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An Engineering Approach to Fire-Fighting Tactics

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Abstract:
This report presents a quantified model as a guide for the Incident Commander to determine the most suitable fire-fighting tactics in advance for given conditions at specific objects. The model is applied to two chemical warehouses. The model proves that it is possible to introduce risk management procedures and fire safety engineering models into fire-fighting tactics. If the model and its different sub-models are improved and scientifically validated, fire brigades will gain a powerful tool for predicting their capacity. The model can be used before the fire, in a pre-planning situation, during the fire to analyse the situation, or after the fire for tactical evaluation.

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You have been lazy

The Dean of Borås in Sweden, Ragnar Lundell, once told me a story which can be used to illustrate pre-fire planning used by fire brigades. It is about a German preacher, the priest Claus Harms, in the period of transition between orthodoxy and pietism.

A more pietistic priest urged Claus Harms not to prepare his sermons so well, but to trust in the Holy Ghost. He would be told what to say, at the right moment. The man referred to Luke 12:12: *For the Holy Ghost shall teach you in the same hour what ye ought to say.* [1]

Harms promised to try this, and after the Sunday service, he was asked if the Holy Ghost had told him something.

Yes, was the answer, but he said that I had been lazy.

How is pre-fire planning done by fire brigades? Are operations of the more unusual kind prepared in advance, or do the fire brigades expect the Holy Ghost to tell them what to do? What will the Holy Ghost say to the Incident Commander at the next major industrial fire?

1. Introduction

1.1 Summary

Faced with a rescue operation, the most important decision is whether to launch an offensive or a defensive operation. This report presents a quantified model as a guide for the Incident Commander to determine the most suitable fire-fighting tactics in advance for given conditions at specific objects.

The model presented proves that it is possible to introduce risk management procedures and fire safety engineering models into fire-fighting tactics. If the model and its different sub-models are improved and scientifically validated, fire brigades will gain a powerful tool for predicting their capacity.

The model consists of two parts. The first is the evaluation of the consequences of the fire, where the determination of the rate of heat release plays a central role, together with damage evaluation. The second is the determination of the extinction capacity of the fire brigade, or the rate of heat absorption. If the determined heat absorption is greater than the heat release, it is possible to launch an offensive operation. Otherwise, an offensive operation will fail to reach its aim, and a defensive approach is to be preferred, i.e. to direct all efforts into containing the fire within its boundaries. The concept is similar whether used before the fire, in a pre-planning situation, during the fire to analyse the situation, or after the fire for tactical evaluation.

This planning of intervention is part of the risk management process. During planning, some scenarios might show that an intervention is insufficient to reduce the consequences below the acceptance level. These cases should instead be managed by fire prevention measures.

1.2 Scope

The hypotheses behind this work was that:

- It is possible to introduce risk management procedures and fire safety engineering models into fire-fighting tactics.
- It is possible to determine suitable fire-fighting tactics in advance for a specific object under given conditions.

This project has the sub-heading *Elaborated Examples as a Basis for Guidelines for Fire Brigades at Fires in Chemical Warehouses*.

Elaborated Examples...

This work presents a model structure for decision making at larger fire-fighting operations. The model is applied to two chemical warehouses in Sweden. After some adjustment, the model might be applicable to other types of fires, but here only two examples are given.

...as a Basis for Guidelines...

The model presented here links traditional fire fighting with the risk management concept. Risk management is the effort devoted to preventing damage, and to planning intervention if damage should occur. It is the work of identifying potential risk sources, evaluating the damage, and taking precautions to reach a desired level of safety for people, property and the environment. The actions can be of two types: either to prevent damage from occurring, or planning to be prepared if damage should occur. It is the latter type that this study is concerned with. This means that the pre-fire planning of the fire brigades should be part of the risk management process. It also means that the pre-fire plan must be linked to the consequence evaluation.

The fire-fighting operation is lead by the Incident Commander, i.e. the officer responsible for the whole operation. If he is to make a good decision, he must have good information on which to base his decision. The demand for information varies over the time. At the alarm, information is required to ensure that the right resources are sent to the fire scene; upon arrival information is needed to determine the right tactic for the operation. During longer and more complex operations, there is normally time to acquire additional information. In the phase of addressing a fire-fighting operation, a pre-fire plan would be a useful tool. The aim of the model presented here is to provide the Incident Commander with background material to facilitate the decision making process.

The pre-fire plan should be developed from the scenarios described in the risk analysis. If a scenario can not be handled by the fire brigade, or if the damage is unacceptable, the scenario must be prevented. If, on the other hand, the fire brigade is able to cope with the situation, a good plan ensures that the right tactics are chosen and that the resources are used optimally.

...for Fire Brigades...

This study is focused on the work of the fire brigades, at an operational level. The main objective is to adopt the risk management way of thinking to operational fire fighting. The extinguishing media evaluated are water (interior or exterior attack), foam (low-/ medium- or high-expansion) and dry powder.

The study is not concerned with fire prevention, or technical details of fire fighting. The work of other organisations, i.e. the police or ambulance service, at the fire scene is not addressed.

...at Fires in Chemical Warehouses.

The model presented deals with indoor fires, and has been applied to two Swedish chemical warehouses. As the main concern of the model is the extinguishing capability of the fire brigade, it is assumed that the life-saving operation is very fast or not necessary.

The main difference between fires in chemical warehouses, and other types of fires, is the toxic potential of the stored goods. The model may therefore be further developed to handle other types of fires, e.g. apartment fires, fires in stored materials or pool fires.

It should be remembered that the matter of interest in this study is how a fire develops after ignition. We are interested in the different outcomes *given* that ignition has taken place. As the different outcomes are the results of different decisions, it is not relevant to introduce any form of estimations of probabilities. Thus, one can not use this approach to estimate the risks at a warehouse, but to plan the intervention required.

1.3 The TOXFIRE project

This study is a part of the TOXFIRE project. Most countries have chemical plants and storage facilities which handle or store substantial amounts of hazardous substances, e.g. pesticides. Chemical fires seem to be one of the most important hazards associated with these activities. Today, only limited documentation is available concerning the assessment of the potential consequences of fires at chemical plants and chemical storage facilities. The project *Guidelines for Management of Fires in Chemical Warehouses* (TOXFIRE) was initiated in order to remedy some of these problems [2]. The project is financially supported by the CEC Environment Programme (contract no. EV5V-CT93-0275). The project is carried out during 1993-1996 by a consortium consisting of the following partners:

- Risø National Laboratory, Denmark (co-ordinator)
- NERI - The Danish National Environmental Research Institute, Denmark
- South Bank University, United Kingdom
- VTT Building Technology, Finland
- VTT Manufacturing Technology, Finland
- Lund University, Sweden
- SP - The Swedish National Testing and Research Institute, Sweden
- FOA - The Swedish Defence Research Establishment, Sweden

The project covers a range of topics. Based on a number of characteristics, the chemical substances are classified with respect to ignitability, heat release, burning rate, smoke evolution, combustion products and the influence of the packaging materials on the combustion products. The source characteristics are described by parameters obtained by carrying out combustion experiments on various scales and by studying the effects of scaling. In addition, the fire scenarios are characterised by the degree of ventilation, the packaging material, the stacking of the materials and the response of the building. Suppression is also an important parameter, i.e. active and passive suppression and the fire-fighting tactics employed. The consequences for people as well as the environment are assessed. Finally, existing modelling methods used for risk assessment are studied, together with the management and prevention of accidents. These investigations are leading to the development of the basis for two sets of guideline documents in relation to fires in chemical warehouses: guidelines for fire safety engineers and guidelines for fire brigades. In parallel, a quick decision system to be used by the Incident Commander in cases of chemical fires is developed. The relation between these guideline documents is described in [3].

2. Fire-fighting tactics

2.1 Disaster management

A comparison between the landslide disaster at Aberfan in 1966 and the King’s Cross Underground fire in 1987 shows that disasters of different kinds often have considerable similarities [4]. Eight conclusions were drawn in the comparison:

1. Both disasters were predictable and preventable but the organisations did not learn from history.
2. The disasters occurred in socio-technical systems and did not have a single cause. At both disasters, a number of events accumulated but went unnoticed or were misunderstood.
3. There were no incentives to take preventative measures as previous accidents had not caused any loss of life.
4. The existence of a problem was not observed as the legislation was incomplete.
5. The concept of safety was neither comprehensive nor comprehended in the organisations.
6. The management organisation, e.g. the definition of responsibilities and supervision, was deficient.
7. There were failures in communication, proving that a disaster is energy plus misinformation.
8. Outside criticism and help had in both cases been ignored.

These conclusions are probably valid for fires in chemical warehouses as well, as the failures are often on a management level rather than at a technical level. The conclusions can probably be extended to apply not only to chemical companies but also to fire brigades. From the fire-fighting point of view, the Incident Commander is responsible for matters concerning management. He must consider these aspects to avoid creating an environment where a disaster-provoking behaviour is established.

As an example, we know that at fires in chemical warehouses, run-off extinguishing water is very likely polluted. There have still been fires, even after the Sandoz fire [5], where identical tactics were used, with identical environmentally damaging results.

Another example is attic fires in domestic buildings. The best way to fight such a fire has proved to be either a very fast interior attack, an exterior attack using fog nails or to fill the space with high- or medium-expansion foam. When the attic floor is fire resistant, it may even be allowed to burn until self-extinction. However, there are, from time to time, examples of such fires where the traditional technique is used, to drown the whole building from roof to ground with huge amounts of water, giving rise to severe water damage. This is, I would say, disaster provoking. It also confirms the proverb *What one can learn from history is that one does not learn from history*.

2.2 Decision making

Fire-fighting operations are often characterised by what is called Naturalistic Decision Making. Naturalistic Decision Making is distinguished by eight factors [6, p 7]:

- Ill-structured problems. The Incident Commander may know almost nothing about the actual problems upon arriving at the fire scene.
- Uncertain dynamic environments. The information is incomplete, ambiguous or changing.
- Shifting, ill-defined or competing goals. The wish to save a building competes with the safety of the fire fighters.
- Action/feedback loops. The decisions occur in multiple event-feedback loops.
- Time stress. Obvious during fire-fighting operations.
- High stakes. During fire-fighting operations, decisions are a matter of life and death.
- Multiple players. The Incident Commander is not alone at the scene, many participants contribute to making decisions.
- Organisational norms and goals. The decision maker must balance personal choice with organisational norms and goals.

In a field survey, 75 Swedish Incident Commander s were interviewed [7]. The most difficult decisions to make at a fire scene involved prioritising when the resources available were less than required, evacuation, the choice between an interior and an exterior attack, placement of containment lines, etc.

Researchers on decision making [6] have found that the Incident Commander usually adopt what is called a *recognition-primed decision*, RPD, to handle these problems. A recognition-primed decision means that the Incident Commander chooses a set of actions that he recognises and is familiar with, rather than trying to find the optimum set of actions. For this probable course of events, he determines the foreseeable consequences and the need of action from his experience. He selects *one* possible course of events, rather than evaluating all possible outcomes. This means that a decision is based upon his experience of previous fires and accidents. If the outcome was acceptable, the same method is used at the next fire, *with the same expected outcome*. This type of decision, or simple match, is the first of three different levels of the recognition-primed decision model developed by Klein [6]. The model is illustrated in Figure 1.

As the complexity of the situation increases, a mental simulation process and an expectancy assessment are added to the model. Still, the basic question is: Is the situation familiar?

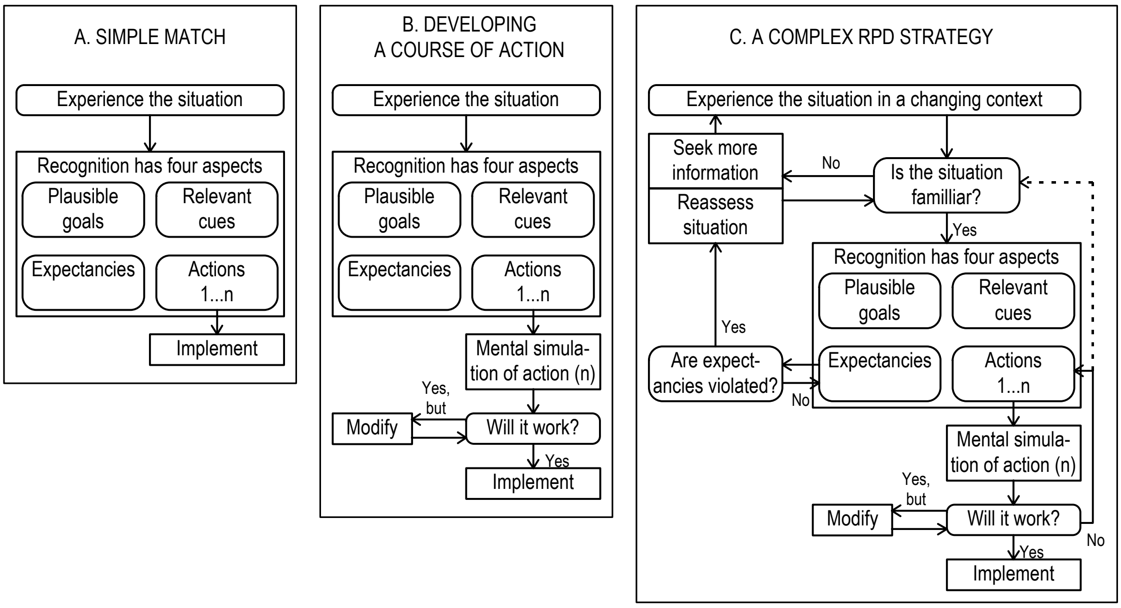


Figure 1. The recognition-primed decision model developed by Klein [6].

Some interesting results from naturalistic decision-making research are that [6, p 18]:

- Experts on decision making frequently generate and evaluate a single option rather than analyse multiple options concurrently.
- Experts are distinguished from novices mainly by their situation assessment abilities, not by their reasoning skill.
- As the problems are ill-structured, decision makers chose an option which is good enough, but not necessarily the best.
- Reasoning is ”scheme-driven” rather than being driven by a computational logarithm. Decision makers try to create casual models of the situation.
- Reasoning and acting are interleaved. Decision making is dynamic and cyclic - it does not consist of discrete, isolated events or processes

A reasonable conclusion is thus that the Incident Commander needs help not only with the gathering of information, but also in the decision making process. This could include resources that facilitate assessment of the situation and the process of transforming the information into actions. The course of events could be determined, and transferred in advance into the commanders base of experience.

A summary of the research on dynamic decision making has been be formulated in the following way [8]: *Subjects who collect more information, who collect it more systematically, who construct adequate goals, who evaluate the effects of their decisions, and who generally behave in a systematic fashion tend to perform better than those who do not.* These points are almost identical to the four defined in the recognition-primed decision model: plausible goals, relevant cues, expectancies and actions.

Engineering models can be used in the recognition process, to develop the situation assessment ability of the Incident Commander . Then, there is a higher probability that the situation fits into a simple match decision, leading to a faster and more accurate decision, even in complex situations. If the situation requires a complex RPD strategy, engineering models are perhaps the only way to ensure that a satisfactory set of actions is chosen.

The model should be the same regardless of whether the evaluation is made

- before the fire (in pre-fire planning),
- during the fire (to determine the tactical approach) or
- after the fire (as a tactical debriefing).

The only difference is that the set of possible courses of events before the fire has changed to one actual course of events after the fire.

2.3 Truths in tactics

There are a lot of truths in fire-fighting tactics. Many of them come from the military traditions of the fire brigade. One such fire-fighting rule is that *attack is more demanding than containment* [9, p 21] or *attack needs more resources than defence* [11]. The rule can also be expressed as *contain first - then eliminate the danger source*. This concept was written down by von Clausewitz in the 19th century, and probably by others before him [12]. von Clausewitz stated that a high objective needs greater power than a lower one.

> *Now, if we want to overcome the enemy by the duration of the contest, we must content ourselves with as small objects as possible, for it is the nature of the thing that a great end requires a greater expenditure of force than a smaller one; but the smallest object that we can propose to ourselves is simple passive resistance, that is a combat without any positive view...*
>
> *No doubt this negative objective in its single act is not so effective as the positive objective in the same direction would be, supposing it is successful; but there is this difference in its favour, that it succeeds more easily than the positive, and therefore it holds out greater certainty of success.* [12, Book I, Ch. II, p 128]

There are other rules like this one. However, there have been few attempts to adopt these rules to an engineering model, so that the results of the new technique can be used in combination with historical experience. If a fire is attacked in an offensive way, and if the fire is not under control within, say 5 to 10 minutes, the fire has probably become so large that it cannot be extinguished by offensive measures. In this case, the defensive mode would be preferable and it is this phenomenon that experienced fire officers refer to when they say that, *The first five minutes decide the next five hours*.

Another old truth is that *the earlier the response, the better the result*. This is self-evident, considering that the heat release rate from a fire increases with the time and that this rate of heat release must be overcome by the fire brigade in order to put out the fire.

2.4 The tactic ideal

The first question an Incident Commander must ask himself is *Why should we launch an operation at all?* The overall doctrine and the reason for every operation is to protect people, property and the environment from damage [14], a fact that should always be kept in mind while discussing fire-fighting tactics.

We also have a golden rule saying that saving life goes before saving property or the environment. This also includes the fire fighters' safety. Reasons for jeopardising fire fighter's life and health are rare, and all of them can probably be prevented with the right education, equipment and preventative fire safety measures.

There may also be more obscure reasons for initiating operations, e.g. that the public demands that the fire has to be attacked. It requires a lot of self confidence from the Incident Commander to explain to the media why the fire brigade let a building burn - even if the building was already a total loss and adjacent water courses were not yet damaged by runoff extinguishing water.

If the strategy defines what is to be saved, the tactics say how to do it. The tactical ideal has been defined in the following way [9, p 30]: *Rescue tactics should be formed as a combination of measures which are as optimal as possible, in time and space, applied locally and strong in relation to the situation.* The definition is explained more thoroughly in [15].

The use of this definition proves to be valuable in determining the extinction capacity of the fire brigade. According to this definition, every operational extinguishing situation must be evaluated as a whole, including extinguishing media, ventilation, containment lines, demand for resources etc. The situation must be evaluated with respect to the time an action may take, it must be evaluated locally, for each room or fire compartment. Also, it must be ascertained whether the extinguishing capacity is greater than the requirement determined by the fire growth.

A good example of the use of this tactical ideal is at large pool fires. There, the extinction capacity of the foam must be greater than the foam breakdown, the foam must be applied for a long time and in a suitable manner and it may be combined with other means of extinction such as dry powder. If the striking power is too small or if the duration is too short, the fire will regain its original strength within a short time and all the efforts will have been in vain.

The tactical ideal says that the resources of the fire brigade must be adequate for the task at every point in time and space. If this is so, an operation - offensive or defensive - can be successful. If not, the operation will doubtlessly fail and the Incident Commander should from the beginning choose a lower aim and select suitable containment lines instead.

The available resources can be linked to the tactical mode of the operation and there are engineering models that can be used for quantification. By comparing the need for extinction capacity, given by the heat release rate, with the available resources, one can determine the probability of a successful operation. In short, this means that;

- if the heat absorption capacity exceeds the heat release, an offensive operation should be planned,
- if the heat absorption capacity is below the heat release, a defensive operation should be planned.

Thus, the overall rate of heat absorption must be greater than the total heat release rate for an offensive operation to be possible. The statements may seem to be categorical. There may be a situation where, for example the fire involves a whole building, where it is possible to start an attack at one end and fight the fire gradually through the building. In this case, the model may be applied if the building is divided into sections following fire compartmentation. Then, the evaluation can be made for each section. The essential fact is that the rate of heat absorption makes the heat release rate decline.

2.5 The aspect of time

In the case of fires, the aspect of time is of greatest importance, for several reasons. It was previously stated that an offensive attack requires greater resources than a defensive one. Situations may, however, arise where a fast offensive attack has a better chance of success than a slower defensive one. The resources required for an offensive attack are greater than those for a defensive one, but the total demand over time may be greater for the defensive strategy, as it has a longer duration.

A fire in its early stages normally develops fast, often following an exponential growth rate curve. An early response means that the resources required to fight the fire are relatively small. If the fire brigade waits for arriving resources to make a concerted attack, the fire may have run out of control at that time.

Another aspect is that the course of events during the first fifteen minutes defines the operation. A battleship heading at full speed in one direction, may not easily be re-directed. The correct decision on aims and means must be made early, as the possibility of changing direction is small once the operation is running.

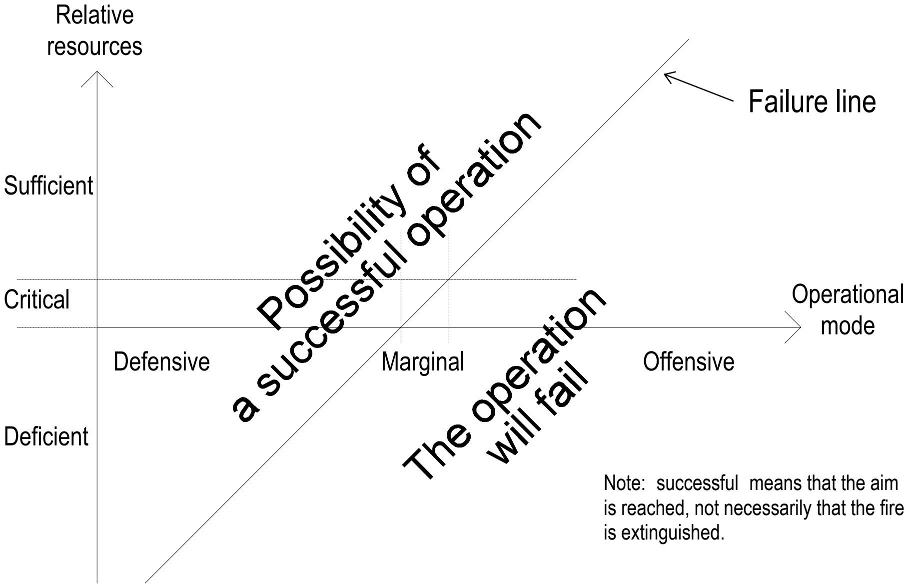
An Incident Commander must also consider that it will take some time to carry out the actions decided upon. The comparison of available resources and the demand for resources by the fire should not be concerned with the present conditions, but the conditions when the actions will be carried out. As a fire often grows exponentially, it may have grown significantly during the few minutes required to realise a decision. This type of action-feedback loop may cause serious difficulties if not addressed properly.

2.6 A new model of rescue tactics

In Figure 2, a new model of thinking is presented, which shows the relation between the resources available and the operational mode of fire fighting. The horizontal axis represents the operational mode, which can be either defensive or offensive. The word defensive means stopping the damage from spreading i.e. preventing people or property not yet damaged by the fire from being affected, in most cases this means containing the fire. The term offensive is used to mean attacking the source of damage - to combat and extinguish the fire.

It is worth noting that both a defensive and an offensive mode require a great deal of action. A defensive operation may include ventilation, evacuation, wetting of threatened buildings, foam filling of compartments adjacent to the burning one and many other types of action. Every defensive action must also be effective in relation to the task. The main difference between a defensive and an offensive mode is the aim of the action. In a defensive mode, the aim is to stop the spread of fire and fire gases until the burning area has run out of fuel. In the offensive mode, the aim is to put the fire out and to stop the production of fire gases.

The vertical axis presents the relative resources. To enable the use of the model at different operations, two variables need to be included: the resources immediately available, and the demand for resources to enable an offensive attack. The relative resources are the difference between the two. When the available resources precisely exceed the need for resources, the situation is referred to as having *critical resources*. The corresponding operational mode, i.e. the interface between the defensive and offensive mode, is called a *marginal mode operation*. The marginal operation is still an offensive one, but the tactical reserve is very small and the demands on tactical skill are very high.



Note: successful means that the aim is reached, not necessarily that the fire is extinguished.

Figure 2. The relation between the operational mode and the resources available.

The sloping line in the figure is the failure line (that the line has a 45-degree slope is just a matter of convenience. Neither of the axes are quantified, and the x-axis is not even a scalar). If an operation finishes above the line, this means that the resources are greater than the demand, given the selected operational mode. It is thus possible for the operation to succeed in the sense that the aim is reached. An operation below the line will fail. The resources are inadequate to achieve the aims, and the operational mode is too offensive. The term fail is here used in relation to the aims defined. It may well be that the fire is put out and the fire brigade is congratulated on their success - but their aims regarding the protection of property, for example, were not reached.

The vertical distance from a point in the diagram representing a specific fire-fighting operation to the failure line is sometimes called the *tactical reserve*, i.e. the over-capacity.

2.7 The tactical situation

The *tactical situation* is a term used to describe the amount of immediately available resources in comparison with the demand, and to define the demands on tactical judgement. Fredholm [9] has defined four situations which are given in Table 1.

Table 1. Categories for tactical problem alternatives [9, p 35].

Situation 4	Unlimited situation. Small resources. Great demands on tactical judgement. e.g. fire-storm, gas leak
Situation 3	Limited situation. Small resources. Less demanding tactically. e.g. fire in a barn.
Situation 2	Limited situation. Critical resources. Great demands on tactical judgement. e.g. apartment fire with high probability of spreading.
Situation 1	Limited situation. Considerable resources. Less demanding tactically. e.g. car fire, normal apartment fire.

These four tactical situations are identified in Figure 3. Situations 1 and 3 are less demanding tactically, while situations 2 and 4 put greater demands on tactical judgement. The reason will here become apparent. The closer to the failure line, the larger part of the available resources are used. This means that the tactical reserve decreases. The smaller the resources in comparison with the need, the higher the tactical demands. With large resources, all actions can be carried out simultaneously. With smaller resources, the correct actions must be taken, and these must be carried out in the right order, i.e. they must be performed according to the tactical ideal. If inappropriate actions are chosen or if the actions are not carried out in the right order, the operation will fail. If there is an over-capacity of resources, errors resulting from not following the tactical ideal may be pardoned.

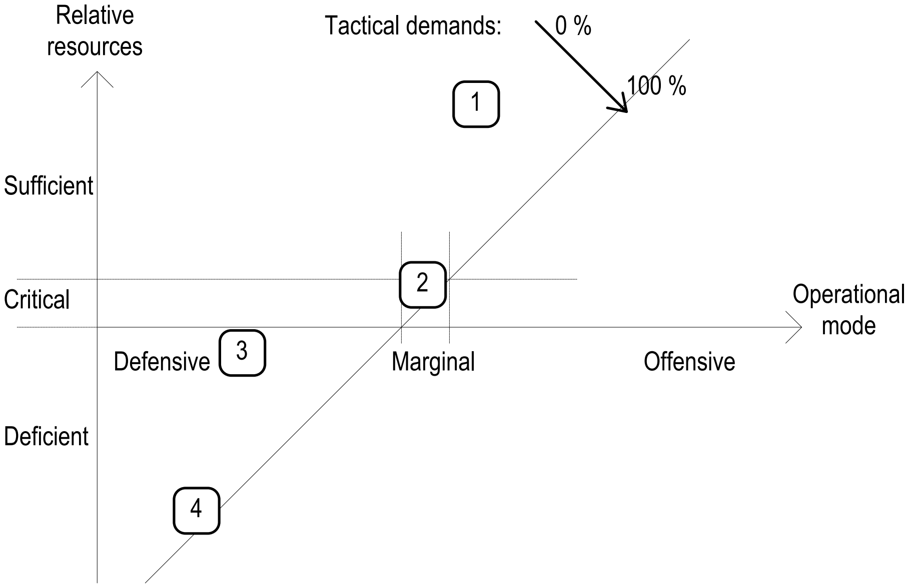


Figure 3. The four tactical situations lead to different tactical demands. The closer to the failure line, the higher the demands.

The tactical demand is illustrated in Figure 4. The figure shows a third dimension of Figure 3. The horizontal axis shows a cross section perpendicular to the failure line. The vertical axis shows the use of the available resources. As the tactical demands increase with the use of resources, the diagram is also representative for the tactical demand. As in the previous figure, the four tactical situations are shown. In the figure, the relation is drawn exponentially, but a straight line would be just as good. The point is that the resources can not be exploited to a larger extent than 100%.

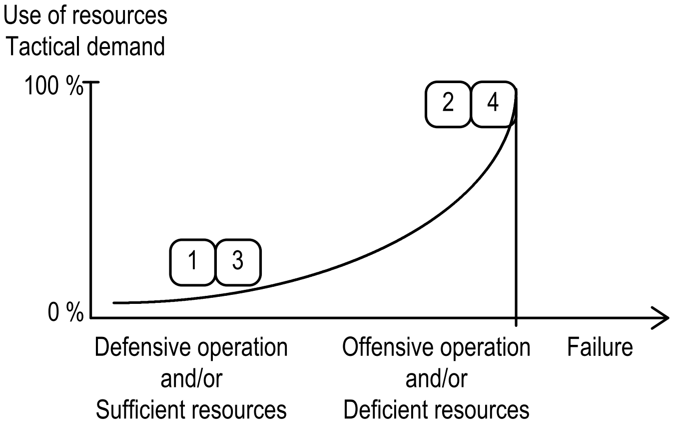


Figure 4. The more offensive and the less resources, the closer the operation is to failure.

It is worth noting that neither the actual nor the required resources are of any interest alone. It is the relation between the two that is of interest. Assume the situation of a traffic accident with two cars involved. One car is on fire and in the other are people with breathing problems. A single person passing by finds himself in situation 3. The person can do something, but can not rescue everyone. A rescue team consisting of one fire engine probably finds itself in situation 2. Through the appropriate actions, the fire can be put out and the injured can be treated, but with the wrong strategy the operation might not succeed. With several fire engines and ambulances, the operation will be in situation 1. There are resources for all actions to be carried out simultaneously, and the demand for tactical priorities is low.

In order to show how common engineering models can be applied to fire-fighting situations it is necessary to define a number of reference object. The following chapter describes the reference objects; two Swedish chemical warehouses.

3. The reference objects

In the following, two reference objects will be used to illustrate how the models and ideas can be applied in real pre-fire planning. Scenario A refers to a two-storey pesticide warehouse of about 1200 m² and Scenario B refers to a pesticide storage building of about 6000 m². Both the reference objects are classified as §43 objects according to the Swedish Rescue Services Law [14]. The paragraph applies to objects that are potentially dangerous even off-site. This implies that the manufacturer or the owner of the plant has a special obligation to provide equipment for fire fighting, to prevent fires and to stop or limit the damage due to fire.

3.1 Description of the reference objects

Scenario A, The small warehouse

The small warehouse was constructed a hundred years ago, originally as a model farm. It is used for the production and storage of insecticides, rodenticides etc. for the Swedish market. Some of the products are stored in a separate storage building.

A large variety of toxic products are handled at the plant. Some of the active substances in the insecticides and rodenticides are boric acid, cypermethrin, isopropyl alcohol and warfarine. Other products that can be mentioned are hydrocyanic acid and methyl bromide. Over 50 different types of raw materials and products are stored, commonly in a two-level rack storage system. The amounts vary, but are commonly of the order of 100 to 500 kg. About ten products are stored in larger quantities than 1000 kg, in all about 30 to 50 tonnes. Most products are stored in the solid phase, but there are also liquid (often flammable), and gaseous products.

Most of the raw materials and products are stored packed in paper sacks or cardboard boxes. The flammable liquids are stored in barrels, and the gaseous products in gas bottles. Almost all products are transported on wooden pallets.

It is of course impossible to describe all possible fire scenarios. An example is the ignition of stored goods on a pallet. The fire will spread rapidly in the cardboard boxes, and in 3 to 5 minutes the rate of heat release will be of the order of 3 to 5 MW. The fire alarm will activate, and 10 to 20 minutes later, the windows will break. This will be at about the same time as the fire brigade arrives. In a few minutes the fire will spread through the windows to the upper floor and through the eave soffit to the loft, resulting in total loss of the building. The fire will develop slightly different depending on the location of the source of the fire. This will be discussed further when the fire calculations are presented.

The warehouse is a two-storey building with a loft, giving a floor area of 53 m · 22 m. The walls of the ground floor are constructed of stone and brick. The walls of the upper floor are of a wooden construction, with a compartment floor consisting of steel beams with brick arches. The loft is all wooden, including the floor construction.

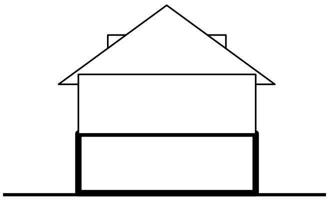


Figure 5. Section through the main building.

A separate storage building is located not far from the main building. It consists of a steel frame covered with corrugated sheets and is furnished with a 3-level rack storage system.

A fire alarm system is installed at the plant, but no extinguishing system. Fire ventilation is lacking, but both the floors have large window areas. The loft only has small window openings.

The old dung-pit can be used to collect extinguishing water by turning a valve in the drainage system. The pit can hold about 200 m³ of water.

The plant is located just outside a small village, at a distance of about 50 m from the nearest buildings. A lake and a small river are located at a distance of 300 m from the plant.

Scenario B, The large warehouse

The second warehouse in the study is much larger than the first. It is a modern construction, less than ten years old, designed for the storage of large quantities of herbicides and pesticides for agricultural purposes.

In each fire compartment, herbicides and pesticides in quantities of the order of 100 to 300 tonnes may be stored. Most material is stored in the solid phase, and the remainder in solution. Some products are solved in flammable liquids. One of the products, Maneb, is known to self ignite when exposed to moisture.

Most of the products are stored in cardboard boxes. The liquids are stored in bottles or barrels. Occasionally, 1000 litre containers are stored. All flammable liquids are stored in one fire compartment, and all aerosol bottles in another.

All products are transported on wooden pallets. A rack storage system is used for the pallets, as shown in a front and side view in Figure 6.

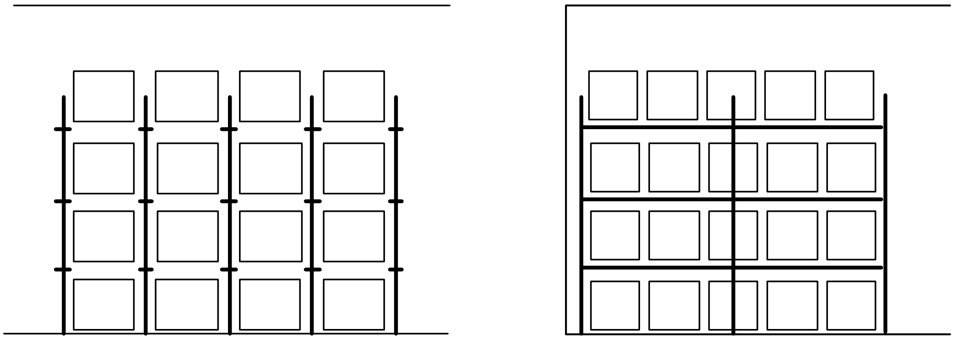


Figure 6. Front and side views of the pallet storage.

As in the previous example, it is not possible to describe all conceivable fire scenarios. The ignition of stored goods on a pallet will, for example, lead to very rapid fire growth. The fire alarm will activate and within 10 minutes the fire brigade arrives. By then, the fire may have grown so large that internal extinguishing is not possible. It may be possible to contain the fire within the fire compartment, unless the fire involves barrels containing flammable liquids. Exploding barrels may damage the fire compartmentation and the roof, and lead to secondary fires far from the point of origin. The scenario description will be discussed further when the fire calculations are presented.

The storage building has a single storey, measuring 100 · 60 m. It is divided into fire compartments as shown in Figure 7.

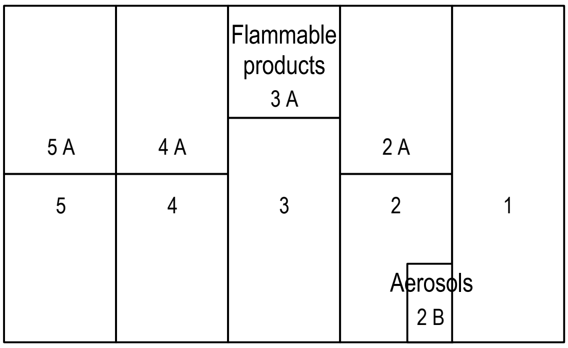


Figure 7. Plan of the storage building showing the fire compartmentation

The outer walls are of a concrete sandwich construction. The inner walls are bricked with lightweight concrete, giving a fire resistance time of at least 60 minutes. The roof consists of corrugated metal sheets with insulation, covered with roofing felt.

The building is equipped with an automatic fire alarm, and with fire ventilation. Extinguishing water can be collected to a level of 0.5 m in each of the fire compartments, giving a volume of 300 m³ per compartment or 3000 m³ in total. Practically, this is arranged by lowering the floor about 0.3 m, in combination with 0.2 m high removable steel sheets at the bottom of each door opening. A sump is connected to each fire compartment.

The warehouse is located in an industrial area, about 2 km from the centre of one of the largest cities in Sweden. The closest neighbouring buildings are 50 m away, and the sea shore is about 200 m from the warehouse.

3.2 Products stored at the reference objects

Scenario A, The small warehouse

The following table shows the amounts of raw materials and products at the plant during the visit of the project group in September 1994. The active substances are also shown in the tables. The physical, chemical and toxicological properties of the substances can be found in [16], [17] and [18].

Table 2. The products stored in the small warehouse.

	Ground floor, room 20 ·20 m^2	**Amount [kg] ***	**Active substance**	**Content [%] ***
1	Racumin, powder	250	Coumatetralyl	0.75
2	Boric acid	300	Boric acid	
3	Basilit B	500	Boric acid Ethanol amine	63 22
4	Isopropanol	400	Isopropanol	99
5	Permetrine, pyrethrum type	150	Permetrine	
6	Shellsol, replacement for turpentine	600 l		
7	Piperonyl butoxide	120	Piperonyl butoxide	
8	Isoparaffin hydrocarbons	400 l		100
9	Pyrethrum extract	550	Pyrethrum	25
10	Mitrol PQ 8	250 l	Oxin copper	55 g/l
11	Dursban	200 l	Chlorpyriphos	65
12	Naphtha	200 l		
13	Paraffin oil	200 l		
14	Chlorpyriphos	400 l	Chlorpyriphos	208 g/l
15	Baytroid	300 l	Cyfluothrin	50 g/l
16	Cymex powder	1920		
17	Deltamethrine, atomizer	2040 l		0.003
18	Myrr C	1838	Cypermethrine	0.125
19	Antisekt	2570	Pyrethrines I+II Piperonyl butoxide Aliphatic naphtha	1 5 71
20	Permex E	105	Permethrine	
21	Pyremex, concentrate	135 l	Pyrethrines Piperonyl butoxide	30 g/l 100 g/l
22	Racumin	5520	Coumatetralyl	0.038
	Ground floor, room 7 ·7 m^2			
1	Warfarine	300	Warfarine	0.038
	Ground floor, room 10 ·20 m^2			
1	Bromadiolon	440	Bromadiolon	0.01
2	Warfarine	160	Warfarine	0.038
3	Racumin	200	Coumatetralyl	0.75
4	Difenacoum	150	Difenacoum	0.01
5	Racumin	175	Coumatetralyl	0.038

6	Warfarine wheat	2880	Warfarine	0.038
7	Warfarine dry bait	1080	Warfarine	0.038
8	Bromadiolon	3360	Bromadiolon	0.01
9	Paraffin, pellets	3360		
	Ground floor, room 15 ·25 m^2			
1	Ant, dose	50	Foxim	0.01
2	Warfarine	50	Warfarine	0.038
3	Traps with pheromones			
4	Dichlorvos	200	Dichlorvos	18.6
5	Crushed seed, 18 pallets with 13 sacks each			
6	Oatmeal, 8 pallets			
7	Talc	500		
8	Coumarine derivative (25 l bottles)	1125 l	Coumarine	0.25
9	Racumin	150 l	Coumatetralyl	40
10	Warfarine	200	Warfarine	
11	Cypermethrine, pyrethrum type	40	Cypermethrine	40
12	Bromadiolon, (15 l bottles)	300 l	Bromadiolon	2.5 g/l
13	Warfarine, powder	400	Warfarine	0.038
14	Warfarine, powder	85	Warfarine	0.038
	Small storehouse 20 ·20 m^2, Northern wall			
1	Methyl bromide, (35 kg pressure vessels)	11550	Methyl bromide	100
2	Aluminium phosphide, (20 kg bottles)	1040	Aluminium phosphide	56
3	Hydrogen cyanide, (1.5 kg bottles)	108	Hydrogen cyanide	72
4	Tetradifon	450	Tetradifon	
	Small storehouse 20 ·20 m^2, Centre			
5	Warfarine, maize bait	640	Warfarine	0.038
6	Packaging material (Polyethylene, paper)	12 pallets		
	Small storehouse 20 ·20 m^2, Southern wall			
7	Organic solvents	4000 l		
8	Dursban	400 l	Chlorpyriphos	65

* unit in [l], [pallets] or [g/l] where specifically stated.

Scenario B, The large warehouse

The tables below show the amounts of raw materials and products stored in the different sections of the large warehouse at the visit of the project group in October 1994.

Table 3. Products stored in the large warehouse

	Section 1	**Amount [kg]**
1	Closely packed sheets of paper, plastic foil	140 000
2	Various pesticides	1000
3	Gas cylinders containing pressurised air	
	Section 2	
1	Flammable liquid, class 3 (pesticide formulations)	20 000
2	Pesticides, solids and aqueous solutions	100 000
3	Herbicides, aqueous solution of phenoxi acids	250 000
4	Maneb/mankozeb	10 000
5	Marshal 40 DB, carbosulphane in xylene	20 000
	Section 2A	
1	Flammable liquid, class 3 (pesticide formulations)	20 000
2	Various pesticides, solid and aqueous solutions	200 000
3	Herbicides, aqueous solutions of fenoxi acids	200 000
4	Oftanol EM, isophenphos	10 000
5	Wetting agent	10 000
	Section 2B	
1	Radar DOS, insecticide, pyrethrines, aerosol with propane/butane	10 000
2	Paint, spray with flammable solvent	10 000
	Section 3	
1	Flammable substance, class 3, pesticides in flammable solvent	90 000
2	Various pesticides, solid and aqueous solutions	150 000
3	Pesticides, organic thiophosphor, carbamates, chlorinated hydrocarbons	15 000
4	Osmocote, fertiliser	5 000
5	Fertiliser in aqueous solution	50 000
6	Maneb/Mankozeb	15 000
7	Aqueous solution of manganese nitrate	75 000
8	Manganese sulphate, solid and aqueous solution	70 000
9	Mineral and rape seed oil	60 000
10	Silotex, Sodium meta bisulphite	1 000

	Section 3A	
1	Flammable substance, class 1, organic solvents, pesticides in solution	4 000
2	Flammable substance, class 2a, pesticides in organic solvents	40 000
3	Flammable substance, class 2b, pesticides in organic solvents	70 000
4	Flammable substance, class 3, pesticides in organic solvents	80 000
5	Flammable, highly toxic pesticides, organic thiophosphor, carbamates, chlorinated hydrocarbons	8 000
6	Volaton, organic thiophosphor, strong odour	100 000
	Section 4	
1	Flammable substance, class 3, pesticides in organic solvents	60 000
2	Various pesticides, solid and aqueous solutions	250 000
3	Tattoo, Mankozeb in solution	60 000
4	Mineral and rape seed oil	80 000
	Section 4A	
1	Flammable substance, class 3, pesticides in organic solvents	50 000
2	Various pesticides, solid and in aqueous solution	300 000
3	Phenoxi acids in aqueous solution	50 000
	Section 5	
	Flammable substance, class 3, pesticides in organic solvents	20 000
1	Various pesticides, solid and in aqueous solution	100 000
2	Various pesticides	1 000
3	Pressure vessels containing compressed air	
4	Packaging material	
	Section 5A	
1	Various pesticides, solid and in aqueous solution	200 000
2	Mineral oil	5 000
3	Packaging material	

3.3 Fire brigade resources at the reference objects

Descriptions of the response crews and of the resources available have been provided by the fire brigades covering the area in which the warehouses are located [19], [20]. The resources that are actually brought to the scene depend on the alarm plan, and on the decision made by the first arriving officer. The resources may vary due to external factors, e.g. the fire brigade may be responding to another alarm. Also, weather conditions, e.g. snow and ice, or the traffic situation at rush-hour, may lead to a longer response time. There may be failures in the equipment, e.g. pumps that do not start. It should be noted that this chapter describes the *expected* fire brigade resources at the reference objects. If a risk analysis were to be made, the resources should preferably be expressed in the form of a probability density function.

Scenario A

The small warehouse is located in the countryside, on the edge of a small village without a local fire brigade. This means that the response time is about 20 minutes for the first arriving units. The initially arriving resources are quite small, and it will take some time to get additional resources to the scene. The response time is 20 minutes for a team of 2 sub-officers and 10 fire fighters from two part-time stations. Within 30 minutes, additional resources from another station arrives: a fire chief, a station officer, a sub-officer and 4 fire fighters from a full-time station. The resources available in terms of extinguishing media are shown in Table 4.

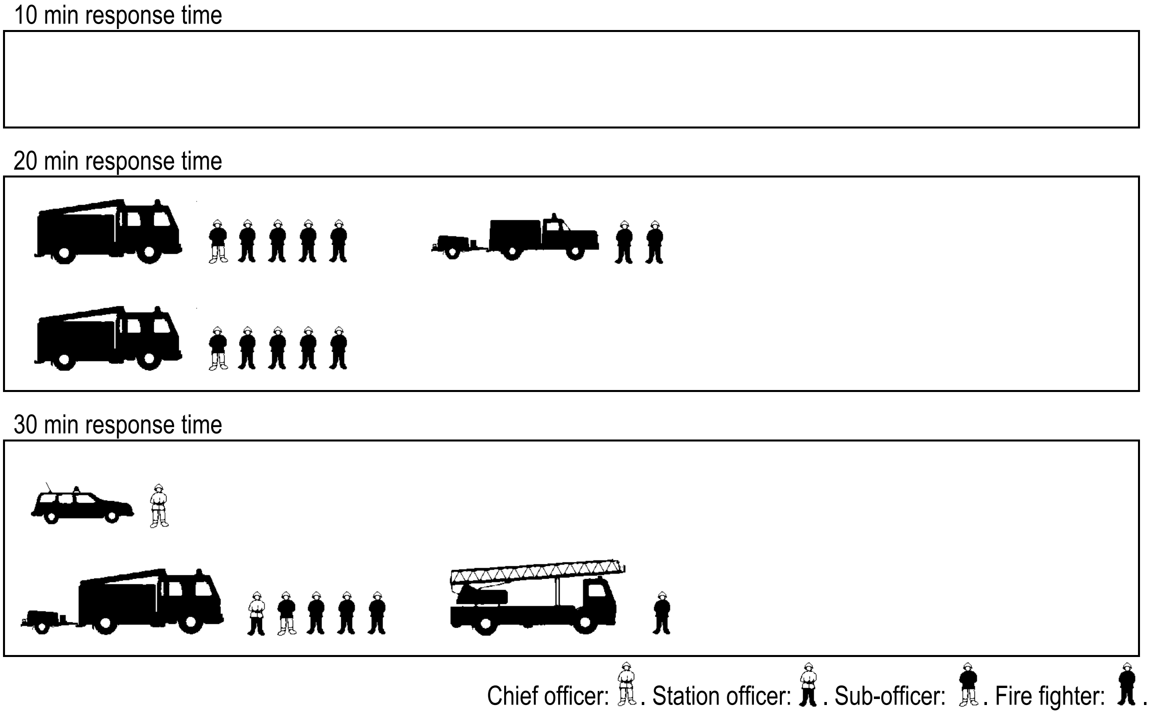


Figure 8. The fire brigade response team at scenario A [19].

Table 4. The resources of the fire brigade in scenario A [19].

Agent	Flow rate at 10 to 20 min	Flow rate at 20 to 30 min	Flow rate at 30 min
Water (internal)	-	500 l/min	1000 l/min
Water /Low-exp. foam	-	2000 l/min	7000 l/min
High-exp. foam	-	-	160 m^3/min
Dry powder	-	10 kg/s *	10 kg/s *

* Total amount 300 kg.

Scenario B

The large warehouse is located in an industrial area of a large city. The response time is 10 minutes for a team of a station officer, 2 sub-officers and 15 fire fighters from two stations. Within 20 minutes, additional resources from two stations arrive: a divisional officer, 2 station officers, 4 sub-officers and 18 fire fighters. Within 30 minutes, a chief officer responds, together with a manned command vehicle and forces from at least four neighbouring cities. The whole crew, except seven part-time fire fighters, comes from full-time stations. The resources available in terms of extinguishing media are shown in Table 5.

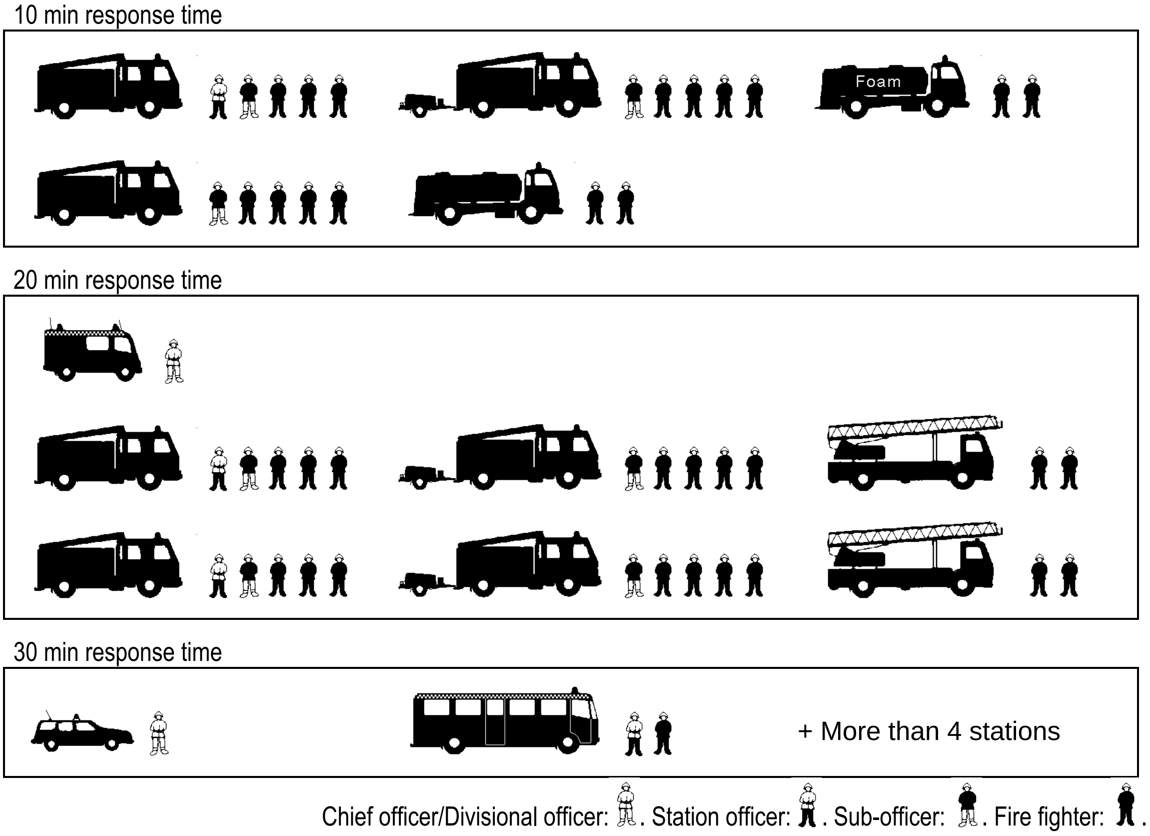


Figure 9. The fire brigade response at scenario B [20].

Table 5. The resources of the fire brigade in scenario B [20].

Agent	Flow rate at 10 to 20 min	Flow rate at 20 to 30 min	Flow rate at 30 min
Water (internal)	1000 l/min	1400 l/min	1400 l/min
Water /Low-exp. foam	5000 l/min	15000 l/min	30000 l/min
High-exp. foam	-	160 m^3/min	480 m^3/min
Dry powder	-	6 kg/s *	6 kg/s *

* Total amount 200 kg.

3.4 Existing pre-fire plans at the reference objects

Both the reference objects have a pre-fire plan [19], [20]. In both cases it consists of a sheet of A3 paper folded to A4 format. On the front page, facts and figures are gathered in text format, e.g. who to contact, stored goods, special hazards, fire-fighting installations etc. The first pages are shown on the following pages. The plans have been partially masked as they contains names, phone numbers and addresses. The centre spread shows a map of the building. These are on scales of 1:385 or 1:350, and contain information essential for the fire brigade. There is information about volume and location of tanks containing flammable liquids, location of entry points, fire compartments, dimensions of fire-fighting installations, water supplies etc. The back pages show maps on scales of 1:10000 or 1:70000. The location of the building and of the previously selected staging areas are marked.

As can be seen, the plans include very sparing tactic hints on fire fighting. The plan for the small warehouse does not have any recommendations at all. The plan for the large warehouse recommends restricted use of water and extinguishing with alcohol-resistant foam, dry powder or CO_2 instead. This recommendation is too broad to facilitate the decision process.

In addition to the pre-fire plan, the larger warehouse has a file, 5 cm thick, with information on the stored goods, and a continuously updated board giving amounts and locations of goods. These are located at the company’s reception desk, at a distance of about 20 m from the warehouse building. This information is extremely valuable in making long term decisions when the fire-fighting operation is running, but to make quick, initial decisions, the information must be more easily digestible.

Scenario A, The small warehouse

PRE-FIRE PLAN

Number	XXX	Object	XXX
Phone day:	XXX	Address:	XXX
night:	XXX	Property:	XXX

Keys	XXX
Approach	From road XXX
Staging point	The old railway station.
Water	Hydrants or motor pump at the lake. Re-use from collecting basin.
Activities	Production of pesticides and storage of different poisons.
Hazards	Flammable liquids class 2b and aerosol bottles. Hot paraffin. Gas tubes (pressure containers). Insecticides. Pyrethrum, ethylene bromide, cyanide, warfarine.
Building	Main building ground floor: ”Fire proof”. First floor: Fire resistant. Loft: unprotected wood. Storage building: steel.
Fire safety installations	Internal fire alarm to XXX. Smoke detectors and evacuation alarm.
Persons	11 employees
Alarm pattern	Engine Tanker Chief Officer Ambulance Police
Contact	XXX
Miscellaneous	Breathing apparatus or chemical protecting clothing. Chemicals in form of gases and powder. W = do not use water.
Extinguishing water.	Shall be collected in the drainage system and led to the collecting basin via a special valve. Volume approx. 200 m³. The water should be re-used for extinguishing to prevent overflow.
Revision	Date: 940608 Signature: XXX

Scenario B, The large warehouse

PRE-FIRE PLAN

PRE-FIRE PLAN FOR XXX

ACTIVITIES

STORAGE OF CHEMICAL PRODUCTS - MAINLY PESTICIDES.

SMOKE

PHOSGENE, SULPHUR- AND NITROGEN OXIDES, EVAPORATED CHEMICALS E.G. OF NERVE GAS TYPE (ORGANIC TIOPHOSPHOR).

EXTINGUISHING

USE RESTRICTED AMOUNTS OF WATER DUE TO RELEASE AND DECONTAMINATION.

EXTINGUISH WITH ALCOHOL-RESISTANT FOAM OR DRY POWDER - CO_2.

DRAINAGE

SHUT VALVE TO DRAINAGE SYSTEM AT THE GATE

SEAL DRAINAGE COVERS (SEE MAP, FLAP 2)

DESCRIPTION OF STORED GOODS

BRIEF STORAGE PLAN: SEE FLAP 5.

DECLARATION OF CONTENTS: SEE FLAP 6.

UPDATED STORAGE SHEETS: SEE FLAP 9 IN "§43" - FILE AT ALARM DEVICE AT XXX

CONTACTS:

XXX

OTHER PHONE NUMBERS: SEE FLAP 1

4. The consequences of fire

4.1 Identifying the risks

The planning of intervention in a fire is, or at least should be, part of the risk management process. This means that pre-fire planning must be done in parallel with other areas of risk management: identification of risk sources, evaluation of damage et cetera.

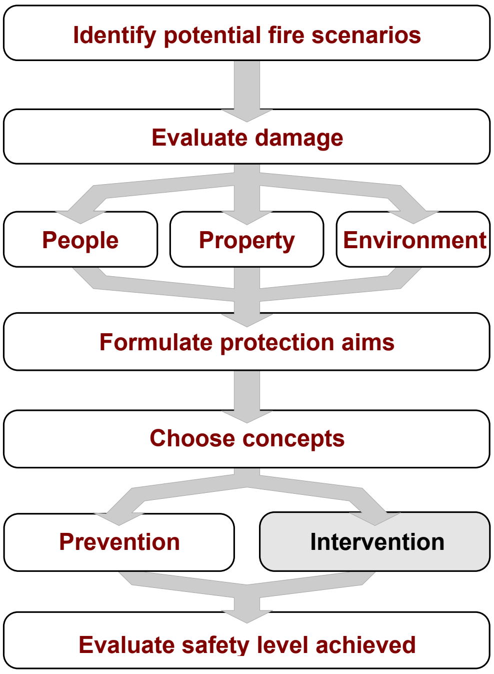


Figure 10. Pre-fire planning of the intervention is part of the risk management process.

What has not been considered before the fire, is often too late to think about when the fire has started. This is true for both areas of the risk management process; planning of intervention and fire prevention. For example, it is too late to clear a loading ramp from stored goods when the fire has already started.

The fire safety measures can be seen as a number of barriers. For a fire on the loading ramp, a scenario which has resulted in many major industrial fires over the years, the first barriers could be:

- Prevent admittance to the area
- Ensure detection of unauthorised persons
- Prevent storing of goods on the loading ramp
- Ensure fast detection of a fire
- Prevent fire from spreading from the loading ramp to the adjacent building

These ”barriers” normally appear in pairs; the actual barrier and some form of surveillance that ensures detection if a barrier is broken.

There are other approaches to. One is the UFOE concept, where an accident is regarded as an Uncontrolled Flow Of Energy [3]. The hazard source is some confined amount of energy (e.g. chemically bound in the fuel) which is released. Confinement requires active and passive barriers and other control systems. The presence of sufficient energy and unsuccessful confinement results in an uncontrolled flow of energy. If a vulnerable object (e.g. people, property or the environment) is exposed to an uncontrolled flow of energy, the incidental consequence becomes a fact. If there are no vulnerable targets, the energy release can be regarded as a near-miss incident. This study may be regarded as an application of the UFOE concept, as a comparison is made between the energy release (in fire studies usually denoted the rate of heat release) and the energy confinement (in this case the heat absorbed by extinguishing media).

4.2 The event tree approach

The method of identifying potential dangers in the case of a fire, used in this report, is the event tree approach. With an event tree, the different ways in which a fire may develop can be described. As each branch is evaluated, the number of different paths should be kept as small as reasonably possible. Each branch should be the effect of an action or a decision which gives a substantially different outcome, and may vary from almost no damage at all to the worst possible case, with severe damage to people, property and the environment.

The action or event that leads to a new branch in the event tree, may be defined as a *critical event*, and if the event is a result of an order from the Incident Commander , his decision may be defined as a *critical decision*. In the same way, the information needed to make the decision of which branch to follow, may be defined as *critical fire ground factors*.

Note that so far the fire is being studied from a technical perspective, and the response of the fire brigade has not yet been included. With the event tree, the rescue problems are identified and the development of the situation is predicted. The link to the actions of the fire brigade appears when we start to define which actions and resources are needed to follow the different paths in the event tree.

The easiest way of constructing the tree is to see how the fire would develop if the fire brigade did not respond. After ignition, the fire would spread from the original location and, at a certain time, lead to flashover in that fire compartment. After some time, the fire would spread to adjacent compartments and eventually envelope the whole building. Depending on the location of the burning building, the fire may also spread to neighbouring buildings.

When the main damage targets have been identified, the next step is to identify the action that leads to protection against damage for each target. The salvation of the main building in the small warehouse scenario would require a very rapid response, as the fire load is high, and the building is made of wood with poor fire compartmentation. We know that the response time of the fire brigade is about 20 minutes, and therefore it can be said, that the probability of successful extinguishment is small.

With this type of reasoning, four situations can be identified at the warehouse: an early alarm with fast suppression, the decision to launch an offensive or defensive attack, the attainment of the tactical objective, i.e. that the attack is well dimensioned regardless of whether it is offensive or defensive, and finally the non-use or containment of extinguishing water which might be polluted. The four situations or branches in the event tree can be defined as the critical events. At other buildings, the events may be different.

An event tree for the four situations is drawn with respect to time, with time = zero at the left, as in Figure 11. The first stage of the fire, i.e. the ignition process, is deliberately not included. The development of the fire previous to the arrival of the fire brigade is not of interest here. The only difference in the event tree between a rapid and a slowly developing fire, is the time at which the first branch is reached. A slowly developing fire will allow more time to detect the fire and for the personnel to fight it, but the chain of events is similar to that of a rapidly developing fire. Thus, the interesting point is not the explicit time, but rather the time in relation to the different branches. A response time of 20 minutes for the fire brigade, is of less importance than whether the response time is shorter or longer than the first branch.

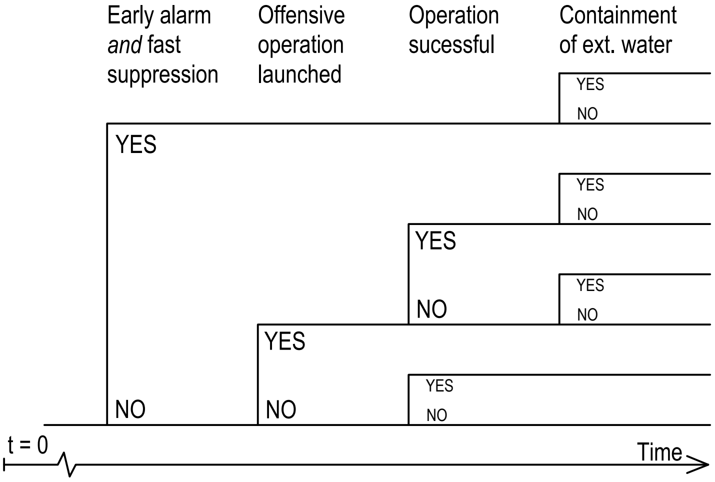


Figure 11. An example of an event tree for a small warehouse.

Actions leading to a critical event mean that one follows a new branch in the event tree. The no-action line at the bottom represents the LSB strategy (”Let the Shit Burn”). This strategy will not necessarily result in the worst consequences. Branches that are irrelevant are not included. The decision of whether to launch an offensive or a defensive operation is, for example, of no interest if there is fast detection and early suppression of the fire. If no water is used, the question of containing the water is, of course, irrelevant.

All answers are of the Yes/No type. Note, however, that a No answer to the question ”offensive operation launched” means that a defensive operation is launched. According to the definition, an operation is *either* offensive *or* defensive.

The question of containment of the extinguishing water is most relevant if water is sprayed onto the fire, i.e. if an offensive operation is launched. During a defensive operation, the aim is to prevent the fire from spreading, meaning that the nozzles are not directed onto the burning fuel. Unless the water flows along the ground through the fire compartment or comes into contact with other chemicals, it will not be polluted, and the question of containment is not relevant. This is an important question as there are examples of severe damage to water courses due to fire-fighting operations [5].

4.3 Consequence evaluation

Now the chain of events is determined for a number of different scenarios. Using risk management nomenclature, the risks are identified. The next step is to determine the consequences of each scenario.

For humans, toxic smoke is the main problem. In most chemical warehouses, the means of escape for personnel are good. This is also the case at the two reference objects. This means that the prediction of the production and dispersion of smoke in the neighbouring area is of main concern.

Problems associated with evacuation from other types of buildings may be greater. At a hospital, the smoke outside the building may be of less importance as the fuel may be less toxic, and the evacuation of people from the building will be the main concern.

Environmental problems also arise from the spread of toxic substances to the air, which may cause polluting fallout on the soil. Extinguishing water is a well known pollutant, as toxic substances dissolve in the runoff water. These ecotoxicological aspects are of vital importance at fires in chemical warehouses, as many chemicals are designed to interfere with the ecological system.

Direct fire damage mostly concerns the damage to property, i.e. the building itself and its contents. Of course, other types of damage may be included. Loss in public relations for the company could be included, and so on. However, as the number of damage targets grows, the complexity of the model grows, and looses its main advantage, i.e. its ease of use. For the small warehouse, there are four major damage targets; the warehouse building, people in the neighbourhood (since the means of escape are good, the personnel in the building are not considered), the air and the adjacent water courses.

The main objective is to calculate the order of magnitude of the consequences. The uncertainties in both the models and in the input data are so large, that it is only possible to make a rough estimation. The calculation process is a combination of a number of sub-models. There are models for determining the temperature and mass flow of smoke, the dispersion of smoke, the toxicity that people and the environment are subjected to, the possibility of extinguishing using different methods, and so on.

In Figure 12, the information needed to perform these calculations is gathered. The information needed, also called the *fire ground factors,* is presented vertically. The models used to calculate the fire ground factors are shown horizontally. The arrows represent the flow of information. As an example, the room dimensions are used as input for a fire calculation model that gives the pyrolysis rate as output. The selected models will be used practically in the following, and are described in greater detail when they are applied to the two reference objects.

It is important to note that the fire ground factors shown are only valid for fires in chemical warehouses and when this set of sub-models is used. For an apartment fire, the first and most important question is whether anyone is in the apartment. Here, it is assumed that all personnel have been evacuated. Other types of emergencies give other sets of fire ground factors.

VARIABLES	**Fire consequence models**		**Fire extinction models**						**Damage estimation models**			
	Fire calculation	Smoke dispersion	Water	Low- and medium-expansion foam	High-expansion foam	Dry powder	Waste extinguishing media release	Fire-fighting tactics	Damage to people	Damage to buildings and other property	Damage to air and soil (ecotoxicological)	Damage to water (ecotoxicological)
Building												
Room dimensions	↑		↑	↑	↑	↑						
Openings	↑	↑										
Lining materials	↑											
Fire												
Rate of heat release	↑		↑	↑		↑						
Heat of combustion	↑											
Pyrolysis rate	←	↑										
Smoke temperature	←	↑	↑	↑	↑	↑						
Mass flow of smoke	←	↑										
Yield of toxic substances	←	↑										
Dispersion												
Wind speed		↑										
Weather stability class		↑										
Surface roughness		↑										
Concentration/distance of toxic substances		←							↑	↑	↑	
Dose/distance of toxic substances		←							↑	↑	↑	
Radiation level/distance	←								↑	↑		
Population												
Number of people									↑			
Distribution of people									↑			
Characterisation of people									↑			
Extinguishing resources												
Fire brigade resources			↑	↑	↑	↑	↑	↑				
Water flow rate			←				↑	↑				
Low- and medium-expansion foam flow rate				←			↑	↑				
High-expansion foam flow rate					←		↑	↑				
Dry powder flow rate						←	↑	↑				
Waste extinguishing media							←	↑				↑
Offensive or defensive operational mode								←	↑	↑	↑	↑
Damage												
People									←			
Property										←		
Air / soil (ecotoxicological)											←	
Water (ecotoxicological)												←

Figure 12. Calculation sheet describing variables required for the calculations. The arrows represent the flow of information.

There are some problems with the information sheet. First of all, the time scale is not included. Secondly, the table does not take the possibility of different actions leading to different paths in the event tree into account. The need for action becomes the output from the model, but the actions do not affect the input. To account for this, one must define the event tree, and for each path set up a separate information sheet. This is one of the reasons for keeping the number of paths in the event tree as low as practically possible.

4.4 Fire scenarios

Firstly, the fire scenarios must be defined. The results of calculations of the development of the rate of heat release may appear as in Figure 13. The fire increases as αt^2, where α is the growth constant and t is the time. At a certain time, the fire reaches a plateau, which usually corresponds to flashover. The fire may then continue to grow, i.e. spread to adjacent compartments, it may decline due to fire-fighting measures or lack of fuel, or finally, it may remain constant for a period. If the fire spreads, it eventually reaches another constant level.

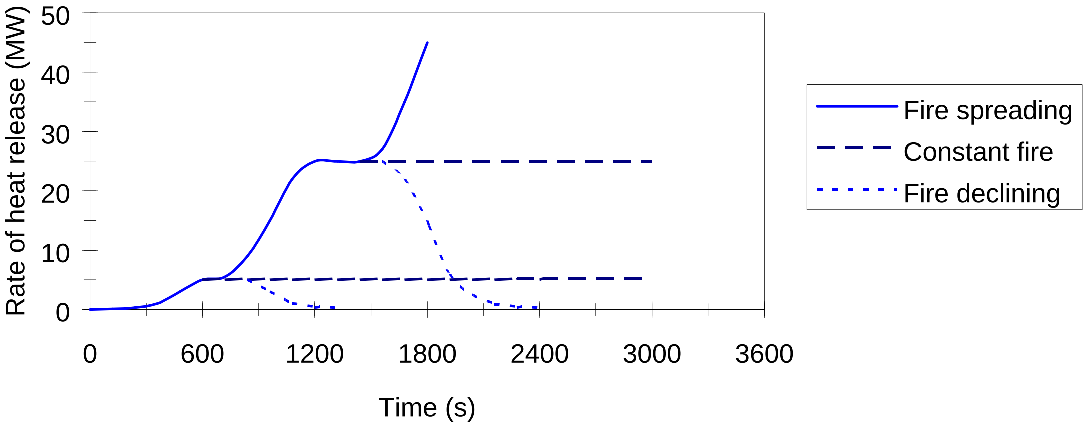


Figure 13. The rate of heat release for a fire in the small warehouse for different scenarios.

The time scale in the figure should be regarded as an example as this will vary with the fire-prevention measures. An open door in a fire wall will, of course, not afford any protection against the spread of the fire, while a completely sealed wall may resist the spread of the fire for a long time. At flashover, the fire may break the windows, which in some cases will lead to fire spread along the facing to other fire cells. The time depends on the resistance of the windows and other components.

The event tree helps us to identify the different plateaux and paths, and the calculation models identify the times and levels.

To be able to determine the release of toxic substances, one has to estimate the production rates. This may be done by using experimentally determined yields [21]. The yield is defined as the mass of a toxic substance released per unit mass fuel burned, i.e. in [g/g].

$$Y = \frac{m_{substance}}{m_{fuel}}$$

Fire calculation models predict the rate of heat release and the generation of toxic substances. These parameters can be used as input for the dispersion model, resulting in toxicity-distance maps for each scenario.

Now we are able to make an assessment of the fire damage to each target. However, the fire-fighting operation does not only affect the rate of heat release curve. It may also dissolve the burning fuel in the extinguishing water, thereby causing environmental damage. Thus, we must evaluate the consequences of the fire-fighting operation before we can estimate the total damage.

Normally, a sensitivity analysis of the fire and dispersion calculations would be necessary. However, in this case such an analysis may give a false sense of security. This is because the largest error is not found here, but in the calculation of the actions of the fire brigade and in the extinguishing effect. If the calculations in this study are of the right magnitude, this is satisfactory.

A sensitivity analysis also includes the selection of fire sources. The main question in this study is not whether a forklift truck or a cigarette in a wastepaper basket caused the fire, but what would happen if the fire brigade was faced a fire of a given size.

4.5 Fire scenarios at the reference objects

When the different scenarios have been defined, each scenario should be evaluated with respect to the development of the fire, the spread of toxic gases, the possibility of extinguishment using different methods, and finally with respect to the damage to people, property and the environment. Thereafter appropriate fire-fighting tactics can be selected.

Firstly, the fire scenarios must be defined. The ignition source may be a forklift truck or an electric installation. In fact, the ignition source is of minor interest, as all the scenarios are described given that ignition has occurred. For each reference object we have three different scenarios: 1) a pre-flashover fire, 2) a post-flashover fire in one compartment and 3) a severe fire when the whole building is engulfed in flames. Each scenario is presented here in more detail. All rates of heat release presented in this chapter were determined using references [22] and [23].

Scenario A1: The small warehouse, Limited fire on the ground floor

A fire that starts in the stored goods on the ground floor will spread rapidly. A fire in the pallet system will spread vertically in the gaps between the stored cardboard boxes. Within a few minutes, the flames will reach the ceiling, and will start to spread laterally. The rate of heat release is now about 3 to 5 MW. If it is assumed that the fire spread stops, and that the fire remains at a constant level, we obtain our first fire scenario, a constant fire of about 4 MW. When flashover occurs, we go over to scenario 2. The average heat of combustion for the stored products can be estimated to be 25 MJ/kg. As the temperature is still quite low, no windows will break. This means that the opening area is small. In fact, there are only leakage areas, mainly through the doors. The total opening area can be estimated to about $0.5 \cdot 2$ m².

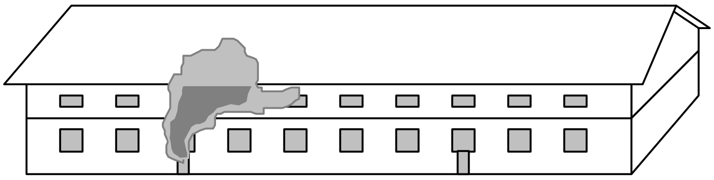


Figure 14. Scenario A1 is a limited fire on the ground floor.

Scenario A2: The small warehouse, flashover in one compartment on the ground floor

If the fire continues to spread from the first section of the pallet system, it will accelerate and soon the whole room will be enveloped. Within 10 to 20 minutes, the windows will break and we reach the second possible constant level: flashover in one of the storage rooms on the ground floor.

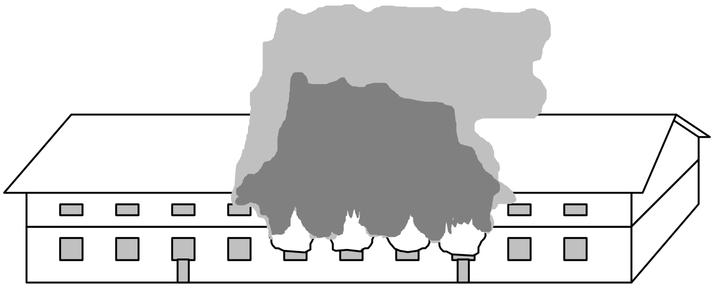


Figure 15. Scenario A2 is a flashover fire in the largest storage room on the ground floor.

The development of the fire can be calculated in a similar way to the first scenario. When the windows have broken, the rate of heat release inside the building will increase to about 17 MW, according to the computer simulations presented in the next chapter. A flashover fire gives a mass loss rate corresponding to a rate of heat release of about 25 MW, giving 8 MW burning outside. The average heat of combustion of the stored products is estimated to be 25 MJ/kg.

Scenario A3: The small warehouse, structural fire on both floors and in the loft

If the fire continues to develop from scenario 2, it will spread through the lift shafts and ventilation shafts inside the building, and/or through the windows to the first floor, and further up to the loft. There are no barriers, except the brick compartmentation on the ground floor. A structural fire will develop rapidly involving most parts of the building, and within a short time, the roof will collapse.

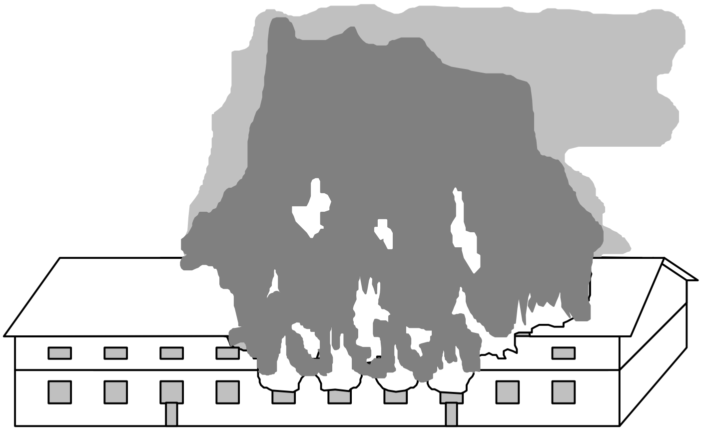


Figure 16. Scenario A3 is a fully developed structural fire involving most of the building.

The fire will burn through the roof, which means that the fire can be approximated by a pool fire. The dimensions are 20 · 50 m², and the average heat release rate is about 0.5 to 1.0 MW/m². This gives a total rate of heat release of 500 to 1000 MW. Although a high total number, this can be regarded as a low level. An ordinary hydrocarbon fuel fire has a heat release rate of 2.0 to 2.5 MW/m², while other fuels have a higher level. As will be seen later, this proves to be irrelevant; not even assuming the lower level of heat release can the fire be extinguished offensively.

Scenario B1: The large warehouse, limited fire in one compartment

Assume a compartment with limited amounts of stored goods. A fire in the pallet system will grow rapidly and spread vertically in the gaps between the stored cardboard boxes. Within a few minutes, the flames will reach the ceiling, and will start to spread laterally. The heat release is now about 4 to 6 MW. If it is assumed that the fire ceases to spread, and remains at a constant level, we obtain our first fire scenario, a constant fire with a size of 5 MW. The risk of flashover depends on the spread of the fire. When it occurs, we end up in scenario 2.

As there is not yet any flashover, and as the temperature remain reasonably low, the surrounding construction will remain stable. This means that the opening is only the compartment door. The average heat of combustion for the stored products can be estimated to 25 MJ/kg, as there is a significant amount of paper, cardboard and wood. This gives a mass loss rate of 0.2 kg/s.

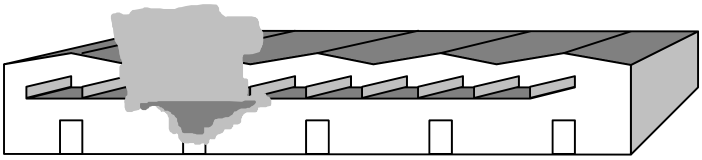


Figure 17. Scenario B1 is a limited fire in one compartment.

Scenario B2: The large warehouse, fully developed fire in one compartment

The second scenario is a fire that starts at floor level in a similar way as the first scenario. The fire is here assumed to start in an area with goods stored to full height. The fire growth will be very fast. Within 1 - 3 minutes, the flames will reach the ceiling, and will start to spread laterally. The heat release rate is now about 1 - 2 MW. As the access to air is limited, the flames will start to spread laterally in the gaps between the pallets. This means that the fire will spread horizontally, and a heat release rate of the order of 10 - 20 MW is not unrealistic.

Stored flammable liquids will lead to a pool fire when the containers are weakened and rupture. The fire will now spread to involve the whole section of the pallet system giving a heat release rate of 50 - 100 MW within 5 - 10 minutes. The level of radiation is now so high that the fire will spread to the section on the other side of the passage.

As the wooden pallets only rest on 5 cm wide runners, they will soon be weakened and collapse. This may start to occur within 5 - 10 minutes, depending on the strength of and load on the pallets, and will have a retarding effect on the fire.

It is worth noting that although the doors between the fire compartments will stop the spread of fire for a certain time, they may not completely stop the spread of smoke. This will lead to slow smoke filling of the adjacent compartments.

The average heat of combustion for the stored products is estimated to be 25 MJ/kg, as there is a significant amount of paper, cardboard and wood. This gives a mass loss rate of 2.4 kg/s for the fully developed fire at 60 MW.

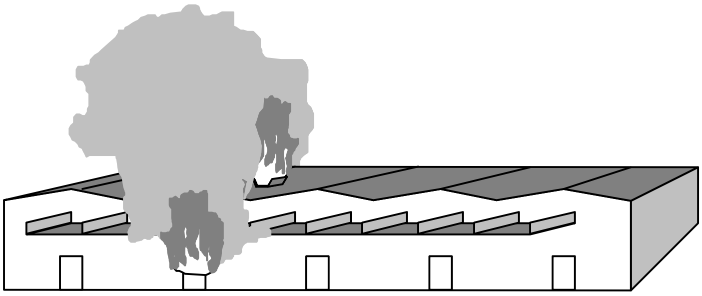


Figure 18. Scenario B2 is a fully developed fire in one compartment.

The scenario can be divided in two phases. At ignition we assume both doors and vents to be closed. (10% of the door and 1% of the vent are open as a leakage areas). When the fire brigade arrives, the smoke vents and the outer door are opened. According to the pre-fire plan, the fire brigade is responsible for the opening of the fire vents. This time is set at 600 s.

Scenario B3: The large warehouse, fully developed structural fire

A fire that starts in a similar way to the previous scenarios, may lead to flashover in the fire origin compartment within 5 - 10 minutes. As the outer doors are left open and the smoke ventilators are opened, the fire will increase in size due to the increased access of air. The resistance of the roof has not been determined, but when it collapses, the fire will increase.

Although the doors between the fire compartments will stop spread of fire for a certain time, they may not completely stop the spread of smoke. This will lead to slow smoke filling of the adjacent compartments.

There is also the possibility that if the doors and vents to the fire compartment are closed, and suddenly opened by the fire fighters, there might, in the very worst case be some form of fire gas explosion which ruptures the fire compartment walls. Other, and more plausible, causes of wall damage may be that when the pallet system starts to collapse, stored goods fall against the wall, or the roof might drag the wall with it when it collapses. It is also possible is also that barrels containing flammable liquids explode. They may damage the walls or the roof when thrown up into the air and create secondary fires upon landing.

All these cases will lead to rapid smoke filling and fire spread to adjacent compartments. This means that it is possible for the fire to spread through the building, leading to a fully developed fire involving most of the building

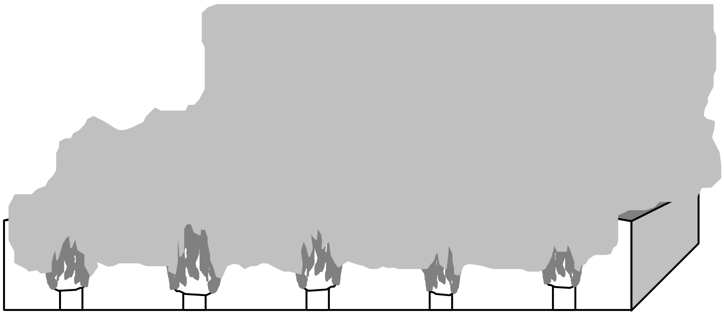


Figure 19. Scenario B3 is a fully developed structural fire involving most of the building.

The fire will burn through the roof, which means that it can be approximated by a pool fire. The dimensions are 60 · 100 m^2, and the average heat release rate is about 0.5 to 1.0 MW/m^2. This gives a gigantic total rate of heat release of 3000 to 6000 MW. A comment similar to that in scenario A3 may be needed. The heat release rate is calculated for a small per unit area level. This will, however, not make any difference in the forthcoming calculations.

4.6 Fire calculations for the reference objects

When the fire scenarios have been defined, the next step is to calculate the behaviour of the fire. Many models may be used, from simple empirical correlations to advanced CFD calculations. In this study a two-zone computer model was used. This type of model gives reasonably good accuracy and requires a moderate time for calculations. The results define the flow of smoke from the building, which will be used in the following dispersion calculations.

Scenario A1

For the previously described fire scenario, calculations were performed using the computer software HAZARD I [24]. A relatively simple room configuration can be used, as shown in Figure 20.

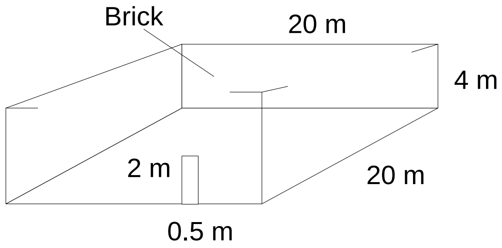


Figure 20. The room configuration used in the first scenario, A1.

Assuming a constant fire of 4 MW, the following results were obtained, which can be used as input for the dispersion calculations.

Mass loss rate:	0.16 kg/s
Mass flow of smoke through vent:	0.80 kg/s
Temperature of out-flowing smoke:	200°C

With survival fractions of 1, 10 and 50%, i.e. if 1, 10 or 50% of the pyrolysing pesticide is unaffected by the fire, the corresponding mass flows of unburnt pesticide will be 0.0016 kg/s, 0.016 kg/s and 0.08 kg/s, respectively.

Scenario A2

For fire scenario A2, the computer software HAZARD I was used, although it can be argued that the two-zone model has a lower accuracy after flashover than for pre-flashover fires. A similar configuration to that in the first scenario was used, but with an additional ventilation opening due to broken windows. The windows were opened at t = 150 s.

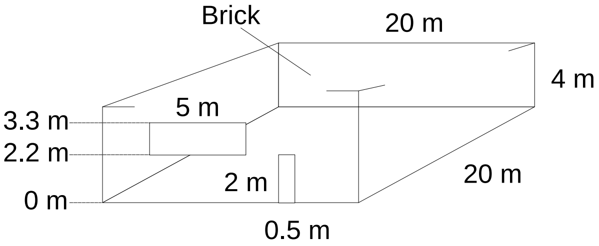


Figure 21. The room configuration used in scenario A2.

Assuming a constant fire of 25 MW, the following results were obtained. There may be secondary burning when the smoke leaves the building and is mixed with fresh air. This will of course increase the temperature.

Total mass loss rate:	1.0 kg/s
Mass flow of smoke through vent:	5.3 kg/s
Temperature of out-flowing smoke:	400°C
Heat release rate outside the fire compartment:	8.5 MW

With survival fractions of 1, 10 and 50%, the corresponding mass flows of pesticide will be 0.01, 0.1 and 0.5 kg/s, respectively.

Scenario A3

For this scenario, a two-zone model is not applicable. The fire can be approximated with a pool fire and the rate of heat release and the dimensions of the pool are entered directly into the dispersion model. The dimensions of the estimated burning area are $20 \cdot 50$ m² or 1000 m². If the pool is circular, the radius is 17.8 m

Rate of heat release:	500 MW
Radius of pool fire:	17.8 m

The average heat of combustion for the stored products and the building construction is still estimated to be 25 MJ/kg. This gives a mass flow of 20 kg/s for the burning substance. With survival fractions of 1, 10 and 50%, the corresponding mass flows of unburnt pesticide will be 0.2 kg/s, 2.0 kg/s and 10.0 kg/s.

Scenario B1

With the assumptions described in this fire scenario, calculations were performed with HAZARD I. A relatively simple room configuration can be used, as shown in Figure 22.

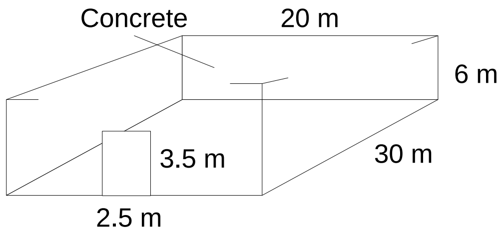


Figure 22. The room configuration used in scenario B1.

Assuming a constant fire of 5 MW, the following results were obtained.

Total mass loss rate:	0.2 kg/s
Mass flow of smoke through vent:	7.1 kg/s
Temperature of out-flowing smoke:	200°C

With survival fractions of 1, 10 and 50%, i.e. if 1, 10, or 50% of the pyrolysing pesticide survives the fire, the corresponding mass flows of pesticide will be 0.002 kg/s, 0.02 kg/s and 0.1 kg/s.

Scenario B2

Calculations were performed using the previously described assumptions, with the model HAZARD I. A room configuration according to Figure 23 was assumed. The roof ventilation is located at the top of one wall, so that it can be opened with a time lag. The delay was set to 600 s.

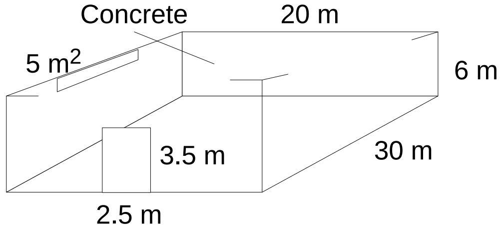


Figure 23. The room configuration used in the second scenario, B2.

Using a constant fire of 60 MW (which is the upper limit for the software), the following results were obtained for the out-flowing smoke. There may be secondary burning when the hot smoke leaves the building and is mixed with fresh air. This will of course increase the temperature.

Total mass loss rate:	2.4 kg/s

Phase 1, before fire brigade intervention at 600 s

Mass flow of smoke through vent:	2.4 kg/s
Mass flow of smoke through door:	9.2 kg/s
Temperature of out-flowing smoke:	650°C
Heat release rate outside of fire compartment:	35 MW

Phase 2, after fire brigade intervention at 1200 s

Mass flow of smoke through vent:	19.6 kg/s
Mass flow of smoke through door:	3.2 kg/s
Temperature of out-flowing smoke:	500°C
Heat release rate outside the fire compartment:	0 MW

With survival fractions of 1, 10 and 50%, the corresponding mass flows of unburnt pesticide will be 0.024 kg/s, 0.24 kg/s and 1.2 kg/s, respectively.

It is important to draw attention to a 70 MW peak in the rate of heat release out of the vent when the doors and vents are opened. This indicates that the amount of unburned decomposition products is substantial. Under certain conditions, it would, therefore, not be unrealistic to get a backdraft when the door is opened.

Scenario B3

A two-zone model may not be applied to this scenario but, on the other hand, there is no need for a model at all as the heat losses in the building are small compared with the overall heat release. As in scenario A3, the fire is approximated by a pool fire and the rate of heat release and the dimensions of the pool are put directly into the dispersion model. The dimensions of the estimated burning area are $60 \cdot 100$ m² or 6000 m². If the pool is circular, the radius is 43.7 m

Rate of heat release:	3000 MW
Radius of pool fire:	43.7 m

The average heat of combustion for the products stored and the building is still estimated to be 25 MJ/kg. This gives a mass flow of 120 kg/s for the burning substance. With survival fractions of 1, 10 and 50%, the corresponding mass flows of unburnt pesticide will be 1.2 kg/s, 12 kg/s and 60 kg/s.

4.7 Dispersion calculations for the reference objects

There seem not to be many cases where people outside a burning chemical store have died of poisoning or even been severely injured [25]. Cases which points out the high risks at chemical facilities are mainly concerned with accidental releases of gaseous substances without any fire. The Bhopal disaster is an example of this kind [26]. Considering fires in chemical warehouses in particular, the accidents usually referred to did not cause death and very few led to health problems, but rather environmental problems. For example, the Sandoz fire caused severe pollution in the river of Rhine, but no cases of serious illness directly resulting from the fire were reported [5]. Health problems will certainly occur for unprotected people, i.e. fire fighters, close to the fire.

Unlike the fire calculations, there are few models which can be used to determine the spread of smoke. There are a number of different models which describe toxic gas releases and for calculating the concentration as a function of the distance from the source. Models of this kind are CHEMS+, GReAT and WHAZAN.

None of these models takes the plume rise into account. The buoyant force of a large fire leads to a significant plume rise. One effect of plume rise is that the plume looses contact with the ground. When it falls back and regains ground contact, the concentration may have decreased below the toxicity level. Concentrations at ground level determined by these models may therefore be highly overestimated. The only models available that take the plume rise into account, are models developed for calculation of releases from chimneys. These are empirically derived and have not been validated for extended area sources as in case of a fire.

This leads us to the conclusion that a prediction of the concentration of toxic substances due to a burning building can not yet be made with a satisfactory degree of confidence. Thus, there is a need for the development of a model that includes the plume rise in the determination of the spread of toxic substances.

The following dispersion calculations were carried out at the Swedish Defence Research Establishment [27], in order to make a rough estimation of the distance from the building at which casualties were not likely to occur. As input for the calculations the previously determined mass flows of toxic substances were used. The model is a modified Gaussian plume model in combination with a modified Briggs plume rise model [27].

The resulting concentration-distance maps may be used in determining the inner and outer cordon, in estimating the area necessary to evacuate of people outdoors, and the need to broadcast the (radio)message ”stay indoors and close windows and ventilation” to people living in the area.

The weather conditions used for modelling were a wind speed of 5 m/s and neutral stratification. This is a common weather situation at both reference objects. Other weather situations, may have different effects on the fire. For example, rain may cool the smoke down very rapidly. The uncertainty in the calculations due to variations in the input parameters could be identified in a sensitivity analysis.

The selection of a suitable model is the first problem regarding dispersion. The second is the selection of a toxicity concentration for a very complex smoke gas mixture. Here, it is sufficient to state that different substances have different toxic potencies. The toxicity of different products stored at the two reference objects will not be discussed here. To avoid pointing out a specific product, the fictitious pesticide *Fictivion* is used.

Pesticides can be divided in groups, depending on their relative toxicity [17]. Group A represents the most toxic chemicals, group B toxic, group C harmful and group D unhealthy pesticides. At both reference objects, there are products representing all four groups. However, one can never tell which compound is burning at any given time. Fictivion has therefore been assigned the properties of a group A pesticides. The LC_{05} value (i.e. the concentration that gives an expected mortality of 5%) is set to 1.1 mg/m³, and the LC_{50} value is set to 5.6 mg/m³. In both cases, the exposure time is 5 minutes. This corresponds to the time necessary for people to move out of the area. As smoke from industrial fires is normally dense and unpleasant, one can assume that people leave the area even at non-toxic concentrations.

Scenario A1

In scenario A1, the source term becomes 0.016 kg/s. The release source is 10% of the mass loss rate and the yield of Fictivion is assumed to be 0.10 gram per gram Fictivion burned. As the amount of smoke is small in comparison with the building size and as it is relatively cold, no plume rise was introduced in this scenario. According to Figure 24, the LC_{05} distance would be 240 m, and the LC_{50} distance about 50 m.

Scenario A2

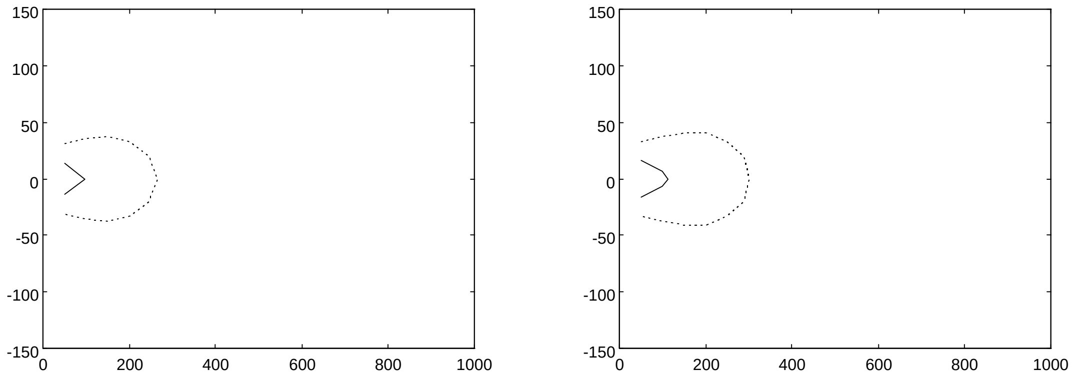
The source term is 0.10 kg/s in scenario A2, with the same assumptions as in the previous scenario. There is a small plume rise, indicating that the concentration close to the building is lower, but the area affected is larger. The LC_{05} distance would be 450 m, but no LC_{50} concentration was detected at ground level.

Scenario A3

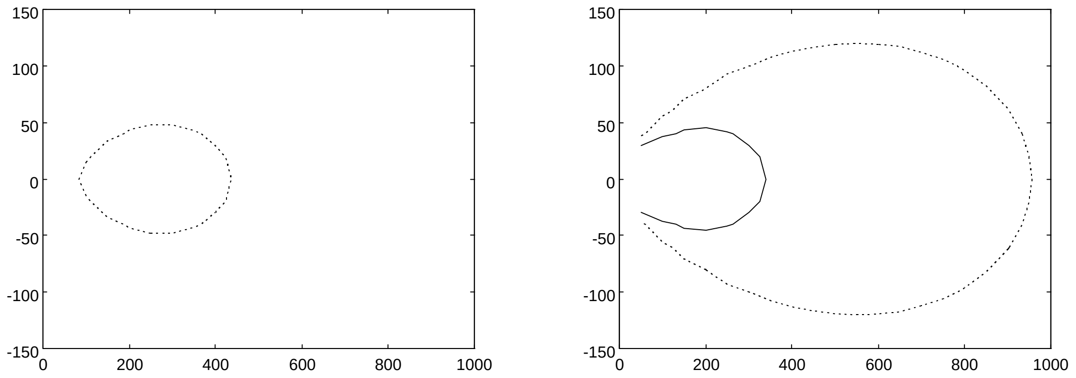
The structural fire is close to the limits of the calculation model. The mass flow of unburned material has increased to 2.0 kg/s. In this case more than just the group A pesticides must be burning e.g. other chemicals and packaging materials. As a consequence the smoke is less toxic. The LC values are higher making the affetcted area smaller.

The plume rise is significant. The centreline of the plume will therefore be high above the ground and the smoke at the ground will be more diffused. This will decrease the resulting concentrations at the ground, making the affected area even smaller. The source strength, however, will of course be larger which will act in the opposite direction.

In comparison with case A1 and A2 this scenario may affect an even larger area, but on the other hand, greater plume rise and lower LC values might result in concentrations lower than the toxic limit set by this actual LC value.



Scenario A1 Scenario B1



Scenario A2 Scenario B2

Figure 24. Down- and cross-wind distance [m] to concentration iso-lines for different fire scenarios. The outer line represents LC_{05} and the inner line LC_{50}.

Scenario B1

In scenario B1, the source term is 0.020 kg/s. As in scenario A1, no plume rise was introduced. This scenario is fairly similar to scenario A1, but a slightly larger release source gives somewhat greater distances. The LC_{05} distance was determined to be 260 m, and the LC_{50} distance to about 60 m.

Scenario B2

In this scenario, the source term is 0.24 kg/s. The plume rise is small, as the smoke arises from smoke ventilators which are distributed evenly over the roof area. This gives a large effective diameter of the plume. The LC_{05} distance increases to 950 m, and the LC_{50} distance to about 320 m.

Scenario B3

As in scenario A3, modelling of this scenario could not be made. The strong source makes the area affected by smoke larger. A lower LC value and a greater plume rise will, however, not necessarily lead to greater concentrations. These estimations are, however, quite uncertain. [27]

5. Fire extinction

We have now determined the nature and course of the fire, and wish to evaluate the capacity of extinguishment required to bring it under control. It should be emphasised that the relations described are simplified and that the estimations should be regarded as exemplifications of a complex system.

5.1 Capacity of the fire brigade

There are a number of parameters which affect the extinction capacity of the fire brigade, of which four are of vital importance: the striking power, the effectiveness, the persistence and the response time. These parameters can be described as follows.

- The striking power is the actual value of the rate of heat absorption.
- The effectiveness is the relation between the actual and the maximum theoretical value of the heat absorption capacity of the extinguishing media.
- The persistence is the period during which the operation can maintain its full power.
- The response time is the time elapsed from the start of the fire (or usually from fire alarm) until the rate of heat absorption starts to grow.

The capacity of heat absorption can be plotted as in Figure 25, similar to Figure 13 previously drawn for the heat release rate. A diagram like this can be drawn for each method of extinguishment available to the fire brigade. The fog nozzle of a BA team (i.e. fire fighters using Breathing Apparatus) has a high heat absorption capacity as it can be applied close to the fire, but a limited operational time as the fire fighters run out of air, in this case after half an hour. Fire fighters using external hose lines have a longer persistence, but a lower efficiency due to the increasing distance from the fire source.

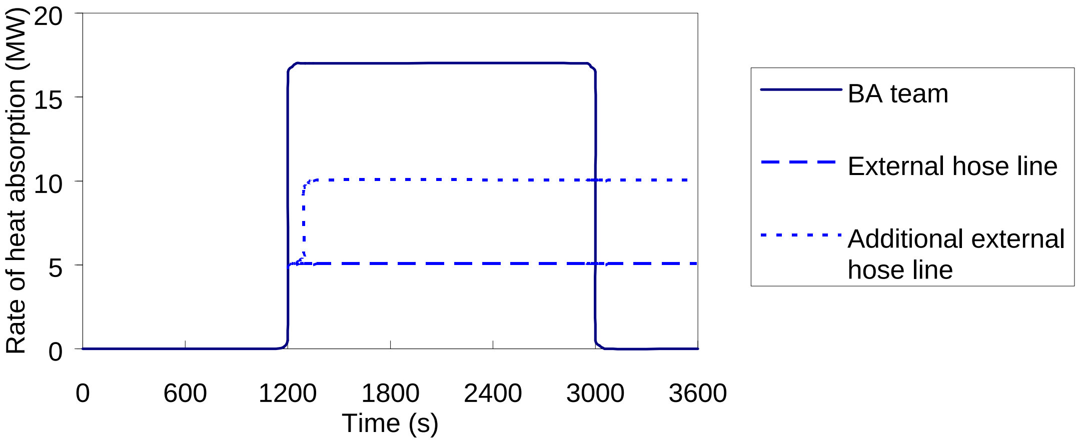


Figure 25. The rate of heat absorption of the fire brigade can be described in the same units as the rate of heat release.

As similar approach is used in the ADD-RDD concept developed by Factory Mutual Research Centre (FMRC), and applied to rack storage sprinkler systems. There, the Actual Delivered Density from the sprinkler system is measured and compared with the

Required Delivered Density to put the fire out. The ADD and RDD are determined experimentally, and the sprinkler system is designed for extinction, which is equivalent to an offensive operation.

However, before the extinction capacity can be determined, we must deal with the matter which distinguishes fires in chemical warehouses from other fires: the potential of polluting water courses. Chemicals and waste extinguishing media must be collected to prevent environmental damage.

5.2 Waste extinguishing media

When used to fight a fire at a chemical warehouse, the extinguishing water will almost certainly be polluted by chemicals. As many of the stored products are designed especially to interfere with the ecological system, they have the potential to cause substantial damage should they be released or dissolved in runoff water. Therefore, all water from the fire scene should be collected and prevented from reaching water courses or drainage systems. Different methods can be applied.

- The building itself can be designed to contain the water by having a floor lower than the surrounding area and interior doors with high sills.
- An exterior basin can be used - either as a sealed pit in the ground or as a tank.
- Portable spill basins could be used to collect the water.
- If the amount of liquid is limited, absorbents can be used.

The choice of method of spill water collection varies with the on-site conditions: the area available, possibilities of joint use of the system with other companies etc. Whatever the methods used, the system must be designed to contain:

- the volume of water calculated to be used during the operation,
- the stored goods that may leak out, and
- if the container is in the open or if it collects water from the surface around the building, the amount of rain than may fall during the operation.

It is an advantage if the system is designed with an inherent robustness, i.e. if the water is automatically led to a tank and there is no need to collect the water using pumps. This is an advantage for systems where the container is located below the floor level of the building. There are examples where holes for containers have been drilled into the ground [28]. A sealed pit in the ground is used at the small warehouse. There are also examples where the building itself is used to contain the water, as is the case at the large warehouse. The system must be designed to operate under different conditions. During the winter, for example, a valve in a drainage system may freeze and it may not be possible to open or close it.

Portable spill basins commonly have a volume of about 10 m³. A system of portable spill basins is, as the name indicates, very flexible. It does not require expensive fixed installations and it can be used in a variety of operations. There may, however, be some practical problems during large operations, as at fires in chemical warehouses, which are studied here.

- A large number of basins are required to meet the required capacity.
- A flat surface area is required to stand the basins on, about $5 \cdot 5$ m^2 per basin.
- The pump capacity to fill the basins must be equal to the water flow released.
- The water must be collected in some way.
- Personnel must be detailed to run the system.

At fires in chemical warehouses these practical problems may be such that the aim of collecting all the extinguishing water is not achieved. If there is a stationary tank which can be brought into use just by turning a valve or preferably by doing nothing at all, valuable resources are released to fight the fire.

Portable spill basins are presumably best suited for spills of chemicals without fire hazards. The required volume is then only the volume of the released chemical. At small fires, i.e. when a fire involving chemicals is put out within a few minutes by a sprinkler system the basins may also be valuable to urge on the overhaul work.

When foam is used as the extinguishing medium, the same dimensioning rules can be used as with pure water with the addition of water to break down the foam. One must bear in mind that water containing foam has a decreased surface tension which may increase the infiltration rate in soil. It should also be noted that a substantial foam layer may be created when water mixed with foam is pumped, and that this foam layer may overflow the spill basins.

When using dry powder, the only volume that should be collected at the fire is the spill of any liquid chemicals. However, dry powder is rarely used solely at the fire brigades, so the basins must be dimensioned for the other extinguishing agents, commonly water or foam.

Scenario A

At the small warehouse, an old dung-pit is used to collect extinguishing water by turning a valve in the drainage system. The pit can hold about 200 m^3 water.

Scenario B

At the large warehouse, extinguishing water can be collected up to a level of 0.5 m in each of the fire compartments, giving a volume of 300 m^3 per compartment or a total volume of 3000 m^3. The floor is lowered about 0.3 m, in combination with 0.2 m high removable steel sheets at the bottom of each door opening. A sump is connected to each fire compartment.

5.3 Water

Theoretical absorption capacity

At most fires, water is used as the extinguishing medium. The extinguishing effect comes from the heat absorbed by the water as it is heated and vaporised. The water is usually applied in one of three different ways:

1. The water is applied in small droplets, with a diameter less than about 1.0 mm [29], into the flames, in the gas phase of the fire. The heat absorption cools the flame down and when the adiabatic flame temperature falls below about 1600 K at stoichiometric conditions, the flame goes out [30]. The ratio of the lower limit of flammability for the fuel to stoichiometric concentration is 50 to 60% for many pre-mixed flames. The diluent is therefore responsible for absorbing about 45% of the energy released to extinguish the flame. For diffusion flames, the removal of 30 to 35% of the released energy is sufficient [30]. This is because a diffusion flame looses more energy due to radiation than a pre-mixed flame, and that combustion does not only occur at stoichiometric conditions. This indicates that for diffusion flames, the theoretical absorption capacity should be multiplied by a factor of 3 to obtain the extinction capacity. A good example of this type of extinction is when a BA team overcome a flashover fire by simply aiming the fog nozzle into the burning smoke layer. Another example is the fog nail which is inserted into a burning compartment through the roof or the wall, giving a fine water spray right in the smoke.
2. The burning fuel surface is cooled by the water, leading to a reduction in the pyrolysis rate, and the flame goes out due to lack of fuel. This is the case when a BA team has knocked down the flashover and are to extinguish the fire itself. Another example is when external extinguishing is applied. Here the water droplets often becomes so large, more than 2.0 to 3.0 mm in diameter [29], that they passes through the flames nearly unaffected.
3. The surface of a not yet burning fuel is cooled by water, and the pyrolysis rate does not increase enough for the fuel to ignite. This is the case at a defensive operation where a wall is protected from ignition by wetting.

Both points 2 and 3 are focused on the fuel with the difference that in point 2, the surface is burning, and in point 3, it is not. The difference is vital when discussing fire-fighting tactics and the difference between an offensive and a defensive operation.

The heat absorption capacity of water can easily be calculated:

- To heat water from 10°C to 100°C, the energy input required is
  90°C · 0.00418 MJ/kg°C = 0.38 MJ/kg
- To vaporise water at 100°C requires 2.26 MJ/kg.
- To heat the steam further requires an energy input that equals
  (T - 100) · 0.00201 [MJ/kg], where T [°C] is the actual steam temperature.

This means that to transform 1 kg of water at 10°C to steam at 600°C, an energy input of 0.38 + 2.26 + (1000-100) · 0.00201 = 3.6 MJ is needed. The heat absorption capacity is 3.6 MJ per kg of water used to its maximum at 600°C.

Water that is not vaporised, which can be seen flowing along the ground at many fire scenes, has a maximum absorption capacity of only 0.38 MJ/kg.

Theoretically, a hose delivering 1 kg/s might absorb the energy given in Figure 26. Unfortunately, the water is rarely applied in an optimal way, which means that an efficiency factor must be included.

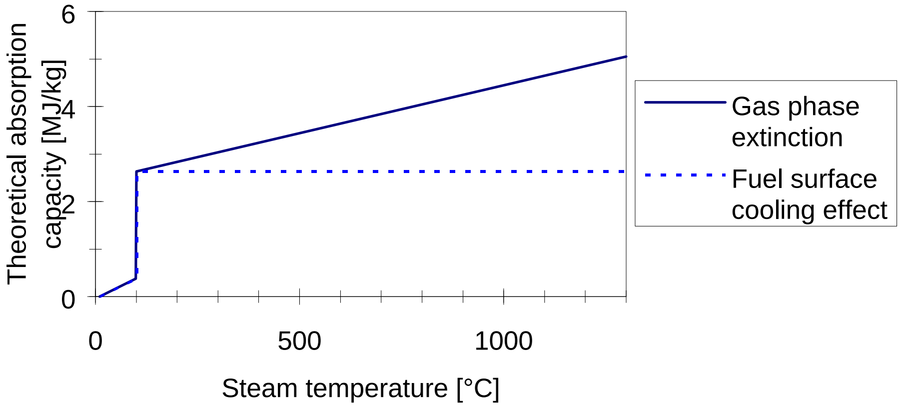


Figure 26. How the maximum theoretical absorption capacity of water at 10°C varies with the steam temperature.

Applied absorption capacity

In a series of tests, where a BA team used a fog nozzle to overcome a flashover fire, the maximum efficiency factor proved to be about 0.3 [31]. The investigation included four extinguishing tests, which are summarised in Table 6. As these tests were performed in a small room and under the best of circumstances, we should regard the efficiency factor as an upper limit. With a larger nozzle in a larger room, there will be a distribution problem. At the point where the nozzle is aimed, there will be over-kill, while surrounding areas are not covered. This indicates that the mere size of the nozzle has an impact on the efficiency.

Table 6. An experimental study of the extinguishing efficiency of a BA team.

Water flow* [kg/s]	Room temp. * [°C]	Theoretical absorption capacity [MJ/kg]	Theoretical extinction capacity [MW]	Extinction*	Rate of heat release* [MW]	Efficiency factor [-]
1.320	820	4.08	16.0	Definitely	1.8	0.11
0.608	800	4.04	7.4	Just able to	1.8	0.24
0.608	780	4.00	7.3	Just able to	2.1	0.29
0.272	720	3.88	3.2	No control	2.2	(0.69)

* From test report [31].

Others have suggested an efficiency factor of 0.32 for a water hose delivering water at a rate of 10 kg/s [32]. This efficiency factor concerns the fuel surface cooling effect. Here it was assumed that the steam is not heated above 100°C, giving an heat absorption capacity of 0.8 MJ/kg.

In Figure 27 the actual used water flow in relation to the area of the fire is shown [29]. The data are derived from real fires, and taken from reports published in the late 1950's [33] and 1960's [34]. These may not be valid after forty years. One reason is that breathing apparatus has made it possible to attack a fire at a much smaller distance. This, of course, leads to a much lower water demand.

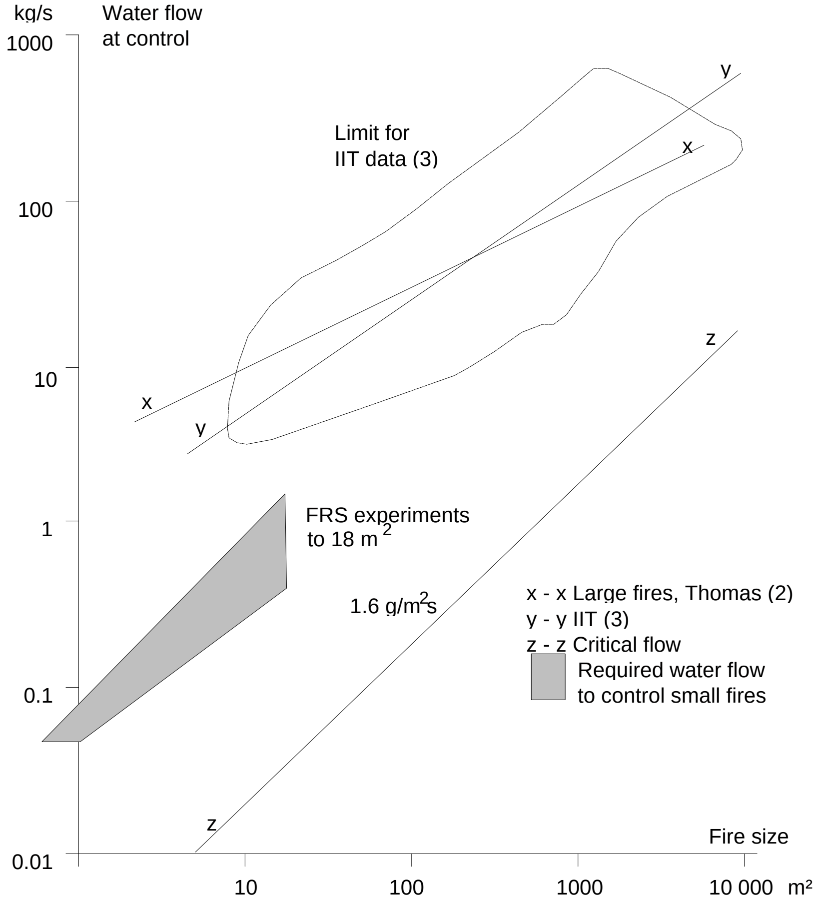


Figure 27. The actual water flow in relation to the fire area at real fires [29], [33], [34].

The figure is in many aspects obscure. For example, the horizontal axis shows the fire size, but it is not clear if this is defined as the floor area or the actual fuel surface area. Also, in flashover fires, it is not the floor or fuel area, but the size of the ventilation openings that determines the rate of heat release. The figure is, however, clear on one point. It suggests that the fire brigades used of the order of 100 times more water than should be required theoretically. This indicates a potential for improvement of fire-fighting operations.

As large fires are of main concern, the correlations x-x and y-y in the figure will be studied somewhat closer. The fire size can be recalculated as a heat release rate (using 0.5 MW/m²). In the same way, the water flow can be transformed to an absorption capacity (using 2.6 MJ/kg). If the absorption capacity is then divided by the heat release rate to give an efficiency factor, something interesting appears. Both correlations in the figure have a decreasing water demand per unit area. The efficiency increases linearly with the size of the fire and it becomes greater than 1 for fires bigger than about 200 m². Of course, an efficiency factor larger than 1 has no physical meaning, but there is an explanation for the occurrence. If we recall the difference between an offensive and a defensive operation, it may well be that the largest fires are not extinguished by an offensive operation, but in a defensive one. This leads to a much lower water demand. There may be cases where the fire is simply retained within its boundaries and runs out of fuel after a couple of hours. The data in Figure 27 must therefore be rejected for the purpose of determining an efficiency factor for water.

The efficiency factor varies with the method used, with the hose operator and with the equipment. Unfortunately, there are no systematic measurements of the actual extinction capacity of water. Thus, the efficiency must be estimated. In this study, the following practically applicable assumptions were made.

- The maximum heat absorption capacity for water is
  $2.6 + (T - 100) \cdot 0.00201$ [MJ/kg].
- For nozzles delivering droplets smaller than 1 mm, T [°C] is the smoke temperature. As a temperature of 600°C is commonly used as a flashover limit, it is convenient to use the same temperature here. This gives a maximum heat absorption of 3.6 MJ/kg, which is multiplied with a factor of 3, giving 10.8 MJ/kg in flame extinction capacity.
- An efficiency factor of 0.2 is used for interior fog nozzles.
- For nozzles delivering droplets larger than 2 mm, T is 100, giving a maximum heat absorption of 2.6 MJ/kg.
- An efficiency factor of 0.2 is used for long-range, well placed monitors.
- An efficiency factor of 0.3 is used for long-range, well placed nozzles.
- An efficiency factor of 0.4 is used for short-range, well placed nozzles.

In Table 7 flow rates for different types of nozzles, all commonly used by Swedish fire brigades are presented [35], [36], [37]. The assumptions listed above, concerning absorption capacity and nozzle efficiency, has been used in the table.

It is, of course, assumed that the equipment is used properly. If the distance from the nozzle to the fire is greater than the reach, the extinguishing capacity is naturally zero. Similarly, the precision may be poor at long distances and if a large-capacity hose is used for the external attack on an attic fire, the roof will protect the fire from water, as if it were raining. Thus, it is better to use one correctly applied fog nail than three erroneously placed large-capacity nozzles. In addition to the probability of extinction increasing, the water required decreases from 50 to 1.2 kg/s.

At large fires, the radiation from the fire may be so great that it is not possible to attack the fire at a close range. It is then necessary to choose a nozzle from which the water can reach the fire. The choice of nozzle is a balance between an efficient nozzle applied close to the fire and a larger nozzle at a safe distance.

Table 7. Heat absorption capacity for different nozzles.

Equipment	Maximum heat absorption [MJ/kg]	Water flow rate [kg/s]	Efficiency factor [-]	Heat absorption capacity [MW]
Standard nozzle (7 mm) [35]	2.6	1.3	0.4	1.4
Standard nozzle (14 mm) [35]	2.6	4.8	0.4	5.0
Standard nozzle (22 mm) [35]	2.6	9.2	0.3	7.2
Large-capacity nozzle [36]	2.6	16.7	0.3	13
Monitoring nozzle [36]	2.6	40	0.2	21
Fog nail [37]	3.6 ·3	1.2	0.2	2.6
Fog nozzle (BA team) [35]	3.6 ·3	5.0	0.2	11
Fog nozzle (BA team) [35]	3.6 ·3	7.9	0.2	17

Different nozzles demand different additional resources. The most obvious is the need for pumps and water (reservoirs or pipes), but personnel requirements also differ. For example, a BA team on an offensive interior attack requires one officer and four fire fighters, according to Swedish safety regulations [38]. An exterior nozzle requires, in principle, only one man.

Scenario A1

The first scenario is a limited fire on the ground floor in the small warehouse. The rate of heat release is estimated to be 4 MW. Before flashover, it may be safe to launch an interior attack which would provide 17 MW in extinction capacity. The fire brigade may employ a BA team and the amount of water would be small and could be contained. The resources are therefore sufficient to handle the scenario.

Scenario A2

At flashover in one compartment on the ground floor, the rate of heat release is estimated to 17 MW. It may not be safe to launch an interior attack, and it would not in any case be sufficient. Exterior nozzles may overcome the fire. Using 4.8 kg/s nozzles with a cooling power of 5 MW, four nozzles would be sufficient, provided that the reach was good. As a storage facility is normally greater than 10 · 10 m and as the owner normally tries to use the space as effectively as possible, it may be difficult for fire fighters standing outside the building to reach the back of the racks and in between the boxes. The fire fighters must approach the building and therefore every man should be equipped with breathing apparatus.

Four 4.8 kg/s nozzles lead to 35 m^3 of waste water in 30 minutes, which is less than the 200 m^3 volume that is available to collect the waste water. The manpower is sufficient, but the heat absorption capacity means that the technical resources are critical.

Scenario A3

When virtually the whole building is engulfed in flames, i.e. a structural fire on all floors and in the loft, the heat release rate is estimated to be greater than 500 MW. The size of this fire is many times larger than the heat absorption capacity of a small fire brigade. The number of large-capacity nozzles required is in the order of 40 to put the fire out, perhaps more as the reach will be poor when the radiation prevents the fire fighters from approaching the building. The fire-fighting problems grow when one remembers that every nozzle requires a fire fighter who should be equipped with BA. In this scenario, the fire has grown so large that an offensive operation is not possible.

Forty nozzles delivering 16.7 kg/s would mean a water volume of 1200 m³ in 30 minutes. This is far more than the available collection resources, unless the water is re-used in the fire-fighting operation. This is, however, not common in fire-fighting operations. We can thus conclude that the fire brigade resources are highly deficient in this scenario.

Scenario B1

The pre-flashover scenario of 5 MW can be overcome by one BA team with an extinguishing potential of 17 MW. As the storage layout is very compact, the reach may be poor leading to a decrease in the efficiency.

A fog nozzle giving 7.9 kg/s, results in 14 m³ water in 30 minutes. This is less than the storage volume in the warehouse. As the fire brigade can employ several BA teams, the resources are sufficient.

Scenario B2

At a fully developed fire in one compartment, the RHR in the fire compartment is about 33 MW (while the total RHR is about 100 MW). Even if it could extinguish the fire, an interior attack using multiple BA teams at a post-flashover fire in a warehouse is not inherently safe. This is due to the risk of falling storage goods and exploding containers.

An external attack would require a number of nozzles: three or four with a large capacity. Unfortunately, the access is poor as the three-dimensional storage configuration is very compact.

Four 16.7 kg/s nozzles give a waste water volume of 120 m³ within 30 minutes. This is less than the 300 m³ storage volume (per fire compartment). In all, the resources at the scenario appear to be critical.

Scenario B3

At the fully developed structural fire involving most of the building, the heat release rate would probably reach the incomprehensible value of 3000 MW. This is so high that even if the amount of water required were available, the management of the operation would probably fail. The radiation levels would be so high, that unmanned nozzles would have to be used, which would decrease the efficiency to a very low level.

The 150 monitoring nozzles required to overcome the fire would require 11000 m³ water storage capacity which is far more than the 3000 m³ available. Even so, the method of extinction is unrealistic and the conclusion is that the resources are deficient.

5.4 Low- and medium-expansion foam

There are three different types of foam available for fire-fighting purposes: low-, medium- and high-expansion foam. High-expansion foam will be discussed in the next section.

Low- and medium-expansion foam are often used simultaneously in fire-fighting operations, mainly to smoother and extinguish pool fires. Low-expansion foam has a good reach but a moderate covering effect. Medium-expansion foam has a poor reach but an excellent covering effect on pool fires.

At fires in chemical warehouses, and at other types of warehouses, low-expansion foam is more useful, as fire fighters need to reach the fire from a safe distance, due to the heat radiation. The extinguishing effect of foam is due to the feed back breakage from the flames to the fuel surface and thus causing pyrolysis to cease.

Traditional methods of dimensioning are based on the principle that the whole burning area should be covered with foam within a few minutes. This method is applicable mainly to pool fires with a well-defined burning surface.

As warehouse fires are commonly fought with water rather than with foam, there are no rules for foam dimensioning in this case. A study of sprinkler effectiveness [39] showed that by adding AFFF foam agent to a conventional sprinkler system, the water density required decreased by 25 - 50% for pool fires. A normal water sprinkler system requires 6 - 7 l/m²min. In the test with foam agent added, 4 l/m²min was found to be sufficient for rapid control of the fire; results that have been confirmed by other tests. There are, however, few tests involving manual fire fighting and the knowledge available is too weak on which to base any recommendations. As the aim of this work is to connect different models rather than to evaluate specific models, some rough estimations will be made. For this purpose, the same model of extinction is used as for water, and the same efficiency factors are used.

There is, however, one case in which the use of foam will lead to a significantly different outcome than the use of water alone. That is at pool fires. Liquid fuel floats on extinguishing water and the fire may spread due to the extinction attempt. Under the same conditions foam will cover the fuel and extinguish the fire.

Scenario A and B

As the same model of extinction is used as for water, the example will give similar results. The case of liquid fuel is not considered when using water or foam. In real life, this would of course make a big difference, as there is a fire compartment storing flammable liquids.

5.5 High-expansion foam

High-expansion foam is used to fill a building or compartment when an interior attack is not possible for technical or safety reasons. The foam expansion ratio is high, by definition greater than 200 and is commonly of the order of 500 to 1000. The recommended dimensioning for high-expansion foam systems is as follows.

NFPA [40]	Swedish Rescue Services Board [41]
• The foam depth should be not less than 1.1 times the highest hazard.	• Each object should be covered with not less than 0.6 m of foam.
• The submergence time should be 3 to 6 minutes, depending on the scenario.	• The submergence time should be about 5 (3 to 8) minutes.
• Resources must be provided to permit continuous operation of the system for 25 minutes or to generate four times the submerging volume, whichever is less, but in no case less than 15 min.	• Resources must be provided to generate twice the submerge volume.
• The foam cover should be maintained for at least 60 minutes.	• The foam cover should be maintained for at least 30 minutes.

Another method of dimensioning is to state that the foam depth should increase by not less than 1 m/min [42]. This rate of rise may have to be increased, depending on the type of fuel, the geometry etc.

Foam filling must be used in combination with suitably placed ventilation to reduce the overpressure in the building caused by the foam filling process. This means that all openings should be closed below the foam filling depth and that some openings should be made above this level.

The NFPA figures assume that the system starts to operate within 30 seconds of the alarm, while the recommendations of the Swedish Rescue Services Board are mainly used for prevention of fire spread to adjacent fire compartments. Therefore, we must compensate for the increase in foam breakdown due to the heat flux from the fire.

The normal foam breakdown is about 0.1 m/min [43] without external radiation. A radiation level of 10 kW/m² increases the breakdown to about 0.2 m/min. At a radiation level of 20 kW/m² the foam destruction may increase to 0.4 m/min, depending on the type of foam liquid, the flame geometry and on the expansion ratio.

The foam discharge rate can be calculated from $R = \frac{V}{T} \cdot C_N \cdot C_L$, where

R [m³/min] is the required discharge rate

V [m³] is the submerging volume, normally the room volume.

T [min] is the submerging time, normally 5 min.

C_N [-] is the compensation for foam shrinkage. Assuming a foam filling rate of 1 m/min, $C_N = 1.1$ for compartments unaffected by fire. For a compartment filled with smoke, C_N = 1.2 and at flashover C_N = 1.4. (NFPA recommends the constant C_N = 1.15.)

C_L [-] is the compensation for leakage. If there is no leakage, C_L = 1.0.

If it is possible, a combined attack would be preferable: to overcome the flames with, for example, dry powder at the beginning of foam filling to reduce the thermal foam breakdown due to radiation from the flames. This can only be done provided that the powder itself does not break down the foam. Smoke may also break the foam down if it is sucked into the foam unit. This can be prevented by using a smoke-resistant foam agent.

It is worth noting that some foam agents used for high-expansion foams are not alcohol resistant. If there is an alcohol spill, this will break down the foam at the same rate as it is produced. Other foam agents, suitable for high-expansion foam, are alcohol resistant.

A normal high-expansion foam unit with a foam expansion ratio 800 has a production rate of 160 m³/min using 200 l water and 6 l foam liquid (3%) per minute. Assuming a foam depth increase of 1 m/min and a breakdown coefficient C_N of 1.2, the correlation above gives a maximum surface area of 130 m² per unit.

In all scenarios, the high-expansion foam resources proves to be deficient. There are, however, some advantages which should be mentioned. The first is that high-expansion foam places low demands on personnel resources. A few fire fighters can handle foam units for a large building with the right equipment. Secondly, in comparison with water, high-expansion foam have a very low water demand. This would suggest that there is a potential for using high-expansion foam at more operations in the future.

Scenario A1

In the first scenario, the floor area of the fire compartment is 20 m square, i.e. 400 m², and the room height is 4 m. With the recommended rate of foam rise, the capacity should be $R = \frac{V}{T} \cdot C_N \cdot C_L = \frac{1600}{5} \cdot 1.2 \cdot 1.0 = 384 \approx 400$ m³/min of high-expansion foam to enable the extinction of the fire. With an expansion ratio of 800 and a mixture containing 3% foam agent, the required flow would be:

- mixture flow 500 l/min,
- foam agent flow 15 l/min,

Using the NFPA recommendations, which requires foam and water to create a foam volume that is four times the submerging volume, the total demand would be:

- water demand 10000 l,
- foam agent demand 300 l

The demand for resources for the different scenarios are presented in Table 8.

Scenario A2

This scenario is identical to the previous one, except that the radiation level caused by the flashover has increased, changing C_N from 1.2 to 1.4. This means that $R = \frac{1600}{5} \cdot 1.4 \cdot 1.0 = 448 \approx 450$ m³ foam/min is required to extinguish the fire.

Scenario A3

At a fully developed fire, as in this scenario, the radiation levels are so high, and the ruptures of the building are so many, that foam filling leads to a number of practical problems. Therefore, extinction of a structural fire which involves most parts of the building is probably more difficult than reasonably accomplishable with high-expansion foam. Two floors and a loft of 1000 m² each would require a number of foam units larger than that available in the whole region. (On the other hand, if the operation is defensive and the strategy is to prevent the spread of fire, the not yet burning parts of the building may by filled with foam.)

Scenario B1

The floor area of the fire compartment is 20 m · 30 m, i.e. 600 m², and the room height is 6 m. With the recommended foam filling rate, the foam capacity should be $R = \frac{3600}{5} \cdot 1.2 \cdot 1.0 = 864 \approx 850$ m³/min to enable the extinction of the fire. However, if the warehouse is filled with stored goods, the area of the goods will take about 200 m², decreasing the foam rate to about 600 m³/min.

Scenario B2

With the increasing radiation level from a fire at flashover, the foam breakdown will increase, giving $R = \frac{3600}{5} \cdot 1.4 \cdot 1.0 = 1008 \approx 1000$ m³/min or 850 m³/min with the smaller floor area. This means that unless the fire is knocked down, e.g. with dry powder, additional foam units will be required.

Scenario B3

Extinction of a 6000 m² structural fire is with no doubt more difficult than reasonably accomplishable with high-expansion foam, requiring a number of foam units larger than that available in the whole region.

Table 8. The resource required using high-expansion foam (the foam expansion ratio is 800).

Scenario	Required foam flow [m³/min]	Water demand [l]	Foam agent demand [l]	Available foam flow* [m³/min]	Relative amount of resources
A1	400	10000	300	- / - / 160	Deficient
A2	450	11200	340	- / - / 160	Deficient
A3	Not applicable	Not applicable	Not applicable	- / - / 160	Deficient
B1	600	15000	450	- / 160 / 480	Deficient
B2	850	21200	680	- / 160 / 480	Deficient
B3	Not applicable	Not applicable	Not applicable	- / 160 / 480	Deficient

* After 10 / 20 / 30 minutes, respectively

5.6 Dry powder

Dry powder is commonly used in two different ways by Swedish fire brigades; either in small (6 to 12 kg) fire extinguishers or in larger powder units (100 to 300 kg). It is the latter type that is considered here.

Fire brigades at airports have used dry powder for a long time in combination with foam. Room fire tests have also been carried out in which powder has been used in a fast initial attack [44]. In spite of this, and in spite of being an extinguishing medium with a very high extinguishing capacity, there seems to be a lack of experience in using dry powder at real fires in storage buildings.

A large number of different dry powders are available. Some of the most common ones are mixtures of $NH_4H_2PO_4$ (MAP), KCl, KOH, $KHCO_3$, NaOH and $NaHCO_3$ [29]. There is a large difference in heat absorption capacity between these powders. An estimation of the capacity could be made in a similar way as for water, using the energy needed to heat and to evaporate the powder. In some cases, heat is also absorbed when the powder is decomposed. In order to use this method of calculation, we must know the chemical properties of the powders, and we must also assess a coefficient of efficiency.

Another approach is to use the REMP value. The Required Extinction Media Portion of an extinguishing media can be determined experimentally. This is defined as the relation between the amount of extinguishing media and the amount of fuel at extinction:

$$\mathrm{REMP} = \frac{m_{\text{ext. medium}}}{m_{\text{fuel}}}$$

The lower the REMP value, the more efficient the powder. The REMP values in Table 9 were derived in experimental studies of fuel gas and powder mixtures [45]. These are commonly of the order of 0.5 to 1.0 for flames with a low Froude number, i.e. for pool fires.

Table 9. REMP values for different powders determined in different experiments.

Test	Urea-K powder	K powder	MAP powder	Na powder
250 kW propane [45]	1.03	-	-	1.03 - 2.08
250 kW propane [46]	1.37	2.45 - 3.31	1.68 - 2.70	2.26 - 2.53
500 kW propane [45]	1.75	-	1.42 - 3.70	2.50 - 3.50
500 kW propane [46]	0.50	1.62 - 1.58	1.07	1.24
4.5 MW heptane [47]	0.47	0.56	0.66	1.42
8.8 MW heptane [46]	-	1.01 - 1.23	0.62	1.18

As we are interested in the extinguishing potency, not in relation to the fuel mass flow but to the rate of heat release, the heat of combustion of the fuel is introduced into the relation:

$$Q_{ext.} = \frac{\Delta H_C}{REMP} = \frac{m_{fuel} \cdot \Delta H_C}{m_{ext.\ media}}$$

Using a high-quality MAP powder with a REMP value of 0.6 and assuming the heat of combustion to be 25 MJ/kg (as in the fire calculations), the theoretical heat absorption potency would be 42 MJ/kg. As with other types of extinguishing media, an efficiency factor which depends on the operator, the distance from the nozzle to the fire etc. must be included. Some assumptions were made to facilitate the calculations .

- An efficiency factor of 0.1 was used for short-range exterior, well placed nozzles.
- An efficiency factor of 0.2 was used for short-range interior, well placed nozzles.

Table 10. Heat absorption capacity using dry powder.

Equipment	Maximum heat absorption [MJ/kg]	Mixture flow rate [kg/s]	Efficiency factor [-]	Heat absorption capacity [MW]
Dry powder unit , 100 kg [48]	42	2.9	0.1	12
Dry powder unit , 300 kg [49]	42	7.5*	0.1	32
Dry powder unit , 100 kg [48]	42	2.9	0.2	24
Dry powder unit , 300 kg [49]	42	7.5*	0.2	63

* Using two nozzles

Using these assumptions, the heat absorption capacity of dry powder seems to beat that of all other extinguishing media. There is, however, one drawback. Some powders (class BC powders) are effective only in the gas phase and do not extinguish a smouldering fire. If a BC powder is used in a room fire, the fire will rapidly re-ignite as heat is accumulated and as the pyrolsis continues. Measures must be taken to prevent re-ignition. This can be achieved using foam or water in an attack running parallel with the powder attack. Class ABC powders prevent re-ignition to some extent, but also in this case, a water or foam backup is recommendable.

It is also worth noting that in some cases, the stored chemicals may react with the dry powder. It is important to know what chemicals are stored and what type of dry powder is available in order to assess what reactions may occur and thus when not to use the powder.

Scenario A1

The first scenario is a limited fire on the ground floor in the small warehouse. The rate of heat release is estimated to be 4 MW. Before flashover, a trained BA team with a dry powder unit would without doubt overcome the fire. The amount of water required to finalise extinction is small and can be contained. The resources are thus sufficient.

Scenario A2

At flashover in one compartment on the ground floor, the rate of heat release is estimated to be 17 MW. An exterior attack using a dry powder unit at 32 MW may easily knock down the fire if the nozzle is placed correctly and if the reach is good. There may, however, be difficulties in reaching the back of the racks and between the boxes with an exterior attack. This means that an attack using water and/or foam must follow.

Waste water arises only from the secondary attack, which means that the 200 m³ storage volume available would be sufficient. The requirements on manpower are moderate, leading to the conclusion that the resources are sufficient.

Scenario A3

When virtually the whole building is engulfed in flames, the RHR is estimated to be 500 MW. This is ten times the capacity of a dry powder unit. The fire has grown so large that an offensive operation is not possible and that the resources are insufficient.

Scenario B1

In the first scenario, the rate of heat release is estimated to be 5 MW. Before flashover, a trained BA team with a dry powder unit will easily knock down the fire. As the storage layout is very compact, the reach may be poor, decreasing the efficiency. The amount of water required to finalise extinction is small and can be contained. The personnel demand is moderate, and the overall resources are sufficient.

Scenario B2

At a fully developed fire in one compartment, the RHR in the fire compartment is about 33 MW (while the total RHR is about 100 MW). An exterior attack using a dry powder unit of 12 MW will have difficulty in suppressing the fire even if the nozzles are placed correctly and if the reach is good. It may be too difficult to reach the back of the racks and in between the boxes.

The waste water arises only from the secondary attack, which means that the available 300 m³ storage volume (per fire compartment) would be sufficient. Although the personnel resources are also sufficient, the overall resources are insufficient.

Scenario B3

At the fully developed structural fire involving most of the building, the RHR probably reaches about 3000 MW. This is many times greater than the capacity of any dry powder unit, indicating that this method of extinction is unrealistic in this case, and that the resources are highly deficient.

5.7 Gaseous extinction media

There are a large number of different gaseous extinguishing media: nitrogen, carbon dioxide, halons (which are to be replaced for environmental reasons) and different halon-related compounds. Except for very special operations, gaseous extinguishing media are rarely used by the fire brigade. One exception is a fire in a silo, where the smouldering fire is easier to put out with a gaseous extinguishing agent than with water or foam. In this type of deep seated fire, gaseous agents are valuable.

For use at fires in chemical warehouses, there has not yet proved to be any gaseous extinguishing medium of practical use (except perhaps for halon). This means that gaseous extinction media can, for the present, be excluded from this specification.

6. Guidelines for the fire brigades

It has been mentioned that all calculations in this report shall be regarded as exemplifications of a complex problem. This concerns also the guidelines. Changes in the calculation models may give a different result, which must give corresponding changes in this chapter.

6.1 Damage evaluation

Let us now summarise the resulting damage from different scenarios, when different fire-fighting methods are used. Considering the small warehouse, there are four different damage targets: People in the vicinity, the warehouse building, the atmosphere and the adjacent water courses. The damage to each target is given in Table 11.

Table 11. The damage resulting from different scenarios.

Scenario	People	Property	Air	Water*
A1	Small	Small	Small	Small / Moderate
A2	Small	Moderate	Small	Small / Severe
A3	Moderate	Severe	Moderate	Small / Severe
B1	Small	Small	Small	Small / Moderate
B2	Moderate	Moderate	Small	Small / Severe
B3	Moderate	Severe	Moderate	Small / Severe

* Damage if ext. media is contained / not contained.

Fire-fighting operations can be evaluated in economical terms and certainly, it would be convenient to use a quantified damage model - perhaps even to use currency units [50]. However, as neither environmental damage, nor casualties among people can easily be expressed in economical terms, one may choose a qualitative model instead.

The dispersion modelling revealed low concentrations of toxic substances in all scenarios. Scenarios 1 and 2 could even be classified as non-hazardous from the neighbours' point of view. At the fire scene, the smoke is obviously to be regarded as toxic. At scenario 3, the uncertainty in the calculation is great, but the concentrations will probably be moderate [27].

An estimate of the damage to property can be made based on the size of the fire. In scenario 1, the building and its contents are saved. In scenario 2, there is a total loss of the burning fire compartment, and presumably damage due to smoke in the whole building. In scenario 3, there is a total loss of the building and its contents.

The release to the air is difficult to assess as only the source term can be determined but not the damage. It is, however, possible to state that scenario 3 would almost certainly be worse than scenario 1.

Although the release to air is difficult to assess, the release to water is much easier. Many chemical products, and almost all of the ones stored in the two reference objects, are especially designed to interfere with the ecological system. Even a small amount of these chemicals is enough to cause severe damage. One can therefore state that if the extinguishing water is not successfully contained, there will be severe damage to the life in the water system. Also, if large volumes of water are released, the damage would be greater than if the volume released was small.

6.2 Resource-demand comparison

With the model used to evaluate different methods, the acceptance criterion is that the rate of heat absorption is greater than the heat release rate for an offensive operation (or than the spread of heat for a defensive operation) to be possible. In Table 12, the relative resources for different methods for the different scenarios are assembled.

Table 12. The relative resources for the different scenarios using different fire-fighting methods.

Scenario	Water (internal or external)	Low-exp. foam	High-exp. foam	Dry powder
A1	*Sufficient*	*Sufficient*	Deficient	*Sufficient*
A2	Critical	Critical	Deficient	*Sufficient*
A3	Deficient	Deficient	Deficient	Deficient
B1	*Sufficient*	*Sufficient*	Deficient	*Sufficient*
B2	Critical	Critical	Deficient	Deficient
B3	Deficient	Deficient	Deficient	Deficient

Knowing the relative resources, the optimum operational mode can be determined. Recalling Figure 3, a similar diagram can be constructed with the actual scenarios, as in Figure 28. Every scenario should be located above the failure line. The operational mode should be either offensive or defensive, and the closer to the failure line, the higher the demands on command and control of the operation. In situations where the resources are sufficient or critical, an offensive mode could be selected. With deficient resources, a defensive operation should be chosen.

It has previously been stated that the closer to the failure line, the less the tactical reserve and the higher the tactical demands. It can thus be concluded that:

- as scenario B2 is close to the failure line, the tactical demands will be high, and
- scenarios A1, A2, A3, B1 and B3 leads to moderate tactical demands as there is a tactical reserve available.

These conclusions are valid only if the correct actions are taken. For example, if the dry powder unit is not brought with the responding unit, scenario A2 falls to a critical level of resources, leading to high demands on tactical judgement.

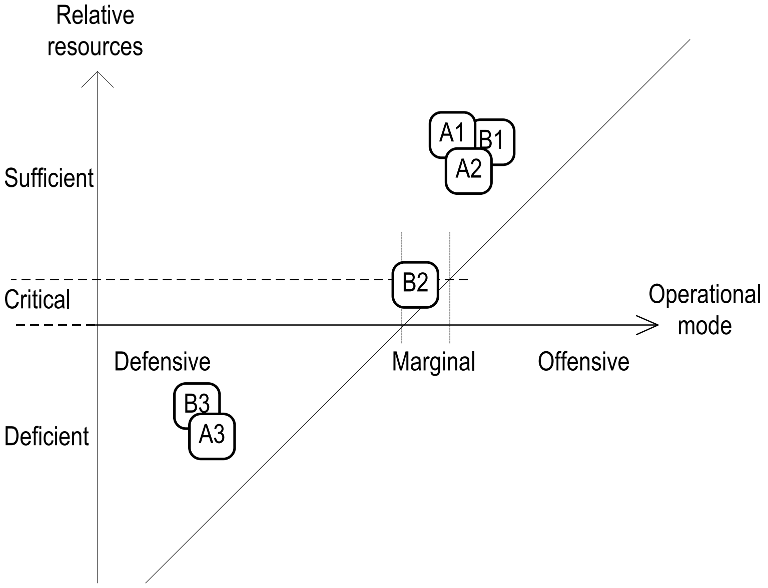


Figure 28. The scenarios from the reference objects plotted in the tactical model.

6.3 Pre-fire planning

So far, in the risk management process, the potential risk sources have been identified and the damage evaluated for people, property and the environment. The probabilities of the fire brigade extinguishing the fire have been determined for each situation.

Now comes the phase of transforming this knowledge into an operational pre-fire plan. That is, to plan the intervention so that the right path in the event tree is selected when the fire occurs. In some cases, a situation may be discovered where the fire leads to unacceptable consequences, but where the fire brigade may not be able to extinguish the fire. In such a case, the only way to deal with the situation is not to plan for the intervention, but to prevent the damage from occurring and/or to reduce its consequences.

The damage outcome can be related to the previously used event tree, as in Figure 29. Here, the damage evaluation is transferred to a grey scale, where white denotes small damage and black severe damage. Obviously, some of the outcomes are more attractive than others, indicating that it is now time to choose a set of actions that correspond to a desired outcome.

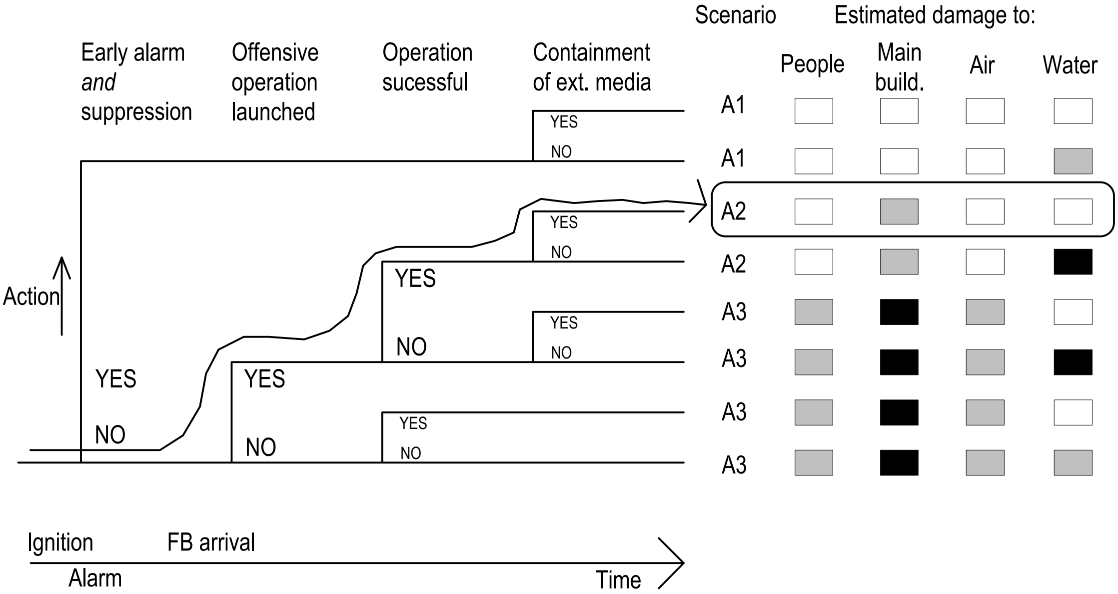


Figure 29. Each path in the event tree gives a different outcome.

The study reveals in which scenarios the fire brigade has the possibility of attacking the fire in a successful way. This can be expressed in a short form as in Table 13. When adopted to real pre-fire planning, the table must contain resources needed to launch the operation. It could also be extended to specify the situation if the fire breaks out in different fire compartments.

The time is not included in the table. This is because the fire may develop with a growth rate that is best described by a probability density function. This is also the case with the time that the fire may be contained by the containment walls. In my opinion, it is better not to determine an explicit time, but rather to make it possible to determine in what phase a fire is. This would provide information on both what the next phase may be and what signs to look for when the phase is changing.

Table 13. Recommended actions at fires in the two reference objects.

Scenario A

Situation	Actions	Criterion for re-evaluation of the situation
Pre-flashover fire	Offensive attack by a BA team using low-exp. foam. Contain the water used.	Flashover or fire is not declining. No possibility to contain ext. media.
Flashover in one compartment	Offensive attack with a dry powder unit followed by a BA team using low-exp. foam (beware of collapsing structures). Contain the water used.	Fire spread from the compartment of fire origin or spread of dense smoke. No possibility to contain ext. media.
Flashover in more than one compartment	Defensive attack. Secure containment lines. Use water only to protect surroundings. Contain water flowing from the building.	Containment lines break. No possibility to contain ext. media.

Scenario B

Situation	Actions	Criterion for re-evaluation of the situation
Pre-flashover fire	Offensive attack by a BA team using low-exp. foam. Contain the water used.	Flashover or fire is not declining. No possibility to contain ext. media.
Flashover in one compartment	Marginal attack with external low-exp. foam nozzles. Contain the water used.	Fire spread from the compartment of fire origin or spread of dense smoke. No possibility to contain ext. media.
Flashover in more than one compartment	Defensive attack. Secure containment lines. Use water only to protect surroundings. Contain water flowing from the building.	Containment lines break. No possibility to contain ext. media.

7. Discussion

In the model presented in this work, a number of sub-models are linked together. As with all new models, the presented one here requires additional refinement. In principle, every equation and calculation sub-model can be replaced as the fire engineering area develops. Results from one sub-model are used as input to the next one, leading to a growth in the calculation errors. It is important to bear in mind that it is the sub-model with the lowest accuracy that determines the overall accuracy, and that judgements of the accuracy in the calculations must be made.

A two-zone model is used in the fire calculation part. There are also engineering correlations which might fill the same purpose, and highly sophisticated CFD models. The same choice has to be made in the dispersion calculations, where models are available with a range of accuracies. Most of them do not yet have a satisfactory degree of confidence. Under normal conditions, a calculation process like this should include a sensitivity analysis. In this case, the calculation errors in the other parts of the process are so large that a sensitivity analysis may give a false sense of security.

It is among the extinguishment models that the largest calculation errors are found. The accuracy in this part of the calculation procedure determines the overall error more than any other factor. This is because there have been few attempts to quantify the response of the fire brigade. One example is that it was necessary to assume efficiency factors for the extinguishing media. The efficiency factor for a nozzle changes depending on whether it is located close to the fire or at the maximum distance of reach. If the results are in the right order, this is satisfactory.

In the chapter on extinction only relations used to estimate the potential of the extinguishing agent required to overcome the total heat release rate are presented. There should not be any major obstacles to a similar calculation process regarding defensive operations. An estimate of the radiative heat flux may be made and can be compared with the cooling potential available using different agents. The stop of smoke spread is also a defensive technique that can be determined quantitatively. The overpressure created by the fire causing smoke spread to compartments adjacent to the burning one can easily be determined with and without smoke ventilation. This pressure can be compared with the pressure which can be created with positive pressure ventilation or other methods.

The evaluation of damage is also a delicate matter, especially concerning damage to people and to the environment. Therefore, a qualitative model was selected. The damage to property is easier to quantify, as it mainly is caused by heat (causing severe damage) or smoke (causing moderate damage).

A general comment is that the model assumes that the operation is launched under normal conditions. However, equipment may malfunction. In the winter snow and ice on the roads may make the response time longer, or the valve that opens the basin for storage of extinguishing media may be frozen, etc. These types of problems must also be taken into account.

One objection can be made to the model. It is assumed that no life-saving operation is needed (or that it is very fast). I can not see any major obstacles in deriving a model for a BA unit search and rescue operation - especially as the operation does not interfere with the development of the fire to any greater extent.

In conclusion, the calculation process must be developed further, and the model could be extended to include probability density functions for the variables. This would provide a quantified risk analysis with results described by a complementary cumulative distribution function, CCDF, of the risk. The CCDF can easily be compared with some form of limiting curve, defined by the authorities.

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Lund, November 1996

Stefan Särdqvist

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