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## An Analysis of Appropriate Fire Safety Measures

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Deaths in Residential Fires – an analysis of appropriate fire safety measures
Dödsbränder i bostäder – en analys av lämpliga brandskyddsåtgärder

Fredrik Nystedt

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**Abstract:** The objective of this study was to investigate fire deaths and appropriate preventive actions. The risk of death due to fire is modelled by comparing fire development calculations with the modelling of human response. The risk of fire death is a function of the fire frequency, the probability of a fire developing and the probability that the occupant will not be able to escape before death occurs. The uncertainties are considered by employing statistical sampling methods such as Monte Carlo simulation. The fire risk model provides valid results for the estimation of the effectiveness of fire safety measures. The results show that previous studies on the effectiveness of smoke detectors and residential sprinklers have probably overestimated their effect. In many fatal fires the occupant is intimately involved in the fire development and could therefore not be rescued by either smoke detectors or sprinklers. The overall risk-reducing effects of smoke detectors and residential sprinklers are 11% and 53%, respectively. Mandatory installation of smoke detectors in homes is considered a cost-effective investment on a national level. The cost per life saved is USD 229,000. Residential sprinklers do not show the same effectiveness, the cost per life saved being USD 69 million. Sprinklers are, however, considered cost-effective in homes for the elderly homes with a cost per life saved if USD 440,000. With residential sprinklers, people with impaired mobility are exposed to the same risk as those with normal mobility having no fire protection.

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# Table of contents

# Summary

Many Swedish local authorities are already requiring smoke detectors in all homes. However, the fatal fires continues to increase and it is therefore probably the right time to introduce a safety measure that actually does something about the fire itself, This dissertation analyses the models the risk-reducing effects of various safety measures. The result could therefore be used to estimate the effect of different home fire safety measures such as smoke detectors and sprinklers prior to the arrival of empirical data. The dissertation should guide decision-makers at all levels in the most appropriate choice of measure to reduce the risk of death due to fire for a certain group of occupants.

Residential fires are characterised through literature studies on fire statistics and previous studies on the effectiveness of fire safety measures are scrutinised. A model is proposed in which state-of-the-art knowledge on fire dynamics and human response is used, allowing fire development and human behaviour in residential fires to be quantified. The risk of death due to fire is modelled and all known major uncertainties and variabilities are treated explicitly.

Residential fires are a serious problem. In the past years, approximately 110 fire fatalities per year have been recorded in Sweden. The residential fire risk has increased due to changes in fire load and fire behaviour. A few decades ago, it was rare for a single burning item to cause flashover. Today, furniture materials produce more heat in less time. The time available for escape is thus shorter as the fire develops quickly in residential buildings. Smoke alarms are lacking in about 80% of all fatal residential fires. Although requirements on smoke alarms in homes have increased over the recent years, it is arguable whether they are sufficient. Some people will be unable to escape by themselves regardless of whether a smoke detector is activated or not. Examples of such are the elderly and the very young. There are also cases where death results from a fire in which the victim is intimately involved, such as smoking or intoxication and those with mental disabilities. The statistical risk of death due to fire in Sweden is 1 in 50,000 per home per year.

Most people believe that the risk of fire in their own home is small. Approximately 60-70% consider the risk to be small or very small, and most people are unprepared regarding which action should be taken when exposed to a fire at home. The presence of smoke detectors in Swedish homes has increased over recent years. Four of five houses have smoke detectors, while only half of the apartments have a smoke detector. A functional smoke detector was found only in 10-20% of the fatal fires. About half of those who become fire fatalities are found a few metres from the exit. This indicates that they initiated their escape too late. A smoke detector would have provided additional time for these people to escape. Residential sprinklers control or extinguish a fire before untenable conditions occur. The system uses a minimum of water and responds quickly.

The risk of death due to fire is modelled by combining fire development calculations with the modelling of human response. The risk of death due to fire is a function of the fire frequency, the probability of a fire developing and the probability that the occupant will be able to escape before death occurs. There are two alternatives for the occupant to be safe. He is either able to escape before he becomes unconscious, or someone rescues him before conditions become lethal. Either the fire service or another person may rescue the occupants. It is always necessary to treat uncertainties when modelling fire safety problems. Especially as engineering tools are associated with a number of limitations and simplifications. The uncertainties are considered by employing statistical sampling methods such as Monte Carlo simulation.

The developed fire risk model was found to provide results valid for making estimates of the effectiveness of fire safety measures. The results show that previous studies on the effectiveness of smoke detectors and residential sprinklers probably have overestimated their effect. In many fatal fires the occupant is intimately involved in the fire development and could therefore not be rescued by either smoke detectors or sprinklers Three types of occupant are characterised among the fire fatalities: those who are intimately connected with the fire, those who have normal abilities and those who have impaired mobility. The occupants may be either in the room of fire origin or in an adjacent room. They may be either asleep or awake. The combination of occupant type, location and status, results in a number of scenarios in which fire safety measures are more or less efficient. The overall risk-reducing effect of smoke detectors and residential sprinklers are 11% and 53%, respectively.

Mandatory installation of smoke detectors in homes is considered a cost-effective investment on a national level. The cost per life saved is USD 229,000. Residential sprinklers do not show the same effectiveness having a cost per life saved of USD 69 million. Although sprinklers save far more lives, the installation and maintenance costs are much higher. Sprinklers are however considered cost-effective in homes for the elderly, with a cost per life saved of USD 440,000. With residential sprinklers, people who have impaired mobility are exposed to the same risk of death due to fire as those with normal mobility having no fire protection.

The developed fire risk model was unable to predict the probability that an occupant at risk of dying in a fire would be saved either by an external resource such as a neighbour, or by the fire service. This is one of the reasons why the results of the fire risk model differ from statistical measures of risk of death due to fire. The model shows great sensitivity to small absolute changes to the calculated time to unconsciousness. This sensitivity is characteristic for fire risk analyses that uses the well-known state function of time to untenable conditions minus the time required for escape. In contrast to load-bearing structures, where the design load is much greater than the normal load, the normal load and the accident load in fire life safety are very similar. There are also major uncertainties related to the design fire, human tenability and fire development that require further quantification before the results of the risk model can be expected to agree with true values.

# Sammanfattning (summary in Swedish)

Trots samhällets insatser för att minska antalet olycksfall har antalet dödsbränder ökat under de senaste åren. Många svenska kommuner kräver redan att brandvarnare skall finnas i alla bostäder. Det är troligen dags att introducera ett nytt skyddssystem som gör något åt själva branden, tex boendesprinkler. Denna avhandling har finansierats av VINNOVA – verket för innovationssystem med målsättningen att undersöka dödsbränder och lämpliga brandskyddsåtgärder. Syftet är att utveckla och validera en modell där brandrisken vid bostadsbränder kan kvantifieras. Resultat skall kunna användas för att uppskatta effekten av olika skyddssystem som brandvarnare och boendesprinkler innan dess att tillförlitlig statistik finns att tillgå. Avhandlingen skall vägleda beslutsfattare på alla nivåer om vilka brandskyddsåtgärder som är mest lämpliga för att reducera antalet dödbränder. Avhandlingen karakteriserar bostadsbränder genom en noggrann litteraturstudie av brandstatistik och tidigare studier om brandskyddsåtgärders effektivitet. Den föreslår en modell där brandförlopp och mänskligt beteende kan kvantifieras. Brandrisken modelleras och med en explicit hantering av de mest betydelsefulla osäkerheterna.

Bostadsbränder är ett problem. De senaste åren har drygt 110 människor omkommit vid brand i bostad. Brandrisken i bostäder har ökat genom att förändrad brandbelastning och beteende. I mitten av sextiotalet var det sällsynt att ett enstaka brinnande föremål kunde orsaka en övertändning. Dagens inredningsmaterial och möbler producerar mer värme på kortare tid. Brandvarnare saknas i nästan 80% av alla dödsbränder. Även då brandvarnarkravet finns i de flesta kommuner då är det diskutabelt om brandvarnare är tillräckligt för att minska antalet dödsbränder. Många av dem som omkommer kan ej utrymma oavsett om de blir varse om branden eller inte. Exempel på sådana grupper är äldre människor och barn. Det finns även ett antal dödsbränder där den omkomne är nära involverad i brandens uppkomst och spridning. Sådana dödsbränder orsakas ofta av rökning, alkoholpåverkan och förvirring. Den statistiska dödsrisken pga brand är 1 på 50000 per bostad och år.

De flesta människor anser att risken för brand i deras egen bostad är liten. C:a 60-70% tycker den är liten eller mycket liten samt de flesta är oförbreda på vad de skall göra om en brand uppkommer i hemmet. Användningen av brandvarnare har ökat under de senaste åren. C:a fyra av fem villor har brandvarnare. Motsvarande siffra för lägenhetsinnehavare är 50%. Hälften av dem som omkommer i bränder återfinnas endast några få meter från dörren. En brandvarnare hade kunnat göra dessa människor varse om branden tidigare så att de hade hunnit ut innan förhållanden blir kritiska. Boendesprinkler släcker eller kontrollerar branden innan dessa att förhållandena blir kritiska för utrymning. Systemet använder minimalt med vatten och aktiveras snabbt.

Brandrisken beräknas genom att värdera brandförloppsberäkningar mot en modell för mänskligt beteende. Brandrisken är en funktion av brandfrekvensen, sannolikheten att brand tillväxer samt sannolikheten att den boende hinner utrymma innan han dör. Det finns två möjligheter för den boende att undkomma branden. Antingen utrymmer han själv eller så får han hjälp av någon annan, exempelvis en granne eller räddningstjänsten. Det är alltid nödvändigt att hantera osäkerheter vid brandteknisk dimensionering. Det är särskilt påtagligt när ingenjörsverktygen är förknippade med en rad förenklingar och antaganden.

Brandriskmodellen visar sig ge tillfredställanden resultat för att kunna jämföra effektiviteten mellan olika brandskyddsåtgärder. Resultatet visar att tidigare effektivitetsstudier troligen har överskattat effekten av både brandvarnare och boendesprinkler. Detta beror på för stora förenklingar i beräkningarna. De som omkommer i dödsbränder kan delas in i tre olika kategorier – de som är nära involverade i branden, de som har normal fysisk kapacitet och de som är rörelsehindrade. När branden utbryter kan den boende antingen vara i brandrummet eller utanför. Han kan antingen vara vaken eller sova. Kombinationen av kategori, vistelse och status ger ett antal scenarier där de olika brandskyddsåtgärderna är mer eller mindre effektiva. The sammanvägda effektivitet i att förhindra dödsbränder bedöms till 11% för brandvarnare och 53% för boendesprinkler.

Det anses kostnadseffektivt att kräva brandvarnare i alla bostäder. Kostnaden per sparat liv är c:a 2,2 miljoner kronor. Värdet på ett statistiskt liv rekommenderas vara 30 miljoner kronor i flera kostnadsnyttoanalyser. Ett nationellt krav på boendesprinkler bedöms däremot inte vara en kostnadseffektiv åtgärd. Kostnaden per sparat liv är 655 miljoner kronor i detta fall. Att kostnaden blir så hög beror på den förhållandevis låga brandfrekvensen i kombination med systemets krav på underhåll. Boendesprinkler bedöms däremot vara kostnadseffektivt att installera i samtliga äldreboenden, nya såväl befintliga. Kostnaden per sparat liv blir här 4,2 miljoner kronor. Om alla äldreboenden förses med boendesprinkler blir det samma risknivå i dessa som i vanliga bostäder för människor med normal fysisk kapacitet (utan sprinkler).

Brandriskmodellen lyckades inte uppskatta sannolikheten att den som utsätts för en potentiell dödsbrand räddas av någon utomstående som en granne eller räddningstjänsten. Detta är en av anledningarna till att resultat från brandriskmodellen skiljer sig från den statistiskt beräknade risken. Modellen är känslig för relativt små förändringar av de beräknade tiderna för medvetslöshet och dödsfall. Denna känslighet är ett kännetecken för brandteknisk dimensionering när tillståndfunktionen med tid till kritiska förhållanden minus tid för utrymning används. Till skillnad från bärande konstruktioner där den dimensionerande lasten är mycket större än den normala, ligger normallasten och olyckslasten mycket nära varandra när det gäller personrisk vid brand. Det finns också stora osäkerheter när det gäller val av dimensionerande brand, kritisk påverkan på människor, brandförloppsberäkningar, etc som kräver vidare utredning innan riskmodellen stämmer bättre överens med verkligheten.

# 1 Introduction

The citation below is taken from the Swedish National Rescue Service Agency's vision regarding their accident prevention activities.

*"The fire risk should continuously decrease. The number of fire deaths and seriously wounded as well the amount of severe damage to the environment and major losses of property should be brought as close to zero as possible"*

The trend regarding fire deaths is, however, increasing and not decreasing. Smoke detectors are required according to Swedish building regulations when building new residential buildings. Many local authorities have also taken decisions in recent years stating that smoke detectors are required in homes. It would therefore be an appropriate time for the introduction of a safety measure that can affect the fire directly. Residential sprinklers are an example of a safety system that truly changes the behaviour and the development of a fire. Residential sprinklers are perhaps the next step in safety awareness following campaigns on drunk driving, seat-belt use and ground fault interrupters.

The work on which this dissertation is based was financially supported by VINNOVA, the Swedish Agency for Innovation Systems. "Residential Sprinklers" is the name of a project based on active industrial collaboration where technology and knowledge transfer is an integral part of the project. The project was carried out on a national basis and was aimed at creating well-functioning, active residential fire protection at a reasonable cost. The project was also intended to introduce and communicate the possibilities, advantages and values to the parties involved. Participants in the project are researchers and industrial representatives.

## 1.1 Background

### 1.1.1 The problem of death due to fire

Residential fires are a serious problem. In the past ten years, approximately 110 people per year have lost their lives due to fire. The risk of residential fires has increased due to changes in fire load and fire behaviour. A few decades ago, it was rare for a single burning item could cause flashover. Today furniture materials produce more heat in less time. The time available for escape is thus shorter as the fire develops more quickly in residential buildings. There are a number of ways of increasing fire safety. One way is prevention, e.g. through education and training. People should be aware of what they can do to prevent fires and how to respond in the case of a fire emergency. However, there are groups in society that are unable or unwilling to participate in educational activities. Alternative safety measures are thus also required to decrease the risk of death due to fire, such as tightening building fire regulations. It would then be possible to provide better protection for occupants through the use of more extensive regulations on fire safety in residential buildings.

Smoke alarms are lacking in about 80% of all fatal residential fires according to Swedish statistics. Although requirements on smoke alarms in homes have increased over the recent years, it is arguable whether they are sufficient. Some people will be unable to escape by themselves regardless of whether a smoke detector is activated or not. Examples of such are the elderly, the very young and the handicapped. There are also cases where death results from a fire in which the victim is intimately involved, such as smoking or intoxication. Residential sprinklers could perhaps be a suitable measure for protecting occupants, regardless of their physical or mental state.

### 1.1.2 Risk perception and safety awareness

The annual risk of death in today's society from any cause exceeds one in 1000 in only exceptional cases. Risks of this magnitude are considered too serious and society's intervention is required. Society is willing to devote extensive resources to risk prevention measures. Society is only willing to provide limited resources when the risk of death, i.e. the risk of dying in a car accident. At risks of the order of one in 100,000, society is still willing to undertake minor preventive action. Risks lower than one in 10,000,000 are considered so low that no preventive measures need to be taken. People, however, do not react to the numerical value of the risk. Reactions to risks are based on how the risks are perceived. Risks related to new unknown technologies are often greatly exaggerated, while known risks are often underestimated. We can therefore more easily accept the risk of fatal car accidents than the risk of a meltdown at a nuclear power plant, despite the fact that the number of traffic deaths far exceeds the number of deaths due to nuclear power accidents.

It is important to consider voluntary and involuntary risks differently. Voluntary risks are those to which a person has chosen to expose himself. Involuntary risks are risks to which one is exposed without having any choice in the matter. A risk cannot be considered involuntary if at least one option with lower risk can be chosen without greater sacrifice. A distinct difference between exposure to voluntary and involuntary risks is that the person exposed to voluntary risks has a greater possibility to influence his situation. Möller (1986) argues that society should act more strongly against involuntary risks based on this difference. Society can take three fundamentally different approaches to risk control:

- Reduce the risk without restricting the activity causing the risk
- Inform people of the risks involved in an activity
- Restrict the activity

Möller discusses whether society should act to remove voluntary risks. Consider the examples of bathing and sailing. These activities are voluntary, but if an accident occurs, society mobilises resources in terms of the rescue services. In order to deal with risks, the individual must be aware of a risk or danger. Risk awareness is therefore a fundamental condition for safe behaviour. Enander & Johansson (1999) presented a model for the relation between safety awareness and social safety. The model is illustrated in Figure 1.1.

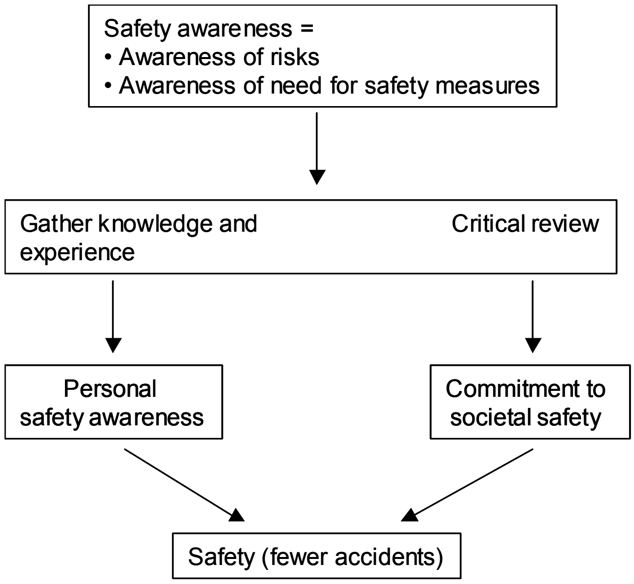



*Figure 1.1 A model on the relationship between safety awareness and societal safety (Enander & Johansson, 1999).*

Safety awareness is a measure of a person’s awareness of and knowledge concerning risks and safety measures. This awareness is expected to stimulate that person’s interest in gathering additional knowledge and gaining experience as well as critically reviewing society in terms of risks and accident prevention measures. However, some researchers such as Adams (1995) and Wilde (1994) believe that an individual strives to maintain his risk exposure at a constant level. This can be interpreted as: less toxic cigarettes causing increased consumption, ABS brakes leading to shorter distances between vehicles, etc. There are also cases where the installation of sprinkler systems has led to increased fire frequencies. It is necessary to change people’s attitudes in order to ensure that accident prevention and damage control systems are effective. Green (1980) shows how accidents affect the individual’s awareness and attitude (Figure 1.2).

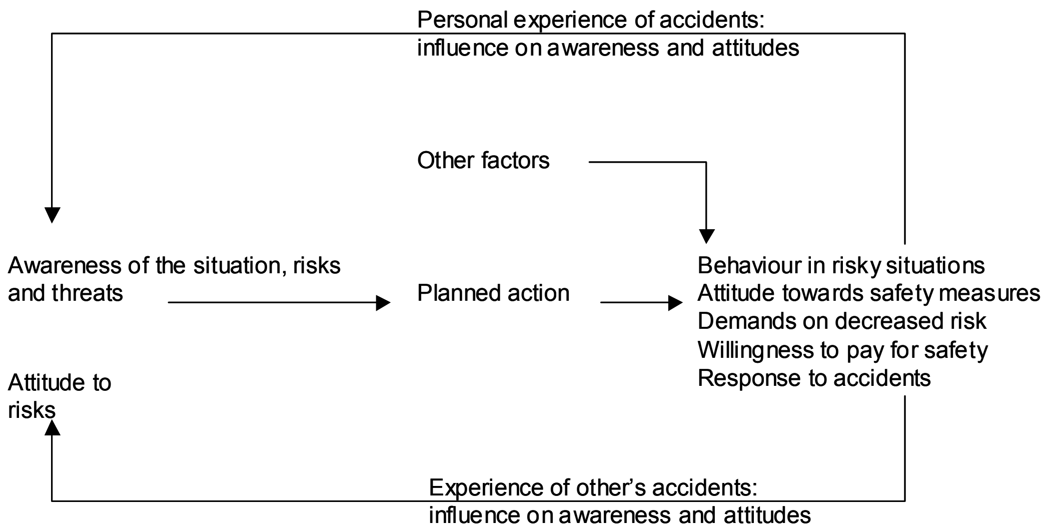



*Figure 1.2 The influence of accidents on awareness and attitudes (from Green, 1980).*

It is reasonable to assume that people's awareness will be affected when an accident happens. If awareness and attitudes are unaffected, an accident is considered acceptable However, if the person's attitudes change, the accident is considered unacceptable. These statements are also considered valid for society as a whole.

### 1.1.3 Acceptability of risk

Methods of developing acceptable risk have been discussed in society over the past decade. During this process, a number of fundamental risk evaluation principles have been developed. Risk can be evaluated and risk criteria established using four different principles (Davidsson et al., 1997).

- *The principle of reasonableness* says that an activity should not involve risks, which by reasonable means, could be avoided. Risks, which could be eliminated or reduced by technically and economically reasonable means, are always dealt with, irrespective of the actual risk level.

- *The principle of proportionality* states that the total risk associated with an activity should not be disproportionate to its benefits.

- Using *the principle of distribution*, risks should be appropriately distributed in society, in relation to the benefits of the activity involved. Individuals should not be exposed to disproportionate risk in comparison with the advantage that the activity affords them.

- *The principle of avoiding catastrophes* states that it is better that risks be realised in accidents with a lower number of fatalities. When discussing risk reduction, terms such as *ALARP (*As Low As Reasonably Practicable) and *ALARA* (As Low As Reasonably Achievable) are frequently used.

It is necessary to interpret these fundamental principles in terms of fire safety design. The principle of reasonableness is taken into account by following the performance requirements in the regulations. The principle of proportionality says that higher fire risks are acceptable in a certain building if certain financial benefits can be derived. The owner of a building has a much greater responsibility to establish a reasonable fire safety level. The principle of distribution is related to requirements on division into fire cells, separation between buildings, etc. Those who cannot control the outbreak of a fire should not be affected by it.

### 1.1.4 Regulating safety

The installation costs and the annual maintenance costs of the safety system are easily computed by using present value methods. The effectiveness of the safety measure can be derived either by the use of empirical data or by predictions. The difficult part lies in deciding the value of human life. Möller (1986) discusses whether society is willing to devote greater resources on preventing the premature death of certain people. He discusses whether the characteristics of a potential victim such as age and social utility, should form a basis for the allocation of preventive resources. This concept is controversial, but it already practised in medical care. Catastrophes place great strain on medical resources and it is necessary to prioritise both personnel and material resources. Some authors, Mattsson (1979) among others, consider that the age of the victim is crucial. Others consider that the total number of saved lives should govern risk-reducing activities. Rescher (1980) considers that age should not be the only guiding criterion. Characteristics such as family status, future expected utility and present usefulness should be taken into account.

Möller (1986), however, considers that all humans have the same value. His view supports the statement that society should be impartial in its risk-reducing efforts. Another interpretation of Möller's view is that levels of risk quantified by risk analysis could form the basis for accident prevention and damage control on a social level. If such analyses show that some groups of people are especially vulnerable to a certain type of accident, this could motivate a concentration on risk-reducing measures for this group. The allocation of greater resources to these groups is not a result of them being more valuable to society, rather the fact that they are more vulnerable (Nash et al., 1975). Examples of such groups in relation to fire are children and disabled people.

Decision making in safety issues has different meanings depending on from which perspective the process is regarded. Regulatory bodies have the overall responsibility to ensure that the risk to society as a whole is acceptable. House owners' decisions regarding safety will be based on their financial status and their safety awareness. Decision making can be difficult due to the complexity of the situation, especially when regarding fire safety from a regulator's point of view. It is difficult to answer an important question like whether a proposed regulation will have the desired effect or not, without using empirical data.

## 1.2 Objectives

The objective of this work was to investigate fire deaths and appropriate preventive measures. Attention was concentrated on a model that can be used to evaluate the risk of death due to fire considering various safety measures that could be controlled either by regulations or by the occupant.

The aim was to develop and validate a reliable model for the quantification of the risk of death due to fire residential buildings. The results from the model would the be useful in estimating the effect of different home fire safety measures, such as smoke detectors and sprinklers until empirical data become available. The model may be used by decision makers at all levels in their choice of fire safety measures that are most appropriate in reducing the risk of death due to fire for a certain group of occupants.

The dissertation deals with the following questions.

- What are the characteristics of a lethal fire?
- Why do people die in fires?
- What are the effects of various safety measures in preventing fatal fires?
- How should fire development and human behaviour be quantified in residential buildings?

## 1.3 Method

The work presented in this dissertation thesis consists of three main parts. In the first part, residential fires are characterised through studies on fire statistics and previous studies on the effectiveness of fire safety measures. This part goes into detail on why residential fires happen and what role does the occupant play in these emergencies. The second part describes a model in which fire development and human behaviour in residential fires can be quantified. This model employs state-of-the-art knowledge on fire dynamics and human response. The model is used to quantify the time before unconsciousness and death. These quantified measurements are then used in risk analysis. The third part deals with the risk of death due to fire where all known major uncertainties and variabilities are considered explicitly. The results are validated through a sensitivity analysis.

## 1.4 Statistics and probability concepts

The quantitative part of this study involves the use of fundamental statistics and probability concepts. This Section explains the most frequently used terms. For more information, the reader is referred to Vose (2000). *The expected value,* $\mu$, is also expressed as the mean value. The expected value is the centre of the probability distribution. The expected value is a position measure. *The standard deviation,* $\sigma$, is a measure of the spread of a distribution. The uncertainty in a variable is expressed by its standard deviation. Two variables could have the same expected value, but different standard deviations, as shown in Figure 1.3 below.

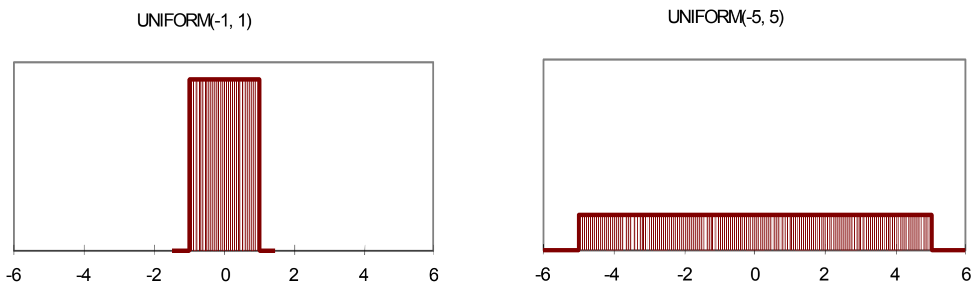



*Figure 1.3 A comparison of two uniform distributions, (-1,1) and (-5,5). Both have the same expected value (0), but they have different standard deviations.*

*The coefficient of variation,* cov, is the quotient between the standard deviation and the expected value, i.e., cov = $\sigma/\mu$. The coefficient of variation is normally given in %. *Probability distributions* are used to describe the uncertainty in the input parameters. Commonly used distributions in fire risk analyses are the normal distribution, the lognormal distribution and the triangular distribution. A schematic illustration of these distributions is given in Figure 1.4.

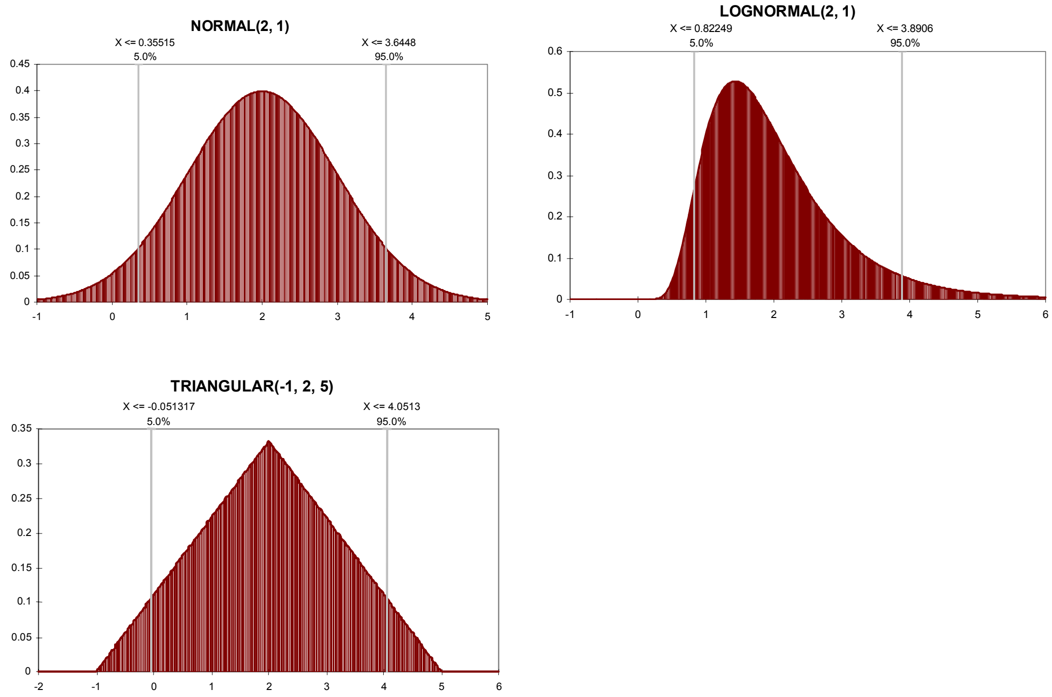



*Figure 1.4 Examples of the normal, the lognormal and the triangular distribution.*

In this dissertation, distributions are written in the following way – DISTRIBUTION (expected value, standard deviation). Some distributions such as the uniform distribution and the triangular distribution are expressed in a different way: UNIFORM (minimum, maximum) and TRIANGULAR (minimum, expected value, maximum). The distribution indicates in which interval the parameter varies and the probability of each value within this interval.

## 1.5 Overview

The report consists of six chapters followed by a discussion. Various aspects of *residential fires* are discussed in Chapter 2. Statistics are presented in terms of incidents, causes and victims. Human behaviour is discussed in terms of attitudes and responses to fire. The effectiveness of fire safety measures is presented. The chapter also contains a statistical analysis of the risk of death due to fire in Swedish residential buildings. Chapter 3 outlines a methodology and input necessary for the *quantification of fire development and human response*. Design fires, tenability criteria and models of human behaviour and fire development are presented. The *modelling of risk of death due to fire* is performed in Chapter 4. Information is given on the treatment of uncertainties, the availability of fire safety measures and modelling prerequisites. The fifth chapter presents an *evaluation of appropriate measures* for preventing fire deaths. The effectiveness of smoke detectors and sprinklers is presented for different occupants. The sixth chapter describes the *cost-effectiveness* of installing smoke detectors or residential sprinklers. Finally, a *discussion* summarizes the results of the work. Model validity, trade-offs and conclusions are presented.

# 2 Residential fires

## 2.1 Statistics on deaths in residential fires

Statistics on fatal fires can provide useful information in the prevention of such fires. This Section contains lethal fire statistics from several countries. Only statistics from fires in residential buildings are shown. Fatal fires occurring in, for example, car accidents are not included. Approximately 90% of all lethal fires occur in homes.

### 2.1.1 Incidents and victim characteristics

Before the year 2000, approximately 80 people dying in residential fires per year in Sweden. The number of deaths has, however, increased during recent years. Table 2.1 gives the distribution of fatal residential fires.

*Table 2.1 Distribution of death fires in different types of residential buildings (Swedish Rescue Service Agency, 2000, 2001 and 2002).*

| Type of dwelling | No. of death fires | | | Total no. of deaths | | |
|---|---|---|---|---|---|---|
| | 1999 | 2000 | 2001 | 1999 | 2000 | 2001 |
| Apartments | 33 | 37 | 41 | 33 | 37 | 42 |
| Detached houses | 30 | 44 | 48 | 31 | 48 | 58 |
| Cottage | 4 | 5 | 6 | 4 | 7 | 6 |
| Home for the elderly | 15 | 6 | 14 | 15 | 6 | 14 |
| Total | 82 | 92 | 109 | 83 | 98 | 120 |

It is rare that a residential fire results in more than one fatality. A Japanese study performed by Sekizawa (1988) derived some interesting conclusions concerning lethal fires.

- 48% of the fatalities were over 65 years old and 9% were younger than 6 years old.
- Disabled people over 65 years of age are exposed to 40 times the risk of dying in fires than the average population.
- More than 70% of the fire victims have difficulties in performing the evacuation.
- 50% are asleep or drunk when they die
- 50% are alone when the fire breaks out.

However, there are differences between Japan and Sweden. Japan has, for example, an older population. Nevertheless, the Swedish population is becoming older an older and it interesting to study the overrepresentation of old and disabled people in the Japanese statistics. Two thirds of all lethal fires take place in the winter months (November-April) and most lethal fires occur late in the evening or at night. Fatal fires are more common during weekends than on working days. The majority of fire fatalities are men aged 45-64. Most female casualties are over 80 years old.

### 2.1.2 Initial fire location and fire cause

Lethal fires are often initiated in bedrooms, living rooms or in the kitchen. These three locations represent 75% of all fatal fires. The first item ignited is usually bed clothing, clothes or flammable liquid (Figure 2.1).

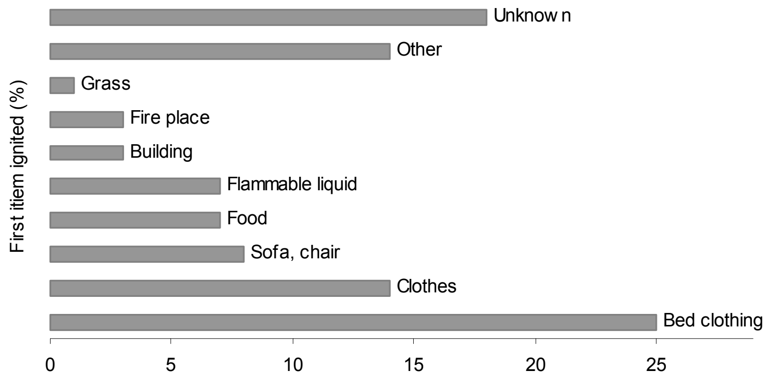



*Figure 2.1 First item ignited (percent) in fatal fires in Sweden 2000.*

As shown in Figure 2.2 smoking causes almost one third of all deaths. Incorrect use of heating installations and fireplaces is a common fire cause among elderly people. Fatalities among women are often caused by accidents when cooking.

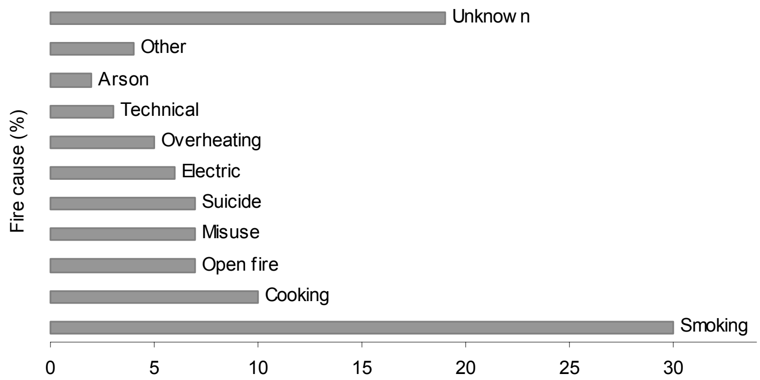



*Figure 2.2 Fire cause (percent) of fires leading to fatalities in Sweden 2000.*

### 2.1.3 Cause of death

Sekizawa (1988) has compiled an interesting summary of the reasons why people die in fires, which is shown in Table 2.2.

*Table 2.2 Reasons for fire fatalities*

| Physical status | Reasons for unsuccessful escape | | | | | |
|---|---|---|---|---|---|---|
| | Delayed detection | Difficulty in escaping | Failed to escape | Clothes on fire | Other | Total% |
| In bed | 13.7 | 55.8 | 18.3 | 9.1 | 3.1 | 13.3 |
| Disabled | 20.0 | 21.2 | 26.3 | 15.6 | 16.9 | 19.3 |
| Elderly with sickness (≥65) | 21.1 | 10.6 | 12.0 | 23.2 | 33.1 | 3.9 |
| Elderly (≥65) | 28.2 | 5.4 | 12.8 | 16.4 | 37.3 | 18.9 |
| Infants (5≥) | 15.0 | 68.3 | 5.0 | 1.9 | 9.8 | 8.8 |
| Sick people | 36.6 | 16.0 | 8.2 | 7.7 | 31.4 | 5.3 |
| Healthy people | 43.0 | 4.9 | 13.2 | 3.8 | 35.2 | 30.5 |
| Total% | 28.2 | 21.3 | 15.3 | 9.9 | 25.2 | 100 |

A Swedish study by (Swedish Fire Protection Agency, 1995) that covers fire deaths between 1983 and 1994 states that 81% of the victims where already dead when the fire brigade arrived. The same study also found that the most common cause of death (70%) was inhalation of toxic smoke. The remaining fatalities suffered fatal burns. These figures are very similar to those found in British statistics (Chandler, 1969) and in the USA (McCarthy, 2000). Purser (1995) also states that the dominating cause of death is carbon monoxide poisoning.

## 2.2 Human behaviour in fires

### 2.2.1 Attitudes to fires and fire safety

A survey of the attitude of the Swedish peoples to and their knowledge on fire safety was conducted by Dertell (1990). Half of the people had received information on fire safety and behaviour. The most common source of information was courses at work. Other sources of information were television programmes, insurance companies, newspapers and the rescue service. It was concluded that people employed in the public sector had received more information than those employed in private businesses. People living in houses had received more information than those living in apartments.

Most people believe that the risk of fire in their own home is small. About 60-70% consider the risk to be small or very small, and most people are unprepared as to what action to take when exposed to a fire at home. Most people state that they would escape through the window if the ordinary exit was blocked by smoke. The majority are aware that smoke spreads faster than fire. The majority would also consider closing the door to the room on fire before leaving the building. It was concluded from the survey that two thirds of the population do not have sufficient knowledge on proper fire safe behaviour.

The presence of smoke detectors in Swedish homes has increased during recent years. Many municipalities require smoke detectors and they are mandatory in all new homes. Four of five houses have smoke detectors, but almost half the apartments do not. An attitude survey on residential sprinklers was recently conducted by Residential Fire Safety Institute (2000). Approximately 50% of those questioned knew of the existence of sprinkler systems for domestic building. Residential sprinklers were considered effective or very effective by 96% of those asked. The majority, i.e., 64% would consider installing sprinklers in their home. Of those who did not consider sprinkler installation attractive, half thought that the system was too expensive and a quarter were afraid of water damage.

### 2.2.2 The role of the individual in ignition, growth and spread of the fire

It is stated by Brennan and Thomas in an Australian investigation (2001) that most people who become fire fatalities were alone when the fire started and were responsible for the fire. If there are multiple fatalities in a fire, the person responsible for starting the fire is usually among them. Those who die in fires have the same characteristics as those who frequently start fires. Occupants who are killed by the fire without causing it often share the same risk behaviour as the fire starter. Brennan and Thomas suggest that, based on these statements, fire is more a social problem than a technical one. The Swedish fire death statistics in Section 2.1 support these conclusions. The most common causes of fire in Sweden are smoking, cooking, forgotten candles, etc. It is also common fore fires to be initiated by the use of flammable liquids. Not all fires are started due to incautious behaviour, however, suicide by setting the home or oneself is on fire is not uncommon. These fire deaths should not be included in models of risk evaluation, but they contribute significantly to the fire death statistics.

Brennan and Thomas (2001) also showed fatal fires are those where the victim's ability to start a fire is high while his ability to act appropriately if a fire arises is poor. Brennan and Thomas also found that the number of fire incidents in the home of the victim before death due to fire is high. Intoxicated smokers who ignite clothing and furniture, people who fall asleep while cooking, covered heating sources, etc. are common in cases of lethal fire.

The growth of the fire is related to the first item ignited, the fuel load of the room and ventilation conditions. A fire that is ignited in a small room with closed doors and windows will probably extinguish itself after a short time. When fire breaks out, it is common for occupants to leave doors open as they escape from their homes. This behaviour often leads to increased fire growth and spread beyond the room of origin. Starting as a threat only to those in the same apartment as the fire itself, the fire now has the potential the affect people in adjacent apartments. Doors that are opened and kept open are also a result of a person who investigates the ongoing fire and is surprised by its strength. The main cause of multiple fire deaths is that doors to the room or apartment on fire are left open. An example of this is an apartment fire in North York, Canada, where six people died in the stairway (Prolux et al., 1995). Fire statistics show, however, that multiple fire deaths are uncommon. During 1999, 2000 and 2001 the number of deaths per lethal fire were 1.01, 1.07 and 1.10, respectively.

### 2.2.3 Response to fire

Canter et al. (1980) described a scheme for human response to residential fire, as shown in Figure 2.3. The scheme was developed through interviews with people exposed to fire. Based on these interviews, human response was structured into three phases – interpret, prepare and act.

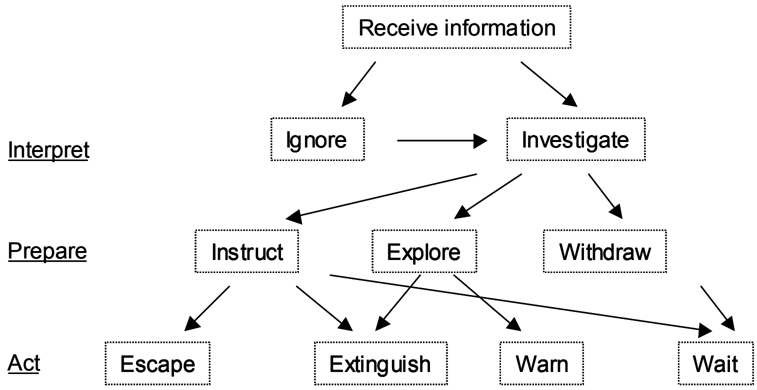



*Figure 2.3 Scheme depicting human response to fire.*

It is common for people to misunderstand ambiguous fire cues. The investigation by Canter et al. shows that men more frequently misunderstand the cues than women. These misunderstandings cause a delayed response. Both men and women show tendencies to want to investigate the fire for themselves. They do this despite the fact that an outsider has notified them of the fire. A common female response to fire is to warn others and wait for further instructions. The male response is to attempt to put out the fire and rescue anyone who may be trapped. Wood (1980) confirms the findings of Canter et al. Wood presents three general responses to a fire, which have been found by investigating 1000 fire incidents, mostly in residential buildings. These are escape, fire fighting and alerting the fire service. It is common for people to respond in an appropriate manner. Approximately 5% act so as to actually increase their risk. Table 2.3 shows a distribution of the first action taken.

*Table 2.3 The first action taken by people in response to a fire (from Wood, 1980).*

| Response | Percent |
|---|---|
| Fight the fire | 15 |
| Alert fire service | 13 |
| Investigate the fire | 12 |
| Warn others | 11 |
| Undertake risk-reducing measures | 10 |
| Escape | 9 |
| Assist others to escape | 7 |
| Other/unknown | 23 |

The more serious the fire was considered to be, the more likely was immediate escape. People who had experienced fires before, tried more often put the fire out. They did not, however, show any increased tendency to alert the fire service. It is not clear if the findings by Wood (1980) are possible to apply for Swedish people. There might be cultural differences and other changes in society from the time (1970s) when the survey was conducted until today.

## 2.3 Effectiveness of fire safety measures

### 2.3.1 Smoke detectors

Many fatalities could have been avoided if fundamental fire safety measures had been undertaken. According to the Swedish study covering 1983-1994 (SFPA, 1995), in only 6% of lethal fires was a smoke detector installed and was found functional. Similar findings have been reported in the USA (McCarthy, 2000). The statistics on the presence of smoke detector given in Table 2.4 have been compiled by Swedish National Rescue Service Agency.

*Table 2.4 Prevalence of smoke detectors in residential fires in 2000 and 2001.*

| Smoke detector status | Percentage of fatal fires | |
|---|---|---|
| | 2000 | 2001 |
| Not present | 56 | 66 |
| Present, not operating | 10 | 5 |
| Present and operating | 10 | 18 |
| No information | 24 | 11 |

A functional smoke detector was only found in 10-20% of fatal fires. Approximately half of those who die in fires are found a few metres from the exit. This indicates that they have initiated their escape too late. A smoke detector would have provided additional time for these people. The effectiveness of smoke detectors in Swedish homes has been analysed by Hygge (1991). He found that smoke detectors play an important role in preventing death due to fire. Based on a statistical analysis, Hygge also concluded that the claim a 50% reduction in risk of death found in American literature could not be proved to be valid for Swedish conditions. According to the same author, there are 3 slightly injured and 9 seriously injured people for every fire fatality.

### 2.3.2 Residential sprinklers

Ruegg et al. (1984) confirm the findings of Hygge presented above. Their investigation showed that the more advanced the safety measures installed in a home, the greater ratio between injuries and fatalities. Table 2.5 summarises the findings of Ruegg et al. (1984).

*Table 2.5 The number of deaths per injured person due to fire in American homes (from Ruegg et al., 1984).*

| Safety measures | No of deaths per injured person |
|---|---|
| None | 0.30 |
| Smoke detector | 0.15 |
| Residential sprinkler | 0.18 |
| Smoke detector and residential sprinkler | 0.10 |

According to McCarthy (2000), no one died in a residential fire during 1999 where sprinklers were installed. Arvidson (1998) studied data from NFRIS and came to the same conclusion. Over the years, there have been very few fire fatalities in homes equipped with residential sprinklers. In cases where there is a fire fatality and sprinklers are installed, this is mainly because the victim is disabled and the fire started in his clothes. There are also a few tragic examples where improper design of the sprinkler system led to death due to fire. One such example is that in a home for the elderly in Bessemer, Alabama, USA where inadequately dimensioned pipes were unable to deliver sufficient amount of water. Four people died in that particular fire.

### 2.3.3 Fire service response

The response time of fire service to a fire has been studied by Sträng (1999). The total response time consists of dispatch time, arrival time, investigation time and set-up time. The dispatch and arrival times were measured in the study. The investigation and set-up times were assumed have a constant value of totally one minute. The total response time is naturally dependent on geographical location, population and city size, etc. Sträng gives cumulative functions on the response time for different types of communities. In the present study, two types are considered. The first type of community are major Swedish cities such as Stockholm, Gothenburg or Malmö, with populations of 1,200,000, 496,000 and 249,000, respectively. The second type of community is a small town with approximately 25,000-50,000 inhabitants. Figure 2.4 shows the percentage of the population reached by the fire service as a function of time, as a cumulative distribution function.

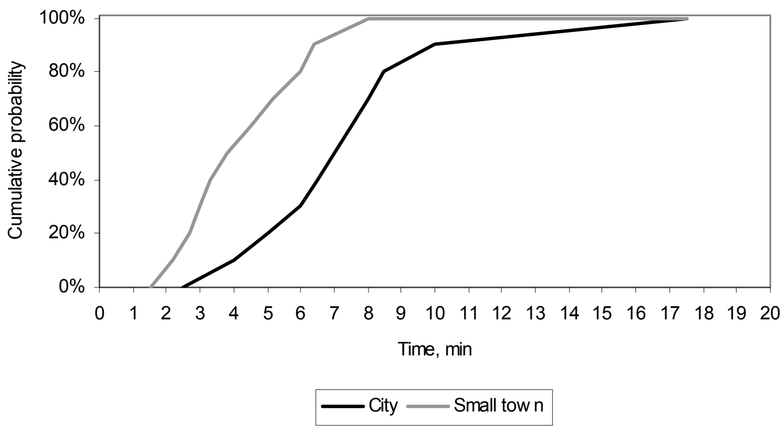



*Figure 2.4 Percentage of the population reached by the fire service per minute.*

## 2.4 Magnitude of risk

### 2.4.1 Previous studies on residential fire risks

By analysing American statistics from 1989-1993, Stenstad (1998) drew conclusions regarding the relationship between fires and the type of construction of the building. In 40% of all fires, smoke spreads in corridors and stairways. In every sixth fire, fire spreads through leakage in the construction. When comparing buildings with a combustible construction with a, for example, a concrete building, there is five times higher risk of fire spread to more than one floor in the building with a combustible construction. This is despite the fact that both buildings should have the same fire rating. Budnick (1984) analysed different fire growth rates and behavioural characteristics to determine when smoke detectors and sprinklers are effective. He suggested that sprinklers combined with smoke detectors would reduce the risk of death due to fire by 73%. He also concluded that it appears to be impossible to save 20 to 30% of fire fatalities with current smoke detector and sprinkler technology. These fatalities occur primarily due to intimate exposure of the individual to the fire. Rapidly developing fires in shielded locations also contribute to the numbers. In these cases, hazardous conditions arise before the safety systems have had time to respond.

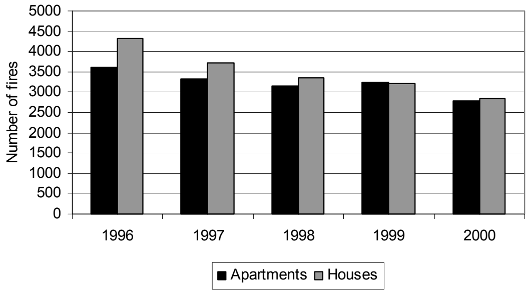
Rohr (2000) reports that the average number of fires in residential properties in USA per year between 1988 and 1997 was 339,700 and the average number of fire deaths was 3,164 per year. The average risk of becoming a fire fatality is thus $9 \cdot 10^{-3}$ per year per fire. The effectiveness of sprinklers and smoke detectors is also investigated by Ruegg and Sieglinde (1984). In 1981, there were 522,175 fires in detached and semi-detached houses in the USA, resulting in 3,895 civilian deaths. The risk of dying in a fire in 1981 was thus $7 \cdot 10^{-3}$ per year per fire. This statistical information was the basis for Ruegg and Sieglinde's estimation of the efficiency outlined in Table 2.6.

*Table 2.6 Reduction of the number of fire deaths in relation to different fire safety measures.*

| Basis for comparison | Smoke detectors only | Residential sprinklers only | Residential sprinklers and smoke detectors |
|---|---|---|---|
| Estimated reduction relative to death rate per thousand fires when no sprinklers or smoke alarms are fitted. | 48% | 69% | 82% |
| Estimated reduction relative to death rate per thousand fires when smoke alarms are fitted. | N.A. | N.A. | 63% |

### 2.4.2 Statistical analysis of the risk of death due to fire

It is possible to use fire statistics when evaluating the risk of fire in a residential property. The Swedish fire service reports every incident to a national database, from which the number of fires, cause, severity, deaths and injuries can be derived. It is then possible through statistical analysis, to assess the risk of dying in a residential fire per year. Residential properties are divided into apartments and detached houses. In order to perform the fire risk evaluation, information on the number of fires, the number of lethal fires and the number of residential properties is required. Figure 2.5 shows these figures for 1996-2000.



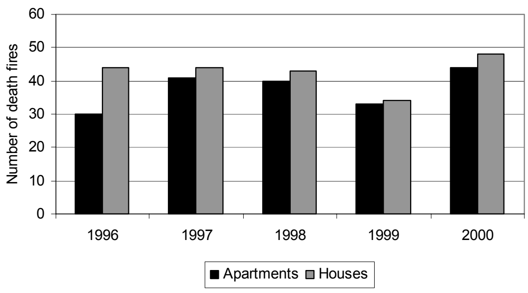




*Figure 2.5 Number of residential fires and number of lethal fires from 1996 to 2000.*

The numbers of residential fires in the Swedish Rescue Service Agency's files differs considerably from the number of fires reported to the Swedish Insurance Federation. The Rescue Service Agency has conducted a survey in order to assess the magnitude of fires not reported through fire service incident reports. This survey showed that at least one in four residential fire does not involve the fire service. Statistics from insurance companies shows that the difference is much greater as can be seen by comparing Figure 2.6 with Figure 2.5.

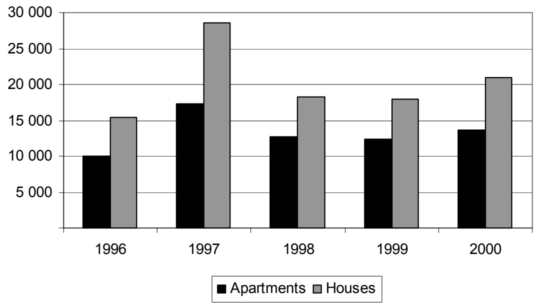



*Figure 2.6 Number of residential fires reported to the Swedish Insurance Federation (2001).*

Based on the differences between the statistics from the Rescue Service Agency and the Insurance Federation, the following equations were derived.

$$F_{fire} = \frac{N_{fires}}{N_{homes}} \tag{2.1}$$

$$P_{growth} = \frac{P_{growth^*} \cdot N_{fires^*}}{N_{fires}} \tag{2.2}$$

$$R_{death} = \frac{N_{deaths}}{N_{homes}} \tag{2.3}$$

$F_{fire}$ is the frequency of an initial fire in a residential property. The number of homes in Sweden is 2,200,000 apartments and 1,900,000 houses. The statistics from the Swedish Insurance Federation will be used for the number of fires.

$P_{growth}$ is the probability that an initial fire will grow and have the potential to cause damage. The equation is based on the assumption that all fires that grow will be reported to the fire service. It is also assumed that fires not reported to the fire service do not have the potential to cause injuries or death. $P_{growth^*}$ and $N_{fires^*}$ represent values from the Rescue Service statistics. The probability of fire growth is 60% for all fires where the fire service is notified. The conditional probability of fire growth is 16%, when considering the total number of residential fires.

$R_{death}$ is the annual risk of dying in a residential fire. This value can be compared with other hazards in society. The magnitude of the risk is calculated using the information in Figure 2.5 and Figure 2.6. The results are presented in Table 2.7, Table 2.8 and Table 2.9.

*Table 2.7 Frequency of fires in residential buildings per year.*

| Residential property | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|
| Apartments | $5 \cdot 10^{-3}$ | $8 \cdot 10^{-3}$ | $6 \cdot 10^{-3}$ | $6 \cdot 10^{-3}$ | $6 \cdot 10^{-3}$ |
| Houses | $8 \cdot 10^{-3}$ | $2 \cdot 10^{-2}$ | $1 \cdot 10^{-2}$ | $1 \cdot 10^{-2}$ | $1 \cdot 10^{-2}$ |

The fire frequencies in Table 2.7 should be interpreted as the number of fires in a single home per year. The coefficient of variation over the years is 15%. The data show that there are twice as many fires in houses as in apartments. The explanation of this may be that many fires are caused by faulty electrical installations and incorrect use of heating devices. Such causes of fire are more likely in houses than in apartments. If the time frame is known it is possible to transfer the frequency to a probability by using the equation below.

$$P_{fire} = 1 - e^{\left(-F_{fire} t\right)} \qquad 2.4$$

During a period of 50 years, there is a 25% probability that any home will have a fire. This statement is only valid if the fire frequency were evenly distributed over all residential buildings.

*Table 2.8 Probability of dying per fire.*

| Residential property | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|
| Apartments | $3 \cdot 10^{-3}$ | $2 \cdot 10^{-3}$ | $3 \cdot 10^{-3}$ | $3 \cdot 10^{-3}$ | $3 \cdot 10^{-3}$ |
| Houses | $3 \cdot 10^{-3}$ | $1 \cdot 10^{-3}$ | $2 \cdot 10^{-3}$ | $2 \cdot 10^{-3}$ | $2 \cdot 10^{-3}$ |

The probability of becoming a fire fatality when exposed to a fire is derived by dividing the number of lethal fires by the total number of fires. This probability is presented in Table 2.8. Note that it is the number of lethal fires and not the number of fire deaths that is used in the equation. As stated in Section 2.1.1, the number of deaths per lethal fire is almost equal to one. There is no significant difference between the two types of residential properties. There is a difference between the American death rate statistics in

Section 2.4.1 and the values in Table 2.8. This difference of a magnitude of two could, however, be the result of differences in reporting fire incidents.

*Table 2.9 Risk of death due to fire in residential properties*

| Residential property | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|
| Apartments | $1\cdot10^{-5}$ | $2\cdot10^{-5}$ | $2\cdot10^{-5}$ | $2\cdot10^{-5}$ | $2\cdot10^{-5}$ |
| Houses | $2\cdot10^{-5}$ | $2\cdot10^{-5}$ | $2\cdot10^{-5}$ | $2\cdot10^{-5}$ | $3\cdot10^{-5}$ |

The total risk that an individual will be killed in a residential fire in Sweden is 1 in 50,000, a risk level that has remained constant over the past years.

# 3 Quantification of fire development and human response

## 3.1 Design fires in residential buildings

Figure 3.1 gives an illustration of the typical development of a residential fire, adopted from Karlsson and Quintiere (2000).

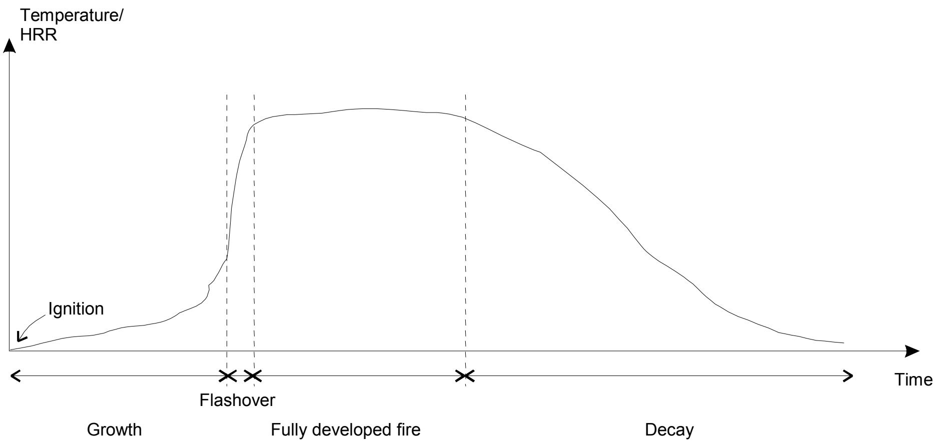



*Figure 3.1 Illustration of fire development in an enclosure.*

Fire development in residential building fires is often rapid. This is due to the heavy fuel load and mixture of different fuels that exist in a normal home. Rohr (2001) has presented a current compilation of the materials that burn in American home fires and came to the same conclusions as the analysis of Swedish statistics in Section 2.1. The four most common items first ignited resulting in fire deaths are upholstered furniture, mattresses, internal wall coverings and clothing. The causes of these fires are outlined in Table 3.1.

*Table 3.1 Fire cause based on first item ignited.*

| Item | Cause |
|---|---|
| Upholstered furniture | Abandoned candles and cigarettes, suspicious causes, falling asleep while smoking, etc. |
| Mattresses and bedding | Children playing with fire, abandoned candles and cigarettes, falling asleep while smoking, etc. |
| Internal wall covering | Short circuit or ground fault, suspicious causes, unattended cooking, etc. |
| Clothing | Lighters, cigarettes, candles, matches, etc. |

As can be seen from Table 3.1, human behaviour causes the majority of the fatal fires. It is possible to identify a number of characteristic modes of fire growth based on information regarding the first item ignited and fire cause. A fire may grow through smouldering, flaming or fast flaming. Smouldering fires are ignited by a minor source and start to develop very slowly. There is no flame, but a great deal of smoke is produced. In time, it is possible for a smouldering fire to generate enough heat to become a flaming fire. All flaming fires have a so-called incipient stage before they start to grow. Data from fire tests (Babrauskas, 1995) support the pre-burning phase illustrated in Figure 3.2.

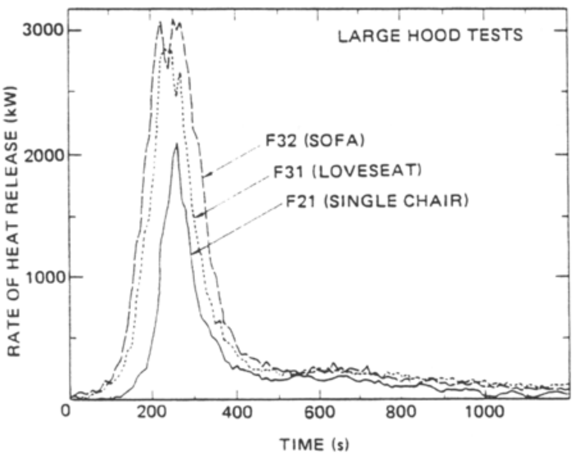



*Figure 3.2 Heat release rate from upholstered furniture (from Babrauskas, 1995).*

The pre-burning time varies depending on which item is ignited. A fibrous material ignited by a cigarette has a relatively long pre-burning time, compared with the ignition of a flammable liquid when the pre-burning time is zero. Höglander & Sundström (1997) have derived design fires for pre-flashover fires by considering characteristic heat release rates of building contents. They used statistics from the CBUF (Combustible Behaviour of Upholstered Furniture) project to define a heat release rate (HRR) equation for domestic fires.

$$\dot{Q} = 2500\exp\left(-0.4(t-3)^2\right) \qquad 3.1$$

$\dot{Q}$ is the HRR in kW and t is expressed in minutes. At time t=0, the HRR is 50 kW. The equation has a safety factor of 2, based on the average measured peak HRR. The time to reach peak HRR has been divided by two. Since the fire model treats uncertainty by statistical simulation (see Section 4.2), it more interesting to write the equation without safety factors, as shown below:

$$\dot{Q} = a\exp\left(-0.4(t-b)^2\right) \qquad 3.2$$

where *a* and *b* are lognormally distributed constants given in Table 3.2.

*Table 3.2 Values of peak HRR and time to reach peak HRR for domestic fires.*

| Constant | Represents | Value (± standard deviation) |
|---|---|---|
| *a* | Peak HRR | 1278 ± 719 kW |
| *b* | Time to peak HRR | 339 ± 278 s |

The difference between the results obtained using an approach including safety factors compared to direct treatment of uncertainties is shown in Figure 3.3. The variation in both heat release rate and time to reach peak HRR is obvious as the could vary between 559-1997 kW and 61-617 s, respectively.

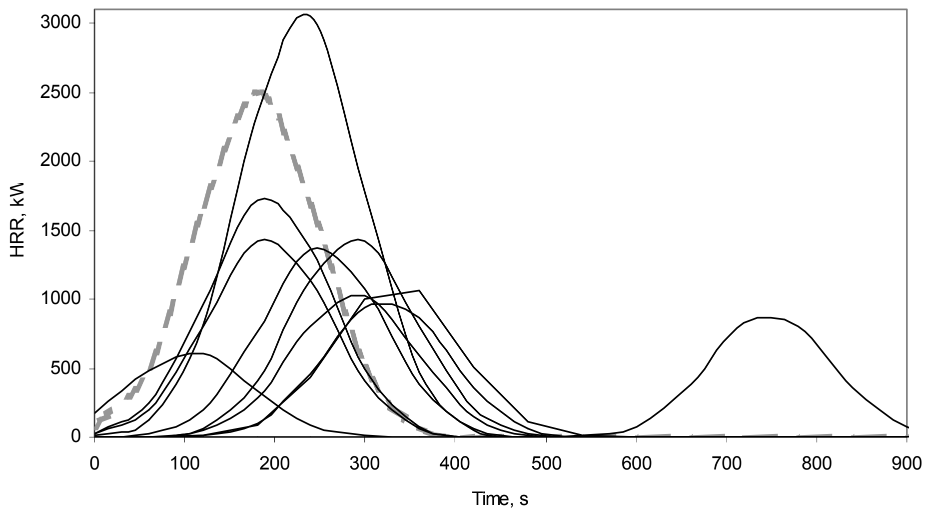



*Figure 3.3 HRR curves for the design fire when using where the hatched graph is the curve when safety factors are adopted and all other graphs are example of curves when the natural variability in the fire development is taken into account.*

The approach developed by Höglander & Sundström is only valid for the first item ignited. In a real situation, the fire will spread to other objects which will contribute to the heat release rate and the design fire must also reflect this. The initial fire will cause the ignition of both wall coverings and adjacent items. Wall coverings will burn based on their fire ration. It is, however, assumed that, compared with the variability shown in Figure 3.3 the contribution of wall coverings and other items will be small in the first few minutes of the fire. Wall coverings and other items will therefore be neglected.

An alternative approach to that of Höglander & Sundström is to use the t-squared fire. In the initial period of a fire the growth is nearly always accelerating. A commonly used approach in the field of fire safety engineering is to represent express the fire growth rate as the square of time together with a constant $\alpha$.

$$\dot{Q} = \alpha\, t^2 \qquad 3.3$$

The fire growth rate is described as slow, medium, fast or ultra-fast. It value depends on how long it will take the t-squared fire to develop 1 MW. This time is 600, 300, 150 and 75 seconds for slow, medium, fast and ultra-fast fires, respectively. For residential buildings, it is recommended that a fire with medium growth rate is assumed. A comparison between the t-squared approach and the domestic fire curves is shown in Figure 3.4.

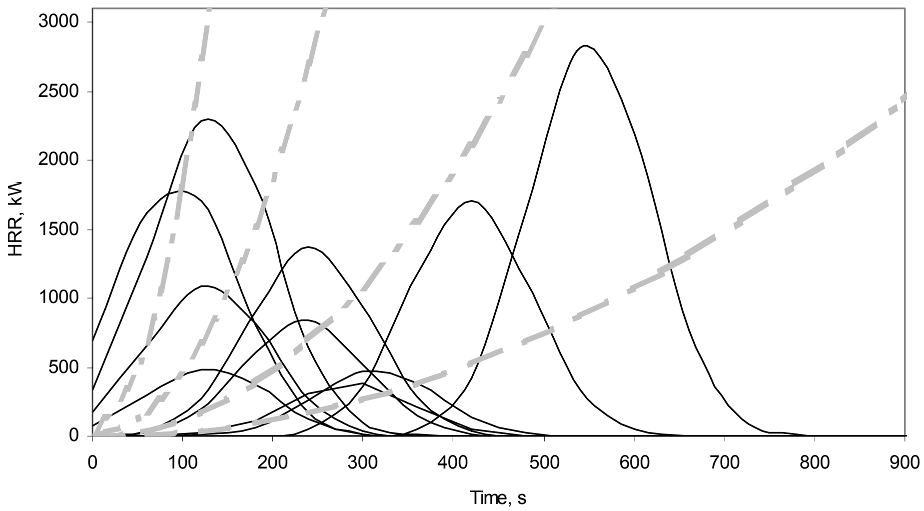



*Figure 3.4 The t-squared fire growth rates (from right to left: slow, medium, fast and ultra-fast) in comparison with randomly derived domestic fire curves.*

Figure 3.4 shows that using the t-squared approach do not represent the possible fire scenarios very well. Depending on which fire growth rate that is chosen, a certain percentile of the possible fires are represented. Neither approach is applicable until the fire growth has started to accelerate. This tales place after incipient phase. Measurements made by Höglander & Sundström (1997) showed that the incipient phase ended when the fire had reached 50 kW. The corresponding value given by Buchanan (2001) is 20 kW or a fire with a diameter of 0.2 m. The time at which this happens depends on both the material ignited and the ignition source. It is assumed that smouldering fires will have a pre-burning time of at least five minutes and that a flaming fire will show accelerating growth after 2 minutes. A fast-flaming fire has no pre-burning period.

## 3.2 Human tenability limits

Fire-induced injuries and death are related to one of the following causes (Ondrus, 1990).

- Heat, which could result in direct burns and/or heat shock.
- Inhalation of carbon monoxide.
- Lack of oxygen
- Inhalation of smoke and other species produced by combustion
- Panic, shock or structural failure

### 3.2.1 Heat

Heat causes burns, heat shocks and dehydration. If a human is exposed to heat, especially in combination with high humidity, there is a considerable risk of unconsciousness and death. The human body can be seriously affected by temperatures as low as 70°C, if the exposure time is long and the air is humid. If the temperature exceeds 150°C, it will be very difficult to breathe. Temperatures around 200°C can only be tolerated for a few minutes time but result in severe burns.

### 3.2.2 Carbon monoxide

Carbon monoxide is produced in all fires, irrespective of what is on fire and which phase the fire has reached. Carbon monoxide combines with haemoglobin in the blood to form carboxyhaemoglobin (COHb). The formation of COHb reduces the body's ability to transport oxygen. Carbon monoxide is easily taken up by the tissues in the lungs. The proportion of COHb continues to increase as long as carbon monoxide is inhaled. It is the percentage COHb that determines the effect this narcotic gas will have on the body. In a pathological study by Anderson et al. (1981) it was found that lethal levels of COHb (> 50%) were found in 54% of all fire fatalities. Seven of ten had concentrations high enough to cause unconsciousness. Table 3.3 describes how different concentrations of COHb affect the body (Purser, 1995).

*Table 3.3 Human response to carbon monoxide.*

| Concentration | Response |
|---|---|
| 15-20% COHb | Confusion |
| 30-40% COHb | Unconsciousness |
| 50-70% COHb | Death |

Carbon monoxide is thus of particular interest as it is always present in fires and it reduces the ability of the occupants to escape ability as it causes confusion and unconsciousness, and it is the prime cause of fire deaths.

### 3.2.3 Oxygen deficiency

As the fire develops the concentration of oxygen decreases. When the oxygen concentration becomes sufficiently low, a person will become unconscious. The time until unconsciousness develops is a function of the occupant's activity and the oxygen concentration in the room. Table 3.4, which is taken from Ondrus (1990), gives information on the effect of reduced oxygen concentration.

*Table 3.4 Response to reduced oxygen concentration in the air.*

| Oxygen content | Physiological effect |
|---|---|
| 21% | None |
| 17% | Increased breathing, reduced muscle strength |
| 14% | Minimum level for successful escape |
| 12% | Dizziness, headache, fatigue |
| 9% | Unconsciousness |
| 6% | Death within 6-8 min |

### 3.2.4 Toxic products

Smoke is a mixture of combustion products, aerosols and soot. Table 3.5 shows the toxic effect of fire gases other than carbon monoxide. In most fires, these gases will not be the direct cause of death, hydrogen cyanide excepted. Nevertheless, these contribute to decreasing the time to untenable conditions are reached. For example, carbon dioxide increases the breathing rate, speeding up the accumulation of other toxic gases. At $CO_2$ concentrations below 3%, there will be no significant increase in breathing rate. At 3%, the breathing rate is doubled and at 5%, it is increased by three times. These levels of carbon dioxide will shorten the time before an occupant becomes unconscious by 50 and 67%, respectively.

*Table 3.5 Effect of combustion gases.*

| Gas | Effect |
|---|---|
| *Carbon dioxide ($CO_2$)*<br>Produced in all fires | Toxic at high concentrations. Stimulates increased breathing rate |
| *Hydrogen cyanide (HCN)*<br>Produced in incomplete combustion of wool, nylon and polyurethane | The victim is suffocated to death. Toxic concentrations are commonly found in fire victims. |
| *Nitrogen dioxide ($NO_2$)*<br>Produced in fires involving clothing and cellulose products | Very irritating to the lungs. Can cause immediate death. |

### 3.2.5 Fractional Incapacitating Dose

Purser (1995) published a set of equations that can be used to assess how toxic gases affect the human body. The concept is based on calculating a Fractional Incapacitating Dose (FID). The values of FID are in the range of zero to one. If the value is zero, an individual is unaffected and when it is one, he is incapacitated. The value of FID increases continuously and does not decline, even if the occupant is, for example, exposed to fresh air. Carbon monoxide is the most important narcotic gas, but the presence of carbon dioxide will increase the respiratory minute volume considerably. FID equations are given below:

$$CO_{Hb} = 3.317 \cdot 10^{-5} C_{CO}^{1.036} \left(RMV\right) t \qquad 3.4$$

$$F_{I_{CO}} = \frac{CO_{Hb}}{D_{I_{CO}}} \qquad 3.5$$

$$RMV = \exp\left(0.2496 \cdot C_{CO_2} + 1.9086\right) \qquad 3.6$$

where $CO_{Hb}$ is the concentration of carboxyhaemoglobin in the blood, %

$C_{CO}$ is the concentration of carbon monoxide in the room, ppm

$t$ is the time of exposure, min

$RMV$ is the respiratory minute volume, l/min.

$F_{I_{CO}}$ is the accumulated effect of carbon monoxide. When $F_{I_{CO}}$ = 1 the occupant will be unconscious or dead and

$D_{I_{CO}}$ is either the concentration of COHb required for unconsciousness or death, %.

$C_{CO_2}$ is the concentration of carbon dioxide in the room, ppm

The concept of fractional incapacitating dose can also be used when evaluating the effect of heat exposure. The following equation from Purser (1995) can be used when the temperature exceeds 37°C:

$$t_{I_h} = \exp\left[5.1849 - 0.0273 C_T\right] \qquad 3.7$$

$$F_{I_h} = \frac{1}{t_{I_h}} \qquad 3.8$$

where $C_T$ is the "concentration" of heat that the person is exposed to, °C and

$t_{I_h}$ is the time to unconsciousness due to heat exposure, min.

## 3.3 Modelling human behaviour

The most common engineering approach to modelling human behaviour is to divide the time from ignition to completed evacuation into three phases – detection, response and travel – as shown in Figure 3.5.

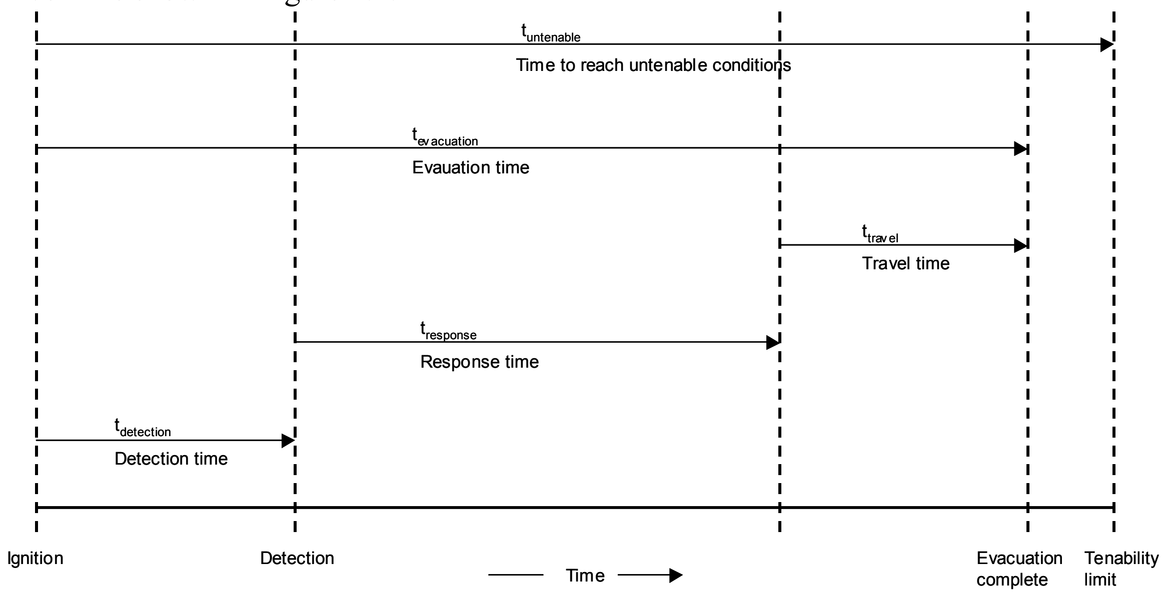



*Figure 3.5 Time-line illustration of the evacuation process.*

In a successful design, evacuation is completed before the tenability limit is reached.

### 3.3.1 Detection time

This phase is the time from ignition until the occupant is made aware of the fire. An occupant can become aware of a fire in two ways: by manually detecting the fire or through the activation of a smoke detector. The detection time is influenced by a number of factors. Fire characteristics such as material ignited, fire growth rate and ventilation conditions are important. It is also important where the occupant is in the building, if he is awake or asleep, if he is sober or intoxicated, etc. If the occupant has been intimately involved in ignition of the fire, he is probably aware of the fire and the detection time is so short that it plays no significant role. For those who are not involved in ignition, the detection time is of great importance.

In residential buildings, the occupants are most commonly notified on the fire by its cues. It is possible to see, feel, hear and smell the fire. However, if the occupant is asleep or in an adjacent room with the door closed, smoke detectors are essential. Research by Bruck & Brennan (2001) shows how people respond to different fire cues. In a series of experiments, people were exposed to different indicators such as crackling noise, flickering light or smoke. The indicators were vague in order to represent the early stage of a fire The results show that 80 to 90% are woken by a crackling sound, 60% detect the smell of smoke and 50% respond to flickering light when asleep Awakening by a smoke detector alarm has been studied by Bruck (1999). Her experiments showed that most healthy, sober adults wake up within 30 s after alarm activation. However, children easily continue to sleep despite the alarm.

### 3.3.2 Response time

The response time is defined as the time from detection of the fire until the occupant initiates escape. This time depends on how the occupant became aware of the fire: whether he has discovered fire cues, been alerted by someone else or by the smoke detector. All activities apart from escape should be included in the response time, see Figure 2.3. The Canadian fire risk model FIRECAM is based on the results of extensive research on human behaviour in cases of fire. The response to various fire cues and alarms has been experimentally tested by Proulx et al. (1995). Response times from this experimental work are given in Table 3.6.

*Table 3.6 Response time to fire.*

| Occupant notified by | Response time, s |
|---|---|
| Heat, smoke or flames from the fire | 50 |
| Fire service arrival | 50 |
| Alerted by others | 100 |
| Spoken message | 100 |
| External alarm bell | 250 |
| Local smoke detector | 250 |

FIRECAM is used to evaluate fire risks in apartment and office buildings. The model moves every occupant individually according to specific rules governing behaviour. There are, however, certain exceptions from these rules. For example, even if smoke detectors are fitted, occupants in the area of fire origin will respond to the fire based on the fire cues. Frantzich (2000) carried out a Delphi exercise to establish pre-movement (response) times for different occupancies. Based on this exercise, it was concluded that the occupant response when fire cues are signal the outbreak of fire, was in the range of 45 to 75 s.

### 3.3.3 Travel time

The travel time is the final phase from the time escape is initiated until the occupant has left the building or reached a safe area. The walking distance from the occupant's initial location to a safe area determines the travel time. If there are many others escaping at the same time it is possible that there will be queues at doors and in other narrow passages. Occupant characteristics are important when estimating the travel time. Disabled people will have difficulty in walking to the exits, and completely disabled persons will need external assistance. People often escape the same way as they entered the building.

The travel time is often of minor importance in residential fires. This is because the travel distance is short. Under normal conditions, the travel time can be neglected. Nevertheless, in some buildings such as homes for the elderly, the travel time has greater importance. In many fires, the occupants choose not to evacuate until they have been instructed to do so. These situations usually occur in apartment buildings and when occupants live adjacent to the apartment on fire.

## 3.4 Response of safety systems

### 3.4.1 Detectors

The activation of a heat detector is influenced by the gas temperature and the speed of the ceiling jets. The activation of smoke detectors is, however, not as easily described. Smoke concentration, particle size and optical properties are some of the factors that influence the activation of a smoke detector. Evans et al. (1985) showed that the heat detector approach could also be used for smoke detectors. The requirement is a relationship between the optical density of the gases close to the ceiling and the temperature rise in the ceiling jet. If this relationship is known, a smoke detector could be modelled as a heat detector with very low thermal resistance and activation temperature. Heskestad et al. (1977) gave this relationship, presented in Table 3.7.

*Table 3.7 Relation between optical density(OD) and temperature increase (ΔT).*

| Material | OD/ΔT, $m^{-1}K^{-1}$ |
|---|---|
| Wood | 0.00118 |
| Polyurethane foam | 0.0236 |
| Cotton | 0.000885 |
| Polyvinyl chloride | 0.04425 |
| Polyester | 0.0177 |

The temperature rise in a detector is calculated using the following equations:

$$\frac{dT_s}{dt} = \frac{U^{1/2}}{RTI}\left(T_c - T_s\right) \qquad 3.9$$

$$\Delta T_c = \frac{16.9\dot{Q}^{2/3}}{z_0^{5/3}} \qquad \text{for } r/z_0 < 0.18 \qquad 3.10$$

$$\Delta T_c = \frac{5.38(\dot{Q}/r)^{2/3}}{z_0} \qquad \text{for } r/z_0 < 0.15 \qquad 3.11$$

$$U = 0.95\left(\frac{\dot{Q}}{z_0}\right)^{1/3} \qquad \text{for } r/z_0 > 0.18 \qquad 3.12$$

$$U = 0.195\frac{\dot{Q}^{1/3}z_0^{1/2}}{r^{5/6}} \qquad \text{for } r/z_0 > 0.15 \qquad 3.13$$

where $T_s$ is the temperature inside the detector, ° C
$U$ is the speed of fire gases as they flow past the detector, m/s
$T_c$ is the gas temperature, °C
$RTI$ is the "response time index" of the detector, $\sqrt{\text{ms}}$
$z_0$ is the room height, m and
$r$ is the horizontal distance from the plume centreline to the detector, m.

Heskestad et al. (1977) derived the optical density at which a smoke detector is activated. By combining this information with the relationship between optical density and temperature rise in Table 3.7, it is possible to calculate the activation time. Table 3.8 gives values of the required optical density for detector activation.

*Table 3.8 Optical density required for smoke detector activation (from Heskestad et al., 1997).*

| Material | Optical density required for activation, $m^{-1}$ | |
|---|---|---|
| | Ionising detector | Photoelectrical detector |
| Wood | 0.01524 | 0.4572 |
| Polyurethane foam | 0.1524 | 1.524 |
| Cotton | 0.001524 | 0.24384 |
| Polyvinyl chloride | 0.3048 | 3.048 |

### 3.4.2 Residential sprinklers

The task of residential sprinklers is to extinguish or control the fire so that escape is possible. In addition, they should prevent the fire from spreading to adjacent rooms. Madrzykowski & Vettori (1992) studied the effect of sprinklers on the heat release rate in a number of experiments. Their aim was to develop an algorithm for sprinkler efficiency. Figure 3.6 is taken from the paper by Madrzykowski & Vettori.

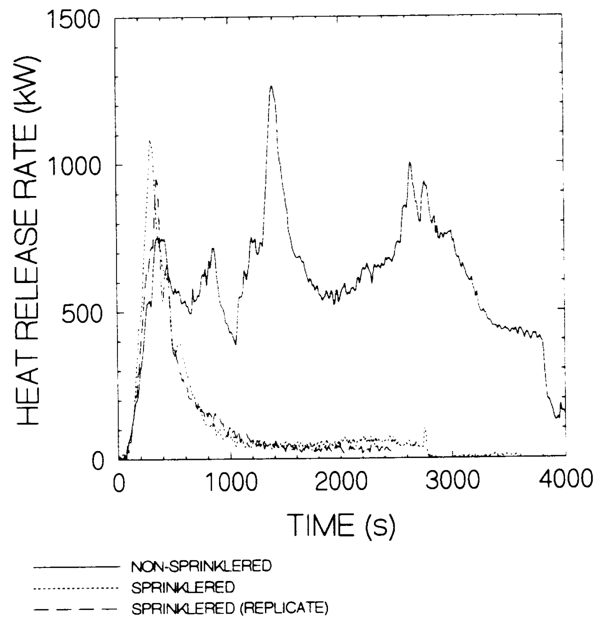



*Figure 3.6 Illustration of sprinkler effect on the fire development (from Madrzykowski & Vettori, 1992).*

Sekizawa et al. (1997) performed an investigation on the environment in the room after the activation of the sprinkler. The study shows that sprinkler activation causes well-stirred conditions in the room. The initial two-zone description of the fire scenario is no longer valid. In most cases, sprinkler activation decreases visibility and in some cases there is an increase in the concentration of carbon monoxide. This is due to the extensive amount of water vapour produced when water is applied to the fire. The rise in carbon monoxide concentration could be explained by reduced combustion efficiency.
Schönberg (2000) carried out ten full-scale experiments in order to investigate whether residential sprinklers had the capability to reduce the production of toxic gases enough to safe human lives. The results of the experiments show that the production of carbon dioxide and carbon monoxide is much lower compared to a fire where sprinklers were not fitted. The oxygen concentration was found to be at a much higher level, and the temperature in the fire room was decreased rapidly after sprinkler activation. Schönberg also points out that the radiation from the upper layer could cause burns prior to the activation of sprinkler. It was also concluded that the visibility is very low after activation.

The activation of residential sprinklers follows the same principles as those outlined for smoke detectors in Section 3.4.1. The quantitative effect on the heat release rate is described in Section 3.5.1.

## 3.5 Modelling fire development

In order to produce an aid for the engineer to perform quantitative analyses of the efficiency of different fire safety measures a model for fire development calculations has been developed. The model consists of a number of manual calculation expressions for heat release rate, enclosure temperature and smoke filling, detector activation, sprinkler efficiency, dose-response, etc. The model should comply with the following requirements.

- It should be simple and transparent in its design.
- It should be possible to treat variability and uncertainty explicitly.
- It should be possible to evaluate the effects on the safety level when changes are made to the design or when trade-offs are made.

In order to fulfil the requirements a spreadsheet model was developed which could be used with add-in risk analysis software. The output from the model is a probability distribution function of the time until incapacitation or death occurs. The model consists of a number of sub-models illustrated in Figure 3.7.

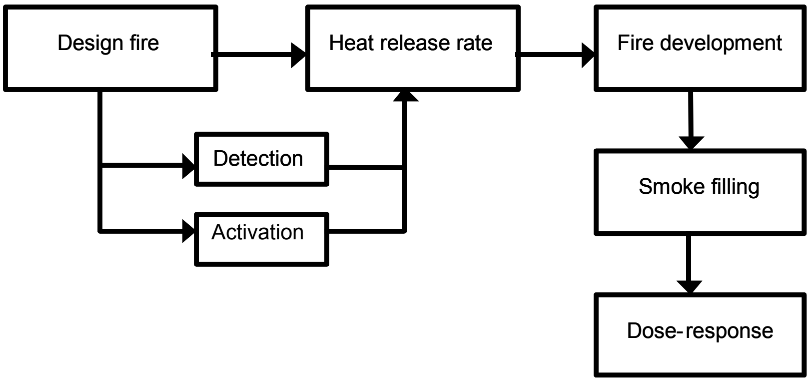



*Figure 3.7 Outline of the fire model developed in this study.*

The quantification of the design fire and detection and activation of safety measures is described in Sections 3.1 and 3.4, respectively. Dose-response equations are presented in Section 3.2.5.

### 3.5.1 Heat release rate

The theoretical design fire must be modified to take into account the presence of a sprinkler and the ventilation conditions. There are a number of scenarios that affect the heat release rate, as listed in Table 3.9.

*Table 3.9 Heat release rate scenarios.*

| Scenario | Description |
|---|---|
| I | Sprinkler operating |
| II | Sprinkler not operating<br>Fire is fuel controlled |
| III | Sprinkler not operating<br>Fire is ventilation controlled |

In scenario I when the sprinkler system is operating, the heat release rate is reduced in accordance with an algorithm developed by Evans (1993):

$$\dot{Q}(t-t_{act}) = \dot{Q}(t_{act})\exp\left[\frac{-(t-t_{act})}{3.0\left(\dot{w}''\right)^{-1.85}}\right] \quad 3.14$$

where $\dot{Q}(t)$ is the time-dependent heat release rate, kW

$t$ is the time, s

$t_{act}$ is the time at which the sprinkler is activated, s and

$\dot{w}''$ is the water density, mm/s per m$^2$.

In scenario II when the fire is fuel controlled and there is no sprinkler operating, the heat release rate is not affected, and the HRR curve from the design fire is applicable.

$$\dot{Q} = \dot{Q}_{design} \quad 3.15$$

where $\dot{Q}_{design}$ is the heat release from the design fire curve, kW

The ventilation-controlled fire in scenario III will have a reduced HRR, due to the lack of oxygen. In order to assess the reduction it is necessary to determine the maximum possible HRR in the fire room. This is done using an expression from Karlsson and Quintiere (2000), where room openings and the heat output from the combustion of oxygen are used:

$$\dot{Q}_{\max} = 1518 A_o \sqrt{H_o} \quad 3.16$$

where $\dot{Q}_{\max}$ is the maximum possible HRR, kW

$A_o$ is the opening area, m$^2$ and

$H_o$ is the opening height.

If $\dot{Q}_{\max}$ is achieved, the fire is ventilation controlled. The heat release rate is chosen according to the equation below.

$$\dot{Q} = \dot{Q}_{\max} \quad 3.17$$

### 3.5.2 Fire development

This Section describes how the burning rate, the gas temperature and the smoke height are calculated. The burning rate is related to the heat release rate, the combustion efficiency and the heat of combustion.

$$\dot{m}_f = \frac{\dot{Q}}{\chi\,\Delta H_c} \qquad 3.18$$

where $\dot{m}_f$ is the burning rate, kg/s

$\chi$ is combustion efficiency, and

$\Delta H_c$ is the heat of combustion, kJ/kg.

The total mass of burnt fuel is calculated for each time step as the previous value plus the average value during the previous time step:

$$m_f = \sum_{i=0}^{t-1} m_{f,i} + Average(\dot{m}_{f,t-1}, \dot{m}_{f,t}) \cdot \Delta t \qquad 3.19$$

where $m_f$ is the total mass of burnt fuel, kg.

The gas temperature is dependent of the geometry of the room, the heat release rate and the physical properties of the surrounding boundaries (McCaffrey et al., 1981):

$$T_g = T_a + 6.85\left(\frac{\dot{Q}^2}{A_o\sqrt{H_o}\,h_k A_T}\right)^{1/3} \qquad 3.20$$

$$h_k = \sqrt{\frac{k\rho c}{t}} \qquad 3.21$$

where $T_g$ is the gas temperature, °C

$T_a$ is the ambient room temperature, °C

$h_k$ is the heat transfer coefficient, kW/(m$^2$K)

$A_T$ is the boundary surface area, m$^2$ and

$k\rho c$ is a material specific constant related to heat transfer, W$^2$s/(m$^4$K$^2$).

The degree of smoke filling is assessed using the heat release rate, the gas temperature and the room geometry. The smoke filling rate Is also related to the flow of smoke out from the room. This is, however, not considered in this study. Budnick et al. (1997) gives the following equations:

$$\dot{m}_s = 0.071\dot{Q}_p^{1/3} z_0^{5/3} \qquad 3.22$$

$$\rho_g = 353/\left(273 + T_g\right) \qquad 3.23$$

$$\dot{z}_s = \frac{\dot{m}_s}{\rho_g A_f} \qquad 3.24$$

$$z_s = \sum_{i=1}^{t-1} z_{z,i} - Average(\dot{z}_{s,t-1}, \dot{z}_t) \cdot \Delta t \qquad 3.25$$

where $\dot{m}_s$ is the smoke production, kg/s
$\rho_g$ is the density of the smoke, kg/m$^3$
$\dot{z}_s$ is the rate of smoke filling, m/s and
$A_f$ is room floor area, m$^2$.

The time of rise of plume fronts from the start of the fire is not included in the smoke filling equations above. Heskestad (2001) comments on this. The time required for a plume front to reach a certain height is correlated with the heat release rate. Rough calculations, however, indicate that this need not to be included in the calculations. The rise time to a height 2.4 m above the floor is approximately 2 s for a 10 kW fire and 0.5 s for a 1 MW fire.

The temperature to which occupants are exposed is dependent on the delay prior to sprinkler activation and the height of the smoke layer. There are two possible scenarios, according to Table 3.10.

*Table 3.10 Scenarios for the temperature to which occupants are exposed and the fire gas volume.*

| Scenario | Description |
|---|---|
| I | Sprinkler operating |
| II | Sprinkler not operating |

For scenario I where the sprinkler is operating, the exposure temperature can be calculated using the equation below:

$$T_{\exp} = \frac{T_{g,act}V_{act} + T_a\left(V - V_{act}\right)}{V} \qquad 3.26$$

where $T_{\exp}$ is the exposure temperature, °C.

The equation gives the exposure temperature after the fire gases have been well stirred due to the activation of the sprinkler. The heat content and volume of each zone are used to calculate the new temperature. If the sprinklers are not operating, the exposure temperature is equal to the gas temperature.

$$T_{\exp} = T_{gas} \qquad 3.27$$

When a sprinkler is activated, there will be a mixture of gases in the room. In order to assess the concentration of toxic gases it is important to know the fire gas volume. Two scenarios (described in Table 3.10) are possible: sprinkler working or not working. If a sprinkler has been activated, as in scenario I, the fire gas volume will be the same as the volume of the room.

$$V_g = V \qquad 3.28$$

If there is no sprinkler operating, the fire gas volume will be a function of the smoke height and the floor area.

$$V_g = A_f \left( z_0 - z_s \right) \qquad 3.29$$

### 3.5.3 Yield of combustion products

The ventilation conditions in the room have a considerable influence on the amount of carbon monoxide that is produced by combustion. If the fire is fuel controlled, in a oxygen rich environment, combustion generates hardly any carbon monoxide. If there is a lack of oxygen, the fire is ventilation controlled. Ventilation-controlled fires generate far more carbon monoxide. The yield of carbon dioxide is also depending on the ventilation conditions, but not to the same extent. Data on carbon dioxide have been taken from Gottuk et al. (1995) and the data on carbon monoxide yield have been taken from Tewarson (1995).

*Table 3.11 Yield of combustion products.*

| | Yield, kg/kg | |
|---|---|---|
| Ventilation conditions | Carbon dioxide | Carbon monoxide |
| Fuel controlled | 1.3 | 0.005 |
| Ventilation controlled | 0.8 | 0.19 |

It is assumed that the fire is ventilation controlled either when the fire gases reach the fire source or when the maximum possible heat release rate is achieved. There are two possible scenarios when assessing the yield, as described in Table 3.12.

*Table 3.12 Scenarios for combustion products yield.*

| Scenario | Description |
|---|---|
| I | Sprinkler operating, smoke layer below untenable height |
| | Sprinkler not operating, smoke layer below untenable height |
| II | Sprinkler not operating, smoke layer above untenable height |

For scenario I, when sprinklers are operating or the smoke layer is below the untenable level, the concentration of carbon monoxide could be assessed using an expression in BSI (1997a):

$$C_{CO} = 858000 \frac{Y_{CO} m_f}{V_g} \qquad 3.30$$

$$C_T = T_{\exp} \qquad 3.31$$

where $C_{CO}$ is the concentration of carbon monoxide in the breathing air, ppm and
$Y_{CO}$ is the yield of carbon monoxide, kg/kg.

In scenario II, when no sprinkler is operating and the smoke layer height is above the untenable level the effect on the human body is practically zero. Definitions of concentration and heat exposure are given below.

$$C_{CO} = 0 \quad 3.32$$

$$C_T = T_a \quad 3.33$$

# 4 Modelling the risk of death due to fire

## 4.1 Risk model

The risk of death due to fire is modelled by comparing fire development calculations to the modelling of human response. Procedures and prerequisites for these models are given in Section 3.5 and 3.3, respectively. The fire death risk model, giving the individual risk of dying in a fire per year, is shown below in mathematical form.

$$R_{death} = F_{fire} \cdot P_{growth} \cdot P\left(t_{death} < t_{safe}\right) \qquad 4.1$$

$F_{fire}$ is the annual fire frequency, the value of which can be taken from Table 2.7. The weighted average is 0.008 fires per year per dwelling. $P_{growth}$ was calculated in Section 2.4.2 and has a value of 0.16. $P\left(t_{death} < t_{safe}\right)$ represents the probability that an occupant involved in a fire will not be able to reach a safe area before lethal conditions occur. An occupant can be brought to safety in three ways. He is either able to escape before becoming unconscious or is rescued before the conditions become lethal. A member of the fire service or another person may rescue the occupant It is also possible that untenable conditions never occurs due to minor fire or the activation of sprinkler. This is expressed below.

$$P\left(t_{death} < t_{safe}\right) = P\left(t_{unconsciousness} < t_{escape}\right) \cap P\left(t_{death} < t_{rescue}\right) \qquad 4.2$$

It is possible to determine $t_{unconsciousness}$ and $t_{death}$ by using the fire model in Section 3.5 to assess the fractional incapacitating dose for unconsciousness and death as shown in Section 3.2.5. The escape time $t_{escape}$ and the rescue time $t_{rescue}$ are calculated as shown below.

$$t_{escape} = t_{dectection} + t_{respone} + t_{travel} \qquad 4.3$$

$$t_{rescue} = MIN\left(t_{fire\ service}, t_{outsider}\right) \qquad 4.4$$

Unfortunately, there is no way of quantifing $t_{rescue}$ without introducing enormous uncertainties. Neither empirical data nor knowledge of model components are available. It is therefore necessary to modify the death risk equation.

$$R_{death} = F_{fire} \cdot P_{growth} \cdot P\left(t_{unconsciousness} < t_{escape}\right) \mid P_{lethal} \qquad 4.5$$

The rescue time $t_{rescue}$ is discussed further in Section 4.3.3. Note that $P_{lethal}$ represents that probability of having conditions arising when escape is unsuccessful. The result,

$R_{death}$, is calculated by running the spreadsheet model through a Monte Carlo simulation. The Monte Carlo algorithm is provided by the risk analysis add-in program @RISK (Palisade, 2002).

## 4.2 Treatment of uncertainties

### 4.2.1 General aspects

Models are simplified ways of describing real world phenomena. They are therefore associated with number of uncertainties. It is possible to characterise these uncertainties into four groups. They may be derived from resources, assumptions, the mathematical model or input. Uncertainties in resources are related to factors such as the state of knowledge, quality control, project management, policies, problem statement, etc. These uncertainties are frequently related to external factors and are not dependent on the engineer or researcher. Uncertainty in assumptions is directly linked to problem solving. Assumptions are made continuously throughout a project. Uncertainties in objectives, limitations and methods of analysis belong to this group. Uncertainties in mathematical models are related to how well the model represents what it is supposed to reflect. Uncertainties related to the fire and human response model are included in this group. The fourth and most specific group of uncertainties are those related to input. Input may take the form of physical properties, response time, technical characteristics, reliability, etc. It is often possible to quantify these uncertainties by employing statistical theories.

It is always necessary to treat uncertainties in fire safety design, especially as engineering tools are associated with a number of limitations and simplifications. One way to treat uncertainties is to employ statistical sampling methods such as Monte Carlo simulation. By performing thousands of iterations of state functions as such as those in Section 4.1, it is possible to take into consideration the stochastic nature of the variables. Naturally, all variables whose variation or uncertainty should be included must be described by their statistical distribution. New values are obtained from the distributions at each iteration and the outcome is calculated. If this process is repeated a great number of times, it is possible to represent the state function by its distribution. The relationship between input and output is shown in Figure 4.1, adopted from Frantzich (1998).

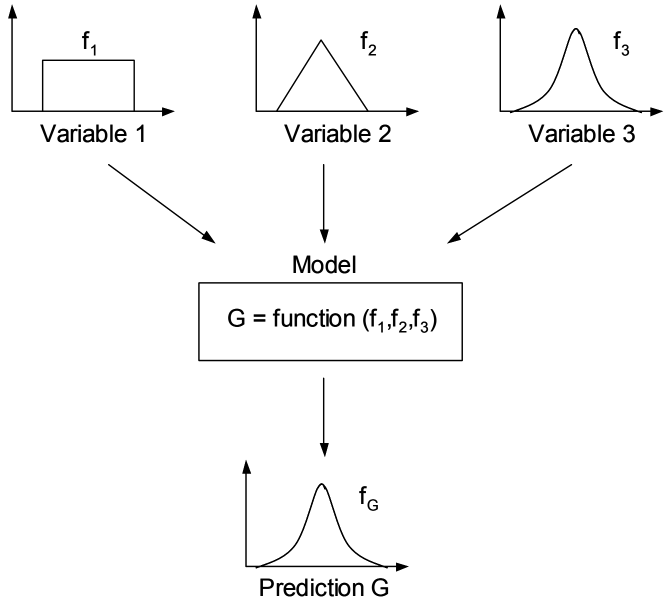



*Figure 4.1 Propagation of uncertainties through a model.*

The fire death risk model considers both model uncertainty and the uncertainties related to input data. The equations included in the model are state-of-the-art expressions which reflect real conditions. In a British Standard (BSI, 1997) these equations are described together with an 80% confidence interval representing their uncertainty. The model uncertainty was incorporated into the model by allotting a statistical distribution representing the confidence interval to each equation. Uncertainties in inputs were treated by allowing the variables to be represented by distributions instead of traditional point estimates.

### 4.2.2 Defining distributions

Distributions may be defined by either statistical methods or expert judgement. There is software designed to find the best-fit distribution to a data sample and there are techniques for evaluating expert opinions (Vose, 2000). Frantzich (1998) recommends the following procedure for defining distributions in fire risk analyses. The first step is to establish the minimum and maximum limits for each variable. The next step is to use current knowledge to estimate mean values, standard deviations or other parameters describing the variables whose distributions are to be defined. The final step is to assign the most credible distribution to the variable. Commonly used distributions in fire risk analysis are the normal distribution, the triangular distribution and the lognormal distribution.

The normal distribution often represents variables that have been derived from a large number of samples. The lognormal distribution is useful for modelling naturally occurring variables that are the product of a number of other naturally occurring variables. For example, the fire growth rate is often lognormally distributed because it is the product of heat contents, material structure, availability of oxygen, etc. The lognormal distribution is suitable for a variable that extend from zero to +infinity and is positively skewed. When only the mean value and the upper and lower bound are estimated, the triangular or the uniform distribution suitable. Abrahamsson (2001) gives extensive information on techniques used for the treatment of uncertainties.

### 4.2.3 Model uncertainty

The procedure of treating model uncertainty in the model follows the BSI (1997b) approach. BSI reviews the state-of-the-art engineering equations for fire safety design with regard to their applicability, limitations and uncertainty. Experts have been asked to assess how well these equations described real world conditions. In doing so, it was possible to establish a confidence interval for each equation. The confidence interval is defined below.

$$\beta = \frac{predicted\ value}{measured\ value} \qquad 4.6$$

By dividing the result from each equation with its value of $\beta$ more realistic results will be obtained. If $\beta < 0$ the result will be an underprediction and if $\beta > 0$ this will lead to an overprediction. Values of $\beta$ can be obtained from the BSI (1997b) for many of the equations given in Sections 3.4 and 3.5. As $\beta$ is obtained from a survey it is possible to, by statistical analysis, establish the confidence interval of the parameter as shown below.

$$\beta_{10\%} < \beta < \beta_{90\%} \qquad 4.7$$

The BSI gives an 80% confidence interval for $\beta$ and an indication which distribution best suits the value of $\beta$. The experts consider that $\beta$ should be represented by a uniform or triangular distribution. An example is shown in Figure 4.2.

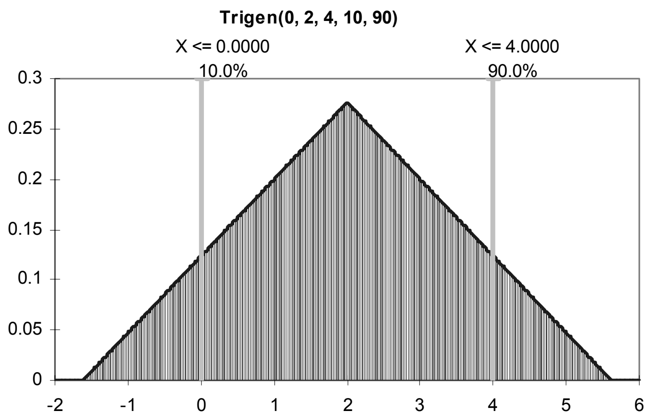



*Figure 4.2* $\beta$ *expressed as a triangular distribution with an 80% confidence interval.* $\beta_{10\%} = 0$ *and* $\beta_{90\%} = 4$. *The mean value is in the middle of these outer bounds.*

Table 4.1 gives values of $\beta$ for the equations in the fire model.

*Table 4.1 Outline of the model uncertainty in the fire model.*

| Equation | $\beta_{10\%}$ | $\beta_{90\%}$ | Distribution | Comment |
|---|---|---|---|---|
| 3.4 | 0.9 | 1.3 | Triangular | Estimated value |
| 3.7 | 0.7 | 1.1 | Triangular | Estimated value |
| 3.9 | 0.5 | 2.0 | Triangular | BSI (1997b) |
| 3.14 | 0.7 | 1.1 | Triangular | Assumption |
| 3.16 | 0.33 | 2.1 | Uniform | BSI (1997b) |
| 3.20 | 0.85 | 1.25 | Uniform | BSI (1997b) |
| 3.22 | 0.7 | 1.5 | Uniform | BSI (1997b) |

All the equations listed in Table 4.1 was modified with their $\beta$ value according to the example below.

$$\dot{m}_s = \frac{1}{\beta} 0.071 \dot{Q}_p^{1/3} z_0^{5/3} \quad 3.22$$

## 4.3 Availability of fire safety measures

### 4.3.1 Smoke detectors

In 1994, Marriott conducted a study on the reliability and effectiveness of domestic smoke detectors (Marriott, 1995). Ten thousand smoke detectors where installed in residential properties. After 18 and 36 months, the smoke detector in each dwelling was inspected. Marriott concluded that after 18 months, 92% of the smoke detectors were functional. The corresponding figure after 36 months was 89%. No significant difference was found between ionising and photoelectrical detectors. The reason for detectors not functioning was that they appeared to be broken. In 25% of all non-functioning alarms, the battery was missing or flat. During the three years of the project, 34 fires in these properties were reported to the fire brigade. In 21 of these fires, the smoke detector alerted the occupants before any other cues. In six other cases, the fire was discovered before the smoke alarm was activated. In seven fires the smoke alarm never sounded. This was due to the fire being in a confined space or the fact that smoke never reached the detector. Marriott states that this supports matches the opinon that a single smoke detector cannot fully protect a dwelling.

Bukowski (1993) came to the same conclusion. Experimental results showed that having a smoke detector on every floor level provided a warning within three minutes in 89% of the experiments. When a single smoke detector was placed outside the bedrooms, only 35% of the fires were discovered within the three-minute time frame. Hall (1988) concluded that roughly one quarter to one third of the smoke alarms in the USA were not operational. Hygge (1991) compared of the operability of smoke alarms given away free and those purchased by the owner. He concluded that there were no differences between them. There are a number of values for smoke detector reliability found in fire engineering guidelines and studies throughout the world. Bukowski (1993) has summarised a few of them, and these are presented in Table 4.2.

*Table 4.2 Suggested values for home smoke alarm reliability (from Bukowski, 1993).*

| Reference | Reliability (%) | |
|---|---|---|
| | Smouldering | Flaming |
| Warrington Delphi | 76 | 79 |
| Australian Fire Engineering Guidelines | 65 | 74 |
| NIST study | - | 75 |

The values in Table 4.2 seem low compared with the results presented by Marriott. A local survey in Malmö, Sweden supports Marriott's findings. Thus, a mean reliability of 90% and lower and upper bounds of 85 and 92%, respectively, are used in the risk analysis. A triangular distribution is proposed.

### 4.3.2 Residential sprinklers

Statistics from the USA covering 1988 to 1997 show that residential sprinklers failed to operate successfully in 6% of 8,650 fires (Rohr, 2000). The reasons for failure were often incorrect installation or lack of maintenance. Failures were caused by shut-off water supplies, painted sprinkler heads and inappropriate location of furniture. Another way of measuring reliability is to study how the fire spread in a building with sprinklers. Sixty-six percent of all fires did not spread beyond the first item ignited. Eighty-six percent of all fires were contained in the room of fire origin. Ninety-four percent of all fires did not spread to another fire compartment. Statistics from Operation Life Safety project show that 90% of all fires can be controlled by a single sprinkler head. Reliability values for sprinkler systems vary between 81.3 and 99.5% (Budnick, 2001). Budnick performed a simple statistical analysis on sprinkler reliability, with the aim of determining values and establishing confidence limits. His results are given in Table 4.3.

*Table 4.3 Reliability estimates for sprinkler systems (from Budnick, 2001)..*

| | Commercial | General | Combined |
|---|---|---|---|
| Lower confidence limit (5%) | 88.1 | 93.9 | 92.2 |
| Mean (%) | 93.1 | 96.0 | 94.6 |
| Upper confidence limit (95%) | 98.1 | 98.1 | 97.1 |
| Number of reference studies | 9 | 7 | 16 |

Bukowski (1993) states that there is an 85% probability that residential sprinklers will operate successfully. The reliability estimates of Bukowski and Budnick are, however, difficult to use in this study. The Bukowski data are from the early years of residential sprinklers and the data presented by Budnick are too general. The data do, however, give an order of magnitude regarding the variance. It is suggested that a reliability of between 90 and 97% be used in this study. A mean value of 94% was therefore used. The distribution should be triangular.

### 4.3.3 Fire service response

The availability of the fire service (or someone else to perform a rescue operation) is very difficult to assess. The response time of the fire service has been quantified in Figure 2.4. However, the time distribution presented in Figure 2.4 is only valid after the fire service has been notified of the fire. The time prior to notification is a very uncertain parameter. Only a small proportion of those involved in a fire consider notifying the fire brigade as their first action (se Section 2.2.3). The fire brigade is more likely to be notified by someone not directly involved in the fire, e.g. a neighbour. If a smoke alarm has been activated by the fire, it is possible for others to be aware of the fire at an early stage. These people can then notify for the fire brigade. A residential sprinkler that is activated will, according to the installation guide, automatically notify the fire service. No attempt was made in the present study to quantify the notification time. It is, however, possible to assess the time difference between the elapsed time prior to unconsciousness and time to death. It is then possible to draw conclusions on the possibility of performing external rescue operations based on the magnitude of this difference.

## 4.4 Prerequisites

### 4.4.1 Scenarios

A variety of scenarios is possible depending on the first item ignited the cause and location of the fire, the occupant's involvement, time of day, etc. The fire risk model should cover most of the following situations.

- Fire initiated in the living room, the bedroom or the kitchen
- Involvement of the occupant in ignition, he is in the same room as the fire origin or he is in an adjacent room.
- A sleeping, physically disabled or conscious occupant.

However there, is a need for considerable caution as many of the possible events are dependent upon each other. There are also events that cannot exist at the same time. Table 4.4 describes the scenarios.

*Table 4.4 Description of scenarios included in the fire risk model.*

| No. | Fire location | Occupant location | Occupant status | Comment |
|---|---|---|---|---|
| 1 | Living room | Intimate | Awake | Incendiary fire. Escape delayed |
| 2 | Living room | Intimate | Asleep | N.A. See no. 3 |
| 3 | Living room | Intimate | Disabled | Incendiary, escape not possible |
| 4 | Living room | Same room | Awake | Normal response to fire |
| 5 | Living room | Same room | Asleep | Delayed response to fire |
| 6 | Living room | Same room | Disabled | Escape not possible |
| 7 | Living room | Other room | Awake | Normal response to fire |
| 8 | Living room | Other room | Asleep | Delayed response to fire |

| No. | Fire location | Occupant location | Occupant status | Comment |
|---|---|---|---|---|
| 9 | Living room | Other room | Disabled | Escape not possible |
| 10 | Bedroom | Intimate | Awake | See no. 1 |
| 11 | Bedroom | Intimate | Asleep | N.A. See no. 3 |
| 12 | Bedroom | Intimate | Disabled | See no. 3 |
| 13 | Bedroom | Same room | Awake | N.A |
| 14 | Bedroom | Same room | Asleep | See no. 5 |
| 15 | Bedroom | Same room | Disabled | See no. 6 |
| 16 | Bedroom | Other room | Awake | See no. 7 |
| 17 | Bedroom | Other room | Asleep | See no. 8 |
| 18 | Bedroom | Other room | Disabled | See no. 9 |
| 19 | Kitchen | Intimate | Awake | See no. 1 |
| 20 | Kitchen | Intimate | Asleep | N.A. See no. 3 |
| 21 | Kitchen | Intimate | Disabled | See no. 3 |
| 22 | Kitchen | Same room | Awake | See no. 4 |
| 23 | Kitchen | Same room | Asleep | N.A. |
| 24 | Kitchen | Same room | Disabled | See no. 6 |
| 25 | Kitchen | Other room | Awake | See no. 7 |
| 26 | Kitchen | Other room | Asleep | See no. 8 |
| 27 | Kitchen | Other room | Disabled | See no. 9 |

After evaluating the scenario descriptions in Table 4.4, it was possible to decrease the total number of scenarios. All situations where the occupant is intimately involved with the fire are difficult to predict in the model. These scenarios can only be evaluated qualitatively. Budnick (1984) supports this statement as he concludes that it is not possible to assess sprinkler and smoke detector efficiency in such fire situations. Nevertheless, there are situations where residential sprinklers save the lives of occupants who are actually on fire themselves (Ford, 1997). The aim of modelling the risk of death due to fire is to evaluate which fire safety systems are appropriate in preventing lethal fires. Hence, the analysis will be performed separately for occupants that are disabled (A), i.e. physically handicapped or elderly and for occupants with normal mobility (B).

Those with impaired mobility will not be able to evacuate without external help. They will only survive a fire if it does not develop into lethal conditions or if sprinklers are activated and extinguish the fire before untenable conditions occur. In case of disabled occupant fire development is only related to the fire location. The fire risk equation (4.5) is modified to suit disabled occupants (A).

$$R_{death,A} = F_{fire} \cdot P_{growth} \cdot P_{lethal\ conditions} \qquad 4.8$$

Scenarios for occupants with normal mobility (B) show more variation. They are dependent on the fire location, the occupant location and the status of the occupant. Scenarios for group B are described in Table 4.5.

*Table 4.5 Scenarios for occupants with normal mobility.*

| Id. | Fire location | Occupant location | Occupant status |
|---|---|---|---|
| B1 | Living room | Same room | Awake |
| B2 | Living room | Same room | Asleep |
| B3 | Living room | Other room | Awake |
| B4 | Living room | Other room | Asleep |
| B5 | Bedroom | Same room | Awake |
| B6 | Bedroom | Same room | Asleep |
| B7 | Bedroom | Other room | Awake |
| B8 | Bedroom | Other room | Asleep |
| B9 | Kitchen | Same room | Awake |
| B10 | Kitchen | Same room | Asleep |
| B11 | Kitchen | Other room | Awake |
| B12 | Kitchen | Other room | Asleep |

The conditional probability is 28, 42 and 30% for the kitchen, the living room and the bedroom, respectively. These figures are derived from Swedish fire statistics (Section 2.1). According to the same statistics, the likelihood of a daytime fire is 43% and thus that of a night-time fire 57%. The probability that the occupant will be in the same room as the fire is difficult to assess, especially when the number of fires with unknown location and cause is large. Nevertheless, where the occupant is when the fire breaks out is crucial in determining the detection time. Budnick (1984) concludes that in 74% of the fatal fires, the occupant is not in the room of origin. Thus, 26% are located in the same room as the fire. These findings from Budnick have been used in the analysis. It is also concluded that 20% are intimate with the fire, 65% have normal mobility and 15% are have impaired mobility. Data from the USA differ from the Swedish fire death statistics for 2001 (Swedish Rescue Service Agency, 2002). In Sweden, 30% are intimately involved with the fire, 41% are assumed to have normal mobility and 29% are have impaired mobility. The Swedish statistics were used in the forthcoming analysis. Table 4.6 shows a summary of the probability of important variables in the occupant characterisation.

*Table 4.6 Summary of important probabilities in the occupant characterisation.*

| Variable | Probability |
|---|---|
| Kitchen fire | 0.28 |
| Living room fire | 0.42 |
| Bedroom fire | 0.30 |
| Occupant awake | 0.43 |
| Occupant asleep | 0.57 |
| Occupant in the same room as the fire | 0.26 |
| Occupant in an adjacent room | 0.74 |
| Occupant intimately involved with the fire | 0.30 |
| Occupant with normal abilities | 0.41 |
| Occupant having impaired mobility | 0.29 |

### 4.4.2 The dwelling and its surroundings

The fire risk model will be applied to a typical Swedish apartment, as shown in Figure 4.3. The flat has an area of 94 $m^2$ and consists of a livingroom, two bedrooms, kitchen, batroom, toilet, hall balcony and storeroom. The ceiling height is 2.4 m. The kitchen has an area of 20 $m^2$. Both bedrooms have the same area of 16 $m^2$, and the living room is twice as big with an area of 32 $m^2$.

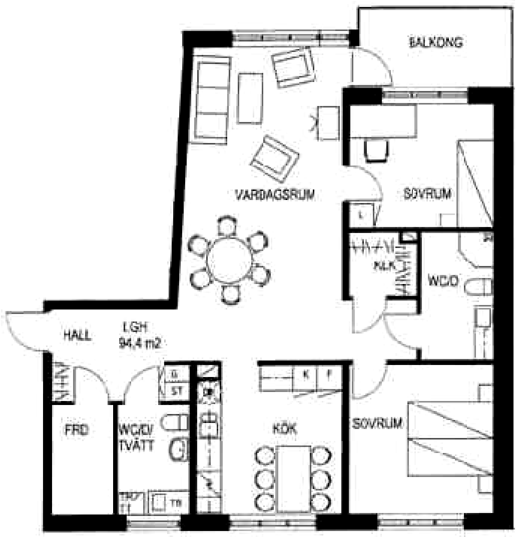



*Figure 4.3 Plan view of a typical Swedish apartment.*

It is assumed that the fire may develop in any of these latter rooms as discussed in Section 4.4.1. Input related to the building and the surroundings is given in Table 4.7.

*Table 4.7 Input related to the dwelling and its surroundings.*

| Variable | Mean | Cov | Distribution |
|---|---|---|---|
| Ambient inside temperature | 22 °C | 10% | Normal |
| Heat capacity | 1 kJ/(kg K) | - | - |
| Height of opening | 2 m | - | - |
| Area of opening | 0.9 $m^2$ | 30% | Normal |
| Floor area | [16, 16, 32] | $m^2$ | Discrete |
| Ceiling height | 2.4 m | - | - |
| $M_{air}$ | 28.8 kg/kmol | - | - |
| $M_{CO2}$ | 44 kg/kmol | - | - |
| $M_{CO}$ | 28 kg/kmol | - | - |
| Critical smoke height, toxicity | 1.7 m | - | - |
| Critical smoke height, heat | 1.2 m | - | - |

### 4.4.3 Fire specifications

The design fire is specified by Equation 3.2 in Section 3.1, and follows the proposal of domestic fires from the CBUF-project (Höglander & Sundström, 1997). The heat release rate, based on expected values, is shown in Figure 4.4.

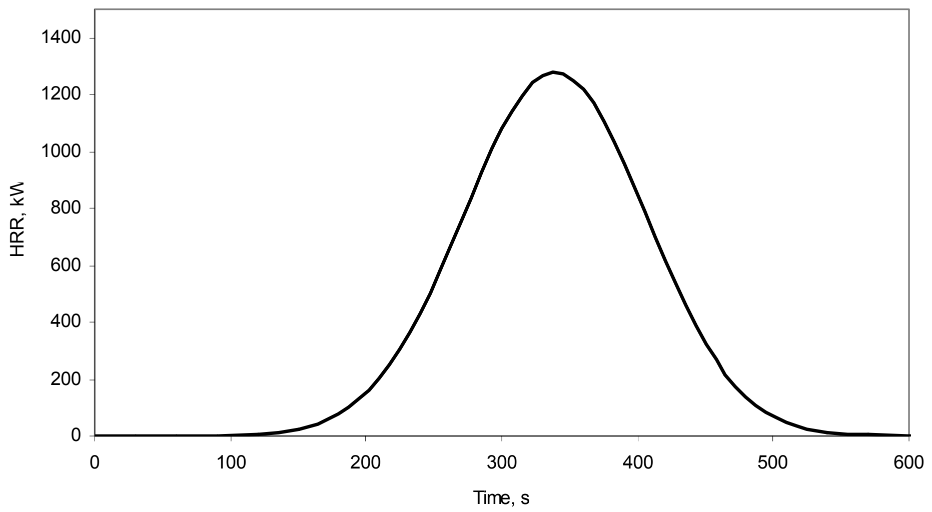



*Figure 4.4 The design fire (based on expected values).*

The uncertainty in the fire model was discussed in Sections 3.4 and 3.5. Table 4.8 summarises these variables.

*Table 4.8 Input for the fire development calculation*

| Variable | Mean | Cov | Distribution |
|---|---|---|---|
| Material burning | Wood | - | - |
| Heat of combustion | 17.5 MJ/kg | 4% | Normal |
| Combustion efficiency | 0.8 | 10% | Lognormal |
| $CO_2$ yield | 1.33 kg/kg | 20% | Lognormal |
| CO yield, ventilation controlled | 0.19 kg/kg | 20% | Lognormal |
| CO-yield, fuel controlled | 0.005 kg/kg | 20% | Lognormal |

### 4.4.4 Safety systems

The fire safety systems are assumed to be smoke detectors and residential sprinklers. Table 4.9 presents the specifications for these safety systems.

*Table 4.9 Safety system specifications for smoke detectors and residential sprinklers.*

| Variable | Mean | Cov | Distribution |
|---|---|---|---|
| Optical density at activation | 0.01524 | 10% | Lognormal |
| RTI, smoke detector | ≈ 0 $(m\ s)^{0.5}$ | - | - |
| Height to detector | 2.37 m | - | - |
| Distance between detectors | 10 m | 20% | Triangular |
| Activation temperature | 68 °C | 10% | Normal |
| RTI, sprinkler | 45 $(m\ s)^{0.5}$ | 5% | Normal |
| Spray density | 0.07 mm/s | 10% | Lognormal |

### 4.4.5 Human response

The most important output when assessing the risk of death due to fire according to the methodology described in Section 4.1 is the time before to unconsciousness and death occur. These times are not only related to the physical properties of the fire, but also to the physiological state of the occupant. The uptake of toxic gases and the effect of heat exposure are thus related to physiological processes. Important variables are given in Table 4.10.

*Table 4.10 Human tenability specifications (from Purser, 1995).*

| Variable | Mean | Cov | Distribution |
|---|---|---|---|
| Respiratory Minute Volume, normal, l/min | 25 | 20% | Normal |
| Respiratory Minute Volume, unconscious, l/min | 6 | 20% | Normal |
| COHb, unconsciousness, % | 40 | 10% | Normal |
| COHb, death, % | 60 | 10% | Normal |

The escape time is set by detection, response and travel time, as described in Section 3.3. These times depend on the specific scenario. The occupant's location and status, and whether or not safety systems have been installed, are important in determining these times. Table 4.11 gives these times for the different scenarios described in Section 4.4.1.

*Table 4.11 Specifications for the escape calculations (see Section 3.3).*

| Variable | Mean | Spread | Distribution |
|---|---|---|---|
| Detection – same room, awake | 30 s | ±10 s | Uniform |
| Detection – asleep, alarm | Calculated activation time | | |
| Detection – asleep, same room, no alarm | When HRR is > 50 kW (growth initiated) | | |
| Detection – other room, no alarm | When HRR is > 250 kW (smoke spreads) | | |
| Detection – other room, alarm | Calculated activation time | | |
| Response – awake, no alarm | 20 s | ±10 s | Uniform |
| Response – asleep, no alarm | 30 s | ±10 s | Uniform |
| Response – awake, other room, alarm | 50 s | ±15 s | Uniform |
| Response – asleep, other room, alarm | 70 s | ±15 s | Uniform |
| Travel | 20 s | ±10 s | Uniform |

### 4.4.6 Simulation settings

A value of $R_{death}$ was calculated for a person with normal mobility and for a person with impaired mobility. The simulation was repeated for four combinations of safety measures; no fire protection measures, smoke detector, residential sprinkler and smoke detector plus residential sprinkler. The results are presented in Section 4.6. The risk model is simulated in @RISK (Palisade, 2002) with 100,000 iterations to ensure convergence. The simulation was performed with the Latin Hypercube sampling technique. The advantage of Latin Hypercube sampling compared with Monte Carlo sampling is that it better represents the original distribution of the input variables.

## 4.5 Model calibration

Initial testing of the model showed that it is highly sensitive to the inherit model uncertainties, mainly in the quantification of fire development. Therefore, it was deemed necessary to calibrate the model prior to applying it for predictions of the risk of death due to fire. The question of whether the fire development model provides reliable predictions or not is therefore essential.

The fire development model was compared with the results from a simulation with both a two-zone model and a field model. FAST v 4.0.1 (Peackock et al., 2000) represents the two-zone model and FDS v 3.0 (McGrattan et al., 2002) the field model. A scenario with fast fire growth (0.047 kW/s$^2$) to a maximum heat release rate of 2 MW was analysed. The room of fire origin had an area of 20 m$^2$ with a 1 m$^2$ opening, representing a half-opened door. The FDS calculation was performed by using large eddy simulation in a 0.05 m grid. Comparisons of upper layer temperature and smoke height above the floor are shown in Figure 4.5 and Figure 4.6, respectively.

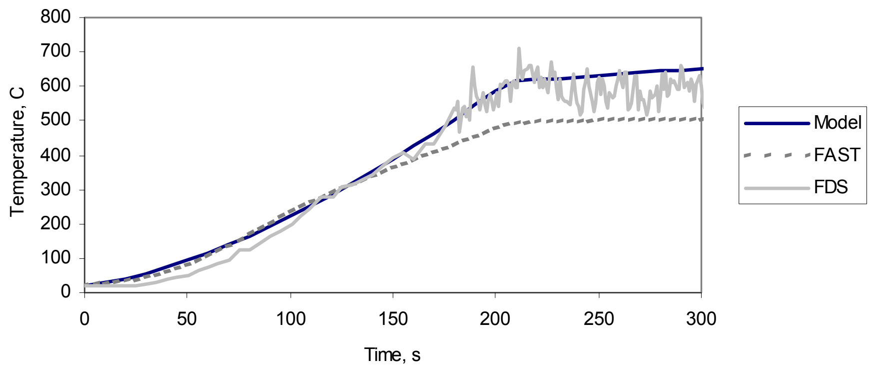



*Figure 4.5 Comparison of upper layer temperature when using different fire models.*

During the first 150 s of the simulation there is quite good agreement between the three fire models. After this point, the FAST curve deviates from the present model and the FDS curve. It is also possible to detect a slight displacement in the timescale of the FDS curve compared with the other two. The displacement is approximately 30 s.

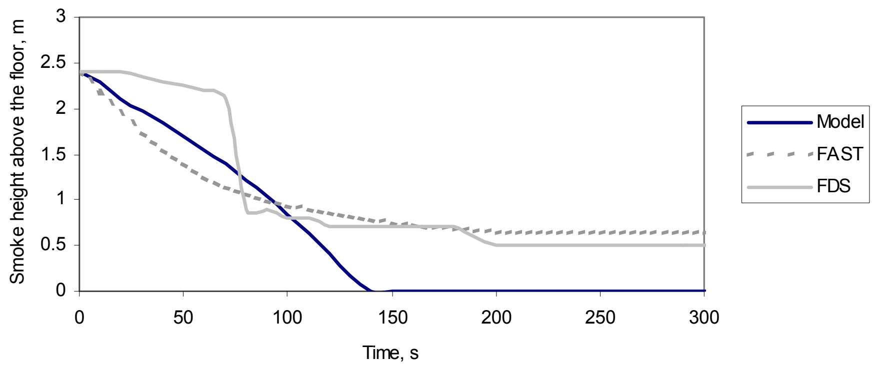



*Figure 4.6 Comparison of smoke layer height when using different fire models.*

When comparing the smoke layer height it can be seen that the output from the FDS simulations differs considerably from the present model and the FAST simulation. The difference can be seen as the same displacement in time as shown in Figure 4.5, i.e. approximately 30 s. The present model and the FAST simulation correspond quite well during the first two minutes. The FDS curve and the FAST curve stabilize at the same value as time increases.

The FDS model has been validated through a number of comparisons between simulations and test results (McGrattan et al., 2002). In rather small-scale applications with a well-defined heat source the FDS model is assumed to give results within 20% of the real fire data. The FAST model, on the other hand tends to overpredict both the smoke-filling rate and the temperature. These findings are made by Lundin (1999) and are valid for a single-room scenario.

Based on the findings in this comparative exercise and the known model uncertainties of the applied fire models, it is concluded that the quantification of fire development by the risk model is conservative. The results should be adjusted by the addition of a time constant of 30 s.

## 4.6 Results

The results outlined in this Section represent 70% of all residential fires. The remaining 30% have not been modelled as they relate to scenarios where the occupant is intimately involved with the fire. The stochastic approach to modelling the heat release rate outlined in Section 3.1 could be fitted to the four characteristic fire growth rates. The expected value of the growth rate is thus 0.014 kW/s$^2$. Table 4.12 shows the percentage of simulations having the same or lower growth rate than the slow, medium, fast and ultra-fast fire growth rates.

*Table 4.12 Fire growth rate in the simulation related to standard growth rates.*

| Growth rate | Value, kW/s$^2$ | Percent of simulated fires |
|---|---|---|
| Slow | 0.003 | 20% |
| Medium | 0.012 | 27% |
| Fast | 0.047 | 24% |
| Ultra fast | 0.19 | 29% |

Figure 4.7 and Figure 4.8 show the distribution of time to unconsciousness and time to death, respectively. These times vary depending on whether sprinklers are installed or not and are only related to the fire development.

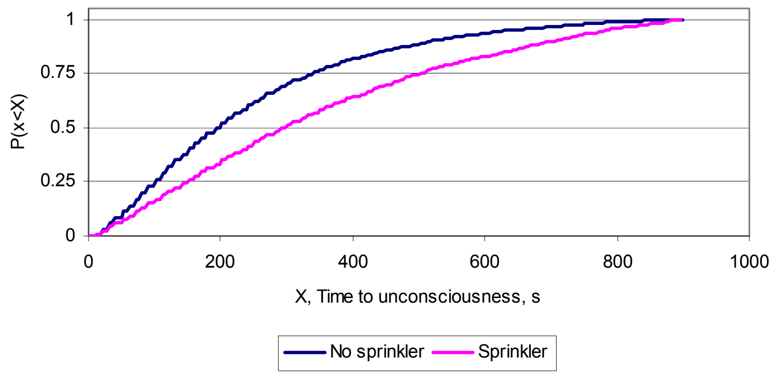



*Figure 4.7 Time to unconsciousness depending on the presence of sprinklers.*

The average value on time to untenable conditions is 220 and 330 s for the non-sprinklered fire and the sprinklered fire, respectively.

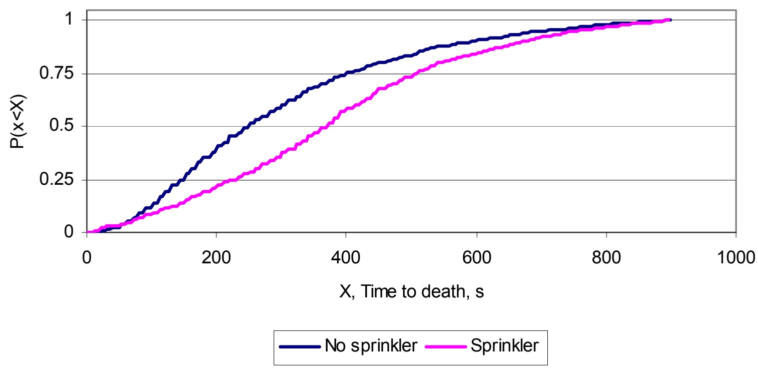



*Figure 4.8 Time before death depending on the presence of sprinklers.*

The average times elapsed before lethal conditions arise is 280 and 400 s for the non-sprinklered fire and the sprinklered fire, respectively. Activation times for a smoke detector and a sprinkler system are shown in Figure 4.9.

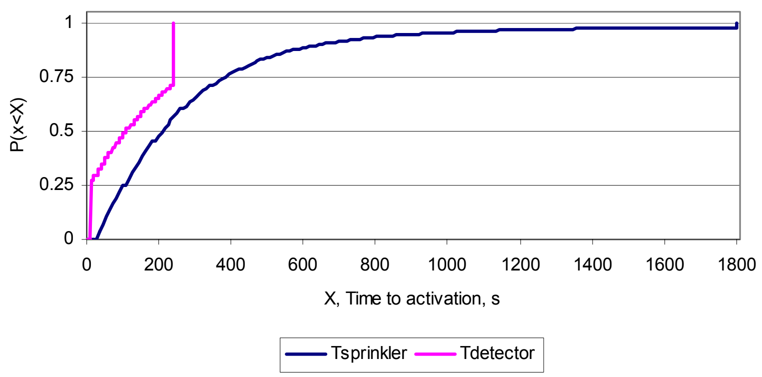



*Figure 4.9 Activation times for a smoke detector and a sprinkler.*

The average detection time for smoke detectors is 110 s, while a sprinkler is activated after an average time of 210 s. The escape time is only slightly related to the time of detector activation, as shown in Figure 4.10.

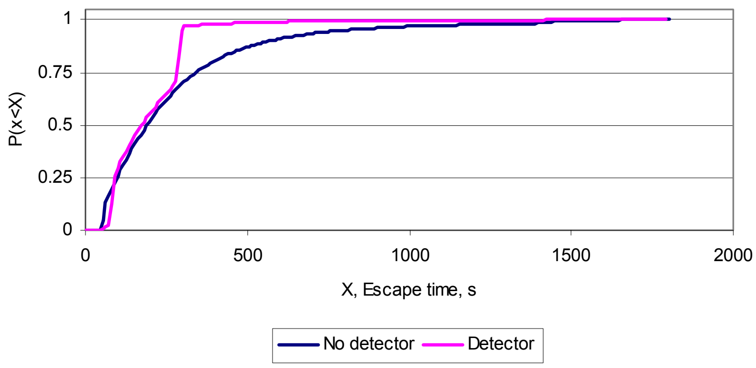



*Figure 4.10 Escape time related to the presence of a smoke detector.*

The frequency of someone being involved in a fire per year for a person with impaired mobility, but not intimately involved is 0.002. Table 4.13 presents the risk of death due to fire for mobility-impaired people.

*Table 4.13 Calculated annual risk of death due to fire for people with impaired mobility.*

| Safety measures | Annual risk of death due to fire |
|---|---|
| None | $8.24 \cdot 10^{-5}$ |
| Residential sprinkler | $2.99 \cdot 10^{-5}$ |

The annual frequency of someone being involved in a fire for those with normal mobility who are not intimately involved with the fire is 0.003. The annual risk of death due to fire for these people, related to the various fire safety measures, is outlined in Table 4.14.

*Table 4.14 Annual risk of death due to fire for people with normal mobility.*

| Safety measures | Annual risk of death due to fire |
|---|---|
| None | $7.02 \cdot 10^{-5}$ |
| Smoke detector | $4.95 \cdot 10^{-5}$ |
| Residential sprinkler | $3.89 \cdot 10^{-5}$ |
| Smoke detector and residential sprinkler | $2.75 \cdot 10^{-5}$ |

The mobile and the mobility-impaired occupants who are exposed to a fire account for approximately 70% of all fire fatalities. The remaining 30% are occupants considered to be intimately involved in the fire. An occupant who is intimately involved in the fire is one who has set his clothes or bed clothing on fire while asleep. The fire risk model cannot quantify the effect of safety measures for these occupants. If it is assumed that all who are intimately involved in fire will die, it is possible to calculate the overall risk of death due to fire in Sweden. The overall individual risk of dying in a fire is thus $7.2 \cdot 10^{-5}$ per year per home. This is equivalent to approximately 295 fire fatalities per year.

## 4.7 Sensitivity analysis

It is of particular interest in a probabilistic model to investigate which input data have the greatest influence on the outcome. Such an investigation is usually called a sensitivity analysis. Depending on whether the variables that have the greatest effect are related to model assumptions, normal variation or uncertainty, a number of important conclusions can be drawn.

No significant difference was found between the effects of the parameters in relation to mobility of the occupants. A general trend was, however, observed and the list of variables given below is sorted in descending order of importance.

- Peak heat release rate of the fire
- Time to peak heat release rate
- Model uncertainty of the maximum possible heat release rate in the room
- Model uncertainty of fire gas temperature
- Model uncertainty of fire plume flow
- Fire location
- Reaction time

When active fire safety measures are incorporated into the analysis, the results show less than average sensitivity to their reliability. Spray density and activation temperature are variables that are of some interest when sprinklers are considered.

It is very interesting to note that the results are most sensitive to variables related to the model uncertainty. This promotes the need for a better understanding of the uncertainties related to fire development models. A quick calculation was performed to analyse the sensitivity of the results to fixed changes in the time to unconsciousness of ± 30 and ± 60 s. The results regarding the risk of death due to fire with no fire safety measures are given in Table 4.15 below.

*Table 4.15 The sensitivity of the annual risk of death due to fire to fixed changes in time to unconsciousness.*

| Change in critical time | Original death risk | New death risk | New/original |
|---|---|---|---|
| - 60 s | $7.02 \cdot 10^{-5}$ | $1.58 \cdot 10^{-4}$ | 2.2 |
| - 30 s | $7.02 \cdot 10^{-5}$ | $1.12 \cdot 10^{-4}$ | 1.6 |
| + 30 s | $7.02 \cdot 10^{-5}$ | $1.48 \cdot 10^{-6}$ | 0.02 |

As can be seen in Table 4.15 the results are very sensitive to small absolute changes in the calculated time to unconsciousness. This sensitivity is charcteristic for fire risk analyses using the well-known state function of time to untenable conditions minus the time required for escape. Olsson & Frantzich (2000) found the same sensitivity of the state function. This sensitivity motivates the use of a time constant of + 30 s, as proposed in the model calibration (Section 4.5).

# 5 Evaluation of appropriate measures

## 5.1 No fire protection

The scenario in which there is no fire protection forms the so-called base case to which all other combinations of fire safety measures are compared. This scenario was chosen as it was concluded that operating smoke detectors are only present in 10-20% of the fatal fires (Table 2.4).

The calculated annual risk of death due to fire when no fire safety measures are present in a residence is $7.02\cdot10^{-5}$ and $8.24\cdot10^{-5}$ for people with normal mobility and those who are mobility impaired, respectively. If the fire frequency is excluded from the annual death risk, a measure of the risk per developing fire is obtained. Those with normal mobility then have a death risk per developing fire of 3.3%. The corresponding risk for those with impaired mobility 6.7%. The risk of dying in a fire is thus about twice as high for the latter group. The probability that untenable and lethal conditions will occur for normal and mobility-impaired occupants is 78 and 41%, respectively.

A comparison with statistics (Section 2.4.2) shows that the fire risk model overestimates the annual death risk by a factor of three. This will be discussed further in Section 7.1. The relation between the risk of death per developing fire for mobility-impaired and mobile occupants corresponds well with the statistics. In 1996-1998 the average death risk in homes for the elderly was 1.97% per developing fire. The corresponding value for other residential buildings was 0.98%. The risk of death due to fire in homes for the elderly is thus twice that in houses and apartments. The calculated risk of death due to fires show the same relationship.

## 5.2 Smoke detectors

Smoke detectors will not have any significant effect on the risk of death due to fire of those with impaired mobility, as they cannot escape by themselves. A smoke detector will, however, add to the likelihood of the occupant being rescued by someone else, as discussed in Section 4.3.3. Smoke detectors will, however, have a significant effect on the risk of death due to fire for those who are able to escape on their own. The installation and activation of a smoke detector will reduce the annual risk of dying in a fire for those with normal mobility from $7.02\cdot10^{-5}$ to $4.95\cdot10^{-5}$, i.e. a reduction of almost 30%. On a national level, the reduction is only 11%, as neither occupants who are intimately involved in the fire nor those who have impaired mobility will be saved. The risk of dying in a developing fire is thus 2.2%. As a smoke detector has no effect on the fire itself, the probability of untenable and lethal conditions is the same as if no fire protection were present.

Smoke detectors are especially effective when the fire starts in a room where the occupants are not present. The alarm is also a reliable system when the occupants are asleep. However, as stated above, smoke detectors have no effect on fire development, and those who cannot escape by themselves are not protected.

## 5.3 Residential sprinklers

Residential sprinklers offer a considerable protection against the serious consequences of fire as the fire is controlled at an early stage. The residential fire sprinkler concept covers both smoke detectors and residential sprinklers. In this analysis, the effect of residential sprinklers alone and smoke detectors in combination with residential sprinklers is assessed. Residential sprinklers alone will lower the annual risk of death due to fire from $7.02 \cdot 10^{-5}$ to $3.89 \cdot 10^{-5}$. This 45% reduction is improved to an overall reduction of 61% when both smoke detectors and residential sprinklers are used. Residential sprinklers increase the probability of having untenable conditions from 78 to 81%. The increase in probability of untenable conditions is somewhat misleading. The time to untenable conditions is not given, only the fact that such conditions will occur. The time before untenable conditions arise is considerably longer when sprinklers are installed and operating. The reason for having an increase in probability is probably the fact that an activated sprinkler causes well-stirred conditions in the fire room, mixing fire gases with fresh air. The corresponding change in probability of lethal conditions is from 41 to 16%.

The annual risk of dying in a fire for those with impaired mobility will be reduced from $8.24 \cdot 10^{-5}$ to $2.99 \cdot 10^{-5}$ by the installation of sprinklers. This corresponds to a reduction of 64%. The risk of dying per developing fire is 2.4%. It can thus be seen that mobility-impaired occupants in premises equipped with residential sprinklers are exposed to practically the same risk of dying per developing fire as people with normal mobility protected by smoke detectors. On a national level the installation of residential sprinklers in all residences would provide a 53% risk reduction. This value was derived by weighting the risk-reduction for those intimately involved in the fire, those with normal mobility and those with impaired mobility. It was considered that residential sprinklers would save half of those who were intimately involved with the fire.

## 5.4 Fire service intervention

One limitation of the fire risk model developed in this study is that the possibility of external rescue cannot be modelled. It is, however, possible to quantify the time available for such rescue operations. Figure 5.1 shows a cumulative probability function of the time before death when no sprinklers are present, given that the occupant will become unconscious, in comparison with the intervention time of the rescue service.

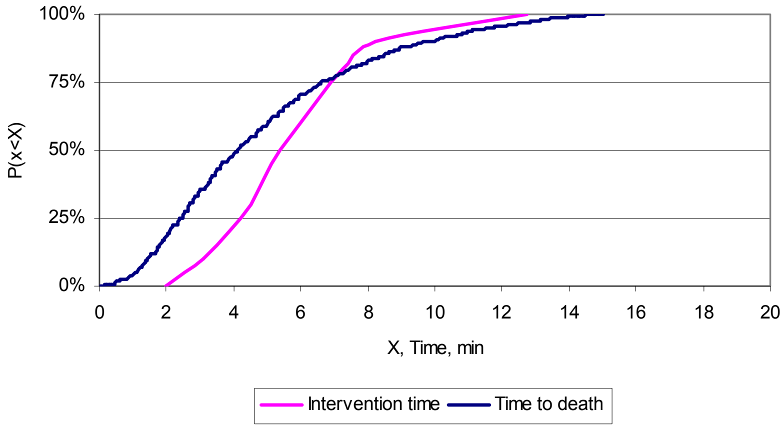



*Figure 5.1 Distribution of time before death from the moment the fire is initiated and the intervention time of the fire service.*

When comparing the distributions in Figure 5.1 it can be concluded the fire service will only have a minor possibility to save the threatened occupants from becoming fire victims. Note that the intervention time does not include the time elapsed from initiation of the fire until the fire service is notified. Assuming a notification time of two minutes the probability of successful rescue is 22%. If the notification time will be two minutes longer, i.e., 4 min, the corresponding probability will be halved to 12%.

The occupants in homes for the elderly do quite often have access to supporting personnel, who could assist them in case of a fire. In such premises, smoke detectors will show better efficiency. It is assumed that an occupant is brought to safety by personnel within two or three minutes after the smoke detector is activated, the probability of a fatal fire will decrease by 54% and 26%, respectively, compared to when no personnel is available. The personnel thus contribute to give the elderly a level of safety that is in the same range as for people with normal mobility living in homes were smoke detectors are installed.

# 6 Cost-effectiveness

A common argument for using safety measures such as residential sprinklers in homes is that it is possible to save money due through trade-offs with other safety measures. Therefore, the installation of a residential sprinkler system affects both the building cost and the fire damage cost. Smoke detectors are mandatory in the regulations for new buildings and could therefore not reduce the building costs. They do, however, have the potential to reduce the financial loss due to fire. Those who are affected by the installation of residential sprinklers are listed in Table 6.1.

*Table 6.1 Parties affected by the installation of residential sprinklers.*

| Party | Influence |
|---|---|
| Society | Reduced number of fire fatalities and lowered rehabilitation costs |
| | Reduced demand for operational fire fighting |
| Owner/user | Possibility of greater architectural freedom |
| | More flexible choice of building materials |
| | Possible building cost reduction |
| | Decreased risk of death due to fire |
| | Reduction in financial loss due to fire |
| Insurance companies | Reduction in compensation for loss of life and property |

All the parties involved will gain by the installation of residential sprinklers. Therefore, it seems natural that they should all contribute to financing the installation. Society may contribute through subsidies in the form of lowered tax on both construction work and property. The owner/user will usually pay for the installation and the maintenance costs. Insurance companies could reduce the insurance premiums for residential buildings in which sprinklers are installed.

## 6.1 Losses due to fire

A fire has the potential to cause injury to people and damage to property and the environment. The severity of the damage varies considerably. Evaluating the consequences of a fire is both difficult and sometimes questionable. The most difficult part is placing a value on human life. This Section gives a brief introduction of how the consequences of fire may be translated into economical terms. Mattsson & Juås (1994) presented a model of the social economic scales, shown in Figure 6.1. The costs are placed on one side and the benefits are on the other side. The investment is considered cost-effective when the scales are balanced.

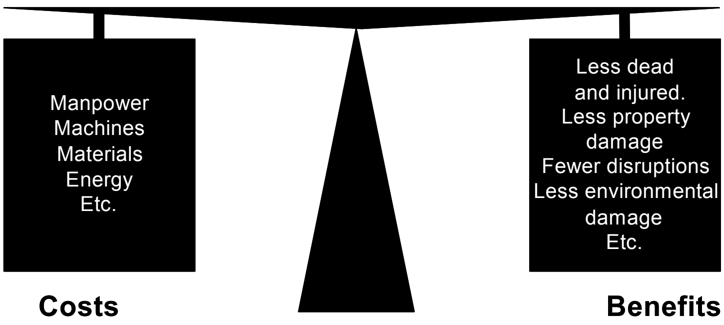



*Figure 6.1 The social economic scales according to Mattsson and Juås (1994).*

### 6.1.1 The value of life

Teng et al. (1995) presented the cost-effectiveness of 500 general lifesaving measures. Cost-effectiveness was measured by studying the cost per life saved. The evaluation is based on a societal perspective. Table 6.2 gives an overview of the cost-effectiveness of some measures.

*Table 6.2 Cost per life saved for various safety measures in the USA (Teng et al., 1995).*

| Measure | Cost per life per year |
|---|---|
| Legislation on seat belt use when driving | USD 69 |
| Redundant braking systems in cars | USD 13,000 |
| Airbags | USD 120,000 |
| Child-proof cigarette lighters | USD 42,000 |
| Seat belts in school buses | USD 2,800,000 |
| Mandatory car inspection | USD 20,000 |
| Prohibition of the use of asbestos in car brakes | USD 29,000 |
| Control of benzene emission from rubber factories | USD 20,000,000,000 |
| Chlorinated fresh water | USD 3,100 |
| Mammography for women over 50 | USD 2,700 |
| Influenza inoculation | USD 140 |
| Smoke detectors in homes | USD 8,100 |

As can be seen from Table 6.2 there is an enormous variation in cost per life saved. Ramsberg (1999) found the same relationship for Swedish conditions. This variation is a problem according to Ramsberg. Resources are allocated to the wrong areas and lives are lost. Table 6.3 gives the cost per life saved based on different categories of life-saving measures.

*Table 6.3 Cost-effectiveness based on nine categories of life-saving measures (Ramsberg, 1999).*

| Category | Mean (USD) | Median (USD) |
|---|---|---|
| Medical treatment | 1,244,874 | 14,000 |
| Radiation | 30,008 | 1,400 |
| Traffic | 242,209 | 66,500 |
| Lifestyle risks | 470 | 340 |
| Fire protection | 211,214 | 15,000 |
| Electrical safety | 1,245,000 | 1,245,000 |
| Accidents | 280,000 | 280,000 |
| Environmental pollution | 235,000 | 67,000 |
| Criminality | 15,000 | 15,000 |

The difference between the mean and median is substantial in most categories. This is probably because there are measures within each category that cost far more than most of the other measures. When a human life is assigned a value, this is discussed in terms of the value of a statistical life. This value is derived from cost-benefit analyses similar to those presented in Table 6.2 and Table 6.3. Kylefors (2001) states that the best assessment of the value of a statistical life is USD 3,000,000. In evaluating a human life, it is necessary to adopt the fundamental principles of risk valuation outlined in Section 1.1.3.

### 6.1.2 The value of property

Swedish insurance companies reported 46,000 cases of loss due to fire during the year 2000. This constituted an increase of 15% in comparison with 1999. Four of five cases are in homes, resulting in a total cost of USD 100 million. The cost of fire damage to property is a combination of property cost, indirect costs and hidden costs. Property costs arise from the loss of the building and personal property, decontamination, personal property, excess, etc. Indirect costs are those resulting from temporary accommodation, moving, insurance administration, and reduced work capability. Hidden costs are related to loss of property and belongings with high sentimental value.

## 6.2 Previous studies on cost-effectiveness of fire safety

Previous studies on cost-effectiveness have been based on analysing whether an investment is motivated from a social point of view. The analysis method requires that market value, willingness to pay, sentimental value, value of statistical life, etc., can be defined. This Section gives a brief overview of previous studies based on specific fire safety measures.

### 6.2.1 Smoke detectors

Smoke detectors are efficient in warning occupants of a fire. They protect property, reduce injury to people and provide an increased perception of safety. Their disadvantages are cost, installation and maintenance. Some people also find them aesthetically disturbing.

Both Mattsson & Juås (1994) and Beever & Britton (1998) found it profitable to increase the number of homes with smoke detectors. They considered that smoke detectors should be connected to the mains and found that it is profitable to replace a battery-powered smoke detector by one supplied by the mains.

### 6.2.2 Fire extinguishers

Fire extinguishers are relatively uncommon in Sweden. About 23% of the Swedish households have one. The recommended domestic model is a powder extinguisher. The advantage of an extinguisher is that the fire can be put out in its initial state and the risk of property damage is significantly reduced. Fire extinguishers have been mandatory in Norwegian houses since the beginning of the 1990s and four of five Norwegian households have an extinguisher (Mostue, 2001). Mostue states that hand-held extinguishers put about 12-15% of the fires reported to the fire brigade. She does also points out that there has been a declining tendency on the number of fire fatalities in Norway since the mandatory requirements on both smoke detector and fire extinguisher was adopted.

Mattson & Juås (1994) found no evidence that fire extinguishers reduce the risk to life. This could be due to the fact that the occupant must remain inside the building to use the extinguisher instead of escaping directly. An extinguisher requires rapid action from the occupant and people who are asleep or intoxicated will have difficulty in using the extinguisher in time. The positive effect of extinguishers on property damage is easier to show. Mattson & Juås (1994) consider it motivated to have fire extinguishers in houses and possibly also in apartment buildings. Beever & Britton (1998) also did not find any evidence that an extinguisher would reduce the risk to life. However, they considered having a fire extinguisher in the kitchen to be motivated due to reduced property damage.

### 6.2.3 Residential sprinklers

The effects of residential sprinklers are clearly described in Sections 2.3.2 and 3.4.2. Neither Mattson & Juås (1994) nor Beever & Britton (1998) consider residential sprinklers cost-effective. This is due to the fact that the probability of fire is relatively low and the installation costs are high. These authors do, however, consider that the cost-benefit analysis should be updated as development in the residential sprinkler market continues to lower the costs. They also believe that residential sprinklers will have increased cost-effectiveness as the general population becomes older. Beever & Britton (1998) also state that there are many other safety measures that could save lives more cost-effectively than sprinklers. Such measures are smoke alarms, extinguishers and measurements to prevent accidents in the home.

## 6.3 Analysis of cost-effectiveness

The purpose of the analysis of cost-effectiveness is to study the cost per life saved for smoke detectors and the residential sprinkler concept. The effectiveness of each safety measure has been assed with the risk model presented in Section 4.1.

### 6.3.1 Methodology

The analysis has two sides: costs and effects. Costs are related only to installation and maintenance and effects are related only to the number of lives saved by the installation of the particular safety measure. The method of present value (Andersson, 1997) was used in the cost estimate. The present value method is based on relating all cash flow over time to the date of the first investment. The present value is the sum of all ingoing and outgoing transactions discounted to the present time. The method is suitable for fire protection as the cost of such investments is spread over time. In order to decide whether an investment is profitable, one must consider the alternative use of the money, i.e. the capital cost. Discounting is performed when future payments are moved in time. Discounting requires information on the interest rate and the rate of inflation. Mattsson (2000) discusses the choice of discount rate. Based on the average returns on the Stockholm stock exchange and the average rate of inflation, a real discount rate of 5% is suggested. A 5% discount rate has been used in many cost-benefit analyses during the 1990s (Mattsson, 2000).

The life cycle cost (LCC) is the total cost of a system during its economical lifetime. It is also possible to include negative costs, i.e., earnings, in the estimate. An estimate based on the LCC will provide a basis for long-term financial decisions. The LCC can be computed using Equation 6.1 below:

$$LCC = C_{inv} + \sum_{i=0}^{n} \frac{M_i}{(1+r)^i} + \frac{C_r}{(1+r)^i} + \frac{C_p}{(1+r)^n} \qquad 6.1$$

where $C_{inv}$ = investment cost

$M_i$ = maintenance cost for year $i$

$C_r$ = reinvestment cost

$C_p$ = phasing out cost

$n$ = economical lifetime

$r$ = discount rate and

$i$ = index for which year the cost will increase.

### 6.3.2 Data

The analysis was carried out for an economical lifetime of 20 years and a discount rate of 5%. During the past few years, there has been an annual increase in the number of residential buildings by 0.4% (SCB, 2002).

It was assumed that there are two smoke detectors in each home, and that the detectors are equipped with a 10-year battery. The operational lifetime of a detector is 10 years. Therefore, it is necessary to reinvest in a new detector every ten years. The cost of a single smoke detector is assumed to be constant over time at USD 8. The overall risk-reducing effect of installing a smoke detector is 11% as described in Section 5.2.

The residential sprinkler concept consists of both sprinklers and smoke detectors. The smoke detectors are assumed to have the same costs as described above. The cost of a residential sprinkler system is more difficult to determine, as there are insufficient installations in Sweden to provide a statistically sound basis. Therefore, a Swedish business organisation for Heating, Ventilation and Sanitation was asked to assess the cost of installing sprinklers in a apartment house with three floors and a total living area of 900 $m^2$ (Arnesson et al., 2001). Their estimate is based on full protection according to the Swedish regulations on residential sprinklers, which have been developed from NFPA 13 R (NFPA, 2000). The installation cost covers design, documentation and installation. Maintenance costs are based on a quarterly inspection and annual service. Table 6.4 outlines the costs.

*Table 6.4 Installation and maintenance costs for a residential sprinkler system in a 3-story, 900 $m^2$ apartment building (Arnesson et al., 2001).*

| Water source | Installation cost<br>Steel piping (USD) | | Plastic piping (USD) | | Maintenance costs (USD) |
|---|---|---|---|---|---|
| | Total | per $m^2$ | Total | per $m^2$ | per year |
| Municipal connection | 14,800 | 16.1 | 16,000 | 17.3 | 840 |
| Municipal connection and electrical pump | 18,400 | 20.1 | 19,500 | 21.3 | 1,050 |

The estimate shows an installation cost of USD 16-21 per $m^2$. The cost will vary depending on the market, local conditions, building size, number of sprinkler heads, architectural design, presence of suspended ceilings, type of water source, etc. An installation with plastic piping was assumed more expensive than a steel pipe installation. This is due to the lack of experience in using plastic pipes in Sweden. Currently, the installation cost for residential sprinklers in Scottsdale, Arizona, USA is USD 6.5 per $m^2$ (Ford, 1997). The sprinkler system will last during the economic lifetime of the building, without reinvestments. The risk-reducing effect of the residential sprinkler concept is 53%, as stated in Section 5.3.

### 6.3.3 Results

The results of the analysis of cost-effectiveness of the safety measures are summarised in Table 6.5. These results are computed over a life cycle of 20 years and a safety measure is considered to be cost-effective if the cost per life saved is less than USD 3 million (see Section 6.1.1).

*Table 6.5 Summary of cost-effectiveness for smoke detectors and residential sprinklers.*

| Measure | Application | Cost (USD) | No. lives saved | Cost per life saved (USD) | Cost-effective |
|---|---|---|---|---|---|
| Smoke detectors | All homes | 36 million | 126 | 229,000 | Yes |
| Residential sprinklers | All homes | 49 billion | 756 | 69 million | No |
| Residential sprinklers | All homes for the elderly | 40 million | 91 | 444,000 | Yes |

The present value of the life cycle cost of a home smoke detector installation is computed to be USD 26. Considering that there are approximately 4.1 million houses and apartments in Sweden, the LCC on a national level is USD 106 million. However, smoke detectors are already present in approximately 80% of houses and 50% of apartments. The net cost for the mandatory installation of smoke detectors in the remaining homes will thus be USD 36 million. The discounted effect of smoke detector installation is the saving of 126 lives during a 20-year period. The cost per life saved is thus USD 229,000.

The LCC of a residential sprinkler installation covering both sprinklers and smoke detectors is estimated to be USD 12,000 per installation per home (94 $m^2$). On a national level, the total cost of the mandatory installation of sprinklers would be USD 49 billion. The discounted effect of providing all residential buildings with sprinklers would be a saving of 756 lives. The cost per life saved is thus USD 69 million.

As stated in Section 6.3.1 the best estimate of the value of a statistical life is USD 3 million. Based on this estimate it can be concluded that the mandatory installation of smoke detectors in all Swedish homes would be a cost-effective investment. Residential sprinklers are, however, not considered cost-effective. USD 69 million per life saved is a high value compared with that determined in an American study on cost-effectiveness by Notarianni & Fischbeck (1998). According to their study, the national median net cost in the USA is USD 7.3 million per premature death averted. This difference is probably because residential sprinklers are currently far more expensive in Sweden than in the USA and the fact that the effectiveness of the safety measures was found to be lower in the present study than in others (see Section 7.1).

The risk of death due to fire is is more of a problem for the elderly and those with impaired mobility than to those with normal physical abilities. It is interesting to see if it would be cost-effective to retrofit residential sprinklers in homes for the elderly.

According to the Yellow Pages (2002) there are approximately 1500 such homes in Sweden. If each home has an average area of 1000 $m^2$, the LCC cost will be USD 40 million. Table 2.1 shows that 12% of all lethal fires occur in homes for the elderly. The discounted effect of residential sprinklers is then estimate to be the prevention of 91 premature deaths. The cost per life saved is thus USD 440,000. Retrofitting of residential sprinklers would thus probably be considered a profitable investment.

If residential sprinklers should are to be cost-effective in homes, it is necessary for the installation of sprinklers to lead to reductions in other building costs, i.e. performing trade-offs. The principles of trade-offs are discussed in Section 7.2. Commonly used trade-offs when introducing residential sprinklers are reduced requirements on fire spread between buildings, alternative building materials and reduction in the requirements on fire cell boundaries (Arvidsson et al., 2002). As a complement to the building cost savings, it is possible to reduce the cost of designing and building new areas as well as the cost of the fire service. In the USA, the RFSI (2000) showed that residential sprinkler installation could reduce impact fees, increase housing density, allow narrower streets, less fire water, reduced accessibility for the fire service, etc.

# 7 Discussion

## 7.1 Model validity

There are differences between the statistical death risk and the modelled risk, as mentioned in Section 5.1. Considering the results of the sensitivity analysis presented in Section 4.7, these differences seem quite natural. Modelling fire is not a precise science and human behaviour is certainly not easy to model. What is important, however, is that the model uncertainties are the same for different scenarios used in the model. This means that a scenario in which a sprinkler operates and the fire is in the living room should have the same set of uncertainties as a scenario with a smoke alarm and fire in the bedroom. The parameters that most affect the results are mainly related to the design fire and to smoke-filling model uncertainties. These parameters are considered to result in scenario-independent uncertainties.

In Section 2.4.1 some results from previous studies on residential fire risk are presented. In the study by Ruegg and Sieglinde (1984), the risk reduction when introducing smoke alarms and residential sprinklers is higher than in this study. They state a 48% reduction in risk when installing smoke detectors and an 82% reduction in risk when using residential sprinklers. Budnick (1984) shows a 73% reduction when using residential sprinklers. The corresponding values for the use of smoke detectors and residential sprinklers in this study are 29% and 61%, respectively. Why do the results differ? One probable cause could be that this study covers the full range of possible residential fires, taking into account both the severe and non-severe scenarios. Occupants could either be in the room of origin or not. If an occupant is not in the room of fire origin, he will have less likelihood of escaping, especially if he is asleep and there is no smoke alarm. To illustrate this fact the relative risk reduction in comparison with having no fire protection at all is given in Table 7.1 for each scenario.

*Table 7.1 Relative risk reduction for each scenario in comparison with having no fire protection at all.*

| Fire protection | Scenario | | | |
|---|---|---|---|---|
| | In room, awake | In room, asleep | Outside room, awake | Outside room, asleep |
| Smoke detector | 0% | 1% | 13% | 34% |
| Residential sprinkler | 20% | 23% | 48% | 46% |
| Residential sprinkler and smoke detector | 20% | 24% | 62% | 63% |

Note that the values in Table 7.1 are valid only for those 70% of all fires where the occupant is not intimately involved with the fire (see Section 4.6). It can be seen that fire safety systems have the greatest effect when people do not have the possibility to detect the fire themselves in its initial state, which reduces their chance of successful escape. It is not only the different occupant scenarios that reduce the effect of safety systems, it is also the fact that all types of fire development are considered. Table 4.12

shows which kinds of fire growth rate the model includes. About half of all fires have a slow or medium fire growth rate and should not result in any particular threat to life. For half of the fire scenarios the occupant can not rely upon a particular safety system, which decreases the relative effect of such systems. It is therefore concluded that the validity of the model is satisfactory for comparison between safety measures. However, the model requires further calibration to fit predict real fire data from residential fires.

## 7.2 Trade-offs

The installation of residential sprinklers goes hand in hand with a request to allow trade-offs on other safety measures. The goal in a trade-off situation is that the overall safety should remain constant. Figure 7.1 shows the principle behind trade-offs.

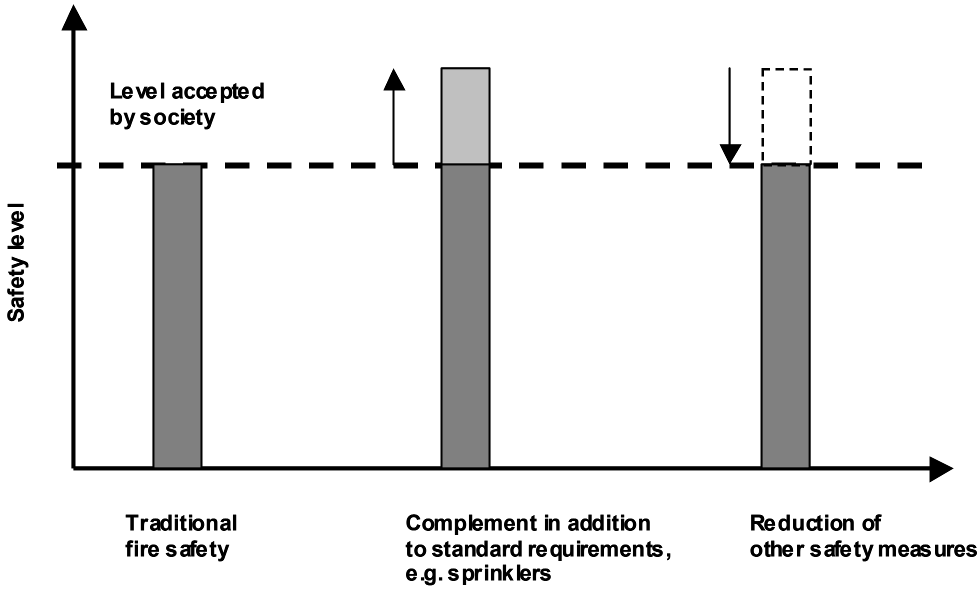



*Figure 7.1 The principle behind trade-offs.*

Installing residential sprinkler systems could make it possible to perform trade-offs on the following safety measures, if verification can show that the performance requirements in the regulations are fulfilled.

- Wooden facades on more than two storeys
- Reduced requirement on fire spread through windows within the same building
- Reduced requirements on surface finishes in homes
- Increased distance to emergency exit
- Reduced requirements on fire spread through HVAC-systems
- Reduction in fire requirements for separating/supporting constructions
- Reduced requirements on surface finishes in escape routes
- Smaller distance between buildings

Arvidsson et al. (2002) verified that residential sprinklers provide sufficient safety with trade-offs regarding wooden facades, fire spread through windows within the same building, surface finishes in homes and increased distance to exits. The other proposed trade-offs need thorough verification to ensure that the safety level is maintained at an acceptable level. However, using trade-offs could be contrary to a national objective to reduce the number of deaths. Trade-offs can only be motivated if the existing building fire regulations provide an acceptable level of risk. One must also exercise care when considering combinations off trade-offs. If a residential sprinkler is installed as a trade-off for both reduced requirements on fire separation and surface finishes, the fire will be very severe if the sprinkler fails to operate.

## 7.3 Conclusions

The applied fire risk model is found to give valid results for making estimates of the effectiveness of fire safety measures. As the model treats uncertainty and variability explicitly, the results are very balanced. The results of this study show that previous studies on the effectiveness of smoke detectors and residential sprinklers probably have overestimated their effect, at least when translated to Swedish conditions. This is might be the result of too simple approach to modelling lethal fires. The overall risk-reducing effects of smoke detectors and residential sprinklers are 11% and 53%, respectively. These values are much lower than previous studies, but they are supported by Brennan & Thomas (2001), who criticise the engineering approach of modelling lethal fires based on the fact that fire victims are most often intimately involved in fire ignition and spread. They state that lethal fires, to some extent, are a social problem and can therefore not be controlled by building regulations.

Mandatory installation of smoke detectors in homes is considered a cost-effective investment on a national level. The cost per life saved is USD 229,000. Residential sprinklers do not show the same effectiveness having a cost per life saved of USD 69 million. Even though the system saves far more lives, the installation and maintenance costs are much higher. The system is, however, considered cost-effective in homes for the elderly with a cost per life saved of USD 440,000. When residential sprinklers are installed, people who have impaired mobility suffer the same risk as those with normal mobility when no form of fire protection is installed.

The fire risk model did not succeed in predicting the probability that an occupant at risk of dying in a fire would be saved by another person, such as a neighbour or the fire service. This is one of the reasons why the results of this fire risk model differ from statistical measures of risk of death due to fire. The model shows great sensitivity to small absolute changes in the calculated time to unconsciousness. This sensitivity is characteristic of fire risk analyses using the well-known state function of time to untenable conditions minus the time required for escape. In contradiction to load-bearing structures where the design load is much greater than the normal load, the normal load and the accident load in fire life safety are very close. There are also major uncertainties associated with design fire, human tenability and fire development that require further quantification before the risk model agrees can predict real values.

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