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'It depends'

Descriptive research into fire growth and the chances of survival

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Foreword

I have great pleasure in presenting the first results of the research conducted by the Netherlands Fire Service Academy and the Netherlands Fire Service into fire development and the chances of surviving fires in the home. This is the first time in the history of the Netherlands Fire Service that such research has been conducted on this scale and under realistic conditions. The town of Zutphen, the Netherlands, has given the Dutch fire service the unique opportunity to research modern fire development in real homes with realistic layouts and furnishings.

Both day-to-day practice and national and international studies have shown that fires have changed in recent years due to the increase in the use of synthetic materials in furniture and fixtures and in the building itself (e.g. insulation). An important question is what the consequences of these ‘modern fires’ are for the occupants, the people living in the home in question. And what are the implications for firefighters who come to help occupants – who cannot escape by themselves – and to put out the fire? Research by the fire service is of significant importance and is badly needed: the fire service *goes science*.

The current research is of a ‘descriptive’ nature for the six fire tests in Zutphen. If there is one thing that has become apparent during the research, it is that minor differences in the situation can have a major effect on fire development. There are many possible scenarios, but studying all of them is impossible, no matter how much we'd like to do so. The results of this research will be put to further use, including as input for the RemBrand project. The fire tests in Zutphen have given us unique film footage. We will use it to produce information and course materials for firefighters, so that we can further improve safety for civilians and firefighters. Though research was conducted into fire development and survivability in Dutch homes, the findings may well have international value. Therefore this English translation has been made available of the former Dutch publication.

This research was carried out with the involvement and cooperation of a great many people. I would like to thank everyone who has been involved in any manner: firstly, the Municipality of Zutphen and housing corporation Ieder1, who have given us permission to use the homes in the De Mars residential area. Furthermore, I would like to thank the local residents and companies for their willingness to accept some nuisance while the fire tests were being conducted. The research also involved many colleagues from all over the Netherlands. Colleagues from the Fire Investigation Teams helped the Fire Service Academy researchers with the collection of data. Firefighter colleagues assisted us in the safety crews and in setting up the test objects. More than 40 firefighters from all over the Netherlands and colleagues from the IFV attended the fire tests every day. This research would not have been possible without their help. It represents an optimum amalgamation of firefighting practice and science. And finally, I would like to thank the parties that funded this research: the Netherlands Fire Service, the Fire Service Academy and the NCTV.

The results of this research into fire growth and survivability show that such research is necessary, that it yields useful results, and that investing in research is not in vain.

Ricardo Weewer
Professor of fire service science

Contents

1 Introduction

1.1 Background

The fire tests carried out by the Fire Service Academy into fire development and survivability in homes took place against the background of the following figures for the Netherlands:

> There are some 14,000 fires in homes and companies every year
> These fires claim between 800 and 900 casualties[1] a year, 32 of which -on average- are fatalities[2].

Expectations are that the ageing population, combined with the increase in the number of people with reduced ability to leave a building without assistance and who live on their own, will lead to a 16 percent[3] increase in the number of fire casualties in the next few years.

Furthermore, these 14,000 fires, roughly speaking, in homes and companies, plus the approximately 20,000 outdoor fires negatively affect the health of local residents and the environment (air, water, soil). And some fires, especially major industrial fires, lead to a certain degree of community disruption because local residents and companies have to be advised to stay indoors and keep their doors and windows closed to keep smoke out.

The joint (Dutch) fire brigades have defined their strategic ambition in '*De Brandweer over morgen*' (The Fire Service for tomorrow), which includes the following points:

> The fire service wishes to minimise the number of casualties (both civilians and firefighters) of fires
> The fire service wishes to increase the effectiveness of its deployment, resulting in fewer economic losses, less community disruption and a lower environmental burden.

Implementing these strategic ambitions requires an understanding of the manner in which fires develop in homes, so that the fire service can take action more effectively in all links of the safety chain in order to prevent fires and reduce the effects of fires.

Furthermore, firefighters have noticed that the actual conditions of fires in the home have changed compared to some 20 years ago. Different furniture and better insulation seem to cause fires to get hotter and grow faster, but fewer fires seem to develop fully. This presumed change in fire development might lead to other risks for firefighters and call for a different approach to fires. This explains the need for research into how fires develop.

1.2 Purpose and research questions

The purpose of this research is to map the development of a fire in a living room, kitchen and bedroom in a common type of home in the Netherlands with an interior that is common to many households in the Netherlands. The chance of surviving – survivability – in the room where there is a fire and in other rooms in the same house has also been mapped in the

[1] Fire Services Statistics 2012, Statistics Netherlands.
[2] Duyvis, M.G., Groenewegen-Ter Morsche, K., Kobes, M., Mertens, C. & Rossum, W. van (2013). *Fatale woningbranden 2008 t/m 2012: een vergelijking*. Arnhem: IFV.
[3] IFV, fire prevention professorship, 2014

context of the national RemBrand project and with the intention of optimising educational and course materials for the fire service.

Research question 1:
How does a fire develop in a living room, kitchen and bedroom in a common type of home in the Netherlands with an interior that is common to many households in the Netherlands and where internal and external doors can be open and closed?

Research question 2:
What are the chances of surviving a fire in a living room, kitchen and bedroom in a common type of home in the Netherlands with an interior that is common to many households in the Netherlands and where internal and external doors can be open and closed?

1.3 Scope

The Netherlands has many different types of homes, all with their own distinctive construction and layout. Examples include terraced houses, apartments, flats, sheltered housing units and 'living over the shop' in old city centres. These various types of homes are often constructed of single or double skin brickwork walls (with or without an insulated cavity wall), timber, concrete or synthetic materials and most have a tiled or bitumen roof. The interior fixtures and fittings of these homes vary as to their types, materials and the exact furniture positions. And finally the homes' use varies: the number of occupants in each home and how they organise their lives and living environments. Aspects relevant to fire growth and smoke development include how the homes are ventilated, the degree of 'order and cleanliness', but also how the electrical installation is maintained. On the basis of the above considerations, we have to come to the predetermined conclusion that the Netherlands has an almost unlimited variation in homes and their interiors. There is no such thing as the typical Dutch home, nor typical Dutch interior fixtures and fittings. At the same time, there are definitely often distinct similarities as regards the layouts and interior fixtures and fittings of Dutch homes.

To obtain an impression of fire development in Dutch homes, six fire scenarios were reproduced in terraced houses in Zutphen; these scenarios are described in more detail below. The research is of a descriptive nature and does not aspire to provide a comprehensive description of typical fire development in a typical Dutch home. At the same time, the six fire scenarios were compared to discover similarities and differences as regards survivability and fire development.

2 Criteria for escaping and surviving

As indicated above, the purpose of the research is to map the development of a fire and the chances of surviving a fire in the home. Therefore, the aim is to determine the factors that are jointly responsible for fire development and chances of surviving.

Based on a literature review[4], the following factors have been identified as relevant:

> Temperature development in degrees Celsius in the different rooms of the home as time passes;

> Radiation heat development in degrees Celsius in the different rooms of the home as time passes;

> The carbon monoxide (CO), nitrogen dioxide (NOx) and oxygen (O2) percentages in the different rooms of the home as time passes;

> Smoke spread in the different rooms of the home as time passes.

These factors will be mapped in the fire tests in order to be able to answer the research questions. Based on international field studies[5] and a pre-test that was conducted on 18 September 2014, it has been established that the effect of open or closed doors on both smoke spread and fire growth is an important element as far as the above factors are concerned. Therefore the possibility to compare fire and smoke spread when a door is either open to fire and smoke spread or closed, relative to the chances of surviving, has been closely examined in the six scenarios.

2.1 Escaping and the chances of surviving

To be able to establish the extent to which possible casualties can survive the fire and smoke conditions in a room, it should first be defined which factors influence survivability and which measurement values should be associated with them. The same goes for the ability to escape without being impeded. Here, the assumption is that a casualty can and wishes to escape until this is no longer possible. However, if escaping is no longer possible, the situation has not automatically become 'unsurvivable'. Even if a casualty becomes dazed or unconscious, the situation is not ‘lost' until a casualty dies of heat, radiation, carbon monoxide and/or NOx. An important consideration in this respect is that the threshold values for escaping and surviving are arbitrary for four reasons:

> There is not 100 percent uniformity as to how to define ‘survivability’ and ‘escape’. Different notions such as lethality, life-threatening value, etc. can be found in the relevant literature.

> According to some definitions, a situation is lethal if 1 percent of the population dies, whereas other definitions refer to 50 percent of the population.

> In addition, survivability and unimpeded escape are not only defined by ‘hard’ instantaneous threshold values, but also by the total volume dose of a substance people are exposed to.

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[4] Purser, D. (2002). Toxicity Assessment of Combustion Products. In: *SFPE handbook of fire protection engineering*, P.J. DiNenno (Ed.). Quincy: National Fire Protection Association; Gann, R.G., Averill, J.D., Butler, K.M., Jones, W.W., Mulholland, G.W., et al. (2001). *International Study of the Sublethal Effects of Fire Smoke on Survivability and Health (SEFS): Phase I Final Report.* Washington: NIST.

[5] NIST and UL, Governors Island experiments

> In the event of a fire, a casualty's health is rarely threatened by only one factor. For instance, if carbon monoxide (CO) is involved, there will often also be NOx and other combustion gases. Where there is a high temperature, there will often also be heat radiation (and CO and NOx). It is almost impossible to quantify the mutual influences of these factors.

A literature review has been carried out to establish threshold values for the fire hazard elements that have been identified: (high) temperature, (high) heat radiation, carbon monoxide, NOx and a low percentage of oxygen.

The assumption adopted in this research for the criterion of 'survivability' was 50 percent lethality among the population if that specific situation occurs. That automatically means that there is something important to note as to the conclusions of this research: where it is stated here that a situation is no longer survivable, a casualty may actually still be alive in a real life situation. However, assuming 100 percent lethality would mean that the majority of the population would die before the value stated in this report was reached. This is in deviation with the intervention values as applied, for example, to determine whether and to what extent the population should be informed or alerted in order to prevent or reduce damage to health in the event of major incidents where hazardous materials are involved.

A fire in a home will change a house into a hazardous environment where heat, reduced visibility due to the smoke, oxygen deficiency, and toxic fire gases threaten the safety of the person or people present in a very short time. The hot toxic fire gases in a fire are the main problem for people. The high temperature of the smoke can quickly cause their lungs to burn and can cause fluid in the lungs. The smoke consists of a complex mixture of particles and substances that lead to suffocation such as CO and hydrogen cyanide gas (HCN), and irritants such as NOx and hydrogen chloride (HCl).

This report assumes two *tenability limits*:

> Survivability: the limit above which it assumed that the chance of surviving reduces greatly and that there is a significant chance of long-term damage to health. This implies that, once this limit is exceeded, the chance of surviving is not '0', but it is limited.

> Escape impediment: the limit above which people with average sensitivity are hindered in their possibility to escape. This is defined as 'for 50 percent of the population, it will be impossible to escape without help when this limit has been exceeded'.

The only direct exit from the home used in the fire tests (see the floor plan in chapter 3) is from the hallway and the living room/kitchen. This means that an occupant who is in another room than the hallway or the living room/kitchen will have to escape through another room. This shows that not only the ambient conditions in the room where people are alerted are relevant, but also that the ambient conditions in the escape route must be analysed as well. The escape routes are as shown below for the following rooms:

Table 2.1: Escape routes

Room	Route
Master bedroom	Landing, hallway
Baby room	Landing, hallway
Landing	Hallway
Living room	Hallway (with an extra exit through the kitchen)

When analysing the effects of the harmful ambient factors in a house on fire, a maximum escape time of 100 seconds is assumed; based on an estimate of ample time a parent carrying a young child needs to reach the exit.

2.1.1 Exclusion of research

The research is of a descriptive nature and does not aspire to deal with all aspects of survivability in Dutch homes. Below, we address some aspects that are not elaborated further in this report, but that do influence survivability in houses that are on fire and their occupants' health.

> To be able to safely escape from a building that is on fire, the available time to escape (Aset) must be greater that the time needed to escape (Reset)[6]. In general, there is a delay between the moment when the fire breaks out and the moment when people start to escape. This 'wake up time' is important for survivability, but this is not taken into consideration in the rest of this report.
> There is also a difference between the ability to leave without assistance of adults, senior, very young and/or physically and/or mentally impeded occupants of a home. The same goes for the degree to which they can physically bear the effects of heat and smoke. Since it is impracticable to analyse survivability and the ability to leave without assistance for all these groups separately within the scope of this research, we have started from the point of view of a grown up occupant who is able to leave without assistance.
> It is a known fact that people who manage to escape from a fire and get to safety can still die of infection reactions in their respiratory tracts and lungs afterwards. The question of whether people have been able to get to safety is the only aspect that is considered as regards the injury criteria for the ability to leave without assistance[7]. This report is explicitly confined to getting to safety.

2.2 Danger factors

Based on a literature review, this research only measured some of the factors that determine danger (temperature, heat radiation, carbon monoxide, NOx and oxygen). Each factor will be discussed separately below. Due to possible combinations with the other factors, this means that, in general, the available time to escape is reduced further.
The physical and chemical factors that determine whether a situation is still survivable or escapable are:

> Exposure to heat and radiation
  a) Skin burns
  b) Burning of the higher respiratory tracts
> Visual hindrance due to smoke
> Toxic fire gases
  a) substances that cause suffocation (carbon monoxide and hydrogen cyanide)
  b) irritants.

These factors will be explained in more detail below.

[6] Aset is the acronym of: available safe egress time. Reset here means: required safe egress time.
[7] Adviesraad Gevaarlijke Stoffen (2012). *Visie op ontwikkeling van letselcriteria voor preventief gebruik door hulpverleningsdiensten*.

2.2.1 Exposure to heat and radiation

In 2003, the former Dutch Ministry of Transport and Water Management published a guideline for analysing scenarios for accidents in tunnels (*Leidraad scenarioanalyse ongevallen in tunnels)*. Pages 50-51 of this guideline state the following as regards thermal injury due to temperature: People who are in hot air or smoke can incur injury as a result of two mechanisms:

- skin burns
- lung burns.

The table below - based on Lemaire (2002) - states the effects of temperature on people, based on dry air:

Table 2.2: Temperature versus response on skin and respiration

Temperature (°C)	Response
127	Breathing difficulty
140	Five-minute tolerance limit
149	Difficult to breathe through one's mouth, threshold for escape
160	Unbearable pains
182	Irreversible damage in 30 seconds
200	Respiratory system breaks down within four minutes

People can safely, be it uncomfortably, stay in an environment where the temperature is below 70 °C for a longer time. Lemaire (2002) gives the following relationship between the maximum exposure time t in seconds and the temperature T in °C for the temperature range of between 70 and 150 °C:

$t = 5.33 \,.\, 10^8 \,.\, (1 / T^{3.66})$

Skin burns will occur in five minutes at temperatures of above 150 °C. For exposure to heat in a ‘water mist’ environment that occurs after the use of a sprinkler, it is assumed - in accordance with the PIARC guideline - that the heat transfer to the skin relative to a dry environment has greatly increased at a temperature of 50 °C. Besides this, the chance of condensation in the lungs increases to such an extent that lethality occurs.

Based on an article by Charters (1992), TNO (1998) proposed the following function. The basic principle is that no lethal injury occurs at 60 °C and that 100% lethal injury occurs at 200 °C:

Death risk = $t / 60 * .\exp(5.1849-0.0273(T-273))$[8]

Where, t = exposure time in seconds, T = temperature in degrees Kelvin.

This results in the below table, where lethality is shown as a function of dwell time and temperature.

[8] Purser, D. (2002). Toxicity Assessment of Combustion Products. In: *SFPE handbook of fire protection engineering*, P.J. DiNenno (Ed.). Quincy: National Fire Protection Association.

Table 2.3: Relationship between temperature and dwell time

		Temperature				
	Celsius	70	80	100	150	190
time (s)	Kelvin	343	353	373	423	463
10		0.6%	0.8%	1.4%	5.6%	16.7%
30		1.9%	2.5%	4.3%	16.8%	50.1%
50		3.2%	4.1%	7.2%	28.0%	83.5%
60		3.8%	5.0%	8.6%	33.6%	100.0%
120		7.6%	9.9%	17.2%	67.3%	100.0%
300		18.9%	24.9%	42.9%	100.0%	100.0%
600		37.9%	49.7%	85.9%	100.0%	100.0%
1200		75.7%	99.5%	100.0%	100.0%	100.0%

In summary, the following critical values are proposed for a person's presence in a hot environment:

> Dry environment
  – *Unpleasant*: temperature = 70 °C (uncomfortable, but safe, people can be in this for a relatively long time)
  – *Lethal*: temperature = 150 °C (skin burns will occur within five minutes).

> Humid environment
  – *Lethal*: temperature = 50 °C if a humid environment.

This research concerns fires in a living environment, but does not consider the fire service attack (moisture). That is why this research assumes a dry environment and leaves the humid environment out of the consideration.

Taking the above into consideration, this research is based on the following assumptions:
> Threshold value for unimpeded escape: 150 °C at 180 cm height
> Lethal injury: > 150 °C at 50 cm height.

On pages 52 and 53 of its *Leidraad scenarioanalyse ongevallen in tunnels* (2003), the former Dutch Ministry of Transport and Water Management stated the following as regards injury due to heat radiation: heat radiation from hot gases and solid surfaces, outside the range of flames and the hot fire gas zone, can also endanger people. The following criteria apply here:
> intensity of the heat radiation to which the skin is exposed
> time of exposure
> the area that is exposed to the heat radiation.

First-degree burns occur after 20 seconds of exposure to 7.3 kW/m^2 or after 100 seconds of exposure to 2.1 kW/m^2. An escape period of 100 seconds and a radiation level of 6 kW/m^2 will cause approximately half the people who try to escape to die; if the radiation level is 2 kW/m^2, half of them will sustain first-degree burns. The relationships apply to bare skin (such as hands and head).

Actually, the CPR 16E does not state clearly whether the damage level of ‘lethal’ or ‘fatal’ is -for example- based on a person dressed normally, who has a limited percentage of bare skin (hands, head). If skin is protected by clothes, the heat radiation is not the only factor that determines the damage that will be caused. The skin temperature is also determined by the insulation provided by one's clothes, which is influenced by such matters as the thickness of the fabric, the number of layers of air between the different layers of clothing, and the degree to which the actual clothing ignites or burns.

In summary, two critical values are suggested for radiation, based on the effect after 100 seconds:

> *Unpleasant:* radiation flux = 2 kW/m^2 (half of the people escaping will incur first-degree burns)
> *Lethal:* radiation flux = 6 kW/m^2 (half of the people who try to escape will die).

Pursuant to the above information, the following threshold values have been established for this research:

> Unimpeded escape: 2 kW/m^2
> Lethal: 6 kW/m^2.

2.2.2 Visual hindrance due to smoke

As smoke in a room becomes ever more dense, the possibility for occupants to find their bearings becomes ever worse. If the smoke density reaches a certain level, people will no longer be able to recognise doors, walls etc. and they may even become disoriented in a familiar environment. Smoke density is an important factor that causes an impediment to the ability to escape. The speed of escape decreases further if the smoke contains irritants (Jin & Yamada, 1985).

Although the height of the smoke layer has been mapped as part of this research, the smoke density has not been measured. Therefore, visual hindrance by smoke is assessed visually in the analysis of the condition of a room, but it is not stated as a separate criterion.

2.2.3 Toxic fire gases

The most important toxic fire gases can be divided into two types: asphyxiating substances, i.e. those that cause suffocation, and irritating substances, i.e. irritants.

Asphyxiating substances
Asphyxiating substances are substances that do not damage the respiratory tracts or the lungs if inhaled. However, these substances are absorbed by the body, after which they exert their effects elsewhere in the body (Meulenbelt, De Vries & Joore, 1996). The most relevant asphyxiating substances in a fire are carbon monoxide and hydrogen cyanide. Both these substances interfere with the oxygen supply in the body. This in turn results in a depression of the central nervous system after which the person in question loses consciousness and eventually dies. The effect of asphyxiating substances is determined by the accumulated dose in the body (also see 2.2.4).

Irritants[9]
Irritants can be distinguished into different compounds, based on water solubility. The first group generally consists of substances that dissolve in water well or very well, such as hydrochloric acid and sulphur dioxide. These substances quickly react with the mucous membranes of people's eyes, nose, throat and respiratory tracts. Even at relatively low concentrations this will lead to teary eyes, throat problems, coughing and a burning sensation behind the sternum. These effects influence the possibility to escape and worsen the effects of the visual impediment by smoke, all dependent on the concentration to which people are exposed. The second type of irritants, such as NOx (nitrogen oxides) penetrates into the lungs more deeply, causing infectious reactions. They may also cause lung oedema. The effects deeper in the lungs mainly depend on the dose and they occur later (sometimes many hours later). As a result, these substances mainly affect people's health after they escaped or were saved from a burning premises. Inhaling soot and fine dust will also have health effects at a later date. A further complicating factor is that higher concentrations of water soluble substances, or such compounds that have been adsorbed to particles, can penetrate deeply into the lungs and cause serious effects.

It can be concluded that, during a fire, an occupant is exposed to several hazard aspects at the same time. Some of these aspects (heat, radiation, CO, NOx, lack of oxygen) were measured as part of the current research. Since there are no validated ways of determining the influence of these five aspects combined, the aspects are discussed separately and the results per aspect are likely to lead to an under-estimation of the combined effect of all the aspects.

2.2.4 Threshold values of substances that cause suffocation (carbon monoxide, hydrocyanic acid)

The Dutch poisoning information centre NVIC (Nationaal Vergiftigingen Informatie Centrum) has compiled[10] table 1.4, showing the relationships between symptoms and HbCO content (carbon monoxide in blood). Actually, this is only an indication of the potential severity of the exposure. The HbCO content levels greatly depend on the carbon monoxide dose to which people have been exposed.

[9] Also derived from: Gann, R.G., Averill, J.D., Butler, K.M., Jones, W.W., Mulholland, G.W., et al. (2001). *International Study of the Sublethal Effects of Fire Smoke on Survivability and Health (SEFS): Phase I Final Report.* Washington: NIST.
[10] See the website www.vergiftigingen.info (© 2006-2014 UMC Utrecht).

Table 2.4: Effect of HbCO contents in blood

HbCO(%)	Symptoms
0.3.-0.7	Normal range due to endogenous CO production, no known adverse effects
1-5	Decrease of O2 capacity of blood, usually compensated
10	No noticeable effects except dyspnoea upon heavy exertion, possibly tension headache in the forehead
15-20	Headache, ringing in the ear, potentially severe intoxication if pre-existing cardio-vascular defects
20	Dyspnoea with moderate effort, headache (pounding), lethargy, nausea
20-40	Severe headache, nausea, vomiting, dizziness
30	Headache, irritability, fatigue, affected judgement, possible dizziness, affected eyesight
30-40	Severe headache, palpitations, nausea, dizziness, loss of functional ability, syn-cope
40-50	Decrease of eyesight, feeling inclined to fall, retinal bleeding, headache, loss of functional ability, syncope, exertional weakness
50-60	Coma, convulsions
>60	Lethal
60-70	Loss of consciousness, convulsions, respiratory insufficiency, lethal
80	Quickly fatal

One should be aware that what is important in carbon monoxide poisoning is the dose that someone has inhaled and not purely the concentration to which the person in question has been exposed.

Although HCN (hydrogen cyanide) was not measured in the context of the research, the im-portance of HCN gas within the category of asphyxiating substances must not be ignored. Although HCN's working principle is different than that of carbon monoxide, their physiologi-cal effects are much alike. HCN is about 25 times as toxic as CO.

According to ISO 13571 (International Organization for Standardization, 2007) the *tenability limits* for asphyxiating substances can be determined as follows:

$$\mathrm{FED} = \sum_{t_1}^{t_\infty} \frac{\varphi_{\mathrm{CO}}}{35000} \upsilon_{\mathrm{CO}_2} \Delta t + \sum_{t_1}^{t_\infty} \frac{\exp\left(\varphi_{\mathrm{HCN}}/43\right)}{220} \upsilon_{\mathrm{CO}_2} \Delta t$$

Figure 2.1: Combination rule for determining a fractional effective dose (FED) for asphyxiat-ing substances (carbon monoxide and hydrogen cyanide)

The fractional effective dose (FED) takes both the presence of carbon monoxide and that of hydrogen cyanide into account. According to ISO 13571, FED=1 is the upper limit above which people with average sensitivity are no longer able to escape. When taking account of people with higher sensitivity (there is great sensitivity bandwidth), FED=0.3 is assumed as a safe threshold which allows people to escape safely in most cases. Since this research is based on adult occupants who are able to leave without assistance, FED=1 is assumed here. This means that the possibility to escape may no longer exist at an earlier stage (FED 0-0.3: 11.4 percent of the population) and the certainty that someone will die is never 100 percent.

The concentration of HCN often increases when the concentration of CO increases during a fire. Wang, Jia and Galea (2010) have argued that the concentrations of these two substances are directly proportional to each other. Since the influence of HCN is very important in fire situations, we have - based on Wang et al. (2010) - calculated the FED as part of this research by assuming the presence of HCN (per ppm CO 0.05 ppm HCN).

It has been found that establishing an exact threshold where mortality occurs is not easily possible. However, in the context of this research, being able to give a rough indication is highly desirable. In professional literature, it is often assumed that a CO concentration of 12,800 ppm (Struttmann, Scheerer, Prince & Goldstein, 1998) will cause people to die within three minutes. We therefore assume the following line of reasoning in order to, besides discussing the possibilities of escape, be able to give a conservative indication of the time/speed factor of when an occupant will die due to carbon monoxide poisoning:

> Carbon monoxide is never the only factor that a casualty is exposed to in a fire. Other factors include at least hydrocyanic acid, as well as other substances such as acrolein. The figure of 12,800 ppm is therefore rather optimistic: in a real-life situation people are more likely to die sooner because, the concentrations of hydrocyanic acid and acrolein also play a role in survivability next to the carbon monoxide concentration.
> There will always be differences in the severity of the effect that carbon monoxide (and other substances) have on the human body.
> A fire is not only characterised by a high concentration of carbon monoxide, but also by a low oxygen percentage which reinforces the harmful effects of carbon monoxide.

The following values and effects as regards survivability have been described in literature[11]:

> People die after one hour in a stable concentration of 1,600 ppm of carbon monoxide.
> People die after three minutes in a stable concentration of 12,800 ppm of carbon monoxide.

Furthermore, Struttmann et al. assert that there is no exact linear relation between survival time and the carbon monoxide concentration. Based on the above figures, we have assumed for this research that the value found of 12,800 ppm per thee minutes can be extrapolated indicatively for this research. It should be noted here that this is probably an optimistic estimate, as the effects of carbon monoxide are reinforced by the combination with oxygen shortage and heat (radiation):

> 12,800 ppm – a maximum survival time of three minutes;
> 6,400 ppm – a maximum survival time of six minutes (half the concentration of 12,800 ppm which can then, as an indication, be withstood doubly);
> 3,200 ppm – a maximum survival time of twelve minutes (one fourth of the concentration of 12,800 ppm which can then, as an indication, be withstood four times as long);
> 1,600 ppm – a maximum survival time of twenty-four minutes (one eighth of the concentration of 12,800 ppm which can then, as an indication, be withstood eight times as long).

[11] Struttmann, T., Scheerer, A., Prince, S. & Goldstein, L. (1998). Unintentional carbon monoxide poisoning from an unlikely source. *Journal of the American board of family practice*,11, 481-484.

2.2.5 Threshold values for oxygen

The following information was derived from the report entitled *De veiligheids- en gezondheidseffecten van werken in een besloten hypoxische omgeving* (Van Raaij & Schefferlie, 2006) on the health and safety effects of working in a confined hypoxic room.

The following symptoms occur when the percentage of oxygen decreases, with the severity increasing as the percentage of oxygen in the air decreases:

- Increased breathing frequency (and volume of breath)
- Increased heart frequency/heart output
- Affected night vision
- Light neurological symptoms (affected sight, reduction in visual
- discrimination, increase in reaction time, increase in errors during neurological tests)
- Headache
- Reducing capacity of physical performance
- Dizziness, nausea, hyperventilating
- Fatigue, sleep disturbance
- Exhaustion, loss of memory
- Unconsciousness, irregular respiration
- Respiration stops, heart failure, lethality.

Lippsett et al. (1994) show the levels of environmental hypoxia and health effects in table 2.5. The same figures are also presented by the Canadian Centre of Occupational Health and Safety (CCOHS). The CCOHS did not state any exposure times for this table.

Table 2.5: Percentage of oxygen and health effects

Oxygen %	Health effects
12-16	Respiration and heart frequency have increased. Muscle coordination has slightly decreased.
10-14	Abnormal fatigue, disturbed respiration occurs if exhausted, emotional reactions.
6-10	Nausea and vomiting, incapacity to move freely, possible unconsciousness.
< 6	Spasms, gasping for breath, respiration stops after some minutes and is then followed by heart failure.

According to Alarie (2002), spreading smoke in which the oxygen level is less than 7 percent will be a primary cause of incapacitation and death. However, such a low oxygen percentage does not occur if there is smoke with a very high temperature at the same time. This will cause the effect of oxygen shortage to occur simultaneously with the skin being burnt and systemic hyperthermia. This effect will occur extremely fast.

Based on the above table, combined with the presence of carbon monoxide and other substances, the threshold of 14 percent of oxygen is assumed as the percentage of oxygen where occupants are no longer able to escape without help due to abnormal fatigue and disorientation. This conservative threshold of 14 percent has been chosen on purpose, since there will then be both an oxygen shortage and a dose of carbon monoxide (and other harmful combustion substances). An oxygen percentage of 6 percent is considered to be lethal.

2.2.6 Threshold values for NOx (nitrous vapours)

In a similar way as the FED (for carbon monoxide and HCN) is determined with asphyxiating substances, the combined influence of irritants can be determined by calculating an FEC (fractional effective concentration). Here, a threshold value of 250 ppm of NOx is assumed as the value above which people with average sensitivity can no longer escape. However, NOx is only one of many irritants that together determine the FEC. Other important substances mentioned for determining the FEC in ISO 13751 are hydrogen chloride (HCl), hydrogen bromide (HBr), hydrogen fluoride (HF), sulphur dioxide (SO2), acrolein and formaldehyde.

The Dutch VRW (*Voorlichtingsrichtwaarde*, threshold at which the general public needs to be informed), AGW (*Alarmeringsgrenswaarde*, threshold for irritation) and LBW (*Levensbedreigende waarde*, neurotoxicity value) intervention values apply to an exposure time of one hour. The Committee on Acute Exposure Guidelines (AEGL) assumes the following threshold values for different exposure times. AEGL values can be compared to, but do not have to be equal to, the intervention values. In that sense, AEGL-1 matches the Dutch VRW, AEGL-2 the AGW and AEGL-3 the LBW for a part of the population that is sensitive to this. A level of 50 percent lethality among the population is only achieved at very high NOx values, but an NOx concentration from AEGL-3 without medical treatment does lead to a major risk of long-term damage to health or, for sensitive groups, even to people dying after some time.

Table 2.6: AEGL nitrogen oxides

AEGL nitrogen oxides						
	10 min.	30 min.	1 hour	4 hours	8 hours	End point
AEGL-1 (ppm)	0.50	0.50	0.50	0.50	0.50	Slight burning of the eyes, slight headache, chest tightness or laboured breathing with exercise in 7/13 asthmatics
AEGL-2 (ppm)	20	15	12	8.2	6.7	Burning sensation in nose and chest, cough, dyspnoea, sputum production in normal volunteers
AEGL-3 (ppm)	34	25	20	14	11	Marked irritation, histopathologic changes in lungs, fibrosis and oedema of cardiac tissue, necrosis in liver, no deaths in monkeys

2.2.7 In summary: threshold values used

The threshold values below are used in this research in order to make an estimate of the degree to which occupants can still escape and survive and/or run a major risk of long-term damage to their health. However, the following should explicitly be noted in this context:

- This estimate concerns healthy adults. Other age groups or people with greater sensitivity will experience an impediment to escaping sooner and will probably also die sooner. The threshold values stated concern 50 percent of the population; this means that the other 50 percent will undergo the effects sooner or later than the moment specified.
- This concerns a theoretical estimate based on individual factors; the combination of factors is difficult to qualify, but will have a, mostly negative, effect in practice.
- The threshold values of the individual factors have been derived from literature and extrapolation. Based on this, an estimate was made of the threshold values; it is possible that further research may lead to their being substantiated better or disproved in the future.

Furthermore, it should be noted that the extra chance to survive due to resuscitation has not been considered in this research.

Table 2.7: Thresholds adopted

Factor	Maximum possibility to escape for 50% of the population	Estimated possible survival time	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	T < 150 degrees Celsius at 180 cm height	T > 150 degrees Celsius at 180 cm height and T < 150 degrees Celsius at 50 cm height	T > 150 degrees Celsius at 50 cm height
Radiation heat	< 2 kW/m^2	Between 2 and 6 kW/m^2	>6 kW/m^2
Asphyxiating substances (CO and HCN)	until FED=1 (based on calculation)	FED=1 until threshold value 'no longer survivable'	➢ 12,800 ppm CO > 3 minutes ➢ 6,400 ppm CO > 6 minutes ➢ 3,200 ppm CO > 12 minutes ➢ 1,600 ppm CO > 24 minutes
NOx	Concentration up to AEGL-2	>AEGL-2 to threshold value of 'Limited chance of survival for 50% of the population or a major risk of long-term damage to health'	a value of >AEGL-3 after more than 10 minutes
Oxygen	21-14% oxygen	14-6% oxygen	<6% oxygen

3 Description, floor plan and interior fittings and fixtures of De Mars houses

3.1 General description

The fire tests were conducted in working class houses that were built on De Marsweg road in Zutphen in 1931. These houses were inhabited until recently. Since all houses were built to the same floorplan, the differences between individual houses are minor. However, the floor-plans of adjacent houses are mirrored.

Every house has wooden floors and a set of stairs. The houses have been renovated to a limited extent over time. This includes double glazing having been installed at ground floor level (ventilation grilles are present here as well) and the ceilings being finished with plaster-board. This has resulted in a higher insulation value and has reduced the risk of fire spread-ing to the first floor. The interior and exterior doors can be closed to fit properly, but some cracks remain. Furthermore, the houses are traditional brickwork structures and have tiled roofs. The front walls of all the houses face west.

In order to be able to compare end-of-terrace houses to regular terraced houses, the side windows of the end-of-terrace houses were lined with Promat[12] (fire-resistant material) to create a closed wall.


Figures 3.1 and 3.2: Front and rear of a house on De Marsweg

[12] Promatect-H 15 mm

3.2 Floorplan of the houses

For an exact English translation of Dutch terms used in the floor plans, we refer to the appendix 'translation'.

3.2.1 Ground floor

The ground floor of the houses that were used for the fire tests consists of a hallway, toilet, living room, kitchen and a bathroom that can be entered from the kitchen.

As the research assumed an open connection between the kitchen and the living room, the door between the living room and the kitchen was kept open in all the fire tests.

The ground floor windows have double glazing, save for some small windows. Ventilation grilles are present.

It was found that some houses had been refurbished, resulting in a somewhat different floor plan. For example, the door to the living room had been moved to the left-hand side wall of the hallway.

The floor of the ground floor was made of joists with wooden floorboards. To achieve the same initial fire load situation in all the houses, all the laminate flooring and carpets were removed. All houses had a basement that could be accessed from the hallway (entrance under the stairs). Furthermore, the houses had a crawl space. In some cases, this crawl space had been excavated to make it so deep that people could stand up straight in it. It could be accessed through a hatch in the floor in the living room.

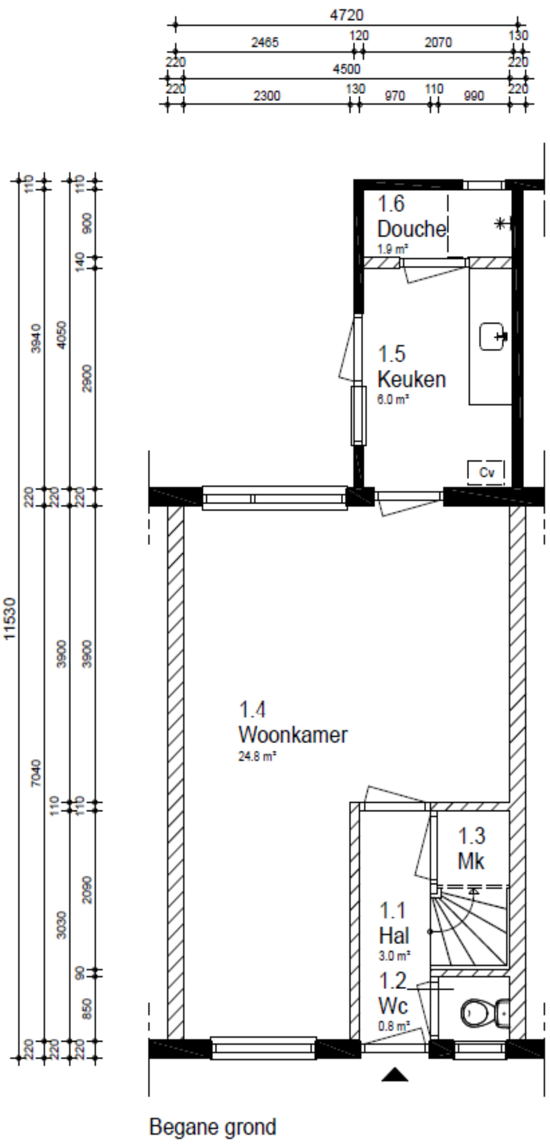
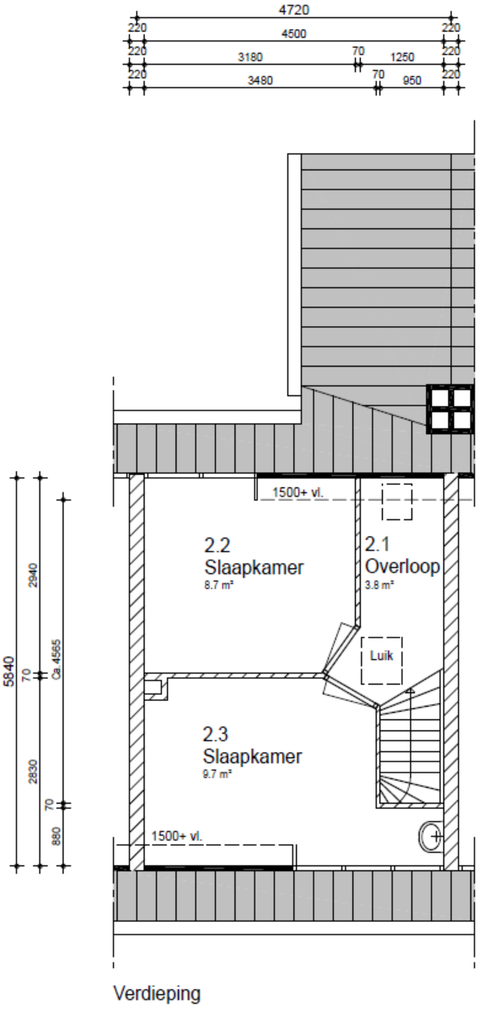


Figure 3.3: Ground floor floorplan

The ceilings of all ground floor rooms had been plastered.

Although the houses on De Mars were built with the kitchen in a separate room, the fire tests assumed an open kitchen. This was achieved by permanently opening the door between the living room and the kitchen.

3.2.2 First floor



The first floor of the houses on De Mars is divided into three rooms: two bedrooms and a landing. The trapdoor to the attic is also located in the landing ceiling. There are no stairs or any similar facilities for this. The first floor ceilings have been finished with plaster.

Virtually all the bedrooms have a dormer window that extends as far as the adjoining house. The baby room (room 2.2 in the floorplan) of scenario 6 has a Velux window instead of a dormer window.

Some bedrooms had wooden wall cabinets built in; to achieve the same initial situation these wooden cabinets were removed. The floor of the first floor is made of timber joists with wooden floorboards.
As was the case for the ground floor, any laminate flooring and carpets on the first floor were also removed.

The rooms on the first floor have single glazing, except for the Velux window on the landing.

Figure 3.4: First floor floorplan

3.2.3 Attic

The attic was a closed attic. The roof framework was timber. To protect the roof framework during the burns, two fognails were installed here in advance to enable a possible fire to be fought quickly and without any risk.

3.3 Interior fittings and fixtures

To simulate the real-life situation as well as possible, the homes had been fitted out with furniture that was customary in the Netherlands in 2014. This furniture had been bought from three different major furniture chain stores, focussing on the ‘cheap’ price segment, bearing in mind the financial situation of a young family. For an exact English translation of Dutch terms used in the floor plans, we refer to the appendix ‘translation’.

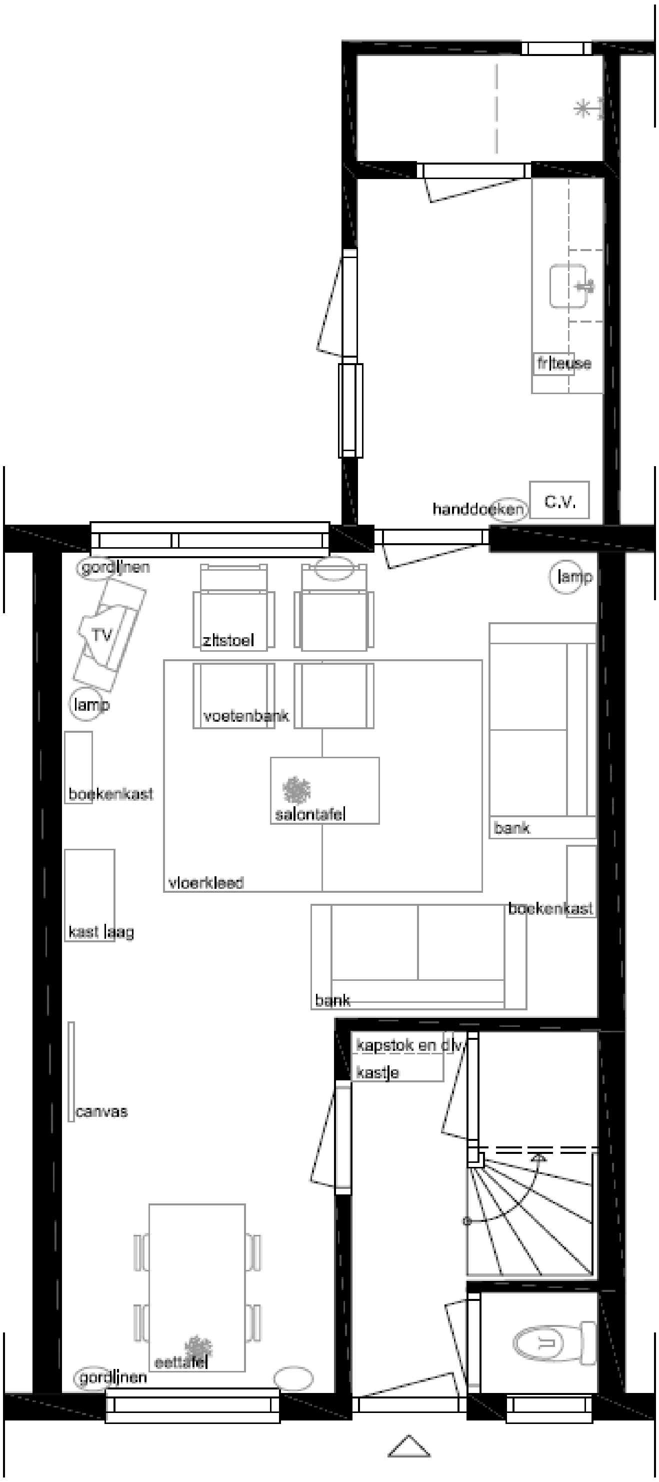


Figure 3.5: Ground floor interior

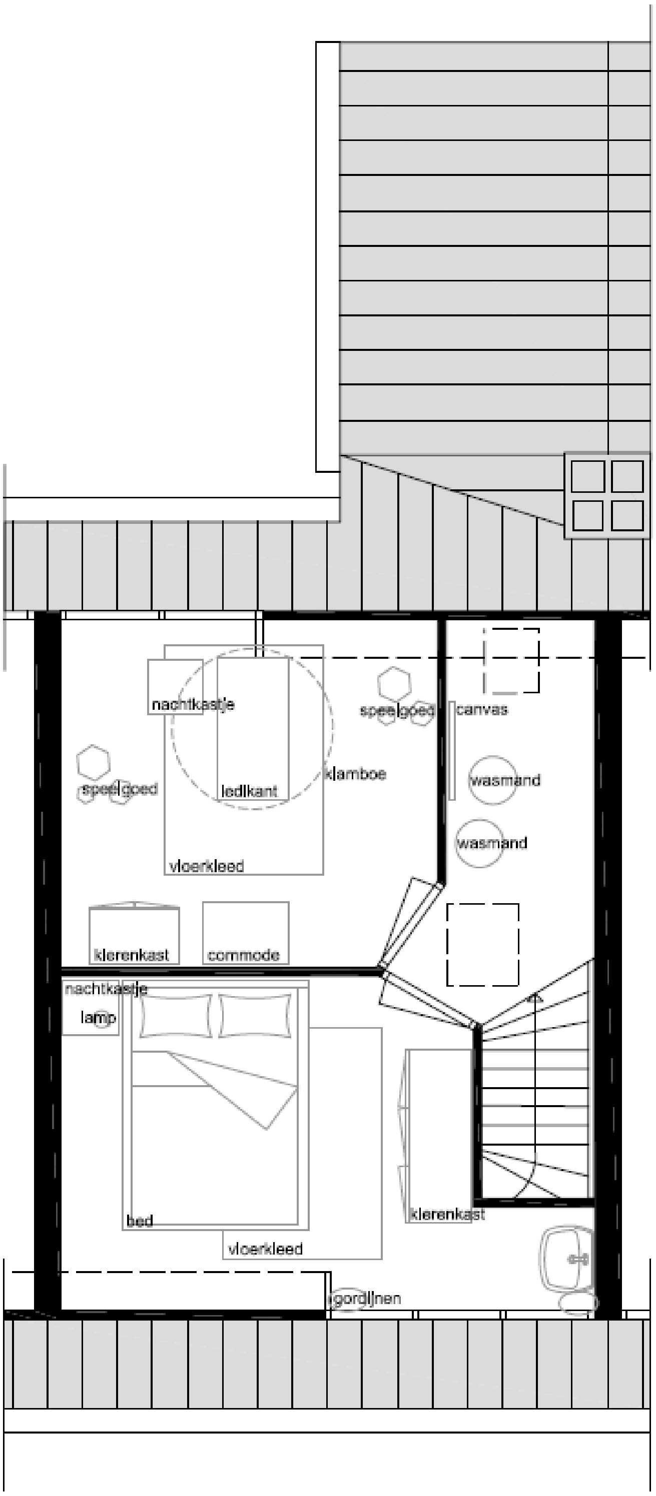


Figure 3.6: First floor interior

3.4 Remarks

The basic idea was that the realistic situation should be simulated as far as possible in the fire tests. However, the following should be noted in advance in this context as regards opting for the houses in De Mars and their interiors for the fire tests:

- The houses were homes that were about to be demolished and that had not been lived in, nor heated, all the time until the day of the fire tests. The relative humidity in these houses was higher than that in 'home with occupants'. However the interior fittings and fixtures had been stored in semi-heated storage.
- All floor coverings and/or laminate floors were removed to create the same initial fire load situation in all the houses. This made the fire load in all these houses identical, but this also resulted in it becoming lower than is customary in a home. To partly compensate for this, carpets were laid down in all the residential rooms.
- The interior fittings and fixtures were determined based on the financial perspective of a young family. This implies that no large and/or expensive items of furniture were put in. It was found in retrospect that this resulted in a relatively low fire load. However, it must be noted that these interior fittings and fixtures do actually occur in lots of Dutch homes.
- The buildings were working class houses from the 1930s with their typical small rooms.
- As regards ventilation, the houses were relatively open, particularly on the first floor.

4 Measuring protocol

4.1 Measurements in every room

Table 4.1: Variables and measurement methods that were applied during the fire tests

Variable	Measurement method	Specifics
Temperature	Thermocouples	Via laptop. Five measurements every second.
CO	CO cell	Via laptop. One measurement every three seconds.
O2	O2 cell	Via laptop. One measurement every three seconds.
NOx	NOx cell	Via laptop. One measurement every three seconds.
Radiation	Radiation meter	Via laptop. Five measurements every second.

Besides the measurement methods shown in the table above, video images were analysed afterwards as a visual observation of the situation in every room during the fire test.

To be able to measure the variables identified, all the rooms in the houses, except the toilet, bathroom and basement, were fitted out with measuring equipment. An open connection between the living room and the kitchen was assumed. Every room was fitted with thermocouples at 180 cm and 50 cm height, a combined gas analysis device for CO/O2 and NOx, a radiation meter and a heat-resistant video camera. During the test week there was one measurement point per room, except for the living room where the temperature was measured at two points, due to the size and the geometry of the room. The following sections will give a more detailed description of how the measuring equipment was used.

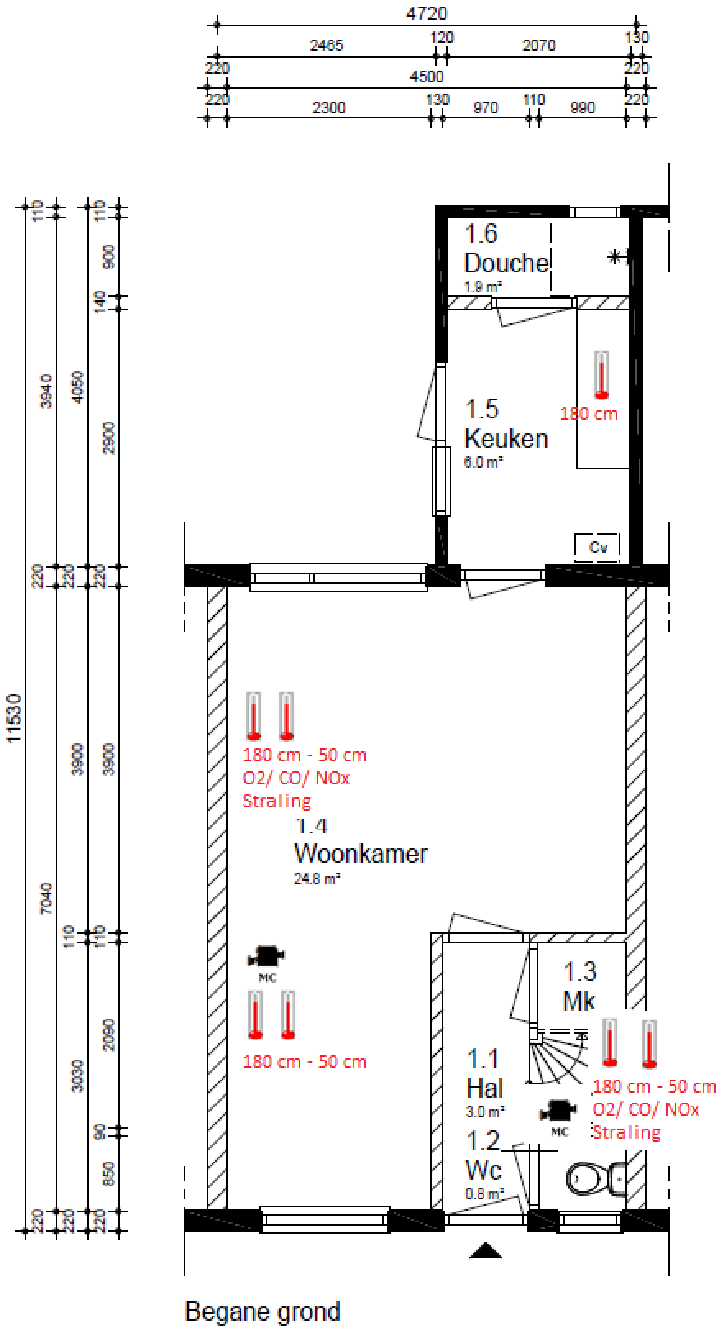


Figure 4.1: Location of measuring equipment on the ground floor

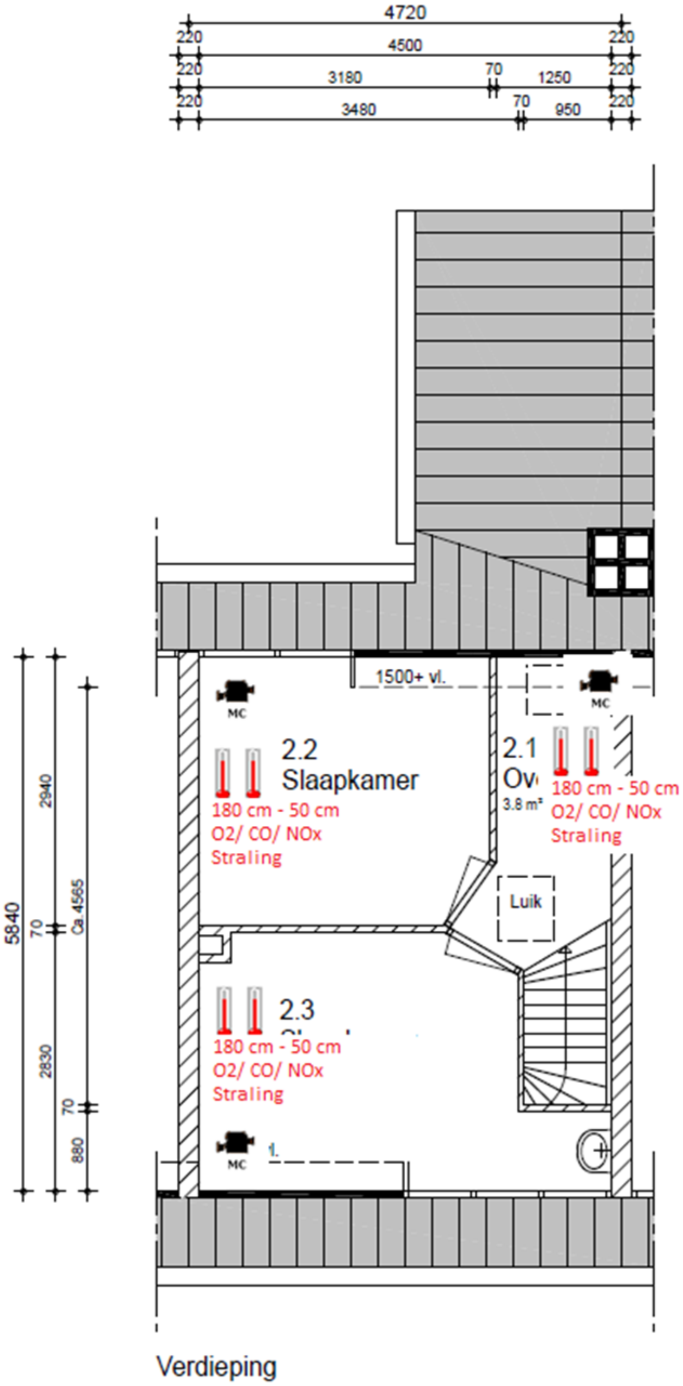


Figure 4.2: Location of measuring equipment on the first floor

4.2 Safety versus effectiveness of measurements

Prior to the fire tests, it had been envisaged that the fire tests might be destructive for the houses and might jeopardise their structural integrity. The measuring equipment was therefore placed in the test houses via holes in the side walls from the ‘neighbours’. This allowed the measuring equipment to be protected from heat so that it could always be retrieved safely after the fire test. However, this also meant that measurements took place along the side walls of the rooms in the test premises, whereas measuring in the centre of the room would have been logical from a measurement perspective. Therefore, a deliberate choice was made to make a concession, be it limited, to the accuracy of measurements in favour of safety during the fire tests.

4.3 Temperature

The temperature development in all rooms was recorded using thermocouples during all fire tests. As the thermocouple heights were determined based on the need to obtain relevant values as regards survivability, a height of 180 cm (the height at which an upright escaping person breathes) and a height of 50 cm (the height at which a crawling person who is trying to escape and/or an unconscious casualty breathes) were chosen. Higher temperatures would probably be achieved at ceiling level, but this was considered as less relevant for this research. The thermocouples measured the current temperature five times per second. The results of the thermocouples were automatically recorded on a laptop computer.

One set of two thermocouples, placed at heights of 180 cm and 50 cm, was installed in the small rooms (hallway, landing, master bedroom and baby room). Although it is known that temperature build-up does not occur evenly throughout the room, it was assumed that placing thermocouples in all rooms would enable the temperature build-up to be described sufficiently well.

Two sets of thermocouples at heights of 180 and 50 cm were installed in the living room. This decision was made because the living room is a larger room and because a division had been made in the room layout: the corner near the kitchen had been furnished as a seating area; the front of the living room had been furnished as a dining area.

4.4 Radiation heat

The radiation was measured at one point in all the five rooms (living room, hallway, landing, master bedroom and baby room) of the houses. To do this, a radiation sensor was stuck through the walls from the neighbouring house, at a 45-degree angle to the ceiling. This enabled both direct heat radiation of burning objects and heat radiation from the smoke layer to be detected. The sensor was placed at a height of 50 cm since this is the ‘casualty height’ as stated above. The results measured by the radiation sensors were automatically recorded on a laptop computer.

4.5 Carbon monoxide/oxygen/NOx

Carbon monoxide, oxygen and nitrogen dioxide (NOx) were measured by placing the sensors of a smoke gas analysis device at a height of 50 cm (‘casualty height’) in all rooms. This gas analysis was carried out every three seconds for each of the three measuring cells. Again, the gas analysis results were automatically recorded on a laptop computer.

4.6 Smoke layer

The height of the smoke layer was measured by placing some LED lights on a vertical line opposite every camera. This enabled the smoke layer and the height in the room to be correlated. Furthermore, the light intensities of the LED lamps as registered gave an indication of the density and colour of the smoke in the room in question.

4.7 Start of measurements and end of measurements

The measurements were started at the moment when the fire was lit by means of a tealight candle. Bearing in mind the objective of the research, the test protocol involved that, once started, the fire could develop freely until:

> One hour (60 minutes) after the fire started.

> The fire had grown to such an extent that an adjoining fire compartment was threatened. The roof framework was a critical aspect in this regard.

There were three moments during the test week where it was decided to make changes to the test protocol during a fire test. This is described in the relevant chapters.

4.8 Fire service intervention

The action by the fire service during the measurements was restricted to preventing fire spread and protecting the roof framework. This was done by keeping the jeopardised protruding elements on the outside of the house, such as gutters, overhangs, etc. wet. This limited intervention enabled the test *in* the house to be carried out unimpeded; if this intervention had not occurred and the fire had been allowed to develop freely outside the test house, it would have been necessary to abort the fire tests at an earlier stage.

4.9 Elaboration of six fire tests

The fire tests were set up such that as many of the options of subsequent comparison as possible were integrated. This setup was also chosen because these fire tests were also used for parallel research into the effectiveness of smoke detectors. Among other things, this meant that it should be able to compare the situations of a fire in a living room and a fire in a bedroom with interior doors open and closed. Furthermore, the test of the fire in the living room was deliberately carried out with the fire being started in two locations so that the effect of the fire development on these two locations could be compared. The following six fire tests were carried out for this research:

Table 4.2: Setup of the six fire tests

Burn	Location of start of fire	Object on which the fire started	Hallway door	Bedroom doors	Ventilation
1	Bedroom	Bed	Closed	Both closed	Everything closed, only bed-room window ajar
2	Kitchen	Deep fat fryer	Closed	1 open/ 1 closed	Everything closed, kitchen door open half-way
3	Living room	Sofa	Open	1 open/ 1 closed	Everything closed, only bed-room window ajar
4	Living room	Sofa	Closed	1 open/ 1 closed	Everything closed, only bed-room window ajar
5	Living room	TV	Open	1 open/ 1 closed	Front door open
6	Bedroom	Bed	Closed	Both open	Exterior doors closed, both bed-room windows ajar

The results of all the measurements can be found in the annexes and they have been incorporated in the chapters 5 to 10 in aggregated form.

5 Test 1: Bedroom fire with the inner doors closed

5.1 Start situation

5.1.1 Scenario and source of the fire

This scenario concerns a home inhabited by a family consisting of a young couple and their baby. The parents are sleeping in the master bedroom at the front, the baby is sleeping in the bedroom at the back. Both bedroom doors are closed. The window in the master bedroom is ajar. A defect in the electric blanket in the master bedroom starts a fire in the night, while everyone is asleep. There are no active smoke detectors.

5.1.2 Configuration of doors and ventilation

Both bedroom doors are closed. The window in the master bedroom is ajar as the parents prefer some fresh air coming into their bedroom.

5.1.3 Meteorological conditions and timing

During the fire test, there was a WSW wind of 6 m/s, a temperature of 15.5 °C and relative humidity of 79 percent.
The bed was set on fire at t=0. The fire raged for a full hour, before the safety crew intervened. The fire was found to have been virtually extinguished then.

5.2 Master bedroom (seat of the fire)

The fire in the master bedroom grew fast. An occupant might still have escaped in the first three minutes after the fire started and the escape route was then still clear. The situation became non-survivable four minutes and 21 seconds after the fire started. What is remarkable is that the circumstances in the room also improved again.

The fire in the master bedroom did not develop fully (no flashover). After a rapid rise in temperature up to 287.2 °C, it also dropped fast again. The remaining oxygen percentage was 20 percent at the peak moment of the temperature, which at first sight might seem to indicate that oxygen is not the limiting factor in the fire growth. After the peak moment, the oxygen percentage quickly dropped to 13.2 percent. The oxygen concentration was measured at a height of 50 cm, whereas the major combustion of oxygen occurred at a greater height. Furthermore, there was still plenty of fuel present at the peak moment. The above reasons led to the conclusion that the fire was tempered by a shortage of oxygen and became a smouldering fire until most of the mattress and the duvet had smouldered away. The energy available during the burning process was insufficient to set other objects in the master bedroom on fire. The fire development found can be explained quite easily: the flame stage of combustion is not possible if the oxygen percentage is 13 percent. Since the flame stage no longer occurs, the temperature and radiation will decrease.

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	3 min. 36 sec.	4 min. 21 sec.
Radiation heat	3 min. 49 sec.	End of test
CO and HCN	6 min. 39 sec.	12 min. 39 sec.
NOx	3 min. 27 sec.	13 min. 33 sec.
O2	6 min. 42 sec.	End of test

5.3 Landing

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	End of test	End of test
Radiation heat	End of test	End of test
CO and HCN	29 min. 45 sec.	53 min. 45 sec.
NOx	End of test	End of test
O2	6 min. 42 sec.	End of test

5.4 Baby room

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	End of test	End of test
Radiation heat	End of test	End of test
CO and HCN	39 min. 6 sec.	End of test
NOx	End of test	End of test
O2	End of test	End of test

5.5 Hallway

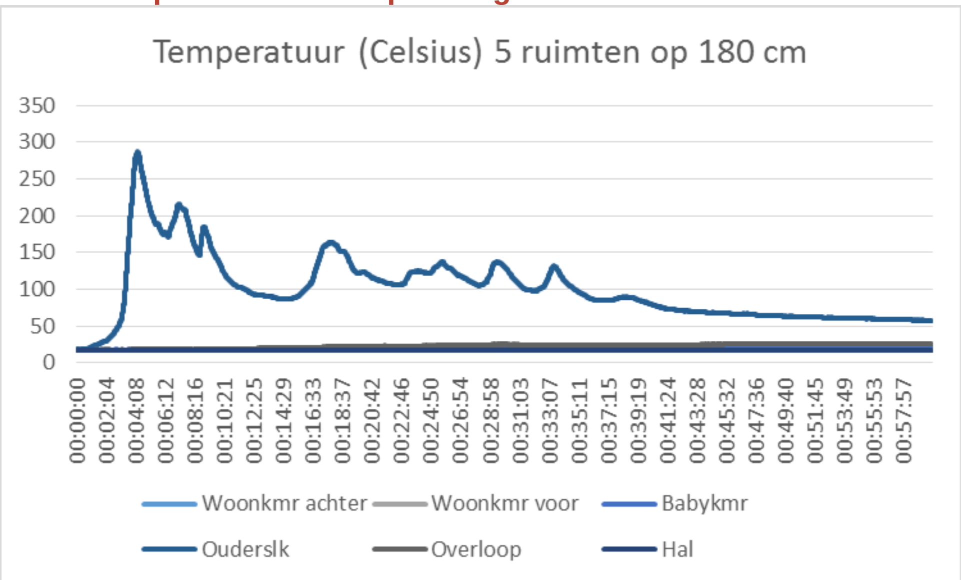
Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	End of test	End of test
Radiation heat	End of test	End of test
CO and HCN	End of test	End of test
NOx	End of test	End of test
O2	End of test	End of test

5.6 Living room

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	End of test	End of test
Radiation heat	End of test	End of test
CO and HCN	End of test	End of test
NOx	End of test	End of test
O2	End of test	End of test

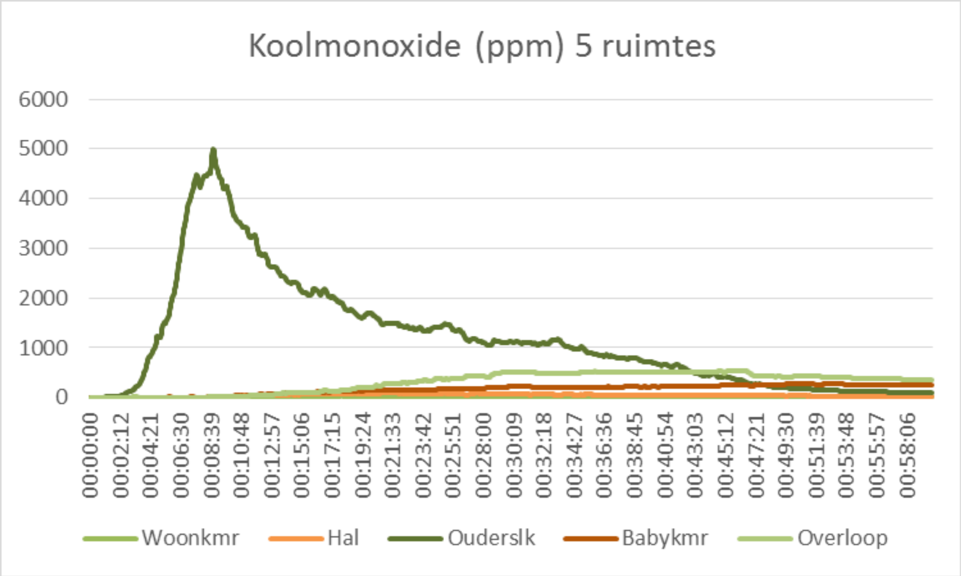
5.7 Analysis of test 1

5.7.1 Temperature build-up throughout the home



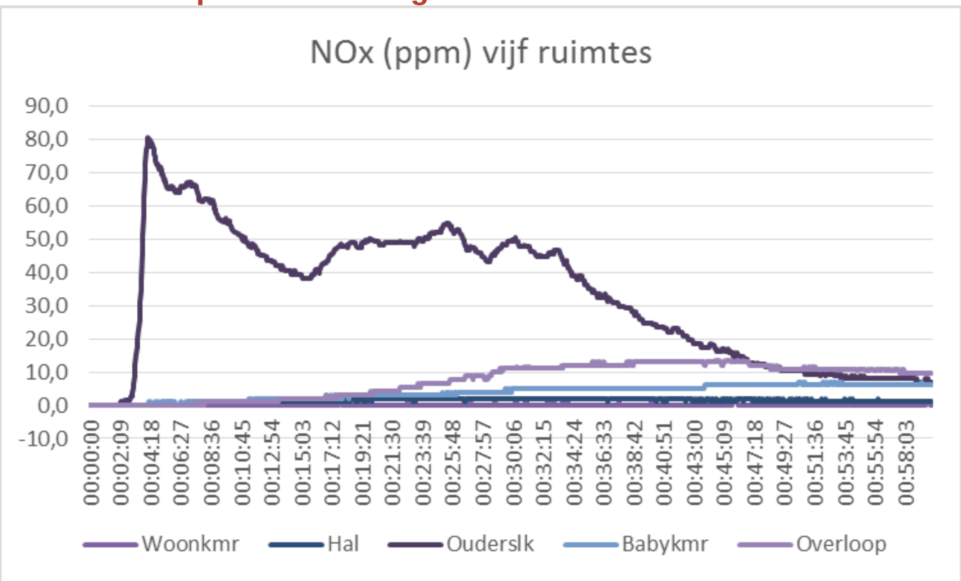
In the first fire test, a major difference could be noticed between the build-up of the temperature in the master bedroom (room on fire) and the other rooms in the home. While the temperature in the master bedroom had considerably exceeded a life-threatening value, the temperature in the other rooms had barely increased. The room on fire was separated from the other rooms by the floor of the first floor (living room) and by doors (landing, baby room, hallway).

5.7.2 Build-up of carbon monoxide throughout the home



There was a major difference in the build-up of carbon monoxide between the room on fire and the other rooms in the house. A difference in carbon monoxide was also measured between the first room behind a closed door (the landing) and the second room behind a second closed door (baby room). The concentration of carbon monoxide stayed well below the value where escape would be impeded in both these rooms, but the lowest concentration measured was clearly in the baby room. This seems to indicate that one door offers a protective effect against carbon monoxide building up, but that the protective action of two closed doors is better.

5.7.3 Build-up of NOx throughout the home



As was the case for the build-up of carbon monoxide, there was also a significant difference between the build-up of NOx in the room on fire and the other rooms in the house. A difference in NOx was also measured between the first room behind a closed door (the landing) and the second room behind a second closed door (baby room). The concentration of NOx stayed well below the value where escape would be impeded in both these rooms, but the lowest concentration measured was clearly in the baby room. This seems to indicate that, just like in the case of carbon monoxide, one door offers a protective effect against NOx building up, but that the protective action of two closed doors is better.

5.7.4 All in all, test 1

The fire in the master bedroom grew quickly. An occupant would still be able to escape during the first three minutes after the fire started but the situation became non-survivable four minutes after the fire started. What is remarkable is that the circumstances in the room also improved again.

The fire in the master bedroom did not develop fully (no flashover). After a rapid rise in temperature up to 287.2 °C, it dropped again quickly. The remaining oxygen percentage was 20% at the peak moment of the temperature, which at first sight might seem to indicate that oxygen is not the limiting factor. But the oxygen percentage decreased rapidly to 13.2 percent after the peak moment and the oxygen concentration was measured at a height of 50 cm, whereas most oxygen burns at a greater height. Furthermore, there was still plenty of fuel present at the peak moment. It is therefore concluded that this fire was tempered by a shortage of oxygen and became a smouldering fire until most of the mattress and the duvet had smouldered away. The energy available during the burning process was insufficient to set other objects in the master bedroom on fire. The fire development found is easy to explain: the flame stage of combustion is not possible if the oxygen percentage is 13 percent.

Room(s)	Internal door	Ventilation	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Master bedroom (room on fire)	Closed	Window ajar	3 min. 36 sec. (temp)	4 min. 21 sec. (temp)
Landing	N/a	None	29 min. 45 sec. (CO)	53 min. 45 sec.
Baby room	Closed	None	39 min. 6 sec. (CO)	End of test
Hallway	Closed	None	End of test	End of test
Living room	Closed	None	End of test	End of test

Room	Route	Room + escape route clear until:
Master bedroom	Landing, hallway	3 min. 36 sec.
Baby room	Landing, hallway	29 min. 45 sec.
Landing	Hallway	29 min. 45 sec.
Living room	Hallway (with an extra exit through the kitchen)	End of test

It can be concluded that test 1 showed a major difference in survivability between the room on fire and other rooms in the home. This difference between life and death was due to a closed door and possibly also due to the floor of the first floor that separated the room on fire from the adjoining rooms.

6 Test 2: Kitchen fire with the internal doors closed

6.1 Start situation

6.1.1 Scenario and source of the fire

This scenario concerns a home inhabited by a family with two children, one of whom is a young baby. It is late afternoon and only the father and the baby are there. The baby is sleeping in the baby room at the back of the house. The door to the baby room is closed. The deep fat fryer in the kitchen is on, unsupervised. The deep fat fryer catches fire and the smoke detector kicks in. An attempt to put out the fire by covering the deep fat fryer with a lid fails and the father escapes from the home through the kitchen door. The kitchen door is left halfway open. The door to the hallway is closed, as is the door of the master bedroom at the front.

6.1.2 Configuration of doors and ventilation

After the father has escaped from the building, the (outside) kitchen door is halfway open. However, he *did* close the door to the hallway on his way down. The door to the master bedroom is open. The door to the baby room is closed.

6.1.3 Meteorological conditions and timing

During the fire test, there was a SSW wind of 8 m/s, a temperature of 11.8 °C and relative humidity of 95%. The deep fat fryer caught fire at t=0/ 10.24.50 hours. At the start of the test, the kitchen door was fully open due to miscommunication among the research staff. At t=11 min. 57 sec., the kitchen door was half closed as this was the initial situation planned in this scenario.
At t=47 min. 42 sec., the fire threatened to spread to the roof of the home and the safety crew therefore started to extinguish the fire. This means that an unimpeded free fire development of almost 48 minutes occurred. If the safety crew had not started putting out the fire, it would have spread to the roof of the home.

6.2 Kitchen (seat of the fire)

In the kitchen there was a fuel-controlled fire until the kitchen door was closed halfway: there was a free supply of oxygen. From the moment when the kitchen door was closed halfway, the fire developed into a ventilation-controlled fire.

Since, for the purpose of this research, the kitchen was considered to be an open kitchen connected to the living room, only one measuring point (temperature) had been applied. The only possibility to visualise the survivability in the kitchen was by means of the thermocouple that had been installed in the kitchen at a height of 180 cm. To prevent a too optimistic situation from being sketched, the temperature at a height of 180 cm is assumed as the critical threshold for a limited chance to survive for 50 percent of the population or a major risk of long-term damage to health.

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	5 min. 41 sec.	5 min. 41 sec.
Radiation heat	Not measured	Not measured
CO and HCN	Not measured	Not measured
NOx	Not measured	Not measured
O2	Not measured	Not measured

This means that very little is known as regards the kitchen: it is possible that the factors of radiation, carbon monoxide, NOx and oxygen content affected the possibility to escape or survivability at an earlier stage. Furthermore, the temperature was measured only at a height of 180 cm and not at a height of 50 cm (i.e. casualty height).

6.3 Living room

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	16 min. 9 sec.	43 min. 45 sec.
Radiation heat	40 min. 24 sec.	43 min. 40 sec.
CO and HCN	12 min. 42 sec.	18 min. 42 sec.
NOx	12 min. 48 sec.	22 min. 48 sec.
O2	15 min. 45 sec.	44 min

6.4 Hallway

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	End of test	End of test
Radiation heat	End of test	End of test
CO and HCN	20 min. 45 sec.	44 min. 45 sec.
NOx	End of test	End of test
O2	End of test	End of test

6.5 Landing

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	End of test	End of test
Radiation heat	End of test	End of test
CO and HCN	21 min. 9 sec.	45 min. 9 sec.
NOx	End of test	End of test
O2	End of test	End of test

6.6 Master bedroom

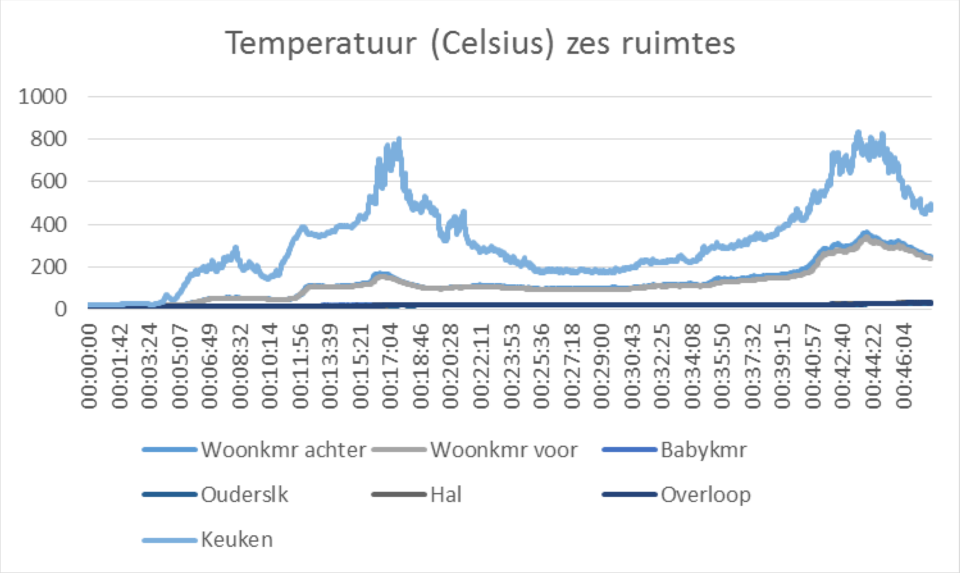
Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	End of test	End of test
Radiation heat	End of test	End of test
CO and HCN	21 min. 9 sec.	45 min. 9 sec.
NOx	End of test	End of test
O2	End of test	End of test

6.7 Baby room

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	End of test	End of test
Radiation heat	End of test	End of test
CO and HCN	21 min. 27 sec.	45 min. 27 sec.
NOx	End of test	End of test
O2	End of test	End of test

6.8 Summary and analysis of test 2

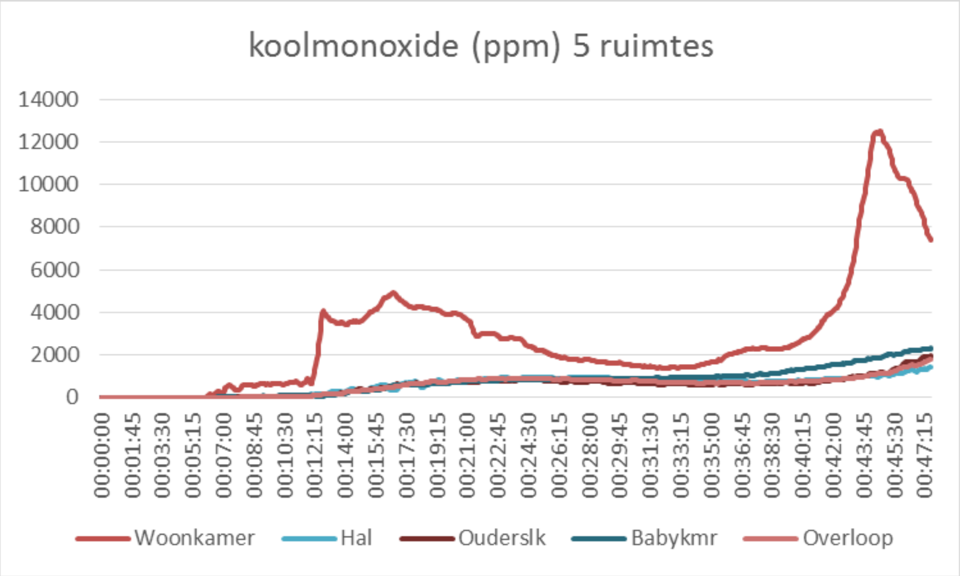
6.8.1 Temperature build-up throughout the home



The temperature build-up seems to have occurred in three zones:

> The actual room on fire (with temperatures rising to 800 °C).
> The adjoining (open) room: the living room (with temperatures rising to almost 400 °C).
> All the other rooms in the home that were separated from the living room and the kitchen (where the temperatures increased to just above 30 °C) by the hallway door and/or the floor of the first floor.

6.8.2 Build-up of carbon monoxide throughout the home

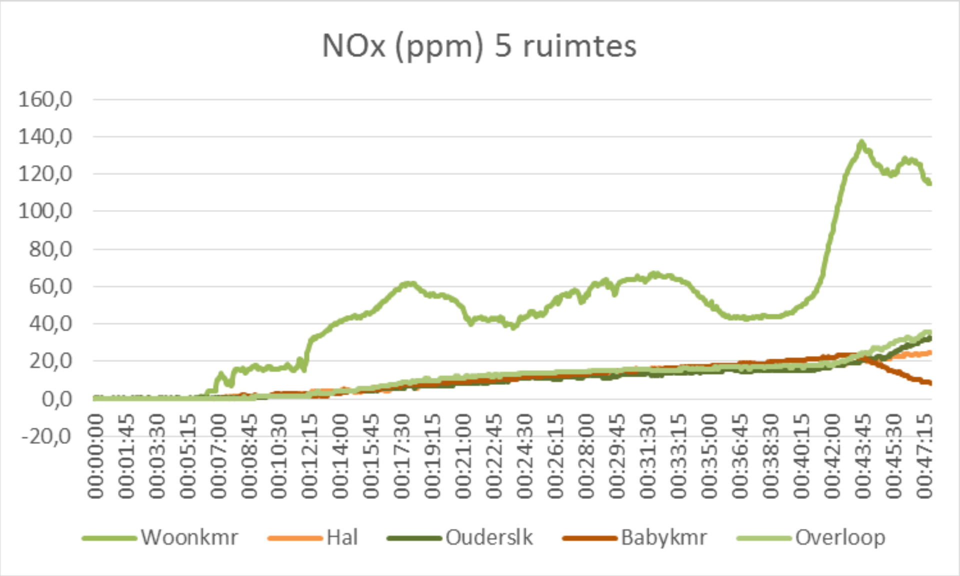


Carbon monoxide seems to have built up in two zones:

> Adjoining (open) room: the living room.
> All the other rooms in the home that were separated from the living room and the kitchen by the hallway door and/or the floor of the first floor and where carbon monoxide was built up almost perfectly evenly, at least during the first half hour.

No carbon monoxide measurements were conducted in the actual room on fire (kitchen).

6.8.3 Build-up of NOx throughout the home



NOx seems to have built up in two zones:

> Adjoining (open) room: the living room.
> All the other rooms in the home that were separated from the living room and the kitchen by the hallway door and/or the floor of the first floor and where NOx was built up almost perfectly evenly, at least during the first half hour.

No NOx measurements were conducted in the actual room on fire (kitchen).

6.8.4 All in all, test 2

A major similarity was found between the values for carbon monoxide and NOx on the landing, in the hallway, and in the two bedrooms. This means that the build-up of e.g. carbon monoxide in the hallway largely took place simultaneously with the build-up of carbon monoxide in the master bedroom, and the building up of carbon monoxide took place quite synchronously with the building up of NOx. This is also logical since both substances, and other combustion gases, were moving through the home. In this respect a ‘hard separation’ (door/floor of the first floor) is a barrier that the smoke needs some time to penetrate.

A major difference was found between the fire conditions when the kitchen door was open compared to the conditions when the kitchen door was closed halfway. From the moment when the kitchen door was closed halfway, a considerable temperature build-up occurred, together with harmful combustion gases building up in the rest of the home.

Test two seemed to show that the degree to which temperature and harmful combustion gases can build up to harmful or even lethal concentrations depends on:

> Ventilation (closing the kitchen door halfway was immediately followed by an increase in temperature and build-up of combustion gases).
> The degree of ‘hard’ separation between a casualty and the seat of the fire: the ambient conditions behind a door and/or when separated by a floor are many times better than in the actual room on fire. This was found to be true even in an old house with wooden floors and doors that do not fully close.

A build-up of temperature and harmful combustion gases was observed in three zones:

> The actual room on fire.
> Adjoining open room.

> All the other rooms in the home that were separated from the room on fire by a door and/or the floor of the first floor.

This test did not enable the degree to which a separation by two doors and/or floors forms an even better barrier to be established.

Due to the relevance of NOx, further research into other combustion gases as part of future experiments (HCN/HCL) should be carried out.

It was remarkable that the smoke spread partly through the (wooden) floor: survivability is expected to be better in modern homes with higher fire and, particularly, smoke resistance.

Room(s)	Internal door	Ventilation	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Kitchen (room on fire)	Open	Door fully or halfway open	5 min. 41 sec. (temp)	5 min. 41 sec. (temp)
Living room	Closed	None	12 min. 42 sec. (CO)	18 min. 42 sec.
Hallway	Closed	None	20 min. 45 sec. (CO)	44 min. 45 sec. (CO)
Landing	N/a	None	21 min. 9 sec. (CO)	45 min. 9 sec. (CO)
Master bedroom	Open	Window ajar	21 min. 9 sec. (CO)	45 min. 9 sec. (CO)
Baby room	Closed	None	21 min. 27 sec. (CO)	45 min. 27 sec. (CO)

Room	Route	Room + escape route free until:
Master bedroom	Landing, hallway	20 min. 45 sec.
Baby room	Landing, hallway	20 min. 45 sec.
Landing	Hallway	20 min. 45 sec.
Living room	Hallway (with an extra exit through the kitchen)	12 min. 42 sec.

7 Test 3: Living room fire with the hallway door open

7.1 Start situation

7.1.1 Scenario and source of the fire

This scenario concerns a home inhabited by a family consisting of a young couple and their baby. The parents are sleeping in the master bedroom at the front, the baby is sleeping in the bedroom at the back. The door to the master bedroom is open, the door of the baby's room is closed. Fire breaks out during the night in the sofa in the living room while everyone is asleep. The door between the living room and the hallway is open, enabling the smoke to rise up quickly to the first floor. There are no active smoke detectors in the home. All the external doors and windows are closed, only the window of the master bedroom is ajar.

7.1.2 Configuration of doors and ventilation

In view of a recent series of burglaries, all the external doors and windows on the ground floor are closed. The door from the living room to the hallway is open. The door to the baby room is closed. The door of the master bedroom is opened and the parents have the bedroom window ajar while sleeping.

7.1.3 Meteorological conditions and timing

There was a westerly wind of 6 m/s during this fire test. The temperature was 11.9 °C and the relative humidity was 89 percent.
The fire was lit at 14.38 hours; this time was defined as t=0 for the fire development. At t=61 minutes, it was decided to stop the test and the safety crew was deployed.

During the test, it was found at about t=22 min. that the delivery of the measuring equipment for CO/O2 and NOx in the master bedroom was too low and that this negatively affected the accuracy of the measurements. Actually, this error message did not cause the measurements to be stopped at that point.

7.2 Living room

After the fire was lit in the sofa, the temperature in the living room rose quickly: in the first two minutes of the test, the temperature at a height of 180 cm rose by 10 °C. In the following three minutes (t=2/ 5), the temperature at a height of 180 cm rose to 449 °C. At the temperature peak moment (t=5 min. 14 sec./ 449 °C), the available oxygen volume was 18.18 percent after which it decreased further fast. This low oxygen percentage seems to be the reason why the fire in the living room died out and did not develop into a flashover. At t=27 min., the temperature increased substantially to approx. 250 °C. The exact cause of this could not be established; no changes were made to doors open/closed. However, it was noted afterwards that the floor in the living room under the sofa had burnt through, making new oxygen available. This seems to be the only plausible reason why the fire flared up a bit again from t=27 min.

The major difference in temperature in the living room at the heights of 180 cm and 50 cm is remarkable: where the peak temperature for the height of 180 was 449 °C at t=5, the value at the height of 50 cm was only 100 °C at t=6. The critical temperature of 150 °C at 180 cm high was reached in the living room (at the rear end of the living room) at t=2 min. 53 sec. However, the temperature of 150 °C was never reached at the height of 50 cm during this test.

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	2 min. 53 sec.	End of test
Radiation heat	5 min.	End of test
CO and HCN	7 min. 42 sec.	19 min. 42 sec.
NOx	4 min. 24 sec.	14 min. 45 sec.
O2	7 min. 9 sec.	End of test

7.3 Master bedroom

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	End of test	End of test
Radiation heat	52 min. 15 sec.	End of test
CO and HCN	7 min. 24 sec.	13 min. 24 sec.
NOx	4 min. 24 sec.	14 min. 54 sec.
O2	6 min. 6 sec.	End of test

7.4 Landing

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	5 min. 26 sec.	End of test
Radiation heat	5 min. 28 sec.	End of test
CO and HCN	7 min. 3 sec.	13 min. 3 sec.
NOx	3 min. 33 sec.	14 min.
O2	5 min. 48 sec.	End of test

7.5 Baby room

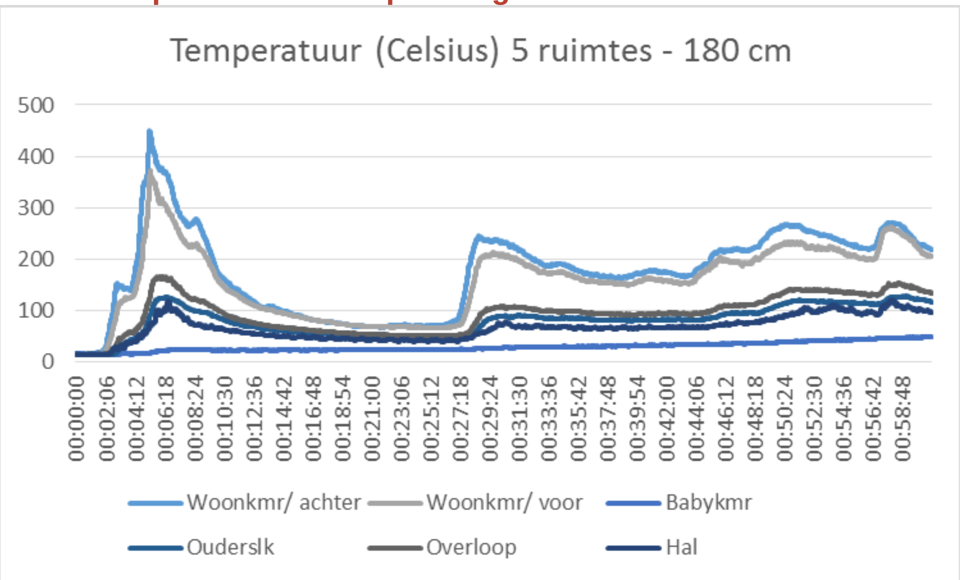
Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	End of test	End of test
Radiation heat	End of test	End of test
CO and HCN	13 min. 6 sec.	25 min. 6 sec.
NOx	9 min. 33 sec.	End of test
O2	59 min. 24 sec.	End of test

7.6 Hallway

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	End of test	End of test
Radiation heat	5 min. 17 sec.	End of test
CO and HCN	6 min. 54 sec.	12 min. 54 sec.
NOx	3 min. 18 sec.	14 min. 9 sec.
O2	5 min. 51 sec.	End of test

7.7 Summary and analysis of test 3

7.7.1 Temperature build-up throughout the home

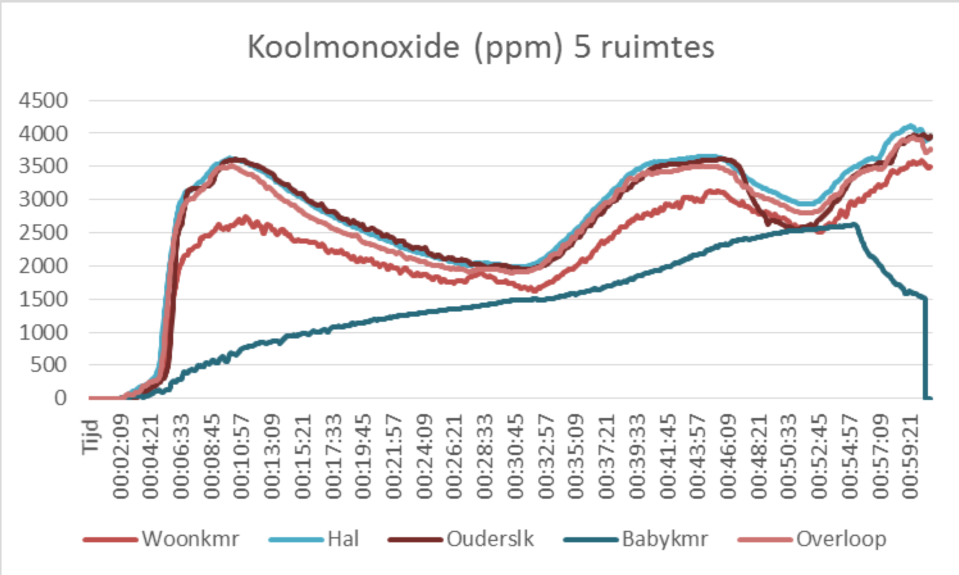


After the fire was lit in the sofa, the temperature in the living room rose extremely quickly: in the first two minutes of the test, the temperature at a height of 180 cm rose by 10 °C. In the following three minutes (t=2/ 5), the temperature at a height of 180 cm rose to 449 °C. At the temperature peak moment (t=5/ 449 °C), the available oxygen volume was 18.18 percent after which it decreased further fast. This is the reason why the fire in the living room died out and did not develop into a flashover.

The major difference in temperature in the living room at the heights of 180 cm and 50 cm is remarkable: where the peak temperature for the height of 180 was 449 °C at t=5, the value at the height of 50 cm was only 100 °C at t=6.

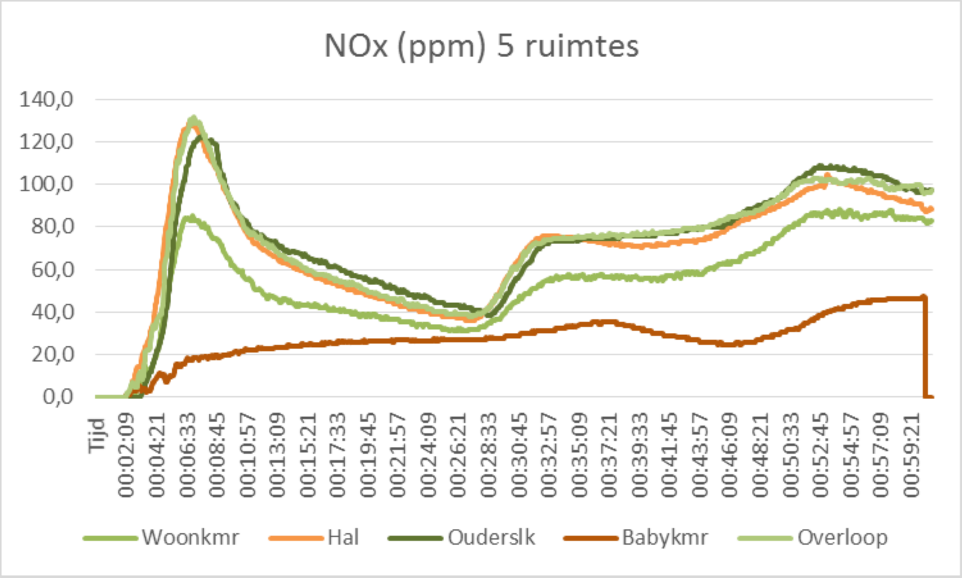
Just as in test 2, temperature build-up is differentiated into three 'zones':
> The actual room on fire (living room).
> Adjacent rooms that were not protected by closed doors: hallway, landing, master bedroom.
> The baby room where the door was closed.

7.7.2 Build-up of carbon monoxide throughout the home



The difference in the build-up of the concentration of carbon monoxide into three 'zones' is also visible:
> Highest value of carbon monoxide in the adjoining rooms that were not protected by closed doors: hallway, landing, master bedroom.
> High value but lower in the adjoining rooms: the direct room on fire (living room).
> The baby room where the door was closed.

7.7.3 Build-up of NOx throughout the home



The build-up of NOx shows great similarities with the conclusions that apply to carbon monoxide. For NOx, there was also a difference in the build-up of the concentration in three 'zones':

- Highest value of NOx in the adjoining rooms that were not protected by closed doors: hallway, landing, master bedroom.
- High value but lower in the adjoining rooms: the direct room on fire (living room).
- The baby room where the door was closed.

7.7.4 Test 3: All in all

In this fire test, escaping would have only been a realistic option during the first four minutes after the fire started. At t=3, the escape routes were no longer safe enough to reach the outside air without assistance and without passing out on the way there. If unconscious, casualties would then have a limited chance of surviving or would incur long-term damage to their health.

However, a casualty in the only room that was separated from the room on fire by a closed door had a considerable better chance of surviving than a casualty in the other rooms. An occupant in the baby room could survive up to t=25 min, whereas this threshold was already reached after some 13 minutes in the other rooms.

Room(s)	Internal door	Ventilation	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Living room (room on fire)	Hallway door open	None	2 min. 53 sec. (temp)	14 min. 45 sec. (NOx)
Hallway	Hallway door open	None	3 min. 18 sec. (NOx)	12 min. 54 sec. (CO)
Landing	N/a	None	3 min. 33 sec. (NOx)	13 min. 3 sec. (CO)
Master bedroom	Door open	Window ajar	4 min. 24 sec. (NOx)	13 min. 24 sec. (CO)
Baby room	Door closed	None	9 min. 33 sec. (NOx)	25 min. 6 sec. (CO)

Room	Route	Room + escape route free until:
Living room	Hallway (with an extra exit through the kitchen)	2 min. 53 sec.
Master bedroom	Landing, hallway	3 min. 18 sec.
Baby room	Landing, hallway	3 min. 18 sec.
Landing	Hallway	3 min. 18 sec.
Hallway	N/a	3 min. 18 sec.

8 Test 4: Living room fire with the hallway door closed

8.1 Start situation

8.1.1 Scenario and source of the fire

This scenario concerns a home inhabited by a family consisting of a young couple and their baby. The parents are sleeping in the master bedroom at the front, the baby is sleeping in the bedroom at the back. The door to the master bedroom is open, the door of the baby's room is closed. Fire breaks out during the night in the sofa in the living room while everyone is asleep. The door between the living room and the hallway is closed. There are interconnected and operational smoke detectors in the home. All the external doors and windows are closed, only the window of the master bedroom is ajar.

The difference between this scenario and the scenario of test 3 is the presence of active smoke detectors and the fact that the door between the living room and the hallway is closed.

8.1.2 Configuration of doors and ventilation

In view of a recent series of burglaries, all the external doors and windows on the ground floor are closed. The door from the living room to the hallway is closed. The door to the baby room is closed. The door of the master bedroom is opened and the window in this bedroom is ajar while the parents are sleeping.

8.1.3 Meteorological conditions and timing

There was a NNW wind of 7 m/s during this fire test. The temperature was 11.5 °C and the relative humidity was 73 percent.
At t=35 min. 45 sec., the measuring instruments for CO, O2 and NOx in the master bedroom and the landing stopped working. The original test was stopped at t=58 min. 21 sec. However, the measuring equipment was kept running by the safety crew opening the kitchen door and carrying out an offensive indoor attack. The time period *after* the original test was found to be at least as interesting as the actual test. The results of these two time periods are presented separately here.

8.2 Living room

As regards the ambient conditions of the living room, the analysis is to be divided into two parts: the time period of t=0 to t=58 (until the kitchen door was opened) and the time period of t=58 to t=68 (when the kitchen door was opened and afterwards).

8.2.1 Time period t=0 to t=58

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	4 min. 3 sec.	59 min. 40 sec.
Radiation heat	5 min. 2 sec.	End of test
CO and HCN	8 min. 12 sec.	14 min. 12 sec.
NOx	3 min. 42 sec.	13 min. 48 sec.
O2	5 min. 33 sec.	60 min. 3 sec.

8.2.2 Time period t=58 to t=68

It was recorded in the logbook that the 'back door' was opened at 11.35.14 (t=58 min. 21 sec.). However, this is the time when this information was recorded. This implies that the kitchen door was opened shortly before this was recorded. Where the temperature in the living room fluctuated between 135 and 140 °C some 10 minutes before this time, it suddenly went up to above 140 °C and increased further from t=58 . That is why t=58 is assumed as the time when the kitchen door was actually opened.

The following changes took place in the measurements in the time period of t=58 to t=68:

- The oxygen percentage started to increase from t=58 min. 21 sec. However, after the kitchen door was opened, the 'fresh' oxygen needed some time to move from the kitchen door to the sensor and the oxygen first passed along the burning sofa which automatically consumed some of this oxygen. At t=58 min. 27 sec., the oxygen percentage was 18.39 percent. This means that the oxygen percentage increased from 17.38 to 18.39 percent in half a minute. Based on literature[13] it can be concluded that this difference in oxygen percentage is sufficient to cause a fire to suddenly grow very fast instead of to only be maintained.
- The temperature rose from 140 °C at t=58 to 154 °C at t=58 min. 27 sec., and then rose very quickly from 273.3 °C at t=59 min. 27 sec. to 687.7 °C at t=60 min. 1 sec.

The temperature of 150 °C was reached at the height of 50 cm at t=59 min. 40 sec. The threshold value of 6 kW/m^2 for a situation that cannot be survived was reached in the living room at t=60 min. 15 sec. The threshold of 12,800 ppm of carbon monoxide (acute lethality) was reached at t=60 min. 18 sec. when the kitchen door had been opened for two minutes. A concentration of almost 40,000 ppm of carbon monoxide as measured a little later, or 4 percent by volume, was very high. The self-ignition temperature of carbon monoxide is 605 °C. The explosion limits of carbon monoxide are 11-76 percent by volume. This means that the Lower Explosion Limit (LEL) of carbon monoxide is 11 percent by volume, resulting in a 10% LEL of 1.1 percent. This means that the 10 percent LEL of carbon monoxide was amply exceeded during this fire test. However, the oxygen percentage decreases greatly at the moment when carbon monoxide concentration increases.

[13] Beyler, C. (2002). Flammability Limits of Premixed and Diffusion Flames, Section Two: Chapter 7. *The SFPE Handbook of Fire Protection Engineering* (3rd Edition), 172-187.

8.3 Master bedroom

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	End of test	End of test
Radiation heat	End of test	End of test
CO and HCN	5 min. 15 sec.	37 min.
NOx	End of test	End of test
O2	59 min. 24 sec.	End of test

8.4 Landing

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	End of test	End of test
Radiation heat	End of test	End of test
CO and HCN	18 min. 6 sec.	30 min. 6 sec.
NOx	5 min. 57 sec.	34 min. 36 sec.
O2	59 min. 24 sec.	End of test

8.5 Baby room

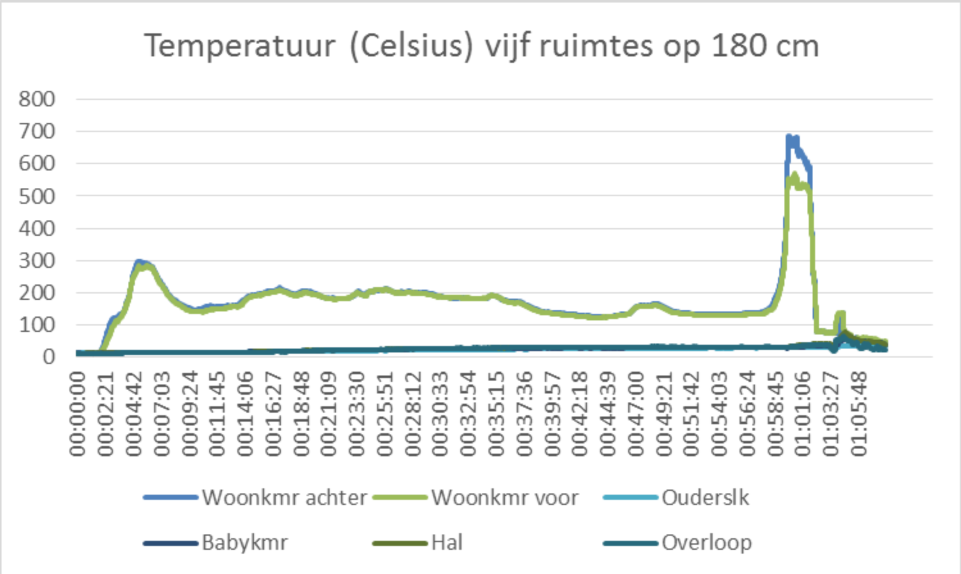
Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	End of test	End of test
Radiation heat	End of test	End of test
CO and HCN	End of test	End of test
NOx	End of test	End of test
O2	End of test	End of test

8.6 Hallway

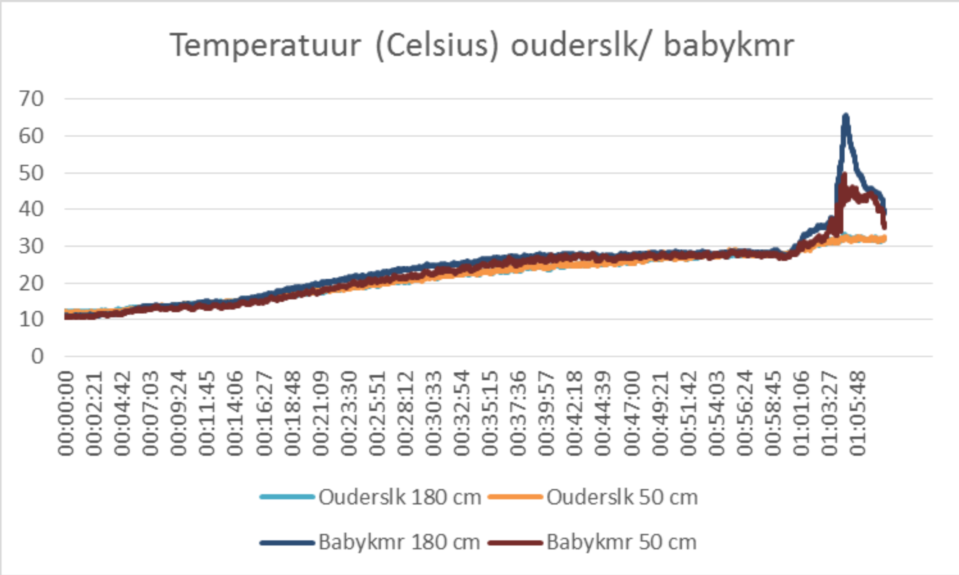
Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	End of test	End of test
Radiation heat	End of test	End of test
CO and HCN	22 min. 9 sec.	46 min. 9 sec.
NOx	13 min. 18 sec.	45 min. 48 sec.
O2	End of test	End of test

8.7 Summary and analysis of test 4

8.7.1 Temperature build-up throughout the home

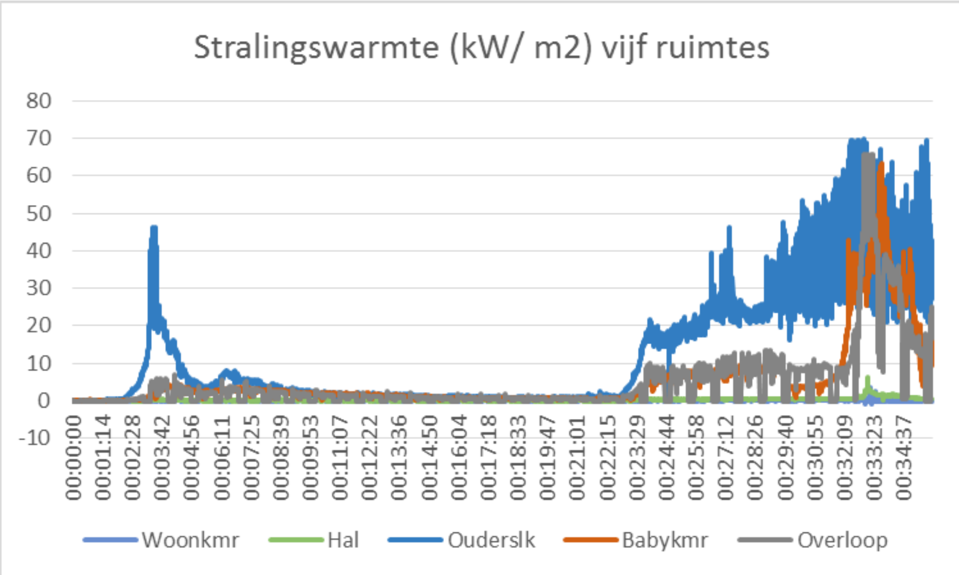


There was a major difference between the temperature build-up in the living room and the other rooms in the home. This difference was caused by the closed door to the hallway and by the floor of the first floor. Here, the difference with test 3 – where the fire was lit under exactly the same conditions save for the opened hallway door – is clearly visible and interesting.



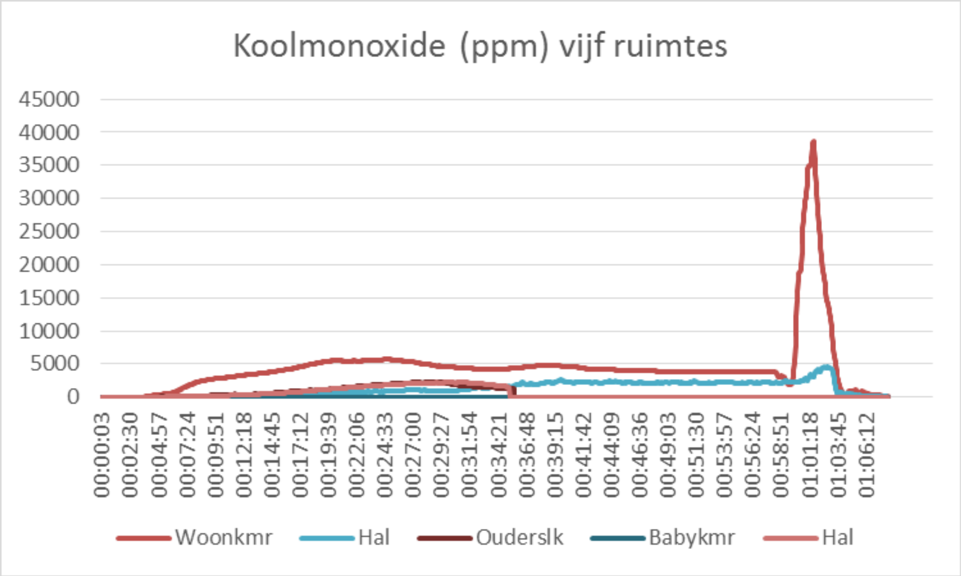
The difference in temperature build-up in the baby room and in the adjoining master bedroom is visible. Both before and after the kitchen door was opened, and before and after the offensive indoor attack, the temperature in the baby room increased less.

8.7.2 Radiation heat throughout the home



Similar to the build-up of temperature, a major difference can be seen for the build-up of radiation heat in the living room and that in the other rooms in the home.

8.7.3 Carbon monoxide throughout the home



A concentration of almost 40,000 ppm carbon monoxide, i.e. 4 % by volume, is high. The explosion limits of carbon monoxide are 11-76 % by volume. This means that the 10% Lower explosion limit (LEL) of carbon monoxide is 1.1 % by volume and that therefore the 10% LEL of carbon monoxide was amply exceeded during this fire test.

8.7.4 Test 4: all in all

The values measured for temperature, carbon monoxide and NOx again point at a considerable difference in survivability between the room on fire and the other rooms in the home. All rooms in the home offered longer survivability than the room on fire. In this test, there was one room (the baby room) that was separated from the room on fire by two doors and again this room scored better as regards survivability than the adjacent master bedroom whose door was open. This means that several doors provide an even better buffer against heat and smoke than one door.

Room(s)	Internal door	Ventilation	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Living room	Hallway door closed	None	3 min. 45 sec. (NOx)	13 min. 48 sec. (NOx)
Hallway	Hallway door closed	None	13 min. 18 sec. (NOx)	45 min. 48 sec. (NOx)
Landing	N/a	None	5 min. 57 sec. (NOx)	30 min. 6 sec. (CO)
Master bedroom	Open	Window ajar	5 min. 15 sec. (NOx)	29 min. 18 sec. (CO)
Baby room	Closed	None	End of test	End of test[14]

[14] End of formal test; i.e. until the kitchen door was opened.

Room	Route	Room + escape route free until:
Living room	Hallway (with an extra exit through the kitchen)	3 min. 45 sec.
Master bedroom	Landing, hallway	5 min. 15 sec.
Baby room	Landing, hallway	5 min. 57 sec.
Landing	Hallway	5 min. 57 sec.
Hallway	N/a	13 min. 18 sec.

9 Test 5: Living room fire with the front door open

9.1 Scenario and source of the fire

This scenario concerns a home inhabited by a family consisting of a young couple and their baby. It's a Sunday afternoon and the family is taking a nap. The father is sleeping on the sofa in the living room, the mother in the master bedroom at the front of the house and the baby in the baby room at the back. The door to the master bedroom is open; the door to the baby room is closed. The window in the master bedroom is ajar. A fire started in the TV set in the living room and the father is alerted by the smoke detector. The father just manages to leave the home through the front door and rings the fire service. The door between the living room and the hallway and the front door are left open. The mother and the baby are still upstairs. 2.5 minutes have elapsed since the fire started.

9.1.1 Configuration of doors and ventilation

The external doors were closed when the fire started. However, while escaping, the father left the door to the hallway and the front door open. This means that the front door was opened at t=3 min. 54 sec. The window in the master bedroom is ajar.

9.1.2 Meteorological conditions and timing

There was a NW wind of 6 m/s during this fire test. The temperature was 11.7 °C and the relative humidity was 71 percent.
The fire test was started with the front door closed. This was opened 10 seconds after the smoke detector in the hallway kicked in at t=3 min. 54 sec. in order to simulate the occupant escaping. At t=27 min. 35 sec., the sofa in the living room was placed nearer to the seat of the fire and the door to the hallway and the front door were closed. At t=44 min. 27 sec., the safety crew started putting out the fire.

9.2 Living room

A small window at the back burst at t=7 minutes, upon which the fire turned into a fully developed fire. After this, the fire seemed to ventilate itself ‘empty’ due to the air flow from the front door, specifically since the large window was also broken at t=14 minutes. After the available fuel had run out at t=28 min. 10 sec., additional fuel was moved closer to the fire and the front door was closed. After this, a steep increase in the temperature and the radiation heat were visible which very quickly led to a situation that could no longer be survived. What is remarkable is that there was hardly any carbon monoxide and NOx in the living room. This is probably due to a significant *supply* of oxygen through the broken windows, enabling optimum combustion, and at the same time the *removal* of combustion gases through the broken windows.

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	4 min. 55 sec.	29 min. 33 sec.
Radiation heat	11 min.	29 min. 16 sec.
CO and HCN	End of test	End of test
NOx	End of test	End of test
O2	End of test	End of test

9.3 Master bedroom

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	30 min. 44 sec.	42 min. 11 sec.
Radiation heat	30 min. 17 sec.	31 min. 47 sec.
CO and HCN	End of test	End of test
NOx	End of test	End of test
O2	End of test	End of test

9.4 Landing

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	29 min. 57 sec.	31 min. 25 sec.
Radiation heat	14 min. 2 sec.	31 min. 58 sec.
CO and HCN	End of test	End of test
NOx	End of test	End of test
O2	End of test	End of test

9.5 Baby room

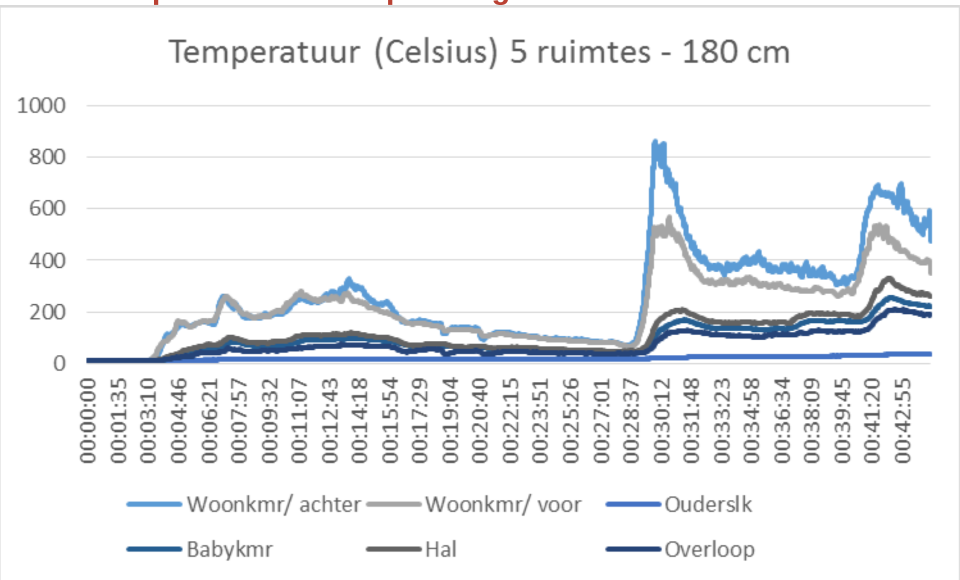
Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	End of test	End of test
Radiation heat	End of test	End of test
CO and HCN	End of test	End of test
NOx	End of test	End of test
O2	End of test	End of test

9.6 Hallway

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	30 min. 46 sec.	30 min. 46 sec.
Radiation heat	12 min. 22 sec.	30 min. 28 sec.
CO and HCN	End of test	End of test
NOx	End of test	End of test
O2	End of test	End of test

9.7 Summary and analysis of test 5

9.7.1 Temperature build-up throughout the home

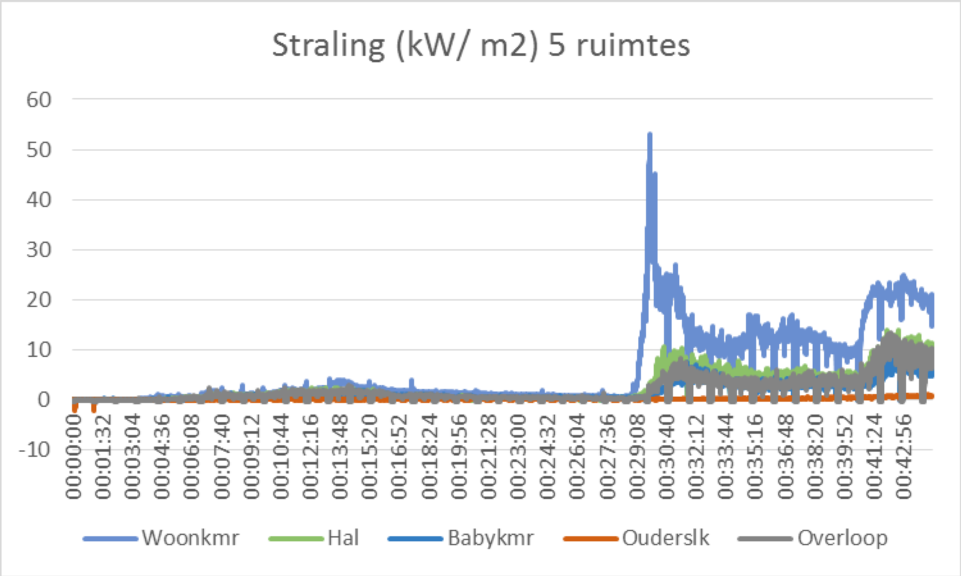


Distinction in temperature build-up:

> The actual room on fire (living room).
> Other rooms in the same home that are connected to the room on fire (living room), through an open connection: hallway, landing and master bedroom.
> The baby room, that had been sealed from the landing by a door, with the landing having an open connection to the room on fire.

The temperature built up the fastest in the primary room on fire. The temperature in connected rooms also increased, but less quickly and the temperatures that could be measured were also less high. In the closed room, the temperature only built up gradually and to a low level.

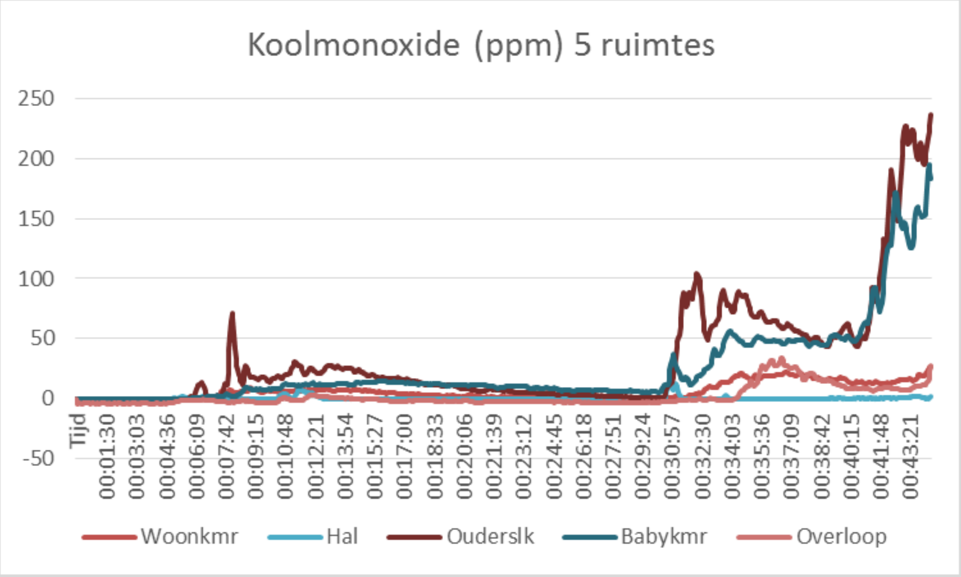
9.7.2 Radiation heat throughout the home



The threshold for a situation that can no longer be survived was not reached until an intervention was made in the scenario. As was the case with temperature, the different build-up of radiation heat could then be witnessed:

> The radiation increased the most in the actual room on fire (living room).
> Radiation also increased significantly in the other rooms in the same home that had an open connection with the room on fire (living room): the hallway, the landing and the master bedroom, but this increase was considerably less than that in the primary room on fire.
> The radiation heat hardly increased in the baby room, which had been sealed from the landing by a door, with the landing having an open connection to the room on fire.

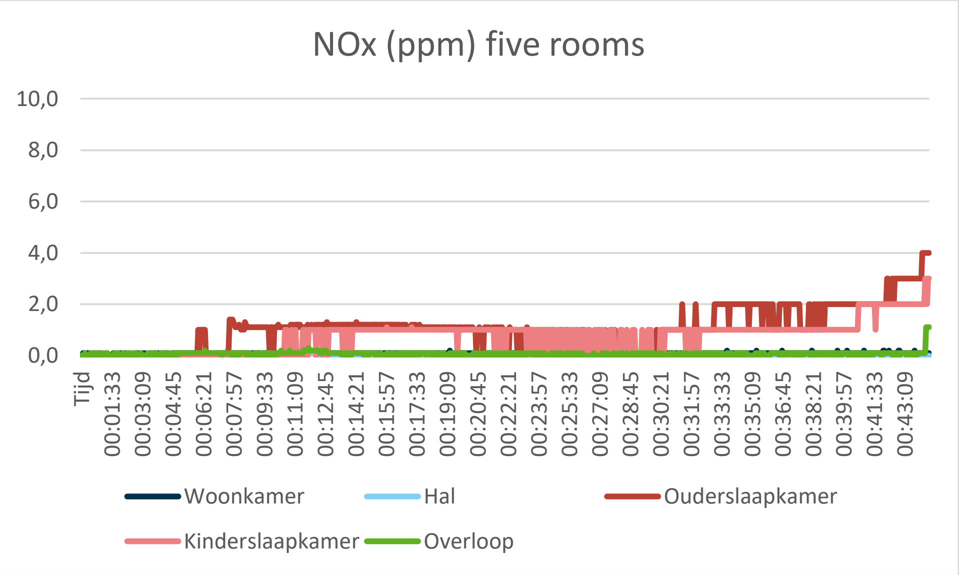
9.7.3 Carbon monoxide throughout the home



Hardly any carbon monoxide had built up in the home until an intervention occurred in the living room at 28 min. 10 sec. There had only been a slight but brief increase in the master bedroom. This is logical: the open front door enabled a major share of the smoke to escape to the outside air and fresh air to enter.

After the intervention, there was still a very low concentration of carbon monoxide in the living room; probably as a result of the optimum combustion that occurred due to an unlimited amount of oxygen flowing into a hot environment. A slightly higher concentration of carbon monoxide then started to build up in the baby room and the master bedroom. As the video images show, this was from smoke that was pressed through the floor and presumably also from gases that were released from the floor. However, given the maximum concentration of 250 ppm, this concentration is still limited.

9.7.4 NOx throughout the home



Only low concentrations of NOx were measured during this fire test. This is remarkable when compared to the earlier tests that showed much higher concentrations. This lower concentration is probably a direct consequence of the different ventilation profile during the fire: the front door was open and/or there was considerable ventilation through the living room window at the back. This enabled much less NOx to build up (concentrations disappeared to the outside air) and cleaner combustion could take place (less NOx was created).

9.7.5 Test 5: all in all

The fire development of the fifth fire test was also remarkable. This was true both for the trajectory *before* and *after* the intervention that occurred at 28 minutes and 10 seconds.

t=0 to t=28 min. 10 sec.

After the fire was lit, the temperature in the living room rose quickly and – once the sofa had really caught fire – it went up to tot 262.7 °C in four minutes and then increased to 297 °C after which the increase in temperature stopped. Although the entire room was filled with smoke, the oxygen percentage was still 21 percent. This means that the only conclusion possible here is that this was a fuel-controlled fire: the fire did not have enough fuel to spread further. However, the factor of ventilation must also be considered in this conclusion: the little window at the back of the living room broke at t=8, creating a direct flow of air from the front door to the broken window at the back. The heat that had built up was carried along with this ventilation path and taken outside, actually causing the temperature to decrease.

t=28 min. 10 sec. to end of test

After the fuel in the living room was placed a bit nearer to the fire and the hallway door was closed, the temperature started to rise from t=28 min. 40 sec. At t=29 min. 54 sec., a temperature of 861 °C was then measured at a height of 180 cm (in the back of the living room). This means that the temperature went up by 787 °C in 1 minute. Actually, this enormous peak in temperature occurred particularly at the back of the home; an increase by 500 °C was measured at the front. The enormous peak in the temperature build-up in the living room only partly occurred in the other rooms of the home.

Indication based on fire test 5:

> All the rooms in the home were survivable in the time frame from t=0 to t=28 min. 10 sec. Escaping from the living room was impeded from t=4 min. 55 sec., for the hallway this started at t=12 min. 22 sec. Occupants in the other rooms could escape unimpeded until the end of the test.
> The circumstances for escaping and surviving worsened greatly in the time period from t=28 min. 10 sec. until the end of the test. Survival was then only possible in the baby room. This again is an indication of the major difference between open and closed doors as regards survivability.
> During the test, a major difference was noted when the sofa was placed closer to the seat of the fire at t=28 min. 10 sec. The fact that the small window in the outer wall near the TV burst quickly also had major consequences. This justifies the conclusion that minor factors in a home's configuration can have major consequences for fire development and survivability. This configuration concerns how the furniture is arranged, the type of furniture and the ventilation regime.

Room(s)	Internal door	Ventilation	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Living room	Hallway door closed	None	4 min. 55 sec. (temp)	29 min. 16 sec. (rad.)
Hallway	Hallway door closed	None	12 min. 22 sec. (rad.)	30 min. 28 sec. (rad.)
Landing	N/a	None	End of test	End of test
Master bedroom	Open	Window ajar	End of test	End of test
Baby room	Closed	None	End of test	End of test

Room	Route	Room + escape route free until:
Living room	Hallway (with an extra exit through the kitchen)	4 min. 55 sec.
Master bedroom	Landing, hallway	12 min. 22 sec.
Baby room	Landing, hallway	12 min. 227 sec.
Landing	Hallway	12 min. 22 sec.
Hallway	N/a	12 min. 22 sec.

10 Test 6: Bedroom fire with the internal doors open

10.1 Scenario and source of the fire

10.1.1 Scenario and source of the fire

This scenario concerns a home inhabited by a family consisting of a young couple and their baby. The parents are sleeping in the master bedroom at the front, the baby is sleeping in the bedroom at the back. Both the bedroom doors are open. Both windows in the master bedroom are ajar, as well as the window in the baby room. A defect in the electric blanket starts a fire in the night, while everyone is asleep. There are no active smoke detectors. All the outer doors, as well as the door between the living room and the hallway, are closed.

The difference between this scenario and the scenario of test 1 is the fact that the doors and windows of the master bedroom and of the baby's bedroom are open.

10.1.2 Configuration of doors and ventilation

Two small windows in the master bedroom are ajar since the parents prefer some fresh air intake at night. The window in the baby room is also slightly open. In view of a recent series of burglaries, all the external doors and windows on the ground floor are closed. The door from the living room to the hallway is closed.

10.1.3 Meteorological conditions and timing

There was a SSW wind of 5 m/s during this fire test. The temperature was 11.5 °C and the relative humidity was 90 percent.
Given the low oxygen percentage on the first floor, the window in the baby room was fully opened at t=14 min. 3 sec. At t=21 min. 36 sec., a visual observation of the master bedroom revealed that the fire had gone out for the major part. The wardrobe was then placed on the fire. At t=29 min. 35 sec., the front door was opened to simulate the start of an offensive indoor attack.
A deviation in the carbon monoxide measuring cell in the hallway was noted prior to the test, but this could not be remedied. This means that these figures have to be considered with some reserve.

10.2 Master bedroom (seat of the fire)

The regime of the fire, which was almost but not completely restricted to the master bedroom in the first half an hour of the test, changed a couple of times. The fire started as a fuel-controlled fire to then become oxygen-controlled until the bed had largely burnt up. The fire then became fuel-controlled again. After fuel had been added, the fire quickly changed from fuel controlled to oxygen-controlled again for a short time. Opening the door changed the ventilation profile as the fire came to a full flashover on the entire first floor with temperatures exceeding 1000 °C. This shows there must have been a good balance between fuel and oxygen to enable the fire to develop fully. What was established during this test is that fire will not grow further if there is little or too little oxygen, but also that fire will not grow any further if the fuel runs out.

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	2 min. 27 sec.	3 min. 10 sec.
Radiation heat	2 min. 24 sec.	2 min. 51 sec.
CO and HCN	3 min. 9 sec.	6 min. 9 sec.
NOx	2 min. 15 sec.	12 min. 24 sec.
O2	2 min. 42 sec.	28 min. 21 sec.

10.3 Landing

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	3 min. 10 sec.	27 min. 9 sec.
Radiation heat	3 min. 15 sec.	23 min. 57 sec.
CO and HCN	3 min. 18 sec.	6 min. 18 sec.
NOx	2 min. 15 sec.	12 min. 24 sec.
O2	2 min. 42 sec.	3 min. 9 sec.

10.4 Baby room

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	2 min. 56 sec.	32 min. 7 sec.
Radiation heat	3 min. 30 sec.	24 min. 40 sec.
CO and HCN	3 min. 9 sec.	6 min. 30 sec.
NOx	2 min. 24 sec.	12 min. 24 sec.
O2	2 min. 51 sec.	3 min. 36 sec.

10.5 Hallway

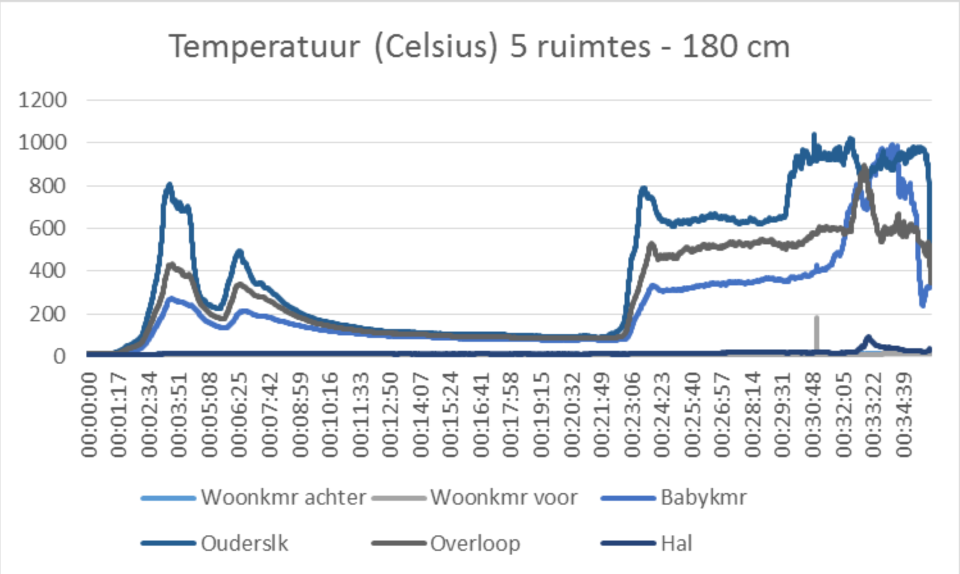
Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	End of test	End of test
Radiation heat	33 min. 1 sec.	33 min. 8 sec.
CO and HCN	End of test	End of test
NOx	End of test	End of test
O2	End of test	End of test

10.6 Living room

Factor	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Temperature	End of test	End of test
Radiation heat	33 min. 15 sec.	End of test
CO and HCN	27 min. 45 sec.	End of test
NOx	End of test	End of test
O2	End of test	End of test

10.7 Summary and analysis of test 6

10.7.1 Temperature build-up throughout the home



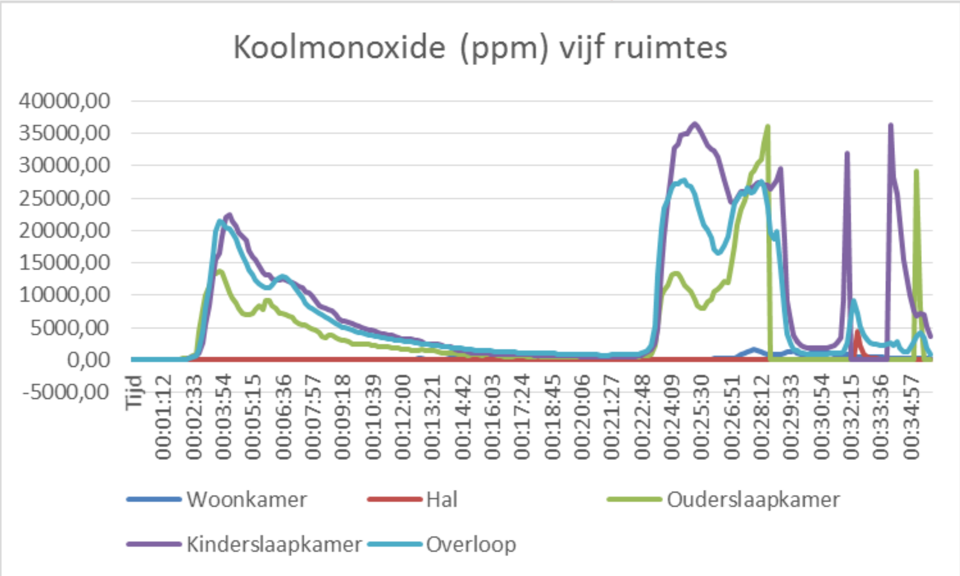
In this fire test, the temperature build-up showed a distinct division into zones:

> Room on fire (master bedroom).
> First connected room (landing).
> Second connected room (baby room).
> Under the fire (hallway, living room).

This division into zones was effective until the moment when flashover occurred in the baby room; the temperature then shot up.

The difference between the temperatures in the hallway and the landing is remarkable: although they had an open connection to each other, there was an enormous difference in temperature build-up. This difference can only be explained by the difference in height: the hallway is three metres lower than the landing.

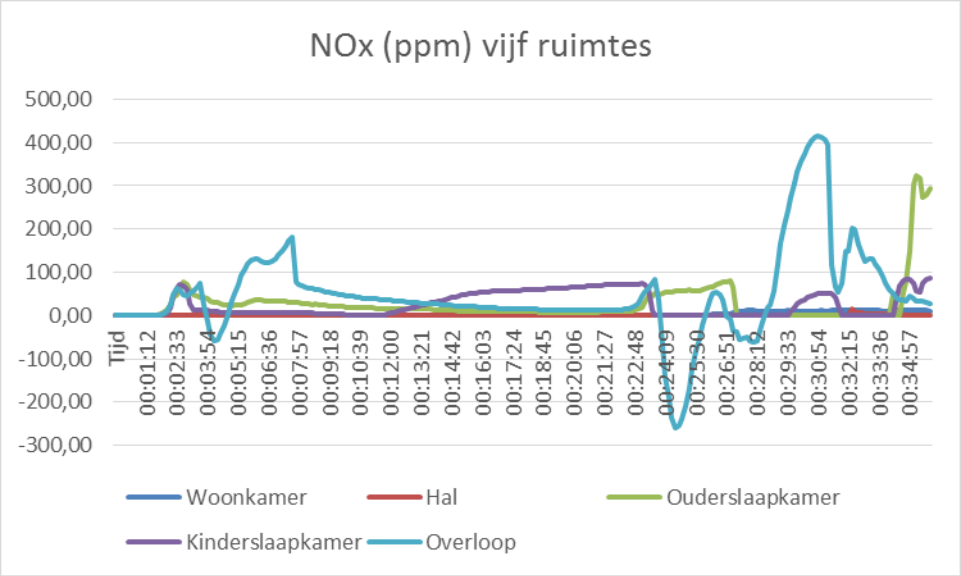
10.7.2 Build-up of carbon monoxide throughout the home



Very high values of carbon monoxide were measured during this fire test, both during the initial fire growth and during the fire growth after new fuel was introduced. When the front door was opened, the concentration of carbon monoxide decreased significantly for some time, to then rise again in the baby room and the landing.

Again, there was great similarity in the build-up of the carbon monoxide between the two rooms that bordered on the room on fire. They scored higher values than the actual room on fire. Carbon monoxide was hardly an issue in the hallway and living room, even at the moment when the front door was still closed.

10.7.3 Build-up of NOx throughout the home



NOx built up in an irregular pattern during the sixth fire test. No significant concentration was established in the hallway and the living room. However, there were high concentrations of NOx on the first floor that initially increased equally in the master bedroom, the baby room and the landing, but then became highly divergent.

10.7.4 Test 6: all in all

The regime of the fire, which was almost but not completely restricted to the master bedroom in the first half an hour of the test, changed a couple of times. The fire started as a fuel-controlled fire to then become oxygen-controlled until the bed had largely burnt up. The fire then became fuel-controlled again. After fuel had been added, the fire quickly changed from fuel controlled to oxygen-controlled again for a short time. Opening the door changed the ventilation profile, as the fire came to a full flashover on the entire first floor, with temperatures exceeding 1000 degrees Celsius. This shows that there must have been a good balance between fuel and oxygen in order for the fire to grow into a fully developed fire. What was established during this test is that fire will not grow further if there is little or too little oxygen, but also that fire will not grow any further if the fuel runs out.

What is remarkable is the difference between the temperature in the hallway and the landing. Although there was an open connection between the two rooms, there was an enormous difference in temperature build-up. This difference can only be explained by the difference in height: the hallway is three metres lower than the landing.

Room(s)	Internal door	Ventilation	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
Living room	Hallway door closed	None	27 min. 45 sec. (CO)	End of test
Hallway	Hallway door closed	None	33 min. 1 sec. (rad.)	33 min. 8 sec. (rad.)
Landing	N/a	None	2 min. 15 sec. (NOx)	3 min. 9 sec. (O2)
Master bedroom	Open	Window ajar	2 min. 15 sec. (NOx)	2 min. 51 sec. (rad.)
Baby room	Open	None	2 min. 24 sec. (NOx)	3 min. 36 sec. (O2)

Room	Route	Room + escape route free until:
Living room	Hallway (with an extra exit through the kitchen)	27 min. 45 sec.
Master bedroom	Landing, hallway	2 min. 15 sec.
Baby room	Landing, hallway	2 min. 24 sec.
Landing	Hallway	2 min. 15 sec.
Hallway	N/a	33 min. 1 sec.

11 A different ending?

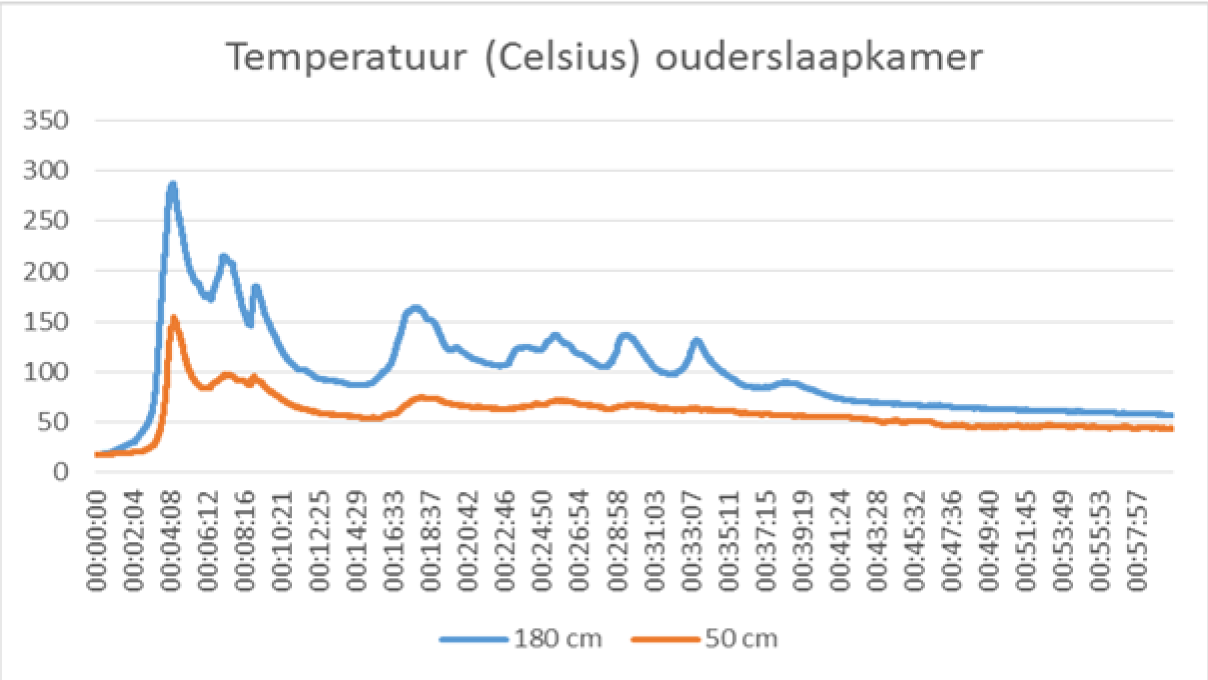
11.1 Introduction

Earlier in this report it was established that minor differences in the configuration of a home can lead to a different fire development and, as a result, a different outcome of a fire. Such minor differences can be another layout of the room, a window being open instead of closed or another type of furniture with another fire load and another development of its heat release rate. One of the tests where this was shown was fire test 2, where the fire development changed considerably when the kitchen door was closed halfway instead of being fully open.

Based on modelling in the framework of Fire Safety Engineering, a number of alternative scenarios was simulated to give an impression of 'a different ending' of the scenario when changes are made to the building or to the fuel characteristics.

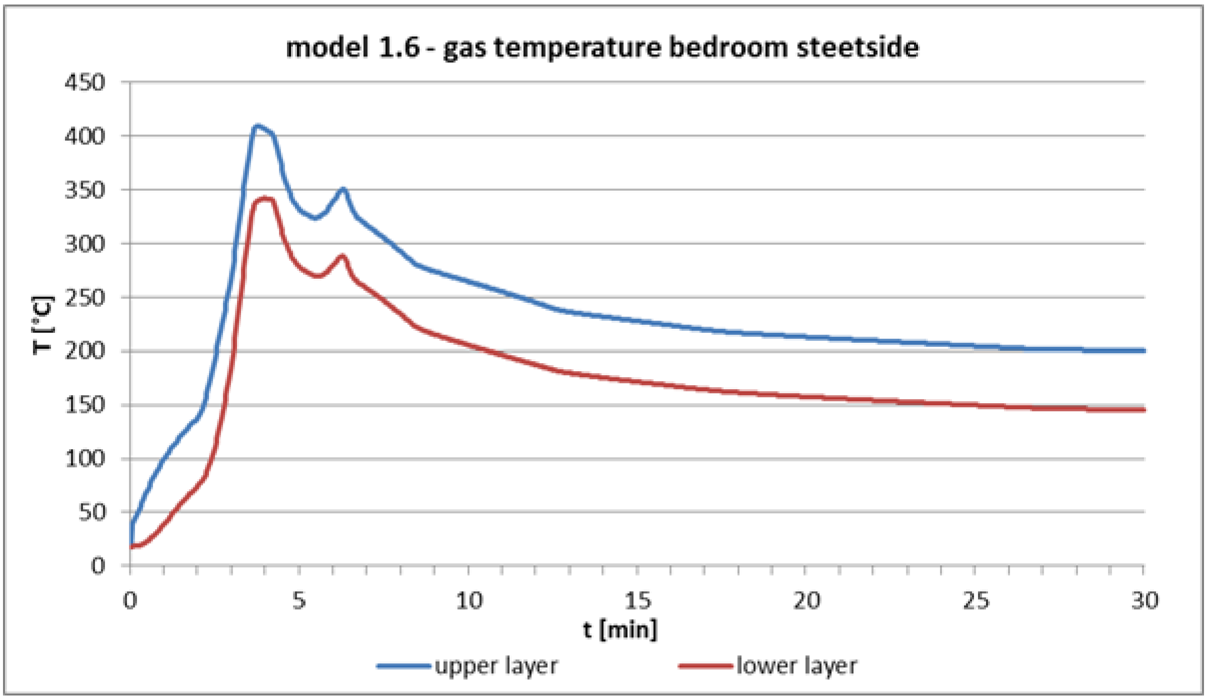
11.2 Alternative simulation of fire test 1

During fire test 1, the following temperate development was actually observed in the master bedroom:



During the fire test, there was a rapidly growing fire in the master bedroom. The fire in the master bedroom did not turn into a fully developed fire (no flashover). After a rapid rise to 287.2 °C, the temperature dropped fast again. The remaining oxygen percentage was 20 percent at the peak moment of the temperature, which at first sight might seem to indicate that oxygen is not the limiting factor. However, the oxygen percentage quickly dropped to 13.2 percent after the peak moment. Furthermore, the concentration of oxygen was measured at a height of 50 cm, whereas most oxygen is burnt at a greater height. Furthermore, there was still plenty of fuel present at the peak moment. It is therefore concluded that this fire was tempered by a shortage of oxygen and became a smouldering fire until most of the mattress and the duvet had smouldered away. The energy available during the burning process was insufficient to set other objects in the master bedroom on fire. The fire development found can be explained quite easily: the flame stage of combustion is not possible if the oxygen percentage is 13 percent. Since the flame stage no longer occurs, the temperature and radiation will decrease then.

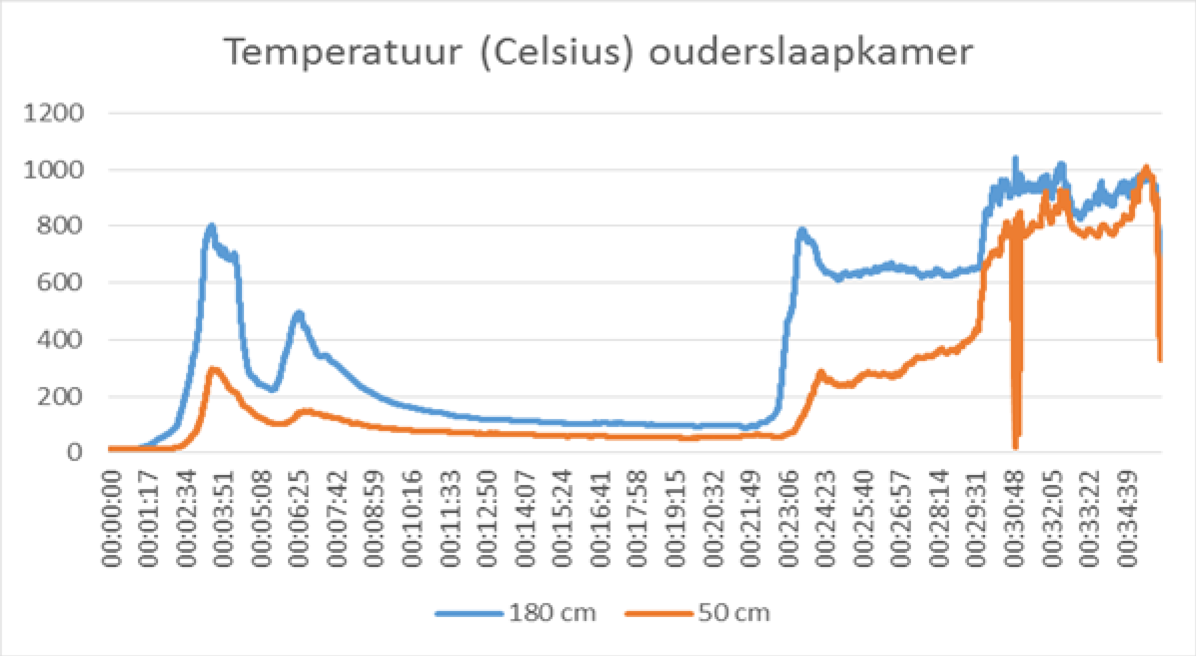
A simulation was next carried out where the natural ventilation from ‘window ajar’ was doubled. The fire load was replaced by a thick mattress (i.e. a box spring) instead of a thin mattress (innerspring type). A slightly higher peak in temperature then occurred, enabling the wardrobe and the bed stand to also catch fire.



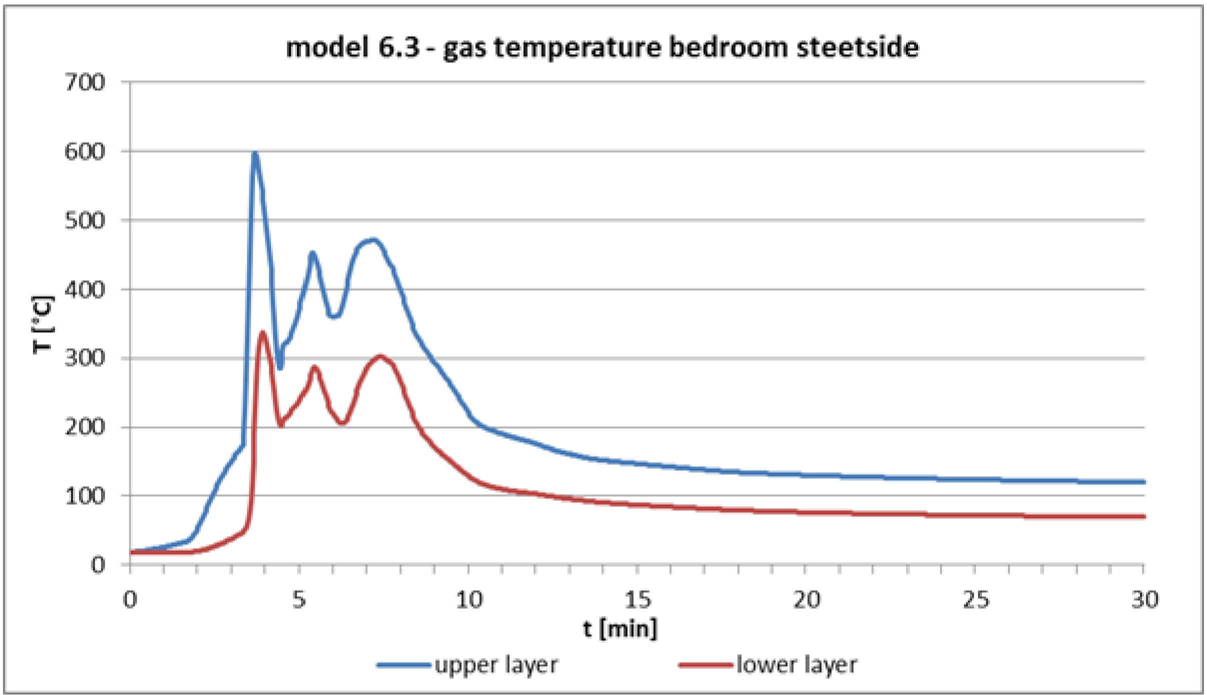
Therefore, it must be concluded that changes to the construction or to the fuel characteristics lead to a different fire development. At the same time, it must be noted that the conditions to survive in the master bedroom would have stayed virtually the same in this case.

11.3 Alternative simulation of fire test 6

During fire test 6, the following temperature development was actually observed in the master bedroom:



During the fire test, the fire was initially, and in spite of the high temperature, restricted to the mattress and the duvet. The bed stand, the clothes in the wardrobe and the wardrobe itself did not catch fire until they had been placed closer to the fire. This leads to the assumption that radiation release by the flames was responsible for the fire spread. Although the temperature of the hot zone was high, the radiation flux from the hot zone was apparently not enough to have the rest of the furniture catch fire. This is due to the limited dimensions of the bedroom.



When carrying out the simulation with another mattress in the same room (box spring instead of a traditional innerspring type mattress), the model shows that the bed stand and the wardrobe did start to burn. The extent to which the bed stand and wardrobe catching flame could also have other consequences outside the master bedroom has not been calculated further. However, based on these simulations, it is quite plausible that another mattress or bed would lead to another result.

12 Analysis and conclusions

12.1 Fire development

This section answers the following research question:

How does a fire develop in a living room, kitchen and bedroom in a common type of home in the Netherlands with an interior that is common to many households in the Netherlands and where internal and external doors can be open and closed?

The six test fires grew fast. This rapid fire growth occurred in the interior fixtures and fittings: it was not until a later stage that the actual building structure was involved in the fire. This rapid fire growth in the fixtures and fittings had previously been noticed by the Fire Service Academy[15] and it is almost certainly the result of the use of 'fast' fuels in furniture such as foam rubber and other plastics. These fuels contain so much energy that can be released in a short time that they can enable the fire to develop fast.

At the same time, this rapid fire growth calls for a large amount of oxygen. It was found that the volume of oxygen required by the fire is greater than the oxygen supply. This was even the case in the houses used for these tests, which had only been partially insulated. In other words, if the doors were closed or windows were only partially open, the fires quickly became ventilation-controlled and transitioned to the smouldering stage. Every fire initially grew quickly, after which it was strongly influenced by the ventilation profile: opened or closed windows and doors.

Both the graphs below are significant in this respect: two fires in a living room that were both lit in the same sofa at the same spot. However, the hallway door was open halfway in the first test, whereas it was closed in the second test.

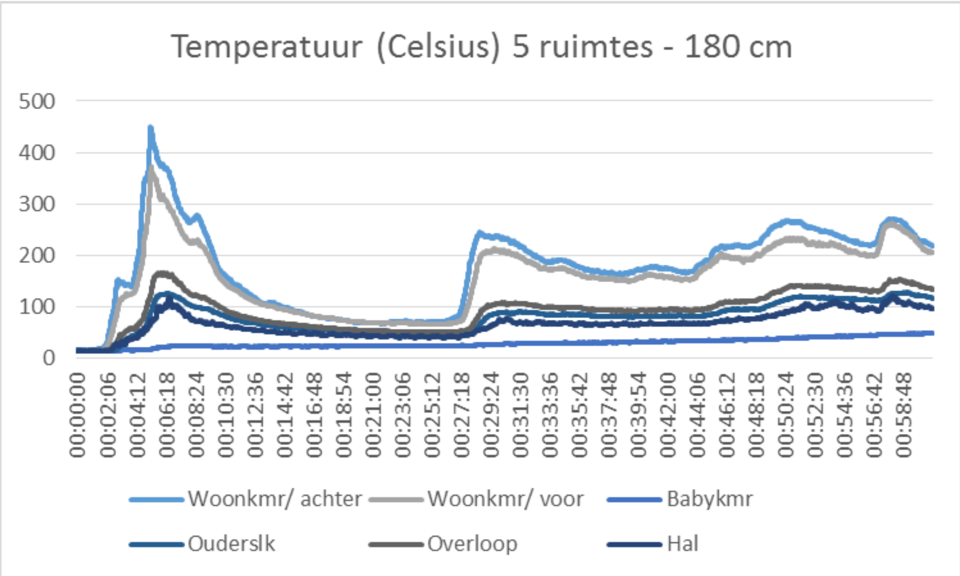


Figure 12.1: Fire in the living room, hallway door open

[15] Nibra demonstration test; March 2002.

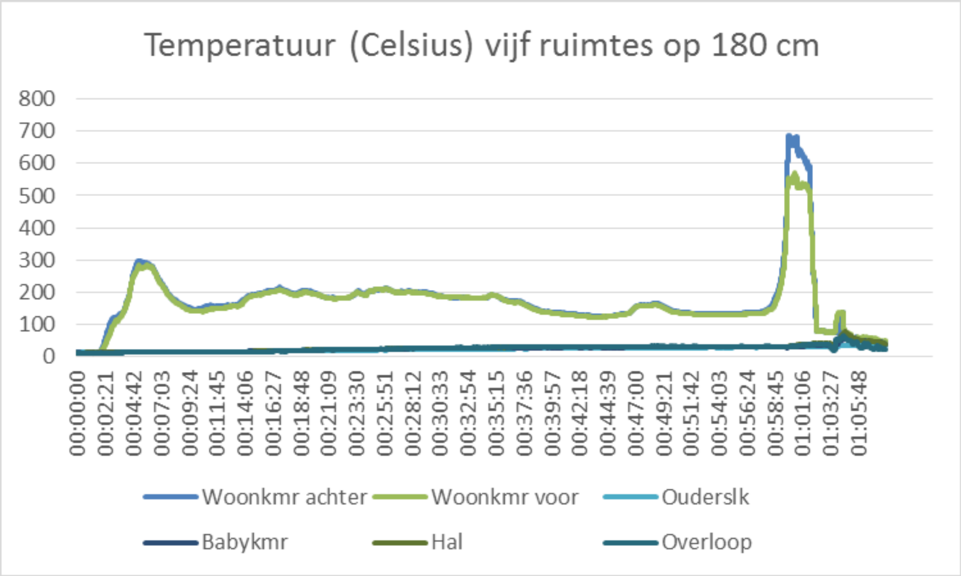


Figure 12.2: Fire in the living room, hallway door closed

The above comparison shows that a closed door (here the hallway door) reduces heat (and smoke) in the rest of the house. It also reduces the amount of oxygen being drawn in from the rest of the house, making the peak of the fire less fierce. For order's sake it should be noted here that the peak of 700 °C at t=59 min. was the consequence of the kitchen door being opened, resulting in an influx of oxygen.

In the fire tests, closed windows and doors resulted in a ventilation-controlled fire within a matter of minutes, which then transitioned into a smouldering phase. Where sufficient fuel was available, the fire could easily smoulder for an hour. It has also been found that if an external door is opened, as shown by figure 12.2, the fire can fully develop again in a very short time. This may potentially lead to a very dangerous situation for anyone opening the door to enter the house. A fire that almost seems to have gone out can show a temperature increase by 500 °C within seconds of new oxygen being supplied and turn into a conflagration almost instantaneously.

The influence of the ventilation profile is so strong that a major difference has even been found between a kitchen door being fully open or only open halfway. It has also been established that a lot of ventilation (with an inlet and an outlet) can contribute to heat and fuel (in the form of fire gases) being discharged, which actually leads to a fuel-controlled fire.

A fire in a house where doors (or several windows) are *open* develops fundamentally differently than a fire in a house where the windows and doors are *closed*. The manner in which the fire service influences ventilation during its repressive attack is also highly relevant for the fire development and, as a result, for its own safety, especially when opting for an inside attack. This is usually expressed when an outer door is opened in the event of a ventilation-controlled fire. So far, this seems to have been given insufficient attention in fire service attack tactics. Ventilation is sometimes desired, and sometimes it is not; this requires an understanding of fire growth and attack procedures that deliberately take into account this form of fire development and the ventilation profile that is present and that changes due to the attack.

Fire development depends on minor elements in the configuration of a home and the manner in which the occupants have arranged their living habits. Is the door open or is it not open? Are there modern or traditional furnishings? Is the bedroom window ajar or open wide? Where is the sofa? Does the sofa have plastic, fabric or leather upholstery? Does a window break? This is confirmed by international research such as that of Underwriters Laboratories in New York (Governors Island).

The conclusion is that it is not possible to determine a standard configuration of the typical Dutch house and, therefore, that no standard fire development can be established. The manner in which fire development occurs is largely determined by the deliberate and accidental choices that the occupants of a house have made while arranging their living habits and home on the one hand and, on the other hand, and to a limited extent, by the fire service that arrives on the scene after a fire is reported.

Another conclusion that has to be drawn is that internationally famous film clips of earlier fire tests that demonstrated fast fire growth (such as the well-known Christmas tree) are often wrong as regards one fundamental aspect: they were not recorded in closed rooms with a limited ventilation profile. The results of the tests in Zutphen justify the conclusion that flashover in 1-3 minutes is simply not possible if insufficient oxygen is available or is made available. But this does not mean that fires are less dangerous: the speed of smoke development and spread is high and still reduces survivability under unfavourable conditions (open doors etc.) to a matter of just a few minutes.

In conclusion, it is noted here that in the six fire tests smoke spread occurred through the open connection (hallway, landing), but also through the floor. This leads to the expectation that smoke is less likely to spread to any higher or lower rooms in new houses with concrete floors that have been constructed with better smoke resistance. However, pipe ducts and conduits can still be weak links in fire and smoke compartmentation in such houses.

12.2 Analysis of escaping and the chances of surviving

The following research question is answered in this section:

What are the chances of surviving a fire in a living room, kitchen and bedroom in a common type of home in the Netherlands with an interior that is common to many households in the Netherlands and where internal and external doors can be open and closed?

The degree to which occupants can still escape or can survive if they do not manage to escape is just as important as the manner in which fire growth (and smoke spread) take place. To be able to determine this, the concentrations of carbon monoxide, NOx and oxygen as well as the temperature and radiation heat were recorded in all the rooms in the house.

Table 12.1: The threshold value reached first is indicated for every fire test and for every room

Test	Room(s)	Internal door	Ventilation	Maximum possibility to escape from the room for 50% of the population	Limited chance of survival for 50% of the population or a major risk of long-term damage to health from:
1	Master bedroom (room on fire)	Hallway door closed	None	3 min. 33 sec. (NOx)	4 min. 21 sec. (temp)
	Landing	Hallway door closed	None	29 min. 45 sec. (CO)	53 min. 45 sec. (CO)
	Baby room	N/a	None	39 min. 6 sec. (CO)	End of test
	Hallway	Open	Window ajar	End of test	End of test
	Living room	Closed	None	End of test	End of test
2	Kitchen (room on fire)	Kitchen door open	Outside door half open	5 min. 41 sec. (temp)	Unknown[16]
	Living room	Hallway door closed	None	12 min. 42 sec. (CO)	18 min. 42 sec. (CO)
	Hallway	Hallway door closed	None	20 min. 45 sec. (CO)	44 min. 45 sec. (CO)
	Landing	N/a	None	21 min. 9 sec. (CO)	45 min. 9 sec. (CO)
	Master bedroom	Door open	Window ajar	21 min. 9 sec. (CO)	45 min. 9 sec. (CO)
	Baby room	Door closed	None	21 min. 27 sec. (CO)	45 min. 27 sec. (CO)
3	Living room (room on fire)	Hallway door open	None	2 min. 53 sec. (temp)	14 min. 45 sec. (NOx)
	Hallway	Hallway door open	None	3 min. 18 sec. (NOx)	12 min. 54 sec. (CO)
	Landing	N/a	None	3 min. 33 sec. (NOx)	13 min. 3 sec. (CO)
	Master bedroom	N/a	Window ajar	4 min. 24 sec. (NOx)	13 min. 24 sec. (CO)
	Baby room	Door open	None	9 min. 33 sec. (NOx)	27 min. 6 sec. (CO)
4	Living room (room on fire)	Hallway door closed	None	3 min. 45 sec. (NOx)	13 min. 48 sec. (NOx)

[16] Only temperature was measured at a height of 180 cm; no other factors

	Hallway	Hallway door closed	None	13 min. 18 sec. (NOx)	45 min. 48 sec. (NOx)
	Landing	N/a	None	5 min. 57 sec. (NOx)	30 min. 6 sec. (CO)
	Master bedroom	Door open	Window ajar	5 min. 15 sec. (NOx)	29 min. 18 sec. (CO)
	Baby room	Door closed	None	End of test	End of test
5	Living room (room on fire)	Hallway door open	None	4 min. 55 sec. (temp)	29 min. 16 sec. (rad.)
	Hallway	Hallway door open	None	12 min. 22 sec. (rad.)	30 min. 28 sec. (rad.)
	Landing	N/a	None	14 min. 2 sec. (rad.)	31 min. 25 sec. (temp)
	Master bedroom	Door open	Window ajar	30 min. 17 sec. (rad.)	31 min. 47 sec. (rad.)
	Baby room	Door closed	None	End of test	End of test
6	Master bedroom (room on fire)	Door open	Two win-dows ajar	2 min. 15 sec. (NOx)	3 min. 10 sec. (temp)
	Landing	N/a	None	2 min. 15 sec. (NOx)	3 min. 9 sec. (O2)
	Baby's room	Door open	Window ajar / fully open later	2 min. 24 sec. (NOx)	3 min. 36 sec. (O2)
	Hallway	Hallway door closed	None/ front door open later	33 min. 1 sec. (rad.)	33 min. 8 sec. (rad.)
	Living room	Hallway door closed	None	27 min. 45 sec. (CO)	End of test

This leads to the prudent conclusion that the ventilation profile, and how this is influenced, is a very important factor in fire growth. The observations after six fire tests are that the temperature and smoke (including harmful combustion gases) are built up in three zones:

> The primary room that is on fire.
> The rooms next to and over the primary room on fire, with an open connection to the primary room on fire.
> The rooms next to and above the primary room on fire that are screened off from the primary room on fire by a door or a floor and the room(s) under the primary room on fire.

It was demonstrated that rooms that have an open connection to the room on fire are filled with smoke in a very short time, thus greatly reducing the possibilities for escaping and surviving. At the same time, it has been established that the conditions to escape and survive are considerably better for some time in rooms that have *no* open connection to the room on fire. This implies that closing a door is highly significant in terms of survivability. A first indication is that there is a survivable situation behind a closed door for at least another 10 minutes. Several doors provide an even better buffer against heat and smoke than one door.

What is remarkable is that, besides carbon monoxide, NOx (one of the main 'standard' combustion products of modern fittings and fixtures) also reaches high values quickly after the start of the fire. Given the relevance of NOx, further research into other common combustion gases (HCN/HCL) should be carried out as part of future experiments.

A situation that can no longer be survived is measured in the room on fire within a few minutes of the fire starting. This can be as soon as after two minutes, but it may also take five minutes.

12.3 All in all

Fire development and the possibilities of surviving fires in the home depend on minor elements in the configuration of a home and the manner in which the occupants have arranged their living habits. Is the door open or not open? Are there modern or traditional furnishings? Is the bedroom window ajar or wide open? Where is the sofa? Does the sofa have plastic, fabric or leather upholstery? Does a window break?

The conclusion is that it is not possible to determine a standard configuration of the typical Dutch home and, therefore, that no standard fire development can be established. The manner in which fire development occurs and the degree to which an occupant can still survive if fire breaks out is largely determined by the deliberate and accidental choices that the occupants of a house have made while arranging their living habits and home on the one hand and, on the other hand, and to a limited extent, by the fire service that arrives on the scene after a fire is reported.

The following action points for occupants and the fire service can be indicated pursuant to the six fire tests in Zutphen as part of a joint effort to reduce the risks that accompany fires in the home.

Lessons for civilians in the context of a fire-safe environment

> Close the living room and bedroom doors before going to sleep.
> Smoke detectors are still of great importance; the Fire Service Academy has also conducted research into the optimum placement of smoke detectors, the results of which are to be published in October 2015.
> If a smoke detector alerts you to a fire, then try to escape as quickly as possible. If your escape route is clear: go out directly and close doors behind you so that the fire cannot grow further.
> If you are alerted to a fire and you cannot escape any more, then go to a room that is as far removed from the fire and smoke as possible, and close the door. Call the fire service and tell them that you cannot escape, where you are, and whether more people are present.

Lessons to be learnt by the fire service

> The situation in a burning house with casualties inside may still be survivable if the occupants have sought shelter behind a door and have been alerted by a smoke detector in good time. The chance of the fire service saving lives in fires in the home is increased immensely if the initial conditions (smoke detectors present and doors closed) are favourable.
> Nowadays a fire needs a lot of oxygen to grow rapidly to its maximum extent. Besides the amount of fuel, ventilation is the main item from the moment when a fire starts until the attack by the fire service has ended. This implies that the fire service have to be alert

to the specific characteristics and risks of their attack if the fire is ventilation-controlled: test 4 revealed that even a ventilation-controlled fire in a small living room can involve risks if an offensive indoor attack is opted for without due consideration. Thought should be given to the action perspective if a fire is ventilation controlled and practising for this situation should become an important area of attention.

13 Unexpected results

Two safety crews were made available for the fire tests every day. They were assembled from colleagues of the IJsselstreek brigade and experienced firefighters from twelve fire service regions. The tests were an eye opener for many of the firefighters present: they had not previously been able to observe so well how fire develops under realistic circumstances, and how a ventilation-controlled fire occurs. Regardless of the central research question of this research, this is a valuable observation in itself: apparently the existing knowledge of the different fire regimes has not been sufficiently embedded in the fire service in the Netherlands. However, it should be noted here that the facilities that enable these fire regimes to be practised are far from ideal at present. Most training centres currently do not offer any facilities for practising on life-size ventilation-controlled fires.

The Fire Service Academy will further develop the results of the tests in Zutphen as interactively and visually as possible in order to give colleagues throughout the Netherlands the opportunity to take in the knowledge that has been gained. However, at the same time, it should be noted that this digital exercise can only be a first step. For the fire service – bearing in mind the safety of firefighters – to act effectively in the event of a fire, it must be able to practice this effective action under realistic circumstances. In this regard, realistic circumstances means a realistic fire load with realistic smoke development in realistic premises. It was established in the research that ventilation-controlled fires will occur ever more often in the future. This means that the fire service should be able to practice recognising and fighting such a phenomenon under realistic circumstances, because only this *situational awareness* enables the right attack tactics to be chosen, based on the 4-quadrants model.

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15 Translation table

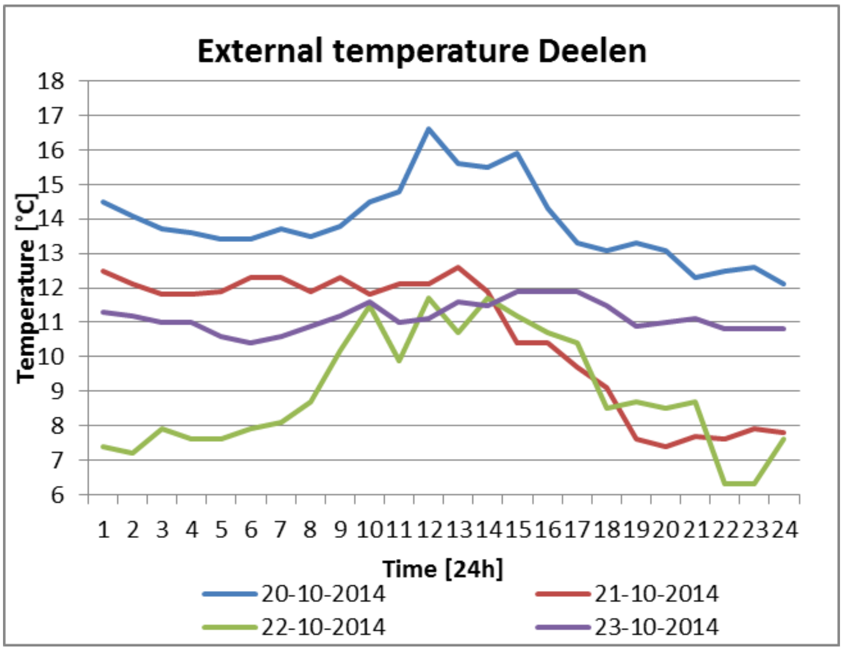
Dutch word	English translation
Badkamer	Bath room
Babykamer	Baby room
Bank	Sofa
Bed	Bed
Boekenkast	Book cupboard
Canvas	Canvas painting
Commode	Dresser
CV	Central heating
Douche	Shower
Eettafel	Dining table
Friteuse	Deep fat fryer
Gordijnen	Curtain
Hal	Hall way
Handdoeken	Kitchen towels
Keuken	Kitchen
Kapstok	Coat rack
Kastje	Small cupboard
Klamboe	Mosquito net
Klerenkast	Wardrobe
Lage kast	Low cupboard
Lamp	Lamp
Ledikant	Bed stead (for baby)
Luik	Hatch
Nachtkastje	Night stand
Ouderslaapkamer	Master bedroom
Overloop	Landing

Salontafel	Coffee table
Slaapkamer	Bedroom
Speelgoed	Toys
TV	TV
Vloerkleed	Carpet
Voetenbank	Ottoman
Wasmand	Laundry basket
WC	Toilet
Woonkamer (voor/ achter)	Living room (front/ behind)
Zitstoel	Arm chair

16 Meteo

Major Test Monday: 20/10/2014					Major Test Tuesday: 21/10/2014				
Time [h]	Wind speed [m/s]	Temp [°C]	RH [%]	Wind direction [°]	Time [h]	Wind speed [m/s]	Temp [°C]	RH [%]	Wind direction [°]
1	6	14.5	88	240	1	5	12.5	90	220
2	6	14.1	91	240	2	5	12.1	91	210
3	6	13.7	92	230	3	5	11.8	92	200
4	6	13.6	93	230	4	5	11.8	92	210
5	6	13.4	94	230	5	6	11.9	92	200
6	5	13.4	92	230	6	6	12.3	89	200
7	5	13.7	91	230	7	7	12.3	88	200
8	5	13.5	94	220	8	7	11.9	92	180
9	5	13.8	94	240	9	8	12.3	88	200
10	**5**	**14.5**	**90**	230	**10**	**8**	**11.8**	**95**	190
11	5	14.8	92	240	11	9	12.1	94	190
12	6	16.6	80	240	12	9	12.1	95	200
13	5	15.6	80	260	13	8	12.6	96	200
14	**6**	**15.5**	**79**	240	**14**	**6**	**11.9**	**89**	270
15	6	15.9	72	240	15	7	10.4	84	270
16	6	14.3	77	250	16	5	10.4	83	260
17	4	13.3	83	230	17	5	9.7	82	270
18	3	13.1	85	230	18	5	9.1	81	260
19	4	13.3	85	230	19	7	7.6	88	250
20	4	13.1	86	220	20	6	7.4	91	240
21	4	12.3	91	210	21	4	7.7	90	270
22	4	12.5	88	210	22	6	7.6	91	270
23	5	12.6	88	220	23	5	7.9	90	280
24	5	12.1	91	220	24	7	7.8	91	260

Major Test Wednes-day: 22/10/2014					Major Test Thursday: 23/10/2014				
Time [h]	Wind speed [m/s]	Temp [°C]	RH [%]	Wind direction [°]	Time [h]	Wind speed [m/s]	Temp [°C]	RH [%]	Wind direction [°]
1	5	7.4	88	260	1	4	11.3	87	240
2	4	7.2	88	270	2	4	11.2	86	200
3	5	7.9	84	270	3	5	11	87	200
4	5	7.6	87	290	4	5	11	84	210
5	6	7.6	88	290	5	5	10.6	85	210
6	6	7.9	87	300	6	4	10.4	89	210
7	6	8.1	83	290	7	5	10.6	87	210
8	5	8.7	85	290	8	5	10.9	83	210
9	6	10.2	78	300	9	5	11.2	82	200
10	**7**	**11.5**	**73**	310	**10**	**5**	**11.6**	**80**	200
11	7	9.9	86	300	11	5	11	91	190
12	6	11.7	74	320	12	5	11.1	92	220
13	7	10.7	78	330	13	5	11.6	91	210
14	**6**	**11.7**	**71**	320	**14**	**5**	**11.5**	**90**	210
15	6	11.2	73	310	15	5	11.9	87	190
16	6	10.7	74	310	16	5	11.9	85	190
17	4	10.4	75	300	17	4	11.9	86	190
18	3	8.5	85	280	18	4	11.5	90	190
19	1	8.7	87	270	19	4	10.9	97	190
20	2	8.5	90	250	20	4	11	97	190
21	2	8.7	93	240	21	4	11.1	96	200
22	1	6.3	97	200	22	5	10.8	98	200
23	1	6.3	98	190	23	5	10.8	97	190
24	1	7.6	95	250	24	5	10.8	98	190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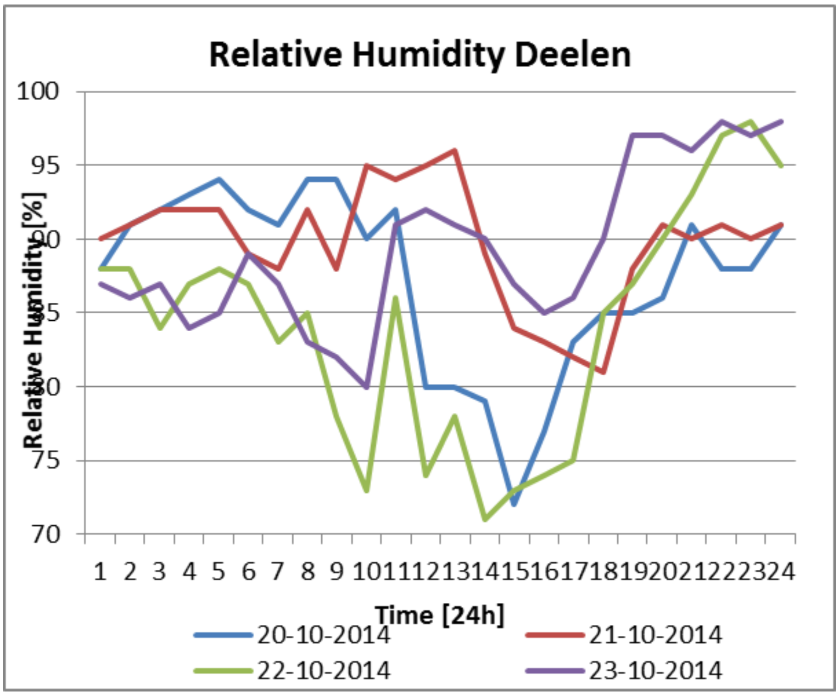
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