supply.

2.20 (left) *Many fire engines with a centrally-mounted pump have a pressure outlet and a control panel for the pump at the front and the rear of the vehicle.*

2.21 (right) *A front-mounted pump is easily accessible but it is in an exposed position.*

the pump. There are pumps on the market to meet all requirements, from simple manual pumps to fully automatic pumps with high- and low-pressure outlets, the option of taking water from a static water supply and built-in foam mixing equipment, flow metering and monitoring the tank contents, temperature and other important functions.

In fire engines the pump is generally mounted in the centre of the vehicle behind the engine. This central position means that the connection between the engine and the pump is a simple one. The pump is protected, but is also accessible for servicing, particularly if the vehicle has a tilt cab. The water outlets are positioned in such a way that the pipes are as short and have as few bends as possible. The pump is electronically controlled which means that the outlets and control panels can be positioned almost anywhere in the vehicle. Centrally-mounted pumps generally do not have suction hoses and pump primers, which means that they cannot take water from a static water supply without a feeder pump.

Pumps can also be mounted on the front of the vehicle, which is common on older fire engines. The disadvantage of a front-mounted pump is that it is exposed to dirt and cold air. The advantage of this position is that the pump is easily accessible. Finally, the pump can also be rear-mounted, which also

2.22 Class 1 (below), 2 (above right) and 3 (above left) portable and trailer pumps in accordance with SS 3496, 1989.

makes it easily accessible. However, long shafts are needed to transfer power between the engine and the pump.

Free-standing pumps with their own engine, which is generally a two-stroke or four-stroke petrol engine, are called portable or trailer pumps. They are divided into different groups depending on their performance. The classifications below, which are taken from SS 3496, 1989, can be used. A future classification system will probably be based on both operating pressure and flow.

Class 1 pumps are the smallest type and are designed to be used by one person. They must be able to produce 400 l/min at a pressure of 0.6 MPa and a suction height of 1.5 m, or 120 l/min at a pressure of 0.6 MPa and a suction height of 7.5 m. They must weight a maximum of 40 kg not including the suction hose but including fuel for one hour of operation.

Class 2 pumps have a higher capacity: 1200 l/min at a pressure of 1 MPa and a suction height of 3.0 m or 360 l/min at a pressure of 1 MPa and a suction height of 7.5 m. The total weight of class 2 pumps must be a maximum of 400 kg. It must be possible to lift these pumps off their chassis, when they must weigh a maximum of 200 kg, including fuel for two hours. These pumps can be carried by four people.

Class 3 pumps are the heaviest trailer pumps. They must be able to produce a minimum of 2400 l/min at a pressure of 1 MPa and a suction height of 3.0 m, or 720 l/min at a pressure of 1 MPa and a suction height of 7.5 m.

Class 1 pumps can normally be operated by one person.

They are most often used when a small amount of water is needed in an inaccessible place. Class 2 and 3 pumps are normally trailer-mounted and towed behind a fire engine. They can also be mounted together with a water tank on a swap body or semi-trailer.

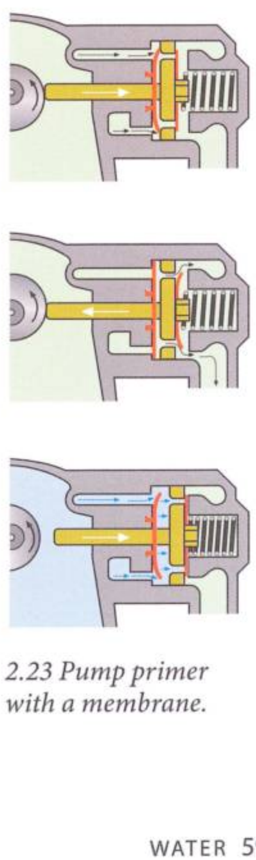
Pumps for dedicated purposes are not included in this system, for example small pumps for forest fires where low weight is more important than a large capacity, or very large pumps for cistern fires where weight is irrelevant provided that the pump has sufficient capacity.

When you suck the air out of a straw in a drinking glass, atmospheric pressure pushes the drink up into the straw so that you can drink it. This is how a pump primer works.

USING A STATIC WATER SUPPLY

One disadvantage of centrifugal pumps is that they cannot start pumping water if there is air in the pipe on the suction side. The pipe must be full of water to allow the pump to start working. If the pump is attached to a water pipe with positive pressure, for example a pump in a fire engine with a water tank or a sprinkler pump with a pressurised water pipe, the water automatically flows into the pump which starts working immediately. However, if the pump is to take water from a static water supply, the pump must be equipped with a suction hose and a pump primer. This sucks out the air so that the pressure in the pipe falls and atmospheric pressure pushes the water into the pipe.

A vehicle-mounted pump with no suction hose and pump primer which cannot take water from a static water supply can be combined with a submersible feeder pump. Different types of submersible feeder pump are available, including pumps which are powered by the vehicle's hydraulic system and electric pumps. There are also pumps which use the standard fire pump as the prime mover. This type of water jet pump or centrifugal turbine pump takes in a small amount of water at high pressure and outputs a large amount of water at a lower pressure.



2.23 Pump primer with a membrane.

Trailer pumps generally have a plunger pump (for example Trokomat) or a membrane pump (for example Membramat) for priming purposes. The design varies depending on the model, but the primer often consists of a cylinder with two spring-loaded pistons mounted on the pump housing. The pistons work in two different directions and are driven by an eccentric cam on the pump shaft. When the pump shaft rotates, the pistons move backward and forward which sucks air from the pump housing and blows it out. When so much air has been sucked out that the water flows in and fills the suction hose and the pump, the centrifugal pump can start working. The pressure increases and the water pressure pushes the spring-loaded pistons away from the pump shaft which disconnects the pump primer.

Ejector-type pump primers are also used. These can be powered by exhaust gases or compressed air (for example Pneuvac). These work on the same principle as a foam injector, where a medium flowing through a pipe creates negative pressure in a connecting pipe. Older trailer pumps often have exhaust gas ejectors.

A suction hose is connected to the water intake. The hose of a trailer pump is normally 110 mm in diameter and has DIN couplings with handles. A suction hose is semi-rigid, which means that it can withstand negative pressure without collapsing. Trailer pumps normally have two suction hoses, each 4 m long. Small portable pumps have one smaller suction hose, normally also 4 m long. When the hose is connected to the pump, it must slope downwards away from the pump along its entire length, to prevent air pockets forming. If the hose runs over a sharp edge, such as the edge of a quay, it must be protected so that the vibrations don't cause wear and tear to the hose.

A suction strainer is fitted in the end of the suction hose to prevent debris being sucked into the pump. A counterbalance line is fitted to the strainer, which is used to control the position in the water. The strainer must be 0.5 m below the surface of the water to prevent turbulence and to prevent air being sucked in with the water. However, it must not be so close to the bottom that debris is sucked in. The best solution is to use the counterbalance line to point the strainer upstream, as the flow of water will push its way into the suction hose. If there is a significant risk of impurities being sucked into the hose, the suction strainer can be placed in a bucket which is partially buried in the bed of the water course. A suction strainer with a built-in float will never sit on the bottom and will prevent air from being sucked in. This will improve the quality of the water if the bed is muddy or if the surface of the water is covered with debris.

There is a non-return valve in the strainer in order to prevent the pump losing water if it is switched off. This is called the bottom valve. A suction hose which is full of water is heavy. In order to allow the water to be released, there is a valve opening line connected to the bottom valve. If it is stretched while the pump is operating, there is a risk that it will open the bottom valve and release the water by accident.

If the pump primer is not working, the water can be "pulled up" by jerking the suction strainer rapidly up and down. The bottom valve opens when the hose sinks down into the water and closes when the hose rises. The quantity of water in the hose gradually increases. The larger the pump, the harder work this process is. For a class 3 pump two people are needed.

Another method of filling the suction hose if the pump primer is not working is to pour water into the back of the pump by hand.

In winter the suction strainer can be replaced with an ice pipe if the pump is set up on an ice-covered lake. The ice pipe is one metre long and has an elbow and a coupling at one end and a perforated strainer in the other. An ice drill is an essential piece of equipment in this situation.

OPERATING PUMPS

The principles of using a pump are the same for a fully automatic pump mounted on a fire engine, for a trailer pump from the emergency equipment store and for a portable pump for fighting forest fires. The information in this section applies primarily to trailer pumps, but it can also be used where applicable for other types of fire pumps.

Every pump has an instruction manual and a technical description which covers the pump's performance, for example the pump curve, the measures to be taken before, during and after operation, troubleshooting information and a maintenance schedule. The instructions should always be kept with the pump, and should preferably be laminated.

The following instructions can be used for a trailer pump which is taking water from a static water supply. However, the actions and the instructions may vary depending on the make of the pump.

Checks before use

1. Check the pump engine: fuel, oil, battery and coolant.
2. Check the suction hoses: suction strainer, non-return valves, gaskets.
3. Grease any grease points.
4. Check the pump primer.
5. Close all pressure outlets and drain taps.
6. Check that the pump is disengaged.

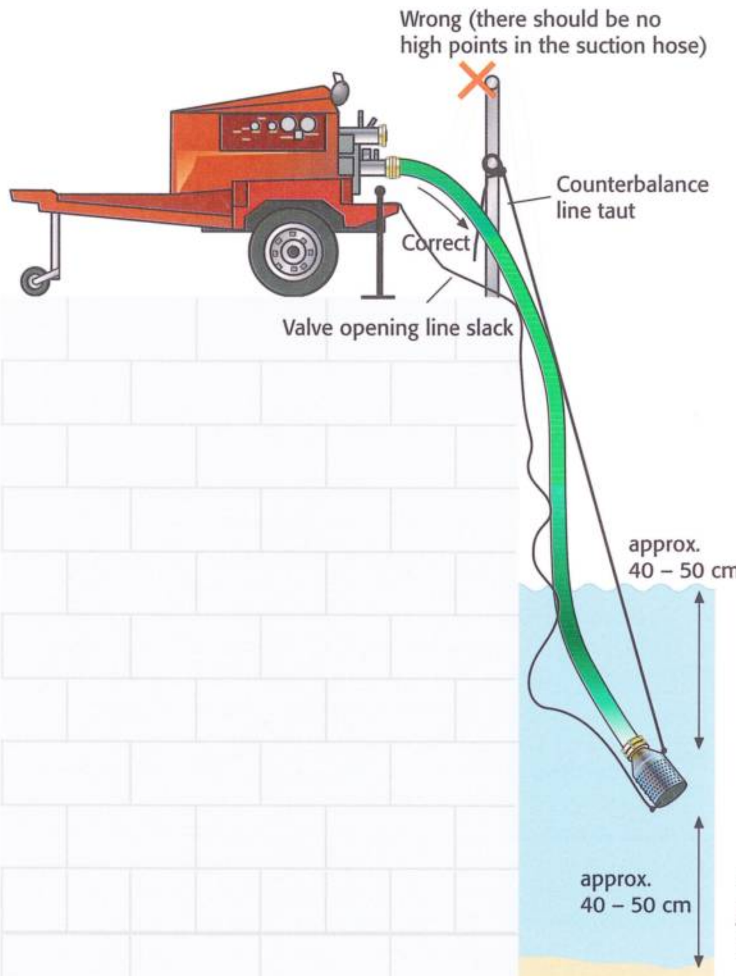
A correctly set-up and connected trailer pump has a horizontal pump shaft and has no load on the axle to ensure that the pump does not roll away as a result of vibration. In addition the suction hose must be lower than the connection to the pump along its entire length, otherwise air pockets may form and the pump may lose water. All the valves except the petrol tap must be closed before the pump is started.

Setting up the pump

1. Position the trailer pump on a solid surface near the water supply and ensure that the suction height is 7.5 m or less.
2. Lower the tow bar slightly, drop the rear legs and lock them in position.
3. Raise the tow bar again, drop the front legs (or the jockey wheel) and lock them in position.
4. Check that the pump shaft is horizontal and that there is no load on the axle.
5. For pumps with an air-cooled engine, check that the air intake is not blocked. With other types of pumps the engine hood must be opened and any covers removed to reduce the risk of overheating. Where the engine is cooled by the pump water, a small amount of water must always be taken out of the system.

Connecting up the pump

1. Connect the suction hoses and the suction strainer together and tighten the couplings. Fix the counterbalance line and the valve opening line to the suction strainer and the valve opener.
2. Check the net in the pump inlet and wash it out, if necessary.
3. Put the suction strainer in the water, fix the suction hose to the pump and tighten it.
4. Stretch and secure the counterbalance line so that the suction strainer is correctly positioned. Fix the end of the valve opening line in place.
5. Connect the pressure hose to the pressure outlet.



2.24 Setting up a trailer pump next to a static water supply.

Priming the pump

1. Check all protective clothing. Pump operators must wear ear protection.
2. Start the pump engine and allow it to warm up for a short period. This can be done before the pump is connected.
3. Engage the pump gearbox.
4. Connect the pump primer if it is not automatically connected and run the engine at 1/4 throttle. If the pump has an exhaust gas ejector, run the engine at full throttle.
5. During the priming process stand with one leg resting on the suction hose. This will allow you to feel the hose sinking with the weight of the water being sucked in.
6. The reading on the vacuum gauge should initially fall to around –0.8 MPa, and then rise to a value which corresponds to the suction height.

The five buttons on old-fashioned firemen's uniform jackets were sometimes used to represent the words in the sentence: Never forget the pump gearbox! Even though the uniform has changed, the rule remains the same. If no water is coming out of the pump, the most common cause is that one of the pressure outlets or one of the drain taps is open.

7. The manometer shows a reading.
8. The noise produced by the pump primer changes.
9. Water comes out of the pump primer outlet. This is the last of five indications that the priming process has been successful. It is possible to see, hear and feel that the priming process is working.
10. Stop the priming process. When the go-ahead is given, open the pressure outlet to begin supplying water. Open the outlet carefully to prevent the pump from losing water.

Leakage test

A leakage test can be carried out to check that the pump is functioning correctly.

1. Fit the cover on the water intake and make sure that the pressure outlet and the drain taps are closed.
2. With the pump disengaged, start the engine and allow it to warm up.
3. Prime the pump. When the vacuum gauge reaches its maximum reading, the priming process is stopped and the engine shut down. The pressure should be lower than –0.8 MPa.
4. Listen for any leaks and check that the pressure does not increase by more than 0.2 MPa in 3 minutes.
5. When the checks have been completed, equalise the pressure by opening a pressure outlet.
6. Keep a log of the test so that it is obvious when the pump was last tested. The leakage test can be carried out a few times a year with suction hoses connected to the pump. The water intake cover should be placed in the end of the suction hose instead. This test puts a strain on the suction hose and should not be carried out too often or over a long priming period.

Troubleshooting

- The manometer shows a reading, but no water is coming out. This can be caused by a blocked or frozen pressure outlet.
- The pump is losing water when a pressure outlet is opened. This can be caused by the outlet being opened too fast, by the suction height being too great, by there being a high point and therefore an air pocket in the suction hose or by the suction strainer being so close to the water surface that the pump is taking in air.
- The pump is producing a reduced amount of water and then finally no water at all. The pump primer cuts in. This can be caused by a blocked suction strainer or bottom valve. The suction hose can be leaky or have collapsed, resulting in a

It is not a good idea to stand astride the suction hose, as it could cause an injury if it comes loose as a result of a water hammer.

smaller cross section. The suction height may have increased if water is being taken from a water supply with a limited volume. Impurities may have found their way into the impeller or the volute.

- The pump has run and then after being stopped for a while does not produce any water. This is probably caused by the pump losing water through a leaky bottom valve.
- The engine speed drops, the manometer reading falls and the vacuum gauge reading rises. This can be caused by more water being used at the scene of the fire, or by a burst pressure hose.
- The engine speed increases, the manometer reading rises and the vacuum gauge reading falls. This can be caused by less water being used at the scene of the fire or by pressure losses increasing.
- Despite a long priming process no water comes out of the pump. There is no reading on the vacuum gauge. This is caused by the pump being in contact with the air. A drain tap or pressure outlet may be open. The suction strainer may be so high in the water that it is sucking in air. There may be a leak in the pump or the suction hose. There may also be a fault in the pump primer.
- Despite a long priming process no water comes out of the pump, but the vacuum gauge shows a reading. This is caused by the flow resistance being too high. This may be the result of the suction strainer being blocked either externally by debris or internally by a loose O-ring. The suction height may also be too great.

THE PUMP FLOW

Pump performance can vary considerably. The pump curve is a diagram that shows the pump pressure as a function of the flow. The major factors determining the shape of the pump curve include the design of the volute, the pitch and outlet angle of the impeller and the number of stages in the pump. The outlet angle is the angle between the impeller blade and the tangent to the outer edge of the impeller. If the outlet angle is small, the pump curve will be flat. A larger angle results in a steeper curve.

The pump curve is influenced not only by the design of the pump, but also by the operating conditions. Each combination of engine speed and suction height produces a different pump curve.

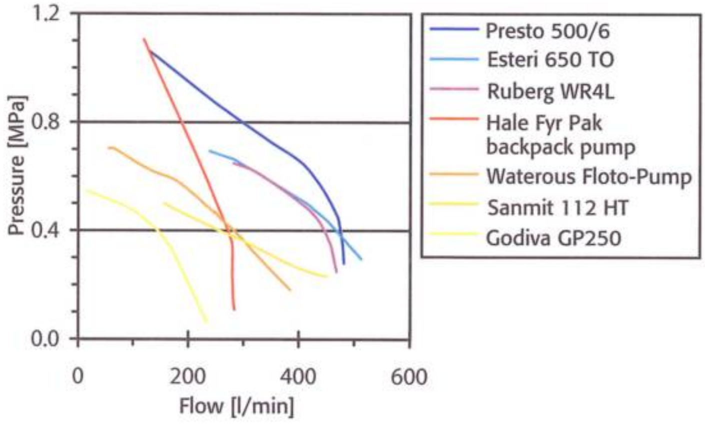
Capacity test

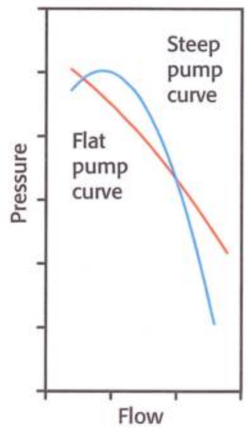
A capacity test is carried out to ensure that the pump is performing correctly when the pump is delivered and during maintenance. In between these tests a simplified capacity check can be carried out. For a trailer pump this includes the points listed below. Other pumps can be checked in a similar way.

1. Set up, connect and prime the pump.
2. Fit a jet/spray branchpipe directly to the pump's pressure outlet. The nozzle pressure is roughly the same as the pump pressure and is shown on the manometer.
3. Open the pressure outlet fully and run the engine on full throttle.
4. Varying the diameter of the nozzle changes the pressure. The flow can be calculated using the nozzle formula (see page 102). For example, a 14 mm nozzle produces around 300 l/min at a pressure of 0.6 MPa.
5. A class 3 pump should generate pressure of at least 1.0 MPa with two 22 mm and one 14 mm nozzle. In this case the flow is around 2400 l/min.
6. Vary the number of branchpipes and the branchpipe diameter. The flow through the nozzle can be calculated using the nozzle diameter and pressure. It is then possible to draw a pump curve that is a pressure/flow diagram.
7. Finally the test should be logged and the pump drained and reset.

The fire service needs systems which are as robust as possible and which make it easy to keep the pressure constant regardless of the flow. This conflicts with the efficient running of centrifugal pumps. A pump which has a steep pump curve is most efficient. This problem can be solved in two ways. The first is to fit the pump with a pressure monitoring and regulating system. This will keep the desired output pressure and works in principle as when a pump operator controls the pressure by changing the engine speed. The monitoring system checks the water outlet and adjusts the engine speed accordingly. This allows the choice of a pump with a steep pump curve and a high level of efficiency across a wide flow range.

The other way of keeping the pressure as constant as possible is to use a pump with a flat curve. If the pump impeller blades have a small outlet angle, the pressure will generally remain constant up to a relatively high flow rate. At this point there is a bend in the curve which then falls sharply until it reaches the pump's highest flow rate. The disadvantage of this method is that the pump's efficiency falls and that a more powerful engine must be used. This is no problem for a vehicle-mounted pump as the engine of the vehicle is designed to move the vehicle which requires more energy than pumping water.





2.25 (left) Examples of pump curves for portable pumps (from Test av bärbara motorsprutor, 1999).

2.26 (right) Depending on how the pump will be used, it can be designed to have a steep or flat pump curve.

THE PUMP CURVE AS A FUNCTION

The pump curve for centrifugal pumps can often be expressed as a quadratic function. This can generally be described using the following equation:

$$p = Aq^2 + Bq + C$$

p [Pa] output pressure
q [m^3/s] flow
A, B and C are constants

The equation shows that the pump curve can be determined by measuring the pressure and flow at a few different points. The constants are then determined using a calculation aid or successive elimination. When the pump curve has been identified, the pressure at different flows can be calculated.

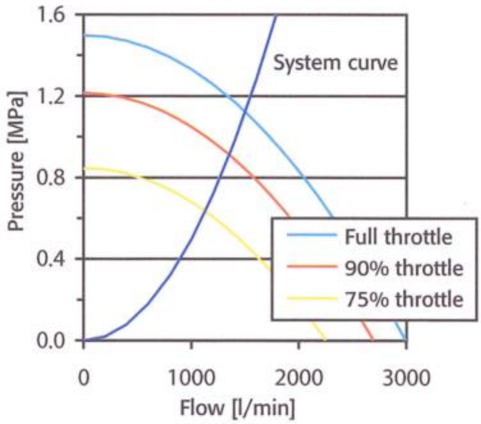
THE EFFICIENCY AND POWER REQUIREMENTS OF THE PUMP

The efficiency of a pump varies with the water flow, but normally falls when the flow is high or low. The efficiency of a pump can be determined using the following equation:

$$\eta = \frac{\rho g q h}{P}$$

η [–] efficiency
P [W = Nm/s] engine power
ρ [kg/m^3] density
g [N/kg] general gravitational constant

The laws of affinity are three equations which explain how a change in the pump's engine speed affects the flow, pressure increase and power requirements. All three equations have the same structure. The first equation shows that the flow through a pump is directly proportional to the engine speed. By



2.27 The performance of the pump changes when the engine speed is adjusted.

dividing the equation for situations before a change by the equation after a change, all the constants disappear, leaving the flow and the engine speed. The equation is used to regulate the flow of a pump with a variable-speed engine. For example, by halving the engine speed, the flow through the pump is also reduced by half.

$$\frac{q_2}{q_1} = \frac{n_2}{n_1}$$

$$\frac{p_2}{p_1} = \left(\frac{n_2}{n_1}\right)^2$$

$$\frac{P_2}{P_1} = \left(\frac{n_2}{n_1}\right)^3$$

q [l/min] flow
n [min^{-1}] engine speed
p [Pa] increase in pressure in the pump
P [W] power requirement

By combining the equations it is possible to relate the change in pressure, the flow and the power requirement to one another.

$$\frac{p_2}{p_1} = \left(\frac{q_2}{q_1}\right)^2 = \left(\frac{P_2}{P_1}\right)^{2/3}$$

Many hydraulic calculations are based on the fact that pressure is proportional to the square of the flow.

If the nozzle of a vacuum cleaner is blocked, the motor speed and the frequency of the motor noise increase. When the fan runs without air being pulled through the vacuum cleaner, it needs less energy and the fan can rotate faster. On the other hand if the vacuum cleaner hose comes loose, the flow losses are reduced and a larger quantity of air is sucked through the vacuum cleaner. The motor has to work harder and the motor speed falls. This can be heard because the frequency of the motor noise also falls.

PRESSURE AND SUCTION HEIGHT

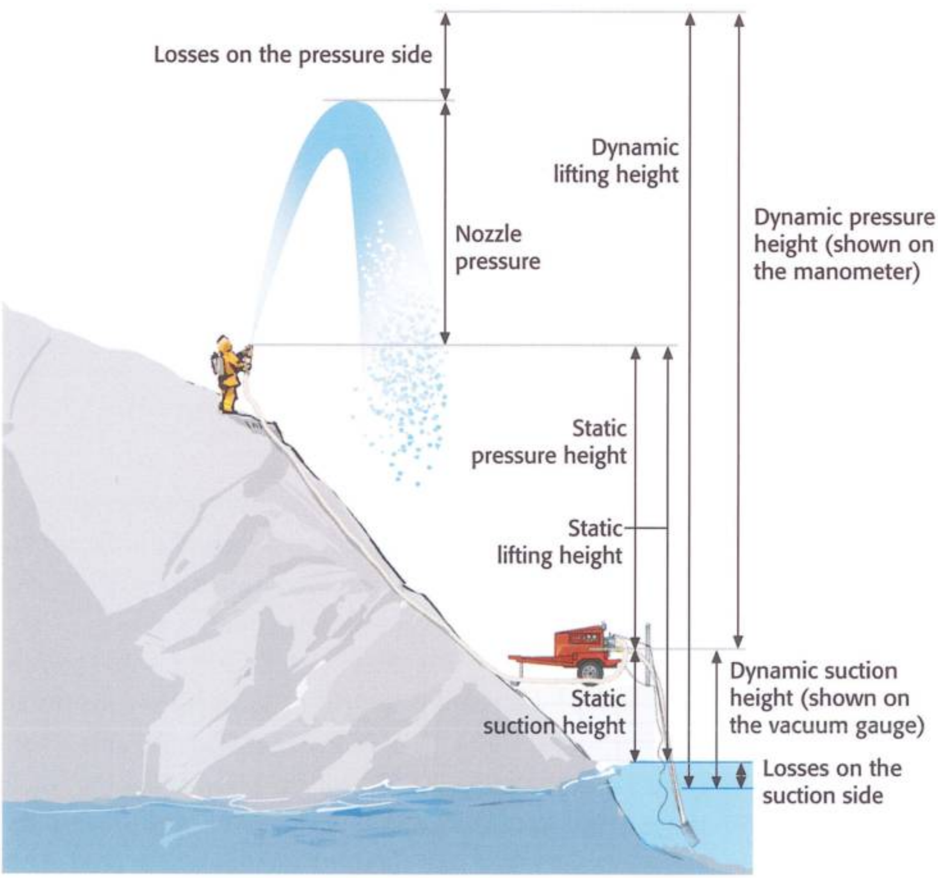
The lifting height is the difference in height between the surface of the water and the nozzle. This height can be broken down into a static suction height, which is the distance from the water surface to the pump and a static pressure height, which is the distance from the pump to the nozzle.

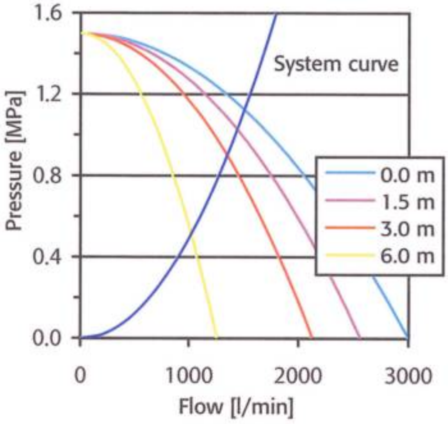
The dynamic suction height is the static suction height plus the flow losses up until the pump. In a similar way the dynamic pressure height is the total of the static pressure height and the flow losses from the pump to the nozzle, plus the nozzle pressure.

Adding together the dynamic suction height and the pressure height produces the dynamic lifting height, which is the total change in pressure which the pump applies to the water. This difference in pressure can be seen as the difference between the pump's ingoing and outgoing pressure.

The largest practical suction height is 6–7 m, as the water in the suction hose has a specific velocity energy, because there are flow losses in the suction hose and it is not possible to generate a complete vacuum. In addition the pump's performance deteriorates as the suction height increases. The location where

2.28 The components of pressure height and suction height.





2.29 The effect of the suction height on a pump curve for an imaginary pump. The fact that the maximum flow is reduced at high suction heights is because the pressure in the suction hose becomes too low and cavitation occurs.

MAXIMUM THEORETICAL SUCTION HEIGHT

The suction hose starts filling with water when the pump primer creates negative pressure in the suction hose. Atmospheric pressure pushes the water into the suction hose. If it was possible to create a complete vacuum in the suction hose, the water would have been pushed up to a height corresponding to the atmospheric pressure. This can be expressed using a simplified form of the Bernoulli equation.

$$\rho_w g z_w = p_l$$

ρ_w [kg/m^3] water density
g [N/kg] general gravitational constant, 9.81
z_w [m] height of column of water
p_l [Pa] air pressure

The flow losses in the suction hose and the kinetic energy of the water have been omitted here. As the flow increases, these factors play a more important role. In addition the fact that water cannot be subjected to lower pressure than its own steam pressure without starting to boil has also been disregarded.

If the air pressure is 101,300 Pa, the maximum theoretical suction height without flow is:

$$z_w = \frac{p_g}{\rho_w g} = \frac{101300\,\text{N/m}^2}{1000\,\text{kg/m}^3 \cdot 9.81\,\text{N/kg}} = 10.3\,\text{m}$$

Air pressure varies with altitude. At 500 m above sea level, the air pressure falls to 95,500 Pa which means that the maximum theoretical height drops to 9.7 m (CRC, 1986, p. F-150).

the pump is to be set up can always be investigated in advance. A height of 5–6 m between the pump site and the surface of the water should be regarded as the maximum reasonable height. The suction hose on pumps is normally only 8 m long.

The suction height is irrelevant for submersible pumps, because they are positioned below the surface of the water. Smaller pumps with a built-in float are also available. These are used in the same way as normal pumps, but the whole pump is put in the water so that the water inlet is below the surface of the water. As a result no suction hose is needed.

CAVITATION

The lowest pressure is always at the centre of the impeller and this allows the water to flow into the pump on the suction side. In some cases the pressure becomes so low that it falls below the steam pressure of the water and the water begins to boil. This is called cavitation. At 100°C the steam pressure of water is the same as atmospheric pressure, that is, 101,300 Pa. At this temperature water boils. If the pressure falls, water boils at lower temperatures. If the pressure is very low (2300 Pa), water will boil at room temperature, which is what happens in the pump. Water boils and vaporises. The steam moves out of the impeller and the impeller slows down because the channel has become larger. The pressure increases and the steam condenses to form water again. The gas bubbles break down in the impeller. This causes knocking noises which can be clearly heard and which cause serious wear on the impeller. The simplest way of preventing cavitation from occurring is to reduce the engine speed of the pump. A low suction height also reduces the risk of cavitation.

If cavitation occurs because the water outlet is so small that the water in the pump heats up, this can be resolved by increasing the flow of water. The simplest way of doing this is to open a pressure outlet. Cavitation can also be avoided by installing a thermostat which releases water when it becomes too hot.

If there is a long pipe between the tank and the pump on a fire engine, flow losses in the pipe can restrict the capacity of the pump. The greater the flow, the greater the flow losses will be. When cavitation occurs, water can no longer flow through the pipe. In this case the reading on the vacuum gauge will fall to around –0.80 to –0.85 MPa.

THE PUMP AS A SOURCE OF HEAT

Even if the pressure in a hose falls as a result of flow losses, the energy does not leave the water. Instead, kinetic energy is converted into heat energy. This process is called dissipation. This means that the water becomes slightly warmer when it reaches the nozzle. This is not normally noticeable, but if the hose is connected back to the pump for recirculation, the circulating water will heat up. This can be useful, for example in winter, when circulating water will warm up and is prevented from freezing. It can also be useful in operations where casualties or emergency services personnel have to be decontaminated. The pump's capacity for heating water depends on the type of pump and the extent of the flow losses. Connecting a

25 m long 76 mm hose from the pressure outlet to the inlet it takes only few minutes to produce lukewarm water. The greater the flow losses, the faster the water will heat up.

If a centrifugal pump is run for a while with a closed valve, there is a risk that it will overheat. This applies in particular if the engine is running at high speed but the nozzles are closed. In this case the pump will overheat rapidly. Many vehicle-mounted pumps have an automatic monitoring system with a thermostat which opens and releases water if the water gets too hot. The solution for other pumps is to lower the engine speed and take out a little water if the nozzle remains closed for a long period.

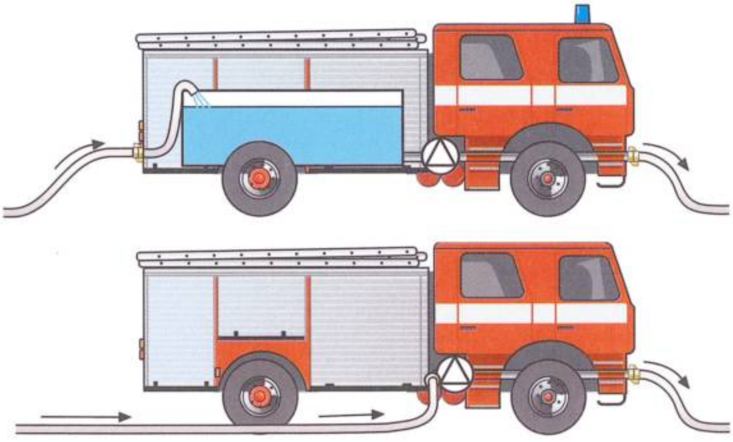
RELAY PUMPING

If there is a very long distance between the water supply or fire hydrant and the scene of the fire, more than one pump must be used. This is called relay pumping. A distinction is made between open and closed relay pumping. If the water flows from the first pump to a container from which the second pump takes its water, this is called open relay pumping. If the water flows directly to the suction side of the second pump, this is referred to as closed relay pumping.

In closed relay pumping it is almost impossible to maintain a constant pressure across the two pumps, while the nozzles are opened and closed at the other end of the hose system, without the help of additional equipment.

Open relay pumping is generally the best solution. The two pumps are separated, the system is less complex and it is easier to regulate the pressure and the flow. Open relay pumping also provides a buffer for the second pump which means that the system is less susceptible to faults. If a pump fails or a hose bursts in the first part of the system, this will not affect the second part of the system until the buffer runs out.

It is often a good idea to have the water tank in the fire engine as a buffer and to use a trailer pump to supply it with water. The inflow can be regulated using an inlet valve, either manually or with an automatic level control system, to ensure that the tank does not overflow. A self-righting water tank makes an excellent buffer for relay pumping over long distan-



2.30 Open and closed relay pumping.

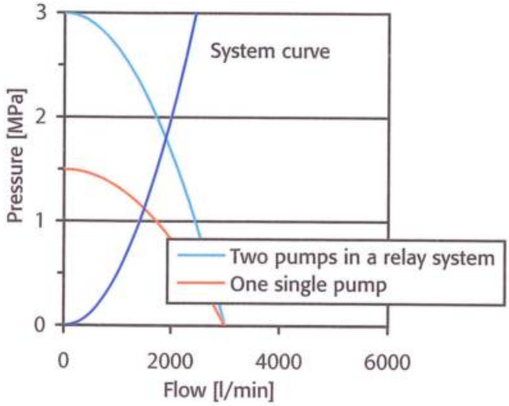
ces. This means that a fire engine does not need to be taken out of action just so that its tank can be used. If an open tank is used, the level can be regulated using the engine speed of the first pump, depending on how much water is taken out.

The relative positions of the pumps for relay pumping are governed by pressure losses. The first pump should always be close to the water supply or fire hydrant.

If the required nozzle pressure is half the pump pressure and two similar pumps are being used, the second pump must be positioned two-thirds of the distance from the water supply to the scene of the fire. The energy from the first pump is used to combat pressure losses in the hose, while the energy from the second pump is divided equally between pressure losses and nozzle pressure.

If the distance between the pumps is governed by the capacity of the pumps, it does not matter in which order large and small pumps are used. There is the least risk of a miscalculation being made if the largest pump is closest to the water supply. However, there may be reasons for placing a smaller pump closest to the water supply, for example if the water supply is difficult to access. If there is any doubt about the choice between two positions for the second pump in a relay pumping system, the position closest to the water supply should be chosen.

In closed relay pumping the incoming pressure to the second pump should be at least 0.1 MPa. If the pressure is



2.31 The change in the pump curve in a relay pumping system.

lower, there is a risk that the hose will be sucked flat and that the supply of water will be interrupted. This can be prevented by carefully planning the position of the pumps from the start. If the hose is nevertheless sucked flat, this can be rectified by increasing the pressure of the first pump and/or reducing the pressure of the second pump.

If all the nozzles are closed, the flow of water and therefore the flow losses will stop. In this case the pressure in the second hose will be the same as the total of both pump pressures and there is a risk that the hose will burst.

In a closed relay pumping system the pump operators must regulate the engine speed so that the outgoing pressure from the first pump is 1.0–1.2 MPa. The engine speed of the second pump must be regulated so that the incoming pressure is higher than 0.1 MPa. This will allow the system to produce the maximum quantity of water at the highest pressure. If the incoming pressure is higher than 0.3–0.4 MPa, the second pump is not being used to its full capacity. The pressure of the first pump can be reduced.

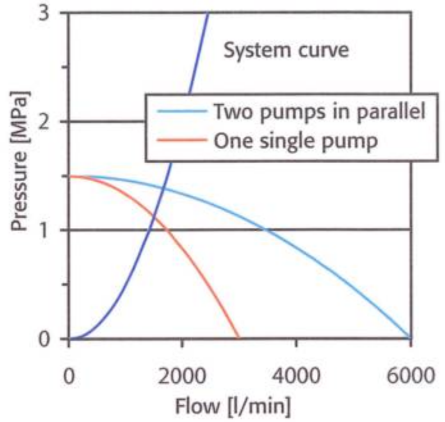
A pump curve which is equivalent to the curve of two pumps connected in a relay system can be produced by adding the two curves together vertically. If the pumps are identical the total maximum flow will be the same, but the blocked pressure will double.

PARALLEL PUMPING

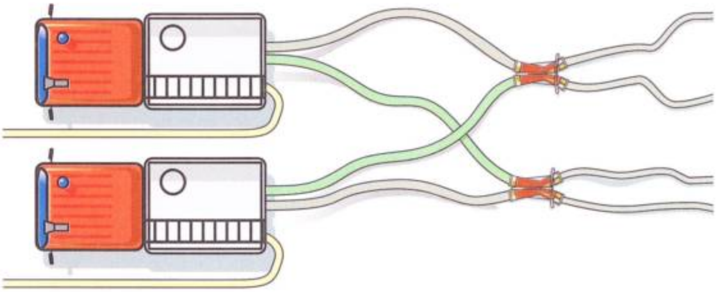
Parallel pumping does not normally have any benefits for the fire service because the system tends to become unnecessarily complex. It is usually best to set up separate systems where the nozzles are supplied via large diameter hoses and dividing-breechings from different pumps.

However, there is one situation where connecting pumps in parallel can be advantageous. This is when the system needs to be made more reliable. If it is essential that there is a reliable flow of water to a group of firefighters, the attack hose can be laid via a dividing breeching with a collecting breeching. This allows two parallel systems to be set up which supply the dividing breeching with water independently. This increases the level of redundancy in the system and means that the effect of one of the supply hoses bursting, of the water supply running out in one place or of a pump failing is less crucial.

A pump curve which is equivalent to the pump curve of two pumps connected in a parallel can be produced by adding the two curves together horizontally. The maximum flow will double, but the blocked pressure will remain the same.



2.32 The change in the pump curve in a parallel pumping system.



2.33 Parallel pumping

The components of the hose system

FIRE HOSES

A pressure hose is designed to withstand pressure greater than atmospheric pressure and is used after the pump. The most common type of pressure hose used by the fire service is the lay flat hose. These are usually made of circular woven nylon or polyester fabric and are rubber coated on the inside. This results in a strong, watertight hose with low friction losses. Some types of hose also have a coating on the outside to make them more durable.

Hoses are identified by their internal diameter. The majority of hose sizes correspond to even inches. Three inches is equivalent to 76 mm. Examples of hose sizes are 17, 25, 38, 42, 51, 63, 76, 110 and 150 mm.

The sizes of lay flat hose most commonly used in the fire

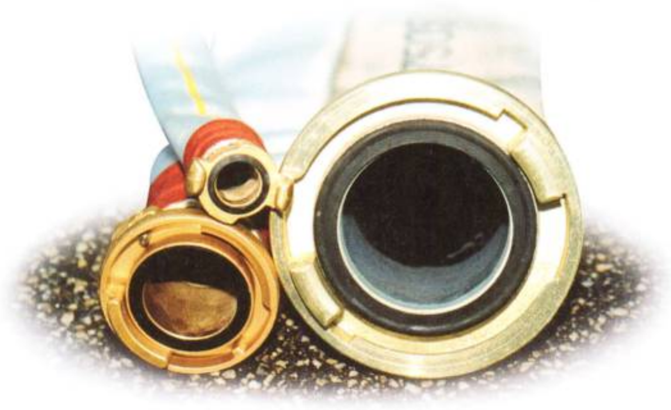
2.34 Hoses 110, 76, 63, 51, 42 and 38 mm in diameter.

service are 38 mm and 42 mm, often called small diameter hoses, and 63 mm and 76 mm, often called large diameter hoses. Hoses are normally 20 or 25 m long, but hoses of other lengths are also used. Hoses designed to transport water over long distances often come in 50 m lengths.

The smallest hoses (38 mm and 42 mm) are normally used as attack hoses, that is hoses which can be moved and have a nozzle at the end. Hoses 51 or 63 mm in diameter can also be used as attack hoses, but two people are needed to handle the nozzle effectively. Two smaller nozzles are often more effective. Hoses used to supply water to a dividing breeching or a monitor or to connect a hydrant and a pump are called supply hoses or transport hoses. These are larger hoses, normally 76 mm in diameter. If large quantities of water have to be transported over a long distance, a 110 mm supply hose will save a lot of effort.

Some hoses are more important than others. For these reasons hoses for BA firefighters may be of a different colour than other hoses. Hoses are available in a range of different colours, including fluorescent shades. Giving BA firefighters the newest and least worn hose is one way of reducing the risk of a hose bursting for the most vulnerable group of firefighters at the scene of the fire.

Hose couplings are standardised, but vary from country to



country. Some countries use couplings with male and female connectors. Swedish hose couplings have two similar components. Small diameter hoses use a 32 mm hose coupling, generally called a claw coupling. Large diameter hoses use a 63 mm hose coupling, sometimes called a normal Swedish coupling. Suction hoses on trailer pumps and 110 mm diameter hoses use a 110 mm DIN or Storz coupling. The first types can be connected and disconnected without a key. There may be a handle on the DIN coupling, otherwise a specific key is needed. The three types of coupling are described in SMS 1176, SMS 1150 and DIN 14323.

2.35 Normal (left), claw (top) and DIN couplings (right) are the three most common types of hose coupling used by the Swedish fire service.

The fact that different countries use different couplings means that a specific adapter, consisting of one national coupling and one coupling of the neighbouring country, is needed at international operations. A specific connector may also be needed for firefighting on board ship. This type of land connector connects the ship's flange coupling to a normal hose coupling.

Semi-rigid hoses can be used in low-pressure systems, but are always used in high-pressure systems. These systems have pressures of around 2 MPa and above. Hoses designed for higher pressure have thicker walls. They are semi-rigid and

2.36 A semi-rigid hose on a reel has advantagwes when speed and flexibility are crucial.

2.37 A dividing breeching and two combined collecting and dividing breechings.

reinforced with steel or plastic threads. However, semi-rigid hoses which weigh approximately the same as lay flat hoses are also available. High-pressure hoses are often 19 or 25 mm in diameter. Because these hoses allow high pressure losses in the hose, the water can travel at high velocity and the same quantity of water can be transported as in a larger diameter hose at a lower pressure. High-pressure systems have thinner, more flexible hoses which allow the fire to be tackled more quickly. According to Rimen (1990) this is one of the major benefits of high-pressure systems.

Semi-rigid hoses are stored on reels in fire engines. This is standard equipment which can be deployed quickly. The hoses are normally between 40 and 80 m long. If there are two reels in the fire engine, the hoses can be joined together. Tools are needed to connect the screw couplings used on high-pressure hoses. Therefore if the hoses are joined together, the time benefits are lost. If the distance between the fire and the appliance is greater than the length of the high-pressure hose, it is quicker to use a lay flat hose.

HOSE FITTINGS

Fittings is a collective term used to describe all the couplings which can be used to divide or bring together hoses and to connect different types of hoses and pipes. Nozzles also fall into the category of fittings. However in this book they will be covered separately. Fire hydrants have already been described.

Dividing breechings are used to divide a hose system into sections and to create branches in a hose network. Dividing breechings are always connected to the end of the supply hose near the scene of the fire. Dividing breechings or shut-off valves placed at regular intervals in a system make it less susceptible to faults. For example, it is not necessary to empty the water out of the whole system if a length of hose bursts and has to be replaced. Strategically positioned branching points give the system the flexibility it needs when there is no way of knowing how a fire will develop. In most cases it is quicker to lay out a new hose from a dividing breeching than to move an existing hose.

2.38 When water starts flowing through a hose, there is a risk that the hose will twist and overturn the dividing breeching. Some dividing breechings have a swivel mechanism on the coupling to the incoming hose. This ensures that the dividing breeching remains stable even if the hose twists.

Many different types of dividing breeching are available. The larger models have several outlets and are used to branch a large transport hose into several smaller hoses. The smaller models, three-way couplings or wyes, allow a hose to be divided into two with the same type of coupling. The smallest type of dividing breeching is called a water thief and consists of two couplings connected to one another. Between them is a drain valve with a smaller coupling. The water thief is used primarily when working in parallel over longer distances where the same supply hose can be used, e.g. at forest fires.

A collecting breeching is used to bring together two hoses, for example when running pumps in a relay system with a double hose or when running a shuttle service with water tenders. Collecting breechings have a flap which shuts off the flow if the pressure in one of the supply hoses becomes lower than in the other. This prevents the water from flowing out via a hose with higher pressure and back via a hose with lower pressure. However the flap can never close both hoses. A non-return valve is needed for that.

During damping down, when less water is needed, it is often possible to connect hoses directly from the hydrant to the dividing breeching. This means that the fire engine can be released and is ready to respond to new emergencies. If the dividing breeching has a collecting breeching, hoses can be switched over without interrupting the water supply.

The dividing breeching is often placed at the entry point of the firefighters. It is sometimes called "the church". Just as the church can be found in the middle of a town, the dividing breeching is in the middle of the fire operation. In addition the oldest models had a cross-shaped handle on the top.

To use a 110 mm hose together with a trailer pump, a collecting head is needed which brings together four 63 or 76 mm hoses. In the same way the hose is branched at the end with a manifold. The manifold has one incoming 110 mm coupling and four outgoing 63 mm couplings.

2.39 A collecting head and a manifold for large diameter hoses.

An adapter is used to connect different types of coupling, for example if a small diameter hose needs to be connected directly to a hydrant. With the older types of dividing breeching, which had a small diameter outlet with a globe valve on the top, connecting a small diameter hose to this outlet resulted in large pressure losses. The losses are significantly reduced if an adapter connects the small diameter hose to the large diameter outlet.

A cover must be used with all external hose couplings on vehicles and trailer pumps in order to prevent dirt and debris being brought in. This applies in particular to couplings on the suction side, which cannot be flushed out. The cover must

2.40 Usage and storage of hose ramps.

be fixed in place with a chain so that it does not get lost (see the picture on page 57).

HOSE ACCESSORIES

Sometimes hoses have to be laid across roads which are not closed off completely. In this case the hose must be protected using hose ramps, or hose bridges. Ramps must always be used if there is a risk that vehicles will drive over the hose. They are always put out in pairs the same distance apart as the wheels of the cars driving over them. Note that lorries and cars have different axle widths and wheelbases. The ramps can cover the width of the lane. When hose ramps are in use, warning signs must be set up on both sides of the road.

Hose clamps are used to cut off the flow of water in a hose when it is being changed or when a dividing breeching is being connected etc. A hose clamp allows the pressure in the hose to be maintained.

2.41 Hose bandage and hose hook.

In the case of small leaks a hose bandage is used to seal the hose temporarily so that it does not need to be replaced during an ongoing operation. An alternative is to put tape round the hose. This has the advantage that it is obvious that the hose has a hole in it and that the location of the hole is clearly marked when it is taken for repair.

Hose hooks are used to secure a hose which is being pulled up through a window or onto a roof, for example. Hose hooks are also called hose holders. They consist of a steel hook with a cord which has a fixed loop. The cord is put round the hose and the hook is fed through the loop and hooked firmly onto a window sill, ladder etc. The weight of the hose pulls the running noose tight.

A small wedge which forms part of a firefighter's equipment can also be included under the heading of hose accessories, as it is used to prop open doors to make hose laying easier. It can also be used for other purposes, for example temporarily shutting off sprinkler heads which have been activated.

STORING HOSES

Hoses must be packed so that they can be handled easily, both during the call-out and at the scene of the fire. The dif-

2.42 Hoses can either be rolled or folded for storage. Rolled hoses are either single-rolled or double-rolled. Folded hoses need some sort of storage equipment.

ferent methods of storing hoses have different advantages and disadvantages. Lay flat hoses are either rolled up or folded for storage. Both methods are used in the fire service. The most appropriate method should be chosen for each situation. With the exception of semi-rigid hoses on a reel, fire hoses must always be laid out before the water supply is turned on, otherwise the hose will inevitably become so tangled that it cannot be used.

Single-rolled hoses have one coupling in the centre of the roll and one on the outer edge. They are thrown out into position and then connected to the pump and the nozzle. A certain knack and an area of level ground are needed to throw out a single-rolled hose. The hose roll is held vertically and thrown outwards in a similar way to a bowling ball, whilst keeping hold of the outer coupling. The roll must be thrown with such force that the hose is completely unrolled. Sometimes the hose needs to be jerked when it is partially unrolled, to roll out the last section. If a single-rolled hose has a rope knotted round the middle of the roll for use as a handle, it can be run out.

A double-rolled hose has both couplings on the outer edge of the roll and can be laid out in two ways. One way is to throw out the hose and connect it afterwards. The other way is to connect the hose first at both ends and then to run out the nozzle. The hose will unroll itself. Several double-rolled hoses can be connected together and run out at once. Throwing out a double-rolled hose is easier than a single-rolled hose, because the rolling distance is only half as long. For attack hoses the benefits of double-rolling hoses outweigh the disadvantages, if there is only a short distance between the fire engine and the fire.

Hoses can also be rolled into eight, which means that they can be handled in the same way as a folded hose, but do not need any specific storage equipment.

Folded hoses are often stored in hose baskets of different types. One end of the hose is connected up and then the firefighter can run out the hose. If more than one hose needs to be laid out, this can be done more quickly if they are stored in hose baskets. When the hose is folded up, alternate layers are folded so that they reach the end of the basket and the

layers in between are stopped a few centimetres short of the end. This prevents the folded edges of the hose from forming a sloping line.

Supply hoses are almost always folded for storage. However, fire engines sometimes have a short rolled hose for connecting to a nearby hydrant or to a dividing breeching close to the vehicle.

The weight of large diameter hoses makes laying them out by hand very labour-intensive. A hose basket containing two lengths of large diameter hose weighs about 30 kg. As a result of their weight these hoses are sometimes packed in a crate which can be carried on the firefighter's back.

Long hoses can be folded up or double-rolled and pre-connected on a flat bed on hose trailers, fire engines or hose-laying lorries. Storing the hose in two separate compartments makes it possible to lay either a single or a double hose at the same time. This saves both time and effort when laying out long hoses, but the area must be accessible to vehicles. Because of the weight of the hoses, this is generally the only possible method for laying out long hoses and 110 mm or larger hoses. When a hose is laid, it is connected at the end and is given a neat bow of a few metres. The vehicle is then driven forwards. The hose unfolds automatically and is laid out behind the vehicle. Each coupling must be carefully checked, which means that two people must be available: one to drive the vehicle and the other one to walk behind it. Hoses are normally laid out from

2.43 A hose bandage or tape is used to help prevent a hose bursting if it springs a leak.

2.44 When throwing out a double-rolled hose, the firefighter must keep hold of both ends.

2.45 A hose-laying vehicle at work.

2.46 A rising main in a tall stairwell means that hoses do not have to be laid out. The inlet has a warning sign and is usually located behind a locked cover.

the water supply towards the scene of the fire, because the pump is often on a trailer behind the hose tender. Hoses can however also be laid out in the opposite direction, starting at the fire and working towards the water supply. This is easier if the vehicle drives to the scene of the fire first. However, a site for the trailer pump must have been investigated in advance. If the hose is laid out and it emerges that water must be taken from another source, this causes unnecessary problems.

A wheeled hose reel can be used as an alternative way of laying out longer hoses, for example to a hydrant. The principle is the same as for garden hose reels. To facilitate the hose laying, one person should be able to manage the reel.

A complete system with a folded attack hose in a hose basket can be connected in advance. The hose basket is best stored horizontally and with the opening facing outwards. A half-metre long section at the end of the hose should be left outside the basket at the start of the process of folding the hose. This allows both the couplings to be connected in advance. When the firefighting operation starts, the firefighters simply need to take hold of the nozzle and pull out the hose. When the hose has been fully laid out, an automatic valve can be used to turn on the water supply.

Some fire services keep one length of double-rolled supply hose, a dividing breeching and two lengths of double-rolled attack hose with a nozzle pre-connected in the fire engine. When a firefighting operation starts, one person simply needs to take the dividing breeching and the nozzle and run out the hose to have the whole system ready in position.

An extreme example of a pre-connected hose is the rising main. Installing a system of pipes in tall stairwells means that the time-consuming and labour-intensive work of laying out hoses up the stairs is no longer needed. Both the inlets and outlets must be clearly labelled. A large diameter hose is connected from the pump of the fire engine to the ground level inlet and a small diameter hose is connected to one of the upper outlets. The disadvantage of rising mains is the risk of neglected maintenance. When using a rising main, check that

2.47 When laying out a hose on a ladder, the hose is always positioned to one side. The attack hose is fastened in position and can hang freely.

all outlets are closed, except the used one, and that there is no debris in the pipes.

Rising mains are often also installed in fire service aerial appliances. If this is not the case, then an extra long, large diameter hose may be needed for use on turntable ladders. If a standard length hose is used, there is the risk that the hose couplings will get stuck in the ladder. Hoses are always laid to one side of the ladder so that the access is not blocked. When firefighters are using an aerial appliance, a hose reel fixed to the top of the ladder is the easiest to handle. If loose attack hoses are used, they must be fastened with a hose holder and hang outside the ladder. Otherwise they can take up so much room that it is not possible to climb down the ladder and the firefighters' retreat route is therefore blocked.

HOSE LAYING

When laying hoses in the street it is best to position the hoses in a straight line along the side of the street, so as not to obstruct traffic or the work at the scene of the fire. If there are several hoses running in parallel, they should be in the same order relative to one another along the whole stretch. The larger the operation, the more important it is that the hose laying

2.48 Discipline is needed in order to keep the hoses separate, even at relatively small operations.

process is disciplined, in order to make troubleshooting and extending the system easier.

When an attack hose is laid out, it should be positioned so that the firefighter responsible for it can advance without being obstructed. This is particularly important at interior firefighting. If the attack hose is coupled to a breeching at the entry point, it is often best to lay out the hose in five metre bows before entry. This makes both attack and retreat easier.

If a breeching is positioned in a corridor or a stairwell, there may be a large number of hoses in one place which can soon get tangled up. In this type of situation it may be sensible to put the breeching in place first and then lay out the supply hose from the breeching back to the fire engine, a reverse hose laying. In the case of a fire in an apartment block where the breeching is put in the stairwell it may be helpful to lay out the attack hose in bows one flight of stairs up. This is because it is easier to feed a hose downwards rather than upwards.

There is not necessarily a link between the amount of hose at a fire scene and the quantity of water reaching the fire. There is a risk at large fires that the incident site will start to look like a plate of spaghetti. For this reason it is important that the vehicles are parked in such a way that the hoses can be laid out clearly and that the system can be extended to create a straightforward structure. Dividing-breechings can be used to reduce the number of hoses and to provide a flexible solution for supplying water to the scene of the fire. It must be obvious how nozzles are supplied. This is a question of safety, in particular in the case of interior firefighting.

There must be no kinks in the hose. Kinks will cause large pressure losses and a reduction in the flow through the nozzle.

The weight of a full hose means that discipline when laying out hoses is important. The hoses must be laid out in a carefully planned way right from the beginning. The weight of a hose is determined by the volume of water it contains. A large diameter hose which contains 4.5 kg of water per metre is hard to move once it has been laid out. In the same way a long attack hose will become unusable if the firefighter has to drag the whole hose with him. The weight of the hose itself can be added to the weight of the water. A 38 mm hose weighs around 0.2 – 0.3 kg/m and 76 mm hose between 0.45 and 0.65 kg/m depending on the make. This does not include couplings and nozzles.

Always start the hose laying, for example from a fire engine or a hydrant, with a bow of a few metre, to eliminate the risk of the hose kinking when the water is turned on.

2.49 If a kink forms in a hose, this will cause significant wear.

Avoid laying hoses on rough stone surfaces or where there are sharp edges which can damage the hose. Hoses vibrate and move about on the ground during use. This is why it is important that there is nothing which can wear a hole in the hose when it is supplying water to a vital area. Bear in mind also the risk of a hose bursting as a result of a burning object falling on it, for example the base of a roof, and do not lay hoses close to the facade of a burning building.

Lay flat hoses are durable and will withstand rough handling, but there is a risk of a hole wearing in a hose, for example if it is filled but not pressurised and is dragged over a tarmac surface. This will cause the hose to fold and a corner of the fold is pressed against the tarmac by the weight of the hose. The corner will wear through very quickly.

When the water is turned on it exerts a powerful force, particularly in large diameter hoses. Hoses and breechings can be moved several metres by the force of the water. Therefore the water should always be turned on with caution.

Valves should never be opened without a go-ahead from the other end of the hose that everything is in order. It is important to make sure that the entire hose is unfolded and that the nozzle or the breeching is in place.

A classic initiation exercise for trainee firefighters is to lay out a large diameter hose in a strip on a landing stage. The trainees stand on the farthest end of the stage with the largest branchpipe that the fire service has to offer. The branchpipe is open and the pump is then started on full throttle. As the pressure in the hose increases, it straightens out and becomes slightly longer than the stage. This is a good lesson for the trainees.

When a globe valve is opened, for example on a breeching or a hydrant, the tap must always be turned until it is fully open and then closed a quarter turn. This makes it clear whether the tap is already open or simply stiff. A ball valve is always open if the handle is pointed in the direction of the hose. It is closed if the handle is at right angles to the hose. If a ball valve is not fully opened, the flow of water and the vibration can sometimes result in the valve closing, if it moves too easily.

Hose systems are often long and the scene of a fire is a very noisy place. For this reason a system of hand signals has been developed to allow nozzle men and pump operators to com-

2.50 Ventilate the nozzle before entering.

2.51 *A hose reel saves time when rolling up a hose.*

municate with one another by indicating, for example, that the water can be turned on or turned off, or that the pressure can be increased or reduced. These signals must comply with applicable regulations for visual signals.

When a system with lay flat hoses is coupled together, the hoses always contain air. The air is released by carefully opening the nozzle. When the nozzle has been ventilated, the hose system is ready for use. In the case of a semi-rigid hose on a reel the nozzle does not need to be ventilated.

Fire hoses which are incorrectly coupled together can cause major problems. For this reason the inlet and outlet for water and foam on a fire engine is often marked with arrows and different colours. However there is no standardised system of colours. A water tender which supplies firefighters with water at the scene of a fire normally has two hoses coupled to it. One of these is an incoming hose from a fire hydrant and the other an outgoing hose leading to a dividing breeching. If the outgoing hose is coupled to the suction side, this will be noticed immediately, as no water will come out of it. However, if the incoming hose from the hydrant is wrongly connected, this will only be noticed when the water level in the tank starts to fall. Depending on whether the pump or the hydrant has the higher pressure, water from the tank can be pushed out into the hydrant network. This is also possible if a hydrant is accidentally connected to a trailer pump which is pumping water from a static water supply. In the worst case this will only come to light when the water level in the water tower starts to rise. If water containing impurities has been pumped out into the mains network, it must be flushed out and treated with chlorine to avoid an outbreak of stomach bugs.

A hose with a nozzle on a branch section has been laid in a loop round the scene of a fire. Water is supplied from a direct connection to a hydrant in one part of the loop and from a water tender in the other. If too little water is taken out of the nozzle, there is the risk that the higher pressure of the water tender pump can push water backwards from the tender into the hydrant network. In this case it is a good idea to have a booster pump between the loop and the hydrant.

After the fire has been extinguished all the equipment must be collected and returned to a state of emergency readiness. The hoses must be emptied and rolled up on site. Once the crew returns to the fire station, the hoses can be replaced with new ones. The used hoses must then be washed, pressure tested and dried before operational use. Hoses must be repaired in accordance with the manufacturer's recommendations, a job which requires specific expertise.

MANAGING PUMPS AND HOSE SYSTEMS IN WINTER

When extinguishing fires in winter, there is the risk that the water will freeze. It will stop flowing and come to a standstill in the hoses if the flow is too small and the temperature too low. Moisture, for example in valves, can also freeze and act like glue. As a result it will not be possible to move the valve. Water which has come to a standstill will freeze and expand. Water which has turned into ice will always take up slightly more space. In addition, ice cannot be compressed, which means that the force exerted when ice expands is sufficient to burst most pieces of equipment, for example valves and

2.52 *Firefighting in the winter sets specific demands.*

pumps. Therefore it is important that the water remains in motion throughout the system.

When the temperature is a few degrees below freezing this is not normally a problem for firefighting operations, because the majority of operations are completed quickly and it takes a relatively long time for the water to cool down from the temperature it was at in the fire station. The problems start to become obvious at temperatures between –5 and –10°C. When the temperature is lower than this, there can be a serious impact on the results of an operation, unless the temperature is taken into account. Preventive measures and discipline are important aspects of firefighting in winter.

The equipment must be carefully checked in advance. The valves must be lubricated with water-resistant grease. The gaskets in couplings and valves must be carefully checked, because even a small leak can cause problems if the leaking water turns into lumps of ice. Hose couplings and pumps should be treated with glycol as a preventive measure before use.

Insulation is one method of preventing equipment from becoming too cold. A front-mounted pump must be well insulated, but even for a built-in pump a few carefully positioned sheets of insulation can be useful. This applies in particular to vehicles which were not originally designed for winter use.

If the weather is very cold, trailer pumps can be started before leaving the fire station and can be left idling during the call-out. Larger trailer pumps should be equipped with a thawing mechanism in case the impeller becomes frozen in position during the journey to the scene of the fire (SS 3496, 1989). This can involve circulating the coolant from the engine round the pump housing or taking hot exhaust gases through a metal pipe to the area which needs to be thawed. If the impeller has frozen in place, the exhaust gases can be taken into the pump via the water intake. If the pump does not have a built-in heating mechanism, a blowlamp can be used.

The solution to the problem of water freezing in hoses in winter is to ensure that the water is constantly flowing through all the hoses that are filled with water. All the nozzles must be kept slightly open and pointed in a direction where the water will not do any damage. For nozzles which are inside a building, it may be enough to allow the water to run out of the dividing breeching outside the building. Otherwise they must be positioned so that the water runs down a drain.

Systems running at tickover in this way must be carefully flushed out at regular intervals. Otherwise ice crystals that have formed along the walls of the hose will be swept away and block the nozzle when the flow is increased. The system can be flushed out by removing the nozzle and increasing the flow. Fog nozzles have the disadvantage in winter that ice crystals may block the nozzle. Jet/spray branchpipes are more reliable during long operations.

The position of the dividing breeching is critical in winter. It must be positioned so that no loose snow can enter the valves which may cause ice plugs to form and prevent the valves from being used. If a closed nozzle is inside a building, there must be a small flow of water from the dividing breeching. This means that the location of the dividing breeching must be carefully chosen, in order to ensure that the running water does not turn the scene of the fire into a sheet of ice. A return hose may be fitted to recirculate the water.

The fact that objects tend to become hidden in the snow is a problem, particularly if they are likely to be needed during a later stage of the operation. Discipline is therefore important in winter to make sure that equipment does not disappear. Snow and ice can also cover the water source, whether this is a hydrant or a static water supply. This means that it will take longer to pressurise the nozzle.

At very low temperatures hoses can be insulated with snow to reduce the risk of the water freezing. The disadvantage of this is that the hoses cannot be seen. As a result a burst hose will not be discovered until the water stops flowing out of the nozzle. When laying out the hoses, the couplings in particular must be handled with care to ensure that there is no snow on the coupling surfaces.

When it is time to disconnect the hose system, it is important to plan the course of events before any of the valves are closed. With water still flowing through the hose, the first stage of the decoupling process is to disconnect the nozzle. After this the hoses must be disconnected, emptied and collected up in one go. When the last hose has been removed, the pump can be disconnected and drained. Treating the pump with glycol will prevent remaining moisture from freezing. After emptying the nozzles and breechings, they must be put somewhere warm, for example in the fire engine, with the valves fully open. The water supply from a hydrant is disconnected in a similar way. If a hydrant is used, it must be carefully drained and any insulation replaced after use.

If a hose has frozen, it is difficult to return it to the station. A frozen hose must not be folded. The hose can be thawed sufficiently, for example in hot water, for it to be folded a few times. Another alternative is to hire a very long truck. The simplest solution is to find a heated building near the scene of the fire where the hose can be allowed to thaw.

NOZZLES

The purpose of the entire firefighting water network is to get the water to the right place. At the end of the network, a nozzle distributes the water. It can consist of anything from a simple smooth-bore nozzle weighing a few hundred grams to a large monitor which produces a water fog and weighs tens of kilos.

2.53 (left) Many different types of nozzle are available. This picture shows a simple fog nozzle and a jet/spray branchpipe.
2.54 (top right) A fog nozzle with a pistol grip for a low-pressure system.
2.55 (bottom right) High-pressure nozzle with an ergonomically designed angled hose mounting.

The nozzle serves two purposes. It is used to regulate the water flow or to shut it off and it is used to produce a spray pattern of a desired shape. Different nozzles have different applications and are used with different flows and pressures. The shut-off mechanism normally consists of a ball valve or a globe valve. Both are effective at regulating the flow with a reasonable drop in pressure.

The design of the nozzle depends on the make and model. The spray pattern varies considerably from a solid jet through to water sprays and a water fog. The terms flow, cone angle, range, droplet size and water density are often used to describe a water spray. A solid jet of water has a low capacity in extinguishing flames. Although it has a long range, it has a small target area and therefore a small surface effect in relation to the flow of water. A water spray has a large target area and a good surface effect providing that the droplets are large enough to penetrate flames. If the water droplets are small, they are effective at suppressing flames, but unfortunately have a short range. The superiority of the water spray over the solid jet has been known for a long time. (See Molin, 1955).

Some nozzles are also able to produce a protective shield. This is a screen of water at least two metres in diameter with a large cone angle which protects the firefighter.

A solid water jet breaks up naturally by the resistance of the air. Whether the jet breaks up or not depends on whether the flow is laminar or turbulent. In the case of a turbulent flow a solid jet breaks up naturally by the resistance of the air, if its velocity is sufficiently high. The higher the velocity of the water, the faster the jet is broken up and the smaller the droplets. The jet expands to form a cone, densely packed with droplets and surrounded by a layer of smaller droplets.

By reducing the diameter and increasing the velocity of the jet, it can be made to break up when it hits the air. A combination of high pressure and a small nozzle can be used to create a very fine mist. Fine jets placed next to one another produce a shower spray. The nozzle has a simple design and can produce the required droplet size. Unfortunately it is not possible to alter the spray pattern and the small holes are easily blocked by debris. On the other hand this type of nozzle does not use large quantities of water.

There are several different ways of producing a water spray. Two impinging jets create small droplets, a technique used, for example, in piercing nozzles and applicator nozzles. Fine jets either hit one another or bounce off a surface. The extent to which the spray is atomised is determined by the collision angle and the diameter of the jets.

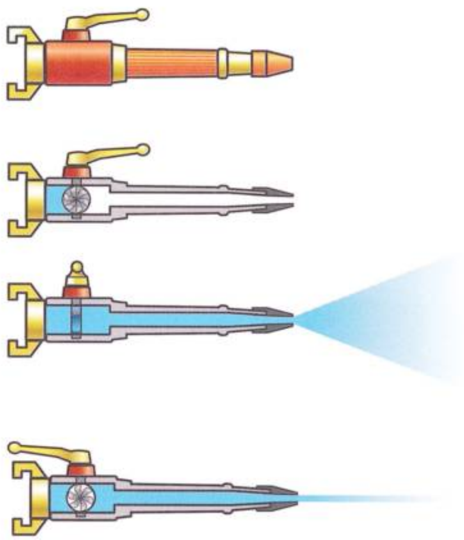
A jet/spray branchpipe consists of a narrowing pipe with a shut-off valve. The size of the opening determines the pressure loss in the nozzle and therefore the flow of water. Jet/spray branchpipes have a number of removable nozzles of different sizes, referred to as stacked tips. The normal sizes are 7, 10, 14, 18 and 22 mm. Adding or removing a tip can alter the flow and the nozzle pressure. Jet/spray branchpipes have two modes: a solid jet or a water spray. The solid jet is produced because the nozzle becomes narrower whilst interfering as little as pos-

2.56 Piercing nozzle

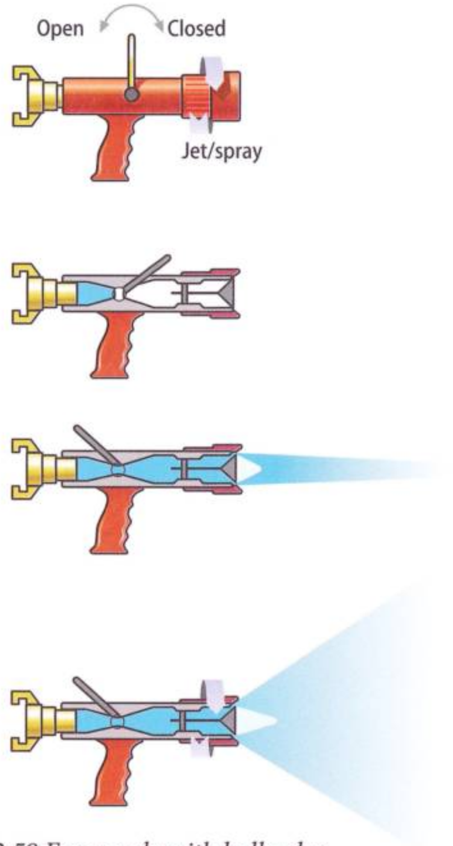
sible with the flow. The solid jet no longer plays a significant role and is largely used only when circumstances require a long range or when the impact of the solid jet is needed.

The spray from a jet/spray branchpipe is created by a built-in fixed propeller that rotates the stream of water. The rotating jet breaks down as soon as it leaves the nozzle. The advantages of the design are that it is simple and robust. The disadvantages, which in most situations, and in particular when extinguishing enclosure fires, outweigh the advantages, are that the droplets are too large to have an impact during the gas phase and that the angle of dispersion is narrow and cannot be adjusted.

2.57 A small jet/spray branchpipe with a claw coupling and a large one with a normal coupling. The branchpipe is closed if the handle is pushed forward. If the handle is vertical it produces a water spray and with the handle facing backwards a solid jet.



2.58 *Jet/spray branchpipes*



2.59 *Fog nozzle with ball valve.*

2.60 *Curtain nozzle (left) and monitor with fog nozzle (right).*

2.61 *Different types of fog nozzles.*

In some nozzles, a spray plate breaks up the water stream. Sprinkler heads are often designed in this way where a jet of water collides with a spray plate and breaks up (see the picture on p. 140). Sprinkler heads are designed for a specific application and therefore it is no disadvantage with a fixed spray pattern. Curtain nozzles have a similar design in which a solid jet hits a semi-circular disk which spreads the water out in a curtain. The disadvantage of curtain nozzles is that the water consumption is high.

An experienced chef takes care of his knives and makes sure that they are always sharp and ready for use. How does a firefighter look after his most important tools: the hose and the nozzle?

Fog nozzles can contain a disk which is used to break up the stream. By adjusting the position of the disk it is possible to produce everything from a solid jet to a water fog. Adding a toothed ring to the fog nozzle allows the water spray to be further divided and the size of the droplets to be reduced. The appearance of the spray is determined by the design of the teeth. Some designs create a ring of small jets with space between them. This can be prevented by rotating the water in a fog nozzle which transforms the fine jets into spirals. The jets can be made to rotate by using either a rotating toothed ring or a built-in propeller as in the branchpipe. If the jet is rotated, the water droplets start to move outwards. A nozzle which rotates the water can produce a spray pattern shaped like a hollow cone. For this reason some nozzles have an extra opening in the middle to spray water into the inside of the cone.

Finally there are nozzles in which the jet is broken up by introducing air or another type of gas into the nozzle.

The design of nozzles of different sizes can in principle be the same. A monitor can be designed, for example, to produce a solid jet or a water fog.

The disadvantage of some water fog nozzles is that they have a complex design. They need to be maintained and handled with care. However, they give a spray pattern with a good extinguishing effect, although practice is needed in using the nozzles to produce the best possible effect.

Nozzles based on the principle of allowing the water to flow through a number of small holes have the disadvantage that they are easily blocked by debris and particles in the water. This can often happen when water is taken from a static

2.62 A fog nozzle with a rotating, toothed, ring which produces fine spiral jets. The spirals cannot be seen when the nozzle is in use.

water supply. Therefore this type of nozzle usually has a net. If the nozzle starts to produce a low flow or a strange spray pattern, cleaning the net may resolve the problem. Fog nozzles often have a cleaning mode, allowing debris to be flushed out without disconnecting the nozzle.

Nozzles can have automatic pressure or flow regulators. In order to understand the finer points of these systems, it is essential to be familiar with the relationship between pressure and flow in nozzles without any control mechanism.

THE FLOW THROUGH A NOZZLE

Each nozzle has a recommended operating pressure. The main task of the pump operator is to ensure that the firefighters' nozzles maintain this pressure and to guarantee a reliable supply of water. The officer is always responsible for deciding where the water is most needed. As the water supply can be limited, a firefighter must never change to a larger nozzle or remove tips from a branchpipe on his own initiative. This can cause another firefighter to be left without water.

A firefighter must never change to a nozzle with a larger flow on his own initiative.

Good pumps are equipped with flow meters. If the pump does not have a flow meter, then the water flow can be calculated. The calculations are based on the fact that there is a link between pressure, flow and the diameter of a nozzle. The changeover from jet/spray branchpipes to fog nozzles during the second half of the 20th century has made the connection less obvious, but the principle still applies.

CALCULATING THE WATER FLOW FROM A NOZZLE

The flow in a nozzle is determined by the velocity of the water and the cross-sectional area. For a nozzle with a circular opening it is:

$$q = c \cdot v \frac{\pi d^2}{4}$$

q [m³/s] flow
c [–] discharge coefficient
v [m/s] water velocity
d [m] nozzle diameter

The velocity can be determined using the Bernoulli equation, which in a simplified form is as follows:

$$p_1 + \frac{\rho v_1^2}{2} = \frac{\rho v_2^2}{2}$$

p [Pa] nozzle pressure

The left-hand side of the equation refers to a point in the hose before the nozzle and the part to the right refers to a point just after the nozzle. The velocity at the nozzle opening is normally significantly higher than the velocity in the hose. In addition, when the velocities are squared the velocity in the hose is negligible.

Even at a pressure as low as 0.47 MPa, the velocity of the water is 110 km/h (30 m/s).

$$v_2 = \sqrt{\frac{2 p_1}{\rho}}$$

The velocity of the water flowing through a branchpipe at 0.7 MPa is:
$\sqrt{2 \cdot 0.7 \cdot 10^6 / 1000} = 37$ m/s.

The flow can be determined by combining the two equations.

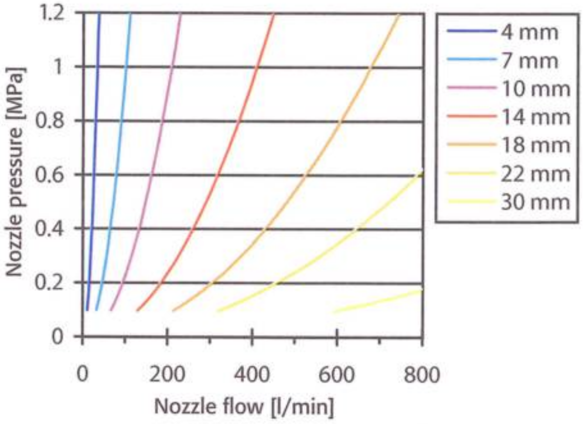
$$q = c \cdot \sqrt{\frac{2 p_1}{\rho}} \cdot \frac{\pi d^2}{4}$$

If both the pressure and flow values are known, the discharge coefficient can be calculated. In tests using a cutting extinguisher, the flow was shown to be 50 l/min ($0.83 \cdot 10^{-3}$ m³/s) at a nozzle pressure of 18 MPa. The nozzle diameter was 2.6 mm (0.0026 m). The velocity of the water was:

$$v = \sqrt{2 \cdot 18 \cdot 10^6 \text{ Pa} / 1000 \text{ kg/m}^3} = 190 \text{ m/s}$$

As a result the discharge coefficient was:

$$c = \frac{4q}{v \pi d^2} = \frac{4 \cdot 0.83 \cdot 10^3 \text{ m}^3/s}{190 \text{ m}/s \cdot 3.14 \cdot 0.0026^2 \text{ m}^2} = 0.82$$



2.63 The flow from a nozzle varies depending on the pressure and the nozzle diameter (using data from Herterich, 1960).

THE NOZZLE FORMULA

The equation can be simplified by bringing together all the constants for calculating the flow. The discharge coefficient for solid jets from branchpipes with no specific losses is normally 0.99. The density of the water is approximately 1000 kg/m^3. Using these values and switching from SI units to l/min produces the so-called nozzle formula, which corresponds with the experimental data (Herterich, 1960). (If the pressure is specified in MPa, the constant is 2.1.)

$$q = 2.1 \cdot 10^{-3} \cdot \sqrt{p} \cdot d^2$$

q [l/min] flow
p [Pa] nozzle pressure
d [mm] nozzle diameter

The flow through a 10 mm nozzle at 0.7 MPa is shown by the nozzle formula to be $q = 2.1 \cdot 10^{-3} \cdot \sqrt{0.7 \cdot 10^6} \cdot 10^2 = 175$ l/min.

d [mm]	q [l/min]
7	75
10	150
14	300
18	500
22	750

2.64 The approximate flow from different nozzles at 0.6 MPa. An increase or reduction in the pressure of 0.1 MPa produces a corresponding change in the flow of around 10%. The figure for 0.2 MPa is around 20%.

The fact that the flow changes by the square of the nozzle diameter explains by the nozzle branching rule. The branching rule states, for example, that a 14 mm nozzle delivers the same amount of water as four 7 mm nozzles. The cross-sectional area of the large nozzle is the same as the areas of the four small nozzles combined.

In order to produce a system curve for a system, it is helpful to turn the formula round.

$$p = \left(\frac{q}{2.1 \cdot 10^{-3} \cdot d^2} \right)^2$$

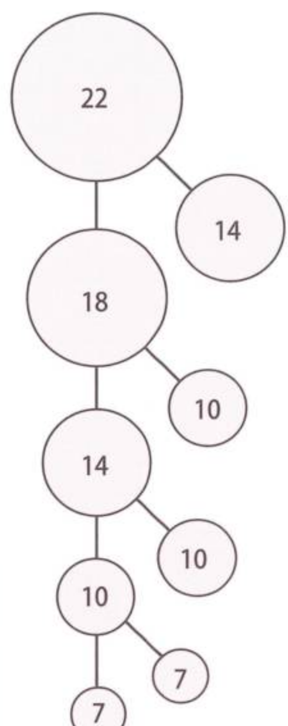
The equation can still be used even if the nozzle does not have a circular cross-section. If the relationship between the pressure and flow is known, an imaginary diameter can be calculated for a fog nozzle. However this only applies to standard pressure nozzles or when the figures are outside the adjustment range of an automatic pressure nozzle. By turning the equation around, the diameter can be shown to be:

$$d = \sqrt{\frac{q}{2.1 \cdot 10^{-3} \cdot \sqrt{P}}}$$

If we know the imaginary diameter, then standard pressure nozzles or automatic pressure nozzles outside the range of the regulator, can be treated in just the same way as jet/spray branchpipes in the calculations. This is why we have gone into so much detail about solid jets, despite the fact that they are seldom used and ineffective for extinguishing fires.

Two standard pressure nozzles, having a nozzle diameter equivalent to 7 mm and a nozzle pressure of 0.6 MPa are used at the scene of a fire. Each nozzle delivers 75 l/min. If there is 1000 l of water left in the tank when the hose system is full, the water will last for just over 6 minutes.

A monitor mounted on a water tender deliver 2000 l/min. If the water tender contains 8000 l of water, the water will last for four minutes.



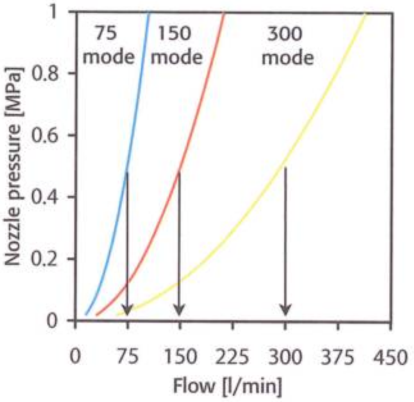
2.65 The nozzle branching rule.

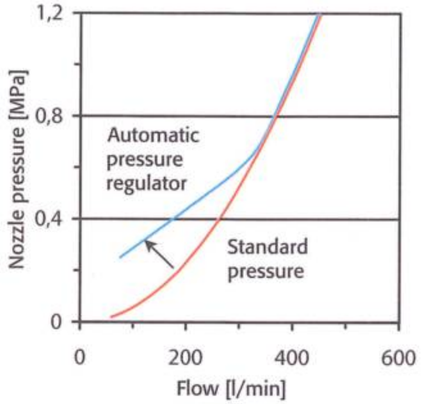
FLOW REGULATED AND
AUTOMATIC PRESSURE NOZZLES

Some nozzles have a continuous adjustment for flow resistance in the shut-off valve so that the flow can be varied. Others have preset modes, for example 100 or 300 l/min at a specific reference pressure. Sometimes the nozzle produces a different flow as a result of the setting for the spray pattern.

Some fog nozzles have a flow regulator which works like the stacked tips on a jet/spray branchpipe. The flow resistance is set by turning a ring on the nozzle in almost the same way as by adding or removing a stacked tip on a jet/spray branchpipe. A reference flow is specified on the ring, for example 115, 230 and 345 l/min. This flow applies at a reference pressure, in the same way as a 7 mm nozzle on a jet/spray branchpipe produces 75 l/min, but only provided that the input pressure is 0.6 MPa.

Automatic nozzles are equipped with an automatic pressure regulator. This consists of a spring in the nozzle which controls the size of the opening so that the nozzle pressure remains constant. The advantage of this system is that





2.66 (above left) A nozzle with a flow regulator produces different flows, depending on the regulator setting. The reference flow is the flow at a specific nozzle pressure.

2.67 (above right) In an automatic pressure nozzle, the flow is restricted to maintain the pressure and range. As the flow is reduced, the flow losses in the hose also drop. The reduction in pressure is therefore not linear.

the spray pattern is less dependent on the pressure. For example the range and the spray pattern remain the same. On the other hand the nozzle flow is changed significantly without the appearance of the spray changing. This means that it is difficult to get a feeling for how much water is actually being used.

By using a restriction mechanism it is possible to compensate for low input pressure, but this cannot compensate for a low flow rate. The lower the input pressure, the less water flows through the nozzle. If the pressure is too low, the flow of water is completely cut off. In the same situation a standard pressure nozzle would produce a small flow with a low pressure.

The spring in the automatic nozzle restricts the flow so much that the nozzle become unusable if the input pressure is too low. For this reason, there are dual pressure nozzles, where the pressure level can be adjusted. These are intended for use in tall buildings where the water pressure is low. The adjustment involves setting the spring load in the pressure regulator. In practice, a dual pressure nozzle functions in a similar way to nozzles with a ring for regulating the flow, but instead there is a setting for 0.3 or 0.6 MPa input pressure, for example.

For automatic nozzles, the relationship between pressure and flow in the nozzle can be quite different. Sometimes this can be expressed in the form of an equation, but sometimes this is not possible. In this case a diagram showing the values is needed.

The pressure range within which the automatic pressure regulator works is called the nozzle's adjustment range. Above this range, it follows the nozzle pressure formula, because the pressure spring has reached its lowest position. The adjustment range for one of the most common Swedish nozzles is up to 0.6 MPa nozzle pressure. When the pressure rises above this level, the nozzle has a diameter equivalent to 8 mm in its 100 litre mode and 14 mm in its 300 litre mode. Other nozzles have different adjustment ranges.

THE FLOW FROM A PIPE

It is possible to estimate the flow from a free-flowing hydrant or from a hose without a nozzle. The estimate is based on the assumption that the jet of water is solid and that the air resistance can be disregarded. The jet is only affected by gravity and produces a parabola. The more solid the jet, the more accurate the estimate. The water flow from a pipe consists of the velocity multiplied by the cross-sectional area:

$$q = v \cdot \frac{\pi d^2}{4}$$

q [m³/s] flow
v [m/s] outflow velocity
d [m] outflow diameter

At the same time the water forms part of the parabola.

$$-z = l \tan\alpha - \frac{gl^2}{2v^2 \cos^2\alpha}$$

z [m] height
l [m] range
α [°] angle
g [m/s²] gravitational constant, 9.81

If the flow comes out horizontally, α will equal 0 and the equation will be much simpler:

$$-z = \frac{gl^2}{2v^2}$$

$$v = \sqrt{\frac{gl^2}{2z}}$$

The minus sign before z is due to the fact that the parabola is based on the assumption that something is being thrown up and not falling down as is the case here. The equation is combined with the velocity of the water to produce the flow.

$$q = \sqrt{\frac{gl^2}{2z}} \frac{\pi d^2}{4}$$

Using the correct constants it is possible to produce an equation which can be used when only the outflow diameter, height and length of a horizontal jet are known.

$$q = \frac{1{,}7ld^2}{\sqrt{z}}$$

When a system is being pumped out, the water flows horizontally out of a hose coupling with an internal diameter of 63 mm. The vertical drop is 1.0 m and the distance to the point of impact is 2.0 m. As a result the flow is:
$1.7 \cdot 2.0 \cdot 0.0632 \cdot 1.0^{-0.5} = 0.013$ m³/s or 800 l/min.

CALCULATING REACTION FORCES

The reaction force from a flow can be determined as follows using Newton's second law:

$$R=\frac{d}{dt}(mv)=\frac{dm}{dt}\cdot v+\frac{dv}{dt}\cdot m$$

If the state is stationary, the last term is 0, which means that the equation can be simplified and developed:

$$R=\dot{m}v=c\rho Av^2=c\rho\frac{\pi d^2}{4}\frac{2p}{\rho}=0.5c\pi d^2 p$$

- R [N] reaction force
- m [kg/s] water flow
- v [m/s] water velocity
- c [–] outflow constant
- ρ [kg/m^3] density
- A [m^2] cross-sectional area of the nozzle
- d [m] nozzle diameter
- p [Pa] nozzle pressure

The reaction force is calculated on the basis of a completely solid jet of water and therefore represents the largest possible value. If the water takes the form of a spray, the reaction force will consist of a number of forces, aimed laterally at an angle. These lateral forces partially counteract one another, which means that the actual reaction force is reduced.

The force from the nozzle produces torque. This is calculated by multiplying the force by the length of the lever:

$$M=Rl$$

This torque must be counteracted by a corresponding torque resulting from the weight of the person holding the nozzle.

The reaction force from a 22 mm branchpipe at a pressure of 0.6 MPa giving a solid jet and if c is assumed to be 0.96 are $R = 0.5 \cdot 0.96 \cdot 3.14 \cdot 0.022^2 \cdot 0.6 \cdot 10^6$ N = 440 N. This force corresponds to a weight of 44 kg.

If a firefighter holds the branchpipe at a height of 1.3 m, the forces will produce torque of $440 \cdot 1.3 = 570$ Nm. The firefighter must compensate for this with an opposing torque. A firefighter who weighs 100 kg produces a downward force of 981 N. To produce the same torque but in the opposite direction, the lever must be 570 / 981 = 0.58 m. This means that the firefighter must have one foot 60 cm behind his centre of gravity in order to stand upright.

REACTION FORCE FROM A NOZZLE

The reaction forces in large branchpipes and monitors can be considerable. For this reason monitors must have a stable base and the hoses must be laid in such a way as to stabilise the monitor, otherwise the monitor may lift off its base or roll over. The reaction forces in monitors mounted on an aerial appliance are the same as for monitors on the ground. If the reaction force act in the wrong direction or if the monitor is opened or closed suddenly, the stability of the vehicle can be put at risk when the ladder or the boom is at its full extension.

2.68 As a result of reaction forces, large branchpipes, for example back-up nozzles, must be handled by two people, otherwise the large flow of water cannot be used very effectively. (Monument in London to firefighters who died in service during the Second World War).

When firefighters are extinguishing a fire from a scaling ladder or an extension ladder, only small diameter hoses and small nozzles must be used because of the reaction force and the risk of pressure surge. When extinguishing a fire from a ladder, the top of the ladder must be fixed in place. Firefighters should climb the ladder with an empty hose and attach the nozzle and also themselves to the ladder. Only then can the hose be filled carefully and the nozzle used. If larger diameter hoses and nozzles are needed, with a flow higher than around 100 l/min at 0.6 MPa, the fire should be extinguished from an aerial appliance. If a fixed monitor is used, it must be manoeuvred manually to produce the best extinguishing effect.

If two large nozzles are supplied from the same source, they must be opened and closed with great care. If both nozzles are open and one is closed, the water pressure and flow will increase in the other. If the firefighter is not prepared for this, there is a risk that he will not be able to control his nozzle.

The flow in a hose system

When all the components of a hose system are known, the next stage is the most important i.e. putting the components together to form a complete system. The pump, hoses and nozzles must be chosen carefully so that they combine to form an effective system. In addition the system must meet the requirements of the situation.

2.69 The hydrant, pump, hose and nozzle form a complete system. In addition, the water must end up in the right place.

PRESSURE RESTRICTIONS ON THE HOSE SYSTEM

The pressure in the hose system is controlled by the pump operator who ensures that the nozzle pressure is suitable for the equipment in use. Different components put different restrictions on the water system. The lower limit is normally set by the pressure needed in the nozzle. The upper limit is usually the pressure which the hoses can withstand and sometimes the capacity of the pump. Large diameter lay flat hoses have a maximum operating pressure of 1.5 MPa and a minimum burst pressure of 3.5 MPa. Attack hoses have the same operating pressure, but the burst pressure is slightly higher at 4.5 MPa. Larger supply hoses have a maximum operating pressure of 1.2 MPa and a minimum burst pressure of 3.0 MPa (SS 2840, 1987). The maximum operating pressure for breechings and other fittings is normally higher at 2.0 MPa.

For fire extinguishing purposes an appropriate maximum pressure for the pump is 1.0 MPa. If there is only a low risk of pressure surges and the hoses are small, the pressure can be increased, but never above the maximum working pressure.

On the other hand if there is a major risk of pressure surges or the hoses are large, it may be necessary to reduce the pressure.

Different types of system have different operating pressures. For example, high-pressure systems have a pressure of between 2 and 4 MPa and some equipment has an operating pressure over 20 MPa.

When using a pump with combined low and high pressure, the required pressure must be set on the high-pressure side, but it must not be too high for the low-pressure side.

PRESSURE SURGES

A hose system may contain several tonnes of moving water. If a valve, for example in a nozzle, is closed quickly, the mass of water will stop behind the closed valve. A work is needed to bring the water to a dead stop. This work is the force times the stopping distance. The faster the valve is shut, the shorter the stopping distance for the water and the larger the force needed to stop the water. The force is governed by the mass of moving water and the velocity. The more water is taken out, the greater the momentum and the greater the force needed to stop it.

The water which bounces off the closed valve produces a pressure surge throughout the entire system. The greater the flow of water and the faster the valve is closed, the larger the pressure surge. Pressure surges can easily be prevented by closing ball valves and nozzles slowly. It should take around a second to close the valve.

Always close the nozzle slowly to avoid pressure surges.

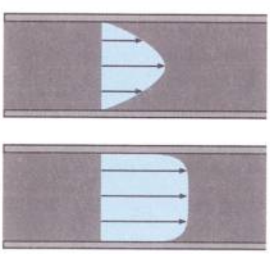
Pressure surges are damped by the elasticity of the hoses which allows them to stretch slightly. The more hoses that are in use, the more effective the damping. However, the walls of metal pipes are not elastic and are therefore more susceptible to pressure surges.

If fast pulses of water are being used to extinguish a fire, there will be large pressure fluctuations in the hoses. Measurements on a system of fire hoses showed a difference between the highest and lowest pressure in a pressure surge of 1.2 MPa. The tests were carried out using a fog nozzle and a pump pressure of 1.2 MPa. In the pump the difference between the highest and lowest pressure was reduced to 0.15 MPa (Nystedt, 1994).

During a firefighting operation a 14 mm nozzle was closed and opened so quickly that a pressure surge formed in the hose.
The pressure increased to 1.0 MPa, dropped to 0.2 MPa and then returned to its original level of 0.6 MPa. In this case the change in force was
$dR = 0.5 \cdot 0.96 \cdot 3.14 \cdot 0.0142 \cdot (1.0 \cdot 10^{-6} - 0.2 \cdot 10^{-6})\ N = 240\ N.$
This is the equivalent of catching a 25 kg sack of cement.

There are two main risks involved with pressure surges. The most important is that the surges can spread through branches of the hose system and produce unwanted force on other nozzles. This could, for example, unbalance a firefighter on a ladder. The other reason for avoiding pressure surges is to protect the equipment. Pressure surges can produce higher levels of pressure than the hoses are designed to cope with, which increases the risk of hoses bursting. When water is being taken from a static water supply, the pressure that spreads back through the hose system can be so high that it exceeds the pressure in the pump and creates positive pressure in the suction hose, causing the non-return valve to shut and the suction hose to break off.

LAMINAR AND TURBULENT FLOWS



2.70 Velocity profiles differ in hoses with laminar and turbulent flows.

A laminar flow in a hose means that the velocity of the water flowing through the hose varies a great deal at different points in the cross-section of the hose which are close to one another. There is no sudden change in velocity by the hose wall and the flow losses are small. All the particles are moving in smooth, parallel tracks.

In contrast a turbulent flow is characterised by eddies and irregular flows. The average velocity of the water is very similar throughout the entire profile of the hose. There is a significant difference in velocity at the hose walls. The friction losses in hoses actually consist up to around 90% of flow losses because of the turbulent flow. Only around 10% of the pressure losses are caused by friction between the water and the hose. Normal flows in fire hoses are always turbulent, which unfortunately results in large losses of hose pressure.

THE REYNOLDS NUMBER

The Reynolds number is a dimensionless parameter which determines whether a flow is laminar or turbulent. Flows are laminar up to a Reynolds number of around 2100. If the Reynolds number is 100,000 or more the water flow is always turbulent. The Reynolds number is calculated as follows:

$$Re = \frac{vd}{\upsilon}$$

v [m/s] flow velocity
d [mm] hose diameter
υ [m^2/s] kinematic viscosity

The lack of accuracy for determining whether a flow is laminar or turbulent is because the velocity of a turbulent flow must be significantly reduced in order to stabilise the flow, hence the lower limit. When the velocity of a laminar flow is gradually increased, it can remain laminar even at relatively high velocities, hence the upper limit. Only a very small disturbance is needed to create a turbulent flow. The Reynolds number for fire hoses is normally between 100,000 and 500,000.

The fastest certain laminar flow which can be achieved in a 42 mm hose can be calculated because the Reynolds number for the transition to a laminar flow is known:
$v = Re\, v/d = 2100 \cdot 1.0 \cdot 10^{-6} / 0.042 = 0.050$ m/s

This results in the following flow:
$q = v \cdot A = 0.050 \cdot \pi \cdot 0.0422 / 4 = 0.000069$ m^3/s, that is 4 l/min.

FLOW LOSSES IN HOSES

The basic principle behind firefighting hydraulics is that short, wide hoses supplies large quantities of water, allowing several large nozzles to be used. Long, narrow hoses allows a smaller flow and can only be used with a few small nozzles.

A normal fire pump has a pressure of around 1.0 MPa. A high-pressure pump can produce about 4 MPa. The additional increase in pressure can be used either to allow the use of a thinner, more flexible hose with greater losses, to produce a greater range or to generate smaller water droplets.

The losses can also be calculated. In the hose itself the losses can be determined using the Darcy-Weisbach equation. The main factors involved are the flow rate, the structure of the hose surface and the length and diameter of the hose. This last factor is familiar from the Bernoulli equation.

p_f [Pa]	pressure losses in the hose
f [–]	the friction factor of the hose
l [m]	the hose length
d [m]	the hose diameter
v [m/s]	water velocity
ρ [kg/m³]	density

ε [m] sand roughness

$$p_f = f \cdot \frac{l}{d} \frac{\rho v^2}{2}$$

The term "sand roughness" is used to compare the relative granularity of different surfaces. The term comes from experiments where grains of sand of a known size were glued to the inside of pipes. The flow losses in the pipes were measured and compared with the equivalent losses in pipes made of different materials. If the diameter of the hose and the velocity of the water are known, the Reynolds number can be calculated and, together with the relationship between the surface roughness and the hose diameter, can be used to produce the friction factor from a Moody diagram. The flows in fire hoses are almost always turbulent. If a calculation needs to be made for a laminar flow, the loss factor is always f = 64/Re.

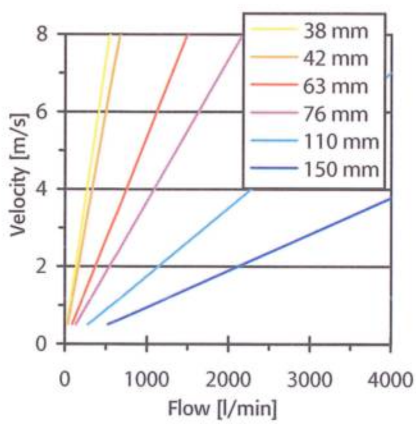
Pipe material	Sand roughness, [mm]
Concrete	0.3–3.0
Cast iron	0.25
Galvanised iron	0.15
Steel	0.046
Plastic	0.0015

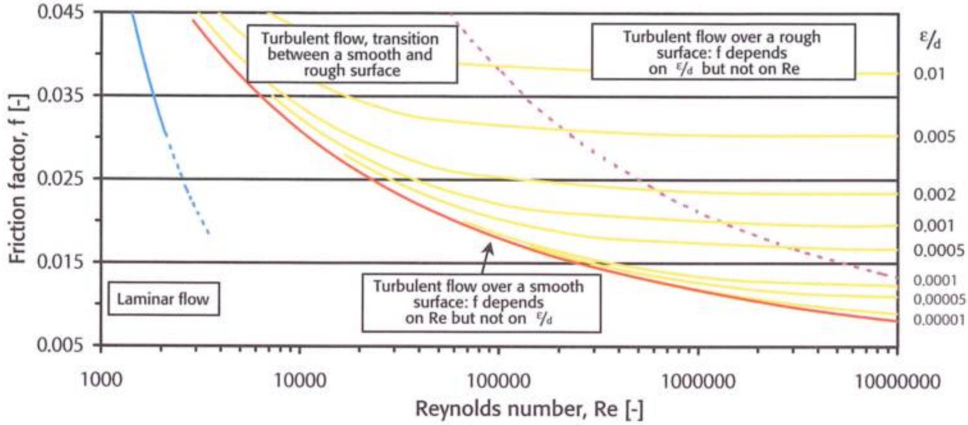
2.71 Sand roughness in different types of pipe.

In a new fire hose the value for $^{\varepsilon}/_{d}$ is calculated to be 0.0001, on the basis of the pressure loss measurements in 38, 42 and 150 mm hoses including couplings (Tryckfall i Setex brandslang, 1995; Gustavsson, 1995). If the flow in a 38 or 42 mm hose is 300 l/min, f will be approximately 0.017. If the flow in a 110 mm hose is 1000 l/min, f is about 0.015. At these flow rates the water velocity is 3 to 4 m/s, which is normal for lay flat hoses.

The coupling is included in the loss factor for the hose.

2.72 The water velocity is determined by the flow rate and the size of the hose. Flow losses increase by the square of the velocity.





2.73 f, the friction factor, can be determined from a Moody diagram.

On a 38 mm hose the claw coupling represents about 7% of the losses over a length of about 25 m. The relative loss in a coupling for a 42 mm hose, which generally uses the same type of coupling, is larger at around 14% of the total losses in the hose (based on data from Tryckfall i Setex brandslang, 1995). In other words, the design of the coupling is a relatively important factor with regard to pressure losses. The gasket inside these couplings has a V-shaped inner. This is to ensure that the inside of the coupling is as smooth as possible when the hose is connected and the gasket is compressed. The gasket illustrates the importance of small details and shows that older equipment can be brought up-to-date. By replacing an old-style smooth gasket with a one with a V-shaped inner, the performance of an old coupling can be improved to the level of a brand new one at very little cost.

The water velocity is not always known, but as the flow can be determined, the loss equation can be rewritten.

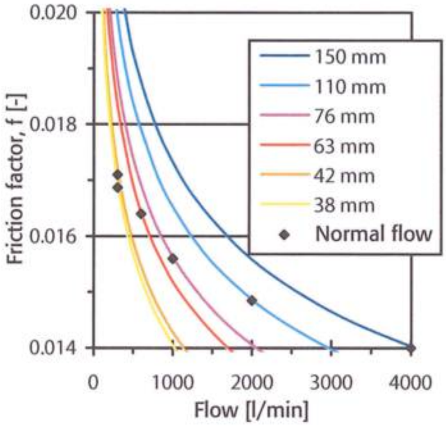
$$p_f = f \cdot \frac{l}{d} \frac{\rho (q/A)^2}{2} = f \cdot \frac{l}{d} \frac{\rho q^2 16}{2\pi^2 d^4} = \frac{8 f \rho}{d^5 \pi^2} l \cdot q^2$$

p_f [Pa] pressure loss
ρ [kg/m^3] density
q [m^3/s] water flow
d [m] diameter
A [m^2] cross-sectional area of hose

Combining all the constants gives the k value of the hose, which applies to hoses of that size at a specific reference flow. Note that this is not the same as the K factor for the nozzle.

$$k = \frac{8 f \rho}{d^5 \pi^2} \cdot \frac{1}{60000^2}$$

k [min^{2}Pa/l^{2}m] friction loss constant



Hose diameter [mm]	k value [min²Pa/l²m]	Reference flow [l/min]
38	$48 \cdot 10^{-3}$	300
42	$29 \cdot 10^{-3}$	300
63	$3.7 \cdot 10^{-3}$	600
76	$1.4 \cdot 10^{-3}$	1000
110	$0.21 \cdot 10^{-3}$	2000
150	$0.044 \cdot 10^{-3}$	4000

2.74 (left) Assuming that ε/d in a fire hose is approximately 0.0001, f can be determined for different hoses and flows. The dots show the normal flow in hoses of different sizes.

2.75 (right) k value for different hose diameters.

The last part of the equation results from changing the unit for the flow from m^3/s to l/min. The equation provides a straightforward method for calculating hose losses.

$$p_f = klq^2$$

q [l/min] water flow

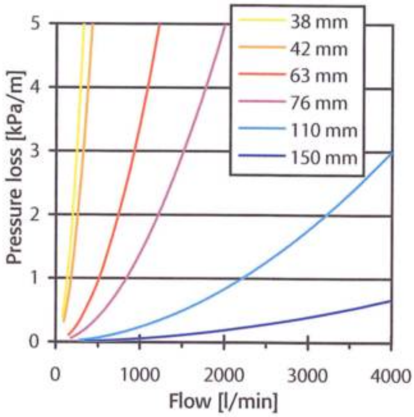
The k value reflects, amongst other things, the diameter and coating of the hose. If the flow differs significantly from the reference flow, if the hose is worn or is of an odd size, the losses can be calculated using the friction factor.

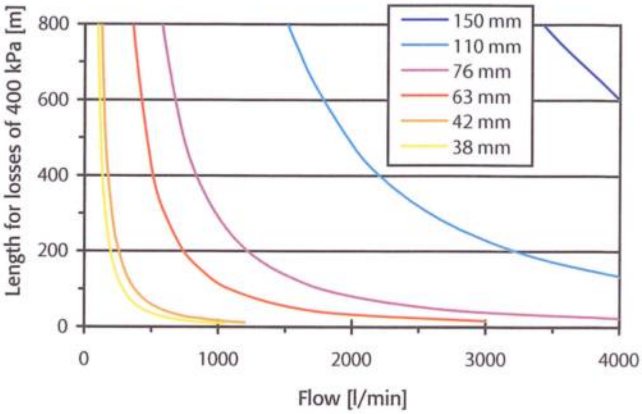
The k value $48 \cdot 10^{-3}$ min²Pa/ l²m means that a 100 m long hose with a flow of 100 l/min has a pressure loss of 48 kPa.

The equivalent hose length for different hose sizes can be calculated by dividing the k values by one another. One metre of 38 mm hose therefore has the same flow losses as $48 \cdot 10^{-3} / 1.4 \cdot 10^{-3} = 34$ m of 76 mm hose.

Kinks in hoses create large pressure losses and should be avoided.

Pressure losses are also affected by how the hose is laid out. The pressure losses given above are based on the assumption that the hose is straight. A single kink in a hose can produce the same pressure losses as the entire length of a straight hose. Kinks are more likely to occur in hoses at a low operating pressure than at a high pressure.





Normally the nozzle pressure is approximately 0.6 MPa and the pump pressure is 1.0 to 1.2 MPa. Of this 0.4 MPa can be lost in the form of flow losses. If the hose is 38 mm in diameter and the loss is 4.3 kPa/m at 300 l/min, the maximum possible length is 100 m. If the hose is 42 mm in diameter and the loss is 2.7 kPa/m, the maximum possible length is 150 m. With a 76 mm hose and a flow of 1000 l/min, the loss will be 1.4 kPa/m and the maximum possible length almost 300 m.

2.76 Pressure loss per metre, based on hose diameter and water flow.

2.77 Hose length for losses of 0.4 MPa at different flows. The smaller the flow required, the longer the hose that can be used.

2.78 A short, narrow hose produces the same pressure losses as a long, broad hose. At the same flow 25 m of 42 mm hose will generate the same pressure loss as just over 500 m of 76 mm hose.

THE HAZEN-WILLIAMS EQUATION

The disadvantage of the Darcy-Weisbach equation is that the friction factor and therefore the flow calculation depend on the water velocity. A similar equation, the Hazen-Williams equation, is usually used for sprinkler system calculations, but can in principle also be used to determine fire hose losses.

$$p_f = 6.05 \frac{lq^{1.85}}{C^{1.85} d^{4.87}} \cdot 10^4$$

p_f [MPa] pressure loss
l [m] hose length
q [l/min] flow
d [mm] hose diameter
C friction loss factor in accordance with Hazen-Williams

The equation has been developed empirically and C is a constant which varies depending on the surface structure of the hose. For a new fire hose, C is approximately 150, on the basis of experimental data which includes the losses from couplings (Tryckfall i Setex brandslang, 1995; Gustavsson, 1995). The constant is not dependent on the size of the hose and only takes into account its surface. The diameter is included separately.

If the two pressure loss equations are compared, it is obvious that they largely use the same parameters and that it is the exponents and constants that differ.

In a relay pumping system with two similar pumps, the second pump is placed two-thirds of the distance from the water supply to the scene of the fire. In this case 1.0 MPa from the first pump and 0.4 MPa from the second pump are used to compensate for flow losses. The total length will be around three times the distance in the example on page 115.

DOUBLE HOSES

Where water needs to be transported over long distances or where there is a large flow, it is always a good idea to consider using double hoses. This will result in extra work in the initial stages of an operation, but often pays off in the long term.

The flow in hoses is always such that the losses between two points in the system are the same, regardless of the route. If two hoses are used to increase the flow, for example by using dividing and collecting breechings, the pressure losses will remain the same, regardless of which of the two routes the water follows. The sum of the two flows is:

$$q = q_1 + q_2$$

As a result the total flow is:

$$q = \sqrt{\frac{p_f}{k_1 l}} + \sqrt{\frac{p_f}{k_2 l}} = \sqrt{p_f}\left(\sqrt{1/k_1 l} + \sqrt{1/k_2 l}\right)$$

A double hose always has lower pressure losses than a single hose. If a double hose of the same size is used, half of the flow will pass through each hose and the flow rate in the hoses will be halved, although the total output remains the same. As a result the flow losses are reduced to a quarter, because the pressure loss is dependent on the square of the velocity.

In a double hose the flow values are the same as for a single hose with half the total flow.

A 40 m long 76 mm hose is laid between two breechings in parallel with a 40 m long 38 mm hose. If the water travels through the large hose, the total loss factor for the dividing breeching, 40 m of hose and the collecting breeching is $4 \cdot 10^{-3}$ min^{2}Pa/l^2. For the dividing breeching, adapter, 40 m of small diameter hose, adapter and collecting breeching the total loss factor is $145 \cdot 10^{-3}$ min^{2}Pa/l^2. If the total flow is 1000 l/min, then the total loss is 0.12 MPa. This pressure loss is the same in both hoses. The flow is 860 l/min in the large diameter hose and 140 l/min in the small diameter hose.

LOCAL LOSSES

Pressure losses also occur in other parts of a hose system, including bends, valves etc. In the hose systems used by the fire service these losses can be significant.

When the diameter of a water flow is changed, for example when the water flows from a tank into a pipe or through an adapter, the losses are usually negligible. If the design is poor, they can be the same as the losses in 100 m of 38 mm hose. This also applies to water passing through valves. The losses are caused by turbulence which forms in the water and are larger when the diameter is reduced than when it is increased.

In many cases it is simplest to measure the drop in pressure in a component at a specified flow and then to calculate its loss factor. A k factor for breechings and other fittings can be calculated in the same way as the k factor for hoses.

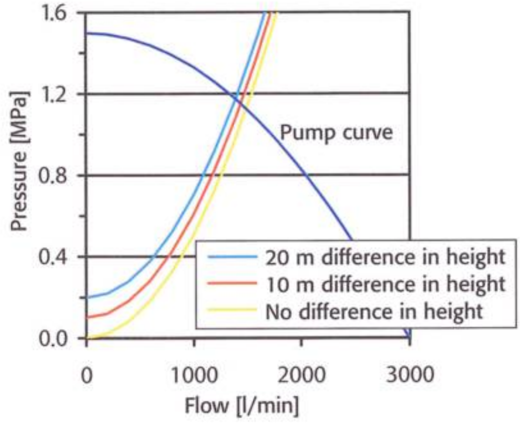
$$k = p_f / q^2$$

This equation is largely identical to the loss equation for hoses. This allows losses in breechings etc. to be converted into losses in an equivalent length of hose.

2.79 Losses for different components estimated on the basis of experiments and the equivalent hose lengths. Note that the values are only approximate.

The drop in pressure varies with flow. A dividing breeching with a k factor of 0.88 min²Pa/l² produces a pressure drop of $0.88 \cdot 300^2 = 79{,}000$ Pa or almost 0.1 MPa at a flow of 300 l/min.

Component	k factor [min²Pa/l²]	Equivalent length of hose 38 mm	42 mm	63 mm	76 mm
Collecting breeching	0.060			15	40
Old model of dividing breeching with normal coupling outlet	0.6			160	420
Old model of collecting and dividing breeching with normal coupling outlet	0.65			180	460
New model of dividing breeching with normal coupling outlet	0.044			10	30
Old model of collecting and dividing breeching with right-angled adapter on normal coupling outlet	1.08	20	40		
Old model of collecting and dividing breeching with tapered adapter on normal coupling outlet	0.88	20	30		
Old model of collecting and dividing breeching with claw coupling outlet with ball valve	0.88	20	30		
Old model of collecting and dividing breeching with claw coupling outlet with globe valve	2.75	60	100		
New model of dividing breeching with claw coupling outlet	0.54	10	20		
Right-angled adapter, normal to claw	0.43	10	15		
Tapered adapter, normal to claw	0.23	5	10		
Right-angled adapter, claw to normal	0.27			70	200



2.80 The system curve moves vertically if a difference in level between the pump and the nozzle is added.

CALCULATING LOCAL LOSSES

It is possible to calculate local losses. This is done using a method similar to that for calculating friction losses in pipes.

$$p_f = \zeta \frac{\rho v^2}{2}$$

The constant ζ depends on the type of change which takes place in the flow. There are tabular values for losses in a flow from a tank to a pipe, from a pipe to a tank, for abrupt or tapered reductions or increases in the pipe diameter and for different types of valves. (Vennard & Street, 1982; Titus, 1995)

This type of calculation is needed in the design of new systems, for example to evaluate which type of piping is most suitable for a new fire engine.

DIFFERENCES IN LEVEL

Differences in level between the pump and the nozzle result in pressure energy being converted to potential energy. If the pump is located lower than the nozzle, the difference in height will result in a pressure loss. The difference in energy can be expressed in corresponding metres of water column. In contrast to other flow losses, this type of loss does not vary with the flow.

The change in pressure is 0.01 MPa per metre. This means that a nozzle which is 10 m higher than the pump needs 0.1 MPa more pressure from the pump to produce the same flow as a nozzle at ground level.

If the nozzle is lower than the pump, then both the height and the pressure loss will be negative. In this case the difference in height results in additional energy and an increase in pressure. When evaluating possible locations for trailer pumps and water tenders, it is therefore important to study the local topography and to choose a location for the pump where the differences in height can be used to best effect.

HOSE SYSTEMS

The quickest method of setting up a hose system for firefighting is to use a hose, pre-coupled directly to the fire engine. This may be either a semi-rigid hose on a reel, or a lay flat hose.

Assume that a 42 mm attack hose is directly connected to the fire engine's pressure outlet. Allowing a margin for pressure surges, 1.0 MPa is the highest output pressure from the pump. The recommended nozzle pressure is 0.6 MPa and, according to the nozzle manufacturer, the flow is 300 l/min at this pressure. The losses in the hose system can therefore be a maximum of 0.4 MPa. In this case the maximum possible hose length is:

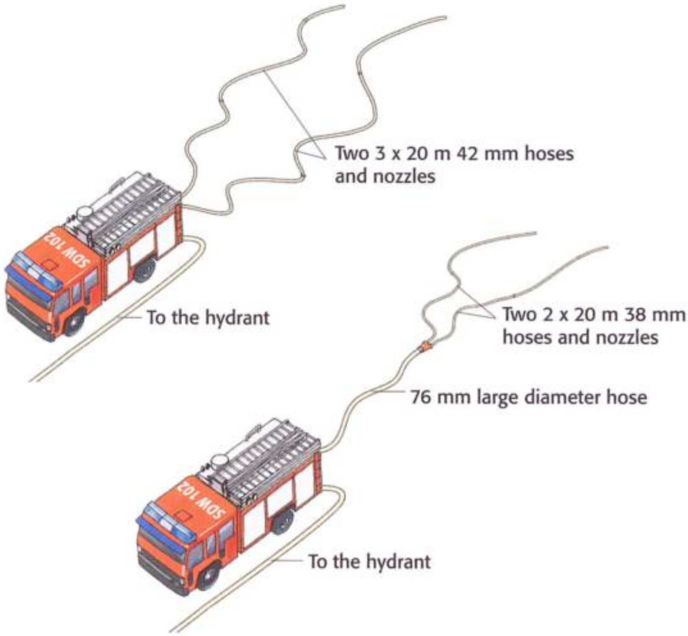
$$l = \frac{0.4 \cdot 10^{6}\ \text{Pa}}{29 \cdot 10^{-3}\ \text{min}^2\text{Pa/l}^2\text{m} \cdot (300\,\text{l/min})^2} = 150\,\text{m}$$

In other words six lengths of 42 mm hose will not pose a problem for the flow required. If the firefighter is allowed to move up by 10 m, the acceptable hose losses are reduced to 0.3 MPa.

If a large diameter hose, a dividing breeching and two lengths of 38 mm hose are used under the same conditions, the maximum possible hose length will change. With 50 m of 38 mm hose the pressure loss after the dividing breeching will be as follows:

$$p_f = 48 \cdot 10^{-3}\ \text{min}^2\text{Pa/l}^2\text{m} \cdot 50\,\text{m} \cdot (300\,\text{l/min})^2 = 0.22 \cdot 10^{6}\ \text{Pa}$$

If the adapter for the large hose outlet produces a pressure loss of 0.08 MPa, then the total loss is 0.3 MPa. The pressure loss in the 76 mm hose leading to the dividing breeching is only 0.0001 MPa/m, which is negligible for single lengths of hose. If a second nozzle is opened, with supply from the same breeching, the flow in the hose up to the breeching will double. The loss in this hose will then increase to 0.0005 MPa/m.

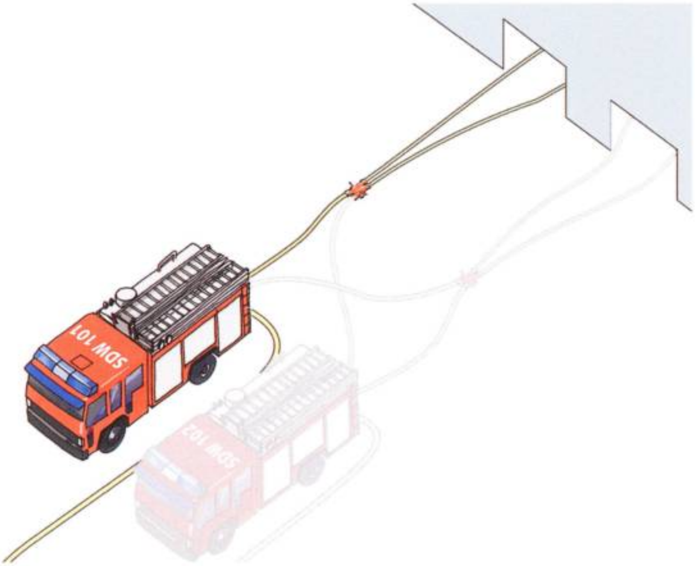


2.81 Two common ways of setting up a hose system for a firefighting operation. Coupling some lengths of 42 mm hose directly to the fire engine produces quick and flexible results. With a large diameter hose and a dividing breeching coupled to two lengths of 38 or 42 mm hose, the proximity of the fire engine to the scene of the fire is not as important. A long length of large diameter hose can be used without too large pressure loss.

The conclusion from these two examples is that connecting hoses directly to the fire engine, if it can be positioned close to the fire, is an excellent way of producing the required pressure and flow in the nozzle. The losses in a large diameter hose with a small flow are largely negligible. In contrast it is the dividing breeching and the small diameter hoses that produce the large losses.

The structure of a hose system must be carefully thought out before it can be set up. In the case of a firefighting operation which is likely to grow in size, the following system can be set up with standard equipment.

1. A supply hose is taken from the fire engine to a dividing breeching with a collecting breeching at the firefighters' entry point. From here a few lengths of attack hose are laid out for the firefighters and a similar safety hose. A supply hose is laid between the hydrant and the fire engine. With 25 m of 76 mm hose, a dividing breeching with a collecting breeching, 50 m of 42 mm hose, nozzle pressure of 0.6 MPa



2.82 Extendable water supply system for interior firefighting.

and a nozzle which supplies water at 300 l/min, the pressure loss is:

$$p_f = \left(1.4 \cdot 10^{-3} \cdot 25 + 1.08 + 29 \cdot 10^{-3} \cdot 50\right) \cdot 300^2 = 0.23 \cdot 10^6 \text{ Pa}$$

This means that the pump pressure must be at least 0.83 MPa. The dividing breeching is responsible for around half the pressure loss in the hose despite the fact that the hose is coupled via an adapter to a normal coupling outlet.

2. If there is a need for additional nozzles the system can be extended by adding an extra fire engine. The second fire engine will supply a new dividing breeching with collecting breeching via a supply hose. The special feature of the collecting breechings is that additional supply hoses can be cross-connected between the fire engines and the dividing breechings. The second fire engine is coupled to the same hydrant as the first one. This is why initially only one hose is connected. This type of system provides a water supply from two pumps, which means that the redundancy and the reliability of the system are increased. A back-up nozzle can be connected to the new dividing breeching and this gives the team leader, if required, a larger flow and a longer range than with a standard nozzle. The idea behind the back-up nozzle is that it can be used to knock down a flashover which may occur during the operation.

3. In the third stage a team connects its hose to the first dividing breeching, which is now supplied by two pumps. Other teams can couple their hoses to the second dividing breeching. When the system is fully extended, it can supply three nozzles from each dividing breeching, providing that the flow from the hydrant is sufficient. With three nozzles and a double hose to each dividing breeching, the flow in each nozzle will be 300 l/min and in each supply hose 450 l/min. In this case the pressure loss between the pump and the nozzle will be:

$$p_f = 1.4 \cdot 10^{-3} \cdot 25 \cdot 450^2 + \left(1.08 + 29 \cdot 10^{-3} \cdot 50\right) \cdot 300^2 = 0.234 \cdot 10^6 \text{ Pa}$$

Therefore the pressure loss is the same as when a single nozzle is used. The largest drop in pressure occurs in the attack hoses.

For an attic fire two piercing nozzles are used through the roof, connected to a hose from a fire engine. The flow is 70 l/min at 0.8 MPa. How long can one attack hose be if the nozzle pressure must be at least 0.8 MPa? A single 42 mm hose is laid to a dedicated dividing breeching. From here a 5 m length of 38 mm hose is taken to each piercing nozzle. There is no information available about the losses in the breeching, so we will use an estimate. The loss in the breeching and in the system after it is:

$$p_f = \left(48 \cdot 10^{-3} \cdot 5 + 0.5\right) \cdot 70^2 = 3.6 \cdot 10^3 \text{ Pa}$$

In other words the loss is negligible. When using piercing nozzles there is only a small risk of pressure surges if the flow is turned on and off carefully. This means that a higher pressure than normal can be used. If the pump pressure is 1.2 MPa and the roof is 20 m higher than the pump, the hose losses will be 1.2 – 0.8 – 0.2 – 0.0036 = 0.2 MPa. The possible total hose length is therefore:

$$l = 0.2 \cdot 10^6 \text{ Pa} / \left(29 \cdot 10^{-3} \text{ min}^2\text{Pa/l}^2\text{m} \cdot (140 \text{l/min})^2\right) = 350 \text{m}$$

This may seem long, but this is a result of the low flow and the high pump pressure. However, there is some uncertainty in the figure for the losses from the breeching.

There is also system of pipes in the fire engine. The flow losses in these pipes are the reason why a vehicle-mounted pump may have a different capacity depending on whether an outlet near the pump or at the other end of the vehicle is used.

The pressure meter on the pump shows the pressure at the measuring point. Therefore the pressure losses up to the pressure outlet must also be included. The other option is to reset the pressure meter so that it shows the pressure at the outlet.

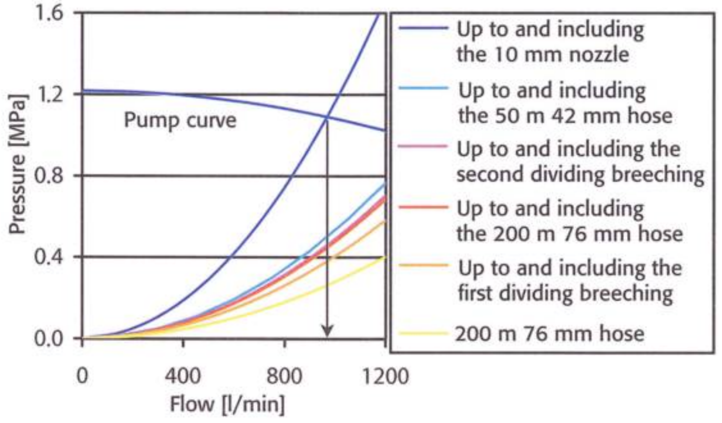
A containment line is set up with six nozzles supplied by a trailer pump at a static water supply. A 200 m long 76 mm hose is laid from the pump to a breeching. At this point the system is divided into two identical parts, each of which consists of another 200 m length of 76 mm hose and a dividing breeching. Three 10 mm fog nozzles each with 25 m of 38 mm hose are connected to the second breeching. As the system is symmetrical, the flow is the same in all the nozzles. The pump pressure is equal to the total losses in the hoses and the nozzle pressure.

1) The loss in the 200 m 76 mm hose is $p = 1.4 \cdot 10^{-3} \cdot 200 \cdot q^2$
2) In the breeching, where half the water flows into each hose, the loss is $p = 0.6 \cdot (q/2)^2$
3) The loss in the 200 m 76 mm hose is $p = 1.4 \cdot 10^{-3} \cdot 200 \cdot (q/2)^2$
4) The loss in the breeching, where the flow is reduced to one sixth for each hose is $p = 0.6 \cdot (q/6)^2$
5) The loss in the 25 m 38 mm hose is $p = 48 \cdot 10^{-3} \cdot 25 \cdot (q/6)^2$
6) The pressure in the 10 mm nozzle is $p = 1/(2.1 \cdot 10^{-3} \cdot 10^2)^2 \cdot (q/6)^2$

The total of all these figures gives the following system curve: $p = (0.28 + 0.15 + 0.07 + 0.02 + 0.03 + 0.63) \cdot q^2$, which is $p = 1.18 \cdot q^2$.

The pump curve for the specified pump running at full throttle can be produced using the following equation: $p = 1.2 \cdot 10^6 - 0.13 \cdot q^2$

The point where the system curve and the pump curve intersect, which is where the two expressions are equal, gives the flow: $1.18 \cdot q^2 = 1.2 \cdot 10^6 - 0.13 \cdot q^2$
The total flow in the system is 957 l/min, which equates to 160 l/min per nozzle.



2.83 System curve and pump curve for the hose system in the example.

A fire hydrant supplies water at 900 l/min at a pressure of 0.4 MPa to a fire engine. If a 63 mm hose is used and the incoming pressure at the fire engine must be 0.1 MPa, the loss must be no more than 0.3 MPa. In this case the maximum distance between the hydrant and the fire engine is $l = 0.3 \cdot 10^6$ Pa / ($3.7 \cdot 10^{-3}$ min^{2}Pa/l^{2}m $\cdot$ (900 l/min)^2) = 100 m. If the distance is greater, the flow will be smaller.

Hose systems for firefighting are generally quite forgiving and try to compensate for changes. For example if a nozzle is moved up a few storeys in a building, the difference in height will move the system curve upwards. As a result the water flow will reduce. The other flow losses are dependent on the water velocity. When the velocity falls, the losses are reduced. At the same time the flow through the pump falls, and as a result the pump pressure increases slightly. Overall this means that the water flow is not reduced as much as might be expected. The intersection of the pump curve and the system curve always represents the current flow.

THE VOLUME OF WATER IN THE HOSE SYSTEM

In many cases only a limited amount of water is available in the initial stages of a firefighting operation. It is therefore important to be aware of how much water is needed to fill the hoses and how quickly the water is used. The water volume in a fire hose is determined by its cross-section and length:

V [m³]	volume
A [m²]	cross-sectional area
l [m]	length
d [m]	diameter

$$V = A \cdot l = \frac{\pi d^2}{4} l$$

The volume of water used is determined using the following equation: $V = q \cdot t$

q [m³/s]	water flow
t [s]	time

A 50 m long 76 mm hose is laid from a fire engine to a dividing breeching. Two 50 m long 42 mm hoses are connected to the breeching. The volume of the hoses is calculated using the values from the figure:

$$V = 4.5 \text{l/m} \cdot 50\,\text{m} + 2 \cdot 1.4 \text{l/m} \cdot 50\,\text{m} = 360\,\text{l}$$

Assume that the fire engine has a capacity of 1800 litres. When the hoses are full 1800-360 =1440 litres remains. If the two nozzles have a flow of 300 l/min, this water will last for:

$$t = V / q = 1440\,\text{l} / (2 \cdot 300\,\text{l/min}) = 2.4\,\text{min}$$

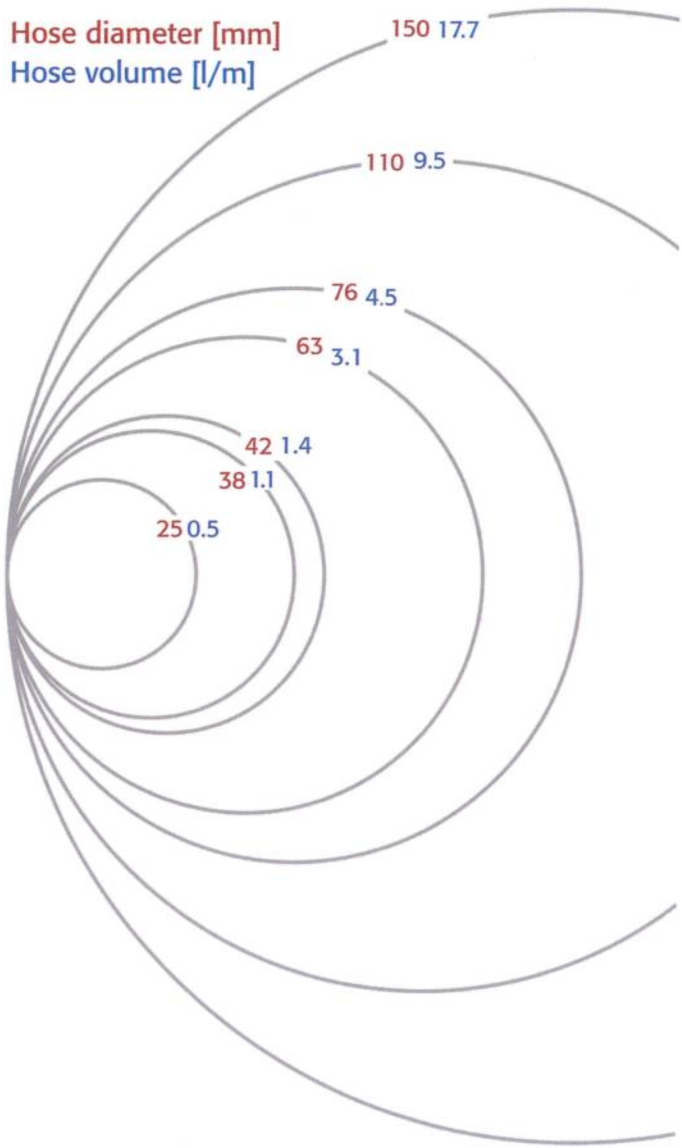
Two and a half minutes is enough to knock down a small fire. In order to allow a continuous flow the fire engine must be connected to a hydrant or another tank very quickly.

A small fire is extinguished using the water from a water tender. The water is used at a rate of around 500 l/min. If the tender has a capacity of ten cubic metres of water, this will last for:

$$t = V / q = 10000\,\text{l} / 500\,\text{l/min} = 20\,\text{min}$$

In this case there is no immediate need to connect the tender to a hydrant, because the water supply is plentiful. However, it is important to have the water tender refilled in order to ensure that it is ready for the next call-out.

In the case of a barn fire, 300 l/min is used to protect the house near the barn. The first water tender arrives ten minutes after the fire engine. If the fire engine has a tank with a capacity of 1800 litres, the operation must be re-evaluated, because the water will run out after only six minutes.



2.84 Cross-section and volume per metre of hose with different diameters.

2.85 The shape of the water spray is determined primarily by the angle of the cone, the pressure and the flow.

Water sprays

The design of the nozzle and the pressure determine what the water spray pattern will look like. Normally the aim is to produce a spray which as far as possible reaches and covers the area which is burning.

PROJECTION RANGE AND HEIGHT

The range of the water is limited by gravity and is determined largely by how solid the flow is. When the cross-sectional area increases, the droplet velocity falls and the droplets start to move in parabolas.

Water cannot extinguish fire from a distance.

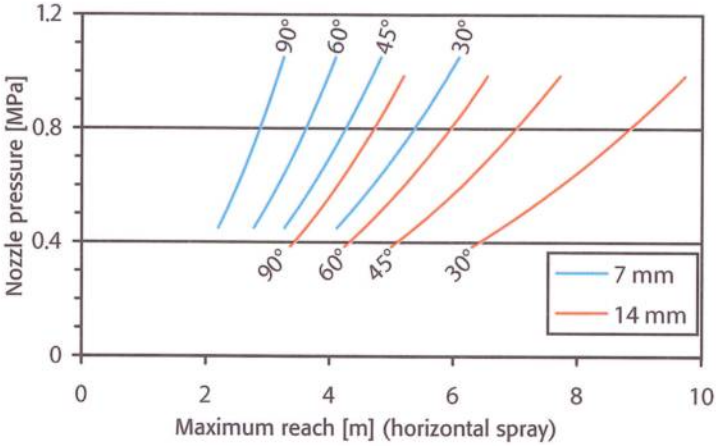
This gives an indication of the reach of water sprays. In order for a nozzle to be useful, the burning object must be within reach. Generally the water is used more effectively, if the nozzle is brought closer to the fire.

An approximate range can be calculated for water sprays as a function of the cone angle, using an equation produced on the basis of experiments. The equation has been validated for cone angles between 30° and 90°. (Fire Research 1955, 1956):

$$l_{max} = \frac{7.8 \cdot q^{0.36} \cdot p^{0.28}}{\alpha^{0.57}}$$

l_{max} [m] maximum reach
p [MPa] nozzle pressure
q [l/min] flow
α [°] cone angle

On the basis of a nozzle pressure of 0.6 MPa, a change in the pressure of 0.1 MPa will produce a corresponding change of around 5% in the range for normal manual nozzles. This is equivalent to between 1 and 2 m.



2.86 Calculated range for a water spray

Class of nozzle	Flow at 0.6 MPa [l/min]	Reach of jet [m]*
1	75–150	ca 20
2	75–300	ca 25
3	300–750	ca 30

* Flow dependent

2.87 The nozzle standard (SS3500, 1997) puts a demand on eg. reach.

A water jet is affected by gravity. It will therefore follow the parabola for an object moving under constant acceleration. This equation can be found in any standard collection of tables and formulae. The theoretical maximum range and height of the jet can then be calculated:

$$l = \frac{v_0^2 \cdot \sin(2\beta)}{g}$$

$$z = \frac{v_0^2 \cdot (\sin\beta)^2}{2g}$$

z [m] height
l [m] reach
v_0 [m/s] initial water velocity
β [°] angle to the ground

If the jet is pointed straight upwards, the sine term in the equation for the height of the jet disappears. What remains is the equation for kinetic energy from the Bernoulli equation. As the velocity in the nozzle depends on the nozzle pressure, it can be substituted when calculating the theoretical maximum range and height of the jet.

However, the air resistance is neglected in the two equations. The air slows in reality down the jet considerably which results in a lower height and a shorter range. The maximum range is achieved when the angle to the ground is approximately 32°. An empirical equation for the maximum length and height of a large, solid jet according to Freeman (1889) and quoted by Herterich (1960) is as follows:

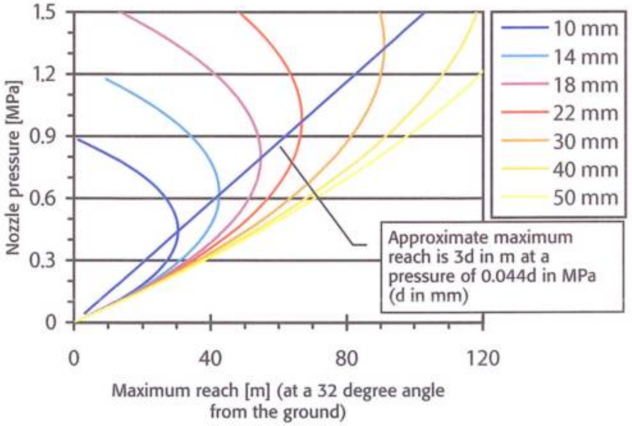
$$l_{max} = \frac{4}{3} z_{max}$$

l_{max} [m] maxium reach
z_{max} [m] maximum height

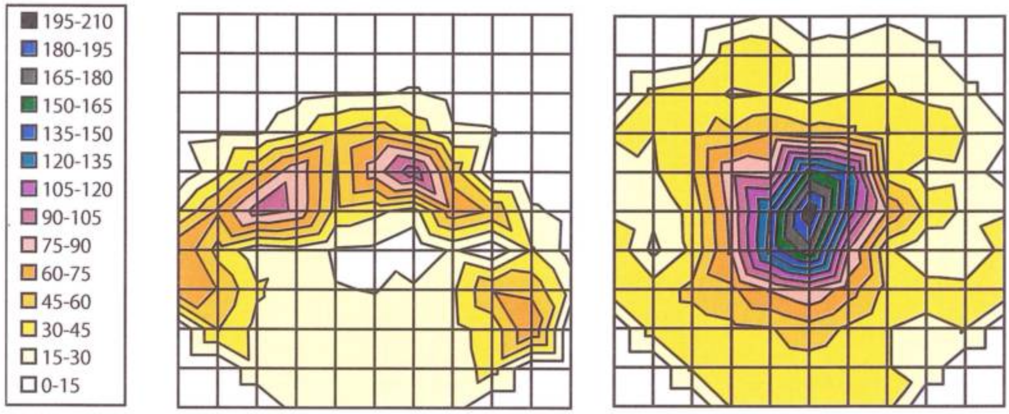
$$z_{max} = 100p - 1100\frac{p^2}{d}$$

p [MPa] nozzle pressure
d [mm] nozzle diameter

The equation has been tested at nozzle pressures above 0.5 MPa and for nozzle diameters between 20 and 50 mm.



2.88 The throw of a jet depends on the nozzle pressure and diameter (from Freeman, 1889).



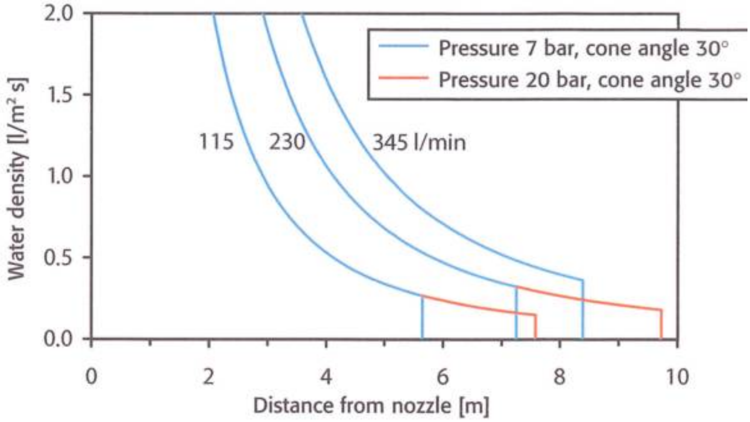
WATER DENSITY

An even water distribution from nozzles is normally desired. The water distribution can be determined using a standard test (SS 3500, 1987). The empty proportion of the cone must not be too large. Also, the highest water density must not be too great, compared to the average value. Most modern nozzles meet the requirements, but the spray patterns vary significantly. It is worth noting that it is difficult for the firefighter to assess how even the dispersion pattern of a water spray is (Rimen, 1990).

2.89 (top) Test method used in SS 3500 to determine the water distribution from a water spray.

2.90 Measurement of water distribution in l/m^2min from two different fog nozzles (from Handell, 2000).

The illustrations showing the measurements of water distribution were taken from a study of the gas phase cooling effect of nozzles. The differences in the spray pattern, amongst other things, were responsible for the fact that the time needed for a specified reduction in the smoke temperature varied significantly. The fastest nozzle took less than half the time of the slowest (Handell, 2000). The extinguishing effect of nozzles differs widely, but this difference in quality is not always noticeable, because the suppression time normally is very short anyhow.



2.91 A rough theoretical estimate of the water density of jets at different distances from the nozzle. The cone angle is 30° in all cases. Gravity has been disregarded in these calculations.

The water access to the fire is of major importance. Physical obstacles can reduce the extinguishing capacity to zero or nearly zero. It does not take much to interfere with the water. A row of pallets is quite enough to make the extinguishing effect negligible.

Sprinkler systems also produce an uneven distribution of water. In some cases parts of the area to be covered can be completely shaded. As a result the water is distributed over the remaining area instead. (Walmsley, 2000) This is one of the reasons why some form of extinguishing is needed after a fire has been brought under control by a sprinkler system.

Roofs can be very impractical. They protect buildings from firefighting water in just the same way as they protect them from rain.

Each type of nozzle has an ideal distance from a fire, depending on its range and the distribution of the droplet sizes. If the nozzle is further away from the fire, a longer range is needed and as a result the spray pattern will change. In the case of an ideal conical spray where gravity is disregarded, the average flow [l/m^{2}s] through the cross-section of the spray can be estimated in geometrical terms:

$$q''_{average} = \frac{q}{\pi(l \cdot \tan(\alpha/2))^2}$$

q [l/s] water flow
l [m] distance from the nozzle
α [°] cone angle

This assumption is simplified, but it still fulfils its purpose. The calculation shows that the average flow is in reverse proportion to the square of the distance from the nozzle.

When the distance between the nozzle and the fire is small, the water density is many times greater than that needed to extinguish the fire. The more solid the jet, the higher the water density and the smaller the covered area.

2.92 *Pools of water at the fire ground are the most obvious sign that the water has not been used effectively.*

If the nozzle and the fire are a long distance apart, a large flow nozzle with a small cone angle must be used in order to achieve the required range. This means that the average application rate is high where the jet hits the fire, and that the jet must be moved about vigorously in order to cover the large area made possible by the water flow. Where the jet hits the fire it is far more powerful than necessary, but at the same time in practice it cannot cover a very large area. Pools of unused water will form on the ground clearly demonstrating that the suppression was ineffective.

DROPLET SIZE DISTRIBUTION

Water spray systems can be classified according to the size of the water droplets they produce. In a class 3 water spray fewer than 90% by volume of the droplets are smaller than 0.4 mm. Many manual nozzles and sprinkler heads fall into this category. In a class 2 spray 90% by volume of the droplets are between 0.2 and 0.4 mm. A water fog falls into class 1, because more than 90% by volume of the droplets are smaller than 0.2 mm. (NFPA 750, 2006)

Individual droplets can be described using a sample diameter. However sprays always contain droplets of many different sizes and therefore statements like "The nozzle produces a droplet size of 0.2 mm" are completely meaningless.

MEAN DIAMETERS

There are several different methods for describing the predominant droplet size. It is important to be aware of them when making comparisons between different sets of figures. A calculated mean of the droplet size is often used to categorise a spray. Different means can be useful, depending on the purpose. The most common mean value used in the context of fire suppression is the Sauter mean diameter or the volume-surface mean diameter (The Mechanism of Extinguishment…, 1955).

The different expressions differ significantly from one another. For a high-pressure nozzle the geometric mean was measured to 0.111 mm, the surface mean diameter was 0.135 mm, the volume mean diameter 0.156 mm and the Sauter mean diameter 0.208 mm (Rimen 1990).

The arithmetic or geometric mean diameter is the mean of the diameters of all the droplets.

$$d_{geometric} = \frac{\sum x_i \cdot d_i}{\sum x_i}$$

xi is the number of droplets with the diameter d_i

The volume mean diameter is the diameter of a droplet with the same volume as the mean volume of all the droplets.

$$d_{volume\ mean} = \left(\frac{\sum x_i \cdot d_i^3}{\sum x_i} \right)^{1/3}$$

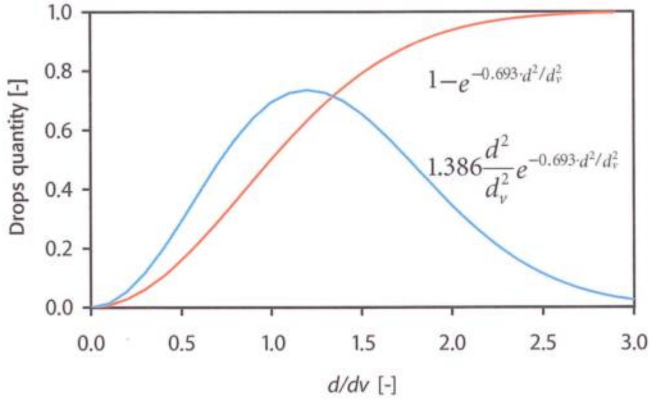
The mass mean diameter is the diameter of a droplet with the same mass as the mean mass of all the droplets. As the density is the same for all the droplets, the mass mean diameter is the same as the volume mean diameter.

$$d_{mass\ mean} = \left(\frac{\sum x_i \cdot d_i^3 \cdot \rho}{\sum x_i \cdot \rho} \right)^{1/3}$$

The Sauter Mean Diameter is the diameter of a droplet with a relationship between volume and surface area which is the same for all the droplets. This mean is often referred to as the volume-surface mean, SMD or D32 and is often used to characterise a spray.

$$d_{sauter\ mean} = \frac{\sum x_i \cdot d_i \cdot d_i^2}{\sum x_i \cdot d_i^2}$$

In some contexts the median is used instead of the mean value. This is the diameter of the droplet in the spray which is



2.93 A Rosin-Rammler distribution function gives the probability that a droplet have a specific diameter. The cumulative distribution function is also shown.

smaller than one half of the droplets and larger than the other half.

The median can be used to specify both volume and surface diameters.

Two jets with a diameter of 1.5 mm which cross one another at an angle of 90° and have a pressure of 0.7 MPa have an approximate mass mean diameter of 0.35 mm and a Sauter mean diameter of 0.32 mm. The droplet size becomes significantly smaller at increasing pressures up to around 0.7 MPa. The relationship is more complex for higher pressures. It decreases and depends on the spatial distribution.

DISTRIBUTION OF DROPLET SIZES

Another way of describing a spray is to give the upper and lower quartiles of a distribution.

In this case 25% or 75% of the droplets are larger than the value. Droplet sizes in sprays normally take the form of a Rosin-Rammler distribution:

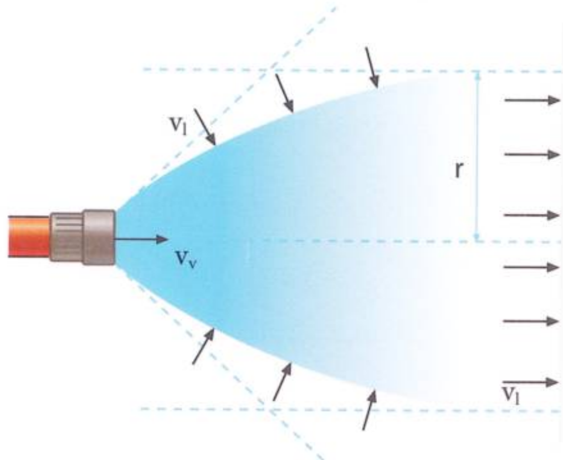
$$P_v(d)=\frac{1.386\cdot d^2}{d_v^2}\cdot e^{-0.693\cdot d^2/d_v^2}$$

d_v [mm] volume mean diameter
d [mm] diameter of specific droplet

The volume proportion of droplets with a diameter smaller than d can be identified using:

$$V(d)=\int_0^d P_v(d)\mathrm{d}d=1-e^{-0.693\cdot d^2/d_v^2}$$

d_v is roughly dependent on the root of the nozzle diameter.

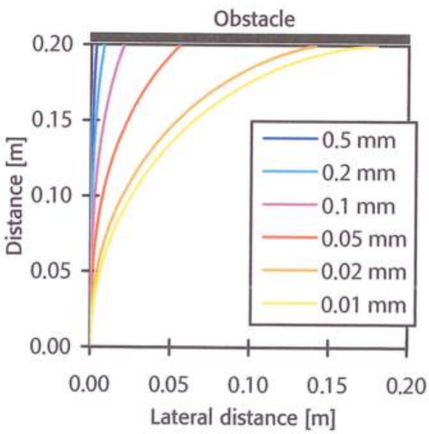


2.94 Injection of air into a spray.

THE AERODYNAMICS OF THE SPRAY

The reaction force from a spray nozzle is smaller than that from a nozzle with a solid jet. This is because the water is thrown out to the sides, which produces lateral counter forces. These counteract one another as the spray is largely symmetrical. A spray with fine droplets with a dispersion angle greater than 50° will transfer its momentum to the air within a few metres of the nozzle. The droplets are slowed down to the velocity of the air current.

An interesting limit for the size of water droplets is approximately 0.02 mm. This is how small a water droplet must be to begin to follow an air current. If the droplet is larger than this, which is normally the case for fire service equipment, the droplet will continue straight on when the air current deviates as a result of an obstacle. The air velocity is also a decisive factor. The higher the velocity, the smaller the water droplets have to



2.95 Calculated path for water droplets of different sizes in an air current moving at 4 m/s towards a wall. Droplets smaller than 0.02 mm follow the air current. Droplets larger than 0.1 mm continue straight on and hit the wall. (From Andersson & Holmstedt, 1999.)

NOZZLE VENTILATION

A wide spray can be used to vent out smoke. In many cases a draught is quite effective and the capacity is worse than with a fan, but nozzle ventilation is a quick method that can be used as long as there is a nozzle available. To avoid unnecessary water damage the nozzle is opened outside the window. The firefighter then moves backwards across the room until the spray covers most of the window but not the window frame. Don't forget the supply-air opening. (Svensson, 2005)

The volume of air that is set in motion can be estimated by the fact that the momentum is maintained and is the same as for water (w) and air (a) at the nozzle (1) and in the spray a short distance away from the nozzle (2). The exit velocity of the air is zero, and in the spray the water and air have the same velocity. Because of the lateral spread of the water only the quantity f is transferred to the air.

$$f\dot{m}_w v_1 = \dot{m}_w v_2 + \dot{m}_a v_2$$

The mass flow of the air is given by the velocity, the cross-sectional area and the density,

$$f\dot{m}_w v_1 = \dot{m}_w v_2 + v_2 A_2 \rho_a v_2$$

This second degree equation can be reformulated to solve

$$v_2^2 + v_2\left(\frac{\dot{m}_w}{A_2\rho_a}\right) - fv_1\left(\frac{\dot{m}_w}{A_2\rho_a}\right) = 0$$

The exit velocity of the water is taken from page 102 and the velocity is

$$v_2 = -\frac{1}{2}\left(\frac{\dot{m}_w}{A_2\rho_a}\right) + \sqrt{\frac{1}{4}\left(\frac{\dot{m}_w}{A_2\rho_a}\right)^2 + f\sqrt{\frac{2p_1}{\rho_w}}\left(\frac{\dot{m}_w}{A_2\rho_a}\right)}$$

$\dot{m}$ [kg/s] mass flow
v [m/s] velocity
A [m²] area
q [m³/s] flow
ρ [kg/m³] density
$_a$ air
$_w$ water

A fog nozzle gives 4.5 kg/s. When the radius of the spray is 0.5 m the content is as that in the formula's brackets.

$$\left(\frac{\dot{m}_w}{A_2\rho_a}\right) = \frac{4.5}{\pi 0.5^2 \cdot 1{,}2} = 4.81$$

The density for water and air is respectively 1000 and 1.2 kg/m³. If half of the energy is transferred to the air and with 600000 Pa in the nozzle the air velocity will be

$$v_2 = -\frac{4.81}{2} + \sqrt{\frac{4.81^2}{4} + 0{,}5 \cdot \sqrt{\frac{2 \cdot 600000}{1000}} \cdot 4.81} = 7.0 \text{ m/s}$$

That is to say, the nozzle works like a fan with the capacity

$$q_l = A_2 v_2 = \pi 0.5^2 \cdot 7.0 = 5.5 \text{ m}^3/\text{s}$$

---

be to follow the air current. (Andersson & Holmstedt, 1999)

It is important to bear in mind the fan effect of the spray for cooling smoke. If water is sprayed from a nozzle held horizontally (or pointing slightly upwards) at the bottom edge of a smoke layer, the smoke will be sucked in by the ejector effect and the cooling process will therefore be faster. However, if the nozzle is held close to the floor pointing upwards, it will suck in air from the layer of fresh air. As a result the water droplets are less likely to vaporise and more air will be mixed into smoke. The smoke volume will therefore not be reduced as much as it could be.

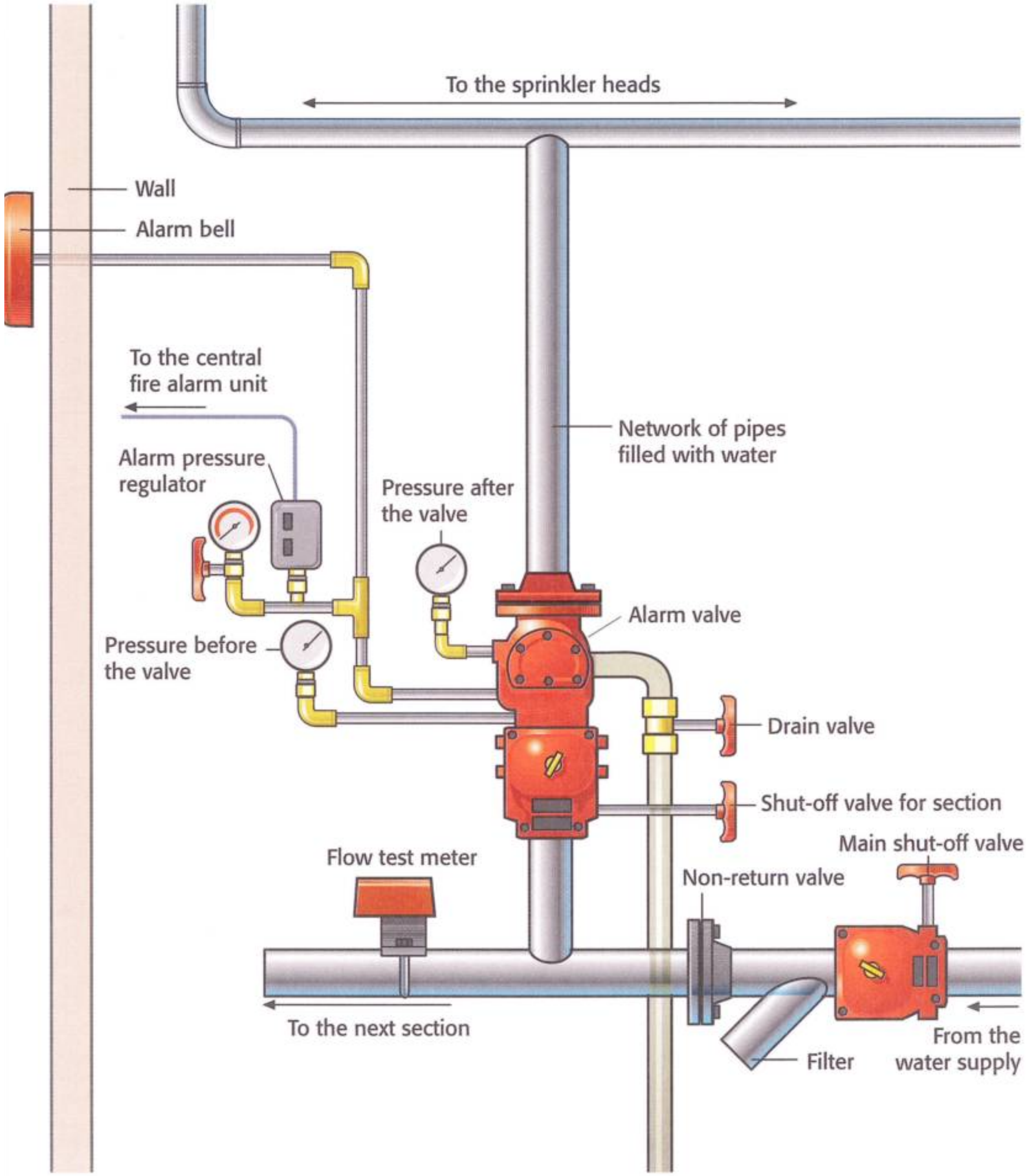
Water sprinkler

Sprinkler systems are installed for a number of different reasons. The owner of a building may want to protect it, or there may be a legal requirement for the building to be designed to meet the owner's needs. Insurance companies may also require a sprinkler system to be installed, or they may encourage the installation of a system by offering a discount on the premium. Some systems are used to control fires until they are extinguished by the fire service or have burnt out of their own accord. Other types of system are designed to extinguish the fire themselves.

Depending on the purpose, different standards can be used when designing the system. Most countries have their own sprinkler code, e.g. the SBF 120:5 (2001) in Sweden. Most widespread are those produced by the NFPA. The sizing of sprinkler systems is discussed together with the sizing of other operations using water.

DIFFERENT SPRINKLER SYSTEMS

The most common type of sprinkler system is the wet pipe system. There is water under pressure in each sprinkler head in the system. When a sprinkler head is activated, water flows out of the nozzle. The pressure in the system drops, opening a valve in the sprinkler room and activating the alarm and the sprinkler pump, if there is one.



2.96 Outline diagram of a central control unit for a wet pipe system.

2.97 Activated sprinkler head.

If sprinklers are installed in locations where there is a risk of frost, dry pipe systems are common. These are filled with compressed air instead of water. Dry pipe systems are activated in the same way as wet pipe systems. When a nozzle opens, the air pressure in the system drops. As a result the sprinkler valve opens in the sprinkler room and the pipes are filled with water. From this point onwards the system acts as a wet pipe system.

If only part of the system may be susceptible to frost, for example in a loading bay, a wet pipe system with a dry pipe extension can be used. The dry pipe extension is filled with air at a higher pressure than the water in the remainder of the system. When the normal sprinkler head in the dry pipe extension opens, air is released, the pressure drops and a water valve opens.

Preaction systems work in the same way as dry pipe systems, except that the valve which releases the water is controlled by a fire alarm system. One or more smoke detectors are normally activated first and allow the water to fill the pipes before any sprinkler head has opened. This means that the water is already in motion when the sprinkler head is activated, which reduces the response time of the system. In addition there is the possibility of fast manual intervention to extinguish the fire, because the fire alarm is activated while the fire is still too small to activate the sprinkler head. As the sprinkler valve is controlled by the fire alarm system, no water will be released in the case of accidental damage to a sprinkler head.

In normal sprinkler systems of the types already referred to here one sprinkler head is activated at a time. In deluge systems several nozzles are activated at once. Therefore the nozzles do not have a glass bulb or a similar opening mechanism. This type of system is used where there is the risk of a fire growing very rapidly. It is activated, for example, by smoke detectors or a small pilot line which opens a group valve for a specific part of the system.

Dedicated extinguishing systems are needed in high risk situations, for example special cooling sprinklers to protect gas tanks.

Residential sprinkler systems have the same design as a normal wet pipe system, but they are smaller in size and have a lower capacity (NFPA 13, 2007). In contrast to conventional systems, plastic pipes can be used in residential systems.

Other types of sprinkler system include water mist systems

2.98 In the case of an alarm it is the job of the fire service to manage the sprinkler system. It is important that the firefighters know how the system works.

2.99 A sprinkler system designed to cool a gas tank in the event of a fire. The system is supplied with water by the fire service. The fire service must plan for the water demand in advance.

which have a much lower water flow than normal systems. However, the water pressure is higher, the nozzles are finer and the water droplets much smaller (NFPA 750, 1996).

SPRINKLER HEADS

As sprinkler technology has developed, a large number of different types of nozzle have been introduced. Different types of nozzle are used for different purposes. Sprinkler heads often consist of a circular nozzle and a ring with a deflector or spray plate fastened to it. The nozzle contains a plug to prevent water from being released. There is a glass bulb clamped in position between the plug and the ring. When the heat from the fire causes the glass bulb to shatter, the water pressure pushes the plug out. The water flows out and hits the deflector to produce the desired pattern. Depending on the deflector design the water either flows through it or bounces off it and leaves the nozzle in the opposite direction.

Conventional sprinklers are the most common type of sprinkler heads. Their design directs approximately half the water upwards and half downwards. Thereby part of the water is sprayed directly onto the fire and the remaining bounces off the ceiling. The sprinkler heads can be installed either upright or pendant, and is marked with the letters U/P.

In a spray sprinkler only a small amount of water is deflected upwards. The majority of the water is sprayed downwards in a similar way to a shower head. The momentum of the droplets is greater in a spray sprinkler than in a conventional sprinkler.

Wall sprinklers have a deflector with an additional plate mounted in the direction of the water jet. This type of sprinkler is always installed horizontally.

Large drop sprinklers are used where the water has to travel a long distance down to the seat of the fire. Small drops do not have enough force to make their way through the flames. The idea behind large drop sprinklers is to install the sprinkler nozzles in the ceiling and use large drops of water to control a fire, for example in a rack storage system.

ESFR sprinklers provide early suppression and a fast response. Because the sprinkler is activated quickly and produces a large flow of water, the fire can be knocked down in its early stages which means that only a few sprinkler nozzles are needed. Like large drop sprinklers, ESFR sprinklers are designed primarily for use in warehouses.

Sprinkler heads with a large opening are called ELO, or extra large orifice sprinklers. Using this type of head is one way of ensuring that the system has sufficient water density, for example when it is being upgraded as a result of an increased risk. Heads for extended coverage, EC, are also available.

2.100 EC and ESFR sprinkler heads with fusible links and wall sprinkler and conventional sprinkler heads with glass bulbs.

THE K FACTOR IN SPRINKLER NOZZLES

The K factor is used to describe the size of the water flow through a sprinkler nozzle.

The higher the K factor, the larger the opening and the larger the water flow from the sprinkler head.

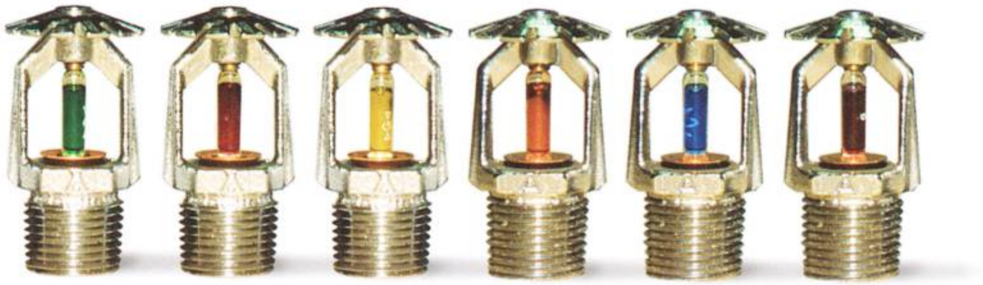
$$q = K \cdot \sqrt{p}$$

q [l/min] flow
p [kPa] nozzle pressure
K [l/minkPa$^{0.5}$] K factor

The smallest nozzle size is generally used in low risk areas, that is where there is only a small quantity of flammable materials. Medium-sized nozzles are used in normal risk areas, which includes ordinary businesses and industrial sites. In high risk areas, such as warehouses for example, large nozzles are used.

Nominal nozzle size [mm]	K factor [l/mink Pa$^{0.5}$]
10	5.7
15	8.0
20	11.5

2.101 Example of the K factor.



Activation temp [°C]	Colour of glass bulb
57	Orange
68	Red
79	Yellow
93	Green
141	Blue
182	Mauve
227–343	Black

2.102 The colour of the glass bulb indicates the activation temperature.

Activation temp [°C]	Colour of yoke in fusible link
57–77	No colour
80–107	White
121–149	Blue
163–191	Red
204–246	Green

2.103 The link between the colour and the activation temperature in sprinkler heads.

ACTIVATION TEMPERATURE

The temperature at which the system is activated is determined by the fluid in the glass bulb or by the type of solder used in the fusible link. The colour of the glass bulb indicates the activation temperature. The temperature is also stamped on the nozzle.

SPRINKLER ACTIVATION

Sprinkler systems are normally activated when the heat from the fire affects the glass bulb or the metal link in one of the sprinkler heads.

The glass bulbs contain a fluid with specific thermal properties. When the fluid reaches a certain temperature, it starts to boil, which increases the pressure and causes the bulb to shatter. As a result the plug in the sprinkler nozzle is no longer being pressed into position and it is pushed out by the water pressure.

A fusible link consists of two very thin metal plates which are soldered together. The solder joint is created using metal which melts at a known temperature. This is the activation temperature of the fusible link. When the link reaches its activation temperature, the two metal plates split apart and the sprinkler head is activated in the same way as with a glass bulb.

Three different factors determine when the sprinkler head is activated: the activation temperature, the RTI value and the C factor. The response time in real situations can be estimated using a computer program.

SPRINKLER ROOM

The whole sprinkler system is controlled from the sprinkler room. It should be positioned where it is easily accessible, nor-

THE RTI VALUE

The Response Time Index or RTI value of a sprinkler nozzle is a measurement of how quickly the activation temperature is reached.

A large glass bulb has a large volume and needs a lot of energy to heat it up. However a small glass bulb only needs a little energy to warm up. A nozzle with an RTI of 30 will activate much more quickly than a nozzle with an RTI of 300 in the same stream of hot gases. The RTI value is also influenced by how effectively the hot gases heat up the bulb or the metal. If the bulb or the metal is shielded, it will take longer to heat up and have a higher RTI value than if it could easily be accessed by the gases.

A sprinkler head which activates quickly is sometimes called a QR or quick response head and has an RTI value of around 30. The corresponding figure for a medium response head is around 100 and for a normal response head between 200 and 500. Quick response sprinklers are the standard choice. Under the same circumstances the activation time is proportional to the RTI value. In a situation where a quick response sprinkler is activated within a few seconds of being exposed to the hot gases, a sprinkler with a high RTI value could take minutes to activate.

The RTI value of a sprinkler head is determined by exposing it to a well-defined stream of hot air in a wind tunnel. The activation time is measured and then the RTI value of the sprinkler head, which is a measurement of the heat transfer rate, can be calculated (Gustavsson, 1988).

$$\mathrm{RTI} = -\frac{t\sqrt{v}}{\ln\left(1-(T_{act}-T_0)/(T_g-T_0)\right)}$$

RTI [$m^{0.5}s^{0.5}$] RTI-value
t [s] activation time
v [m/s] air velocity
T_{act} [°C] activation temperature
T_0 [°C] room temperature
T_g [°C] gas temperature

Sprinkler heads are tested in a wind tunnel with an air velocity of 2.5 m/s and a temperature of 197°C. The ambient temperature is 20°C. The sprinkler head is marked with 68°C and is activated after 16 seconds. Therefore its RTI = $-16 \cdot 2.5^{0.5} / \ln(1 - (68-20)/(197-20)) = 80\ m^{0.5}s^{0.5}$.

2.104 A small glass bulb has a low RTI value and is activated quickly. The RTI value of a large glass bulb is high and the sprinkler head takes longer to activate.

THE C FACTOR

In small activating devices the heat transfer from the glass bulb or the fusible link to the metal is significant. The heat is taken by conduction from the bulb to the sprinkler head. The amount of heat lost is described by the C factor.

mally near an entrance. The sprinkler room contains shut-off, alarm and drain valves for each section of the system. Any booster pumps are placed here. If a water tank is needed to ensure a reliable water supply, this is often positioned nearby.

The inspection log is stored in the sprinkler room. This documents the inspections of the sprinkler system. If the building is protected by the sprinkler system or by another type of active protection system, it is important that the functioning of these systems is monitored.

USING SPRINKLER SYSTEMS

Drawings of the sprinkler system must always be available to allow the fire service to use the system. These drawings must show how the system is intended to function and the fastest route to the place where the system can be activated.

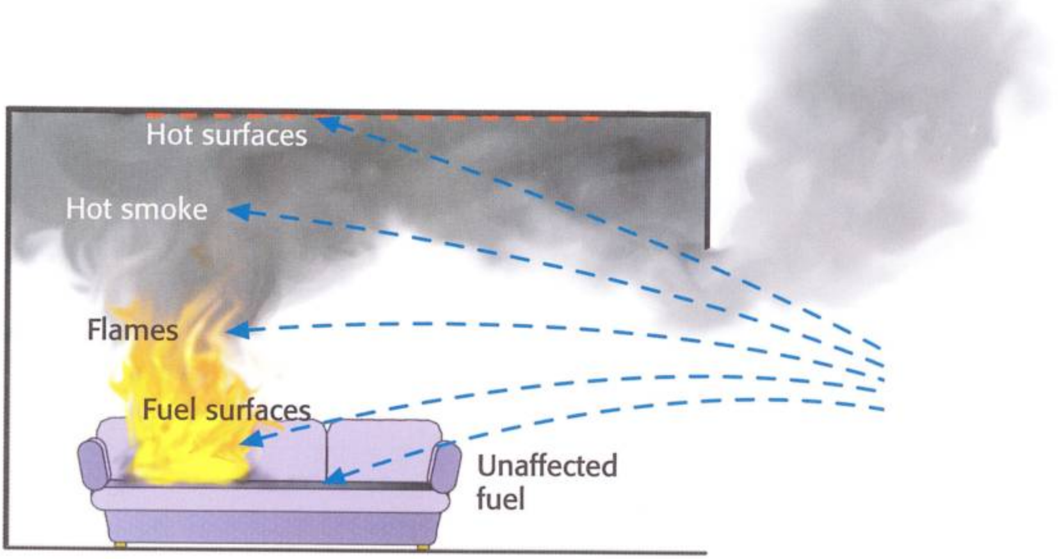
In the case of a call-out to a fire in a building with a sprinkler system, a member of the firefighting team should always go to the central sprinkler control unit. In the case of an incident this will allow the system to be shut off quickly. In the case of a fire this will allow the firefighters to ensure that the system is functioning and to obtain any necessary information.

When there is a fire in a building with a sprinkler system it is generally the incident commander who decides when the sprinkler system is to be shut off. There is no reason for shutting off a sprinkler system until the fire is under control, and before this happens there must be enough resources in place at the scene of the fire. The sprinkler nozzles are closer to the fire than the firefighter's nozzle in the case of larger fires.

In the case of a call-out to a building with a sprinkler system, a member of the firefighting crew should always go to the central sprinkler control unit.

There have been occasions when the fire service has closed off a sprinkler system in an industrial building in the belief that it had the fire under control. The fire has then flared up and when the sprinkler system was started again, the fire had become too big for it to control. (Brandsjö, 2001)

However, if the fire has already been put out or if a sprinkler head has been activated accidentally, the system must of course be shut off as quickly as possible to prevent unnecessary water damage. It is therefore important to find out quickly why the system has activated.



Water application

2.105 Five different places where water droplets can vaporise. These are combined to three extinguishing techniques: smoke cooling, fuel cooling and extinguishing with steam.

In principle there are five different ways in which water can be used to attack a fire. It can be used to cool hot smoke, or to cool and therefore extinguish flames. It can be used to cool fuel surfaces to stop the process of pyrolysis. It can keep cool fuel surfaces not yet involved in fire. Finally it can vaporise on hot surfaces to make a fire room inert using steam. In principle these factors can be combined in three different ways, all of which have advantages and disadvantages: smoke cooling, fuel cooling and suppression using steam.

In the case of large fires, monitors or larger nozzles may be needed to provide sufficient reach to damp down the fire and reduce the risk of it spreading. As a result such large quantities of water will be used that a static water source may be needed.

In order to prevent objects that are at risk from igniting during large fires and to create firebreaks, free-standing sprinklers are another option. Spray nozzles with a low flow can prevent objects and buildings from igniting. These applicator nozzles can either be positioned on the ground like a water spray or pierce a ceiling like a normal sprinkler head. This type of equipment is primarily defensive and is used to reinforce a containment line. Curtain nozzles, which are designed to create an impenetrable wall of water, can also be used. Radiant heat, flying brands and hot smoke cannot pass through a water curtain of this type. Unfortunately curtain nozzles often have a high water consumption.

Water is an excellent solution for fixed extinguishing systems, including traditional sprinkler systems, local systems and water mist systems.

Snow can be used as an extinguishing agent in winter when water is a long distance away or because of the extreme temperatures. If there is a frontloader or a snow blower at the scene of the fire, these can be used to apply the snow. Otherwise the snow can be shovelled onto the fire. Dry, loose snow is much easier to handle than heavy, wet snow. Snow extinguish a fire by means of surface cooling and is therefore primarily suitable for smaller or more restricted fires. It can also be used to protect objects which have not caught fire. For example, in the case of a fire in a mountain hotel, the neighbouring buildings can be covered with snow to prevent fire spread while the fire service is attending.

Fires can flare up quickly when water is used on certain metals, hot oils and reactive substances, such as carbide (CaC_2), which forms acetylene gas when combined with water. This fact has been known for almost as long as water has been used to put out fires. (Lindgren, 1864)

Burning metals, such as magnesium or aluminium, react with water to form metal oxides and hydrogen. The hydrogen can then react with the oxygen in the air. The combination of oxygen and hydrogen is called oxyhydrogen and can cause damage or injury when it is ignited partly because of the pressure wave and partly because of the shards of burning metal. Some metals, including sodium, potassium and calcium, can produce the same reaction with water when they are not on fire.

Water cannot normally be used against burning gases or liquids with a relatively low flashpoint. However, small fires of this type can be extinguished using nozzles which produce small droplets of water. The mean volume diameter of the droplets must be less than 0.5 mm.

FIREFIGHTING TECHNIQUES

It is important to understand what is to be achieved before the nozzle is opened. The extinguishing effect depends on what you do with the water and not primarily on the equipment you are using.

None of the three methods, smoke cooling, fuel cooling or the use of water as a gaseous extinguishing agent, is used in isolation. The water which passes through the flames during smoke cooling also cools the fuel surfaces and reduces pyrolysis. When water vaporises, the steam which forms has a damping effect on the fire. The best results can be achieved with a combination of these different methods of using water.

When fighting a fire you must always be aware of what you are trying to achieve with your nozzle. You must make sure that the water has the desired effect. Otherwise you should review your actions.

Generally the most effective method is for a firefighter to get close to the fire and attack the seat of the fire. It is often not possible to get close to the fire from outside the building and spraying water onto the flames from outside is generally not of any help.

Firefighters who adopt a low position will find that thermal stress is reduced and visibility improved. It is best to crawl along the floor. When working in conditions of extreme radiant heat, it may be a good idea to take shelter behind a suitable object such as a door. Before the attack it is important to make sure that the hose is long enough for the entire attack. It is better to have a hose that is too long than one that is too short. A long hose can be folded into five metre bends to make it easier to handle.

A firefighter close to the floor experiences reduced thermal stress and improved visibility.

In a fire of a limited size a water spray is used to dampen the whole burning surface of the fuel as quickly as possible. In the case of fires in individual objects, the nozzle should be adjusted so that the spray covers the entire object in one short sweep.

When the fire has been knocked down, the flow should be reduced immediately and when no more signs of the fire can be seen, the nozzle should be shut off. Any smouldering fires can then be extinguished individually.

A fully developed enclosure fire is extinguished by sweeping the spray through the hot smoke and thereafter by damping down all fuel surfaces.

In the case of a fully developed fire inside a building, the most effective method is often to use sweeping movements to cover the entire surface of the fuel, rather than pulsations (Palm, 2000). The smoke, wall and ceiling are cooled using sweeping movements from side to side or in a circular pattern, depending on the shape of the room. It is important to use the nozzle actively. Check the spray pattern by starting the sweeping movement parallel with the floor. The spray pattern must be as wide as possible to cover the gaseous mass, but it must be sufficiently focused so that the droplets only just reach

2.106 The nozzle will have a better effect if the firefighter moves close to the fire. Here the jet is being used to protect a neighbouring building. If a protective nozzle is not being used, the firefighter must protect himself in some other way.

the opposite wall. A cone angle between 30 and 60° is usually appropriate. This is refferred to as offensive or 3D fire fighting.

The desired effect can often be achieved most quickly by directing the nozzle at the most intense part of the fire. When the first sweep has been completed, the firefighter should move forwards or sideways to improve his access to the burning surfaces. One easily avoidable cause of a poor extinguishing effect is attacking the fire from an unsuitable position in the room.

The tools should be chosen according to the situation. In the case of a small apartment fire a fog nozzle with a semi-rigid hose on a reel and a high-pressure pump can be appropriate equipment. In a fire on an industrial site it may be better to use a low-pressure system and a slightly larger fog nozzle. If the radiant heat is very high, an oscillating water mist monitor may be necessary. The tools must be chosen to produce the required effect.

Smoke cooling

Smoke cooling is often used in fully developed fires when the firefighters cannot immediately get close to the seat of the fire. This method is used only inside buildings. In enclosure fires which have reached flashover, the firefighter must first facilitate the attack by suppressing the flashover before cooling the fuel surfaces. This is done by smoke cooling where the water is vaporised directly in the hot flames and smoke. The major advantage of fog nozzles is the large target area of the water. This means that the water can affect a large gas volume. For smoke cooling to be effective, the water droplets must vaporise in the smoke or in the flames. The size of the droplets is of major significance.

Flaming smoke gases can be cooled and extinguished by small water droplets vaporising and the resulting steam being heated. The suppression takes place in the gas phase and depends on the thermal stress on the flames becoming so great that they go out.

The droplets must be large enough to reach the hottest gases in the room. At the same time the droplets must have vaporised completely before they hit the opposite wall. This means that high-pressure systems which generally produce smaller droplets are better for cooling smoke than low-pressure systems.

The best effect can be achieved by sweeping the nozzle so that it covers the whole smoke volume. The larger the room is, the longer the sweeping movement and the larger the flow that is needed. The cone angle must also be adjusted so that the smoke is covered in the most effective way. In a short, wide area a large cone angle is best. However, if the room is narrow and long, a narrow cone angle is more appropriate. The water should preferably just reach the opposite wall.

In a similar way it is better to aim the nozzle at the bottom edge of the smoke layer, pointing upwards so that the water spray follows the smoke layer, rather than aiming the

2.107 A fog nozzle can be used to attack even a powerful fire. The water flow here is only around 75 l/min.

spray upwards at a steep angle from the floor. This ensures that the path of the water droplets through the smoke is as long as possible and the likelihood of the droplets vaporising is increased.

When an enclosure fire is suppressed with water, the pressure ratio within the fire room will be affected. Vaporising water produces an increased volume of gas and therefore an increase in pressure. At the same time the smoke is cooled, which reduces the volume and reduces the pressure. Depending on how the water is used, the conditions for a firefighter in a fire room can become either worse or better. The circumstances that are worst for the fire are not necessarily the best for the firefighters.

Depending on which extinguishing technique is used, either negative pressure or positive pressure is generated. Negative pressure forms in most cases when smoke cooling is applied. This causes fresh air to flow into the room, which can result in a fire flaring up. When fuel surfaces are cooled the volume of gas increases as a result of the water vapour and the expanding smoke have to flow towards the firefighters and out through the opening behind them. With smoke cooling on the other hand, where the water vaporises in the smoke without hitting any hot surfaces, the volume of gas in the fire room is reduced and the firefighters can feel fresh air flowing in from behind.

2.108 In a few seconds the fire is knocked down. The clouds of steam indicate that the water is not just cooling the smoke but has also hit some of the hot surfaces.

VOLUME CHANGES DURING SMOKE COOLING

The extent of the change in the volume of smoke during a fire-fighting operation where a fog nozzle is being used to cool the gases can be estimated using the ideal gas law.

Before the application of water: $P_0 V_0 = n_0 R T_0$

After the application of water: $P_1 V_1 = n_1 R T_1$

As the pressure remains largely constant in a normal fire room, the relationship between the smoke volume before and after the application of water is:

$$\frac{V_1}{V_0} = \frac{n_1 T_1}{n_0 T_0}$$

The fact that the water vaporises in the fire room indicates two things. Firstly the smoke will cool because they have used up energy to heat the water. As a result the smoke will reduce in volume. Secondly the volume will increase because of the steam that has been introduced. Which of these two factors predominates depends on where the water vaporises. The energy used to vaporise the water can either be taken from the smoke, or from the hot surfaces in the fire room. The energy used to heat the steam further is taken from the smoke.

The amount of energy given off by the smoke is the same as the energy needed to vaporise the water and to heat it to the same temperature as the smoke. We assume that the process happens so quickly that no energy leaves the gases. The system is said to be adiabatic.

P [Pa = N/m^2] pressure
V [m^3] volume
n [mol] number of gas molecules
R [J/molK] general gas constant, 8.31
T [K] temperature

$C_{p,g}$ [J/molK] specific heat capacity of smoke, approximately the same as for air, 33.2 at 1000K
$C_{p,w}$ [J/molK] specific heat capacity of steam, 41.2 at 1000K
b [–] proportion of water which vaporises in the smoke
M_w [g/mol] molecular weight of water, 18.0
$L_{V,w}$ [J/g] vaporisation heat of water, 2260 (corresponds to 40,68 kJ/mol)

$$n_0 C_{p,g}(T_0 - T_1) = (n_1 - n_0)(bM_w L_{V,w} + C_{p,w}(T_1 - 373))$$

This means that:

$$\frac{(n_1 - n_0)}{n_0} = \frac{C_{p,g}(T_0 - T_1)}{bM_w L_{V,w} + C_{p,w}(T_1 - 373)}$$

The equation can be combined with the equation which describes the change in volume. The formula is long but it contains mostly constants.

$$\frac{V_1}{V_0} = \frac{n_1}{n_0}\frac{T_1}{T_0} = \left(\frac{C_{p,g}(T_0 - T_1)}{bM_w L_{V,w} + C_{p,w}(T_1 - 373)} + 1\right)\frac{T_1}{T_0}$$

$$\text{Aid}: \left[\frac{n_1}{n_0} = \frac{(n_1 - n_0)}{n_0} + 1\right]$$

During smoke cooling the water vaporises in the hot smoke and the energy for vaporisation is taken from the smoke. In this case b equals 1. When the surface of the fuel is cooled, the vaporisation heat is taken from the hot surfaces, which means that b equals 0 and that steam at a temperature of 373K (100°C) is added to the smoke.

If the temperature of the smoke is 873K (600°C) from the start and by fuel surface cooling is reduced to 573K (300°C), the gas volume will increase

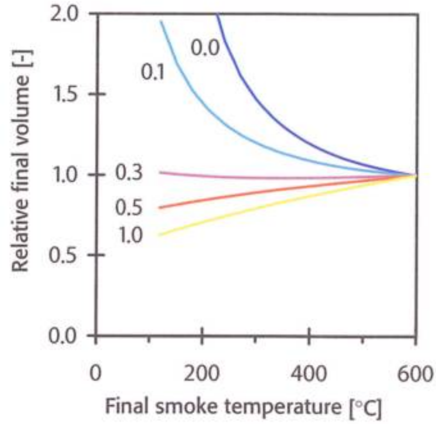
$$\frac{V_1}{V_0} = \left(\frac{34.0(873 - 573)}{41.2(573 - 373)} + 1\right)\frac{573}{873} = 1.47$$

If the water droplets vaporise in the smoke instead, the change in volume will be:

$$\frac{V_1}{V_0} = \left(\frac{34.0(873 - 573)}{1 \cdot 18 \cdot 2260 + 41.2(573 - 373)} + 1\right)\frac{573}{873} = 0.79$$

In this case the volume of the gas in the fire room is reduced by a fifth.

When almost 70% of the water vaporises on hot surfaces and 30% vaporises in the smoke at 600°C, the two effects evens out and the gas volume remains constant. Therefore it is sufficient for a relatively small proportion to vaporise in the smoke in order to reduce its volume. In some cases a reduction in smoke volume can cause air to flow into the fire which can increase its intensity.



2.109 (above) The difference in volume in a fire room before and after the application of water, depending on whether the water is sprayed onto hot surfaces or whether it vaporises in the smoke. The initial temperature in the calculations is 600°C.
2.110 (left) The volume of the smoke increases significantly when the water is sprayed onto hot surfaces. A wide spray covers a large area, but its reach is limited.

2.111 Combined cutting and extinguishing equipment. Using high pressure and the addition of fine sand to the water, the water jet from the cutting extinguisher can cut through most materials. The water is atomised when the jet is broken up.

COOLING CAPACITY

The capacity for cooling smoke can be estimated by creating an energy balance. If atomised water is used to cool smoke, the energy balance will be:

$$\Delta H_{v,w} m_w = \Delta T_g c_{p,g} V_g \rho_g$$

ΔH_v	[kJ/kg] change in total heat content of water during vaporisation and heating		V	[m^3] volume	
m	[kg] mass		ρ	[kg/m^3] density	
ΔT	[K] drop in temperature		$_g$	smoke	
c_p	[kJ/kg] specific heat capacity		$_w$	water	

where the left-hand side represents the energy used to vaporise the water and the right-hand side the energy taken from the smoke. The number of m^3 of the smoke which can be cooled per kg of water is:

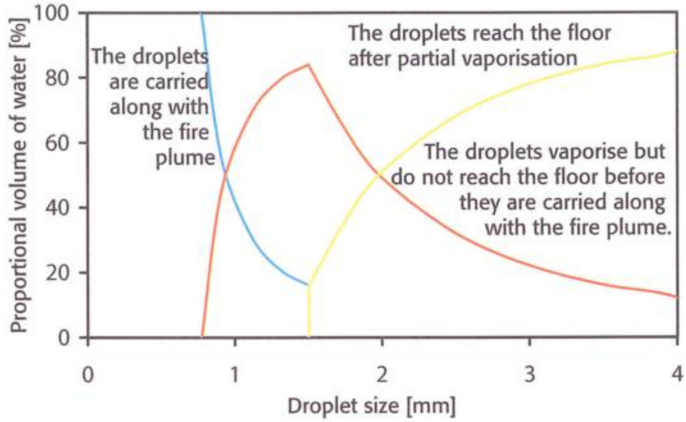
$$\frac{V_g}{m_w} = \frac{\Delta H_{v,w}}{\Delta T_g c_{p,g} \rho_g}$$

If all the water is fully vaporised and the smoke is cooled from 600°C to 100°C the result is:

$$\frac{V_g}{m_w} = \frac{2260}{(873-373)\cdot 1.0 \cdot 353/873} = 11.2 \text{ m}^3/\text{kg}$$

The extinguishing properties of the so-called cutting extinguisher are a result of the very small droplets of water it produces. The droplets have an mean volume diameter of around 0.1 mm. With a flow of 50 l/min 560 m^3 of smoke can be cooled from 600°C to 100°C per minute. The cutting extinguisher is therefore an effective tool for smoke cooling. The calculation assumes that all the water is completely vaporised.

Despite the fact that the water droplets are so small, the water content of the spray is so small when the spray is broken up, that it is not sufficient either to inert or to extinguish a diffusion flame, which would need 280 g/m^3 or 140–190 g/m^3, respectively. At a distance of 6 m the water content of the air is 140 g/m^3 and at a distance of 7 m the water content of the air is 106 g/m^3. Even if this is not enough to extinguish the flames, it is an excellent method of cooling smoke. This can be sufficient to knock down a flashover and allow a firefighting operation to take place. However the surface cooling effect is small. (Skärsläckaren – tillkomst och utveckling, 2000)



2.112 Schematic representation of the proportion of water which vaporises, the amount which is carried upwards by the flames and the amount which passes straight through them.

THE FALL AND VAPORISATION OF WATER DROPLETS

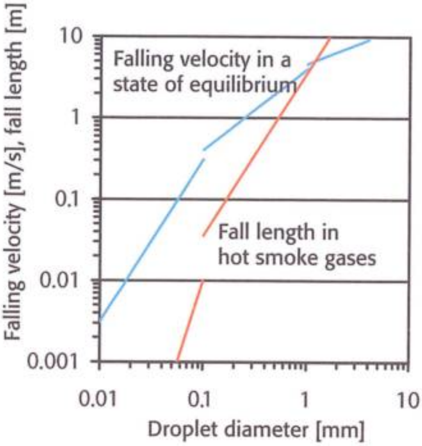
One requirement for the change in volume of the smoke is that the water vaporises. This is not always the case. Large drops largely pass unaffected even through flames, while the smallest are already vaporised by the hot smoke. The droplet size determines to what extent they vaporise before landing.

Even small droplets can survive a journey of several metres through hot smoke. This has a practical significance for how the nozzle should be handled when smoke is cooled. If the nozzle is angled so that the water droplets quickly hit the ceiling, the cooling effect on the smoke will be limited. The longer the trajectory through the smoke, the better the cooling effect on the smoke.

Both the course of the water droplets' fall and their vaporisation must be taken into account. A free-falling water droplet will increase in speed until gravity is balanced by the force of the air resistance. After this the velocity of the droplet will remain constant.

Droplets with a diameter smaller than 0.1 mm will vaporise very quickly. Droplets larger than a few millimetres in diameter will not vaporise in the flames and will not make a significant contribution to extinguishing the flames, unless the flames are very deep. The water droplets will to a large extent pass unaffected straight through the flames.

2.113 The falling velocity at equilibrium, together with the fall length for complete vaporisation of water droplets in stationary smoke in accordance with the calculations on the following pages. ($T = 700°C$, $k = 0{,}1$ W/mK and $Nu = 100\sqrt{d \cdot v}$)



2.114 The approximate speed of water droplets falling freely at room temperature and atmospheric pressure. The forces of gravity and air resistance are in balance. (Herterich, 1960)

Droplet diameter	Falling velocity
0–0.1 mm	$v = 31 \cdot 10^6 d^2$
0.1–1 mm	$v = 4 \cdot 10^3 d$
1–4 mm	$v = 150\sqrt{d}$

v [m/s] falling velocity
d [m] diameter of droplet

THE VAPORISATION OF WATER DROPLETS

When a water spray meets hot gases or flames, the heat is transferred to the water droplets which heat up and start to vaporise. In small droplets the heat transfer takes place largely through natural convection. Larger droplets have a higher velocity and therefore the convection is forced. The heat transfer to a droplet is:

$$\frac{dQ}{dt} = hA\Delta T = h4\pi\left(d/2\right)^2 \Delta T = h\pi d^2 \Delta T$$

$\frac{dQ}{dt}$ [W] heat transfer

A [m] surface of the droplet
d [m] diameter of the droplet
ΔT [K] difference between the temperature of the droplet and the gas
h [W/m^{2}K] convective heat transfer coefficient

The volume of a water droplet is:

$$V = \frac{4}{3}\pi\left(\frac{d}{2}\right)^3$$

The change in the volume of the droplet over time is:

$$\frac{dV}{dt} = \frac{4}{3 \cdot 8}\pi \frac{dd^3}{dt} = \frac{4}{3 \cdot 8}\pi \cdot 3d^2 \frac{dd}{dt} = \frac{\pi}{2} d^2 \frac{dd}{dt}$$

The majority of the energy is used to vaporise the water. The energy needed to heat the droplet up to boiling point is largely negligible. The energy used to vaporise the water can be described as follows:

$$-\frac{dQ}{dt} = H_v \rho \frac{dV}{dt} = H_v \rho \frac{\pi}{2} d^2 \frac{dd}{dt}$$

L_v [kJ/kg] vaporisation heat of the water = 2260 kJ/kg
ρ [kg/m^3] density of water = 1000 kg/m^3
V [m^3] volume of water droplet

Because the same amount of heat is transferred to the droplet as is used to vaporise water the two expressions can be equated:

$$-H_v \rho \frac{\pi}{2} d^2 \frac{dd}{dt} = h \pi d^2 \Delta T$$

This can be simplified to:

$$\frac{dd}{dt} = -\frac{2h\Delta T}{H_v \rho}$$

The equation can be solved as follows:

$$h = \frac{Nu \cdot k}{d}$$

k [W/mK] thermal conductivity coefficient of the gas

The dimensionless Nusselt number, Nu, is:

$$Nu = 2 + 0.6 Pr^{0.33} Re^{0.5}$$

Pr, the Prandtl number, is approximately constant and can be defined as follows:

$$Pr = \frac{c\mu}{k}$$

Re, the Reynolds number, depends on the velocity of the water droplet in relation to the air and is defined as follows:

$$Re = \frac{vd}{\upsilon}$$

Now the equation can be resolved, but the solution depends on the size of the droplet.

THE VAPORISATION OF VERY SMALL DROPLETS

Droplets smaller than 0.1 mm are so small that they are at rest in relation to the gas. In this case natural convection prevails and the Reynolds number is almost zero. Nu = 2 and therefore h = 2k/d.

$$\frac{\mathrm{d}d}{\mathrm{d}t}=-\frac{4k\Delta T}{dH_v\rho}$$

The difference in temperature is assumed to be constant and

$$\int_{d_0}^{d} d\mathrm{d}d=-\frac{4k\Delta T}{H_v\rho}\int_0^t \mathrm{d}t$$

$$\frac{d^2}{2}-\frac{d_0^2}{2}=-\frac{4k\Delta T}{H_v\rho}t$$

When the diameter is zero, the droplet has vaporised completely. The time needed for this, which is the duration of the droplet, is therefore:

$$t_{life}=\frac{d_0^2 H_v\rho}{8k\Delta T}$$

As both the duration and the falling velocity for the little droplet are known, its fall length can be calculated. Because the velocity depends on the size of the droplet and the droplet size is gradually reduced, the equation must be integrated.

$$\int_0^l \mathrm{d}l=\int_0^t v\mathrm{d}t$$

The velocity of a droplet smaller than 0.1 mm in diameter is $v = 31 \cdot 10^6 d^2$ m/s

$$d^2=d_0^2-\frac{8\,k\Delta T}{H_v\rho}t$$

$$\int_0^l \mathrm{d}l=\int_0^t\left(31\cdot 10^6\left(d_0^2-\frac{8k\Delta T}{H_v\rho}t\right)-v_c\right)\mathrm{d}t$$

$$l=31\cdot 10^6\left(d_0^2 t-\frac{8k\Delta T}{H_v\rho}\frac{t^2}{2}\right)-v_c t$$

In stationary smoke, length [d = 0] will be the maximum fall

$$t_{life}=\frac{d_0^2 H_v\rho}{8\,k\Delta T}$$

$$l_{max} = 31 \cdot 10^6 \cdot \frac{d_0^2}{2}\left(\frac{d_0^2 H_v \rho}{8k\Delta T}\right)$$

The fall length is therefore equal to the initial velocity multiplied by half the duration. It is also proportional to the diameter to the power of four. If the gas moves upwards, the fall length will be shorter. The droplet will initially move downwards until its falling velocity corresponds to the upward velocity of the gas, and then it will move upwards. Instead of using the duration of the droplet, we will use the time where dl/dt = 0. In practice the fall length of droplets as small as 0.1 mm is so short that the droplets vaporise almost immediately when they meet the hot gases. See the figure on page 158.

THE VAPORISATION OF LARGER DROPLETS

If the droplets are larger than 0.5 mm in diameter, then forced convection will predominate over natural convection. The Nusselt number is still:

$$Nu = 2 + 0.6\left(\frac{c\mu}{k}\right)^{0.33}\left(\frac{vd}{\upsilon}\right)^{0.5}$$

The velocity of the droplets is so great that the Nusselt number is much larger than 2. In this case the two can be disregarded. The equation contains a large number of constants. To simplify the calculations from now on we will use the temporary constant:

$$C_1 = 0.6\left(\frac{c\mu}{k}\right)^{0.33}\left(\frac{1}{\upsilon}\right)^{0.5}$$

which gives:

$$Nu = C_1\sqrt{vd}$$

and

$$h = \frac{C_1\sqrt{vd}\cdot k}{d}$$

Inserted into the same equation as for the small droplets:

$$\frac{\mathrm{d}d}{\mathrm{d}t} = -\frac{2h\Delta T}{H_v \rho}$$

This gives:

$$\frac{\mathrm{d}d}{\mathrm{d}t} = -\frac{2C_1\sqrt{vd}k\Delta T}{dH_v \rho}$$

For droplets between 0.1 and 1 mm, $v = 4 \cdot 10^3\, d$ m/s:

$$\frac{\mathrm{d}d}{\mathrm{d}t} = -\frac{2C_1\sqrt{4 \cdot 10^3 d^2}\; k\Delta T}{dH_v\rho} = -\frac{2C_2\, k\Delta T}{H_v\rho}$$

where the constant is increased to: $C_2 = C_1 \cdot \sqrt{4 \cdot 10^3}$

Integration with the initial diameter d_0 when time $t = 0$ gives:

$$\int_{d_0}^{d} \mathrm{d}d = -\frac{2\, kC_2\Delta T}{H_v\, \rho}\int_0^t dt$$

$$d - d_0 = -\frac{2kC_2\Delta T}{H_v\rho}t$$

When the diameter is zero, the droplet has vaporised. In this case the duration of the droplet is:

$$t_{life} = \frac{d_0 H_v \rho}{2kC_2\Delta T}$$

A water droplet does not normally move in a fire when the air is stationary. In the fire plume the hot gases are moving upwards at velocities of up to 5-10 m/s. As a result the falling velocity of the droplets must be greater than the upward velocity of the surrounding air in order for the droplets to fall. The relative velocity is:

$$\frac{\mathrm{d}l}{\mathrm{d}t} = v - v_l$$ v_l [m/s] convective upward speed of the air

The falling velocity of the droplet depends on its diameter: $v = 4 \cdot 10^3 d$

$$d = d_0 - \frac{2kC_2\Delta T}{H_v\rho}t$$

$$\frac{\mathrm{d}l}{\mathrm{d}t} = 4 \cdot 10^3\left(d_0 - \frac{2kC_2\Delta T}{H_v\rho}t\right) - v_l$$

The length of the fall before the droplet turns can be determined if the equation is integrated over time.

$$\int_0^l \mathrm{d}l = \int_0^t\left(4 \cdot 10^3\left(d_0 - \frac{2kC_2\Delta T}{H_v\rho}t\right) - v_l\right)\mathrm{d}t$$

$$l = 4 \cdot 10^3\left(d_0 t - \frac{2kC_2\Delta T}{H_v\rho} \cdot \frac{t^2}{2}\right) - v_l t$$

If the smoke is not moving, the maximum fall length [d = 0] is:

$$t_{life} = \frac{d_0 H_v \rho}{2kC_2 \Delta T}$$

$$l_{max} = \frac{4 \cdot 10^3 d_0}{2} \left(\frac{d_0 H_v \rho}{2kC_2 \Delta T} \right)$$

The distance the droplet falls is therefore proportional to the square of the droplet's original size. See the diagram on page 158. If the smoke is moving upwards, the actual fall length is shorter.

Surface cooling

The most common way of fighting fires is to spray water directly onto the burning fuel surfaces which are cooled to such an extent that they can no longer give off a sufficient quantity of pyrolysis gases. This surface cooling method is sometimes referred to as direct extinguishing and is most effective in the case of fires that are restricted to individual objects and that are easily accessible. As this applies to the majority of fires which the fire service attends to, this method is the most commonly used.

With this method there are no specific requirements, for example relating to the size of the water droplets. However, the droplets must be able to reach the seat of the fire. The more quickly the fuel surface is covered, the more quickly the fire will be extinguished. This means, for example, that a jet/spray branchpipe can be used, but fog nozzles are much more effective because the dispersion pattern is larger and more even.

"Aim at the base of the fire" is a common instruction on portable fire extinguishers. The reason for this is that the base of the fire is where the extinguishing agent will have the greatest surface cooling effect.

The fact that the water must reach the surface means that a nozzle with very small droplets is less suitable, as there is a risk that the droplets will vaporise before reaching the surface. They may also have so little momentum that they do not manage to reach the target.

When water is sprayed onto a hot surface, the heat is absorbed by the water which then vaporises. The vaporisation heat of the water is high and by using this property to its best effect, a significant cooling effect can be achieved. However, water

2.115 The most common method of putting out fires is by cooling the burning surface.

cannot penetrate through solid objects. If a surface effect is desired, the firefighter must move constantly to ensure that all the surfaces involved in the fire are covered. In order to cover all the fuel surfaces, the firefighter must know where the fire is being fed from. Otherwise there is the risk that the firefighter will spray water in a place where there is nothing to extinguish. A burning ceiling and a pile of pallets, for example, each require a different response. In the first case the water spray must be aimed upwards and in the second case forwards. It is usually clear immediately whether or not the firefighting is having an impact. The smoke change colour, become lighter and gradually stop being produced.

Surface cooling involves reducing the temperature of the fuel to such an extent that the material can no longer give off flammable gases in a sufficient quantity to maintain the fire. In this case the extinguishing process has a thermal effect on the surface.

Piercing nozzles are excellent for extinguishing fires in straw bales and other compact materials.

It is worth mentioning retardants in this context. These can be made from thickening agents which make the water viscous and allow it to adhere better to different surfaces. This keeps the surface cool and prevents it from burning. As a result retardants are sometimes used in water bombing ahead of the

flame front in large fires. A coloured dye can be added to the water to ensure that the overlap is not too great.

In some cases cooling the surface is the most important task, even it if does not affect the fire. For example, it may be necessary to prevent gas cylinders from heating up or to keep firewalls within a building cool to ensure that they can function effectively. A large amount of water is used as it has to be applied over a long period.

Using water jets to try to reach the concealed seat of a fire from a long distance away is an ineffective way of cooling the fuel which will result in significant water damage. This method must only be used when water damage being caused is unimportant, when no other means of suppression are available, when the water is easily accessible and when it is assessed as necessary to extinguish the fire.

A special case of surface cooling is when a flammable polar fluid which can mix with water is diluted to such an extent that it can no longer give off a sufficient quantity of flammable gases to maintain the fire.

Even though in many cases the material must be cooled to lower the temperature, in some cases this must be done slowly and carefully. In normal buildings this is not a problem, but

2.116 The fire is knocked down in only a few seconds when the fuel is covered by the water.

2.117 As the water begins to take effect the firefighter can move forwards.

The incident commander found that the water did not reach the seat of a large warehouse fire: "It was like trying to put out a pile of charcoal".

2.118 Extinguishing a fire from outside with a solid jet is an ineffective use of water. However, here the technique is used to prevent a fire spreading while the ladder is being put in place.

in historic buildings, for example, the structure itself may be valuable. This applies in particular to heated masonry structures, but also to concrete. If they have been heated to a high temperature and are then allowed to cool down slowly, little damage may be caused. However, if the heated stone is cooled with water, the surface layer can crack and split off.

In ancient times mining took the form of heating the rock and then cooling it quickly. Rapid temperature change make the stone to crack and pieces can then be broken off with a bar and a sledgehammer.

THE COOLING EFFECT OF WATER

When water is sprayed, for example, on a bed of embers or a hot steel structure large quantities of steam will form. The formation of steam is subject to the general gas law. With the quantity of gas molecules expressed as a mass divided by the molecular weight, this is:

P [Pa = N/m^2]	pressure
V [m^3]	volume
n [mol]	number of gas molecules
R [J/molK]	general gas constant, 8,31
T [K]	temperature

$$PV = \frac{m}{M} RT$$

1000 g water (one litre) which vaporises gives rise to:

$$V = \frac{mRT}{MP} = \frac{1000 \cdot 8.31 \cdot 373}{18 \cdot 101300} = 1.7 \text{ m}^3 \text{ steam at 373K (100°C).}$$

If the steam is heated to 873K (600°C), 4.0 m^3 of steam is produced from one litre of water.

Water which is sprayed onto a hot wall absorbs the heat. In order to achieve the best possible cooling effect using water, the proportion of the water that vaporises must be as high as possible. If the water flow is small, the relative vaporisation level will be high, but at the same time the temperature of the wall will increase. The risk is that the wall will not be cooled sufficiently. Using a larger flow the wall will be cooled quickly to a temperature below 100°C. As a result the water will not vaporise and the cooling effect will not be fully exploited.

Water running down a wall absorbs energy:

$$Q_w = \dot{m}_w c_{p,w}(T_1 - T_0)$$

and if the water also vaporises the cooling effect will be:

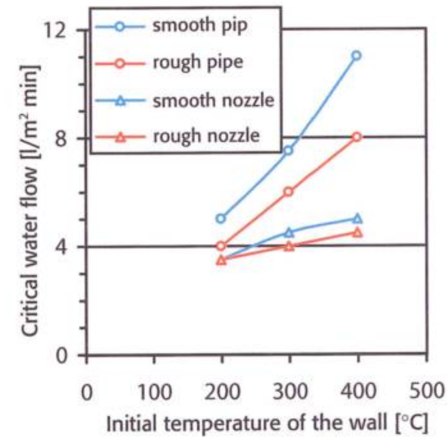
$$Q_w = \dot{m}_w L_v + \dot{m}_w c_{p,w}(100 - T_0)$$

$\dot{Q}_w$ [kW/m²] cooling effect
$\dot{m}_w$ [kg/m²s] flow of vaporised water
L_v [kJ/kg] vaporisation heat of the water
T_0 [°C] initial temperature of the water
$c_{p,w}$ [kJ/kgK] specific heat capacity of the water

The maximum cooling effect on a surface which is drenched with water at a rate of 1 l/m²min will be: $Q = 4.18 \cdot 10^3 \cdot 1/60$ $(100 - 20) + 2260 \cdot 10^3 \cdot 1/60 = 5600 + 37{,}700 \approx 43$ kW/m². Normally only part of the water vaporises.

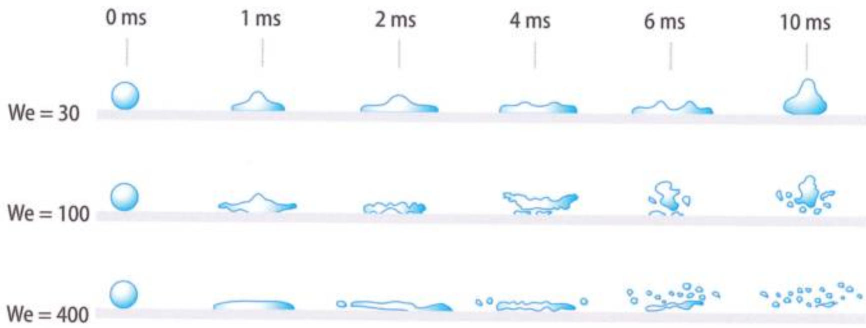
VAPORISATION OF DROPLETS ON HOT SURFACES

If a wall has to be cooled, it is important to create a continuous film of water over the entire wall, as the parts of the wall which remain dry can become hotter. The critical water application rate is the flow that creates a film of water covering the whole surface. The higher the initial temperature of the surface and the smoother it is, the more water will be needed. If the surface is rough, the water will take longer to run off the wall. As a result the water will absorb more heat and have a better cooling effect (Lundqvist, 1991).



2.119 The critical water application rate for cooling a steel wall which has a large fire on one side and is being drenched with water on the other. The water flow required depends on the initial temperature (Lundqvist, 1991).

Depending on whether the aim is to cool the surface as much as possible or to produce as much steam as possible, the amount of water required will differ. To produce as much steam as possible, the temperature of the surface must not fall below 100°C. A very small quantity of water is therefore needed. This will be around 0.1 l/m²min depending on the heat conductivity, density and heat capacity of the surface layer. If a lot of energy is stored in the surface layer, this energy can be used to vaporise the water. Normally a surface temperature high enough to produce good vaporisation is not acceptable. In this case a larger flow of around 1 l/m²min is needed.



2.120 Type I: When We = 30 the droplets form a layer of an even thickness on the cool metal surface, contract as a result of surface tension and then run off the surface without splitting up.

Type II: When We = 100 the events are similar to those in type I, but the droplets split into two or more smaller droplets which then run off the surface.

Type III: When We = 400, the film forms at the same time as the droplets atomise into smaller droplets along the edges. After this the droplets break down into very small droplets.

WATER DROPLET COLLISIONS

The heat transfer from a hot surface to water droplets depends on the collision velocity and diameter of the droplets and the temperature of the wall. The Weber number, We, is a dimensionless number used to describe the relationship in the collision.

$$We = \rho_v v^2 d / \sigma$$

We [–] Weber number
ρ_v [kg/m^3] water density
v [m/s] collision velocity of the droplet
d [m] diameter of the droplet
σ [N/m] the surface tension of the water at the saturation temperature

Tests have shown that droplets break down on polished metal surfaces when the Weber number is greater than about 80.

The behaviour of the droplet when it hits the surface has a significant effect on the heat transfer to the droplet. The longer the droplet remains on the surface, the more it will heat up. After hitting the surface, the droplet spreads out into a thin, even film. Then the droplet starts to contract again as a result of surface tension.

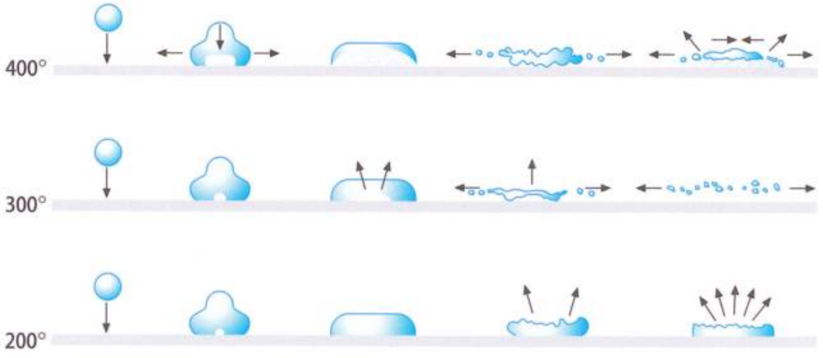
The heat transfer from a smooth, hot surface to a fluid is most effective when the fluid is in contact with the surface. There is an upper limit for the surface temperature, above which cooling using fluids is ineffective. This figure is called the Leidenfrost temperature. In physical terms this means that fluid sprayed onto a surface with a temperature above the Leidenfrost temperature will be insulated from the surface by a layer of steam. A smooth surface with a temperature above the Leidenfrost temperature can not be made wet. The Leidenfrost temperature for water on metals is approximately 300°C. As a result it is not easy to achieve a high vaporisation rate when applying water to very hot metal surfaces.

The vaporisation of the droplets depends on the temperature of the surface. At a surface temperature of around 400°C vaporisation starts in the middle of the droplet. The area of steam spreads quickly and, when the droplet spreads out, only a small part of the water film is in contact with the surface. Immediately after the droplet has spread out to its full extent, the area of steam has reached the edge of the film. As a result the water droplet is insulated from the hot surface by a layer of steam and only a small amount of heat is transferred from the surface to the droplet. The underside of the film boils, which replenishes the layer of steam. This is why a water droplet on the hot plate of a cooker survives for a surprisingly long time.

If the surface temperature is 300°C a large part of the film remains in contact with the surface, even when it is at its largest.

The outer parts of the film boil and the steam spreads out along the plane of the surface. The film becomes thinnest in the middle and then the whole film becomes thinner without contracting. The water boils at the outer edges which lowers the surface tension. As a result the film stops contracting. In this case the cooling effect is greater than for a surface with a temperature of 400°C.

When the surface temperature is 200°C, the vaporisation takes place slowly over the whole of the contact area between the water and the metal.



2.121 Type II vaporisation, surface temperature 400°C. A vapour layer is formed under the film of water and acts as an insulator. The transfer of heat from the metal surface to the water will be slight.

At a surface temperature of 300°C a large amount of the water is in contact with the surface when the droplet is most expanded. In this case, more cooling occurs than at a surface temperature of 400°C.

At a surface temperature of 200°C the droplet vaporises slowly across the whole contact surface between the water and metal. The cooling effect is very considerable.

Water as a gaseous extinguishing agent

Using steam to extinguish a fire, i.e. water as a gaseous extinguishing agent, can be effective in cases where smoke cooling is not appropriate. Note that when water is in gaseous form it is not relevant to talk about droplet size. This technique is only applicable to tackle enclosed fully developed fires where it is possible to vaporise water. It is most effective when used in small enclosures.

Using a water spray, all the hot surfaces within reach are *dampened*, usually the ceiling and seat of the fire. Please note the use of the word "dampened". If too much water is sprayed on the surface the heat released will be used to heat up the water to boiling point but only a small amount of it will vaporise. If a small amount of water is used to dampen the surfaces, a larger fraction will be vaporised. Only after this can more water be sprayed over the surface. The most effective result is achieved when there are large, hot surfaces in a room, which can be recognised from the same hissing sound that can be heard when water is poured on a sauna heater. It is useful if the suppression is made by spraying water from outside the room in through a small opening in an otherwise closed fire room. This prevents the firefighter from being exposed to the

2.122 By drilling a hole in the wall (the drill is on the right) and inserting a piercing nozzle, the heat impact on the fire wall is reduced.

generated hot steam. The water vaporises and the steam fills the enclosure. If the door is open to adjacent rooms the steam will also spread here and suppress any fires. It is because of the ability to knock down fires in adjoining areas that this technique is also described as indirect suppression (Molin, 1955).

When the fire has been knocked down, the fuel surfaces can be cooled. If the fire has not been knocked down after the first attempt the procedure can be repeated. Since the development of fog nozzles, this technique has declined in use. However, if the risks involved with interior firefighting are assessed to be too high this technique can still be considered. The main advantage is that the firefighters at the initial stage of the attack, operate from the outside of the fire room rather than inside it.

In those cases where water has to be applied inside a closed room, a piercing nozzle or a cellar nozzle may be used, allowing water to be sprayed in every direction. It is possible to knock down fires by inserting a nozzle through a basement wall or a joist. This means that firefighters do not have to enter the room until the fire has already been knocked down.

2.123 When steam is to be used to extinguish a fire, the hot surfaces are dampened and then the room is shut tight.

In the case of an attic fire where the fire has not yet burnt through the roof, this technique can be applied, using a piercing nozzle in order to vaporise the water in the roof space where the fire is judged to be burning the most intensely. When the smoke coming out of the building change from grey to a lighter colour, this indicates that the fire has been knocked down and a conventional attack can be carried out to prevent any re-ignition.

When a fire broke out in the engine compartment of a tourist coach, it was noted that the only way to reach the seat of the fire was either from below or by opening the engine compartment's hatches. But crawling underneath the bus with a nozzle was judged to be too risky, while opening the hatches would have caused the fire to spread even more. Instead, a small hole was made in the engine compartment hatch and a piercing nozzle was inserted. This managed to extinguish the fire both safely and effectively.

In the case of a chimney fire, steam is used and the oxygen supply is reduced in order to keep the temperature down in the chimney. A chain is used to keep the flue open, while burning material is pushed down to the hearth where a small amount of water can be poured on it. If the draught can be controlled at the same time the extent of the combustion can be restricted and the fire in the flue can burn itself out under controlled conditions. The presence of steam and the restricted air supply will keep the temperature down to an acceptable level.

Water consumption

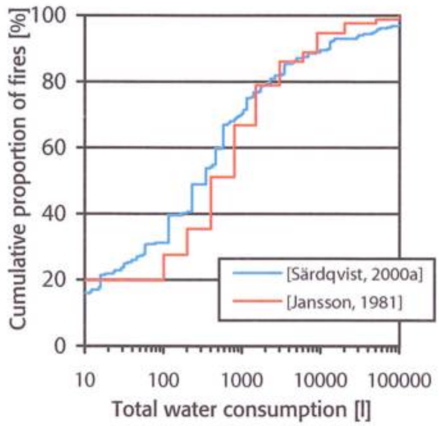
There are two factors which determine the amount of water used in firefighting. The first concerns how much water is actually required to extinguish the fire. The second factor applies to firefighting operations inside buildings and concerns how much water firefighters need to protect themselves.

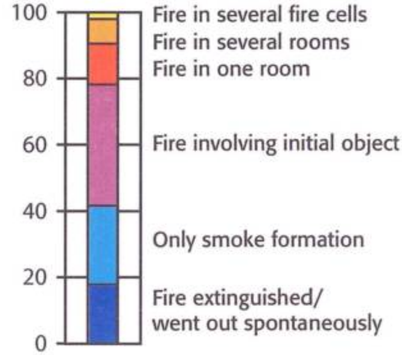
"During interior firefighting, firefighters using BA must have access to a secured water supply for their own protection.." (from provisions from the Swedish Work Environment Authority, AFS 1995:1)

Secure access to a water supply for their own protection means that the water source is reliable and that the risk of a pressure drop in the nozzle is limited. This is the reason why during fire service operations there is always one person responsible for the water supply. Fire engines are also equipped with automatic monitoring systems to warn of any water shortages and faults with the pump.

The required water flow for interior firefighting is not well known. However, none of the systems currently used by firefighters are capable of suppressing an initiated backdraught or smoke explosion. They develop far too quickly. Nevertheless, it is possible, to suppress a flashover in an enclosure. The required water flow is determined by a number of factors, including the size of the enclosure, the quantity and distribution of fuel and the access to air.

Secured water supply can be taken to mean the flow of water required to knock down a flashover fire in the enclosure entered by the firefighters or else, the flow of water needed to protect the firefighters in the event of a retreat. In other words, the minimum flow is not the same, depending on whether the fire is burning in a small apartment or in a high-risk industrial premises.





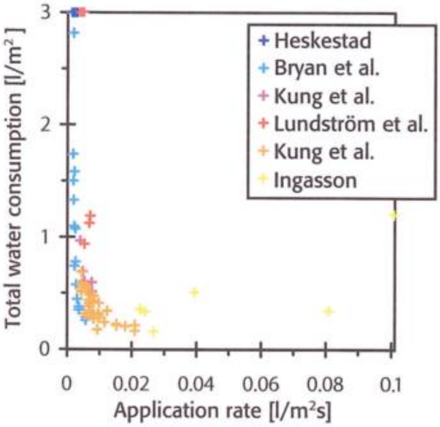
2.124 The amount of water used in firefighting operations, according to Jansson (1981) and Särdqvist (2000).

2.125 Extent of the fire on the fire service's arrival (Räddningstjänst i siffror, 1999).

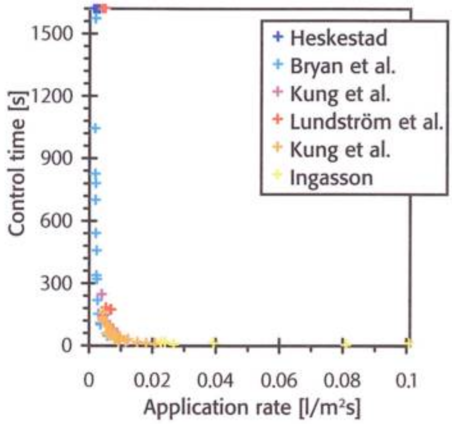
In the case of most fires, water is used as the extinguishing agent. Usually no more than the volume carried on board the engine is used. In the case of fires limited to the first object ignited, the water carried on one fire engine is usually sufficient. Where a fire is burning throughout a whole room or in the case of larger fires, a connection needs to be made to a fire hydrant or several engines carrying water are required. You should note that there is a large statistical scatter, which raises issues if statistics are to be used to scope the size of future operations or vehicle requirements.

There has been a large number of fire tests carried out involving the analysis of water consumption, ranging from operational exercises to scientific experiments. For instance, fires involving wood can be extinguished using a very low application rate, even as low as 0.1 l/m^2min, which has been achieved experimentally. But at that rate, it takes almost for ever to extinguish the fire. The rate at which water's optimum extinguishing capability is achieved is 0.6–1.8 l/m^2min. In this case, the control time is only around 10 s and the total volume of water will be 0.15–0.35 l/m^2. Area is used in this context to mean the wood's exposed area (Särdqvist & Holmstedt, 2001).

In practice as opposed to theory more water is used. There are several reasons for this: some are due purely to issues of definition and others to how the most effective extinguishing performance can be achieved. The critical water application rate, where the time is very long, is 7–8 l/m^2min. In this instan-



2.126 Total water consumption as a function of the application rate during experiments (Särdqvist & Holmstedt, 2001).



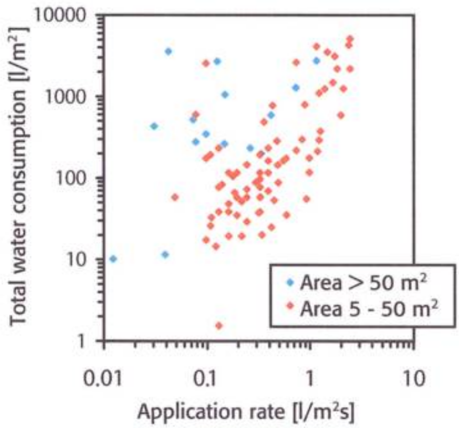
2.127 Control time as a function of the application rate during experiments (Särdqvist & Holmstedt, 2001).

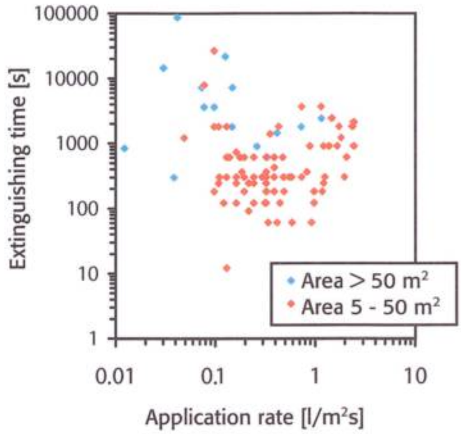
ce, area is used to mean the horizontal fire area, i.e. the floor area. The water reaches its optimum extinguishing performance when the water rate is increased to 9–15 l/m^2min. The total volume of water used is 30–120 l/m^2, with an extinguishing time of around 300 s.

This means that the flow rate is about ten times greater with real fires than in experiments. One explanation for this is the definition of fire area. The fuel surface area is usually at least twice as large as the floor area. The extent to which water is used can also have an impact, which could explain why the flow rate in real fires is roughly five times higher than in the equivalent experiments.

The extinguishing time in real fires is about thirty times longer than the control time in the experiment. One of the reasons for this is the definition of fire control. A controlled fire in experiments is usually not completely extinguished, while firefighters want to be sure that the fire is completely out. This means that the actual time will be five times longer due to different definitions of the concept of control. With the firefighter opening and closing the nozzle, water will be discharged from the nozzle for less than half the extinguishing time. Experiments show that it is beneficial if the scenario has been rehearsed beforehand. These factors, along with those relating to uncertainties about the water flow rate measurements and the size of the fire, explain the discrepancies between the measurements obtained during experiments and those taken in real fires.

Given that the differences in flow rate and time can be





explained, this means that the difference in the total volume of water, around 300 times more, can also be explained.

2.128 Total water consumption as a function of the application rate during real fires (Särdqvist & Holmstedt, 2001).

2.129 Extinguishing time as a function of the application rate during real firefighting (Särdqvist & Holmstedt, 2001).

The scope of the fire also has an impact. In an experimental scenario, you do not have the problem of having to extinguish the fire in stages, which would lengthen the extinguishing time.

In a real fire, using several nozzles, the flow rate per unit area is roughly proportional to the square root of the fire area. The total volume of water used to extinguish fires is proportional to the fire area. The application time is proportional to the square root of the fire area. This means that the larger the fire is, the longer it will take to extinguish it, but a fire must be four times as big for it to take twice as long to extinguish it.

The application rate and application time required to extinguish any given fire using water depends on a number of factors, including the type of fire, the nature of the fuel, the water's droplet size distribution and the application technique used. When a fire is extinguished manually using water the scope of the operation is controlled by the fire's accessibility, access to water, firefighters and equipment available. There is a strong indication that in practice, the fire's accessibility determines the extinguishing capability. After all, the water from the nozzle needs to reach the seat of the fire.

This means that a fire covering an area of 50–100 m² can be extinguished using a normal nozzle; larger surfaces will hardly be covered. If a firefighting team is involved in suppressing an enclosure fire, but the smoke retain their colour or even

OTHER EQUATIONS FOR WATER CONSUMPTION

There have also been statistical analyses carried out into water consumption when fires have been extinguished manually. There is however a very large scatter in the data available. The fire service's total water consumption for extinguishing fires is roughly in direct proportion to the fire area (Särdqvist, 1999).

$V = 115 \cdot A^{1.1}$	1998 study on small fires in buildings in large cities in the UK. The emphasis is on extinguishing small fires using a fog nozzle on a central reel.
$V = 123 \cdot A^{1.2}$	1972 study on medium-sized and large fires in the US.
$V = 940 \cdot A^{0.8}$	1959 study on major fires in the UK. The fires had a larger area than $200 m^2$ and more than 5 jets were used.

V [l] Total water consumption
A [m^2] Horizontal fire area

A balance between the energy that the oxygen in a given volume of air can release and the energy required to produce just as large a volume of steam resulted in the following equation (Royer & Nelson, 1962):

$$q = 1.34Ah$$

q [l/min] required water flow rate
A [m^2] area of room
h [m] height of room

With this dimensioning method water is used as a gaseous extinguishing agent. This equation is based on the assertion that just as much energy is released, calculated per volume of oxygen required, almost regardless of what is burning.

Insurance Services Office suggests, using the same units, the following flow rate (Linder, 1991):

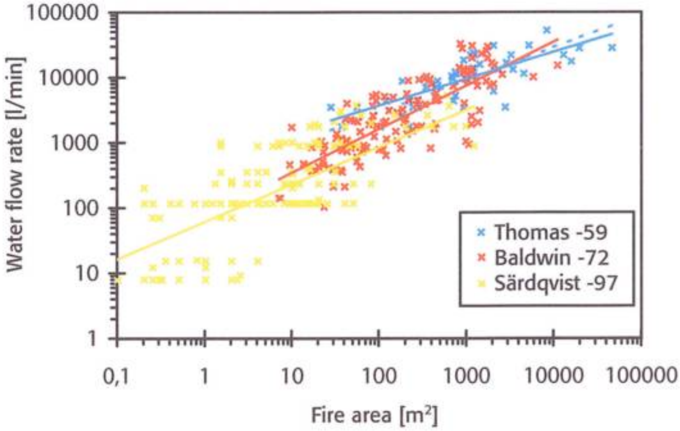
$$q = 220\sqrt{A} \cdot k$$

k is a constant taking into account the building's structure, furnishings, as well as the risk of fire spread.

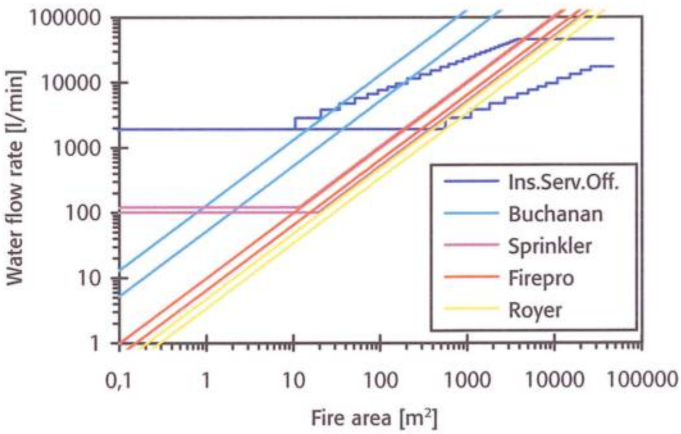
$k = F \cdot O \cdot (X+P)$, where F depends on the building type and varies between 0.6 and 1.5, O depends on how flammable the furnishings are and varies between 0.75 and 1.25. The factors X and P provide an increment if there are adjacent buildings or doors to adjacent buildings. For the average building $k = 1$. This expression has, however, been considerably simplified in this instance. Also, the lowest and highest flow rates are given.

2.130 (opposite page) In many cases, the firefighting operation's effectiveness and therefore, the volume of water used, is determined by how accessible the fire is.


TATTOO-WORLD



2.131 Application rate as a function of the fire area in three analyses carried out on the fire and rescue service's water consumption and in a number of experimental studies. Area is understood to mean horizontal fire area (Särdqvist, 1999).



2.132 Application rate as a function of the fire area, based on available dimensioning models. Area is understood to mean horizontal fire area (Särdqvist, 1999).

become darker, it is likely that the fire is not in the same place as the actual firefighting.

This presumably explains part of the development of major fires. Some fires are so large that firefighters cannot get close enough, which means they cannot extinguish them either. You need huge volumes of water to bring a fire under control from a distance. Even if, in the case of major fires, the water is only used for containment lines, taking into account the time aspect, the total volume will still be large. In many cases, this water requirement can only be met by using trailer pumps with a static water supply. Many fire hydrant networks have too little capacity and water tenders operating in a shuttle service have a problem in sustaining the effort long enough.

WATER CONSUMPTION USING SPRINKLERS

2.133 In a major fire, the water flow rate when extinguishing the fire is actually often determined by the number of jets positioned along a broad front.

When it comes to sprinkler systems, there are various dimensioning guidelines available. The guidelines are usually based on the experience acquired from fires which have occurred and individual experiments. In the US, NFPA issues recommendations for sprinklers. In Sweden, equivalent guidelines, such as SBF 120:5 (2001), are issued by the Swedish Fire Protection Association (SBF).

Depending on the purpose of the sprinkler system, different standards can be used for the design. Factors such as the object to be protected and the restrictions of the sprinkler system determine its size. Different water densities are required, depending on the type of material stored, the quantity stored per unit area and the storage height.

Having a low-risk class, usually residential and public buildings, the codes propose a water density of 2.25 l/m^2min for at least half an hour, with an effective area of $80m^2$. In a normal industrial premises 5.0 l/m^2min for one hour is recommended. The effective area varies according to the type of system. In the case of high-risk premises, 7.5–12.5 l/m^2min is recommended and for high-risk storage 30.0 l/m^2min, for a duration of one and a half hours, with an effective area of up to 300 m^2.

Is it possible to dimension a fire service operation based on sprinkler recommendations? To draw a comparison with a sprinkler, firefighters could tackle a fire in an apartment with an area of 67 m^2 and the same rate, 2.25 l/m^2min, if a nozzle producing 150 l/min is used. To tackle the same area in an industrial fire at a rate of 5.0 l/m^2min, 330 l/min would be required. This shows a clear argument for using small nozzles, which are therefore easier and quicker to handle, to tackle fires in low-risk buildings, and large nozzles for higher risks.

As calculation models are being produced, there is a shift taking place towards design based on engineering principles. The concepts RDD, required delivered density, and ADD, actual delivered density, are used in fire experiments associated with storage scenarios to determine the water density required for the particular fire scenario, along with the water density which the system can actually provide.

Limitations of water

Water is harmless in its normal state and does not produce any hazardous decomposition products. It is also harmless when used with most materials, at least in the short term. But substances which are toxic, corrosive, etc. can dissolve in water.

PHYSICAL HARM

One risk involved with using water as an extinguishing agent is that the jet can come into contact with high-voltage cables or transformers, for instance, which can create a circuit through the firefighter. There are regulations governing safe distances with regard to live parts or cables, and these regulations are just as applicable when involved in extinguishing a fire. There is excellent reference literature available for other electricity-related aspects.

A solid jet of water conducts current, but when it is broken into water droplets its conducting capacity is reduced. The reason for this is because air is introduced between the water droplets, which does not conduct electricity. Solid jets present a potential risk when a fire close to electrical installations is suppressed. This is true irrespective of whether fresh water or sea water is being used, clean or polluted.

Fog nozzles can therefore be used at normal safe distances. However, if a jet has still not been broken up the risk of coming into close proximity of live parts must be avoided. In this case, the nozzle should be operated completely outside the safety area. As it is possible to obtain a jet from water fog nozzles, these are also opened, taking into account the safety distance for the solid jet. When the spray pattern is set, the nozzle can then be used at a suitable, safe distance.

Furthermore, incorrect use can also cause risks, for instance, when extinguishing pool fires or metals with water.

Even if just the hot surfaces are cooled down in a compartment fire, this can produce a considerable amount of steam. The steam can, depending on the firefighter location, lead to heat penetrating protective clothing, and burn injuries.

Extinguishing a fire with water requires firefighters to work close to the fire, which entails particular risks. For example, there may be the risk of exploding gas bottles, of the increased heat impact due to a flashover or backdraught, or the collapse of the building's structure affected by the fire.

WATER DAMAGE TO THE ENVIRONMENT

When a fire is extinguished using water, some of the water is vaporised. The water not vaporised remains as spill water at the fire ground. At most fires, the spill water does not present any major problem. The water is channelled via the drain to the sewage treatment plant, which can handle small volumes. On the other hand, spill water can be a major problem in fires involving different types of chemicals or where large volumes of water have been used over a lengthy period of time. Unfortunately, this topic has not been particularly well researched (Stridsman et al. 1999).

Apart from water, spill water also contains three types of impurities. Residual products from the fuel may be formed at every stage in the breakdown process, from the original fuel to just soot. The substances washed out of the smoke belong to this category. The water may also contain varying amounts of substances present at the site prior to the fire. During the fire fighting they are washed out and become part of the spill water. Finally, substances may have been added during the operation, such as foaming agents.

The occurrence of foreign substances in spill water is determined by the way in which the water has been used. Water used just to cool down structures at risk only contains substances which were available at the site from the outset and are washed out. With the addition of foam concentrate to the extinguishing water, its washing capability improves and the pollution level increases.

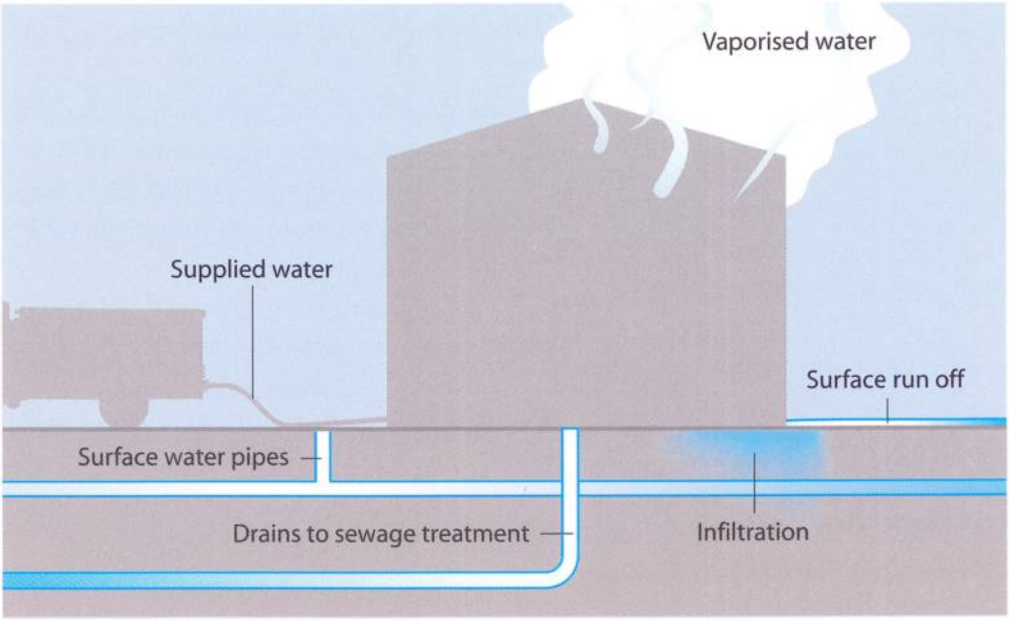
The water used to actually extinguish the fire or wash out the smoke has a considerable surplus of residual products from the fire and in this case, the solubility of impurities can increase with the addition of foam concentrate.

Spill water generally contains all known impurities. This means that it is pointless listing the substances included in the spill water's composition. If you know what is burning you can predict the substances that will be formed and therefore, the values that should be measured for specific substances, e.g. pH value. This should be done as part of the pre-planning.

In a fire involving old car batteries which occurred in Landskrona, Sweden in 2001, large volumes of water were used to suppress the fire. The pile of batteries was huge and the water did not manage to extinguish the fire. However, it was noted afterwards that the water washed out the battery acid effectively as the pH value dropped to as low as 1.9. In the end, the fire was extinguished by covering the pile of batteries with sand (Lundmark, 2001).

To evaluate the scope and duration of the harm caused, the terms acute toxicity, biodegradability and bioaccumulation are used. These describe how toxic a substance is over a short period of time, how easy a substance can disappear from the system and whether it can accumulate anywhere else.

There are general parameters which may be of interest, including the occurrence of solid or liquid material which is insoluble in water, colour changes, pH values, conductivity,



2.134 Spill water flow at the scene of a fire.

oxygen concentration, which can all be measured on site. There are other parameters whose analysis takes a couple of days, such as the content of particles, nitrogen, phosphorus and organically bound carbon, as well as the biological and chemical oxygen demand (BOD/COD). As the water cannot be broken down, just like any other material, the volume of spill water can be estimated by comparing the volume of water supplied to extinguish the fire with the volume which has vaporised. Usually, much more water is used than is vaporised. The remainder will be spill water.

This spill water has to go somewhere. Water leaving the site of the fire may run into the drains, where it will be channelled to the sewage treatment plant. One important thing to find out beforehand is whether the water in the surface pipes goes to the sewage treatment plant or to some watercourse. If the water runs along the ground it can also reach the watercourse this way. Water can also infiltrate the ground, either outside the building or through leaks in the basement.

As the water has to go somewhere, it is generally best if the total volume of water can be kept down. Spill water at a fire ground indicates low efficiency of the fire service operation. The impact of the water used to extinguish the fire determines the outcome of the operation, not the water flow rate achieved.

It is best to try to contain contaminated water at the scene of the fire using a collection system set up beforehand. For instance, a chemical plant can be designed so that the building itself acts as a pool. It is also possible to set up temporary dikes using sand, filled fire hoses or some other way.

If a tank is used for collecting the water and the water collected is reasonably clean, especially in terms of the amount of impurities and particles in it, in many cases it may be worth considering recycling this water. This will help reduce the total volume of spill water, while also easing the problem of having to store it. It is always best, as far as possible, to try to keep impurities collected and concentrated at an incident site.

If it is not possible to actually collect the water it is often possible to delay its spread or direct its path. For instance, a flow rate which is too large for a sewage treatment plant to handle may be possible to treat if it is allowed to discharge over a period of time. By blocking a surface water gulley the water can be directed another route.

This means that the fire crew has a good opportunity to choose where the spill water will go, which also requires a proactive decision to be made.

If the spill water is toxic there is a risk that the activated sludge produced in the sewage treatment's biological phase

2.135 At this chemical plant the building is designed as a large storage tank. The floor is half a metre below ground level and there are pump units pre-installed on the outside.

may be spoiled. In this situation, more of the impurities can be treated during the chemical phase of the process. As a result, the level of pollution in the water discharged will not be so high, but it will still take a couple of weeks for the biological phase to recover. Heavy metals in the spill water will be found in the sludge, which then needs to be deposited.

If a large volume of spill water is channelled to a sewage treatment plant there is the risk that the flow rate will be far too high for the plant to handle. In this case, some of the water flow may be directed, in its untreated state, to the watercourse, which usually receives treated water, with all the repercussions that this entails.

During an industrial fire in 1987 at a surface-treatment plant for plastics and metals in Anderstrop, Sweden, the burning building contained a huge amount of plastics. There were also treatment baths, highly acidic and with a high metal content. The firefighting lasted for five hours and large volumes of water and foam concentrates were used. Contaminated spill water was discharged via floor drains into an internal sewage treatment plant and overflowed, resulting in 30m^3 leaking into a stream before the flow could be stopped. As the pH value had already dropped to 3.2 the stream was treated with lime. The remaining spill water, which escaped from the building via doors and a hole in

2.136 By sealing surface water gulleys and using the actual terrain, it is possible to contain the water used to extinguish the fire in the same way that chemicals are contained at a chemical accident. A culvert which has been blocked up creates a temporary storage area where spill water can be contained.

the concrete slabs, contaminated the ground. The highest concentrations were measured in pipe ducts, i.e. where the permeability in the ground was greater (Stridsman et al. 1999).

During a fire in 1990 in a peat store in Uppsala, Sweden, 70,000 m^3 of water were used in the first week and after that 2,000 m^3 a day. The operation lasted about one hundred days, and about 40 tonnes of foam concentrate was used. As the peat itself is not particularly toxic, the spill water was channelled into the Fyrisån River during the first week. But the water carried in it huge quantities of organic material, and thereafter the surface water was channelled into the sewage system and could be handled by the sewage treatment plant. During the first week the spill water produced about 300 tonnes of COD (chemical oxygen demand) material, compared with a figure of 8,000 tonnes of COD, annually transported by the river (Stridsman et al.1999).

Another surface-treatment plant, located in Mörbylånga, Sweden, was involved in a fire in 1992. During the operation to extinguish the fire, the use of water was reduced in the part of the building where a treatment bath was located containing acid and cyanide. This meant that there was only a small volume of spill water, which it was possible to keep in the internal sewage treatment facility. On the other hand, the smoke contained a high content of various substances, including cyanide. In the case of the other parts of the building, the water was channelled via the surface water pipes directly out into the sea where no pollution was detected. However, when the surface water gullies became blocked after a while, the spill water ran off the surface into a field, destroying new crops covering an area of a couple of thousand square metres (Stridsman et al.1999).

WATER DAMAGE TO PROPERTY

At a small apartment fire, the fire scene is generally dry when a skilful firefighter has completed the extinction. Any excess water will quickly dry up and does not cause any significant damage in relation to the damage caused by the fire.

It is often worthwhile carrying out a rapid salvage operation as damage can be caused even when the volume of water used has been restricted. For instance, moisture can lead to metals being affected by corrosion. The burned material has a major impact on the extent of the damage.

Water damage is a real problem, especially in major fires and in fires where it is not possible to launch an interior attack. If too much water is used there is a risk that the costs resulting from water damage will far exceed those resulting from fire damage. This is particularly the case if the water penetrates the building's structure. If water penetrates walls, joists, the foundations, etc., one of the consequences is that organic materials will be badly affected by mould and dry rot. This is a particular problem with attic fires where the excess water runs down through the floors which have not been affected by the actual fire.

When wood is exposed to water, it expands by around 0.1–0.4% lengthwise and between 2 and 14 % across the direction of the fibre (Restvärdesräddning, 1988). This means that wood exposed to water expands significantly. When water is poured on a fire in a silo or warehouse this can even cause cracks to appear in the building, if the material expands.

Some examples of the direct damage that can be caused by water are as follows (Restvärdesräddning, 1988):

- Carpets can lose their adhesion
- Plasterboard can become loose and break
- Furniture assembled using adhesive can come apart as a f result o the adhesive being dissolved.
- Wallpaper paste can lose its adhesion
- Water-soluble colours in works of art, wallpaper and textiles can be affected
- Water-soluble ink can be affected in documents.
- Gilt can come off because the primer has lost its adhesion

Unmanned nozzles should only be used where absolutely necessary. This can then help to keep water consumption down.

During the winter it is not only fire service equipment that can be damaged by the frost. The water used to extinguish the fire can cause problems if it is lying in an unheated building. Just like water can burst a pump, any water lying in a building can cause damage when water expands during the formation of ice. Damage can be caused, for instance, to masonry soaked in water.

Fires in areas of cultural significance and warehouses are examples of scenarios where lengthy firefighting are required. When water is poured on a fire for a long time, the quantity of water will be large and therefore, the water damage will be great. It is important to plan the operation remembering the main task to keep the overall damage to the minimum.

A water monitor with a flow rate of 1500 l/min, aimed at a building, will spray 90 m^3 in an hour. If the monitor is used over night its consumption will be equivalent to that of 100 water tenders. All that water will have to go somewhere.

The use of unmanned nozzles is probably the most common reason for large volumes of spill water. Even a small flow rate can, over time, lead to large volumes being used overall. A piercing nozzle with a modest flow rate of 70 l/min can reach a volume of over 4 m^3 in an hour. There is good reason for greatly restricting the use of unmanned nozzles. Using a piercing nozzle is extremely effective, but as with all other nozzles, it should only be used for as long as it is having an effect. It should then be turned off immediately. Unmanned nozzles are usually only appropriate when there is unlimited access to water and it is easy to dispose of the extinguishing water used.

Foam

Foam is one of the more common extinguishing agents used when tackling a variety of fires, mainly fires involving liquids and in buildings where interior firefighting is considered to be inappropriate. When combustible liquids in tanks or spills are on fire foam is the most suitable extinguishing agent. Foam got its breakthrough as an extinguishing agent in the 1930s and since then, it has undergone major technical developments. There are a number of available publications on the subject.

Foam is often used in situations where water is not suitable. One reason for this may be that the water cannot reach the fire because the firefighters cannot get close enough to the fire. Another may be the combination of the water and fuel properties, such as in class B fires.

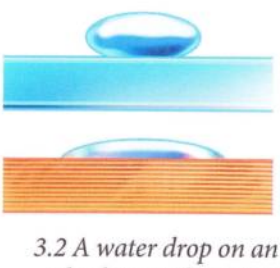
Municipal fire brigades use foam to extinguish different types of fires; airport fire crews use it to quickly suppress fires in aviation fuel to support evacuation, and industrial fire crews use it to protect their premises, etc. In all these cases, the same factors apply in terms of using the right combination of foam generator, foam expansion factor, foam concentrate and application rate.

Foam can also be suitable when there are difficulties with access for normal extinguishing using water. Low-expansion foam can be successfully used, to protect against radiation heat, or to extinguish or knock down a fire to be able to approach it.

When scoping a firefighting operation involving the use of foam, it is important to bear in mind that the system needs to be devised and that the parts in that system need to adapt to

3.1 *Foam is a highly versatile extinguishing agent.*

each other. The process begins by selecting the required flow rate discharged from the nozzle, then the right hose to ensure minimum losses. The next step involves selecting the equipment for the foam concentrate mixture, which must have the right capacity, and finally, a check is made to see that the pump is ready to operate the system and there is a sufficient supply of water and foam concentrate. The best foam concentrate should be chosen. The best proportioner and foam generator are chosen too, along with the best application method and a staff with the best training.



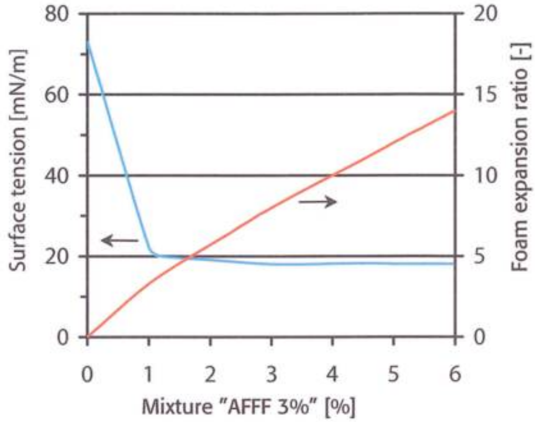
3.2 *A water drop on an oily glass surface stays intact due to surface tension (top picture). On a wooden surface the drop spreads out. If a small amount of detergent is added to the drop it will spread out, even on the glass surface.*

Physical properties

Foam comprises a large number of gas-filled bubbles, separated by thin walls. Liquid foam, with walls of a liquid film, is used for extinguishing fires. Firefighting foam has three basic constituents: water, a foaming agent and gas. The main property of the foaming agent is to reduce the water's surface tension. The gas used is almost exclusively air, but carbon dioxide can also be used or in some cases, smoke.

It is important to distinguish between the types of foam used for class A and class B fires, even though both types appear white and lathery when applied. The first type is intended for extinguishing fires involving fibrous materials like wood, while the other type is intended for liquid pool fires.

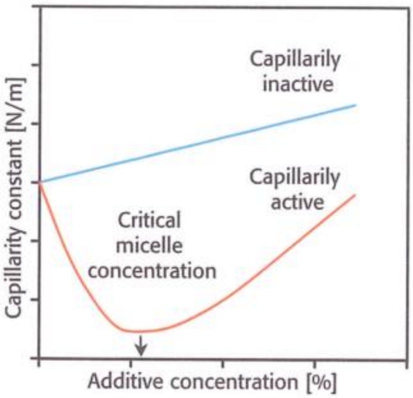
In the case of class A fires, the special feature about the foam concentrate mixture is that the water surface tension is reduced, enabling the water to wet materials better and to be absorbed by porous materials. Adding just a very small amount of wetting agent produces a large reduction in water surface tension. A mixture with a concentration of as little as 0.1% produces a dramatic reduction in water surface tension, resulting in a large improvement in water's ability to be absorbed by fibrous materials. When foam is used to extinguish the fire, one of the main effects is that the heat feedback is broken between the flames and fuel surfaces.



3.3 The surface tension varies with the foam concentrate mixture. This also applies to the foam expansion ratio, in this case, for foam generated using a low-expansion foam tube (Vestergom, 2001).

Also at class B fires the reduction in surface tension is utilised. Using a film-forming agent the water drained from the foam can be made to spread out like a thin film over the fuel surface. This is the same effect which occurs when a drop of petrol spreads over a water surface. The reason for this is that petrol has a much lower surface tension than water. The same thing happens with a water droplet on an oily surface if the surface tension has been lowered to a sufficient level. The water droplet will spread out even though the water still has a higher density than the oil, which means that the water should have sunk.

In the case of class B fires, the ability to produce good quality foam is vitally important. The foam must also not be broken down by the fuel. The formation of foam can be explained at molecular level by the wetting agent being dispersed differently in the walls of the foam bubbles. The wetting agent is made up of molecules which have one end that is polarised, making them soluble in water. The remainder form a non-polar molecular chain, which is therefore not soluble



in water. At certain concentrations in water these molecules form groups of polarised molecules known as micelles, accumulating on the surface. Because of the electromagnetic forces between the molecules, the chains of molecules are positioned in parallel to each other. This allows a layer or aggregates of molecules to form, held together electromagnetically. This layer is no more than the thickness of a molecule, the magnitude of a couple of nanometres (10^{-9} m). The polar ends of the molecules face out towards the water molecules forming the rest of the bubbles' walls. The concentration at which aggregation occurs is known as the critical micelle concentration. This is also the concentration at which the surface tension is at its minimum.

3.4 The capillarity constant varies with the mixture as the foam concentrate is capillarily active (Alvares & Lipska, 1972).

If a liquid film is stretched at the critical micelle concentration the number of surface-active molecules on the surface will decrease. The capillarity constant then increases, along with the surface tension, which counteracts the stretch. Compression is counteracted in a similar way. Consequently, the most stable foam is formed, administered at a dose equivalent to the critical micelle concentration. It is therefore important to follow the manufacturer's recommendation when mixing the foam concentrate. The quality of foam produced will be poorer when the mixture level used is both lower and higher.

The fact that foam can be used to tackle different types of fire has led to a large number of different types of foam concentrates becoming available. Unfortunately, there is no single one ideal for every situation. Those that have the best resistance to different chemicals, for instance, are not particularly good for room filling.

The air mixture in the foam is expressed by the foam expansion factor and represents the ratio between the foam flow rate and liquid flow rate, both in l/s. The expansion factor

3.5 The three types of foam are defined according to the expansion factor.

Type of foam	Expansion factor
Low-expansion foam	Lower than 20
Medium-expansion foam	20–200
High-expansion foam	Higher than 200

is also known as the expansion ratio or foam number. Foams are usually divided into three types, based on the amount of air mixed in: low-expansion, medium-expansion and high-expansion foam. Common expansion factors for these three types are 7, 70 and 700 respectively.

If a medium-expansion foam with an expansion factor of 70 is applied at a rate of 400 l/min during an operation where foam is used, the volume of foam produced is 70 x 400 l/min, or 28 m^3/min.

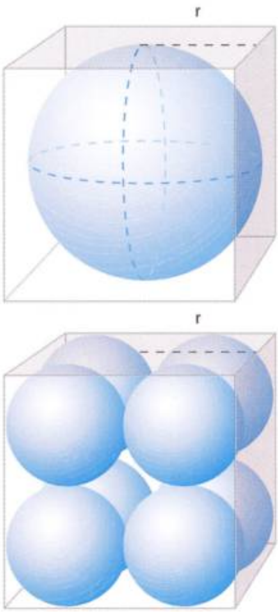
When foam is being produced the energy represented by the nozzle pressure can be converted in different ways. For instance, this energy can be used to provide the foam with a good projection range (low-expansion foam), to provide good foam quality with small bubbles of equal size (medium-expansion foam) or a high expansion factor (high-expansion foam). In general, the foam's extinguishing ability increases with higher expansion factor. Also, the required application rate decreases with higher expansion factor.

If the expansion factor increases the foam's projection range decreases. High-expansion foam generally has no range at all and is so light that it is greatly affected by the wind when used outdoors. Medium-expansion foam has a projection range of a couple of metres, while low-expansion foam has a range of 20–30 metres, depending on the flow rate and the nozzle shape.

It is difficult to assess foam's expansion factor without actually measuring it. A rough estimation of the foam expansion factor is that it is approximately equal to the foam layer height in cm. This rule of thumb applies to a foam layer without any restricting walls (Rosander & Giselsson, 1993).

The expansion factor does not, unfortunately, indicate the quality of the foam. The most stable foam has small bubbles of the same size. With foam bubbles of different sizes the smallest one, with the highest pressure, will disappear into the large bubbles where the pressure is lower. This makes the large bubbles grow further and the number of bubbles decrease.

The more the foam is treated, the smaller the bubbles will be. If two types of foam have the same expansion factor, the one with the small bubbles is more stable than the one with the large bubbles. The smaller the bubbles, the thinner the liquid film between them. This means that the liquid will drain off more slowly and the foam will have a consistency more like whipped cream. With large bubbles the liquid film is thicker and will drain off more easily and the foam will be watery. The draining time can be analysed by measuring the time it takes for 50% or 25% of the foam in weight to drain off.



3.6 With half the radius the surface area becomes twice as big. However, the volume remains equal.

The area of a sphere in a cube is $4\pi r^2$. If it is replaced by eight spheres with half the radius they will all fit in the same cube. The eight spheres will have an area of $8 \times 4r(r/2)2 = 8\pi r^2$. Their combined area is therefore twice as big as the area for the large sphere.

The large sphere has a volume of $4/3 \times \pi r^3$. The volume of the eight small spheres will be $8 \times 4/3 \cdot \pi\, (r/2)^3 = 4/3 \cdot \pi r^3$. This means that the volume is the same. The foam bubbles' combined area will be bigger if the bubbles' size decreases, even though the foam expansion factor is the same in both cases.

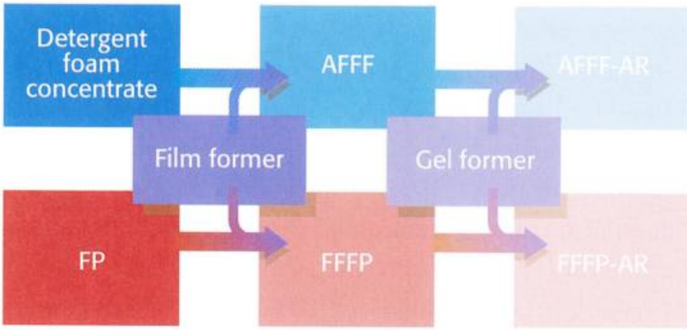
Air can be mixed in at the nozzle, using the ejector effect. Technically, this is the simplest solution. The air can also be mixed with the air immediately after the foam proportioner, which requires the gas to be added under pressure, usually using compressed air.

In general, systems where the air is added before the nozzle, compressed air foam, produces smaller bubbles and a more stable form than when the air is added in the nozzle.

FOAM CONCENTRATES

Foam concentrate is a mixture with many ingredients, giving different properties to different foam concentrates. Foaming agents, which can be synthetic or protein based, are the main ingredient in all foam concentrates. In addition, there are also a number of other possible constituents (Eriksson 1984; Holm & Solyom 1995).

- Stabilisers make the foam concentrate retain water, strengthen the foam bubbles' walls and increase the foam's heat resistance.



3.7 Different foam concentrates have different constituents.

- Solvents are added to achieve the required viscosity so that the mixture will be fluid and pumpable.
- When particular solvents are used, along with other anti-freeze agents, some types of foams can be used at temperatures as low as around –30°C.
- Preserving agents give the concentrate greater durability.
- pH-adjusting agents are added so that a pH of 7 can be obtained.
- Resistance to hard and salty water is achieved by using special additives.
- Thickening agents are often added to make the foam more viscous.
- Different colours are used to distinguish between the various types of concentrate.
- Corrosion inhibitors can be added to protect the equipment against corrosion.
- Water is included in most types of foam in varying quantities, which explains the foaming of some concentrates already in the tank.

There are many different makes and types of foam concentrates. This means that a technical data summary should always be kept by all foam concentrate tanks, including vehicles and storerooms. This will provide information about how the particular foam concentrate acts, for instance, with other foam concentrates or powder types and about how it should be proportioned.

Synthetic foam concentrates are the most common. They are based on synthetic detergents such as fatty acids and petroleum products, e.g. sodium or ammonium sulphate or triethanolamine lauryl ether sulphate, and have similar properties to ordinary washing-up liquid. The product is chemically produced and is therefore referred to as a synthetic foam concentrate. With no further additives it is often known as detergent foam concentrate and gives a surface tension of less than 30 mN/m. Synthetic-based foam usually foam the easiest and provide a higher expansion factor than protein-based foam in the same conditions. The foam is smooth and has a low viscosity. Detergent concentrates can be expanded to low-, medium and high-expansion foams.

Protein foam concentrates are manufactured from hydrolysed animal or vegetable protein materials. The raw material is usually industrial by-products, such as soya beans or horns and hooves from cattle. Other types of protein raw materials have been used as well, but may result in poor quality. Protein foam is stiff and adhesive. When the foam is exposed to heat the water vaporises or is drained off. The protein coagulates and forms a reddish-brown residue, which provides a highly heat-resistant barrier. If there is protein foam residue in metal structures this may cause galvanic corrosion. For this reason, it is necessary to rinse and dry the equipment after using protein foam. Protein-based foam concentrates can be expanded to low and medium-expansion foam. The surface tension is less than 45 mN/m for the foam concentrate mixture.

A number of foam concentrates used for class A fires are of these two types. Their ability to expand and their adhesive capacity decreases with the use of additives that make them alcohol resistant.

These foam concentrates can without any further additives be used at class B fires, where the fuel cannot mix with water, such as oil. They can be used for fires in non-polar fuels, but not in polar fuels like alcohols.

One district had a basic resource for major class B fires, such as a tanker fire. However,it was noted that foam was usually used for filling rooms with high or medium-expansion foam, as well as to reduce the surface tension at small fires in containers, etc. Therefore, the basic resource was supplemented by filling the foam tank on the first fire engine with detergent foam concentrate, which produces a good high-expansion foam. It is also one of the cheaper types of foam concentrate, which means that they could afford to practice more often.

Most foam concentrates are sensitive to contamination from smoke in the air used for expansion. There are certain types of smoke resistant foam, which can be used in fixed installations where the air in the fire room is used to produce high-expansion foam. The benefit of this is that no ventilation openings are required.

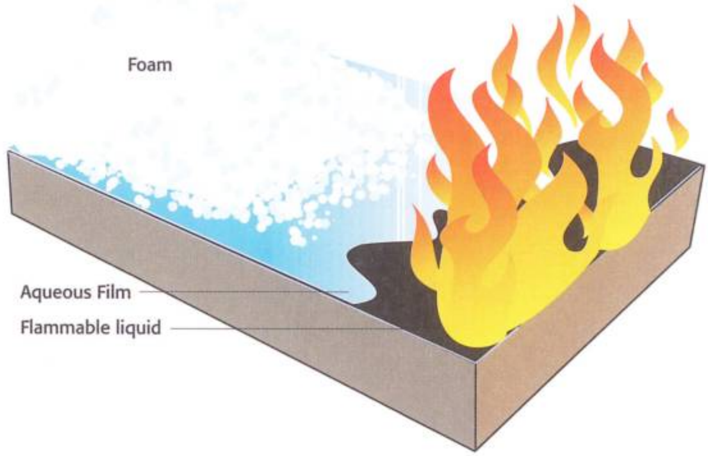
3.8 The P mark on the foam concentrate means that it has been controlled by the Swedish National Testing and Research Institute and complies with certain test criteria.

Foam concentrates intended for use at class B fires must comply with the requirements in EN 1568. In Sweden, the P mark on a foam concentrate means that the product complies with these requirements after being tested at the Swedish National Testing and Research Institute and that the manufacturing process is subject to internal control. There are other marks available, but it is essential that an approved test institute has carried out the tests.

FILM-FORMING FOAM CONCENTRATES

Using a fluorinated surfactant and silicone as the basis for the foam concentrate gives it new properties. In the case of non-polar fuels, i.e. fuels which do not mix with water, such as oil, a controlled surface tension relationship is established between the fuel and the liquid drained from the foam. A thin aqueous film is formed, which spreads across the fuel surface. This has given the foam concentrate its name, Aqueous Film Forming Foam, shortened to AFFF. This film enables the foam to knock down and extinguish fires involving flammable liquids more quickly.

Protein-based foam concentrates can be used to form a film too. They are manufactured on the same basis, but have had fluorinated surfactants added, which can improve the viscosity and extinguishing effect. They are known as FFFP foams have similar physical properties to other protein foam concentrates. Fluoroprotein foam concentrates are used, for instance, to tackle fires at petroleum plants and on board vessels.



3.9 The aqueous film quickly spreads across the fuel surface. The foam then slides out across the film.

The film-forming capability depends on whether the surface tension of drained off liquid has been reduced from the normal 73 mN/m to below 20–30 mN/m, which is typical for most hydrocarbons. If the water's surface tension is lower than that of the fuel the water will not form droplets which can penetrate the fuel but will form a film that can spread across the fuel surface. The fact that the drained water spread across the fuel gave the trade name "light water", although the water still has a higher density than the fuel. This film-forming capability depends greatly on the fuel type. There are fuels which allow the drained water to accumulate as droplets and sink through the fuel layer. It is also possible that no film is formed at all if the liquid's temperature (boiling point) is too high (Persson 1987 b).

The film is only about 0.001 mm thick, but still reinforces well enough the foam's ability to quickly spread across a burning fuel surface. The film is also self-healing and can, to a certain extent, spread out again and cover the surface if broken or damaged.

Airport fire brigades must, at aircraft fires, begin the attack within 90 seconds so that the temperature inside the aircraft is not too high. In this case, foam is needed which can tackle class B fires and spread out as quickly as possible, as the spillage may be large. On the other hand, there are minor problems with hot metal surfaces and the fuel is non-polar. In this case, a synthetic, film-forming foam concentrate is selected.

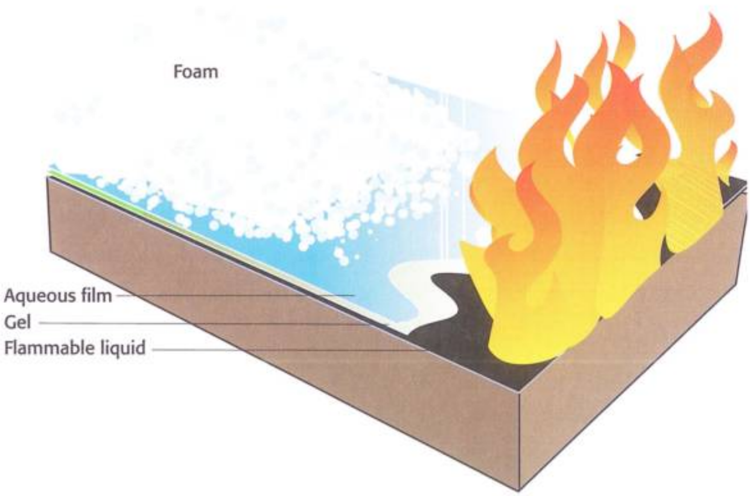
FILM AND GEL-FORMING FOAM CONCENTRATES

One problem with polar fuels, such as alcohols, is that the foam and film are soluble in the fuel. As a result, the fuel will totally break down the foam at the same rate as the application. This means that film-forming foam concentrates, both synthetic and protein based, are available with an additive that makes them alcohol-resistant.

Alcohol-resistant foam concentrates produce a foam which, when it comes into contact with alcohol or other polar fuels, triggers a chemical reaction and forms a gel seal in the boundary layer between the foam and fuel. The gel forms a sealed barrier with the fuel, thereby preventing the foam from breaking down. As the gel formation is a chemical process, the gel is not self-healing. If the gel seal has been broken more foam is required to form a new one.

The alcohol resistant foam can be used with most fuels, but a gel seal is only formed with polar fuels. A film can also be formed with non-polar fuels.

Film and gel-forming foam concentrates produce excellent-quality low and medium-expansion foams. On the other hand, foams with fluorinated surfactants drain too quickly to be suitable for the production of high-expansion foam. One drawback with film and gel-forming foam concentrates is that they are more expensive than other foam concentrates.



3.10 The gel protects the foam from being broken down by the polar flammable liquid.

Fluorinated polymer detergent concentrates are abbreviated to AFFF-AR and the equivalent abbreviation used for protein-based foam concentrates is FFFP-AR, where AR stands for "Alcohol Resistant". There are other abbreviations used too.

When a district council got together with an oil company to discuss pre-fire planning at a tank farm, it was noted that both polar and non-polar fuels were stored at the plant. The time required for rescue operations and the first cool-down operation was estimated to about 10 minutes. However, it would take considerably long for a sufficiently effective extinguishing operation involving the use of foam to be organised. There was the risk of hot metal components being close to the burning surfaces. This is why they opted for a protein-based film and gel-forming foam concentrate.

The fuel determines which foam concentrate is suitable or not. Petrol can contain so many polar substances, such as ethanol, methanol, MTBE and IPA that a film and gel-forming foam is required. Most foam concentrate types can be used with fuels with a polar liquid content of up to around 5%. With a higher application rate they can be used with fuels with a polar liquid content of up to around 10%. On the other hand, film and gel-forming foam concentrates with a 6% mixture can cope with all mixtures of polar liquids. With just a 3% mixture they can cope with the same content of polar liquids in the fuel as film foaming concentrates.

Storing and transporting foam concentrates

Foam concentrates are usually stored in tanks, vats or drums and mixing takes place when they are needed. Even when unmixed and with its packing intact, foam is still a perishable item with a limited shelf life generally of 10–25 years.

The best storage life is guaranteed by keeping it in a cool place, but not exposed to frost. Increasing the storage temperature by 10 degrees halves its storage life. Some foam concentrates have a low viscosity, while others are highly viscous. The viscosity of most foam concentrates increases as the temperature is reduced. This means that the colder it is, the more viscous the foam is. Consequently, to ensure that foam concentrates are ready for use, they should not be stored at a temperature lower than the temperature at which they have sufficient viscosity.

If a foam concentrate is stored in a ventilated tank water will gradually evaporate and the foam concentrate break down. To guarantee optimum storage life, the container should be completely full and unventilated. When it comes to using it, the tank must have a valve allowing air to come in at the same rate the foam concentrate is being used.

It is best if foam concentrates are stored in their original packaging. When selecting and designing storage tanks, it is best to follow the manufacturer's recommendations. There is every reason, when buying tanks, to look into the warranty terms, with regard, for instance, to replenishing the tank when part of its contents have been used.

Different foam concentrates must not be mixed together in the same container as this can cause them to spoil each other. It is possible, however, to use different foam types during the same operation, but two sets of pump, proportioning and application equipment must be used.

Taking foam concentrate samples for testing from the storeroom is a way of ensuring that they retain their quality. Testing can cover such properties as expansion factor and draining, pH value, viscosity, sedimentation, film-forming capacity and durability with polar solvents, refractive index and density. A fire test can also be carried out using some small-scale method.

It is important that the foam concentrate storage tanks are big enough and that they are spotlessly clean before the foam concentrate is poured into them. If any impurities get into the foam concentrate, it makes it age more quickly and/or it loses its function. For instance, alcohol will trigger the formation of gel in gel-forming foam concentrates.

It is also important that the tank storing the foam concentrate is made from the right material. For example, an alcohol-resistant foam concentrate must not come into contact with any component at all made from copper, not even a connector. If this happens, the foam concentrate will react with the copper to form ions and may even corrode acid-proof steel. A tank for storing alcohol-resistant foam concentrates must be made from stainless steel or plastic. The foam concentrate penetrate even the finest pores of many paints or protective enamels, making it to dissolve or come away from the underlying base.

Fire engines often have fixed tanks, holding several hundred litres of foam concentrate. Water tenders can hold more, up to a few cubic metres. If the volume of the foam concentrate tank is 12% of the volume of the water tank, with a 6% concentration, there will be enough foam concentrate to mix the water brought along twice over. Some tenders carry only foam concentrate and no water, holding up to around 10 cubic metres. In this case, the liquid is often divided up into separate tanks.

Vats are not particularly common for storing foam concentrate at incident sites, but are suitable for holding small foam equipment and foam concentrate containers.

Foam concentrate can also be stored in drums. In major operations, logistics is important. Storing foam in drums involves a lot of manpower and is only done in practice when there is very little foam concentrate used, as in the case of an operation involving the use of high-expansion foam. When replacing foam concentrate drums during an operation the tap of the foam pick-up tube is closed while it is moved to the next drum. This prevents any operational disruption caused by air being sucked in.

With a flow rate of 200 l/min through a small foam tube and a 3% concentration, foam concentrate will be used at a rate of 6 l/min. That means it take a good four minutes to empty a 25-litre drum. With a larger foam tube, several tubes or a higher mixture concentration, it will empty even faster. A foam monitor operating at 1600 l/min with a 6% mixture will produce a foam concentrate flow rate of 96 l/min, i.e. equivalent to four drums per minute.

Mixing foam concentrates

Foam concentrates are usually mixed at 3% volume concentration with water for class B fires. At fires in polar fuels, the mixture concentration for gel-forming foam concentrates may need to be doubled, i.e. 6%. With class A fires a lower concentration level of 0.1–1.0% is sufficient. The manufacturer's recommendations should be followed. With this in mind, a plastic-coated product sheet about the foam concentrate should be available at the place where it is being used.

Getting the foam concentrate mixture right is necessary in order to obtain high-quality foam. If the concentration is too high the foam is stiff and does not spread very well. If the concentration is too low this produces watery foam, which quickly breaks down and has a poor resistance to heat and different types of fuels. An unsuccessful operation involving the use of foam is very often due to the proportioner being used incorrectly or not working properly.

The proportioner is the key component in the foam system, but all the parts must be compatible for the system to work properly.

Unfortunately, it is not possible to judge whether the foam is of the right quality by looking at how much it foams. The only way to ensure the right mixture is to use equipment which is calibrated in the hose system being used. Detergent foam concentrates, in particular, are deceptive as they produce foam which looks good at a concentration level of just about 0.3%, but they are not stable enough to extinguish class B fires until the concentration is at 3%.

One feature common to all foam equipment is its sensitivity to external adverse effects. All it needs is for the foam concentrate line to get flattened and the flow rate will drop. Corrosion, blocked lines or impurities can jeopardise the operation completely. As a result, all foam equipment needs to be thoroughly cleaned after use and regularly inspected.

Irrespective of the type of proportioner used, it is vital that it is calibrated in the hose system and with the tubes to be used during firefighting. This is most important when using inductors. Calibration is performed by setting up the system. Then the flow rate of water and foam concentrate is measured. For some equipment there is test data available, which can be used as a starting point (Persson & Andersson, 1995).

To ensure that the foam system is used in a manner compatible with calibration, the way it is assembled should be specified and practiced as a standard procedure. From a preparation point of view, the best systems are those where the equipment is assembled and, for instance, the proportioner is already connected to the foam concentrate tank and the hose system is pre-connected.

Water has the same viscosity, regardless of whether it is moving or not, a property characteristic of every Newtonian fluid. Some liquids do not have this property. Thixotropic paint has a gel-like consistency in the pot, but when it is moved about it quickly becomes free flowing. This means that viscosity can vary. Some foam concentrates are not Newtonian fluids either, especially a number of gel-forming types. They are very viscous in the tank, but as soon as they are moved about they become free flowing. Because of this behaviour the equipment needs to be designed with special care so that the proportioner can make the relevant liquid move so that it becomes free flowing. If the foam concentrate needs to pass through any narrow slits these are features which can make it difficult to use non-Newtonian foam concentrates. When designing foam concentrate lines, the liquid's viscosity therefore needs to be taken into consideration. When carrying out calculations and tests, the results may be wrong if the test liquid has a different viscosity to the actual liquid going to be used (Bobert et al., 1996).

The proportioning of foam concentrates generally takes place using of one of three main types of equipment: premixing in a tank, using a foam pump or foam inductor.

PREMIXING

In some cases the foam concentrate may already be mixed with water in the tank. A fire engine with a 1000-litre water tank can be fitted, for instance, with a 30-litre foam concentrate tank to produce a 3% concentration. During an operation the foam concentrate is decanted directly into the water tank and a pump is used to ensure they are mixed together as required.

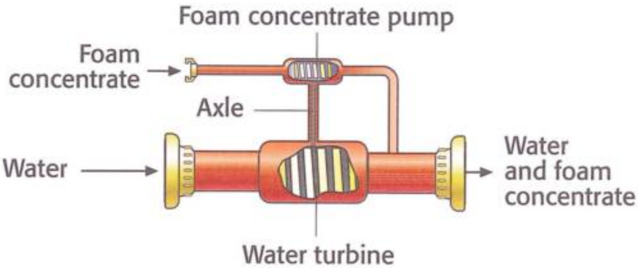
The benefit of this system is that it easily provides the right mixture. If larger quantities are required, however, the system will quickly become unmanageable. After an operation the water tank also needs to be cleaned so that there is no foam residue left to cause corrosion. Another drawback is that the mixture must not be stored, as many foam concentrates are biodegradable. If the mixture is left to stand the foam concentrate will be gradually broken down by the same processes which decompose foam concentrate in nature.

In situations where a low mixture concentration is required, the same principles can be applied with manual mixing. If a class A fire needs to be extinguished using a combination of water and a 0.1% concentration of foam concentrate it is sufficient for 10 litres of foam concentrate to be poured into a tank holding 10 m^3 of water when it needs to be used. This quantity is so small that it can be handled manually using foam drums, provided that stirring can be guaranteed.

FOAM CONCENTRATE PUMPS

A foam concentrate pump follows the water flow rate, which ensures a correct concentration. The major benefit from using pumps, therefore, is that they are not dependent on pressure and the flow rate in the system within the proportioner's area of operation. Consequently, it is possible to use different numbers of foam tubes and different lengths of hose at different operations. This makes a foam concentrate pump easy to handle. Unfortunately, it is more expensive than other proportioners, but it is considerably more accurate for the fire service, as the pressure and flow rate may vary. Foam concentrate pumps can be placed and incorporated at any point in the system. It is most common, however, for them to be assembled with the pump in fire engines or water tenders. Individual pumps can also be positioned beside foam concentrate tanks with external water supply from e.g. a water tender.

Foam concentrate pumps can have different designs. There are two basic types of equipment to distinguish between: mechanical and electronic. Mechanical equipment has a foam concentrate pump driven by the water current. It usually has a set flow rate, which means that the foam concentrate flow rate will always be, for instance, 3% of the water flow rate.



3.11 Mixer type foam concentrate pump.

There are different models available. For example, some have a water motor and foam pump mounted on the same axle and the ratio between displacements is the same as the required concentration ratio. This system is often referred to as a mixer type. In another version, a piston pump is used where either the whole volume of water, or part of it, is used to drive the pump. If a piston pump is used any concentration level can be selected. These mechanical systems are both simple and robust in their design.

Mechanical foam concentrate pumps can provide different performances. Some have fixed settings, such as 3 or 6% concentration. Other pumps have settings ranging from 0.1 to 1.0% and can therefore only be used against class A fires. To handle other concentrations, two or more pumps can be positioned in parallel. Mechanical foam concentrate pumps often use the energy of the water flow. If there is a large proportion of foam to be mixed in the pressure may drop considerably.

Electronic systems are controlled by a processor with a water flowmeter and an electrical foam pump whose flow rate is controlled using a variable current. These systems are both robust and easy to handle. When a processor controls the mixing process it can usually be programmed for any concentration level.

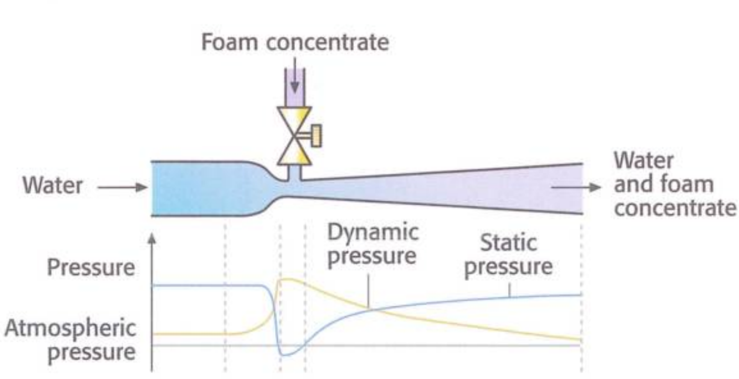
In the case of larger fixed systems, different types of pressure-controlled proportioners, combined with foam concentrate pumps are the most common. They provide high mixing accuracy, but because of their more complex structure, they rely on maintenance and supervision. For example, there are diaphragm valves which, using differences in pressure, automatically add a pre-selected amount of foam concentrate to water which must not be flowing at a constant rate. Both the water and foam concentrate must be pressurised.

FOAM INDUCTORS

Foam inductors operate using the venturi principle. A venturi tube has a cross-section resembling two Vs back to back. When the tube's cross-section decreases in the narrowing tube the water flow rate will increase. But the energy content is constant, which means that the pressure will increase according to the Bernouilli equation. When the water passes through the middle of the tube, all the pressure energy has usually been converted to kinetic energy. When the tube widens again the flow is allowed to expand and it will break up. In a water jet air would have been sucked in, but this is prevented by the walls of the tube. This generates a negative pressure instead. Immediately after the restriction, therefore, there is a chamber with a connection to a hose for the foam concentrate container. The negative pressure is sufficient for the foam concentrate to be sucked up.

A graph of the energy lines can be drawn for the proportioner showing the negative pressure in the unit, similar to the graph os page 40. There are also flow losses in the foam concentrate line, which produces a system curve (Persson & Andersson, 1995).

The actual venturi tube is a mechanical component, which always gives the same foam concentrate mixture at the same pressure and flow rate. There are different ways to control the



3.12 Inductor operating diagram.

proportioning. Through a graded valve, some water may be introduced into the foam concentrate line. The mixture is constant, but part of the mixed concentrate will then contain water. Another option is to lead part of the water outside the venturi tube. The position of the valve controlling how much water is getting through determines how much foam concentrate is mixed with it. Another way of regulating how the foam concentrate is mixed is to increase the loss of pressure in the foam line using a throttle valve. In a similar way, the proportioning can be regulated, manually or automatically, to adjust for variable pressure.

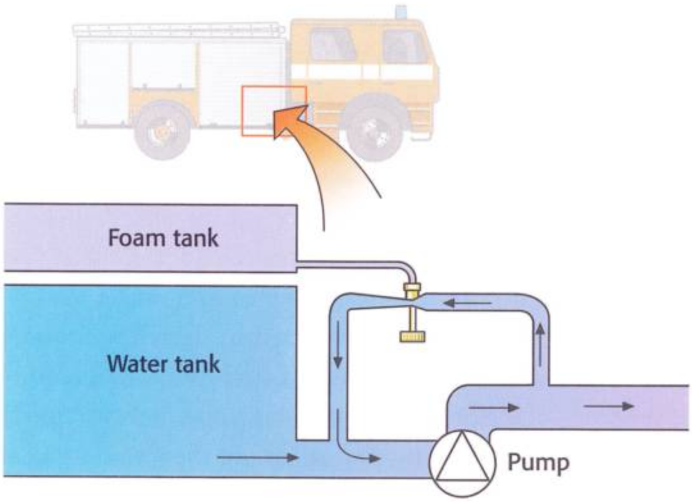
The venturi tube uses more energy than required for the actual effort. This means that it has a low efficiency as a pump. The benefit is a robust structure with usually no moving parts. The main drawback is that inductors provide the correct mixture only when the pressure loss through the inductor is correct. The ratio between the negative pressure in the foam concentrate tube and the foam concentrate's flow rate looks roughly the same as for most pump curves.

When using foam in winter time, it is important that the equipment is dry before the operation starts. Otherwise, there is a risk of lumps of ice forming in inductors.

Inductors are identified according to their location e.g. pump inductor, in-line inductor or nozzle inductor.

PUMP INDUCTOR

A pump inductor, or multi-jet inductor, is placed in a fixed line which branches off from the pressure side and goes back to the fire water pump. This means that it is fitted in a fixed position, for example in a fire engine. Foam concentrate is sucked in from a fixed tank. The difference in pressure between the two sides of the pump determines the concentration level. As the pressure loss in the hose system does not affect the system's performance, the pump inductor provides a system which is not dependent on hose length or on the difference in height between the pump and nozzle. However, the pump inductor is sensitive to an excessively high incoming pressure. If the water is taken from a fire hydrant or via a closed relay pumping the difference in pressure between the



3.13 Operating principle for a pump (multi-jet) inductor.

pump's suction and pressure sides will be too small for the inductor to produce the correct mixture. Fitting a pressure-reducing valve on the inlet will eliminate this problem.

The inductor has a mark indicating the mixture capacity. For instance, PI 50 indicates a pump inductor with a foam concentrate flow rate of 50 l/min with regulated incoming and outgoing pressure. The rate goes up to1700 l/min for a 3% concentration or 800 l/min for a 6% concentration.

A pump inductor does not detect the flow rate in the system. The pump operator must therefore control the pump so that the nozzle pressure, and with it, the flow rate are right. In addition, the foam proportioning level must be set according to the flow rate, i.e. according to the type of foam tube used.

The foam concentrate mixture for a pump inductor varies:

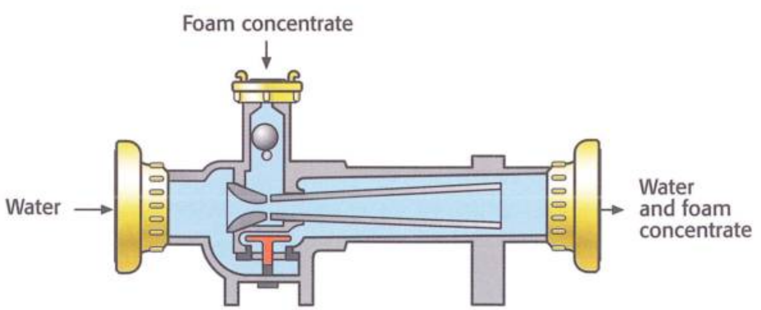
- according to the water discharge, where the percentage value is halved when the flow rate is doubled
- according to the counter-pressure, where the larger the counter-pressure, the smaller the flow rate and the larger the concentration percentage
- according to the incoming water pressure, where the higher the pressure, the lower the concentration percentage.

If the foam tube is closed, the flow stops in the hose. However, water will continue to circulate through the pump inductor line, which actually form a loop round the pump. As the circulation continues, the foam concentrate mixing process will also continue and the foam concentrate tank will gradually empty. The volume in the loop cannot increase, which means that the foam concentrate mixture will be forced back into the water tank. With a proportioning rate set at 3% and a flow rate of 800 l/min, it will take quarter of an hour for the foam concentrate from a 400 l tank to be transferred to the water tank. This is one reason why good communication is required at the scene of the fire, so that the pump operator can stop the foam concentrate mixing process or put the pump into neutral when the nozzle is closed. This is also a very important reason for using a foam tube without any shut-off device. If water is taken directly from a fire hydrant the problem will be even more serious as the foam concentrate is forced into the fire hydrant network.

IN-LINE INDUCTOR

An in-line inductor is placed between the pump and the foam tube. An in-line inductor produces a major loss of pressure in the hose system. This loss usually amounts to 30–50% of the inductor's incoming pressure. This inductor has a robust design but unfortunately, it provides the right foam concentrate mixture only within a small pressure and flow rate range. In order to achieve the right amount of negative pressure when the delivery tube is connected to the inductor, the pres-

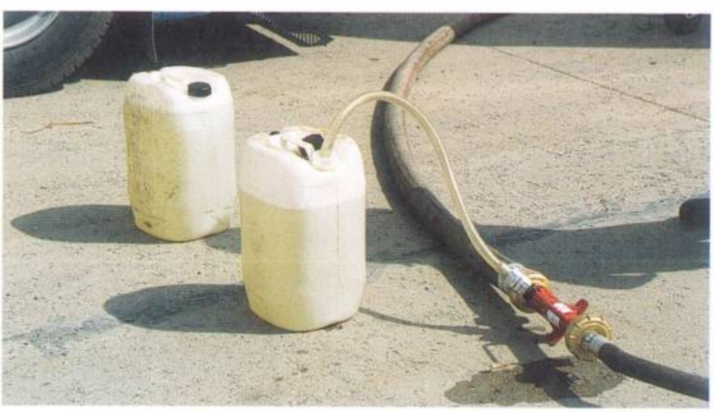
3.14 In-line inductor with a shunt valve.



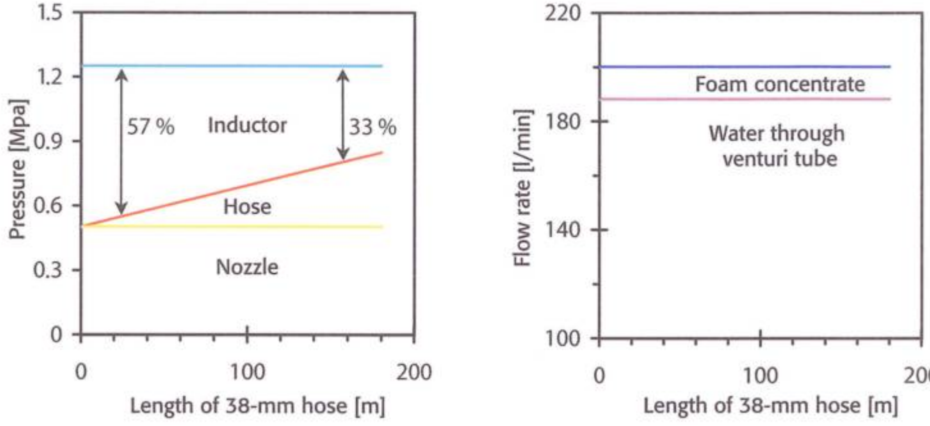
sure loss across the inductor, i.e. the difference between the inductor's incoming and outgoing pressure must be right.

If the pressure loss in the hose system between an inductor and nozzle is too great the entire venturi tube becomes filled with water. A too large counter-pressure may be due to the hoses being too narrow or too long, local pressure loss or to the height difference up to the nozzle being too great. There may even be a positive pressure in the inductor, which causes the water to be pumped out into the foam concentrate tank. The largest counter-pressure is achieved when the foam tube is closed completely. Then the water stops flowing through the inductor and it starts to flow out through the foam concentrate line. Either the in-line inductor must have a non-return valve or the foam tube must lack shut-off device. Some in-line inductors can only support a maximum of two 38-mm lengths of hose after the inductor, while others can handle up to 200 m before the pressure loss becomes too great.

The in-line inductor can also be fitted with an automatic shunt valve to help cope with the sensitivity to pressure loss between the inductor and the foam tube. The shunt is spring-loaded and when there is a slight counter-pressure some water is released, bypassing the inductor. As the counterpressure increases the valve gradually closes and when the counter-pressure is high all the water will run through the venturi tube. Thereby, the inductor will suck in the same quantity of foam concentrate, almost regardless of the length of the hoses used after the inductor.



3.15 Using an in-line inductor and foam concentrate in 25-litre drums. At 200 l/min and a 3% foam concentrate mixture, a 25-litre drum will last a good four minutes.



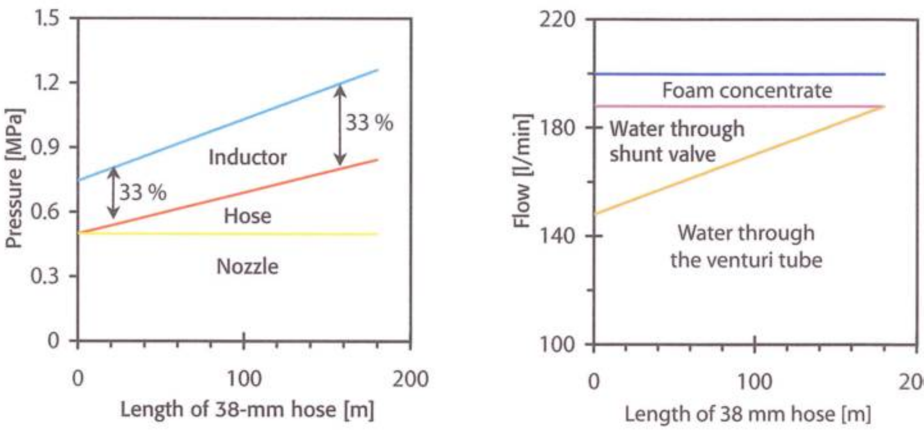
3.16 If an in-line inductor does not have a shunt valve the pump operator needs to maintain the same pressure, regardless of the hose length, to ensure the right foam concentration is achieved. The pressure loss across the inductor will vary greatly.

The in-line inductor is sensitive to foam concentrate residue remaining after use. To clean it after use, 10 litres of water mixed with glycol is sucked in, and the inductor is then rinsed, along the front and back. After drying it thoroughly and checking the valves, as well as to see that there is no rust, dirt, etc. on the inductor, it can be put back, ready for the next operation. In winter a lump of ice can form in the inductor if it is not dry from the start.

The size of the system must be right and it must be calibrated, especially when using an in-line inductor. This means that the inductor and foam tube are set for the same flow rate, that the number of hose lengths after the in-line inductor is correct, that the pump pressure is right, which produces the correct nozzle pressure, and that height differences are avoided, both between the inductor and nozzle and between the inductor and the foam concentrate tank. The in-line inductor is sensitive to variations in suction height and foam concentrate viscosity, which can result in proportioning errors.

If an in-line inductor is used, the system is usually not pre-connected. This requires extra caution so that sand or dirt does not get into the inductor when the system is being assembled or when changing foam drums. There is not much dirt needed to totally wreck the equipment's performance.

An inductor has an incoming pressure of 0.75 MPa. There is a 25–30% drop in pressure across the inductor, i.e. 0.20 MPa, along with a pressure loss of 0.05 MPa in the hose, giving a



3.17 Using the shunt valve in the in-line inductor regulates the pump pressure so that the foam tube's nozzle pressure is correct. The relative pressure loss is not dependent on hose length (Persson & Andersson, 1995).

nozzle pressure of 0.50 MPa and a flow rate of 200 l/min. The system is set up for these dimensions, which appear on rating plates on the inductor and foam tube. If the foam tube is raised 10 m this is equivalent to reducing the pressure by 0.10 MPa. This will result in the flow rate dropping to 175 l/min, while the inductor is still designed to handle 200 l/min. The drop in pressure across the foam inductor then decreases and there is no foam concentrate sucked in. If, on the other hand, the foam tube is lowered 10 m this will produce an excess pressure of 0.10 MPa. As a result, the foam tube will allow a flow rate of 225 l/min through it and with the higher flow rate, the drop in pressure across the inductor will be greater. This also means that the foam concentrate mix proportion will be too high.

NOZZLE INDUCTOR

Foam tubes may have an inductor integrated in the nozzle. This requires the foam concentrate container to be close to the nozzle and is most frequent for small tubes where both the foam concentrate container and the nozzle can be carried together, or for large units where both a foam concentrate tank and foam monitor are permanently attached. The benefit from this is that the foam concentrate tank, proportioner and nozzle are integrated with each other and only a water connection with the right pressure is needed.

There is, for example, a nozzle with a smaller foam container screwed on to it, known as a foam pistol or a foam nozzle with an integrated inductor, which has a pick-up tube connected to an individual drum or a dedicated container, which can be carried by hand or on the back, holding 10–20 litres of foam concentrate. In all cases, an attack hose is attached directly to the foam tube. To ensure the right mixture of foam concentrate is achieved and therefore, good-quality foam, the nozzle pressure must be right. Consequently, the pump pressure must be selected in relation to the hose system so that the nozzle pressure corresponds to the value recommended by the manufacturer. If the equipment is going to be used with different hose lengths it may be useful with a manometer on the nozzle. The fall in pressure across the nozzle varies by how much the opening valve is opened, which can cause a problem with certain types of equipment. This means that the mixing process varies and as a result, the foam quality too. The equipment should therefore be calibrated in the system it is being used in. This type of equipment is often set for a somewhat higher proportioning rate than normal. This is mainly due to poor mixing before discharge from the nozzle. The durability of this type of system is limited, but apart from this, the nozzle with direct suction provides a flexible foam production system.

Foam monitors installed close to a foam concentrate tank also often have a nozzle inductor. This provides a simple solution, for instance, for a monitor installed on a water tender or foam trailer. The equipment is calibrated so that it is clear what the appropriate pump pressure and therefore, engine speed is.

Mobile high-expansion foam units are also fitted with a nozzle inductor.

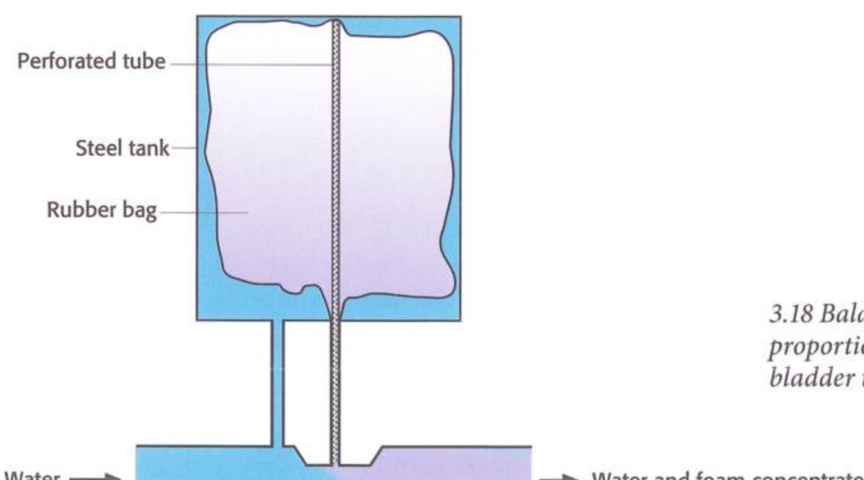
BALANCED PRESSURE PROPORTIONER

A balanced pressure proportioner comprises a system where the proportioner is integrated with the foam concentrate tank. Mixing occurs by fitting a throttle disc on the fire water line. A branch is placed upstream of this with, for instance, 3% of the throttle disc's surface, leading into the foam concentrate tank. 3% of the fire water flow is then channelled to the tank. The foam concentrate tank comprises a steel pressure tank, with an enclosed rubber bag which the foam concentrate is kept in. Because of this design, this is known as a bladder tank. The water is supplied between the steel tank and rubber bag. The pressure then rises and squeezes out the foam concentrate into a line, which is connected to the fire water line downstream of the throttle disc. One feature particular to balanced pressure proportioners is that the system does not have any suction side. The foam concentrate is not sucked in, but squeezed out of the tank, which means that the viscosity level of a high-viscosity foam concentrate is of minor importance.

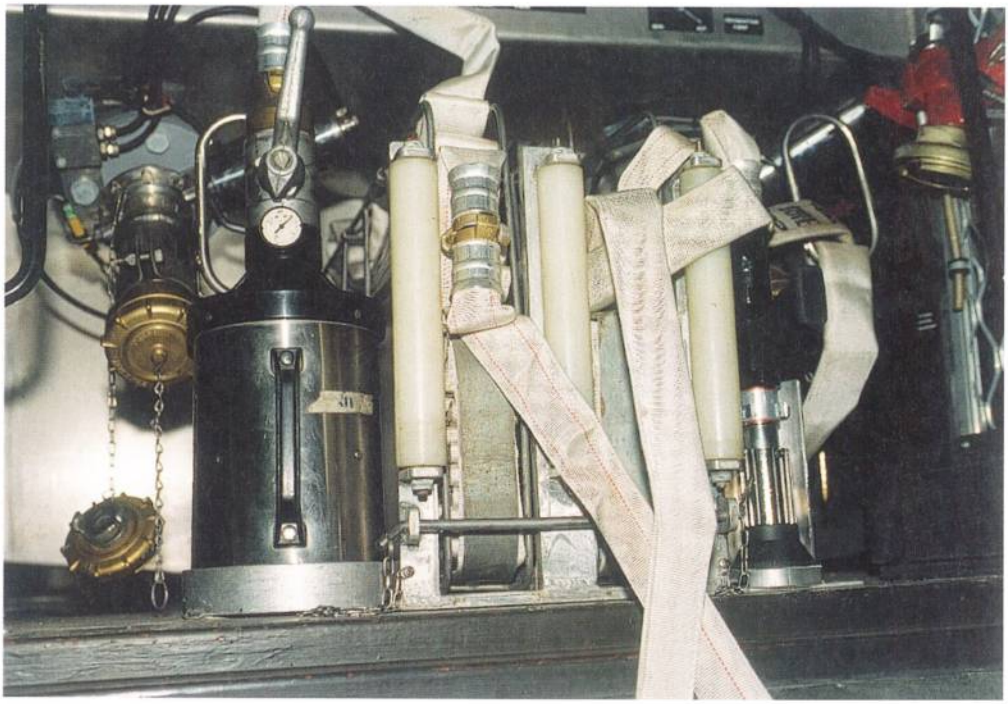
As there is excess pressure in the tank, even though small, it is not possible to fill the foam concentrate container during operation. The pressure tank can also be quite awkward, which means that it is best suited to small or stationary systems. On the other hand, the system is very robust and is not sensitive, for example, to variations in pressure or flow rate.

The most common way to regulate the balanced pressure proportioner's operation is to connect more than one line to the foam concentrate tank. If there are lines with 3% and 6% of the throttle disc's area a 3%, 6% or 9% concentration can be achieved, depending on whether either or both lines are used. It is also possible to have a throttle disc providing a continuously variable restriction.

If both the water and the foam concentrate are stored in tanks the loss of pressure in the line can be regulated before



3.18 Balanced pressure proportioner with a bladder tank.



3.19 The set-up time is reduced with pre-connected nozzles. The valves open automatically when the hose is taken out.

the lines come together immediately before the pump. This provides a proportioner, which is also reliable, maintenance-free and cheap for a fixed system.

WATER SUPPLY

Access to water is always required when using foam. The foam concentrate mixture is relatively small, which means that the water, on the whole, retains its properties. When foam concentrate is added it is mainly the surface tension that is changed. But the changes involved are only small and give a slightly increased flow rate. This means that any hydraulic calculations carried out are actually the same as for pure water.

Before attacking the fire, the whole hose system must be in place. There will be no opportunity for adding further hoses during the operation, so the hoses must extend round the fire from the beginning. If longer hoses are required, it is preferable to use open relay pumping in order to minimise the risk of the water supply being interrupted or the wrong pressure in the system. The foam concentrate must, however, be mixed in after the last pump. If the mixture is prepared earlier, closed relay pumping is required. Otherwise, foaming in the in-line tank will cause major problems. At tank farms and other fixed installations, there are usually specially arranged fire water lines.

A steady water supply is facilitated if the hose lengths and dimensions, as well as the nozzle capacity are fairly similar in the system's different parts. The system should also be as symmetrical as possible.

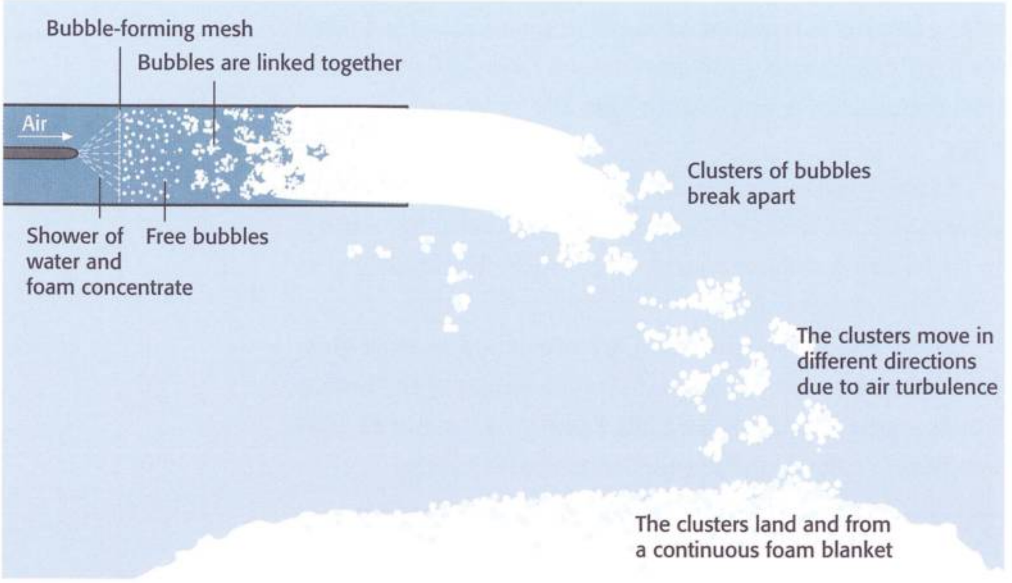
Speed and manoeuvrability are important in extinguishing operations involving foam. As the weight of the hose is similar to the weight of a hose filled with pure water, a 42 or 38 mm hose is suitable for connection to the foam tube.

The fairly low nozzle pressure in low-expansion and medium-expansion foam tubes means that a 42 mm hose, 75 m long (or a 38 mm hose, 50 m long) can be used for a foam tube with a capacity of 400 l/min. In the case of foam tubes with half this flow rate, hoses with a length four times as long can be used. Larger dimensions are required for foam monitors. The hose lengths reflect pressure loss in the hose system. The foam proportioner can require a smaller hose system (Rosander & Giselsson, 1993).

If an in-line inductor is used along with a 38 mm hose the pressure loss limits the flow rate to 200 l/min. If a foam tube with a higher capacity needs to be used either a hose with a larger diameter is required, such as 42 mm, or a proportioner less sensitive to counter-pressure.

Foam generators

Creating foam from a mixture of water and foam concentrate is usually achieved according to the same principle as when blowing soap bubbles. The mixture is sprayed onto a fine-meshed net and when air is blown through the net, bubbles are formed. The more air supplied, i.e. the larger the air inlet in the foam tube, the higher the expansion factor. If you want to indicate that air is being supplied in the foam tube it is called an air foam tube or aspirating foam tube.



3.20 How foam is produced and transported through the air.

The foam demand vary with the size of the fire, which means that foam generators come in every size. There are also different types of foam generator used, according to whether low, medium or high-expansion foam is required. Foam generators can also be made to specific requirements.

LOW-EXPANSION FOAM TUBES

The low-expansion foam generator is often known as a low-expansion foam tube. In some, particularly older, foam tubes, there is conical, fairly fine-meshed net or similar arrangement. Low-expansion foam tubes are generally not especially sensitive to variations in nozzle pressure. If the pressure increases slightly the flow rate increases, but the expansion factor remains fairly constant.

Portable low-expansion foam tubes are most common with a flow rate in the order of 200, 400 or 800 l/min of unexpanded liquid at a pressure of 0.5 MPa. Flow rates of more than 400 l/min are, however, difficult to manage with portable equipment. The reaction force from a jet of low-expansion foam is comparable to that of a solid jet of water at the same flow rate. Because of its high water content, low-expansion foam has a long projection range.

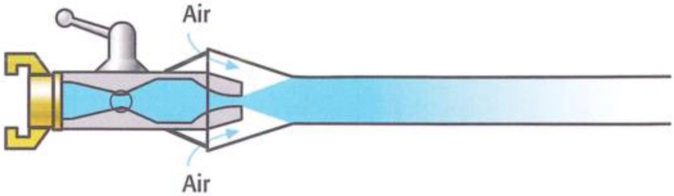
Foam monitors have a larger capacity and longer range.

The flow rate for the smallest portable ones is around 800 l/min and for the largest ones, used for fire boats and off-shore firefighting the rate is 30000–60000 l/min. Foam monitors mounted on vehicles usually have a capacity of 2000–3000 l/min. Foam monitors usually have a good projection range and large capacity, which is a help in knocking down a fire involving a flammable liquid quickly. When the fire is suppressed you can switch over to manual foam tubes to finish extinguishing the fire and maintain the foam blanket. Manual foam tubes have much greater mobility.

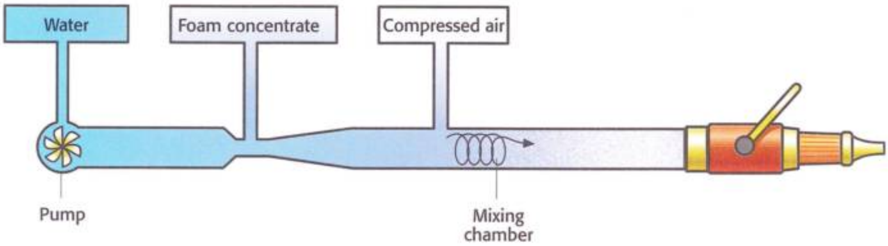
The monitor of a foam tender has the shortest set-up time. It also offers a better range, being positioned at a height. The area needs to be accessible by vehicle if the vehicle-mounted monitor is going to be used. When the monitor is placed on the ground, the best location is always selected according to the wind direction, for example. This type of monitor has less manoeuvrability than vehicle-mounted monitors, which makes it more difficult for the monitor operator to apply the extinguishing agent gently. For instance, the distance to the fire and the range of the monitor needs to be assessed correctly. To achieve the best position, it is often worth contact with a guide who can see the fire and the jet of foam from the side.

There is also a system which does not only mix water and foam concentrate, but air is also added before the mixture reaches the nozzle. This is achieved by using an air compressor, resulting in compressed air foam, or CAF. The biggest difference between compressed air foam and ordinary foam is that compressed air foam has smaller air bubbles at the same expansion factor. This means that the foam is more stable. Low-expansion foam, for example, has the same consistency as whipped cream.

In the conventional foam systems, air is added only in the



3.21 Low-expansion foam tube.



3.22 Compressed air foam unit.

nozzle. With compressed air foam, the air is already added via a compressor before the mixture has reached the nozzle. The compressor limits the extent to which the air is mixed in, giving an expansion factor of around 2–40. The mixture can be squeezed through bristles or a mesh package, or the turbulent current in the hose can produce good-quality foam. The air bubbles expand in the hose as the pressure drops. If the pressure drops from 0.30 MPa to atmospheric pressure the bubbles' volume increases threefold. The best nozzle is a completely open tube, which operates at a low nozzle pressure so that the jet does not split. The main benefits of compressed air foam are that the foam is more stable and the expansion factor can vary.

In some situations the foam concentrate mixture is used without any air supply and expansion in the nozzle. The foam is instead somewhat expanded during its transportation through the air. This is what happens if an ordinary fog nozzle or monitor is used. If there is no air mixed in the system the foam is described as unaspirated. Sometimes it is called premix. This latter term can, however, be confused with the mixing method where foam concentrate and water is mixed together in the tank prior to use.

Some fog nozzles become conventional low-expansion foam tubes with an air-aspirating attachment. Otherwise, the fog nozzle provides a low-expansion foam with a very low expansion factor. If the nozzle is directed against a wall a short distance away a medium-expansion foam can be produced. Any further than this distance results in low-expansion foam. Training is required to produce good-quality foam using a non-aspirating nozzle.

Unaspirated foam is mainly used for tackling class A fires.

Depending on the desired effect, the nozzle can be handled in different ways. It is often a matter of covering and soaking an area as quickly as possible, in which case the water spray is the best solution. The technique for extinguishing class A fires using water with added surfactants is usually the same as when using plain water. The difference is that the surface impact of the extinguishing agent is reinforced. Consequently, it is the surface effect that is desired extinguishing this type of fire.

Unaspirated foam is not suitable for class B fires, except for small fires and limited spills. In this case, a film-forming foam is needed, as other types of foam concentrate are unable to form a continuous foam layer without expansion. In order to ensure that the droplets' impact energy is as low as possible, a fog nozzle should be used. In fires involving polar liquids, the extinguishing agent's impact energy is so great that the gel seal breaks down. This reduces the extinguishing effect, even with a fog nozzle, which is why unaspirated foam should not be used to extinguish fires involving polar liquids.

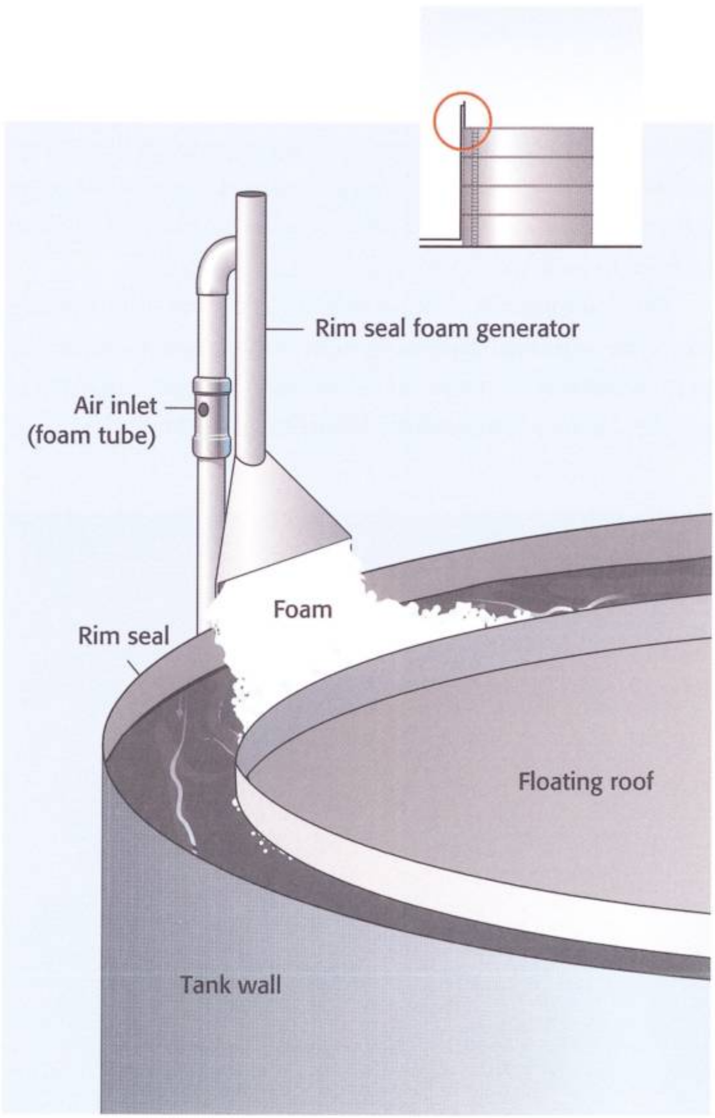
There are foam sprinklers just like there are water sprinklers in wet pipe and dry pipe systems, which operate generally in the same way. However, a special arrangement is required to ensure that foam concentrate is not discharged into the public

3.23 Fire suppressed by foam sprinkler in an industrial process. Sometimes manual extinguishing is also required at the fuel outlet.

water supply network when there are changes in pressure in the system. Foam sprinklers can be installed, for instance, at production facilities presenting a particularly high fire risk due to the presence of flammable substances.

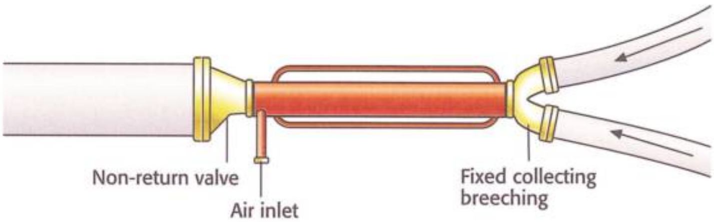
Many systems are semi-fixed, which means that, in the event of a fire, additional firefighting equipment is required. Other devices may be semi-automated and need to be manually activated by firefighters.

Storage tanks for flammable liquids usually have fixed foam systems. The foam is often applied over-the-top, if

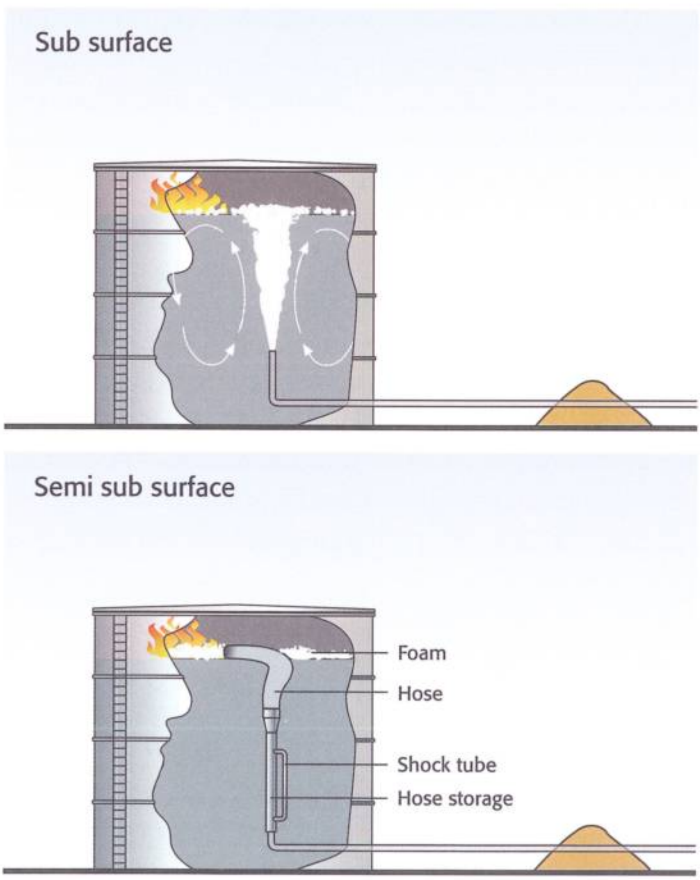


3.24 Applying foam from above using a fixed foam generator for a tank with a floating cover.

the tank has a floating roof. A fixed foam system can extinguish any fire at the edge between the floating roof and the tank wall. The drawback with over-the-top systems is that they can be damaged by the fire. In this instance, there is no option other than to use low-expansion foam monitors. Note that tank fires are only discussed briefly in this section. For those having large tanks in their response area, there is specific literature on large-scale tank firefighting (Storskalig oljebrandsläckning, 2001).



3. 25 Foam generator.



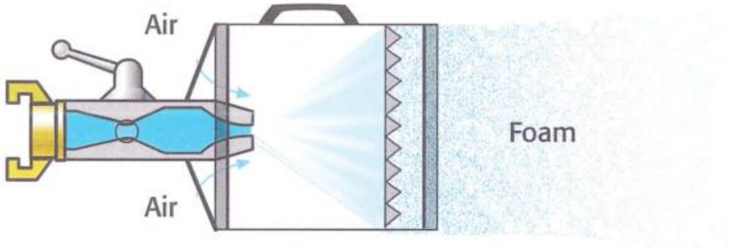
3.26 Injecting from the bottom with or without an upward hose to protect a tank with a fixed cover. In both cases high back pressure foam generators are used.

Foam can also be applied sub surface, a system used for tanks with a fixed roof. This method requires the foam to be injected under pressure. High back pressure foam generator are used for this. They are able to both produce foam and withstand the fluid pressure at the bottom of a tank. The nozzle pressure must be 0.5 MPa, plus the pressure from the column of liquid in the tank, up to a maximum of about 0.2 MPa, giving a total nozzle pressure of 0.7 MPa. The high back pressure foam generator is fitted with an air inlet and bubble former, along with a non-return valve so that the fuel cannot be discharged out through the foam tube. The connection to the high back pressure foam generator is extended distance from the tank. To prevent the foam tube from cracking under the weight of the filled hoses, it should be supported at the back with a scaling ladder, for instance.

Subsurface application is used for tanks containing flammable liquids of class III and higher. Tanks for class I and II liquids have semi-subsurface systems, where the foam is applied via an interior hose directly on to the surface. With semi-subsurface application, the foam is not contaminated and the gel former in the alcohol-resistant foam is not activated before the foam has reached the fuel surface.

MEDIUM-EXPANSION FOAM TUBES

Medium-expansion foam tubes operate in the same way as low-expansion foam tubes, but the air inlet is bigger. The foam is produced by the foam concentrate mixture being sprayed over a mesh. As the spray angle is large the reaction force in the foam tube will be small, for the same reason as the reaction force drops in a water nozzle when switching from a solid jet to a spray. Medium-expansion foam tubes usually have a capa-



3.27 Medium-expansion foam tube's operation.

city in the order of 200, 400 or 800 l/min at a pressure of 0.5 MPa, given for an unexpanded mixture, but larger capacities are available. There are even medium-expansion foam tubes designed for use at low nozzle pressure, for instance, if the water pressure is low. They appear short and thick due to the design of the nozzle and bubble former rather than long and narrow as in the case of foam tubes used at normal nozzle pressure.

3.28 With a combination tube it is possible to choose either medium or low-expansion foam, depending on the situation.

Medium-expansion foam tubes often provide the best foam for firefighting, when it is possible to get close to the fire. Medium-expansion foam tubes produce high quality foam with an expansion factor of 75–100 and a projection range of 5–10 m. One or more medium-expansion foam tubes can be mounted on an aerial appliance in order to compensate for the short projection range. This will increase the range.

There is also a combination tube available, which can be used for both low and medium-expansion foam. Low-expansion foam is used to knock down the fire making it possible to get close to it. The tube is then switched to medium-expansion foam to complete the extinguishing.

3.29 Fixed installation for medium-expansion foam.

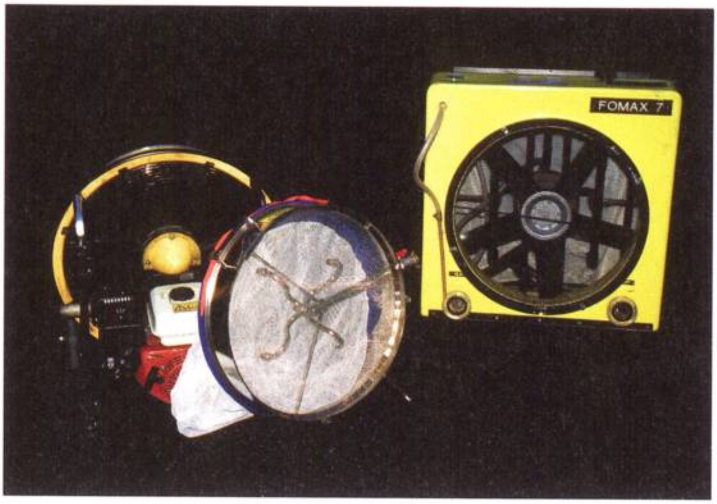
Some fog nozzles have an attachment tube which can be hooked on. This attachment converts the fog nozzle to a medium-expansion tube. This concept is also useful when a fixed hose reel is being used and the pump is fitted with a foam concentrate proportioner.

Foam tubes are calibrated for a particular nozzle pressure, usually 0.5 MPa, which is marked on the tube. If the nozzle pressure is increased the liquid flow through the foam tube will increase, while, in principle, the air flow will remain unchanged. The expansion factor decreases and the foam becomes watery. For this reason, some foam tubes have a restricted flow. Foam tubes also may have a pressure gauge. If this is the case, the firefighter can easily monitor the nozzle pressure and notify the pump operator if any changes are required. If the nozzle pressure is correct the flow rate will be correct, which is a bonus if the proportioner is sensitive to flow rate.

The same problem arises if the air inlet is accidentally obstructed by a turnout jacket, for instance, or if the foam tube is placed on the ground and starts to suck in finished foam.

HIGH-EXPANSION FOAM UNITS

A high-expansion foam unit has a different design to low and medium-expansion tubes. The foam mesh and bubble former are larger and there are several nozzles for spraying the foam

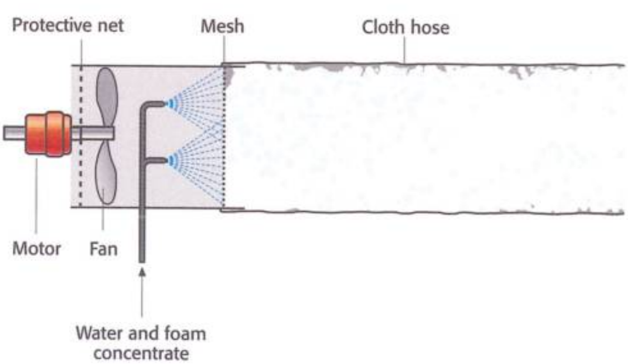


3.30 Fan for positive pressure ventilation with a high-expansion foam attachment and high-expansion foam unit respectively.

concentrate mixture. In this case, the ejector effect is not sufficient to draw in enough air and therefore, high-expansion foam units are equipped with a fan, which unfortunately makes them quite cumbersome. The fan can be operated using an electrical, water-turbine or combustion motor. Some fans used for smoke ventilation are equipped with a high-expansion foam attachment.

If the area is filled right up to the top with high-expansion foam and the unit is switched off the foam may collapse back through the fan. A unit powered by a combustion engine will stop and be difficult to start again.

The liquid and air flow rates are regulated separately and are set for achieving the correct ratio. There are units available with a flow ranging from around 50 m^3/min of expanded foam to 1500 m^3/min. The expansion factor is high, usually



3.31 High-expansion unit's operation.

3.32 Using a high-expansion foam unit with a hose and door adapter.

600–1000. Vehicle-mounted units are also available, offering both a large capacity and projection range. The range for a standard high-expansion foam unit is generally low, as the foam tends rather to pour out. This means that a cloth hose must be connected to the unit to direct the foam.

When high-expansion foam is injected into a building a door adapter should be used. This comprises a foam hose with a bulge at the end. The hose widens three times and then narrows back to its normal diameter again, which means that the bulge can be placed in a door opening, for instance, and be held in place by its own force. The bulge takes up the whole door opening, which means that neither smoke nor foam can escape through the opening.

As high-expansion foam units are generally fairly cumbersome, fire crews should specially practice lifting them using an aerial appliance. This is an important part of the preparation for tackling attic fires.

Spill and tank fires

Foam is used as part of the extinguishing process in a number of different ways, so that the flames are not able to maintain a sufficiently high temperature to sustain combustion. Foam generally interferes with the fire at the fuel surface.

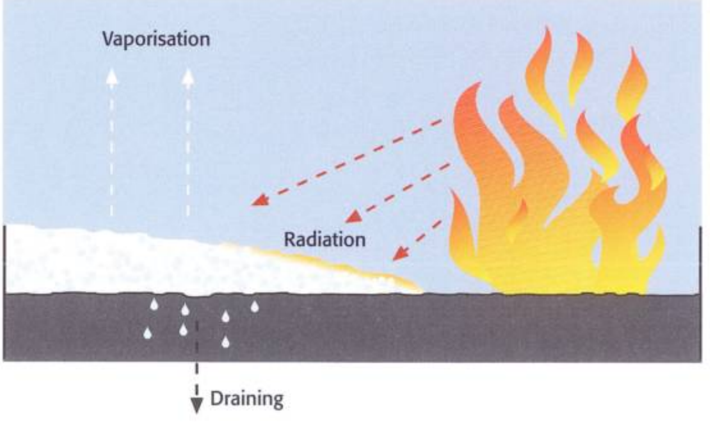
In the case of class B fires, foam is the only extinguishing agent which can be used independently. It can both knock down a fire and provide protection against reignition.

The first foam applied to a burning liquid surface breaks down quickly. The water from the foam vaporises, which means that the fuel surface quickly cools down, reducing the fuel vaporization. The water which vaporises from the foam will also provide the flames with a thermal load. As a result, film-forming foams will extinguish minor spill fires more quickly than non-film forming ones.

When a foam layer starts to accumulate a continuous blanket is formed over the fuel surface, which reduces the gas diffusion. This decreases the amount of fuel vapour penetrating the foam. As a result of this insulating effect, the fuel concentration in the flames becomes so low that the flame temperature cannot be maintained. This effect is most striking with film-forming foam types, where a water film can quickly spread across the fuel surface.

The foam protects the fuel surface from the heat radiated by the flames. As the area burning gets smaller, the effect of heat radiation on the rest of the fuel surface will decrease and the fire's intensity will diminish. The extinguished surfaces will also be protected by the foam's heat-insulation property.

Without external heat flux the foam breaks down slowly, but the rate increases noticeably when it is exposed to heat. At a heat flux of 5 kW/m^2 the breakdown rate for low-expansion foam will already be at around 1 cm/min and will rise linearly to double that value at 35 kW/m^2. The amount of water which vaporises from the foam blanket is about 0.25 g/skW. This



3.33 The foam spreading across the fuel surface affects the fire in a number of different ways.

means that if the fire generates a heat flux of 10 kW, 2.5 g of foam will vaporise per second. About 70% of the incoming heat is used for vaporisation. The foam break down and water vaporisation are usually not dependent on foam concentrate type (Persson, 1993).

As long as the fire surface is hot, it will release large volumes of fuel vapour, which will continue to burn and prevent a stable foam blanket from forming. The higher the vapour pressure the fuel has, the easier the flammable gases are released. The foam blanket is not strong enough to withstand the pressure from a boiling fuel. When the fuel already has a vapour pressure of around 0.03 MPa the extinguishing time will increase. As a result, the foam blanket will not be completely covering. This is most obvious when metal objects protrude through the fuel surface. Metals reach such a high temperature that the fuel close to the metal object boils. Both the metal and the boiling fuel breaks down the foam, which means that the blanket cannot cover the surface. This leads to fires burning at the sides and edges, which is a major factor contributing to the failure of firefighting using foam. It only needs a small edge fire to continue burning for the foam blanket to break down. The fire will then spread again if the operation is aborted. At this stage it is too late to support by cooling down hot metal surfaces, rubber tyres, etc. These

3.34 When extinguishing class B fires, they always need to be extinguished completely to avoid reignition. Medium-expansion foam is effective against side and edge fires, but firefighters should avoid stepping in the fuel spill.

surfaces must be cooled down right from the outset, together with the foam suppression.

The big problem with extinguishing class B fires is to extinguish the fire completely. The fire is either extinguished 100% or not at all, and there is simply no kind of half-way position. When foam is used, however, the fire may possibly reignite, but fairly slowly. When other extinguishing agents are used, suppressing the fire in the gas phase, it can reignite in a couple of seconds.

If the foam blanket is not gas-proof this also means that there is no guarantee against the fire reigniting or combustible gases accumulating, just because there is a thick foam blanket over the fuel. The only way to find out the fuel concentration in the air above the foam blanket is to take a measurement using an explosimeter.

Either medium or low-expansion foam can be chosen to protect flammable liquid surfaces which have not been ignited. At traffic accidents, foam is often used to prevent petrol leakage from igniting, thereby protecting the injured and rescue personnel. The benefit from using foam is that it actually reduces the risk of ignition, which is not the case when powder extinguishers are used, for instance. This will be of great value to unprotected people in the red zone.

Even a small increase in the oxygen content in the air

3.35 Rinsing away flammable liquids at the scene of an accident will prevent ignition. A firefighter remain on standby due to the combination of trapped unprotected people, vehicle extrication, oxygen treatment and the presence of a flammable liquid.

3.36 To cover and protect a remote accident scene, it may be sufficient to use a small foam tube with a proportioner integrated in the nozzle. For a 3% concentration, 33 litres of mixture is produced for every litre of foam concentrate. With an expansion factor of 100 the liquid expands to 3.3 m^3 of medium-expansion foam. If the breakdown is ignored each litre of concentrate can provide a foam blanket with an area of 10 m^2 and 0.3 m thick. But this requires the unit to produce good foam. If the proportioner is not calibrated properly or if it is used incorrectly, it is possible that no foam will be produced or the capacity will become too low. The actual foam production is therefore less.

produces a noticeable increase in the fire's intensity. If any injured are being treated with oxygen it is advised to apply medium-expansion foam to any fuel spillages to prevent the fuel vaporising where there is an increased oxygen content in the air.

In cases where trapped people need to be freed or seriously injured people should not be moved, applying a foam blanket or rinsing will make the site safe. Medium or low-expansion foam is nearly always available, but an unexpanded mixture may be appropriate in certain situations.

The foam blanket can cause problems. For example, the blanket will hide dropped things, and it will also hide obstructions. The liquid also tends to get sucked up trouser legs, which means that proper protective clothing needs to be worn. Fire service staff is usually properly equipped, but it is not self-evident that paramedics, for instance, will wear boots.

DIMENSIONING USING FOAM TO EXTINGUISH SPILL AND TANK FIRES

When foam is used to extinguish pool fires, you wait until the required number of units and personnel have assembled before the fire is attacked. In some situations, however, an attack should be carried out using the immediately available manpower. This applies when the aim is not to extinguish the fire but to break through temporarily in order to bring people to safety or to restrain a discharge by closing a valve. Particular objects may also be cooled down prior to the main attack.

There is a good reason to estimate the total burning time. For the operation to be effective, the total burning time should be much longer than the time it takes to start and carry out the firefighting.

Petrol is burning at a rate of around 4.5 mm per minute and the depth of the fuel determines the duration of the fire. Let us assume that the whole load of a petrol tanker has leaked and caused a spillage of 30 m^3. If the spill area is 100 m^2 the fuel will be on average 300 mm deep and the burning time will be around 70 minutes, even though the time locally will be much shorter or longer, according to the depth of the fuel. A 500 m^2 spillage over a flat surface will be 60 mm deep and will burn out in just under 15 minutes. In other words, most of it has burnt out before the firefighting has commenced.

The foaming agent's effectiveness is determined by the amount of foam concentrate/water mixture required to extinguish a particular type of fire. This is known as the critical application rate and is expressed, in the case of low and medium-expansion foam, in terms of unexpanded liquid per m^2 and minute. The foam will take up much more room once it has expanded. The foam volume is obtained by multiplying the application rate by the expansion factor.

Normal application rates for low and medium-expansion foam are 3–6 l/m^2 min of liquid and is fairly constant, regardless of the fire area up to about 1000 m^2. There is lack of experimental data for larger fires. In most cases, the recommendations of the manufacturer should be applied.

Even with a good projection range, it is still worth remembering that the spill can be considerable on the way to the target. This means that jets should be positioned to give optimum benefit. NFPA recommends a 50% higher application rate in the event of a diked spill, which is extinguished using a monitor, as opposed to using fixed nozzles with a low position. This is due to application problems using monitors.

Scenario	Requirement	Application rate [l/m²min]	Application time [min]
Undiked spill, loading points	P- and FP foam	6.5	15
Undiked spill, loading points	Other foam	4.1	15
Diked spilll	Fixed nozzle at low level	4.1	20/30*
Diked spill	Monitor	6.5	20/30*
Tank, fixed roof	Sub-surface	4.1	55/30**
Tank, fixed roof	Portable foam tubes or monitors	6.5	65/50**
Tank, floating roof	Over top	12.2	20

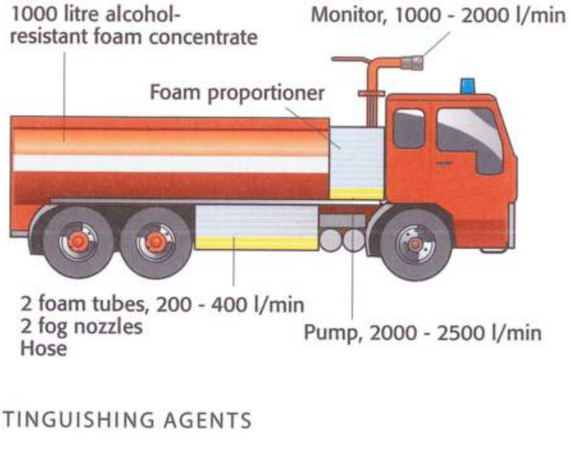
* for class II and class I fuels respectively.

** for polar fuels, as well as fuels with a flashpoint below 38°C and fuels with a flashpoint between 38°C and 93°C respectively.

3.37 Rate of application for medium/low-expansion foam in l/m² min, depending on fire type and type of foam concentrate, based on American recommendations (NFPA 11, 2005).

In 1988 the Stockholm fire service extinguished a tanker fire in the open air using high-expansion foam. The conditions were ideal as it was situated on level ground, with a light following wind (Rosander, 1997).

Wind can be another crucial factor. If the wind is strong and half the foam blows away the result will be the same as if the foam application rate was halved.



3.38 Example of basic foam resource.

Basic foam resources

In many areas, an accident involving a tanker carrying flammable liquids is used as the basis for dimensioning the foam extinguishing capacity. The basic resource is designed to be handled by a firefighting team comprising 1+4 people (Persson, 1990).

The foam is applied using a foam monitor, 1000–2000 l/min and two low/medium-expansion foam tubes, 200–400 l/min. The hose system and proportioner are selected to ensure a correct flow rate and proportioning. The foam is made using 1000 litres of film and gel-forming foam concentrate. A class III pump provides the water flow, 2000–2500 l/min. Two fog nozzles are used for cooling purposes, extinguishing rubber fires, providing personal protection, etc.

The dimensioning is sufficient for the extinguishing of approximately 500 m^2 of petroleum products for 15 minutes. With an application rate of 4 l/m^2min the amount of liquid used will be 30 m^3. With a 3% mix just under 1 m^3 of foam and 29 m^3 of water are required.

During a fire in polar-liquids a higher concentration is required, 6%, and 1 m^3 of foam mixed with 17 m^3 of water. With the same rate of application and time a 300 m^3 fire in polar-liquids can be managed.

Cooperation at regional and national level is useful, especially from an economic perspective. By coordinating activities, it is possible to maintain stocks at a reasonable level, while also having the opportunity to continually replenish the foam concentrate. When fires occur and additional resources are required, it is good to know that there is foam stored at several locations, including at the major foam suppliers.

Large-scale foam resources

In Sweden, the SMC (Swedish extinguishing agent centre), which is owned by the oil companies, supplies equipment for extinguishing major fires in oil tanks, etc. This equipment is designed to be used primarily when an oil tank's fixed extinguishing system is not able, for some reason, to

3.39 Large-scale foam resources.

extinguish a fire. The local fire service may not have the necessary resources to tackle a tank fire.

There are four depots; at the fire service in Gothenburg, Malmö, Stockholm and Sundsvall. Each depot has a coordinator responsible for liaising between the fire service and oil companies. The equipment is stored in a container system possible to transport by truck, train or plane, as required. Each depot has two modules split into eight container units, which have been allocated to four trucks with trailers.

Each module has a pump with a capacity of 10000 l/min at a pressure of 1.0 MPa. The pump is designed to operate with a static water supply as the flow rates will be high. This has a 400 m double 150 mm hose attached to it in fifty-meter sections and a monitor with a capacity of 8000 l/min at a pressure of 0.8 MPa. The proportioner for 3% or 6% concentration can dose the 16 m^3 of film and gel-forming foam concentrate which is available with each module (Storskalig oljebrandsläckning, 2001).

The system is designed for an application rate of 4.2 l/min^{2}min for dike fires and 10.6 l/m^{2}min for application over the top.

Six specifically trained personnel handle the equipment. They work at the fire service departments having a depot. The head of this group is responsible for the operation and works in cooperation with the local incident commander. There is one person responsible for the equipment and who directs the monitors. Two firefighters handle one pump each, along with relevant hoses. Another firefighter handles the foam concentrate supply and the last firefighter manoeuvres the monitors.

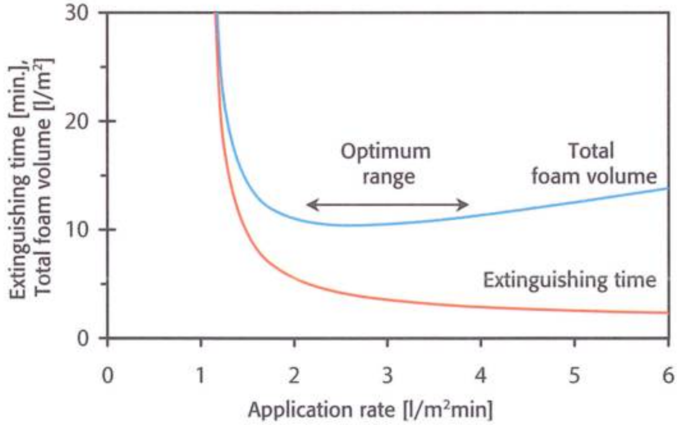
The time it takes to extinguish a large pool fire is determined by a number of factors, such as the pre-burning time, wind speed, choice of foam concentrate and the possibility to approach the fire, etc. This is why it is useful to calculate with a generous application time. In the case of spill fires, the application time is usually 15–30 minutes and for tank fires, 60–90 minutes.

The time required to extinguish a fire decreases as the application rate increases. At high application rates, the extinguishing time is no longer reduced or is reduced only very slightly when the application rate is increased further. In this case it is not the foam's extinguishing capability that is limiting, but the speed at which the foam is spreading across the fuel surface.

The time it takes to cover a burning fuel surface with foam and therefore, extinguish the fire, depends on a number of factors, including the foam application rate, breakdown and spread. The application rate is determined by the foam generator's capacity and the foam's expansion factor. The foam breakdown is affected by the properties of the fuel, especially the vapour pressure at the current fuel temperature. Foam breakdown is also controlled by heat radiation and convection from the flames and other heated surfaces, as well as by how quickly the water drains from the foam. The drain is governed by factors such as the viscosity and height of the foam. The breakdown rate increases with higher radiation. The rate of spread is mainly determined by the viscosity. It is also controlled by fuel movements. If a fire will be successfully extinguished or not depends on if the rate of spread at the flame front continuously exceeds the breakdown.

APPLICATION TECHNIQUE

In all foam operations, the outcome is determined by how the foam is applied. Ensuring that the rate of spread is quicker



3.40 Example of foam efficiency curve.

than the breakdown rate can be translated into tactical guidelines for foam extinguishing.

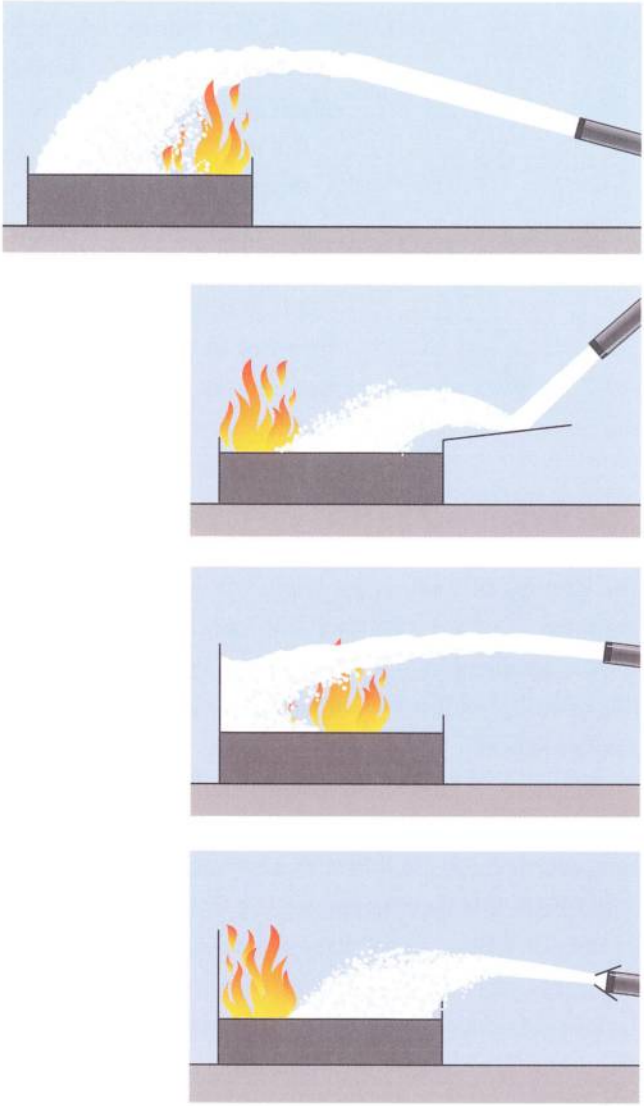
If a low-expansion foam nozzle is aimed directly down into a burning liquid surface the fuel will be stirred up, resulting in an increase in the fire's intensity. The impact energy must, instead, be reduced and the foam applied as gently as possible so as not to stir up the liquid surface.

With a long projection range, the low-expansion foam is split up by air resistance and falls gently down onto the surface, which in most cases, provides a good extinguishing result. When part of the fire has been extinguished the firefighter needs to move forward to reach the rest of the fire. In this case, another technique must be used to apply the foam gently.

The jet can, instead, be aimed down at the ground just in front of the pool of fuel so that the foam bounces off the ground. The expansion factor will increase slightly due to the extra action of being bounced off the ground. This is actually one of the most effective application methods.

If the firefighter has reached the edge of the fuel, it is appropriate to direct the jet against a tank surface or wall, for instance. The impact energy is absorbed when the jet hits the wall and the foam runs gently down along the wall and over the fuel surface. Directing the jet against a tank surface is often appropriate also at the start of an attack. Thereby, the surface is cooled down and the risk of any troublesome edge fires is reduced. The tank also needs to be protected against heat radiation. This is the reason why foam monitors are positioned lengthwise beside burning aircrafts or tanks. The foam lands on the body of the aircraft or tank and runs along its sides, keeping them cool. The foam reaches the fuel and starts to extinguish the fire directly under the body of the aircraft or tank, which is the most difficult place to access using portable nozzles.

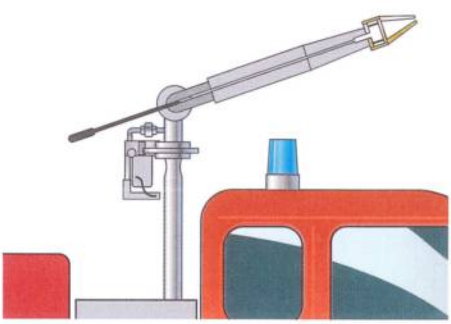
Foam monitors are sometimes fitted with flaps, two metal discs which squeeze together the jet of foam, absorbing some of its energy. The range of the jet is reduced, but it gets a wider and more gentle dispersion pattern and therefore, a better extinguishing effect. The projection range of the monitor can thereby be adjusted without needing to change the pump's rota-

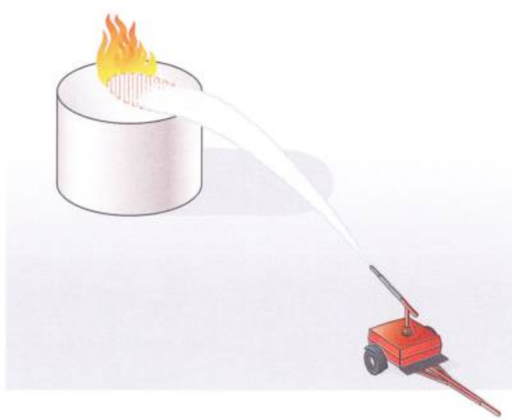


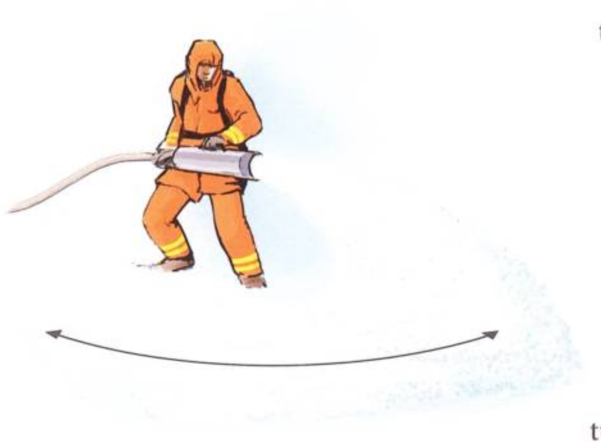
3.41 Different methods for gently applying low-expansion foam using a long projection range, bounce, wall bounce or flaps.

3.42 (bottom left) Foam monitor with flaps.

3.43 (bottom right) The dispersion pattern is roughly elliptical using a foam monitor.







tion speed. The rotation speed does not just control the nozzle pressure, but also the foam concentrate mixing. The rotation speed also controls the pressure in the other nozzles. Putting a hand in front of a portable low-expansion foam tube and letting the jet filter through between the fingers split the jet in a similar way. When a combination tube is used, low-expansion foam is applied initially. A switch to medium-expansion foam then takes place, which can be applied directly.

3.44 Medium-expansion foam is applied in a semi-circular sweeping motion.

Indirect application, whether by allowing it to bounce off the ground or wall, is probably the most common method actually used for applying low-expansion foam manually. Direct application normally produces the worst extinguishing result, but it is the only possible application method for really big fires.

Gentle application, a following wind and having the right resources produce the quickest and most effective extinguishing result using foam (Persson, 1987a).

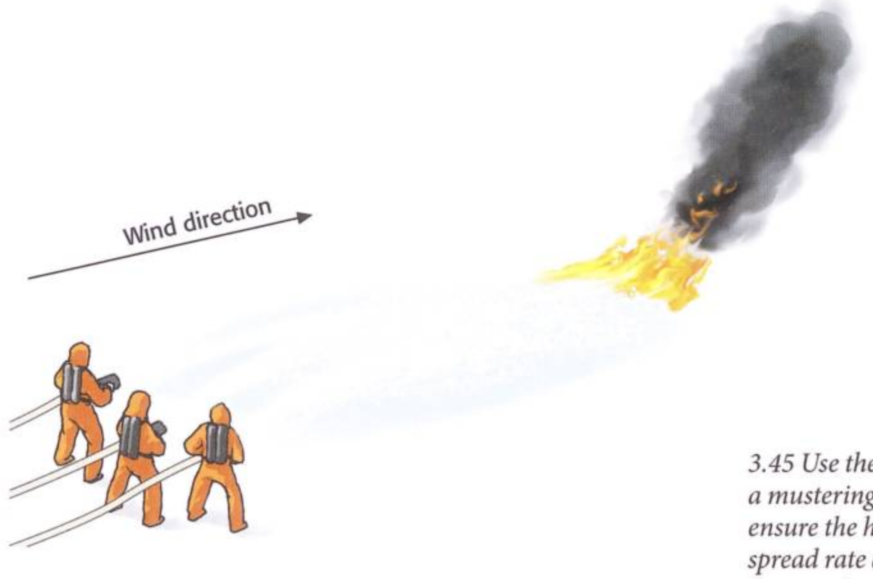
Medium-expansion foam can usually be applied directly, as the jet has a low impact force. Medium-expansion foam does not provide the firefighter with any protection. This means that sometimes it is appropriate for the firefighter to operate with protection from a water spray or a powder cloud.

At the start of an operation, the medium-expansion foam tube is aimed so that the jet hits the edge of the fire. When the foam blanket starts to increase the jet is aimed right behind the front edge of the blanket and is moved from side to side so that the blanket can spread out towards the front and sides.

If the foam tube is designed with a support device it can be placed on the ground. If not, a firefighter should move the foam tube about. Otherwise, the foam will build up round the tube and will get sucked in through the air inlet and short-circuit the foam generation. The air speed is also high, which means that a piece of dirt can get sucked in and block or damage the foam mesh.

Having sufficient resources on site before the attack starts, extinguishing is ensured and the fire will not reignite.

Firefighting using foam is most effective if the fire is knock-



3.45 Use the wind and a mustering of strength ensure the highest spread rate and best result.

ed down quickly. To achieve this, all the firefighters need to be ready to start the attack at the same time and it needs to be carried out well-coordinated. A concerted attack on the fire helps to quickly reduce the radiation heat. With concentrated application, i.e. a number of jets aimed on the same spot, an excess of foam can be applied locally, which can definitely knock down the fire. Once the suppression proves to be efficient, the jets can be separated. Heat radiation is one of the main reasons for the foam break down and for firefighters not being able to approach the fire. It is therefore worth considering to combining the application of foam with powder in with the aim of quickly reducing the radiation heat. Powder may not extinguish the fire but it reduces the radiation temporarily. The powder cloud is directed at the point where the fire is at its most intense.

A foam attack can be summarised in terms of having the right resources available, a concerted attack with the right application rate, protecting the foam blanket, complete extinction and tactical preparedness.

When the foam has expanded it may be affected by the wind. Consequently, expanded foam should, if possible, always be applied with a following wind.

The foam will spread more quickly with a following wind. The impact of the heat on the foam blanket is also less. One upshot with a following wind is that firefighters do not need to stand among smoke and flames, which means they have greater control and can work more safely. Another way of helping the foam to spread quickly is to attack long, narrow fires from the short side.

By gently applying low-expansion foam, this prevents the fuel from splashing up when the foam makes contact with the liquid surface. Medium-expansion foam, which is always applied gently, is then used as soon as the radiation heat allows it.

Being careful with the foam blanket also means avoiding stepping in the spillage and dragging the hose, so that the foam blanket is not damaged, as well as making sure that any cooling using water does not break down the foam blanket.

When the fire has been knocked down, the important task of extinguishing the last few flames remains. Large volumes of foam may be used to extinguish the last edge fires, but all these must be extinguished. Otherwise, the fire will reignite and the whole operation will have been in vain.

The task of extinguishing a fire is made difficult if there are objects protruding above the fuel surface. In this case, the appropriate solution may be a combination of using a medium-expansion foam tube to cover the fuel surface and a fog nozzle to cool down and extinguish other objects. Metal objects are heated up quickly by the fire and can even maintain a temperature above that at which the liquid ignites spontaneously. The foam is also broken down on the impact from the heat. In some cases, the firefighter needs to move about to reach the whole fire area, while also ensuring, in particular, that metal objects are cooled down as much as possible so that the foam blanket can be kept intact.

Similarly, there is a large risk of the fire reigniting when it seems to be extinguished. This means that the team have to be tactically prepared. This involves the firefighters keeping their positions, ensuring that the resources are restored and that the foam blanket is maintained. Medium-expansion foam is the first choice for maintaining an existing foam blanket.

In many cases it is not purely a pool fire that has to be tackled. When confronted with a burning vehicle in a pool of petrol, the operation must be focused both on the burning fuel and on extinguishing the fire inside the car, as well as on cooling down the metal to prevent reignition, not to mention ultimately tackling the fire involving the rubber and/or light metal in the wheels.

Filling a room with foam

High-expansion foam has partially different extinguishing properties and is best suited for filling enclosures. By introducing foam via the air inlet of the fire room, the oxygen concentration will drop. Air released due to the foam breakdown does not have any significant impact. However, the water contained in the foam that breaks down has a major impact. It vaporises and provides the flames with thermal ballast. The foam's water content is small, but as the breakdown process is at its peak when the foam is close to the flames, the water will drain close to the burning surfaces. This will cool the burning surfaces down, which will produce a good extinguishing effect, even against fires involving fibrous materials.

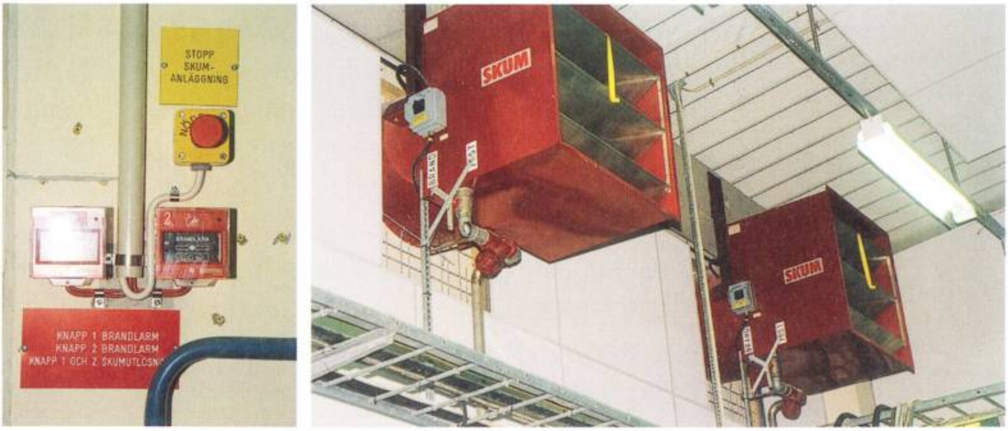
Foam may be the best extinguishing agent to use to fill an enclosure which cannot be reached any other way. By filling with foam, the drained out water can extinguish even smouldering fires. Depending on the size of the enclosure, foam is needed with different spread properties. The smaller the room and particularly, the lower the height of the ceiling, the more free-flowing the foam needs to be, and therefore, the lower the expansion factor. Consequently, medium-expansion foam may be the most suitable for tackling an attic fire in ceiling void just half a metre high, whereas high-expansion foam may be the most suitable for an attic where the ceiling is at full standing height. In some estates made up of old wooden houses, the distances are small between the buildings, sometimes just half a metre. To prevent fire from spreading between them, an alternative may be to fill the alley ways between them with high-expansion foam.

High-expansion foam can also be a useful alternative to interior firefighting in cases of high risks, lack of resources or any other reason. This can apply to cable channels, attics, storage areas, etc. There are a number of examples where high-expansion foam has been applied long after the fire has started and quickly suppressed the fire where other methods had failed. Even with fires in machine rooms, where the combination of flammable liquids and hot metal surfaces creates problems, high-expansion foam can be used effectively (Eriksson, 1965).

In 1990 a fire broke out in warehouse premises in Helsingborg, Sweden, automatically triggering the fire alarm at half past three in the morning. There were tonnes of material on fire, in tightly wrapped packaging made of cardboard and plastic. When the firefighters arrived on the scene the warehouse was full of smoke. After problems getting into the premises, a lengthy BA operation got under way, involving two BA teams. As the time went on, the team members were getting tired and there was a risk of the building collapsing. The tactics were then changed. The firefighters were withdrawn and four large doors were opened. Monitors were positioned in each opening, but there was no significant progress made, even though a lot of steam was generated. Eight hours after the alarm, the operation changed tack again and they started filling the premises with high-expansion foam. An hour later the premises was full of foam and there was no more smoke being produced. The foam blanket was maintained for a further four hours and by then, even most of the smouldering fires had been extinguished (Rosander, 1990).

High-expansion foam can be an effective extinguishing agent for tackling fires in old farm premises, where commonly not even half of the animals can be rescued. The area on fire, such as a loft, can be filled with high-expansion foam. The easiest operations are those where there are ready-made openings available. It is also possible to fill the actual animal enclosure if the animals cannot be evacuated. There are only a very limited number of other options available (Olsson, 1988).

High-expansion foam units are used in areas that are enclosed but with a pressure relief, and often in fixed installations. As high-expansion foam units have absolutely no projection range and are sensitive to the wind, they are rarely used outdoors. On the other hand, they produce a very large volume of foam in relation to the amount of water and foam concentrate used. This makes high-expansion foam an extinguishing agent that uses up few resources. Although the units are large, they require very little involvement from staff. This means that high-expansion foam is an extinguishing



3.46 A high-expansion foam unit for a hangar. Dual command is required to activate it.

agent even worth considering for fire services with small crews (Rosander, 1997).

High-expansion foam, often produced in fixed installations, is used to protect hazardous facilities and premises, such as aircraft hangars and certain types of industrial plants. The premises must have ventilators which open immediately when the foam unit starts up and are designed to cope with the excess air. If this is not the case, the counter-pressure across the unit will be too large and foam production will cease. There are also special foam concentrates available which produces a foam that is not broken down by smoke. This means that foam can be produced in a fixed installation using the air contaminated with smoke available in the fire room. With this type of unit smoke vents are not necessary.

DIMENSIONING OF ENCLOSURE FILLING USING HIGH-EXPANSION FOAM

When an enclosure is filled with high-expansion foam, a different method is used to dimensioning from the one for dimensioning class B fires. Where a premises is going to be protected using high-expansion foam, the relevant calculation for the operation's size is either based on the premises being filled completely or on the burning object being covered. It is often unknown where the fire will occur, which is why the whole room has to be filled with foam. A rate of rise of 1 metre per minute can be used for the foam blanket as a starting point (Wilder, 1969).

A more elaborated calculation is based on the time it takes to fill the whole room or cover the entire fire object with foam. Depending on the fire scenario, this time is taken to be around 2–6 minutes for fixed installations (NFPA 11, 2005). This will then give a typical vertical rate of rise of 0.5–2.0 m/min. If the expansion factor is 1000 this is equivalent to an application rate for the foam concentrate mixture of 0.5–2 l/m²min. Consequently, high-expansion foam requires a significantly lower application rate than medium and low-expansion foam.

The required flow of high-expansion foam can be determined using the following equation:

R [m³/min] Required foam flow rate
V [m³] Filling volume (room volume)
T [min] Filling time, usually 5 min.
C_N [–] Compensation factor for foam breakdown
C_L [–] Compensation factor for leakage

$$R = \frac{V}{T} \cdot C_N \cdot C_L$$

The breakdown rate for high-expansion foam is usually around 0.1 m/min, without any heat impact. With a radiation level of 10 kW/m² the breakdown rate increases to around 0.2 m/min. At 20 kW/m², it increases to 0.4 m/min, depending on the type of foam concentrate used, the size and position of the fire, as well as the expansion factor of the foam (Holmstedt & Persson, 1985).

The compensation factor for foam breakdown can be set to 1.1 for a room which is unaffected by fire. In the case of rooms filled with smoke, 1.2 can be used and in the event of a flashover, the factor will be 1.4. NFPA recommends a compensation factor of 1.15 (NFPA 11, 2005).

If the capacity is known you can estimate beforehand the size of area a high-expansion foam unit can fill.

The compensation factor for leakage will be 1.0 without any leakage.

In the case of fires in areas where there are large hot metal surfaces, etc., the calculation needs to be supplemented (Eriksson, 1965).

For fixed installations, a total quantity of foam is calculated as being larger than the filling volume. The US standard recommends four times the filling volume, but with a maximum operation of 25 minutes (NFPA 11, 2005).

Let us take an industrial premises measuring 20 x 20 m², with a ceiling 5 m high. This gives a volume of 2000 m³. If the premises are filled with smoke, the flow rate required will be

$R = 2000 \times 1.2 \times 1.0 / 5 = 480\ m^3/min.$ to fill the premises in five minutes without leakage. If one high-expansion foam unit produces 160 m^3/min three units are required. With an expansion factor of 800, the liquid flow rate required is 600 l/min. The foam concentrate flow rate for a 3% concentration will be 18 l/min. A total of 2900 litres of water and 90 litres of foam concentrate is required to actually fill the premises. If a safety margin of four times the room volume is required this gives a total of 11600 litres of water and 360 litres of foam concentrate.

TECHNIQUE FOR FILLING A ROOM WITH FOAM

Medium-expansion foam used to tackle a fire in an attic can be applied through most openings. Roof hatches, skylights, pierced holes or holes burnt through are all suitable. However, the opening must be too high for the foam to run out. If an opening is used through which smoke is escaping there is the risk that it will be sucked in through the foam tube and ruin the foam.

This method of applying foam should be especially practiced, as there can be quite a considerable difference in height between the pump and nozzle during attic fires. There is therefore a risk of the foam tube receiving the wrong nozzle pressure or of the wrong proportion of foam being administered.

High-expansion foam units only generate a slight amount of positive pressure. This means that openings need to be made in the room to be filled with foam. Just in the same way as the laws of hydraulics govern the flow in water hoses, they also govern the flow of high-expansion foam. If there is too much resistance, for instance, because there are no vents for outflowing air, the foam will not even flow through the hose. The nozzles in the unit will, however, continue to spray and this foam concentrate mixture will run out of the unit. This is a sign that the counter-pressure is too high.

High-expansion foam units are positioned so that the counter-pressure will be as low as possible, and the foam is applied where the fire, wind and other energy sources are generating negative pressure. The unit should not be operated against the wind or in openings with smoke flowing out.

It is always better to operate them with the wind following and to position the unit so that the foam can flow through the vents providing the fire's incoming air supply. Even though there is a negative pressure at the opening where the unit is placed, a positive pressure will be generated once the unit has fully started up. This means that smoke will start escaping out through openings, which were under the neutral plane from the start.

During the 1970s, the Stockholm fire service carried out tests using high-expansion foam to tackle basement fires. The high-expansion foam unit proved not to withstand the pressure generated by the fire. As a result, the foam ended up in the wrong places and the foam hoses sustained fire damage (Rosander, 1997).

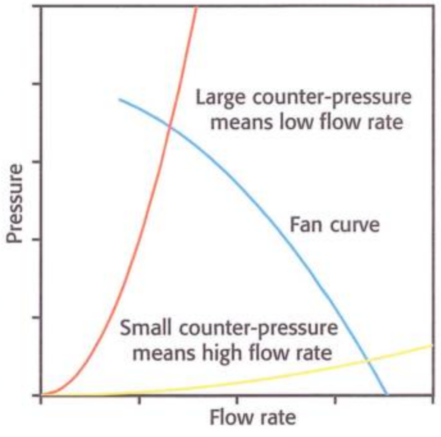
One sunny summer's day, the cutting of a steel tube resulted in an attic igniting. By the time the firefighters had arrived, the attic was full of thick brown, fairly hot smoke. This meant that there was a risk of a flashover. A high-expansion foam unit was requested and hoisted up to the roof. The attic was then filled with foam via a hatch in the attic. It was ventilated by opening up other hatches, one at the time. After waiting for 15 minutes, a large amount of the foam was blown away and the remainder was soaked up by the timber in the attic.

An 80 m hose from a fire engine was used to extinguish the fire, along with a high-expansion foam unit and an appliance with a hydraulic platform to lift the unit up.

The whole operation was over in just about one and a half hours. (Arredal et al., 1977).

Another reason for operating a high-expansion foam unit with the wind following is to prevent smoke from being sucked in. Both the foreign substances in the smoke and the increased temperature greatly contribute to the breakdown of most types of foam (Alvares & Lipska, 1972).

Vents for outflowing air are required as the high-expansion foam unit blows air bubbles into the room. The size of these vents is similar to the size used for fire vents in general. A comparison with a positive pressure ventilation fan indicates that an air vent of around 1 m² is required per high-expansion foam unit. The greater the flow resistance in the building, the larger the openings need to be.



3.47 A high-expansion foam unit's capacity varies with the counter-pressure in the same way as a pump curve for a fire pump.

Some buildings, such as certain types of industrial plants, are so draughty that no additional vents for outflowing air are required, which is evident from a large quantity of smoke escaping from the building. If foam is used to fill attics, sometimes it is simply enough to create an opening for supplying the foam. The outflowing air finds its way out through the normal air vents at the base of the roof. If the medium-expansion foam has too low expansion factor, foam may also run out at the base of the roof. Other types of buildings, such as basements and shelters may be so seal tight that the foam filling operation is totally ruined unless air vents are created. Vents for outflowing air must be created if smoke is not escaping from the building in places other than those required for the foam application.

The impact of the foam is usually noticeable quickly. If the high-expansion foam hose gets wet right next to the unit the counter-pressure is too high, which means that more or larger vents for outflowing air are required. These vents are positioned at the opposite end of the enclosure and as high up as possible. Fire ventilators are suitable.

Vents often need to be opened and closed again in the course of the operation.

If the ventilation surface available is too small the flow rate may be increased by using a smoke fan in a vent to extract air.

During the operation, vents may need to be sealed up if foam is starting to pour out and they may need to be opened up to fill the room completely. You should therefore remember that vents that are opened may need to be closed again. For instance, an open window can be closed, whereas a broken pane of glass needs to be replaced. A roll of plastic and a staple gun may be used if vents need to be blocked up. Where the height of the room to be filled is high, the pressure is so great that a sheet of plywood or similar holds better.

When filling an enclosure with foam, which has not been ignited by the fire, for instance, to prevent the fire from spreading or spilled flammable liquids or gases from igniting, this operation should be carried out as quickly as possible. This means that the vents for outflowing air should be big to reduce the counter-pressure, provided that the wind creates a negative pressure. As the enclosure is being filled and the foam starts to pour out, the vents are closed.

When using high-expansion foam, the foam blanket is retained and reinforced until the fire has been completely extinguished. This may take an hour after the room has been filled, depending on what is burning and the depth of the smouldering.

When the fire has been extinguished the high-expansion foam should be broken down to allow a suitable salvage operation to be carried out. This may be done using a smoke fan, carried through the foam. The fan breaks up the air bubbles, which then collapse. A water spray can also be used, but it takes longer and you have to make sure that the water does not cause any further damage. As high-expansion foam is not usually alcohol-resistant, it can be broken down by adding alcohol to the water.

During winter the foam may freeze. This is especially true of foams with a high expansion factor. In this instance, it takes longer to break down and it cannot be blown away.

Other application areas for foam

When extinguishing class A fires, unaspirated foam more or less acts like pure water. The difference is that the surface tension has been lowered, which means that the surfaces are soaked more effectively and the water is absorbed more quickly. This is a case of making water, which is already effective, even more effective.

Water is used as normal with the foam concentrate mixture, but provides a better surface impact.

When rubber tyres are on fire, extinguishing them with foam or with water combined with an agent designed to reduce the surface tension provides a quicker result than with using pure water. Even with fires involving fibrous materials, water combined with a foam concentrate mixture is more effective than pure water. This means that the final extinguishing is faster if an agent for reducing the surface tension is used in the water to suppress an attic fire or extinguish a container fire.

As regards conventional firefighting against normal enclosure fires, there are studies which maintain that adding an agent to reduce the surface tension will be more effective than just using ordinary water to extinguish the fire (Gravestock, 1998; de Vries, 2000). There are other studies on enclosure fires involving wood as fuel, which have not been able to demonstrate any significantly better extinguishing effect from using a foam additive in the water (Bosley, 1998; Madrzykowski & Stroup, 1998). It is likely that the difference between pure water and water containing additives is smaller, the faster the suppression is. If the extinguishing agent is applied at a sufficiently high rate the suppression time is governed not so much by the flow of extinguishing agent, but rather by the time it takes to cover all the fuel surfaces. There have not been established any guides on how to dimension the attack. The variations between the different operations and the choice of attack method seem to have more of an impact rather than whether the water contains a foam additive or not. This is why it is reasonable to scope the size of operations for tackling class A fires with water and a foam additive in the same way as the equivalent operation which does not involve the use of any foam additive.

How the foam concentrate affects the water droplets' size is uncharted territory. It is well-known that small water droplets vaporise more quickly than large ones. At the same time, the surface tension keeps the droplets together and if it decreases, it is reasonable to assume that the droplet size distribution will be changed and with it, the extinguishing capability of the water spray.

A fire in a small wooden garage was quickly knocked down using water and four nozzles. Due to the risk of collapse, the decision was taken to use medium-expansion foam for the final extinguishing, providing an excellent opportunity for an ad hoc practice session in the use of foam.

3.48 Pool fires often generate powerful radiation heat.

FOAM SHEET

In some areas, there are elderly wooden houses with an old fire safety standard. Usually fires are extinguished very quickly, but every now and then, the fires spread in these areas and are comparable, in extreme cases, to a town fire. Burning wooden buildings produce a high radiation intensity and the distance between elderly houses is often small. Consequently, in the case of major fires affecting buildings standing close together and the level of heat radiated by the fire is intense, a foam sheet may be used. A foam sheet is much more effective than spraying pure water on buildings to protect them from igniting. This is mainly due to the foam's ability to create a continuous foam blanket over a whole area, which pure water cannot do. It also uses up fewer resources. The same argument applies in the case of tank farms and other similar facilities. The radiation heat is intense and there are lines and other objects nearby which need to be protected.

In this case, a type of foam is required which has a good adhesive capacity and is stable enough to be used to form a foam sheet. A layer of low-expansion foam is sprayed on the walls, roof and other parts of the building to be protected. The foam is always applied from bottom to top on a wall. The surface should be dry and should have not been hotter than 80–100°C. If the surface is too hot, the foam will run off.

Limitations of foam

The main limitations in terms of using foam to extinguish fires are primarily related to the objects which are burning and their geometric configuration.

Substances which cannot be extinguished using any water-based foam type include metals and chemicals which react with water. Even very hot substances, such as liquids with a boiling point above 100°C, are very difficult to extinguish using foam.

PHYSICAL HARM CAUSED BY FOAM

Most foam concentrates are not classed as being harmful to health. However, certain care should be taken with prolonged handling as, when they come into contact with the skin, foam concentrates dissolv skin oils which can cause infection and allergic reactions. This is why it is not suitable to let children play in foam at displays.

Foam also conducts electricity and therefore, the same precautions must be taken, as with using water to extinguish a fire, when working close to live installations. The lower the expansion factor, the better the foam's ability to conduct electricity.

In the case of very large pool fires, especially involving polar liquids, which do not produce enough soot to block the radiation, the heat radiated by the fire presents a problem. It is difficult to recreate this intense radiation in practice scenarios. Due to the radiation, proper protective equipment is required and with some types of fire, the firefighting operation needs to start from a distance. As an alternative to wearing extra protective clothing, firefighters can work in pairs, with one using a low or medium-expansion foam nozzle to fight the fire and the other a fog nozzle for protection. A jet of water should not be used, as it will break up the foam blanket. Otherwise, distance is the easiest way to reduce the radiation heat, which decreases in intensity by the square of the distance. This means that with fires where the radiation is intense, a good projection range is vital at the initial stage.

3.49 Is this a way to improve the protective clothing's ability to withstand radiation or did the foam monitor operator aim wrongly? Breathing protection or at least a visor is required during firefighting using foam.

If the surface of a spill of flammable liquid is covered with foam, this does not mean that the location is safe. Even while the operation is being carried out, it is necessary to be alert, should ignition occur. A backup plan should be available, especially if some work is to be carried out inside the area of the spill. There are also other aspects to be taken into consideration, such as whether the substance is toxic, which means that a full suit needs to be worn during the operation, or whether there is an increased risk of accidents caused by falling or slipping.

When fighting fires involving flammable liquids, the risk of explosions in tanks and pressure containers must be taken into account.

Once ignition has occurred, the fuel surface will heat up to the fuel's boiling point. The heat spreads downwards in the fuel, creating a hot zone, covering the part of the fuel with a temperature above 100°C. This may typically occur in the case of fires in tanks with heavy oil, where the boiling point of the fuel is higher than the boiling point of water. If an extinguishing agent is applied from below without a hose the water in the foam will start to boil when it reaches the hot zone. It vaporises and takes some of the fuel with it as it rises into the air. This is known as slop over and the burning fuel is splashing around the tank. There is often some water at the bottom of the tank and more water is added through firefighting operations. As the wave of heat approaches the bottom of the tank, the water at the bottom will gradually start to boil. The vaporised water bubbles up, taking with it the burning fuel when it leaves the tank. This is known as boil over and means that large quantities of fuel are being dispersed around the tank, presenting an obvious risk to fire crews.

3.50 Firefighter after an operation in high-expansion foam.

Filling an area with high-expansion foam before evacuation is complete will hinder the evacuation operation and make it difficult to breathe. It is especially vital to think about this if high-expansion foam is being used in fixed extinguishing systems. Anyone who has been hemmed in by high-expansion foam and lost their sense of direction will find it difficult to get out. Strategically placed handrails can be of some help in this instance.

The risk of harm from inhaling high-expansion foam has not been fully investigated. Tests have been carried out using detergent foam with an expansion factor of higher than about 600–700, involving prolonged periods of exposure. This foam had been created using air. It is easier to breathe if you move your hand back and forward in front of your face to break up the foam. It is totally unsuitable to remain without any breathing protection in foam which has been produced using smoke.

Breathing apparatus is obviously worn during firefighting operations carried out in premises filled with foam. Visibility will be non-existent and the foam will block out most sounds. Those involved in the operation must be aware of this and equip themselves accordingly. As you have a poor sense of direction in foam, a rope should be used if an operation has to be carried out at all in foam. If possible, the premises should only be entered once the foam blanket has broken down.

High-expansion foam does not conduct electricity very well and possibly, the biggest risk is of directly touching live components due to the poor visibility. Consequently, it is a good idea to turn off the power before firefighters enter a room containing electrical equipment filled with high-expansion foam.

ENVIRONMENTAL DAMAGE CAUSED BY FOAM

Even though there is only a small concentration of foam concentrate mixed in, just 3% for instance, it still has an impact, especially if discharged into water. Even as small a concentration as 0.1% can result in a sharp drop in water's surface tension. This concentration requires just as many cubic metres of water as litres of foam concentrate. This means that huge quantities of water will be used to dilute it. But it is worth pointing out that the total quantity of a substance will be just as big, regardless of how much it is diluted.

When ordering foam concentrate, its environmental impact should be included as part of the decision-making process. One of the problems with foam concentrates is that they do not comprise a single substance. They contain a mixture of substances, and the manufacturer is the only one aware of their content. Consequently, the manufacturer has a great deal of responsibility in terms of stating the product's impact on the environment.

The main aspects of interest are the foam concentrate's toxicity, decomposition rate and bioaccumulation. The toxicity level is indicated by the liquid's LC50 value, for instance, which specifies at which concentration half of the laboratory animals die. The higher this value, the lower the toxicity level.

The main constituents in both protein and synthetic based foam concentrates are usually biodegradable. It takes around a month, and even shorter if the water is aerated. Surfactants are used in large quantities in every day life, for instance in washing powders and washing-up liquids, and treatment plants are designed to handle these. However, major firefighting operations may end up exceeding the treatment plant's capacity, in which case some type of reservoir is required as a buffer. Foam concentrates also contain a large quantity of additives, such as different salts, which have a variety of impacts on the environment.

Most foam concentrates break down fairly quickly, at least at 20–25°C, the temperature at which most breakdown tests are carried out (Holm & Solyom, 1995). This breakdown is a natural process involving microorganisms which feed off different impurities. For example, large quantities of oxygen are used to break down glycols and glycol ethers. Oxygen consumption can be measured and this can be used to gauge how difficult it is for the substance to break down. COD, Chemical Oxygen Demand and BOD, Biochemical Oxygen Demand, are the measurements used. COD indicates the total oxygen consumption and should be as low as possible. BOD can be expressed as the oxygen consumption per unit of time and will therefore be less than COD.

Bioaccumulation may occur with substances which do not break down. They simply remain there and are deposited in the environment. Even though the concentrations of this type of substance may be low, they can still pose a real problem as they remain in the ecological system for a long period of time.

Fluorinated surfactants which make foam concentrates form a film and other complex hydrocarbons containing heteroatoms are often both difficult to break down and toxic in fairly low concentrations. The combination of these two properties can cause environmental problems resulting from firefighting operations (Holm & Solyom, 1995), which has led to foam concentrates being removed from the market (Rochna, 2000).

Another property of foam concentrates is that they in many cases can affect other substances. For example, synthetic-based foam concentrates can dissolve oil to form an emulsion, which cannot be separated by an oil separator. The emulsion is also more toxic to aquatic organisms than the oil products and foam concentrate on their own (Holm et al., 1996). Some protein-based foam concentrates and specific use foam concentrates, however, can dissolve oils to a lesser extent (Holm & Solyom, 1995). The manufacturer should be able to supply information about the impact on oil separators.

At training fields, the foam should always be collected and disposed of. Also at real fire situations, the possibility of collecting the foam should be considered. This is obvious in cases where an operation has been carried out to tackle a fire involving a flammable liquid, for instance, where the fuel itself poses an environmental problem or where the foam has been used to cover a chemical spill.

It can also be pointed out that there are good opportunities for minimising the environmental impact of operations involving the use of foam. The most effective way is probably to ensure that the size of the operation is scoped properly and it is carried out correctly. If this happens, the amount of foam concentrate used may well be half the amount which would be required in an operation carried out badly. It also takes time to build up extinguishing resources in fires. In some cases, the total harm caused to people, property and the environment may be less if, for instance, a burning tanker is not extinguished. In other cases, the overall harm will be least as a result of an operation involving the use of foam to prevent a major discharge of combustion products or of hydrocarbons from fuel which is not ignited.

DAMAGE TO PROPERTY CAUSED BY FOAM

Foam contains water and air. The damage caused by foam to material items is therefore partly water damage. The damage increases, the longer the exposure time and the lower the expansion factor.

High-expansion foam usually causes limited damage to property. Foam has a poor penetration capability, which means that a crack just a few centimetres wide is enough to prevent the foam from spreading, if it has a high expansion factor and the filling height is low. This also means that high-expansion foam will not penetrate electronic units, packaging etc. Tidemarks appear, however, on fabrics, for instance, and corrosion attacks unprotected iron components. There are no major obstacles to cleaning up unprotected equipment. It is also worth noting that using high-expansion foam can reduce the level of smoke damage.

Foam concentrate may also cause damage to the equipment used to create the foam. Any foam concentrate residue dries out and creates soap deposits in the hose, proportioner and nozzle. It also causes metal components to corrode. Consequently, all equipment must be properly cleaned after being used in an operation involving foam, especially the proportioner and foam tube/nozzle.

During a house fire in Burseryd, Sweden, the first fire crew to arrive on the scene noticed that the fire had already spread to the joists and partition walls. The house was filled with high-expansion foam and the foam level was maintained up to the ridge of the roof for half a day. The house was totally gutted due to the fire affecting the structure. On the other hand, almost everything with sentimental value, such as jewellery, art objects and even photo albums were, on the whole, unscathed (Karlsson, 2001).

When installing a fixed extinguishing system, the risk of accidentally setting it off must be taken into consideration. A detector-controlled foam system with deluge spriklers in a helicopter hangar happened to be triggered when struck by lightning. The staff on site did not have any clear instructions available and did not know what to do when the system was triggered. As a result, the system ran for 20 minutes, during which time 10 m^3 of foam concentrate flooded out. The clean-up costs were considerable due to the helicopter doors being opened. After the incident, the system was provided with a trigger mechanism based on two detectors.

Powder

Powder is the extinguishing agent primarily recommended for portable fire extinguishers. This is mainly due to a high extinguishing capacity in relation to weight and price.

Physical properties

There are a number of different types of powder on the market. The term "powder" is used specifically to mean all extinguishing agents in solid form. Most often powders used for extinguishing fires comprise mixtures of different salts. Most of these are well-known chemicals which occur in large

4.1 Some properties of the most common powder types. The powders are roughly arranged in order with the most effective against class B fires first (Brandsläckningspulver, 1998; CRC, page B-68-, 1986; Holmstedt et al. 1984).

Name	Chemical formula	Powder type	Melting point [°C]	Boiling point [°C]
Potassium chloride	KCl	BC	770	1500 (sublimates)
Potassium bicarbonate	$KHCO_3$	BC	100–200 (disintegrates)	
Mono ammonium phosphate	$NH_4H_2PO_4$	ABC	190	
Potassium carbonate	K_2CO_3	BC	891	(disintegrates)
Sodium chloride	NaCl	BC	801	1413
Potassium sulphate	K_2SO_4	BC	1069	1689
Sodium bicarbonate	$NaHCO_3$	BC	270 (disintegrates)	
Ammonium sulphate	$(NH_4)_2 SO_4$	ABC	235 (disintegrates)	
Calcium carbonate	$CaCO_3$	BC	900 (disintegrates)	

One type of powder, sodium bicarbonate, is the main constituent in baking powder. Another type, sodium chloride, is also known as table salt.

quantities in industry. The salts are usually made up of a positive sodium, potassium or ammonium ion in combination with a negative chloride, sulphate, bicarbonate or dihydrogen phosphate ion. This means that there are a large number of possible salts, but their effect on fires is rarely described in any particular detail. The most common type of powder is mono ammonium phosphate.

There is quite a variation in density among the various types of powder, but it is usually around 1000 kg/m^3 (Släckmedel pulver, 1999). The compact density extends as far as 1900 kg/m^3 (Holmstedt et al. 1984).

Most types of powder are sensitive to moisture. A moisture-proof agent is therefore often added, such as silicone or magnesium stearate. Other additives include, for instance, silicon dioxide, talc, mica and barium sulphate, even though the active constituent in ABC powders usually amounts to more than 85% (Holmstedt et al. 1984).

Storage and transport

Some types of powder are sensitive to temperature, especially ammonium-based powders, which start to disintegrate at temperatures above about 60°C. This is why it is important to store the powder so that it is protected against moisture and variations in temperature. On the other hand, powder is the extinguishing agent least sensitive to frost, which means it can be used outside, even in winter. Powder units can be used at any temperature the operator can cope with.

The types of powder used as extinguishing agents are fine-grained so that they can flow freely. They are also surface treated with a water-repellent agent, which means that they can flow through hoses and pipes without any trouble.

Powder is usually used in two forms: in portable fire extinguishers, containing a couple of kilograms of powder and in powder units, containing up to a couple of hundred kilograms of powder. Depending on their size, powder units are equipped with one or two nozzles. Smaller trailer mounted units can easily be handled by one person. The largest units contain 600–700 kg of powder and are mounted on a trailer or

4.2 Powder units are probably the most powerful extinguishing resource the fire service has available.

vehicle. They may also be equipped with a powder monitor.

The operating principle is the same, regardless of system type. The container is either already pressurised or becomes pressurised when used. The powder is expelled using air, nitrogen or carbon dioxide. In the case of larger units, a pressure regulator is often used in order to provide an even flow while emptying.

As with other powder extinguishers, powder units also need to be continually monitored, have an annual overhaul and inspection, in accordance with the manufacturer's inspection programme and guidelines for pressure vessels.

Vibration can result in the powder being packed together during transport. This can be avoided by pressurising the unit through supplying gas from the bottom. Otherwise, the powder will need to be broken up by shaking the container.

There is a particular art required to fill powder units, which means that the manufacturer's recommendation must be followed. Only a vacuum suction filling machine should be used to fill extinguishers. If the powder is poured there is a risk that the powder grains' size distribution will change.

Different types of powder should not be mixed together. For example, mixing sodium bicarbonate and mono ammonium phosphate produces a chemical reaction, leading to the formation of monosodium phosphate, plus water, ammonia and carbon dioxide. The water causes the powder to harden like cement and the gases increase the pressure in the container.

4.3 When using a powder extinguisher to tackle a major fire, more than one extinguisher can be used at the same time to achieve a greater impact.

Technique for applying powder

When using a powder extinguisher outside, it is important to remember that powder is sensitive to the wind. A quick way of finding out which direction the wind is blowing in is to release a puff of powder from a powder extinguisher straight up. The powder is so fine that it is immediately caught by the wind.

The time it takes for a powder unit to empty is fairly short, between a half and one minute with a continuous flow. This means that an attack using powder to tackle a major fire requires good planning. Any follow-up measures using water or foam must be prepared and launched simultaneously. The fire is attacked with a following wind, and a powder cloud in front of the firefighter decreases the radiation heat. The powder jet is aimed at the base of the flames and is moved with a slow sweeping action across the fire area.

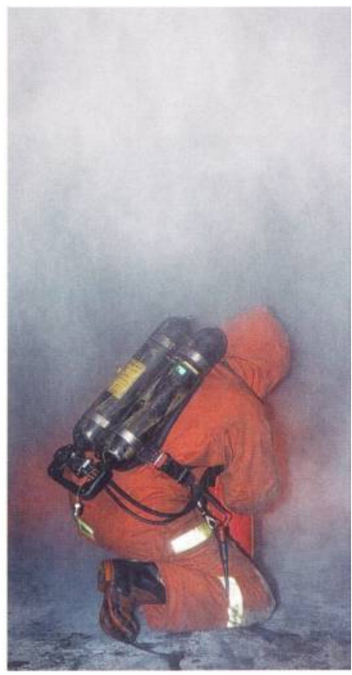
The design of the equipment is governed by two parameters, which are partly contradictory. They are the jet's projection range and impact force, as well as the jet's distribution across the fire area. A jet with a good projection range and penetration can, if aimed down at a burning liquid, cause the liquid to splash about and thereby aggravating the fire. On the other hand, if the jet is too wide, the extinguishing media may not reach the seat of the fire. This means that the shape of the nozzle can vary. But usually the projection range is limited.

After use, it is important to blow the system clean. This is done by turning the container upside down so that the powder delivery pipe comes above the powder. The nozzle is then opened and kept open until no more powder comes out. In the case of powder units, they must be reloaded, even if only part of the powder has been used. This is done in accordance with the manufacturer's instructions. This involves, for instance, fitting a moisture barrier and replenishing the unit with powder using a strainer to prevent any foreign particles from getting in.

Application areas for powder extinguishers

Powder is the extinguishing agent with the largest extinguishing capacity per unit weight. It is worth emphasising that powder units are, in most cases, the most powerful extinguishing resources the fire services have at their disposal. If the right sort of powder is chosen they can also be used to tackle most types of fires. However, the systems do have a limited time of operation and cannot be used continuously for prolonged periods. As a result, powder is best used at the start of operations to knock down a fire, to be followed up by the use of water or foam, for instance.

Powder helps to achieve results quicker than many other systems. There may be an opportunity to attack the fire using a powder fire extinguisher before the density of the smoke requires a conventional firefighting attack to be carried out. This makes it worthwhile considering the use of powder in the initial phase of apartment fires, for instance (Johansson & Mårtensson, 1986; AFS 1995:1).



4.4 A powder extinguisher has a good extinguishing effect, but visibility is poor.

Even if the operation is followed by the use of other extinguishing agents, an ABC powder provides better protection against reignition than a BC powder in fires involving fibrous materials, and should be the number one choice. BC powders are not suitable for tackling fires involving fibrous materials, as they do not provide any protection against reignition. They only operate in the gas phase and do not directly interfere with the pyrolysis process at the fuel surface.

Powder does not conduct electricity, which makes it ideal at fires involving electrical installations. The possible risk of getting an electrical shock is a determining factor. But the clean-up aspects involved with powder may prompt a different recommendation. Consequently, it is advisable to avoid using powder in relay installations inside or in other installations sensitive to dirt (Brandförsvar vid elanläggningar, 1987).

In traffic accidents, a powder extinguisher is often suitable for providing rapid, initial protection at a minor accident scene against fire. This is, however, not the case if a fuel spillage or other flammable liquids are involved. In fact, a powder extinguisher cannot prevent ignition, but can only be used after ignition. On the other hand, rinsing or covering with foam will prevent the fire from breaking out. This is especially valid if there is a high oxygen content at the incident site due to oxygen treatment of any injured.

Powder can also be used in fixed suppression systems, for instance, in heavy machines. The powder's combined good extinguishing effect and frost resistance provide extremely important benefits.

4.5 Simple fire extinguishing equipment comprising sand and a shovel, used during the Second World War.

METAL FIRE POWDER

Extinguishing agents used to tackle fires involving metals are most often in powder form. Substances with a high melting point and which do not disintegrate or react chemically, such as dry sand and cement powder, can be used for this purpose. Even sodium chloride, ordinary table salt, can be used. Specific metal-fire powders cover the seat of the fire, thereby extinguishing the fire and preventing reignition. Only powder designed for class D fires can be used for metal fires. Otherwise, there is the risk of a chemical reaction between the powder and metal. In many cases, dry sand is the easiest extinguishing agent to quickly get hold of in sufficient quantities.

The agent must be applied carefully when extinguishing metal fires. A shovel may be a useful tool if there are no dedicated units for this purpose. Fire extinguishers to be used on metal fires have a specific design so that the extinguishing agent is released with a low velocity.

Large quantities of extinguishing agent are required for metal fires, roughly equivalent to the amount of burning metal. On the other hand, there is generally no other alternative other than to let the metal burn itself out (Handbrandsläckare, 1998).

AEROSOLS

Aerosols can be used to extinguish fires as well. An aerosol is a combination of gas and particles. The particles can be in the form of a liquid or solid. The chemical composition of the particles can be the same as for ordinary powder extinguishing agents. The difference is that the grain size is 10–100 times smaller. The particles must be small enough to be suspended in air. The problem with aerosols is how to produce the extremely small powder grains and get them on site.

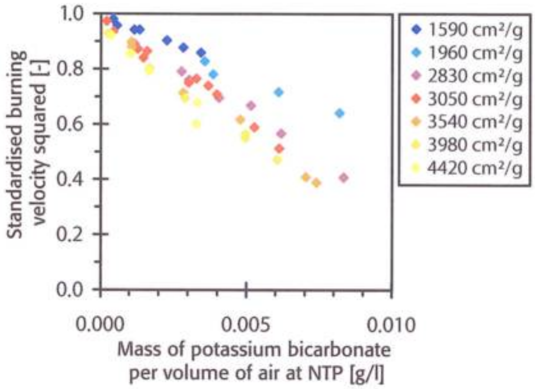
There are examples of smaller fixed extinguishing systems where pyrotechnically generated aerosols are used. The fact that the particles are suspended in air may, depending on the substance's composition, pose a risk to anyone still in the room without breathing protection. The particles are small enough to flow with the current of air into the lungs (Kangedal et al., 2001).

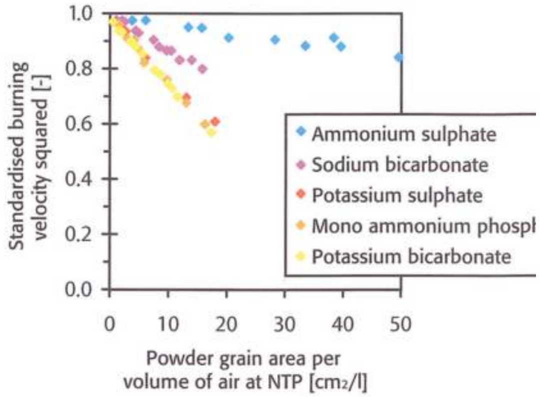
Extinguishing effect

Powder is always extremely fine-grained. Some powders, for instance, can have 0.35 mm as the largest grain size, with the powder grain's area usually around 0.3 m^2 per gram.

The finer the powder's grain size is, the larger the area the powder grain has in relation to its mass. As a result, they will be exposed better to the flames and more heat can be transferred to the powder grain before it has passed through the flames. The extinguishing effect in gaseous form will then be better. If the grain's diameter is halved the same mass of powder will have double the size of grain area. This means, basically, that powder consumption increases linearly with the diameter. The extinguishing effect increases significantly when the powder's grain size falls below 0.03 mm.

When the powder grains are heated, energy from the flames is absorbed. Some types of powder decompose chemically due to the heat impact, releasing carbon dioxide, for example. However, the quantity of carbon dioxide is not sufficient to explain the extinguishing effect. Other substances after decomposition, like sodium hydroxide, melt and vaporise, with more energy being used up for this. The main extinguishing effect is thereby thermal, with thermal ballast being added to the





4.6 Potassium bicarbonate's extinguishing effect (ratio between the burning velocity squared with powder divided by the rate without powder squared) for the stoichiometric mixture of methane and air (according to Hoffman).

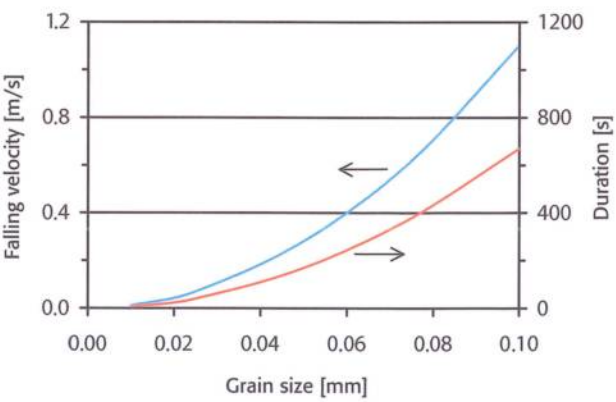
4.7 Different powders' effect on burning velocity for a stoichiometric mixture of methane and air (according to Hoffman). NTP stands for normal temperature and pressure.

flames, which means that the fire cannot sustain a sufficiently high temperature. Some powders also have a small chemical inhibiting effect.

The extinguishing effect of BC powders is most like the effect of gaseous agents, the only difference being that the powder grains falls to the ground.

Extinguishing enclosure fires using an ABC powder achieves a similar effect to using water to extinguish the fire. In this case, the powder interacts with both the flames and fuel surface. When an ABC powder reaches the fuels surface, the powder grains fuse together to form a continuous layer, which physically prevents any exchange of heat and the transfer of pyrolysis gases. It is the phosphate which converts to phosphoric acid.

The laminar burning velocity decreases as the powder particles become smaller and the area per unit weight increases. The heat transfer via convection to the powder grains and therefore, the vaporisation of the powder to form a gas increases as the powder grain diameter decreases.



4.8 Calculation of the falling velocity and duration in a flame for a grain of NaCl. The calculations follow the same patterns as for heating up and vaporising water droplets (Holmstedt et al., 1984).

The particle size is not homogeneous, varying between around 0.005 and 0.080 mm. If the powder grains are too fine, the same thing happens as with water when the spray is too fine. The powder grains will have too little momentum to allow the powder jet to reach the desired projection range. In this case, the larger grains bring the smaller ones with them.

Adding urea to potassium carbonate makes the powder grains burst when they are heated up. The exposed powder surface increases, as a result, along with the powder's extinguishing capacity.

Comparing powders with a similar specific area shows that the chemical content of the powders have a great influence in terms of reducing burning velocity. Different powder mixtures have various efficiency too. This is why the mono ammonium phosphate content is usually specified, in the case of ABC powders. This is the most effective constituent, as well as being the most expensive.

REQUIRED AMOUNT OF POWDER

The amount of powder required is mainly determined by the powder's composition and grain size. Urea-base potassium bicarbonate powder is more effective than sodium powder, which means that a considerably smaller amount of extinguishing agent is required to tackle the same fire.

To extinguish a fire involving a 4 m^2 pool of petrol, about 8–10 kg of sodium bicarbonate, potassium chloride or potassium sulphate is needed, 5–6 kg of potassium bicarbonate or mono ammonium phosphate or 4–5 kg of urea-base potassium bicarbonate.

	Heptane	Xylene	MTBE.*
Urea-K	0.47	<0.57	<0.48
K	0.56	<0.61	<0.51
AB	0.66	0.56	0.42
Na	<1.42	0.61	0.38
CO_2	3.5	3.8	2.9

* methyl tertiary butyl ethers

4.9. Measurements obtained experimentally for the mass of extinguishing agent needed per mass of fuel [g/g] (REMP value) for different combinations of powders and fuels. Carbon dioxide is included for comparison.

Limitations of powder

The fine-grained powder is effective in extinguishing fires, but it also produces a fine dust, which limits the suitability for using powder extinguishers.

4.10 Contamination is the biggest problem with using powder as an extinguishing agent. In this case, powder was used to extinguish a plastic recycling bin.

PHYSICAL HARM

Using powder to extinguish a fire stirs up the smoke, which, combined with the powder cloud, means that visibility will be significantly impaired.

The substances used in fire extinguishing powders are, otherwise, not usually harmful to health. It is mainly the dust which can cause irritation in the airways when handling this type of extinguishing agent. Using powder to extinguish a fire can temporarily cause breathing difficulties if too much powder is inhaled. Breathing protection should be worn when using larger powder units, especially as this is also necessary due to the scale of the fire and the production of smoke.

In areas where powder has been used, a problem with dry air may arise, either in connection with extinguishing a fire or at accidental releases. This means that an extensive clean-up operation is required.

ENVIRONMENTAL IMPACT OF POWDER

As powder is in solid form, this type of extinguishing agent is not particularly active in the environment. As a result, using powder helps prevent the contamination of water and air with impurities. This differentiates it from the liquid-based extinguishing agents, such as water and foam.

Powders comprise mixtures of different rather commonly occurring salts. Some types of powder are related to fertilisers. Consequently, most types of powder have only a limited negative impact on the environment, particularly in view of the small quantities they are usually used in.

DAMAGE TO PROPERTY CAUSED BY POWDER

Contamination of sensitive environments is perhaps the most common objection to using powder to extinguish a fire. These types of environment include manufacturing and processing plants, computer rooms, areas of cultural, artistic or historical value. Powder is fine grained and creates a fine dust which spreads throughout the whole enclosure and generally penetrates everywhere. The damage powder can cause in the event of a fire is often acceptable as, after all, smoke would have caused damage requiring a clean-up operation afterwards. However, if the same damage is caused as a result of a powder extinguisher or unit being accidentally let off it is more difficult to justify the damage caused.

Any clean-up operation after powder has been used inside must get under way as quickly as possible. The salts contained in the powder, along with the moisture from the fire and the firefighting operation, not to mention the moisture which is normally present in the air, can cause corrosion in machinery, for instance. The clean up should begin by sweeping up as much powder as possible. The area should then be vacuumed, and washed off or rinsed. During the vacuuming stage the powder grains will, unfortunately, get through the filter and may damage the motor. Consequently, as much powder as possible should be swept up first and the vacuum cleaner should have a specific filter.

Gaseous extinguishing agents

An extinguishing agent is considered as being gaseous if its boiling point at atmospheric pressure is below room temperature. This includes some common substances such as nitrogen, carbon dioxide and argon, as well as a number of halogenated hydrocarbons and mixtures of these. Some of the gases are marketed under various commercial names. Most of the gases are both colourless and odourless. Carbon dioxide has a slightly pungent odour.

There is a great deal of literature available about gaseous extinguishing agents. This is due to the fact that gaseous extinguishing agents are common in fixed extinguishing systems and that a great deal of effort has been put into finding alternatives to halons, which are being phased out for environmental reasons. Refer, for instance, to Isaksson, et al. (1997).

The name "halon" is an abbreviation for HALogenated hydrocarbON. A halogenated hydrocarbon usually comprises a short carbon chain with some or all hydrogen atoms exchanged with halogens, i.e. fluorine, chlorine, bromine and iodine. Nowadays, this name only refer to substances which are completely chlorinated and/or brominated, such as halon 1211 and halon 1301. They will not be described in any particular detail in this book, but you are referred to other literature on the subject, e.g. Berg & Godby (1993). Fluorinated hydrocarbons are often called FC gases, while partially fluorinated hydrocarbons are called HFC gases. Dry water is the commercial name for a substance that looks like acetone, but in which the hydrogen atoms are replaced with fluorine. Chemically therefore it shares certain similarities with the FC gases. The difference is that the substance has a high boiling point and is in liquid state at room temperature and atmospheric pressure.

Different types of other gases can be used as extinguishing agents for specific purposes, such as steam or combustion gases. Gases from a combustion motor include a mixture of air, nitrogen, carbon dioxide and steam and are used, for instance, in shipping for keeping the tanks on a tanker inert. This area of application is fairly limited, however, and for this reason, we are only looking at the properties of the pure extinguishing agents in this section.

Pure substances	Commercial name	Chemical formula
Argon	IG 01, Argotec	Ar
Halon 1211		$CBrClF_2$
Halon 1301		$CBrF_3$
HFC 125		CF_3-CHF_2
HFC 134a		CF_3-CH_2F
HFC 227 ea	FM200	CF_3CHF-CF_3
HFC 23		CHF_3
Carbon dioxid		CO_2
Nitrogen	IG 100	N_2

Gas mixtures	Commercial name	Mixture
HFC Blend A	Halotron 2b	HFC125+ HFC134 + Carbon dioxide
IG 55	Argonite	50% Argon, 50% Nitrogen
IG 541	Inergen	52% Nitrogen, 40% Argon 8% Carbon dioxide*

* different blends are available

5.1 Many gases are marketed under different names.

5.2 Physical properties for compressed gases (Isaksson et al., 1997).

Substance	Chemical formula	Molar weight [g/mol]	Freezing point [°C]	Boiling point [°C]	Crit. temp. [°C]	Crit. pressure [MPa abs]	Gas density at 20°C 100 kPa [kg/m³]	Heat capacity 20°C [kJ/kg/…
Nitrogen	N_2	28.0	−210	−196	−147	3.39	1.17	1.04
Argon	Ar	39.9	−189	−186	−122	4.90	1.66	0.52

Substance	Chemical formula	Molar weight [g/mol]	Freezing point [°C]	Boiling point [°C]	Crit.temp. [°C]	Crit. pressure [MPa abs]	Vapour pressure, 20°C [MPa]	Liquid den[sity] 20°C
Carbon dioxide	CO_2	44.0	−78	Sublimates	31	7.38	6.08*	720
Halon 1211	$CBrClF_2$	165.4	−160.5	−4	154	4.30	0.23	1580
Halon 1301	$CBrF_3$	148.9	−168	−57,8	67	3.96	1.43	1820
HFC 23	CHF_3	70	−155	−82	26	4.84	4.18	807
HFC 125	$CF_3–CHF_2$	120.0	−103	−48	66	3.60	1.21	1219
HFC 227 ea	$CF_3CHF–CF_3$	170	−131	−16	102	2.91	0.39	1407
HFC 134a	$CF_3–CH_2F$	102	−101	−26	101	4.06	0.67**	1209

* at 22°C ** at 25°C

5.3 Physical properties for condensed gases. Halon 1211 and 1301 are included for comparison, even though they are not usually permitted (Isaksson et al., 1997).

Experiments have also been carried out to get water to function like a gaseous extinguishing agent. But this requires water droplets with a size of less than 0.02 mm in diameter, which is difficult to achieve as droplets of this size tend to join together to form larger ones. As a result, water behaves as a spray rather than as a gas (Andersson et al., 1996).

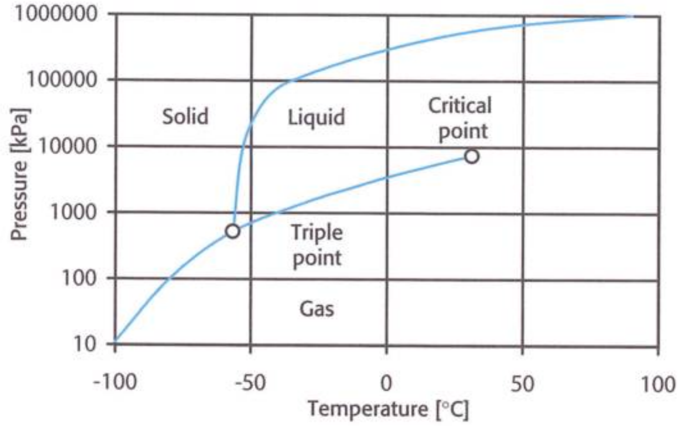
Physical properties

If the pressure of a gas is increased it will be compressed and decrease in volume. Gas density varies greatly with both pressure and temperature. If the pressure is too high or the temperature too low the gas will condense to liquid form.

Gases with a critical temperature below room temperature may be compressed and kept in gas bottles. Gases with a critical temperature above room temperature will condense and are stored in containers in liquid form.

For use in portable fire extinguishers, substances are preferred with a low vapour pressure and a boiling point well below the application temperature. This made the now banned halon 1211 suitable for use in portable fire extinguishers. Otherwise, a pressure container needs to be used, like for carbon dioxide.

Carbon dioxide is a special gas, as its critical temperature is 31.3°C and it also sublimates at atmospheric pressure. This



5.4 Phase diagram for carbon dioxide (Hultqvist & Persson, 1960).

means that it converts directly from a solid to a gas instead of first melting and then boiling.

In the case of mixtures of gases, the components need to be analysed individually. The physical properties are often governed by the component with the highest freezing point and boiling point, as well as the lowest critical pressure.

Storing and transporting gases

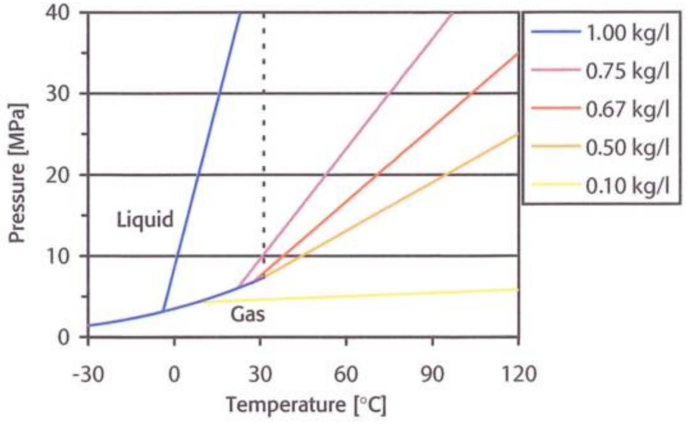
In the case of compressed gases, containers with a pressure of 10–20 MPa are usually used. This requires a stable construction. This means that the containers for compressed gases generally weigh considerably more than their contents.

In the case of high-pressure condensed gases, the size of the gas bottles is based on the vapour pressure at the highest temperature they are expected to be exposed to. This temperature is usually set to 65°C. The pressure is considerably lower than for compressed gases and their construction can be simpler. As the gas is condensing to a liquid, the container can also hold a much larger volume of gas than as is the case with compressed gases. As a result, the quantity of extinguishing agent in terms of kilograms per storage volume is bigger.

As the vapour pressure for high-pressure condensed gases varies greatly with the temperature, a propellant is usually added, often nitrogen, to ensure that the gas escapes quickly, even at low temperatures.

Small quantities of carbon dioxide are stored almost always

5.5. *Impact of temperature and fill level on the pressure in a carbon dioxide container. The temperature is close to the critical point. The general gas law does not apply in this case as carbon dioxide does not behave like an ideal gas (Hultqvist & Persson, 1960).*



as a pressure condensed liquid. The pressure in the container is controlled by the temperature and fill level. Normally, the fill level is around 0.7 kg/l. If the fill level is too high there is a risk that the container might burst due to high pressure induced by increased temperature. The diagram above helps illustrate how temperature and fill level can affect the pressure in a carbon dioxide container. This must be taken into account when filling containers with all high-pressure condensed gases. If the gas bottle is totally filled with the liquid, it will to burst if the temperature increases.

Gases may also be stored in a low-temperature condensed state. This means that the gas is cooled down to below the boiling point and it converts to a liquid. The gas must then be kept cold, but not in a pressurised container. Low-temperature condensing is common when large volumes of gas need to be stored. This is because it is easier and cheaper to build a large cooling tank than a large pressure tank. If large volumes of gas are required for a firefighting operation they are usually delivered in low-temperature condensed form in a tanker or tank wagon. Carbon dioxide and nitrogen gas are examples of gases which can be stored in this way.

Applying gaseous extinguishing agents

The nozzles for applying gaseous extinguishing agents are designed according to how the agent is to be used. The application technique is well known and the problems which can arise often relate to the transition from condensed liquid to a gas. The largest drop in pressure occurs in the nozzle and not in the gas container's valve or in the pipes. The condensed gases vaporise when the pressure drops. This expansion is desirable when the extinguishing agent has left the system and been discharged into the fire room. In the case of fixed systems using a total flooding agent, it is worth selecting the right nozzles and choosing the right number and location for them so that the extinguishing agent can be dispersed as evenly as possible in the room.

Immediately after a gas extinguishing system has been activated, the liquid will vaporise while travelling through the pipes and cool these down, as heat is used for the vaporisation. During the first few seconds this gas streams out of the nozzles. When the pipes have cooled down the liquid flows through the system and vaporises when it comes into contact with the relatively warm air.

When high-pressure or low-temperature condensed gases are applied, the temperature in the room drops. If the fires are small when the extinguishing agent is applied the temperature may drop to a few degrees below zero in the fire room, after the gas has been applied from a system using a total flooding agent.

Portable fire extinguishers using carbon dioxide have a snow horn for a nozzle. This means that the energy required for vaporisation cannot be taken from the air. When the carbon dioxide is discharged from the nozzle the pressure drops and the carbon dioxide vaporises. The temperature then falls and remains sufficiently low for part of the carbon dioxide not to vaporise, but to be converted to a solid in the form of dry ice. The snow horn has a discharge wire to prevent the build-up of any static electricity. The typical projection range for portable fire extinguishers using carbon dioxide is about 1–2 m.

With portable fire extinguishers the extinguishing agent should have a limited dispersion angle, but as long a projection range as possible. Projection ranges and air movement effects are greater for high-pressure condensed gases than compressed gases. It is also desirable for portable fire extinguishers to be designed to apply the extinguishing agent as evenly as possible.

Application areas for gaseous extinguishing agents

Gaseous extinguishing agents are rarely the most effective choice from a technical standpoint, in terms of extinguishing a fire. In fact, the major benefit of this extinguishing agent is that it is clean. Most gases cause no or only slight damage if the extinguishing system is set off accidentally (Isaksson et al., 1997). Gaseous extinguishing agents may be a good choice if something of great value is being protected or the downtime must be kept to a minimum.

The use of gaseous extinguishing agents is limited to fires where oxygen is supplied to the fire via the air. The extinguishing agent works only in the gaseous phase and does not cool down the fuel directly. This means that a fire can flare up when the extinguishing agent is ventilated away. Consequently, gaseous extinguishing agents are most effective for protecting enclosed areas where a high concentration of extinguishing agent can be maintained for a sufficient length of time. The size of fixed systems using these agents is usually determined based on cup burner or inerting data. When scoping the size of a system, there is a safety factor which can vary between different guidelines and compensate for the leakage of extinguishing agents from the room when the agent is being applied and during the 5–15 minutes when the concentration must be maintained to prevent reignition.

5.6. Fixed carbon dioxide installation protecting a room containing vital electronics.

Gaseous extinguishing agents are sometimes used by the fire service to tackle fires in silos. The silo is kept filled with a gaseous extinguishing agent until the seat of the fire has cooled down. It is then emptied, using the utmost caution. When the stored material collapses air pockets may be formed. When these pockets collapse the smouldering material, dust and air may swirl up and come into contact with each other causing an explosion. The extinguishing process is long drawn-out and can take days or even weeks.

Gaseous extinguishing agents are also used in portable fire extinguishers and as streaming agents, usually to tackle fires involving liquids and electrical equipment. Gaseous extinguishing agents do not conduct electricity, which means that the

5.7 Extinguishing a basement fire using carbon dioxide where an interior attack was unsuccessful. Low-temperature carbon dioxide is sprayed via the basement stairs in a department store warehouse. The basement is sealed off. The carbon dioxide gradually makes its way out into the adjoining areas. The temperature in the fire room is measured on an hourly basis through a hole in the concrete joist. But the extinguishing process is slow. It may take days before the basement can be inspected.

5.8 Extinguishing properties against heptane and propane for certain gaseous extinguishing agents. A range indicates that there is varying information available. As can be seen, there is a great variation in the cup burner data (Isaksson et al., 1997).

Extinguishing agent	Cup burner, n-heptan (propane) [vol%]	Inerting (propane) [vol%]
Carbon dioxide	20 (21)	28
Nitrogen	30–34	38
Argon	38–41 (35)	
Argonite	28, >30 (33)	
Inergen	29 (32)	49
HFC 23	12–14	20
HFC125	8.1–9.4 (15)	16
HFC 227ea	5.8–6.6	12
HFC blend A	9?	13?
HFC 134a	9.4–10.5	

risk for direct contact with electrical components will be the determining factor (Brandförsvar vid elanläggningar, 1987).

Gaseous extinguishing agents are generally not used to tackle metal fires. If carbon dioxide or nitrogen is used to extinguish a fire involving magnesium, for instance, the reactions below may occur, resulting in failure to extinguish the fire. Consequently, the extinguishing agent fails to suppress the fire, but the chemical reactions may continue (Madrzykowski & Stroup, 1998).)

$$Mg + CO_2 \rightarrow MgO + CO$$

$$3Mg + N_2 \rightarrow Mg_3N_2$$

Extinguishing effect of gases

Gaseous extinguishing agents act as thermal ballast and reduce the temperature of the flames. Some gases, such as halons, also have a chemical effect.

How effective gaseous extinguishing agents are can be indicated in a number of ways, including a cup burner value for diffusion flames or an inerting value for premixed flames. The extinction limits depend, however, on the fuel. There are fuels like methanol and ethylene, which require significantly higher extinguishing concentrations than heptane and propane.

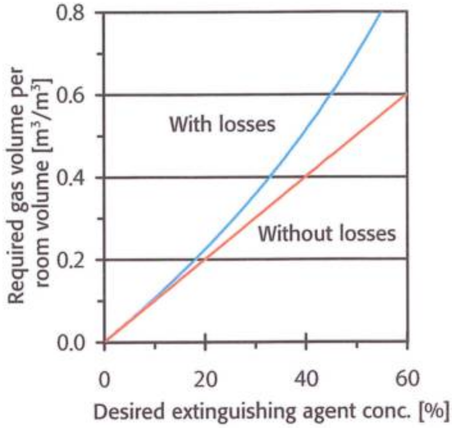
There are also other methods, such as classifying them

CALCULATING
THE REQUIRED GAS VOLUME

The required gas volume can be calculated for gaseous extinguishing agents. The formula assumes well mixed conditions in the room (Harris, 1983).

$$V_e = V \cdot \ln(100/(100-C))$$

V_e [m³] required volume of gas
C [vol%] desired concentration
V [m³] room volume



5.9 Necessary gas volume according to the upper formula. Losses in this context refers to the amount of extinguishing agent that is lost due to pressure relief. Apart from this, compensation must be made for leakage after the release and for incomplete mixing. Substances with a high extinguishing concentration are therefore given greater dimensioning.

For halons and halon-type gases the following formula is usually used:

$$V_e = V \cdot C/(100-C)$$

In the case of total flooding agents, C is selected from cup burner data and for explosion prevention systems the inerting thresholds are used.

A detailed description about the way in which gases mix in a room and how to calculate gas concentrations is provided in other works. Refer, for instance, to Harris (1983).

based on extinguishing various standardised fires. The REMP value can also be used where the flow of extinguishing agent is put in relation to the quantity of fuel burnt per second.

If it is handled properly, a 5 kg carbon dioxide extinguisher will be sufficient to extinguish a burning pool of petrol with an area of around 1.6 m².

In the case of fixed extinguishing systems using a total flooding agent, more extinguishing agent is required in gas bottles than the volume of extinguishing agent remaining in the room after the system has been activated. Part of the extinguishing agent expands along with the air out through the vents which must be available so that the pressure does not exceed the value the room can withstand. This effect is very obvious with extinguishing agents which require a high extinguishing concentration. Another drawback with high concentrations of extinguishing agents is that they take a long time to discharge.

The large gas supply does not only indicate that part of the gas is leaking out, but also that the pressure in the room is increasing considerably. Particularly with systems requiring a high gas concentration for extinguishing fires, the gas concentration achieved is so high that walls will be pushed out if there is no pressure relief.

When designing a gaseous extinguishing system, a similar argument about gas pressure and volume in a fire room applies, as was discussed in the section about cooling down smoke with water. By setting up a gas mass balance in the room, along with an energy balance, it is possible to calculate the pressure and estimate the demand for pressure relief.

Limitations of gaseous extinguishing systems

The problems with gaseous extinguishing agents mainly concern the fact that they are toxic or at least displace the oxygen in the air. Also, some of them have a negative impact on the environment and they cannot be disposed of after a firefighting operation.

PHYSICAL HARM CAUSED BY GASES

Some gaseous extinguishing agents which are high-pressure or low-temperature condensed can produce very low temperatures when the systems are activated. This is why there has to be a warning about touching pipes, etc.

Gaseous extinguishing agents have two different types of toxic effect. On the one hand, they displace the oxygen in the air and on the other, these gases can cause poisoning, with different effects on the body's functions.

In the concentrations required to extinguish fires, most gaseous extinguishing agents will be toxic (apart from some of the halon replacement agents). If there is any doubt as to the concentration of extinguishing agent in a room, breathing protection must always be used if a fixed extinguishing system has been activated. This applies even if there has not been a fire. This also means that a non-toxic gaseous extinguishing agent can still make it impossible to remain in a room where the extinguishing agent has been used. As a result, fixed extinguishing systems will have to have certain safety requirements applied to prevent people from being in areas where a system is to be activated. Possible technical solutions include time delay or alarm devices. Deaths have occurred involving people who have been in areas where an extinguishing system has been activated.

Inert gases, with the exception of carbon dioxide, have no toxic properties in normal use. Carbon dioxide's inherent toxicity is shown in the table below. Consequently, most gases used as extinguishing agents are not toxic in themselves, but they reduce the oxygen content in air. In particular, extinguishing agents requiring high concentrations can produce low and therefore, lethal oxygen levels.

Inert gases do not usually decompose when used for firefighting. Halogenated extinguishing agents, however, break down when exposed to high temperatures (above around 400°C) and steam, which modifies the toxicity. When a fire is extinguished, some gases produce breakdown products which can sometimes be more toxic than the original gas. The main breakdown products are hydrofluoric (HF), hydrobromic (HBr), hydrochloric (HCl) and hydriodic (HI) acids, with the first one predominant. These gases cause irritation and affect the mucous membranes in the eyes, nose and throat, making evacuation difficult. Other products which may also

Conc. [%]	Time	Symptom
2	several hours	Difficulty breathing, headaches
6–10	not specified	Difficulty breathing, headaches dizziness, anxiety, perspiration, numbness
10–15	1.5 minutes	Neurological symptoms such as agitation, muscle spasms
12	8–23 minutes	Loss of consciousness
20–30	1 minute	Loss of consciousness and convulsions

5.10 Physical impact of different concentrations of CO_2 over different exposure periods (Isaksson et al. 1997).

be produced include bromine (Br_2), fluorine (F_2), iodine (I_2), carbonyl fluoride (COF_2) and phosgene ($COCl_2$). Carbonyl fluoride and phosgene, in particular, are both highly toxic, but only very low concentrations have been measured. One factor determining the quantities produced is the extinguishing agent's chemical composition. The toxicity of some of the breakdown products is shown in the table. You should note that the health threshold values are much lower.

Substance	IDLH [ppm]
Bromine	3
Chlorine	10
Fluorine	25
Hydrogen bromide	30
Hydrogen chloride	50
Hydrogen fluoride	30
Phosgene	2
Carbon dioxide	40 000

5.11 IDLH values for the most common breakdown products from halogenated hydrocarbons and for carbon dioxide, for comparison (NIOSH, 1995). IDLH stands for Immediately Dangerous to Life or Health concentrations.

An extinguishing system containing 4 tonnes of halon 1301 was released in a hangar where there was no fire. When the firefighters arrived at the scene the vehicle was parked 25 m from the building. After a thorough search, it was confirmed that there was no fire and ventilation got under way. The gases which had been discharged spread outside the building and were sucked with the air into the fire appliances' engines. The halon reacted in the engine to form hydrogen bromide and hydrogen fluoride. The brown pungent gas made it necessary to switch off the engines. The effect was particularly obvious due to the weather, which was damp and hazy (Hanning, 1992).

ENVIRONMENTAL IMPACT OF GASES

Argon and nitrogen both occur naturally in air. They are extracted from the air and discharged back into it when used. They have not been questioned as harmful to the environment.

The temperature in the atmosphere is kept at a constant level through greenhouse gases in the atmosphere, mainly water and carbon dioxide, absorbing heat radiation from the earth and radiating a large amount of it back to the earth again, instead of letting it be radiated out into space. Whether a gas is able to cause any greenhouse effect is determined by the substance's infrared-absorbing properties and its atmospheric life cycle. The concentration of greenhouse gases in the atmosphere has grown significantly due to human activity. This increase may lead to a rise in the average temperature of the earth.

Gases' greenhouse effects are described along with their GWP (Global Warming Potential), with carbon dioxide used

Extinguishing agent	GWP (100 years) [–]	ODP [–]	Atmospheric life cycle [years]
CO_2	≡ 1	0	–
Halon 1211		3	
Halon 1301	4900–5800	10	77–101
CFC 11 (coolant)	3400	≡ 1	55
HFC23	9000–12 100	0	230–400
HFC125	3200–3400	0	28–36
HFC227ea	2050–3300	0	31–42
HFC 134a	1200–1300	0	16

≡ means, by definition, equal to

5.12 Environmental properties for gases (Isaksson et al., 1997).

as the reference gas. The greenhouse effect can also be calculated using timescales of different length. As comparisons are carried out using information from different sources, this means that it is important to ensure that they are using the same reference gas and timescale. For example, the gas HFC 134a has a GWP of 3100 for the first 20 years, a GWP of 1200 for over 100 years and a GWP of 400 for a period of 500 years. In the case of mixtures of gases, the individual constituents should be analysed separately.

Carbon dioxide is a greenhouse gas, but has not been questioned about being used as an extinguishing agent. Future regulations on other greenhouse gases could affect the possibility of using FC and HFC compounds to extinguish fires. Halons actively contribute to the breakdown of the atmosphere's ozone layer, which is why they have been banned. The sale of portable fire extinguishers and the installation of new fixed extinguishing systems containing halons have been banned in the EU since 1991. With some exceptions, fixed installations using halons have been totally banned in the EU since 1997.

CFC and HCFC gases (fully and partially chlorinated and fluorinated hydrocarbons respectively), with the halons as the most obvious example, break down the atmosphere's ozone layer. FC and HCF gases (fully and partially fluorinated hydrocarbons respectively) have not been shown to have the same impact. The measurement of a substance's ozone depletion capacity is known as its ODP, Ozone Depletion

Potential. This is calculated taking into account factors such as the substance's atmospheric life cycle, transport time to the stratosphere, the rate and height of the substance's breakdown reactions, as well as which reactants can be produced in the stratosphere and in what quantity. The calculations are uncertain and are therefore usually related to an equivalent value for the coolant CFC-11, which is set to 1.

One of the environmental problems with halogenated gases is their long atmospheric life cycle. Halon 1301, for instance, has an atmospheric life cycle of 77–101 years. HFC and HCFC compounds have similar atmospheric life cycles. The life cycle for FC compounds is 10–20 times longer. As the consequences of this cannot be predicted or will only be evident in the longer term, there is a strong argument for avoiding the use of FC compounds too as extinguishing agents.

DAMAGE CAUSED BY GASES TO PROPERTY

One major benefit from the use of gaseous extinguishing agents is that there is no residue left of the extinguishing agent once the gas has been released into the air. However, halogenated gases do generate breakdown products, which have a corrosive effect on metals when they are exposed to heat and damp during a fire.

Otherwise, only a small amount of minor damage is caused, which is perhaps the chief argument for using gaseous extinguishing agents. This means that theoretically, a deep fryer in a restaurant kitchen can be used immediately after a carbon dioxide system has been used to extinguish a fire and the gas has been dispersed. In other places too where cleanness is a priority, gaseous extinguishing agents provide a definite alternative, as these extinguishing agents do not, on the whole, cause any damage to property. Cleanness is also a very positive attribute when accidents occur or systems are activated by mistake, particularly, if the downtime caused must be kept short.

Extinguishing theory

To understand extinguishing fires as a phenomenon, we need to understand what a fire is. The theoretical basics of fires and fire development are described in other works. Refer, for instance, to Bengtsson (2005), Drysdale (1985), Karlsson & Quintiere (1999). This section will focus rather on extinguishing mechanisms.

The knowledge about extinguishing agents and how they operate is incomplete. In some areas of this field, there are works available, such as Lewis (1961), about the flammability ranges for gas mixtures and extinguishing agents' impact on burning velocity. There is, however, little knowledge about how, for instance, heat release rate, temperature, radiation and soot formation are affected during the extinguishing process. Much of the knowledge about extinguishing mechanisms comes from small-scale experiments using premixed gases. This is in contrast to real fires, which are often on a large scale, with the air and fuel coming from different directions. As regards the technical aspects of this field, the knowledge is mostly based on experience.

The usual fire scenario, where turbulent diffusion flames are extinguished above a smouldering fuel surface, is a complicated process. Both the energy balance in the gases and at the fuel surface have an impact on the progress of the extinguishing.

Four scenarios will be discussed in this chapter:

- Gas phase impact with premixed flames
- Gas phase impact with diffusion flames
- Surface impact with diffusion flames
- Surface impact with smouldering fires.

This division has been made according to the part of the fire being analysed, whether it concerns the actual flames (gas phase impact) or the fuel surface (surface impact). We also distinguish between premixed flames, when the air and fuel are mixed together before ignition, and diffusion flames, where the fuel and air come from different directions and the flames are formed in the boundary layer between them. In the case of smouldering fires, decomposition and combustion are occurring inside the solid material.

Extinguishing flames can mostly be attributed to a reduction in the temperature, to the extent that the losses can no longer be compensated for. This is the case in most methods for extinguishing fires, for instance, when you blow out a candle, when a burning bale of straw is dropped in water or when a carbon dioxide system is used to extinguish a fire in a restaurant kitchen.

The flames go out when the rate of reaction has become so slow that the energy lost will be greater than the energy released. This loss may be due to incomplete combustion, radiation, the addition of a heat absorbing extinguishing agent or to convective losses when the flames are close to a solid material or liquid surface.

Extinguishing premixed flames

When fuel vapours have the opportunity to mix with air or oxygen prior to combustion, this produces premixed flames. The fuel is then always in the form of a gas, such as LPG and natural gas, or fuel vapours from a petrol or ethanol spillage. Premixed flames can also occur when a fire has generated pyrolysis gases, which have not been combusted, but have accumulated.

FLAMMABILITY LIMITS AND INERTING THRESHOLDS

The upper flammability limit for hexane in air is roughly 7 % vol and the lower limit 1.3% vol. When diluted with nitrogen gas, the flammability range decreases. When around 43 % vol. nitrogen is added the upper and lower flammability limits falls together. In this instance, the fuel concentration is about 2% vol. hexane (Beyler 1995).

THERMAL EFFECT

The rate of reaction in flames is governed by the concentration of fuel and oxygen, but also by the reaction temperature. The rate is calculated using the Arrhenius formula (Waser et al. 1982):

$$v = AC_f C_o e^{-E_A/RT}$$

v [mol/s] rate of reaction
A reaction constant
C_f [mol/m^3] fuel concentration
C_o [mol/m^3] oxygen concentration
E_A [J/mol] activation energy
R [J/molK] general gas constant
T [K] reaction temperature

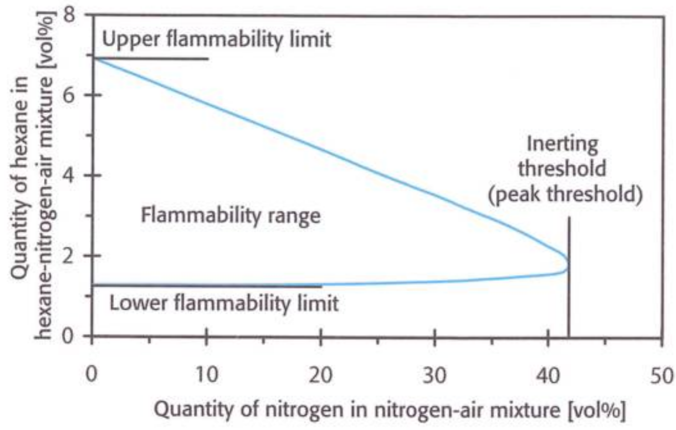
This one-step reaction is a very rough simplification of a combustion process, which usually comprises a large number of chain and radical reactions.

The rate of reaction may be reduced by either reducing the fuel concentration, oxygen concentration or temperature or by increasing the activation energy. When an extinguishing agent is applied the fuel and oxygen have been diluted. This makes the rate of reaction fall linearly. Using an inert gas for dilution at a 50% vol. concentration reduces both the fuel and oxygen's concentration by half. Because the flames become depleted and are suppressed the rate of reaction then falls by a quarter. A similar effect is achieved when diluting with an excess of fuel or air.

This is not, however, the main effect from dilution. It actually produces what is known as a thermal ballast. The entire gas mixture, i.e. even gases which do not take part in any chemical reaction, are heated up in the flames. Energy is used to do this, which results in a lower flame temperature. A lower flame temperature, in turn, reduces the rate of reaction. With a stoichiometric mixture without any ballast, the adiabatic temperature is around 2300K and about 1300K at the extinction limit. Data from high-temperature reactions for some common fuels highlights that EA/R is in the order of 16000K, which means that the rate of reaction has dropped 200 times due to the reduced flame temperature after dilution using an inert gas.

The dilution effect for argon, the extinguishing agent requiring the largest concentration for extinguishing, around 55% vol. at the stoichiometric point, reduces the rate of reaction by about a quarter, while the accompanying thermal ballast reduces the rate of reaction 200 times, i.e. fifty times more.

To reduce the fuel and oxygen concentration without changing the flame temperature or activation energy, the pressure in the flames must be reduced. At low pressure radicals are suppressed at the enclosure's walls, which helps to extinguish the flame. On the other hand, it seems that there is no pressure limit for the extinguishing process in the same way as for temperature.



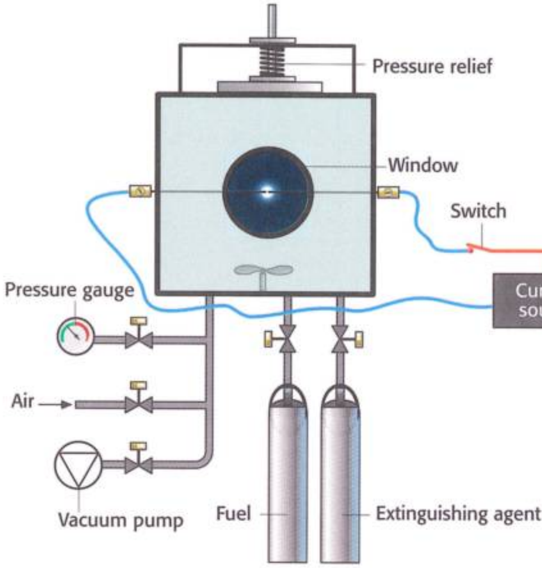
6.1 Flammability limits for mixtures of hexane, air and nitrogen (Lewis et al., 1961).

Flammable gas mixtures lose their ability to burn if a diluting gas is added. An inert gas or an excess of air or fuel can be used for dilution. At the lower flammability limit there is too much air in the gas mixture and at the upper flammability limit the mixture contains too much fuel.

For each mixture of fuel, air and extinguishing agent there is a lowest extinguishing agent concentration, where the mixture cannot be combusted, whatever the ratio between air and fuel. This concentration is known as the inerting or peak threshold. When the extinguishing agent concentration is above the inerting threshold the gas mixture cannot burn, whatever the fuel and air concentration.

The flammability limits widen as the temperature increases. This means that the flammability range for a gas mixture at room temperature is totally different to that for a hot gaseous mass in a fire.

In reality, it is not possible to extinguish large premixed flames by supplying air in order to go below the lower flammability limit. On the other hand, this method is ideal to use, before ignition, to limit the volume where premixed flames can develop. Increasing the ventilation in a building can help to reduce the risk from flammable vapours. The intention is to keep the concentration of combustible gas below the lower flammability limit throughout the whole building, apart from in the small area close to the discharge.

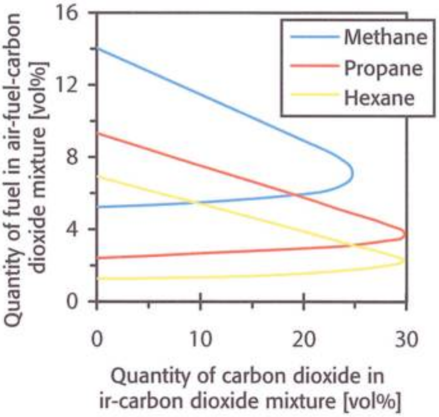


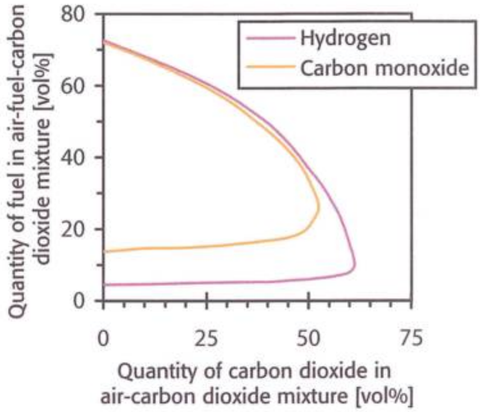
6.2 The explosion bomb is an example of a device used to determine flammability limits and inerting thresholds.

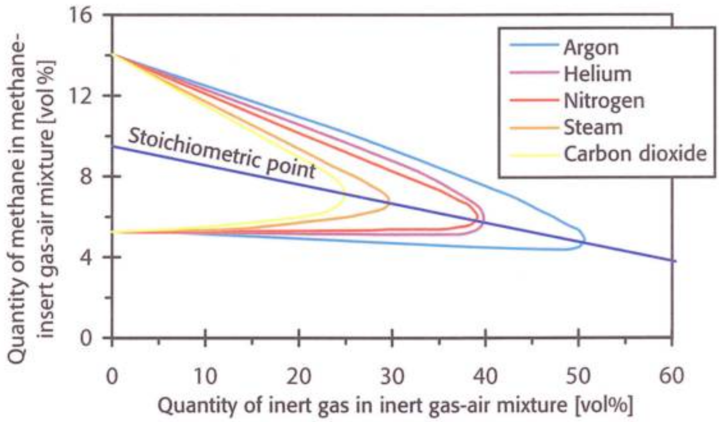
The flammability limits and inerting thresholds represent critical points outside of which a mixture of air and fuel will not react. They are closely connected to the kinetics for gas-phase reactions. The limits can be reached by adding air, fuel, an inert extinguishing agent or chemically active extinguishing agent or by extracting heat from the flames by means of radiation, surface convection, etc.

The flammability limits can be determined by experiment, where gas mixtures are enclosed, mixed and ignited. These tests determine the minimum quantity of extinguishing agent required for ignition to occur, whatever the quantity of oxygen or fuel. Usually most extinguishing agent is needed for a gas mixture close to the stoichiometric point. The inerting thresholds for different extinguishing agents vary according to the fuel used and also to how the tests are carried out. The flammability range varies with the volume of the apparatus, the distance between the electrodes, the ignition energy and also with how the terms combustible and non-combustible are defined. This means that the inerting threshold is not a constant of the extinguishing agent, but varies according to the conditions. This explains why the flammability range can vary.

The graphs illustrate the flammability limits measured for different mixtures of fuel, air and extinguishing agent. The inerting threshold is the lowest concentration of extinguishing agent capable of extinguishing a fire, whatever the fuel







6.3 (top left) Flammability limits for some common hydrocarbons in air, diluted with carbon dioxide at room temperature and atmospheric pressure (Lewis, 1961). Petrol's flammability is similar to hexane's.

6.4 (top right) Flammability limits for hydrogen and carbon monoxide in air, diluted with carbon dioxide at room temperature and atmospheric pressure (Lewis, 1961).

6.5 (bottom left) Flammability limits for methane in air, diluted with various inert gases at room temperature and atmospheric pressure (Lewis, 1961).

concentration. You should note the values on the axes. The fuel concentration is specified as vol% fuel in the mixture of fuel, extinguishing agent and air. The concentration for the extinguishing agent, on the other hand, is specified in the mixture of air and extinguishing agent. This means that the quantity of fuel is not included. The reason for this is because the inerting threshold is often used to scope the size of an extinguishing system. In this instance, the required quantity of extinguishing agent is calculated, regardless of how much fuel there may be in the room.

SAME TEMPERATURE AT EXTINCTION LIMIT

The flammability limits for premixed gases can be calculated using the adiabatic flame temperature. The term "adiabatic" means that all the energy released is assumed to be used for heating the end products. The chemical reactions happen so quickly that there is no time for any heat exchange to take place between the flames and surrounding environment. We can therefore disregard any heat loss to the atmosphere. The adiabatic flame temperature is fictitious and is only used in the calculations. The actual flame temperature is usually much lower.

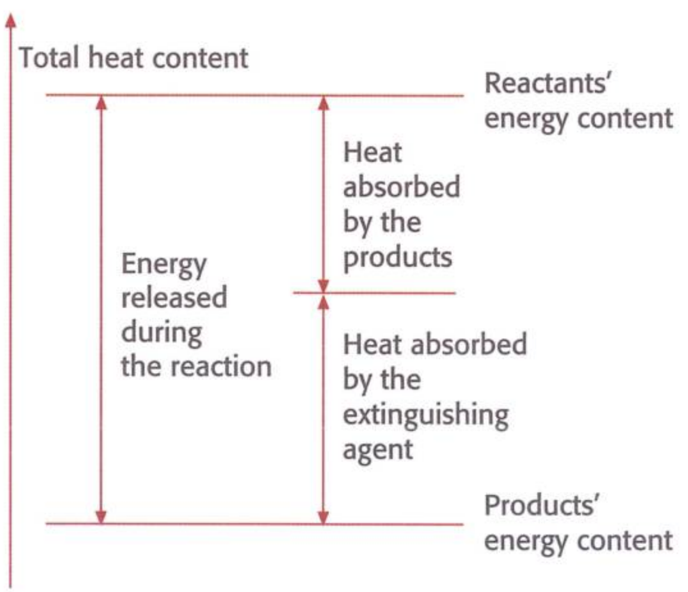
At the extinction limit the adiabatic flame temperature is generally constant and in the order of 1500–1600K for all non-chemically active extinguishing agents and for all hydrocarbon fuels; refer to the tables below. The actual temperature is 200–300°C lower. The temperature limit is due to the fact

Hydrocarbon	Methane	Ethane	n-Propane	n-Butane	n-Pentane	n-Hexane	n-Heptane
Adiabatic flame-temperature [K]	1498	1491	1506	1613	1563	1634	1595

6.6 Adiabatic flame temperature calculated at the lower flammability limit for mixtures of hydrocarbons and air at room temperature.

Inert gas	Air	Argone	Nitrogen	Carbon dioxide	Steam
Adiabatic flame-temperature [K]	1533	1530	1600	1650	1663

6.7 Adiabatic flame temperature calculated at the inerting threshold for mixtures of methane, air and inert gas.



6.8 Total heat content diagram for an adiabatic chemical reaction.

that the rate of reaction will be too low if the temperature drops. The oxygen and fuel do not have time to react before the gases are transported away from the flame. The calculations are delicate. An error of 0.1% vol in the fuel concentration amounts to a change in the calculated adiabatic flame temperature of 50–100K (Lewis, 1961).

The flame temperature is so low at the extinction limit that any dissociation of the combustion gases can be ignored. This simplifies the calculations considerably. Dissociation means that a substance breaks down into simpler molecules or atoms, which occurs at very high temperatures.

Substance	Cp at 1000K [J/molK]
Nitrogen	32.7
Oxygen	34.9
Carbon dioxide	54.3
Carbon monoxide	33.2
Steam	41.2

6.9 Cp for some common gases (Drysdale, 1985).

Substance	–ΔHc [kJ/mol]
Carbon monoxide	283
Methane	800
Ethane	1423
Ethene	1411
Ethyne	1253
Propane	2044
n-Butane	2650
n-Pentane	3259
n-Octane	5104
c-Hexane	3680
Benzene	3120
Methanol	635
Ethanol	1232
Acetone	1786
d-Glycose	2772

6.10 ΔHc for some common flammable gases (Drysdale, 1985).

CALCULATING THE FLAMMABILITY LIMIT

As flames go out at roughly the same temperature, it is possible to calculate the lower and upper flammability limit, as well as the inerting threshold for inert extinguishing agents (Drysdale, 1985; Bengtsson, 2005). The thermodynamic data measured at constant pressure and at 1000K, the approximate average temperature, are usually used as the starting point for the calculations. From an adiabatic perspective, i.e. if any energy lost to the atmosphere is ignored, all the energy released will be used to heat up the combustion products and extinguishing agent.

$$\Delta H_c = \Delta T \sum n_p C_{p,p}$$

$$\Delta T = T_{ad} - T_0$$

ΔH_c [J/mol] heat of combustion
ΔT [K] difference between initial temperature and extinction limit
T_{ad} [K] adiabatic flame temperature at extinction limit, about 1550K
T_0 [K] initial temperature
n_p [mol] quantity of products per mol of fuel
$C_{p,p}$ [J/molK] products' heat capacity

A stoichiometric mixture of fuel and air is used to start with, when calculating the flammability limits. Then either air or fuel is added. This excess will have a cooling effect.

A similar effect is achieved when the mixture is diluted with inert gases, such as nitrogen, carbon dioxide, argon or steam, instead of air or fuel. The inert gas reduces the flame temperature as a result of the energy being used to heat up the extinguishing agent.

$$\Delta H_c = \Delta T \sum n_p C_{p,p} + \Delta T \sum n_e C_{p,e}$$

n_e [mol] quantity of extinguishing agent per mol of fuel
$C_{p,e}$ [J/molK] extinguishing agent's heat capacity

The calculation is for gaseous extinguishing agents. The same argument can also be used for extinguishing agents in liquid or powder form.

The proportion of the reaction heat which the extinguishing agent absorbs from a stoichiometric flame so that it will go out is usually around 45%. The flames will go out when the adiabatic flame temperature reaches roughly the same value as for the lower flammability limit in air.

The inerting threshold for nitrogen gas in a mixture of propane and air at 293K (20°C) is calculated by first writing down the reaction formula. At stoichiometric conditions the overall reaction formula will be:

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

Some nitrogen from the air is added on both sides and some extinguishing agent as an unknown quantity of extra nitrogen.

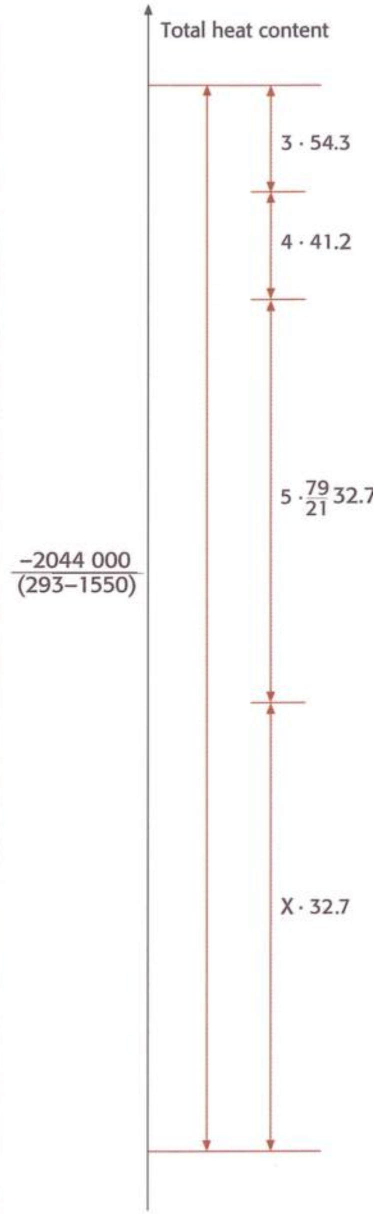
$$C_3H_8 + 5O_2 + 5\cdot 79/21N_2 + X\cdot N_2 \rightarrow 3CO_2 + 4H_2O + 5\cdot 79/21N_2 + X\cdot N_2$$

Given that all the energy released is used to heat up the products means that

$-2044000 = (293-1550)\cdot(3\cdot 54.3 + 4\cdot 41.2 + 5\cdot 79/21\cdot 32.7 + X\cdot 32.7)$

$1626 = 942.8 + X\cdot 32.7$

In this case, the unknown quantity of nitrogen in the reaction formula will be $X = 20.9$ and this gives the inerting threshold.
$20.9/(1+5+5\cdot 79/21 + 20.9) = 0.46$
therefore 46% vol. This can be compared with experimental data, which gives a figure of 43–45% vol.



6.11 Total heat content diagram for the example above.

FLAMMABILITY LIMIT FOR MIXED GASES

In the case of a gas mixture, the lower flammability limit (LL) is calculated according to Le Chatelier's principle:

$$\frac{1}{C} = \sum \frac{X_j}{C_j}$$

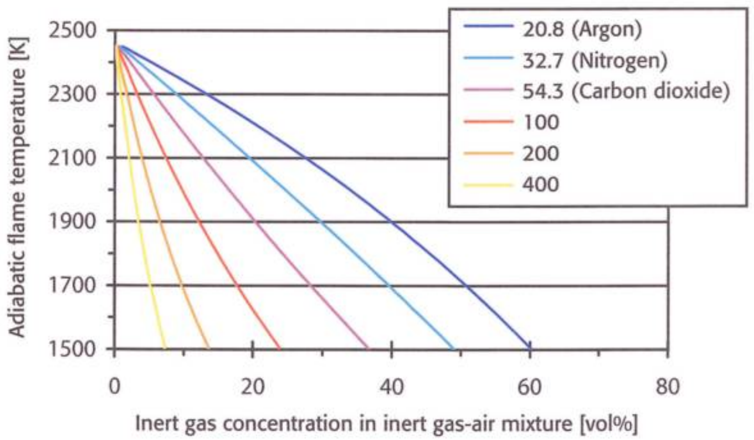
C [vol%] LL of gas mixture
X_j [–] mol fraction of substance j
C_j [vol%] LL for substance j

This principle also applies when calculating the extinction limit for mixtures containing different inert gases. If the extinction limits are known for the different constituents this means that the extinction limit for the gas mixture can be calculated.

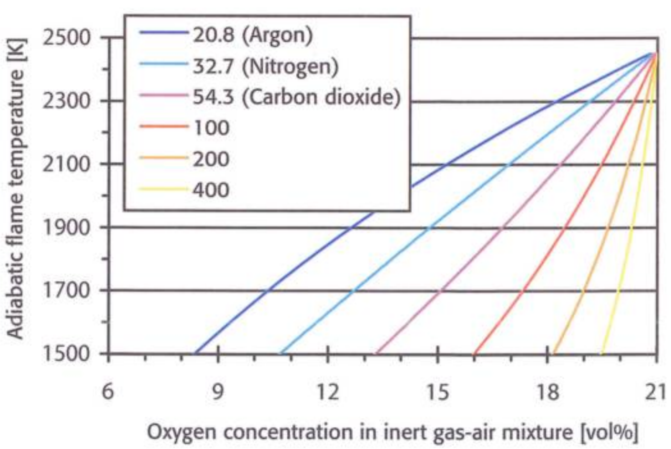
Mol% is roughly proportional to vol% for gases. To obtain the mass% the substances' molar weight needs to be included in the calculation.

OXYGEN CONCENTRATION DURING THE EXTINGUISHING

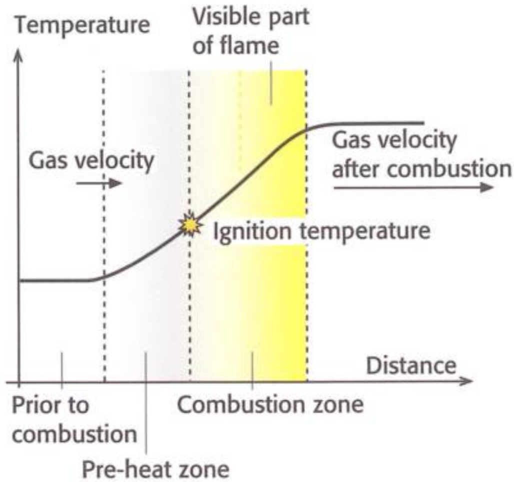
By using a constant adiabatic flame temperature at the extinction limit, the oxygen concentration at extinction may be calculated for different extinguishing agents. The oxygen concentration varies considerably. This means that suffocation, in the sense of extinguishing, through a decrease in oxygen concentration rarely occurs. In the case of powders without any chemical effect, the oxygen content at the extinction limit remains almost unchanged at 21 vol%. For halons it is roughly 19.5, for halon replacement agents 17.8. for carbon dioxide 14 and for nitrogen gas 11.5 vol%. The flames are extinguished instead by the thermal ballast reducing the flame temperature.



6.12. Adiabatic temperature calculated for dilution using inert gases with different Cp values. The extinction limit is equivalent to an adiabatic temperature of around 1550K.



6.13. The adiabatic flame temperature calculated according to the oxygen gas concentration when diluting with inert gases with different Cp values. The oxygen concentration at the extinction limit varies greatly between the different extinguishing agents.



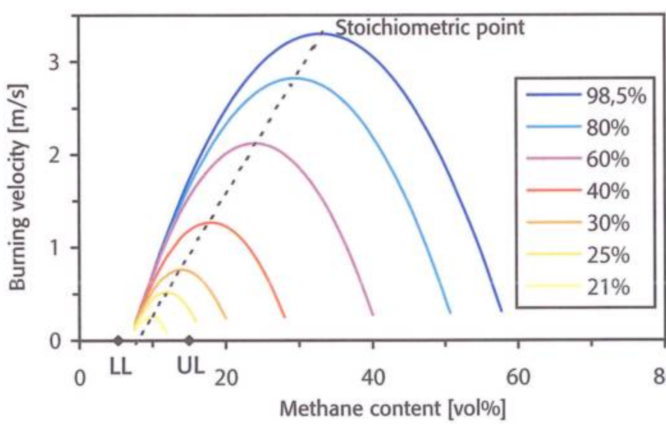
6.14 Temperature profile in a laminar flame's reaction zone.

BURNING VELOCITY

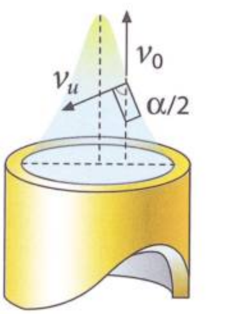
In a premixed laminar flame the burning velocity is the speed at which the cold mixture of fuel gases and air approaches the combustion zone.

In air the burning velocity for the most common hydrocarbons is 0.20–0.50 m/s. The gases' temperature increases in the flame and the gases' expansion provides acceleration after the reaction zone. The speed will then be 5–8 times faster than the burning velocity.

Close to the flammability limit the flames will often be very unstable and easy to make go out. When the mixture's composition approaches the flammability limit the burning velocity drops below 0.20 m/s at the limit. The reaction zone will be so broad at the limit that the flames will be disturbed



6.15 The burning velocity for mixtures of methane, oxygen and nitrogen at room temperature and atmospheric pressure (Lewis, 1961).



6.16 Schlieren cone method used to determine the laminar burning velocity.

MEASURING BURNING VELOCITY

Burning velocity can be measured using the deflection of light in a schlieren cone. A conical, laminar flame is stabilised on a burner. Shining a light on the flame from the side projects it onto a screen. The ratio between the flame's area and the burner area is calculated. As the velocity in the burner pipe is known, the burning velocity can be calculated. There is roughly a 10% uncertainty with this method (Lewis, 1961).

$$v_u = v_0 \sin\alpha/2$$

v_u [m/s] laminar burning velocity
v_0 [m/s] velocity of gas in burner pipe
α [°] taper angle in flame

The burning velocity varies with the mixture's composition and initial temperature, for instance. Figure 6.15 shows the burning velocities being measured for methane burning in air with an increased oxygen content. The curves do not go right down to zero because the flames will be unstable close to the extinction limit. The concentration where the flame velocity will be so low that the flames will go out is where the lower and upper flammability limits respectively are to be found for the gas mixture.

by the convective currents generated by gravity. If the gas flow increases the current will be turbulent, thereby increasing the burning velocity. This is due to the reaction area increasing with the turbulence.

Chemically active extinguishing agents reduce the burning velocity, even when they are added to a combustible gas mixture in small concentrations of a few percent. This is true, for instance, of halon 1301 and halon 1211. The extinguishing effect when the concentration is increased is mainly thermal. There are other chemical compounds too which affect the burning velocity. For example, iron pentacarbonyl has a greater effect than halons. This results from chemical inhibition where the extinguishing agent acts as a reverse catalyst. Few of the most commonly used extinguishing agents have any of this chemical effect to speak of in gas form. This also includes water, most gases, apart from halons and most types of powder.

CHEMICAL EFFECT

Most gas, liquid and powder extinguishing agents mainly have a thermal effect as they absorb heat. One exception to this is a small group of halogenated hydrocarbons, halons, and possibly a few powders. Extinguishing agents have a chemical effect if they extinguish flames at a concentration which is lower than that required thermally to reduce the adiabatic flame temperature at the extinction limit to below 1500–1600K. This reduces the rates of reaction in the combustion zone below the level which would be normal for the equivalent adiabatic flame temperature.

The chemical effect involves the extinguishing agent, or parts of it, reacting with radicals and forming stable compounds. Access to radicals in the flame front is important for breaking down the fuel.

The process is highly complex, but its effect can be compared to an increase in activation energy. Adding a chemically active extinguishing agent modifies the reaction's kinetic pattern by affecting the chain and radical reactions. The extinguishing agent neutralises radicals such as H· and HO· by forming stable products such as hydrogen bromide and hydrogen chloride.

Halons containing chlorine, bromine and iodine produce the largest chemical effect. Among these, halon 1211 and 1301 are worth mentioning, but even for these, the thermal storage capacity has a major impact on the progress of the extinguishing process. Extinguishing agents containing fluorinated hydrocarbons mainly have a thermal effect.

Some flame retardants contain halogenated hydrocarbons. They actually use similar mechanisms to halons to exert their impact on fire.

DETERMINING THE EXTINCTION LIMIT

The inerting threshold is the determining limit for preventing a premixed gaseous mass from igniting. The values listed in tables are usually for a mixture of propane, air and extinguishing agent. These values can be found in the chapter on gases. Other fuels or different compositions of air give different inerting thresholds.

The difference in quantity is much greater between the various extinguishing agents, if calculated on the basis of volume rather than mass. The reason for this is that extinguishing agents with low inerting thresholds also have a large molecular weight. Even though the inerting threshold in vol% can vary greatly between two different gases, the amount can be roughly the same, when expressed in g/m^3. Most gaseous extinguishing agents can cause inerting with a mixture equivalent to 600–900 g/m^3.

In the case of fine-grained powder, the value is usually specified according to the number of grams required to make a volume of gas inert, often in the order of 100 g/m^3. Powder is much more effective per unit weight than gaseous extinguishing agents, for instance. Calculated in grams per cubic metre of air, 5–10 times more gaseous extinguishing agent is required than powder agent. The problem with powder is how to get the powder grains to be suspended in air and disperse.

The inerting threshold does not include the loss the extinguishing agent suffers when the system is activated. In order to make a gas mixture inert, the concentration of extinguishing agent needs to be maintained throughout the whole area where flames can occur.

When using a portable fire extinguisher, the spray of extinguishing agent is directed at the base of the fire. In a fixed extinguishing system a streaming agent is used when it is known where the fire may break out, for example, in a machine. However, it is often not known where the fire may break out and how it will spread. In this instance, a total flooding agent is used to protect the whole room, wherever the fire breaks out. Gaseous extinguishing agents are less suitable for fires outdoors.

When gaseous extinguishing agents are used as part of a total flooding system, they are designed to create a non-combustible atmosphere throughout the whole room when activated. This means that the entire quantity of extinguishing agent is discharged, even if the fire is small. After the system has been activated, it has to be replenished before it is ready to use again.

Extinguishing diffusion flames using the gas phase effect

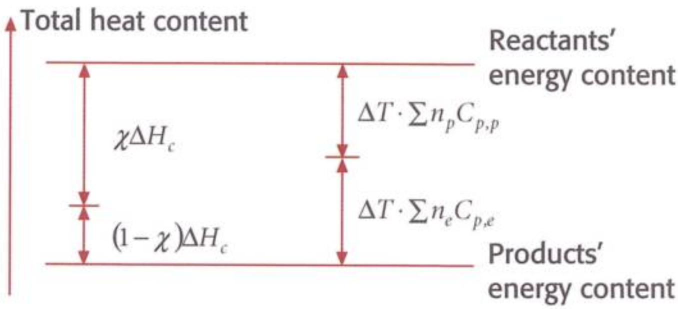
Diffusion flames are flames in which the fuel and oxygen are not mixed from the start. In general, a smaller quantity of extinguishing agent is required to extinguish diffusion flames than premixed flames. This is mainly because the heat loss is greater in a diffusion flame than in a premixed flame. Diffusion flames have a lower combustion efficiency, radiate more heat and are often in contact with cooling surfaces.

When diffusion flames are higher than a couple of metres there are signs that the level of cooling required to extinguish the flames is increasing, approaching the ratio for premixed flames. Diffusion flames contain narrow reaction zones where the fuel and air are mixed with a composition within the flammability limits. The mixture's composition is mostly controlled by turbulence and varies. Unfortunately, there is no single extinction limit for diffusion flames equivalent to the inerting threshold for premixed flames. There must always be, however, a higher concentration of extinguishing agent to extinguish premixed flames at the stoichiometric point than to extinguish equivalent diffusion flames. The powerful turbulence in normal diffusion flames often makes them easy to disrupt. However, it is more costly to design a fixed system for tackling diffusion flames based on the inerting threshold.

SIMPLIFIED THERMAL THEORY

The thermal extinguishing theory for diffusion flames uses also the concept of adiabatic flame temperature at the extinction limit. But in the case of diffusion flames, it is assumed that the adiabatic flame temperature will be somewhat higher, as diffusion flames lose more heat than premixed flames. The temperature is calculated using the extinguishing concentrations measured from experiments and will be the same for all inert gases. Halons, which have a chemical extinguishing effect, reach a somewhat higher temperature.

With no loss, all the energy released is used to heat up the combustion products and the extinguishing agent, in the same way as for premixed flames.



6.17 Total heat content for a diffusion flame.

6.18 Predictions for extinguishing concentrations for diffusion flames produced by heptane (Ewing et al., 1994).

Extinguishing agent	Measured extinguishing concentration [vol%]	Calculated adiabatic flame temperature [K]	Calculated extinguishing concentration [vol
Nitrogen	30.0	1880	29.8
Carbon dioxide	21.0	1880	20.7
Argon	40.5	1880	40.1
Halon 1301	3.5	2100*	3.5
Halon 1211	4.4	1993*	4.6

*The fact that the adiabatic flame temperature will be higher than for inert gases does not reflect the actual flame temperature, but is a way of handling the halons' chemical extinguishing effect.

$$\Delta H_c = \Delta T \sum n_p C_{p,p}$$

Using a reduced concentration of extinguishing agent for the extinguishing operation entails a rise in the adiabatic flame temperature in order to achieve the heat balance. The real flame temperature, however, will not be higher for diffusion flames than for premixed flames. In fact, it is the heat released which falls when complete combustion does not take place. Varying the adiabatic flame temperature is therefore a way of handling the reality.

THEORIES AT MOLECULAR LEVEL

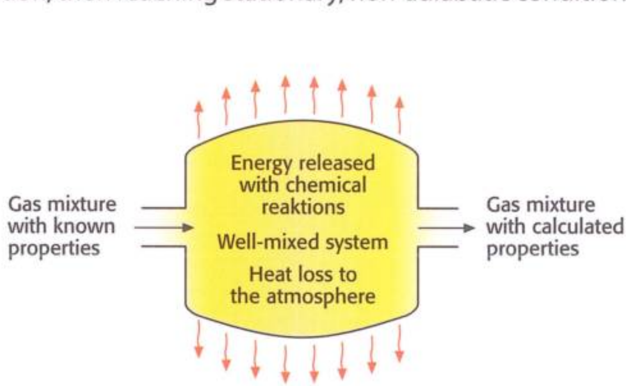
The simplified thermal theories for both premixed and diffusion flames produce adiabatic flame temperatures at extinction limits, which are far beyond the actual temperatures in the flames. To gain a better understanding as to why the adiabatic flame temperature at the extinction limit is relatively independent of both the inert extinguishing agent and fuel and how the chemically active extinguishing agent operates, the reactions must be analysed at molecular level.

In a detailed reaction kinetic study of the inerting threshold for methane, the flame zone is replaced with a well-mixed enclosure of gases. The example, including figures, is based on Tuovinen, (1989). This study only looks at the extinguishing agent's gas phase impact. A simulation was created for the enclosure with a gas mixture without any extinguishing agent being ignited with the initial temperature being set to 2000K.

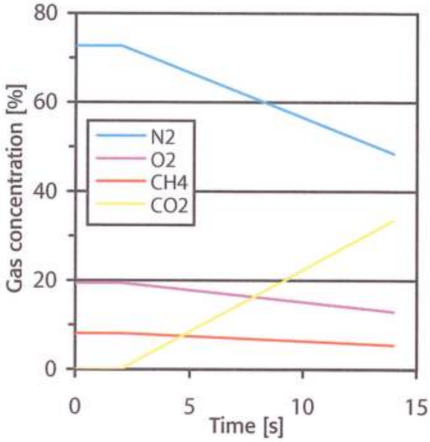
The ϕ-value (phi-value) specifies the quantity ratio between the fuel and oxygen. With $\phi > 1$, there is excess fuel and with $\phi < 1$, there is excess oxygen. With $\phi = 1$ the fuel and oxygen are in equilibrium.

Then a mixture of methane and air at room temperature was supplied from the start (0s) for 2 s. The time taken to pass through the reactor was 0.5 s. After 2 s the incoming gas started to be diluted with an inert gas. The inert gas content increased linearly over time until this mixture became incombustible. The first diagram shows the incoming gas concentration in a simulation with carbon dioxide as the extinguishing agent. The temperature graph shows how the reactor responds to the change in concentration.

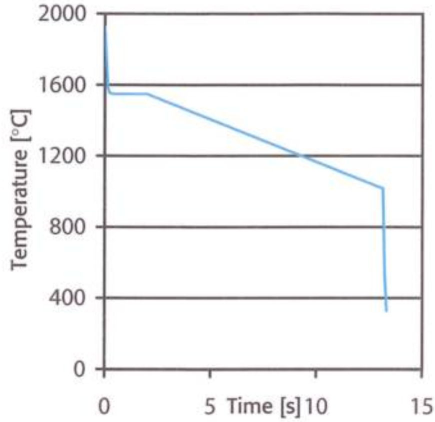
The temperature in the enclosure rises quickly after ignition, then reaching stationary, non-adiabatic conditions



6.19 Air, fuel and extinguishing agent coming from the left towards the well-mixed enclosure. Reaction products and extinguishing agent leave the enclosure to the right. Heat is lost through radiation from carbon dioxide and steam.

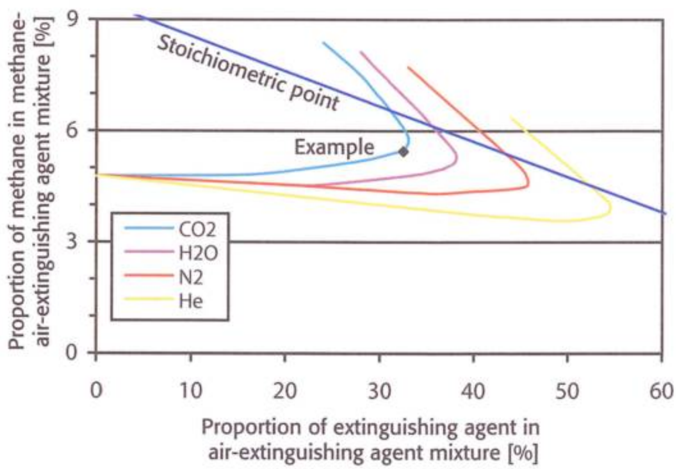


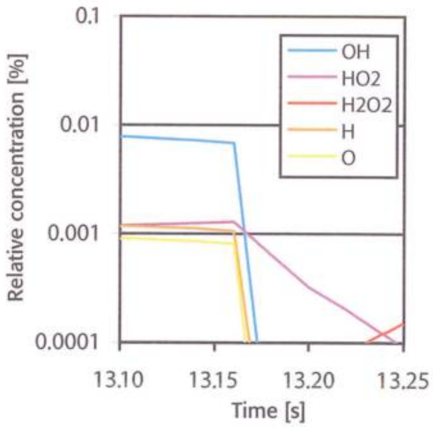
6.20 Gas concentrations in the inflow to the reactor as a function of time.



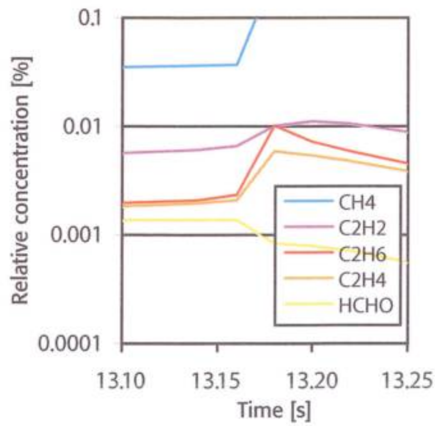
6.21 Reactor temperature as a function of time (ϕ = 0.83).

6.22 Simulated flammability limits for methane mixed with air and an inert extinguishing agent.

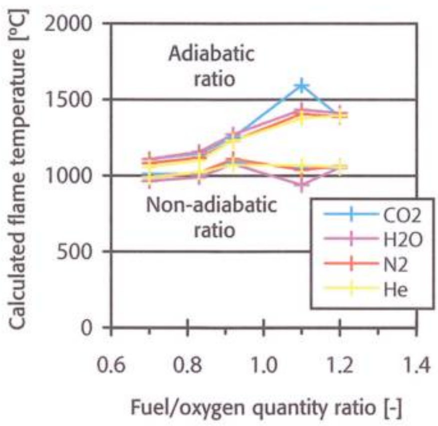




6.23 Concentration of radicals close to extinguishing with carbon dioxide (ϕ=0.83).



6.24 Concentration of larger molecules close to extinguishing with carbon dioxide (ϕ = 0.83).



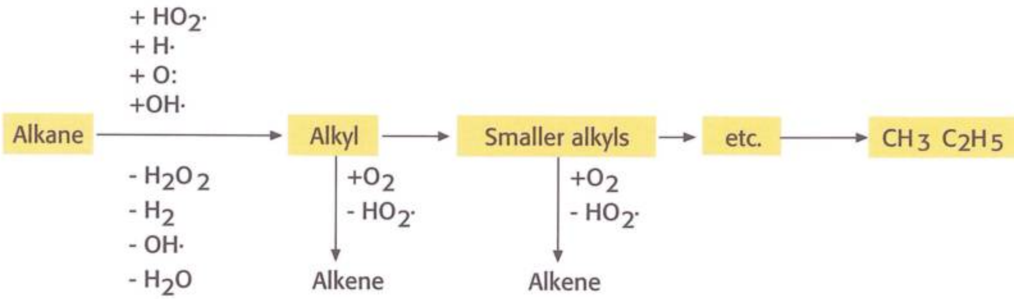
6.25 Non-adiabatic and adiabatic temperatures calculated at the extinction limit. The non-adiabatic temperature takes into account heat loss, which makes it therefore closer to the actual temperature.

after a few tenths of a second. When the extinguishing agent starts being added, the temperature drops as the concentration increases. When the mixture has reached such a level that the flame temperature has fallen to around 1000°C (1300K), the flame goes out. The temperature limit is generally independent of the time spent in the enclosure and of how quickly the extinguishing agent was added. By simulating different ratios between fuel and air, it was possible to obtain the flammability limit for different extinguishing agents. This means that similar curves are obtained as specified by the adiabatic theory. One crucial difference, however, is that the flame temperature at the extinction limit is considerably lower than the adiabatic temperature.

Carrying out simulations also provides the composition of combustion products which leave the reactor, both radicals and larger molecular fragments.

DECOMPOSITION OF MOLECULES

Many fuels start to break down to smaller molecular fragments, such as methane, at fairly low temperatures. Most of the energy is released when these small fragments react to form carbon dioxide and water. Consequently, many of the reactions where methane is oxidised are also significant during the combustion of larger molecules. The reaction pattern is very complex, even for the simplest hydrocarbon compounds and there are many different substances involved in the chemical reactions.



6.26 Principle for breaking down larger molecules.

At higher temperatures (with a small amount of extinguishing agent) the reactions mainly follow the top path in the figure, illustrating the combustion of a methane molecule. When the extinction limit approaches the concentration of radicals (H·, HO·, O:) will be so low that other reaction paths start to dominate. As a result, larger molecules start to be produced. These reactions do not lead to any greater heat release, the temperature drops further and the reactor goes out. The radical concentration in the flame is mainly sustained by the following reactions:

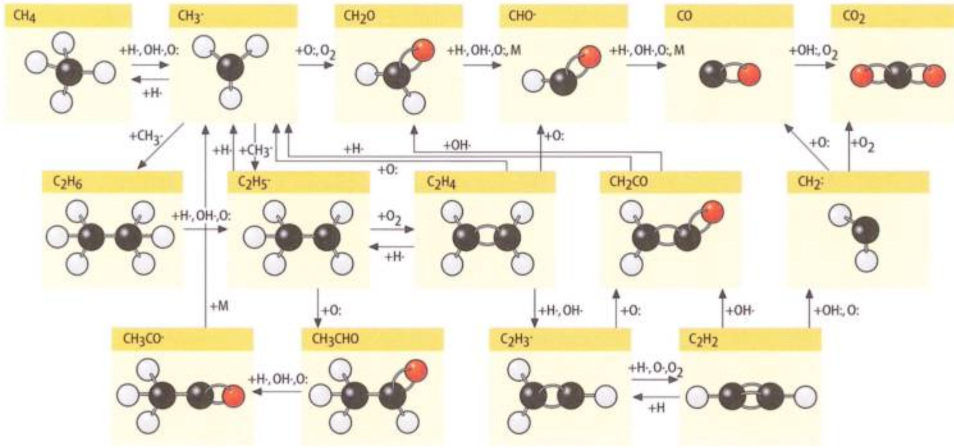
$H\cdot + O_2 \rightarrow HO\cdot + O:$ (chain-initiating reaction)
$O: + H_2 \rightarrow HO\cdot + H\cdot$ (chain-initiating reaction)
$HO\cdot + H_2 \rightarrow H_2O + H\cdot$ (chain-propagating reaction)

The rate of these reactions slows down considerably at temperatures close to the extinction limit and they are important for reactions with all hydrocarbons. This is why the adiabatic flame temperature at the extinction limit is, on the whole, the same for different hydrocarbons. This then applies generally, irrespective of the hydrocarbon fuel chosen.

These radicals also explain why the simpler theories do not apply to hydrogen and carbon monoxide, for instance.

Chemically active extinguishing agents operate on the basis of containing atoms which bind radicals and form stable products in a chain-terminating reaction. Substances containing chlorine, bromine and iodine are examples of this, which can quickly react with an H radical to form HCl, HBr and HI respectively. As a result, the radical concentration decreases, which contributes to the extinguishing process. This means that chlorine, bromine and iodine are common constituents in chemically active extinguishing agents, for example, in different flame retardants or in halon 1301 and halon 1221, which are now banned.

The thermal extinguishing effect is most significant even with extinguishing agents applying a chemical extinguishing effect. This is because these substances often have an excellent heat storage capacity. Consequently, a great deal of energy is used to heat up the thermal ballast.



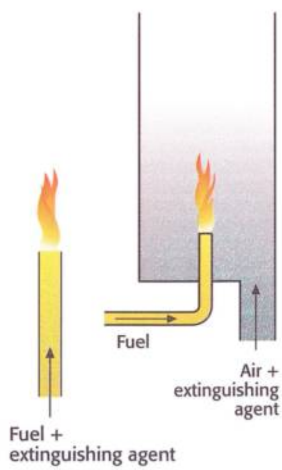
6.27 Overview of main reaction paths during the combustion of a methane molecule.

EXTINGUISHING CONCENTRATION DEPENDENT ON MEASUREMENT EQUIPMENT

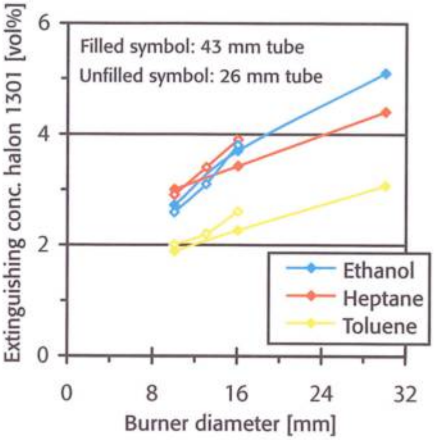
In experiments carried out on extinguishing diffusion flames, the combustible gas is usually channelled to a pipe or porous burner. The extinguishing agent may either be added to air or mixed with fuel.

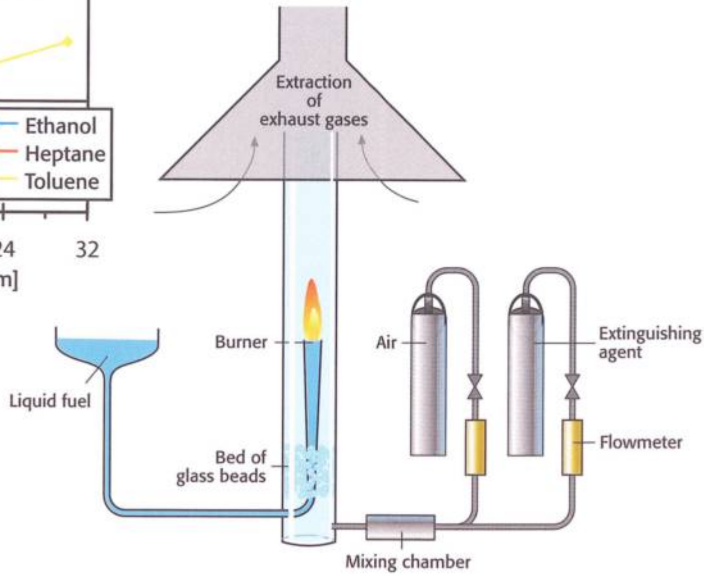
The most common method for analysing how effectively different extinguishing agents extinguish small flames is to use a cup burner, where the extinguishing agent is mixed with air and made to stream past a burner. This method is cheap and only requires a small quantity of extinguishing agent. The drawback is that there are many different variations which sometimes give different results. Another flaw is that it is difficult to translate the results from small-scale experiments to a large-scale scenario. Both differences between laminar and turbulent flames and differences in the heat balance need to be taken into account.

The extinguishing concentration for gaseous fuels is dependent, in all cup burners, on the fuel flow. The situation is more complex for liquid and solid fuels. The test results depend, for instance, on the height and diameter of the burner, the diameter of the external tube, the operator, etc. The equipment design has an impact on the cup burner value. If the burner diameter, for example, increases from 10 mm to 30 mm this will double the extinguishing agent consumption for certain fuels. This means that it is not particularly surprising



6.28 Different experiment set-ups for analysing how diffusion flames are extinguished. The extinguishing agent is mixed either with air or fuel.





6.29 (top) Example of how the result varies according to the test equipment (Saso et al., 1993). The extinguishing concentration measured depends on the fuel's mass loss rate, which in turn depends on the burner's diameter.

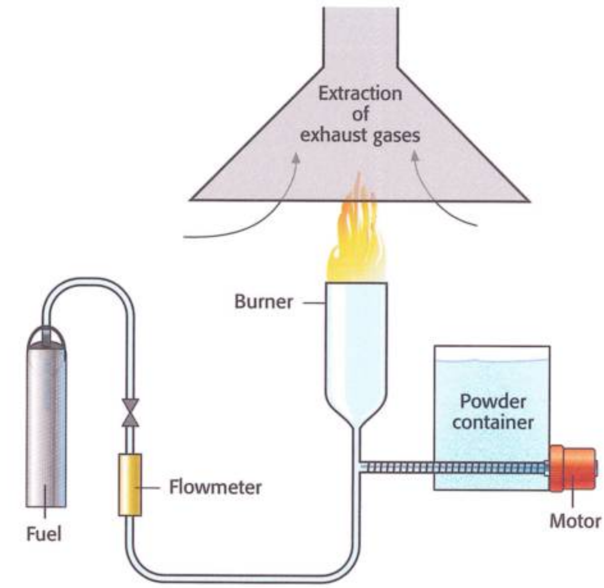
6.30 (left) Cup burner with a liquid fuel and gaseous extinguishing agent.

that cup burners used in different international standards are not properly harmonised and that discrepancies in cup burner data of 50% have been reported. As a result, cup burner data varies considerably more than experimental data for inerting thresholds. Consequently, determining the size of concentration for a total flooding agent, based on cup burner results is fraught with uncertainty.

REMP VALUE

Water and powder-based extinguishing agents cannot be mixed effectively with air. To get round this problem and be able to analyse the process of extinguishing large flames with a heat release of over 100 kW, the tubular tube method has been developed. This method was originally used for analysing the extinction of jet flames at leaks in natural gas pipes with water. The method was later developed for covering the extinguishing of gravity-controlled diffusion flames using powder.

The relationship between the fire's heat release and the extinguishing agent's application rate may be determined using test methods where the ideal application has been achieved, regardless of any manual impact. With the burner method the



6.31 Example of a tubular tube burner design, in this instance, with gas as the fuel and powder as the extinguishing agent.

extinguishing agent is applied to a propane flame. The results from this type of test specify the extinguishing agent's gas phase effect as a REMP (Required Extinguishing Media Portion) value. This indicates the mass ratio at the time of extinguishing between the extinguishing agent and fuel, usually propane.

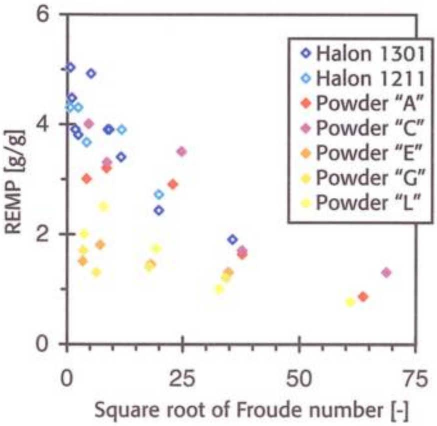
$$\text{REMP} = \dot{m}_e / \dot{m}_f$$

A REMP value of 1 means that 1 g/s of extinguishing agent can extinguish a propane flame with a mass flow of 1 g/s. This fuel flow produces a heat of about 40 kW. The REMP value is an effective tool for estimating how a large fire can be extinguished using different portable fire extinguishers, for instance. A good extinguishing agent has a low REMP value.

Different extinguishing agents have a different effect per weight and therefore, have different REMP values. Water has a best REMP value of 1–2. In this case, the water droplets are small enough, about 0.05 mm, for all the water to vaporise (Andersson et al. 1996). Usually, only a small amount of the water in the flames vaporises, which is why the REMP value may rise. Even with a REMP value of 10–40, the water is used fairly effectively.

The best types of powder have a REMP value of 1.0–1.5. The REMP value depends on the grain size. The more fine-grained the powder is, down to as low as about 10 µm in diameter, the more effective it is.

The REMP value for the halons 1301 and 1211 is roughly 4–5 and inert gases and most halon replacement agents have a value of around 10–15.



6.32 The REMP value is affected by the Froude number. This graph shows data for different types of powder, as well as for halons in an experiment in a tubular tube burner (Holmstedt et al., 1986).

IMPACT FROM FROUDE NUMBER

The REMP value is fairly independent of the heat release rate and the burner diameter, as long as the Froude number, Fr, do not change. The Froude number is a dimensionless number used to classify diffusion flames (Holmstedt et al. 1986). This provides a measurement for the amount of movement by the fuel in relation to gravity.

$$Fr = Av^2 / gd$$

v [m/s] average gas velocity in the burner
g [m/s²] gravity acceleration
d [m] burner diameter

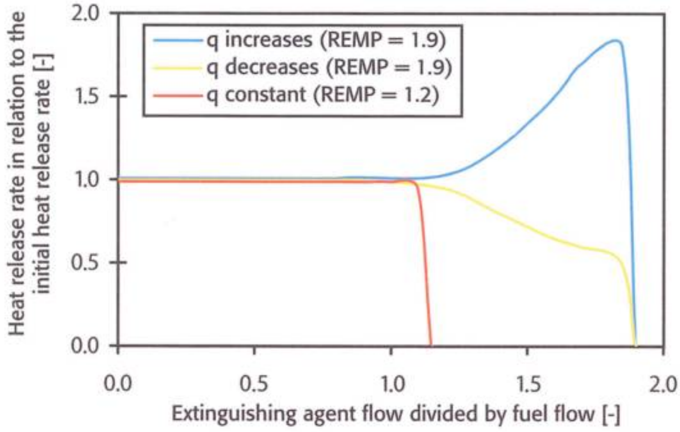
If the discharge rate and hence the burner effect double the Froude number increases fourfold. When mixing a gas with solid particles or liquid droplets, factor A is included, which is defined as:

$$A = 1 + \dot{m}_e / \dot{m}_f$$

$\dot{m}_e$ [g/s] extinguishing agent's mass flow
$\dot{m}_f$ [g/s] fuel's mass flow

If the Froude number is lower than about 500 the flame's appearance is dominated by gravity and the REMP value is fairly high. With a Froude number below about 100, the REMP value is generally constant. This applies to most normal fires.

If the fuel's velocity increases, and with it the Froude number, the REMP value decreases. This is the case, for instance, with fires where gas streams out. Froude numbers above 10000 indicate fully developed jet flames, whose appearance is generally controlled by the extent of the gases' movement. With really high Froude numbers the flames will be unstable and may spontaneously go out. These jet flames usually only appear if pipes in a pressurised system burst.



6.33 Certain extinguishing agents reduce the heat release rate in the flames right before extinction. Others do not have any impact on the heat release rate at all. Others still make the heat release rate increase.

HEAT RELEASE RATE IMMEDIATELY PRIOR TO EXTINCTION

By analysing the heat release rate and heat radiation immediately before extinction, it is possible to obtain information about what may happen if an extinguishing system is not large enough to cope with the fire. Three types of extinguishing agent behaviour can be distinguished. One group, including halon 1301 and large-grain powder, reduces the heat release rate in the flames prior to extinction. Inert gases and fine-spray water do not affect the heat release rate before the extinction limit is reached. Halon alternatives comprising fluorinated hydrocarbons, which contain at least one hydrogen atom, increase the heat release rate until extinction is achieved.

DETERMINING EXTINGUISHING AGENT CONSUMPTION

There is always a degree of uncertainty in determining the size of an extinguishing system using small-scale methods. When portable fire extinguishers are being classified, different pool fires or wood cribs are used. The heat released by these fires varies between a couple of hundred kW to 5–10 MW.

The following approximate equation between the application amount and extinguishing capability can be used for a portable fire extinguisher with a powder or gaseous extinguishing agent.

$$Q = \frac{\dot{m}_e \cdot x \cdot K}{REMP} \Delta H_{c,f}$$

Q [W] possible extinguishing effect

$\dot{m}_e$ [g/s] extinguishing agent's mass flow

$\Delta H_{c,f}$ [J/g] fuel's heat of combustion

x [–] combustion efficiency

K [–] extinguishing agent application efficiency

6.34 A large powder extinguisher has a powder flow of around 400 g powder per second. If the REMP value is 2 the extinguishing capacity will be around 8 MW. This is equivalent to a petrol fire with an area of 4 m². Petrol burns at a rate of a good 4mm/min, which produces a heat release rate of around 2 MW/m².

An extinguishing agent's approximate REMP value can also be calculated, based on thermal extinguishing theory. A REMP value based on inerting premixed flames is roughly 1.5–2 times larger than that required to extinguish diffusion flames. You should note that REMP values do not contain any adjustment for shortcomings in the distribution of the extinguishing agent.

An argument similar to the REMP concept can be used when water is selected as an extinguishing agent. By comparing the fire's heat release rate with the water's capacity to absorb energy as a result of vaporisation and heating, the required flow may be determined for different fire sizes (Särdqvist 1996; Barnett, 1990). 0.00418 MJ/kg°C is needed to heat water, which means that water at 10°C needs 0.38 MJ/kg in order to be heated up to boiling point. After this, 2.26 MJ/kg is required to vaporise the water. The steam at 100 degrees then requires 0.00201 MJ/kg°C to be heated up further. If the final temperature is 600°C the energy required will be 1.00 MJ/kg.

The temperature in a room at the time of a flashover is around 600°C. To convert water at 10°C to steam at 600°C requires 0.38 + 2.26 + 1.00 MJ, giving a total of 3.6 MJ. About 45% of the energy released needs to be cooled down away from the flames. Using propane as the fuel, the calculated extinguishing effect can be used to make a rough estimate of water's extinguishing effect, expressed as a REMP value:

$$REMP = \frac{\dot{m}_v}{\dot{m}_f} = \frac{\Delta H_{c,f}}{\Delta H_v} = \frac{40}{3{,}6/0{,}45} = 5$$

The argument behind this estimate of water's REMP value can be taken further and be applied practically for scoping the size of operations using water.

If water is used effectively, the efficiency factor is in the order of 0.3 (Barnett, 1990). This means that the REMP value increases to about 17 and each litre of water manages to extinguish 2.4 MW. A water spray with a flow of 5 l/s should therefore be able to tackle a fire with a heat release in the order of 12 MW. The problem with extinguishing such large diffusion flames manually is being able to cover the whole flame, which means that the practical extinguishing effect is reduced. This is compensated by the fact that the non-vaporised water often reaches the fuel surface and extinguishes by fuel surface cooling.

It is possible to use the REMP value to determine the size of an operation using portable fire extinguishers or a streaming agent. On the other hand, the REMP value cannot be used to determine the size of an operation using a total flooding agent, where the whole room is filled with extinguishing agent, regardless of how big the fire is and where it started. In this instance, determining the size based on full-scale experiments may provide a viable option. The test parameters should be similar to the conditions in which the extinguishing system is going to be installed, using different fuels and burning times. Unfortunately, the results from full-scale tests in compartments have a number of flaws. The extinguishing result depends on the scenario, which includes the size of the fire and location in relation to the nozzles. The extinguishing agent is often unevenly distributed in the room. A large fire may spontaneously go out when the oxygen concentration drops and the smoke is recirculated. Consequently, assessing full-scale extinguishing

Extinguishing agent	REMP-value
Powder	1–4
Water	2–40[1]
Inert gases	10–12
Halons	4–5

1. Varies greatly with droplet size.

6.35 REMP value at effective application for a number of different extinguishing agents.

Extinguishing agent	Cup burner [vol% ext. agent in extinguishing agent-air mixture]	Cup burner [gram extinguis-hing agent per mol air]	REMP value [gram extinc hing agent per gra
Powder	–	1–2	1–4
Water fog (10 µm)	–	3–4	2–3
Halon 1301	5	5.5	4–5
HFC-gases	7–10	10–12	10–15
Carbon dioxide	20–23	11.8	10–12
Argon	30	12	12–15

6.36 Approximate amount of extinguishing agent required to extinguish diffusion flames.

tests and applying the extinguishing results to scenarios other than those tested often causes problems.

There is a large amount of data available in the literature about extinguishing agents in terms of the required concentration for extinguishing diffusion flames. The most common is cup burner data, REMP values and data from full-scale tests. The need for the extinguishing agent varies, however, with the fuel. When determining the size of an operation then, the relevant type of fuel involved needs to be taken into consideration.

In this case, extinguishing concentrations and efficiency are being compared per unit weight of the extinguishing agent. Data has been taken from cup burner, tubular tube burner and full-scale tests. The cup burner values are considerably lower than equivalent data for inerting a premixed gas mixture.

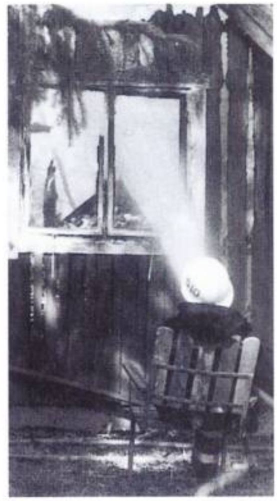
Extinguishing diffusion flames through surface impact

Only a small amount of the water used in extinguishing a fire goes on cooling down flames and smoke and facilitating access, in the case of an interior attack. Most of it is used to cool down the fuel surfaces, which is also confirmed by experiments on manual firefighting (Palm, 2000).

CRITICAL WATER APPLICATION RATE

The water flow rate required to extinguish a fire increases with external radiation and is balanced by the water's heat of vaporisation (Rasbach 1986). The energy required to heat up and vaporise water from 10°C to steam at 100°C is 2640 kJ/kg. This means that 1.0 kg/m^{2}s water, which hits the surface and is vaporised, neutralises external radiation in the order of 2640 kW/m^2. If only this heat balance is taken into account, a radiation level of 10 kW/m^2 requires a water flow rate 0.0038 kg/m^{2}s higher than without radiation.

The critical extinguishing agent application rate is defined as the minimum extinguishing agent flow rate required to extinguish a burning surface, with an infinite period of time available. This flow rate for water has been estimated at about 0.0002 kg/m^{2}s (Heskestad, 1980). The water flow rate was measured per unit area of the exposed fuel and was determined in an experiment where a wooden cribwork about 1 m high was extinguished under controlled conditions. The gas phase effect was small as the water droplets were large. This flow rate has been confirmed by the Fire Point theory. Experimental data varies otherwise between 0.0013–0.0030 kg/m^{2}s. This discrepancy is likely to be due to errors in the test parameters and data collection, but also due to how long an "infinite" extinguishing time is defined as.



6.37 The extinguishing time will be long if too little extinguishing agent is applied, or if the agent is applied in the wrong place.

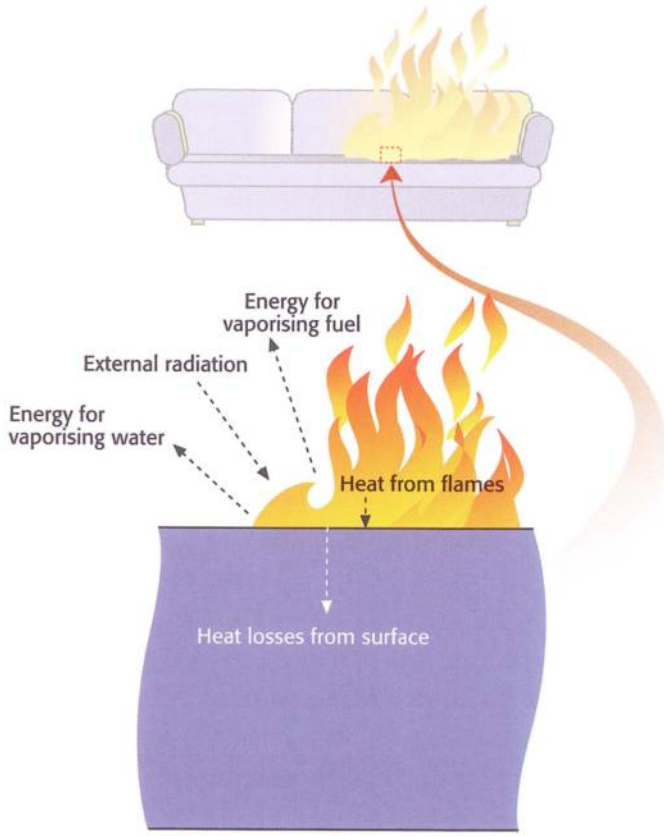
FIRE POINT THEORY

When extinguishing diffusion flames, both the flames and fuel surface cool down. Also, a drop in the flame temperature causes the heat radiation towards the burning surface to decrease. This means that the quantity of pyrolysis gases from the surface decreases. The Fire point theory has been developed for this phenomenon, which is based on an energy balance being achieved at the fuel surface during the extinguishing process (Rasbach, 1976; Beyler, 1992; Delichatsios, 1997).

The energy balance at a fuel surface can be described as:

$$L_v m'' + Q_L'' + Q_w'' = f\Delta H_c m'' + Q_E''$$

which is the same as:



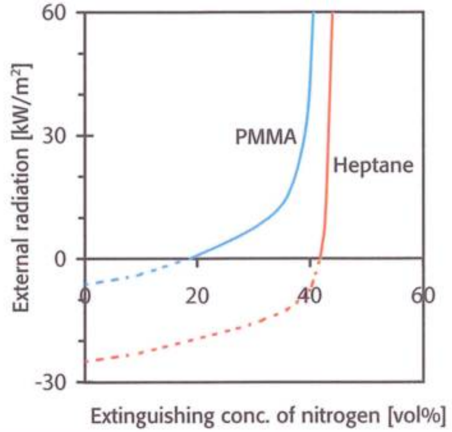
6.38 Energy balance for a burning surface in a compartment fire.

$$\left(f\Delta H_c - L_v\right)m'' + Q_E'' - Q_L'' - Q_w'' = 0$$

f [–] proportion of energy released which is fed back to the surface
ΔH_c [J/kg] fuel's heat of combustion
L_v [J/kg] fuel's heat of vaporisation
m'' [kg/m^{2}s] mass loss rate
Q_E'' [W/m^2] external radiation to the surface from the atmosphere outside the flames
Q_L'' [W/m^2] surface losses
Q_w'' [W/m^2] cooling of surface through application of water

The extinguishing condition is met when flames can no longer be sustained above the surface. The process of extinguishing diffusion flames can be described using the proportion of the energy released, ϕ, which must be channelled away for the flame to go out. In the case of both premixed and diffusion flames, this amount of heat can be specified on the assumption that there is a constant adiabatic flame temperature at the extinction limit. With premixed flames, about 45% of the heat released must be absorbed by the extinguishing agent or cooled down in a different way. The proportion is smaller for diffusion flames, usually about 10–40%. It is lower for chemically active extinguishing agents.

The flames radiate much less and get nearer to the fuel surface when approaching the extinction limit. Close to the extinction limit the radiation from the flames will be very small. During this situation the convective heat transfer from the flames to the fuel surface will dominate. This means that ϕ will replace f in the energy balance at the extinction limit.



6.39 The extinguishing agent concentration required, calculated using the Fire Point theory, varies with the external radiation level. It varies for different fuels. At high radiation levels the concentration approaches the inerting threshold.

$$(\phi \Delta Hc\text{-}L_V)m''_{cr} + Q''_E - Q''_L - Q''_w = 0$$

m''_{cr} [kg/m²s] critical mass flow of fuel at extinction.

The fuel's mass flow is determined by convective heat transfer. What is known as the B number theory is used to calculate the convective heat transfer to a vaporising surface. This gives the critical mass loss rate (Spalding, 1955).

$$m''_{cr} = h / c_p \, ln(1 + B_{cr})$$

$$B_{cr} = Y_O \Delta H_{R,O} / (\phi \Delta H_c)$$

B_{cr} [–] ratio between the amount of energy released and the energy used to vaporise the fuel
Y_O [–] oxygen mass fraction
$\Delta H_{R,O}$ [kJ/g] energy released per mass of oxygen consumed

These terms can be included in the surface energy balance:

$$(\phi \Delta H_c\text{-}L_v)\left[h / c_p \ln\left(1 + Y_O \Delta H_{R,O} / (\phi \Delta H_c)\right)\right] + Q''_E - Q''_L - Q''_w = 0$$

This equation, sometimes called the Fire point equation, fortunately contains many constants, such as the terms h, c_p, $\Delta H_{R,O}$, ΔH_C and L_v, which relate to the fuel.

If water is used as an extinguishing agent the following heat loss will be due to this if the energy for heating the water to boiling point is ignored,

$$Q''_w = c_w m''_{cr,w} L_{v,w}$$

$L_{v,w}$ [kJ/kg] water's heat of vaporisation
c_w [–] proportion of water reaching and vaporising at the fuel surface

By working out the external radiation from the Fire point equation we get:

$$Q''_E = c_w m''_{cr,w} L_{v,w} - (\phi\Delta H_c - L_v)[h / c_p \ln(1 + Y_O \Delta H_{R,O} / (\phi\Delta H_c))] + Q''_L$$

The equation describes a linear relationship between external radiation and the water demand. The direction coefficient is $c_w L_{v,w}$ and the terms to the right of the minus sign gives the intersection with the Y axis. Experiments provide results which consolidate the theory. In reality, it is difficult to add so little water that it is all vaporised on the surface, c_w is therefore small in many cases. The equation means that the extinguishing concentration for diffusion flames also depends on the external radiation.

If reasonable values are assumed the critical water application rate can be calculated (Särdqvist & Holmstedt, 2001). If wood burns under normal conditions ΔHc will be roughly 13 MJ/kg and Lv 1.8 MJ/kg.

With an ignition temperature of 385°C the convective heat transfer coefficient, h, will be about 10 W/m^{2}K and c_p 1.06 kJ/kgK. In well-ventilated conditions Y_O is 0.233. The oxygen content, however, must be reduced due to the vaporising water.

$$Y_O = \frac{\dot{m}''_o}{\dot{m}''_{cr,w} + \dot{m}''_f + \dot{m}''_o + \dot{m}''_{N2}}$$

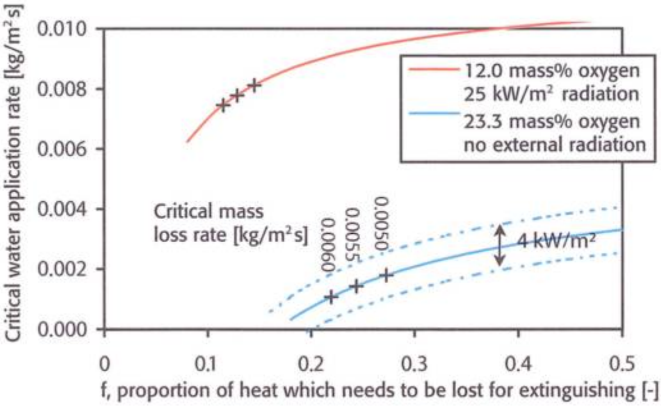
In a small-scale experiment using chipboard, the board's fuel loss was 0.0055 kg/m^{2}s. The chemical sum formula for wood is roughly $CH_{1.7}O_{0.85}$, with a molecular weight of 0.027 kg/mol. At the stoichiometric point one mol of wood requires 1.02 mol of oxygen for combustion. This means that the oxygen content can be adjusted.

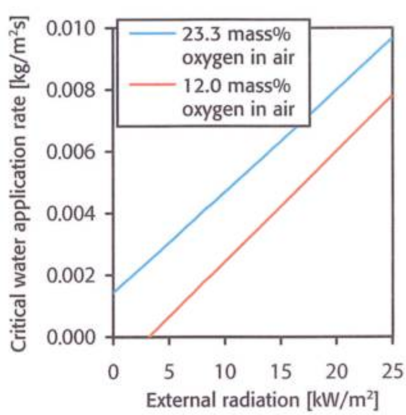
$$Y_O = \frac{\frac{0.0055}{0.027} 1.02 \cdot 0.032}{\dot{m}''_{cr,w} + 0.0055 + \frac{0.0055}{0.027} 1.02 \left(0.032 + \frac{0.79}{0.21} 0.028\right)}$$

$\Delta H_{R,O2}$ for wood is 12.4 MJ/kg. If the fuel surface's reradiation and losses are ignored $\dot{q}''_L$ will be the energy still being conducted in the fuel.

$$\dot{q}''_L = \lambda \frac{dT}{dx}$$

The conductivity, λ, is dependent on the temperature, and the value for wood at the ignition temperature is 0.2 W/mK. dT/dx has been calculated to around 330K/0.010 m. This gives a rough estimate for $\dot{q}''_L$ of 6.5 kW/m^2. There is no data available for c_w, but the lowest water application rate is obtained if we ignore





losses. $L_{v,w}$, the energy used to heat up water from 10°C to 100°C and for vaporisation is 2640 MJ/kg. The relationship between the critical water application rate, $\dot{m}_{cr,w}$ and ϕ will be

$$\dot{m}''_{cr,w} = \frac{(\phi \cdot 13.0 - 1.3)\left[\frac{10}{1} ln\left(1 + \frac{Y_{O2} \cdot 12.4}{\phi \cdot 13.0}\right)\right] - 6.5}{1 \cdot 2640} \text{ kg/m}^2\text{s}$$

Based on this assumption, the oxygen concentration and the critical water flow rate can be interpolated. The oxygen content falls to about 16%. ϕ is usually 0.1–0.4. The terms in square brackets represent the fuel's critical mass loss rate, obviously linked to ϕ as well. The value for the fuel mass loss rate used in the calculations, 0.0055 kg/m²s, is shown in the left figure along with a 0.001 kg/m²s span. This mass loss rate gives a critical water application rate of around 0.0014 kg/m²s, taking into account the assumptions made above. This concords with experimental data. Some estimates are approximate, such as $\dot{q}''_L$. The figure shows the effect resulting from a change of 2 kW/m². It is also worth noting that the heat losses varies with the thermodynamic properties of the fuel.

The vaporised water will influence the gas mixture above the fuel surface. This means that the vaporised water will reduce the oxygen concentration, which affects the amount of water required to extinguish the fire. The figure is based on the example and contains a line showing the relationship between radiation level and the water demand for wood in well-ventilated conditions, as well as a line showing the demand during flashover creating an additional 25 kW/m² of radiation, while the oxygen content is reduced to 12% (before any adjustment for steam) due to smoke recirculation.

The same argument can also be used in a situation with a pure gas phase effect to show how the concentration of extinguishing agent at the extinction limit varies with the external radiation for diffusion flames.

6.40 (left) Relationship between f and the critical water application rate.

6.41 (top) Water demand increases with radiation. The water demand is less with a lower oxygen concentration.

Extinguishing agent	l/m^2min
Water (sprinkler)	5–30
Water manually applied)	9–15
High-expansion foam	1–2[1]
Medium-expansion foam	2–3[1]
Low-expansion foam	4–6[1]

1. Expressed as a water/foam concentrate mixture.

6.42 Some typical application rates for liquid extinguishing agents.

SCOPING THE SIZE OF FIREFIGHTING OPERATIONS

Firefighting operations involving water or foam are often described in terms of an application amount per fire area in l/m^2min, as surface impact is the key factor with these extinguishing agents. The values usually include a safety margin.

It is important to note that the application rate is specified based on the floor area or the horizontal fire area. In an experimental situation, fuel surface is often used instead, which may be much larger. The fire's heat release rate per m^2 varies considerably between about 100–4000 kW/m^2, which is one of the reasons for the range of application rates being fairly large.

Smouldering fires

In certain materials, a fire can develop into a deep smouldering fire. A smouldering fire is not the result of a gas phase reaction, but of reactions at the fuel surfaces of the decomposing material. With surface reactions, it does not help to reduce the temperature in the gas phase above the surface. Instead, the concentration of the extinguishing agent in the air must be held above the inerting threshold for as long as it takes the seat of the fire to cool down.

In a smouldering fire the flames are of secondary importance. It is the chemical reaction inside the fuel, instead, which is the interesting aspect. This is crucial, regardless of whether the fire involves wood with a superficial carbon layer on it or is deep inside a stack of peat, which has spontaneously ignited.

Smouldering fires, especially deep smouldering fires in stored material, are controlled by breakdown processes in the material, often without any significant mixture of oxygen from the air. During these reactions, there is very little of the fuel's energy content released. On the other hand, the surrounding fuel acts as an insulating thermos. The small amount of energy which is released remains in the material, causing the temperature to rise. This effect is one of the main reasons why spontaneous combustion occurs. As the material provides insulation, the heat is released inside the material, causing the temperature to rise. Spontaneous combustion, however, is dealt with in other connections (e.g. Beever, 1995).

TO DIMENSION THE SUPPRESSION OF SMOULDERING FIRES

As the seat of a deep smouldering fire lies within the material, this makes this type of fire difficult to extinguish. The material surrounding the seat of the fire will protect it against most known extinguishing agents. Foam, for instance, will lie on the material's surface, with little effect. Water will either run off or be absorbed by the surrounding material, but will not be able to penetrate through the material properly. Surface tension reducing agents may help the water to penetrate the material, but if it is a far way down to the burning material this will not even be enough. The extinguishing agents which operate in gas phase can often not be used, precisely because of this. They exert an extinguishing impact in gas form, whereas the fire continues to burn inside the material.

Consequently, there are two basically different ways to extinguish a fire in stored material. The first of these invol-

6.43 Deep seated smouldering fires are often enveloped in so much material that they are insulated from the atmosphere, just like the contents in a thermos. This is why they are very difficult to extinguish.

ves tackling the fire by physically moving the fuel away. To start with, the burning material is separated from the material which has not yet been ignited. If possible, the unaffected material is moved to a safe place. Then the burning section is attacked by digging it out, and the excavated material is extinguished bit by bit. This is the quickest method, but requires major resources as the fire will flare up gradually as the smouldering material is released. One variation on this method which is used, in practice, to tackle many fires, for instance in warehouses, is to actually prevent the fire from spreading and let the involved material burn in controlled conditions.

In the second method, an incombustible atmosphere is created round the material using a gaseous extinguishing agent. Then you wait until the temperature has fallen. For this method to be successful, the material needs to be tightly enclosed, for instance, in a silo, and the operation is maintained until the temperature has dropped at the seat of the smouldering fire. If the concentration is too low or if the time is too short, the flames may go out but the fire will flare up when the enclosure is opened again. You should note that the inerting threshold depends on the temperature and that the temperature is increased inside the smouldering material. As a result, smouldering fires require a significantly higher extinguishing concentration over a lengthy period of time. This type of fire can be compared to a charcoal stack and is just as difficult to extinguish when it has started to smoulder.

Using carbon dioxide to extinguish smouldering bales of paper in a loading room, it took a whole day, using double the concentration for the inerting threshold at room temperature. With a carbon dioxide concentration 50% higher than the inerting threshold, it took two days to extinguish the fire (Beene & Richards, 1983).

One requirement for using this method is that the fire was not caused by spontaneous combustion. Any stored material which has spontaneously combusted has actually shown from the outset that it is capable of combustion without an external oxygen supply.

During the entire firefighting operation, firefighters must be prepared for unexpected events. As the fire continues to burn, cavities may form in some materials allowing combustible gases to accumulate. When these cavities collapse the gases may come into contact with oxygen and ignite. Collapse can also mean that a cloud of dust may swirl up. The subsequent dust explosion may be large enough to lift the roof off the silo, or in the worst case scenario, to burst the silo.

When charcoal is made in a stack, the wood's volume decreases to about half during the carbonisation process. The stack then has to be knocked down to prevent cavities from being formed. If cavities still manage to appear there is a risk that the stack will flare up. This means that the covering layer will collapse. The air then gets in and the flames will flare up. This can be prevented by filling any cavities with wood and then covering the surface with cinders, after which the carbonisation process continues.

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List of quantities

The following is a list of the designations and units for the quantities used in this book. Quantities designated by Greek letters come after the letters in the standard alphabet. A list of indices is provided separately.

A	reaction constant
A [m^2]	area, cross-sectional area
A [–]	adjustment term when calculating Froude numbers
B_{cr} [–]	ratio between the amount of energy released and the energy used to vaporise the fuel
C [vol%], [mol/m^3]	gas concentration
c_p [kJ/kgK = J/gK]	heat capacity, per mass
C_p [J/molK]	heat capacity, per mol (air and smoke about 34, steam about 41.2)
c_w [–]	proportion of water reaching and vaporising at the fuel surface
d [m], [mm]	diameter
E_A [J/mol]	activation energy
f [–]	loss factor for hose/nozzle
f [–]	proportion of energy released which is fed back to the surface via radiation and convection
Fr [–]	Froude number, $Fr = Av^2 / gd$
g [m/s^2 = N/kg]	general gravity constant, 9,81
h [W/m^{2}K]	heat transfer coefficient
ΔH_c [J/kg]	fuel's heat of combustion
$\Delta H_{R,O_2}$ [kJ/g]	energy released per mass of oxygen consumed
H_v [kJ/kg]	changes in total heat content, for instance, during heating up and vaporisation
k [W/mK]	coefficient of heat conductivity
l [m]	length (hose, projection, fall, etc.)
L_v [kJ/kg]	heat of vaporisation (water: 2260 kJ/kg = > 40,68 kJ/mol)
m'' [kg/m^{2}s]	mass loss rate
$\dot{m}$ [kg/s]	mass flow
M [g/mol]	molecular weight
n [mol]	amount of substance for molecules
Nu [–]	Nusselt number
p [Pa = N/m^2], [MPa]	pressure

q [m^3/s], [l/min]	flow rate
Q'' [W/m^2]	heat flow, heat radiation
R [N]	reaction force
R [J/molK]	general gas constant, 8,31
Re [–]	Reynolds number
REMP [g/g]	mass ratio between extinguishing agent and fuel on extinction
t [s], [min]	time
T [K], [°C]	temperature
ΔT [K]	temperature difference
v [m/s]	velocity
v [mol/m^3]	rate of reaction
V [m^3], [l]	volume
X [–]	molar fraction
Y [–]	mass fraction
z [m]	height
α [°]	taper angle
ε [m]	sand coarseness
χ [–]	combustion efficiency
ϕ [–]	ratio between quantity of fuel and air in a flame
ρ [kg/m^3]	density
υ [m^2/s]	kinematic viscosity
μ [Ns/m^2]	dynamic viscosity

Indices

0	start position, status before change (zero level)
1	status after change or in the first of two points
2	status in the second of two points
a	air
ad	adiabatic
cr	critical, at extinction limit
e	extinguishing agent
f	fuel
f	loss (in hydraulic calculations)
g	gas
j	component j in a mixture
o	oxygen
p	products, during combustion
u	lower (flammability limit)
w	water

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To convert:	to:	Multiply with:
m^3/s	l/min	60000
Pa	kPa	$1 \cdot 10^{-3}$
Pa	MPa	$1 \cdot 10^{-6}$
Pa	bar	$10 \cdot 10^{-6}$
Pa	atm	$9.87 \cdot 10^{-6}$
Pa	mvp	$102 \cdot 10^{-6}$
Pa	kp/cm^2	$10.2 \cdot 10^{-6}$
MPa	kPa	1000
MPa	bar	10
MPa	atm	9.87
MPa	mvp	102
MPa	kp/cm^2	10.2

(CRC, 1986, page F-299-)

"Water and Other Extinguishing Agents" provides a comprehensive description of the various types of extinguishing agent used to put out fires. About half this book is devoted to the use of water. The section on foam accounts for about a quarter of the book, and the remainder looks at the use of powder and gases, with a substantial section about why fires actually go out.

This book is aimed at those involved in fighting fires. Its content ranges from the practical handling of fire service equipment to the theory behind various extinguishing mechanisms. This makes this book the first in a very long time to cover both practical and theoretical aspects in this area. It also includes common extinguishing agents.

Some of the techniques, methods and especially, the traditions involved vary among different countries. But the way in which extinguishing agents operate remains the same, whatever country they are used in. This means that the theoretical arguments are universally applicable.

Some of the firefighting equipment and principles used have not changed in over a hundred years. Others have kept pace with the development of society and technology. This book covers the whole spectrum, including both traditional firefighting methods and new concepts which are likely to feature as part of firefighting in the future.

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