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Impression tests upholstered furniture and mattresses

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Content

Introduction

1.1 Background

In 2016 the Institute for Safety and a retailer started a co-operation with the purpose to initiate a new approach towards product requirements for upholstered furniture and mattresses. Those requirements should improve consumer safety significantly taking into account current living situations and current research on domestic fire safety. The overall goal is to improve domestic fire safety through safer home furnishing products. In order to achieve this on an industry wide scale the aim is to develop new product standards and to influence regulation in the EU.

The result of the co-operation is a public report with (recommended) test methods for upholstered furniture and mattresses. These test methods are supported by the FEU (the Federation of the European Union Fire Officers Associations) and adopted on the basis of knowledge of the fire service (research) and practical experience in the fire service of fire development, smoke spread, survivability and escape options in dwellings (Federation of the European Union Fire Officer Associations (FEU), 2017). The intention is to produce a report in 2017. The practical research in this study is part of the work within the co-operation in order to achieve a public report.

1.2 Why impression tests

Fire tests in actual dwellings (Hazebroek, J.C., Groenewegen-ter Morssche, K. Van den Dikkenberg, R., 2015) show that fires started in upholstered furniture and mattresses develop fast. Besides upholstered furniture and mattresses also other fittings and other fixtures were used. From these tests it became clear that fire development and the probability of escape and survivability depends on many factors. On the basis of these tests no clear picture could be obtained about the fire behaviour of only the upholstery (furniture and mattresses) and the probability of escape and survivability in the domestic area.

To get a better impression the co-operation decided to perform several tests (experiments) in which the behaviour of upholstered furniture and mattresses, probability of escape and survivability is to be studied when ignited as full scale products in a fire testing environment representing a home environment (single room).

1.3 Purpose and research questions

The purpose of this research is to get an impression of the fire behaviour of the most sold mattresses and upholstered furniture (sofa) of the retailer and the probability of escape and survivability in the domestic area when exposed to different common test ignition sources (cigarette, open flame and/or crib 5). This research is also intended to create a starting point from which improvements can be made in order to increase the fire safety of furniture and mattresses of the retailer. On the basis of these objectives the following research questions are defined.

Research question 1:
What is the fire behaviour in a single room environment of the most sold mattresses and upholstered furniture of the retailer when exposed to common test ignition sources such as a cigarette, open flame or crib 5?

Research question 2:
What is the probability of escape and survivability in a single room environment when only the upholstered furniture (sofa) or mattress is burning?

1.4 Scope

As mentioned above the purpose is to get an impression of the fire behaviour, probability of escape and survivability in a single room environment. In order to get a good impression a limited number of fire tests (experiments) have been carried out. In addition, no such thing as a representative single room environment or representative fire scenario applies for the domestic area. The choice is therefor made to use an available single room environment that fits into the common dimensions of the domestic area and provides in a possible fire scenario. This means that this is a descriptive study to get an impression and does not have the intention to provide a comprehensive description of the fire behaviour, probability of escape and survivability in the domestic area.

2 Research method

2.1 Practical research

This section describes the experimental design of the practical research. The research method consists of the mentioned experiments. Because the purpose is to get an impression of the fire behaviour of the most sold upholstered furniture and mattrasses of the retailer only four experiments are carried out.

2.2 Experimental design

This section describes the experimental design containing a description of: the test facility in general, the fire room, the objects, the ignition sources, test protocol, measurements and measurement protocol.

2.2.1 General description

The experiments are carried out on a fire training area (Crailo, the Netherlands). In this area some small single floor semi-detached dwellings are located. All the dwellings have the same floorplan. The building structure consists of concrete, on the inside the structure is protected with gypsum board. All the windows are single glazed or provided with a cladding.

Figure 1: Semi-detached dwellings

Figure 2: Front of the dwellings

2.2.2 Fire room

In figure 3 the floor plan of the used building is presented. The building consists of two rooms; a hallway and the fire room. The fire room has the dimensions of a small living room or a large bedroom (22.5 m^2).

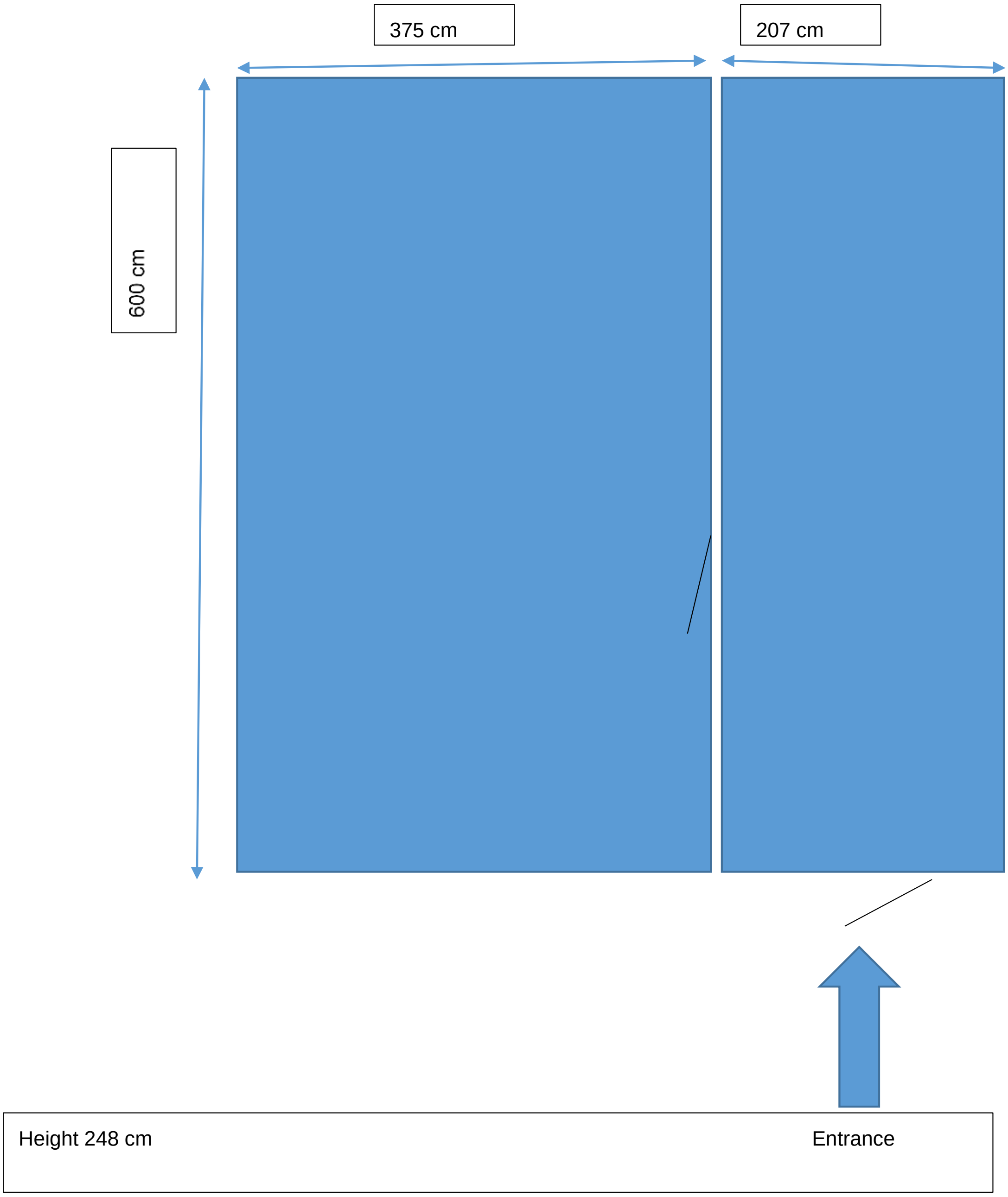

Figure 3: Floor plan

2.2.3 Objects

To get an impression of the fire behaviour of mattresses and upholstered furniture of the retailer the most sold items are tested. Based on information of the retailer the most sold items are two sofas and two mattresses. Both sofas are three-seat sofas with a standard foam filling and different top layers. Mattress 1 is a pocket sprung mattress with foam above and beneath the sprung. Mattress 2 is completely filled with foam.

2.2.4 Ignition sources and test protocol

Prescribed ignition sources from commonly known test methods have been used as much as possible. However, it is not the intention to exactly follow the common known test methods in these impression tests.

The following ignition sources are used:

- Test cigarettes (NIST);
- Open flame (candle);
- Larger ignition source (crib 5).

Figure 4: Test cigarette

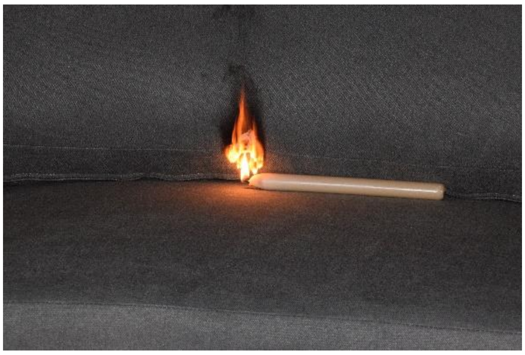

Figure 5: Candle

Figure 6: Crib 5

The following test protocol per ignition source is used:

- Cigarette:
  - If, after 5 minutes after burning the cigarette, no flames are visible, the test is aborted and the open flame test is performed;
  - If flames are visible within start test to 5 minutes after burning the cigarette, the test is completed. The test is terminated when the object is (largely) burned.
- Open flame/candle:
  - Only takes place if the cigarette test is aborted;
  - Open flame is maintained for 20 seconds at the object;
  - If, after 5 minutes after exposure to ignition source, no flames are visible, the test is aborted and the crib 5 test is performed;
  - If flames are visible within start test to 5 minutes after exposure ignition source the test is completed. The test is terminated when the object is (largely) burned.
- Crib 5:
  - Only takes place if the cigarette test is aborted (mattresses) or cigarette test and open flame test are aborted (sofas);
  - Object is ignited by crib 5 as ignition source. The test is terminated when the object is (largely) burned.

In table 1 a summary of the fire tests is presented.

Table 1: Fire tests

Object	Test	Ignition source
Sofa 1	1a 1b	Cigarette Open flame (candle)
Sofa 2	2a 2b	Cigarette Open flame (candle)
Mattress 1	3a 3b	Cigarette Crib 5
Mattress 2	4a 4b	Cigarette Crib 5

2.2.5 Measurements and measurement protocol

During the experiments temperature, radiation heat flux, carbon monoxide (CO), oxygen (O2) and nitrogen oxides (NOx) are measured. The measurements are started when the object is exposed to the ignition source.
The temperature is measured at two positions in the fire room, on three levels (0.5, 1.8 and 2.25 meters). The gas measurements (CO, NOx, and O2) are measured at two positions, on two levels (0.5 and 1.8 meters). Radiation heat flux is measured at two points at the front of the room. One is directed to the fire source. The other faces upwards to the hot smoke layer. There also are heat-resistant video cameras placed in the fire room. One camera is directed to the fire source, the other is directed to the door of the fire room. The test object is placed on a scale to measure the mass loss during the experiment. This scale has three measuring points. On top of those points a steel frame, a wooden panel and plasterboard are placed. The test object is placed on top of the plasterboard.

The details about the measurements, tools and position are included in table 2 and figure 7.

Table 2: Details measurements

Parameter	Measurement tool	Frequency	Position	Details
Temperature	Thermocouple tree	5x per second	2 positions	3 levels 0.5, 1.8 and 2.25 m
Radiation heat flux	Water cooled heat flux meter	5x per second	2 positions	1 faces fire source 1 faces hot smoke layer
Carbon monoxide (CO)	Testo's	Every 2 seconds	2 positions	2 levels 0.5 and 1.8m
Oxygen (O2)	Testo's	Every 2 seconds	2 positions	2 levels 0.5 and 1.8m
Nitrogen Oxides (NOx)	Testo's	Every 2 seconds	2 positions	2 levels 0.5 and 1.8m
Mass loss	Testo's	5x per second	1 position	Average of 3 points

The measurement tools for the gasses were placed through holes in the side walls of the adjacent building, as shown in figure 7. In this way the measurement tools could be protected against heat and safely be retrieved if necessary. However, this means that the measurements have taken place along the side walls of the fire room, while it is logical to take measurements in the middle of the room. This choice is made in favour of the safety of the measurement tools.

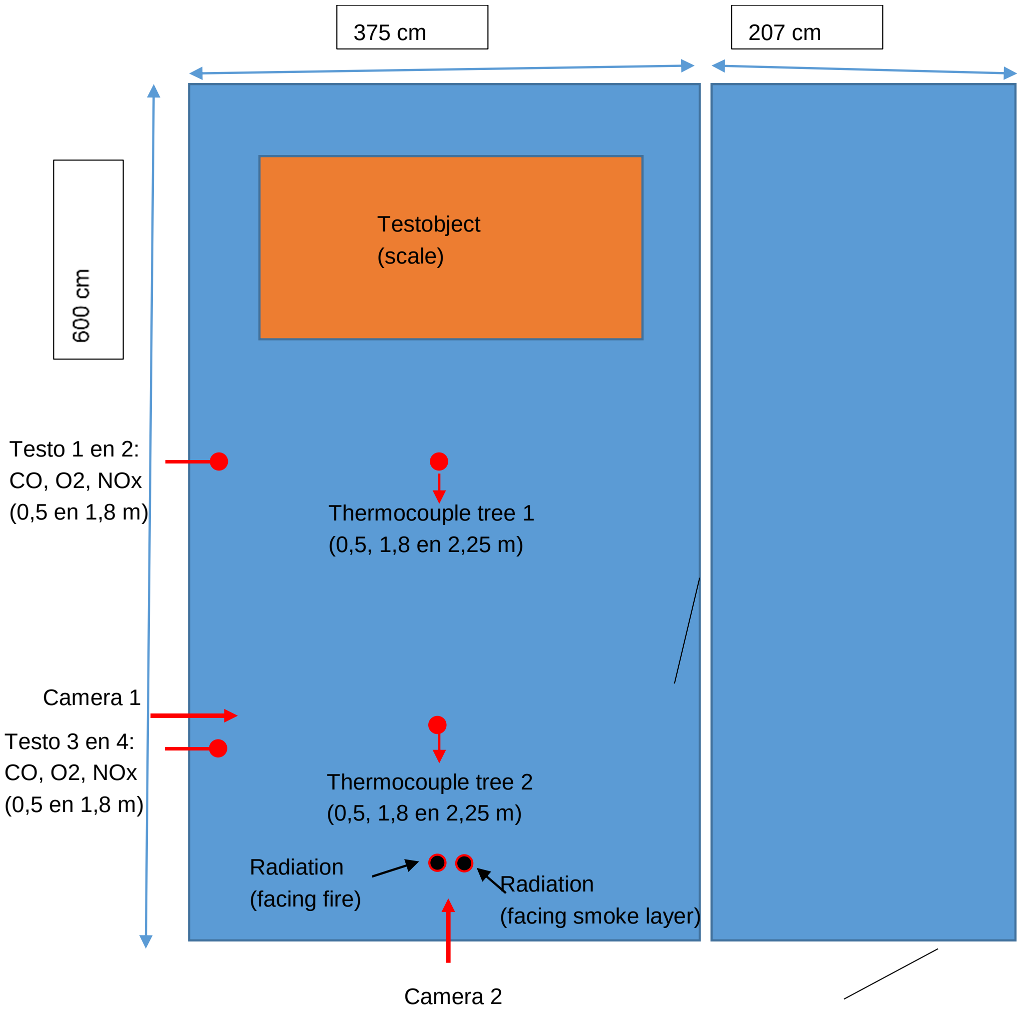

Figure 7: Measurement tools and location on the floor plan

2.3 Data analysis

2.3.1 Limit values for ignition

After the experiments the visible data is analyzed with the limit values for ignition. The used limit values are practical limits which are not the same as limit values from commonly known test methods. However these limits give an impression about the ignitability of the objects. The following limit values are used:

- Cigarette test: no flames visible from start test until 5 minutes after the cigarette is completely burned;
- Open flame test: no flames visible after removing the open flame;
- Crib 5 test: no flames visible after burning the crib.

2.3.2 Limit values for escape and survivability

After the experiments the measured data is analysed and compared with the limit values for escape and survivability. The limit values are based on literature research (Hazebroek, J.C., Groenewegen-ter Morssche, K. Van den Dikkenberg, R., 2015). It is based on values that apply to 50% of the population. A comprehensive motivation of the selected limit values is available in chapter 3 and the report *'Rapport Gebrand op inzicht'* (Kobes, M., Groenewegen-ter Morsche, K., 2015). Table 3 gives an overview of the applied values.

Table 3: Limit values

Parameter	Limit value escape (1.8 m)	Limit value survivability (0.5 m)
Heat (convection + radiation)	FEDheat ≥ 1	T ≥ 120 ºC q ≥ 6 kW/m^2
CO (+ 1% ppm HCN per ppm CO)	FEDtox ≥ 1 or 10 min AEGL-2 (CO ≥ 420 ppm)	10 min AEGL-3 (CO ≥ 1700 ppm) or 30 min AEGL-3 (CO ≥ 600 ppm)
O_2	O_2 ≤ 13%	O_2 ≤ 6%
NO_x	10 min AEGL-2 (NO_x ≥ 20 ppm)	10 min AEGL-3 (NO_x ≥ 34 ppm)

These values are used in this study to estimate the extent to which participants are able to escape, survive and / or have a high risk of long-term health damage. The following comments, however, are emphasized:

- This estimation relates to healthy adults. Other age groups or people with greater sensitivity will earlier experience a threshold to escape and possibly die sooner. These limits focus on 50 percent of the population.
- This is a theoretical estimation based on some factors. The combination of factors can't be quantified but will, in practice, have a (negative) impact.
- The limits of the individual factors are derived from literature. On this basis an estimation of the limit values is made. Also limit values in internationally accepted guidelines for Fire Safety Engineering are considered. More information is available in the report (Kobes, M., Groenewegen-ter Morsche, K., 2015).
- When irritants such as NOx lead to exceeding the limit for survivability not immediately mortality is assumed. Prolonged exposure or exposure to high concentrations can cause pulmonary oedema, lowering blood pressure and blood damage. Depending on the severity and possible complications, this leads to long-term health damage or death.
- (Extra) chances of survival by CPR after rescue is not included in this study.

3 Literature review

In this chapter a short overview of some literature about the probability of escape and survivability is included. For a literature review about for example, the need of fire safe furniture, existing regulations/test methods and statistics is referred to the report of the FEU working group (Federation of the European Union Fire Officer Associations (FEU), 2017).

3.1 General

In the literature four basic risk factors are mentioned for the safe escape and survival in case of fire:

1. The effect of limited visibility, which has an effect on the escape, but not on the survivability.
2. The effect of heat, is divided in the effect of convection (ambient temperature), the effect of radiation (radiation heat flux) and a too high core temperature.
3. The suffocating effect, as a result of, for example, too much carbon monoxide (CO), carbon dioxide (CO_2), hydrogen cyanide (HCN), and a lack of oxygen (O_2).
4. The effect of irritating substances, such as nitrogen oxides (NO_x), hydrogen chloride (HCl), hydrogen bromide (HBr), hydrogen fluoride (HF), sulfur dioxide (SO_2), acrolein (C_3H_4O), and formaldehyde (CH_2O).

Below de four basic risk factors are discussed.

3.2 Visual disturbance caused by smoke

Orientation abilities will decrease if smoke is getting thicker. At a certain smoke density people no longer distinguish doors, walls and similar and become even disoriented in familiar surroundings. Smoke density is an important factor that hinders escape. The speed of escape decreases further as the smoke contains irritants (Jin, T. & Yamada, T., 1985).

3.3 Exposure to heat

Two types of heat transport are important: convection (air temperature) and radiation (radiation heat flux).
People standing in hot air or smoke can be injured by three mechanisms:

> Skin burning
> Lung burning
> A too high core temperature

In the 60s and 80s of the last century, several researchers (Simms, D.L. & Hinkley, P.L., 1963) conducted experiments in which people are exposed to dry heat with temperatures that reached 110 ºC to 180 ºC. The aim of the experiments is to determine the tolerance to convective heat. The researches show for example that people can stay up to 5 minutes in an air temperature of 150 ºC. See also Table 4.

Table 4: Tolerance to convective heat

Temperature (°C)	Maximum duration
200	2 minutes
150	5 minutes
120	7 minutes
110	10 minutes
100	15 minutes
90	Longer than 30 minutes

At an air temperature up to about 120 ºC the exposure time is limited due to the rise of the core temperature. Above 120 ºC the exposure time is limited due to skin burns (Purser, D., 2002).

The tolerance to heat can in a large part be attributed to the human ability to cool itself by sweating (Kenney, W.L, DeGroot, D.W. & Holowatz, L.A., 2004). This also means that the more humid the ambient air, the less one is able to cool itself. However, there is little information available on the heat tolerance in humid ambient conditions since the tests were done with people, carried out in ambient conditions up to 45 ºC.

Even without direct contact to flames or hot smoke, pain can be felt or skin burns can be caused as a result of radiation heat flux. In the 50s to the early 80s of the last century (Simms, D.L. & Hinkley, P.L., 1963) (Veghte, J.H., 1982) (Kaplan, H.L., Grand, A.F., Switser, W.G., Mitchell, D.S., Rogers, et al., 1985) (Buettner, K. , 1951) several fire tests have been carried out to investigate the tolerance to radiation heat flux, with exposure values ranging from 2.4 kW/m^2 to 23.5 kW/m^2. The results are summarized in Table 5.

Table 5: Tolerance to radiation heat flux

Radiation (kW/m^2)	Maximum duration
15	2 seconds
8	5 seconds
6	7 seconds
2.5	Longer than 30 seconds

At an escape time of 100 seconds and a radiation heat flux of 6 kW/m^2 approximately half of the population will not survive.

3.4 Suffocating smoke gasses and lack of oxygen

Suffocating or asphyxiating substances cause, when inhaled, no respiratory or lung damage. These gasses are absorbed by the body, after which they exert their effects elsewhere in the body (Meulenbelt, J., Vries, I. De & Joore, J.C.A., 1996). The most relevant asphyxiating substances during a fire are carbon monoxide and hydrogen cyanide. Both of these substances interfere with the oxygen supply in the body, resulting in a depression of the central nervous system with loss of consciousness and, ultimately, death. The effect of asphyxiating substances is determined by the accumulated dose in the body (Hazebroek, J.C., Groenewegen-ter Morssche, K. Van den Dikkenberg, R., 2015).

In Table 6, the physical effects of exposure to carbon monoxide (CO) are shown at different concentrations. It is important to realize that for carbon monoxide poisoning it concerns the dose inhaled by someone and not merely the concentration to which it is exposed.

Table 6: Effects of CO at different concentrations (source: http://www.antigifcentrum.be/co-vergiftiging/co-wettenschappelijk-bekeken/wat-zijn-toxische-gehaltes-aan-co)

CO (ppm)	% CO in air	Symptoms
200	0.02	Headache, dizziness, nausea, fatigue.
400	0.04	Intense headache. Risk of death after 3 h.
800	0.08	Headache, dizziness, nausea. Unconsciousness after 45 minutes. Death after 2-3 hours.
1600	0.16	Severe symptoms after 20 minutes, death within the hour.
3200	0.32	Headache, dizziness, nausea after 5 minutes, Unconsciousness after 30 minutes.
6400	0.64	Headaches and dizziness after 1-2 minutes. Unconsciousness after 10-15 minutes.
12800	1.28	Immediate unconsciousness, death within 1 to 3 minutes.

In literature it is often assumed that a carbon monoxide concentration of 12,800 ppm (Struttmann, T., Scheerer, A., Prince, S. & Goldstein, L., 1998) leads to death within three minutes. (Brown, S.K. & Cheng, M. , 2000), apply a limit of 8,000 ppm for an acute effect.

In addition to carbon monoxide (CO) hydrogen cyanide (HCN) is an important gas within the category asphyxiating substances that may be released during a fire. The mechanism of HCN is different than that of carbon monoxide, but the physiological effects are very similar. HCN is about 25 times more toxic than carbon monoxide. HCN can be released in a(n) (incomplete) combustion of foam in mattresses and furniture.
Based on ISO 13571 Life-threatening components of fire - Guidelines for the estimation of time available for escape using fire data (ISO 2012), the dose of asphyxiating substances can be determined. The 'Fractional Effective Dose (FED tox)' takes into account both the presence of carbon monoxide and hydrogen cyanide.

Besides suffocating substances a lack of oxygen can also cause negative health effects. Different symptoms occur if the percentage of oxygen decreases. The severity rises if the percentage of oxygen in the air decreases. In table 7 health effects at different oxygen levels are shown.

Table 7: Percentage oxygen and health effects (Lipsett, M.J., Shusterman, D.J. & Beard, R.R., 1994).

Oxygen %	Health effects
12-16	Breathing and heart rate are increased. Coordination of the muscles is slightly reduced.
10-14	Abnormal fatigue, upon exhaustion Disordered breathing, emotional reactions.
6-10	Nausea and vomiting, inability to move freely, possible unconsciousness.
< 6	Convulsions, choking, breathing stops after a few minutes, followed by heart failure.

3.5 Irritating substances

For irritants distinction can be made between different compounds based on the solubility in water. The first group consists generally of substances which are (very) well soluble in water, such as hydrogen chloride (hydrochloric acid), and sulphur dioxide. These substances react fast with the mucous membranes of the eyes, nose, throat and respiratory tract. This results in watery eyes, sore throat, cough and a burning sensation behind the breastbone at relatively low concentrations. These effects influence the probability of escape, intensify the effects of visual disturbance by smoke and are especially dependent on the concentration to which people are exposed.

The second type of irritating substances, such as NOx (nitrogen oxides) penetrate deeper into the lungs and cause infections, but can also cause pulmonary oedema among other things. The effects deeper into the lungs are especially dependent on dose and occur later on (until many hours later). Therefore these substances do not lead directly to death but mainly have an effect on health of people already escaped or rescued from a burning building. In addition, the inhalation of soot and particulate matter also leads to subsequent health effects. Another complicating factor is also that substances soluble in water at higher concentrations, or when these compounds are absorbed by particles, can penetrate deep into the lungs and can cause serious effects.

3.6 Summary

During escape, a person can be exposed to the effects of fire. Such as limited visibility, exposure to heat (convection and radiation), the risk of inhalation of suffocating and irritant substances and a lack of oxygen. One or more of these factors may lead to a situation during a fire at which escape and / or survival is not possible.

4 Results

In this chapter the results are presented. In section 4.1 to 4.4 the results according to the probability of ignition, escape and survivability per test are included. Section 4.5 includes the results about the heat release rate. Section 4.6 is an analysis and summary of all the results.

4.1 Test 1 sofa 1

This section is divided in two sub-sections. In the first sub-section the results from the cigarette test are shown. In the second sub-section the results of the open flame test are presented.

4.1.1 Cigarette test

In figure 8 to 10 pictures are shown on the cigarette test.

Figure 8: Burning cigarette

Figure 9: Burned cigarette

Figure 10: Result

The pictures make clear that the object is not ignited due to a burning cigarette. After the cigarette is extinguished no smouldering appears in the filling or in the top layer of the object. Figure 10 makes also clear that the top layer is melted away due to the burning cigarette. The object has passed the cigarette test.

4.1.2 Open flame test

In figure 11 to 14 pictures are shown on the open flame test.

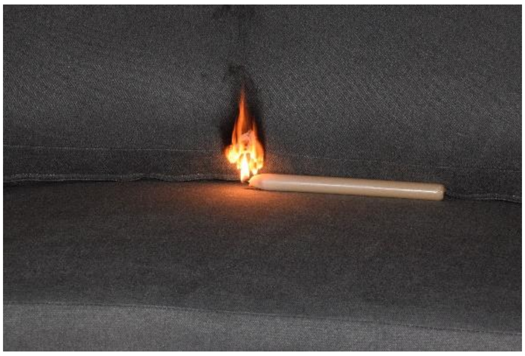

Figure 11: Start open flame test

Figure 12: Fire spread over cushion

Figure 13: Fully developed fire

Figure 14: End result

The pictures make clear that the object is ignited by a bigger ignition source, such as a candle. The ignition of the object starts within the 20 seconds exposure to the open flame. After ignition of the filling the flame spread over the object is in all directions. The temperatures are high enough to break the windows. The object has failed the open flame test.

In the following figures the results of the measurements related to probability of escape and survivability are shown.

Heat

Figure 15, 16 and 17 show the temperature graph, the radiation heat flux graph and the FEDheat graph.

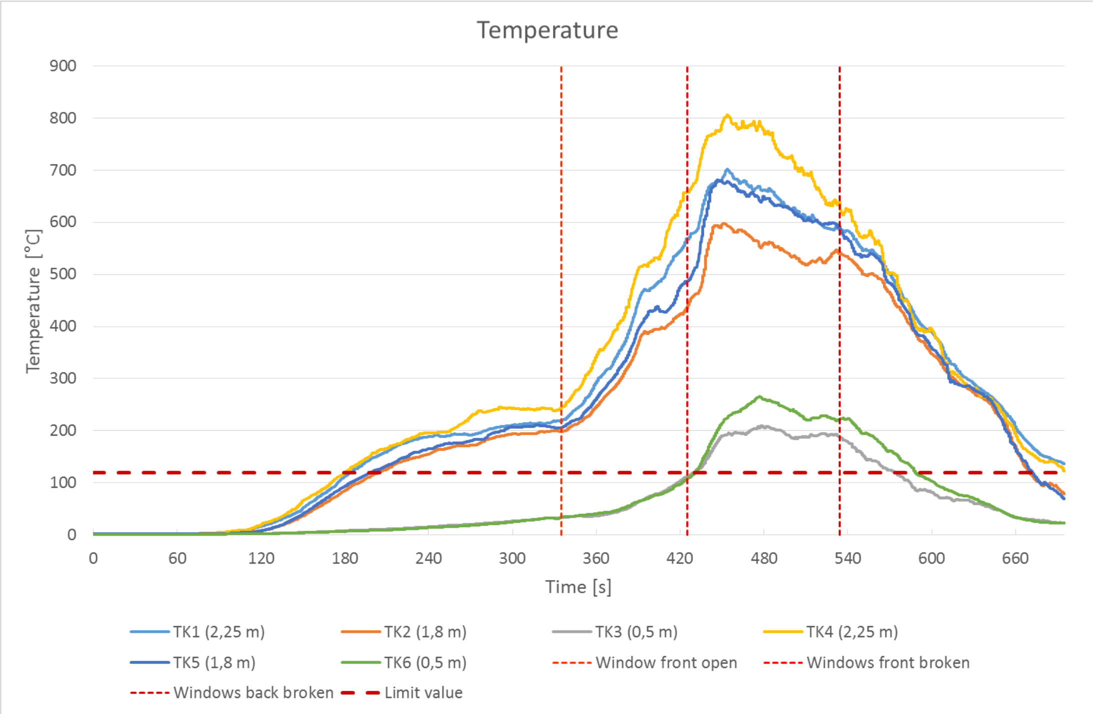

Figure 15: Temperature graph

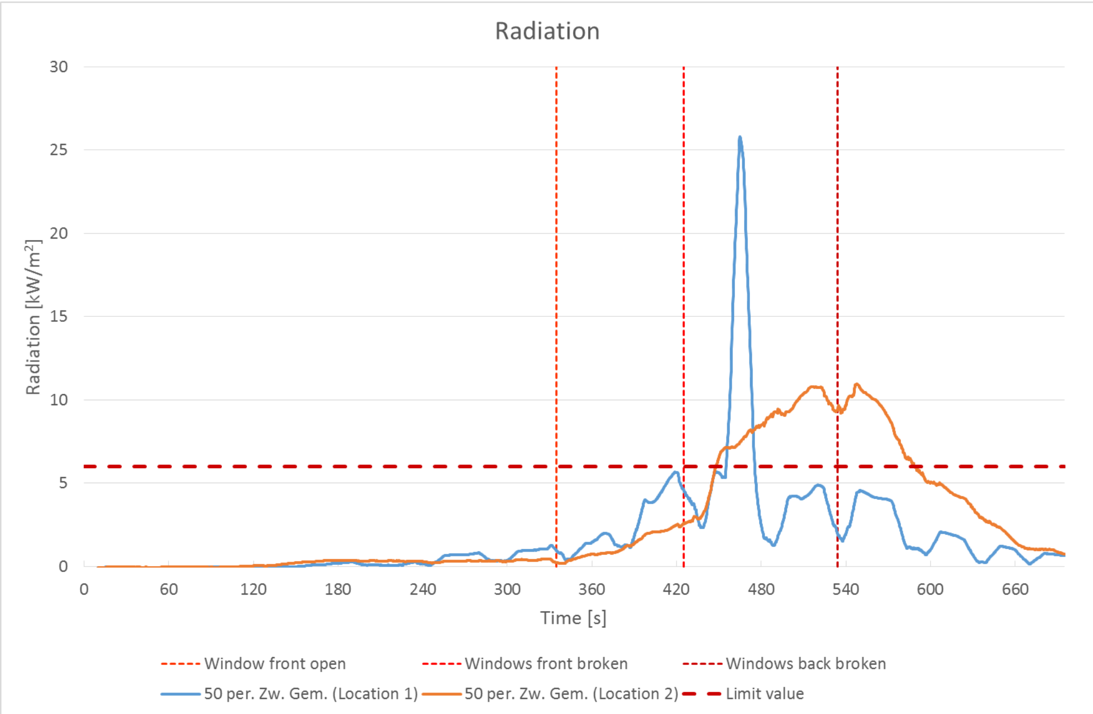

Figure 16: Radiation heat flux graph

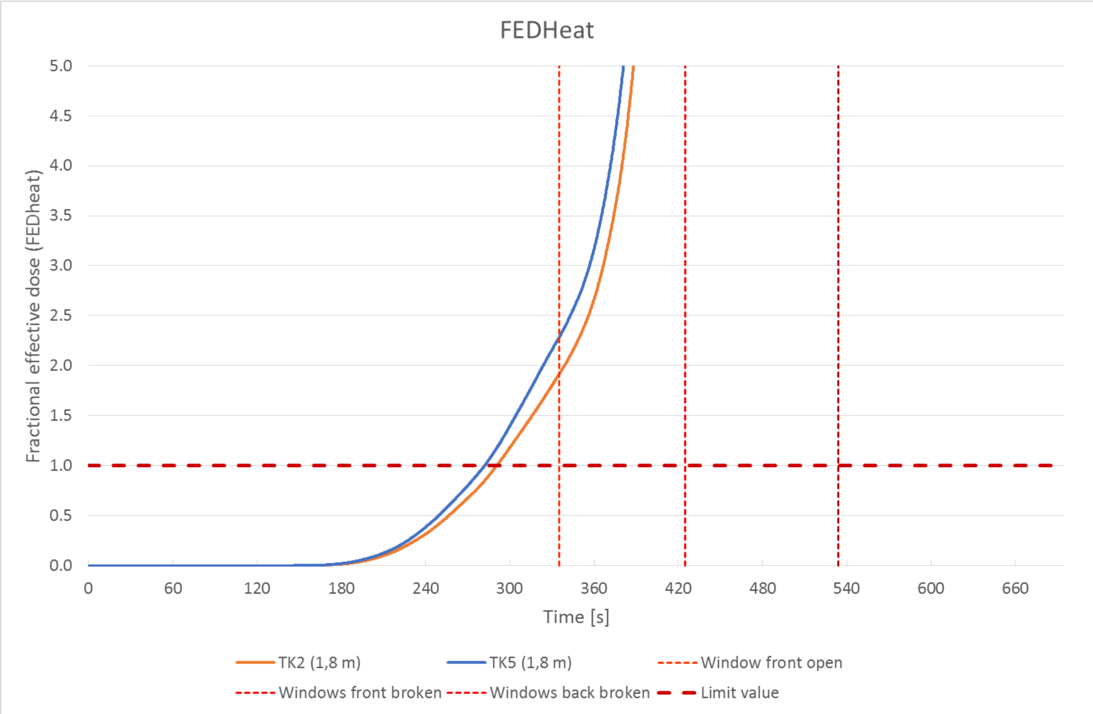

Figure 17: FEDheat graph

Figure 17 make clear that after 4 to 5 minutes the limit value for escape (FEDheat at 180 cm) is exceeded. Figure 15 makes clear that after 7 to 8 minutes the limit value for survivability (120 °C at 50 cm) is exceeded. Figure 15 also shows that after the front windows break the temperatures in the upper layer increase to values between 500 °C to 800 °C. These temperatures are high enough to cause a flashover in a fully furnished living room. The radiation heat flux (figure 16) also exceeds the limit value for survivability ($\geq$ 6 kW/m^2 at 50 cm) after 7 to 8 minutes.

Carbon monoxide

Figure 18 and 19 show the carbon monoxide graph and the FEDCO graph.

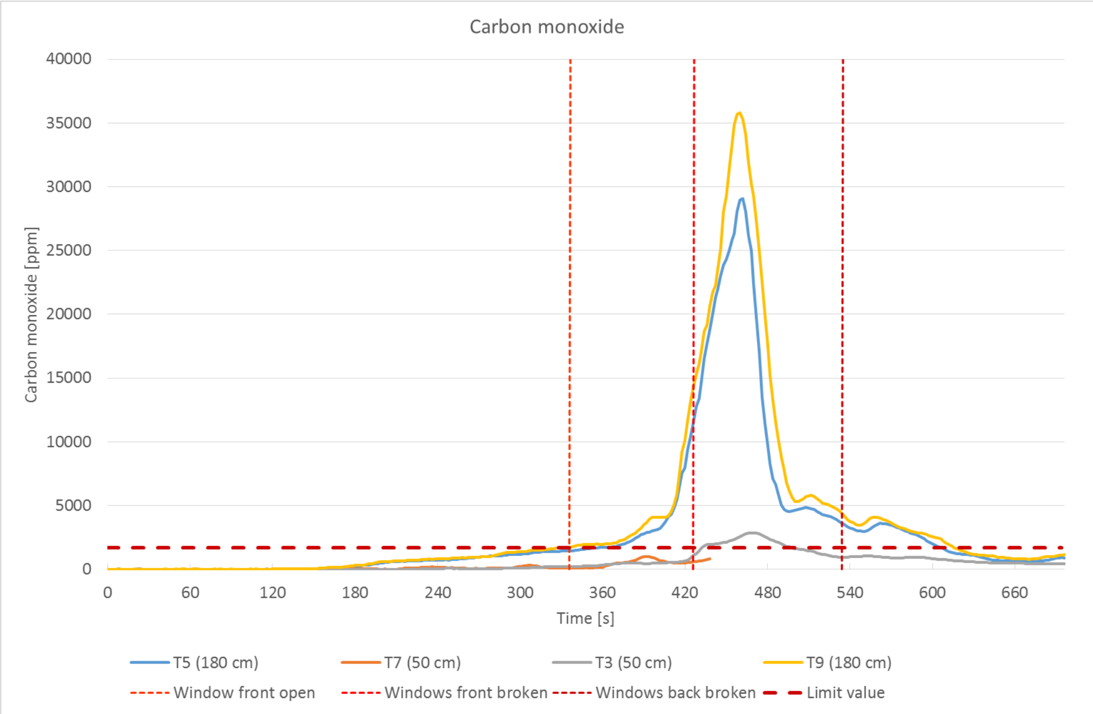

Figure 18: Carbon monoxide graph

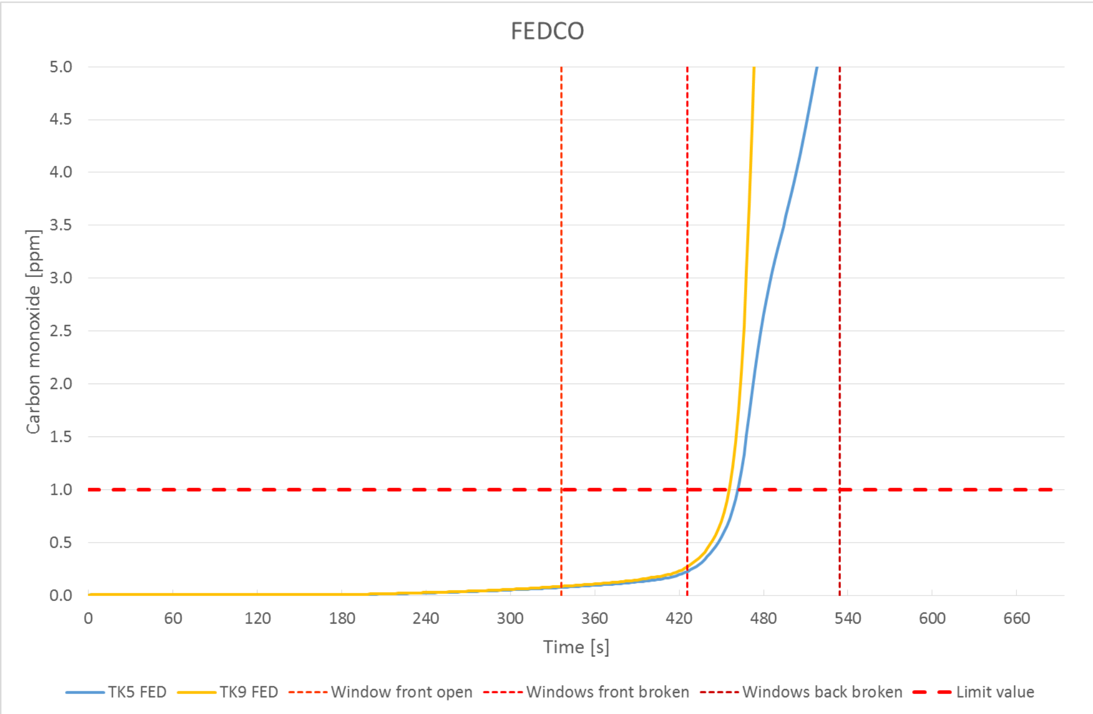

Figure 19: FEDCO graph

Figure 19 makes clear that after 7 to 8 minutes the limit value for escape (FEDCO at 180 cm) is exceeded. The limit value for survivability (10 min AEGL-3, CO $\geq$ 1700 ppm at 50 cm) is not exceeded during the test. The value of 1700 ppm (figure 18) is exceeded between 7 to 9 minutes (2 minutes maximum). In the upper layer carbon monoxide concentration up to 35000 ppm are reached. The carbon monoxide concentration increases after the front windows break and the fire is fully developed.

Oxygen

Figure 20 shows the oxygen graph.

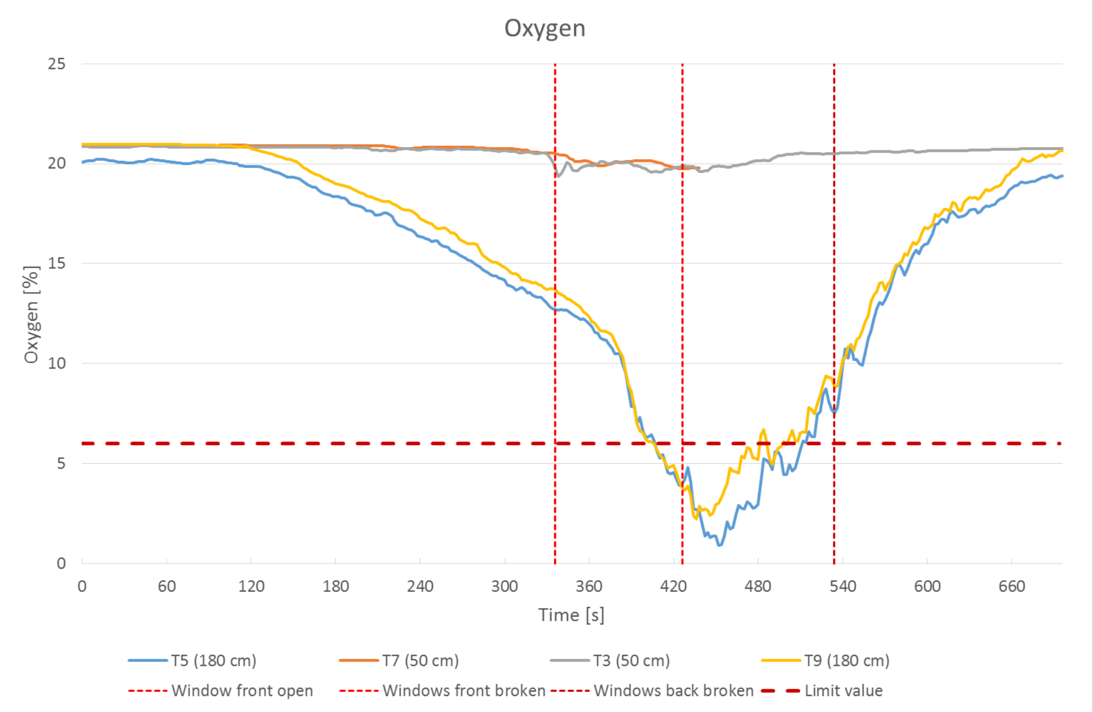

Figure 20: Oxygen graph

Figure 20 makes clear that within 5 to 10 minutes the limit value for escape ($\leq$ 13% at 180 cm) is exceeded. The limit value for survivability ($\leq$ 6% at 50 cm) is not exceeded during the test. Between opening one of the front windows and the breaking of the back windows the oxygen concentration in the upper layer decreases rapidly. The same decrease is not visible at 50 cm above the floor.

Nitrogen oxides

Figure 21 shows the nitrogen oxides graph.

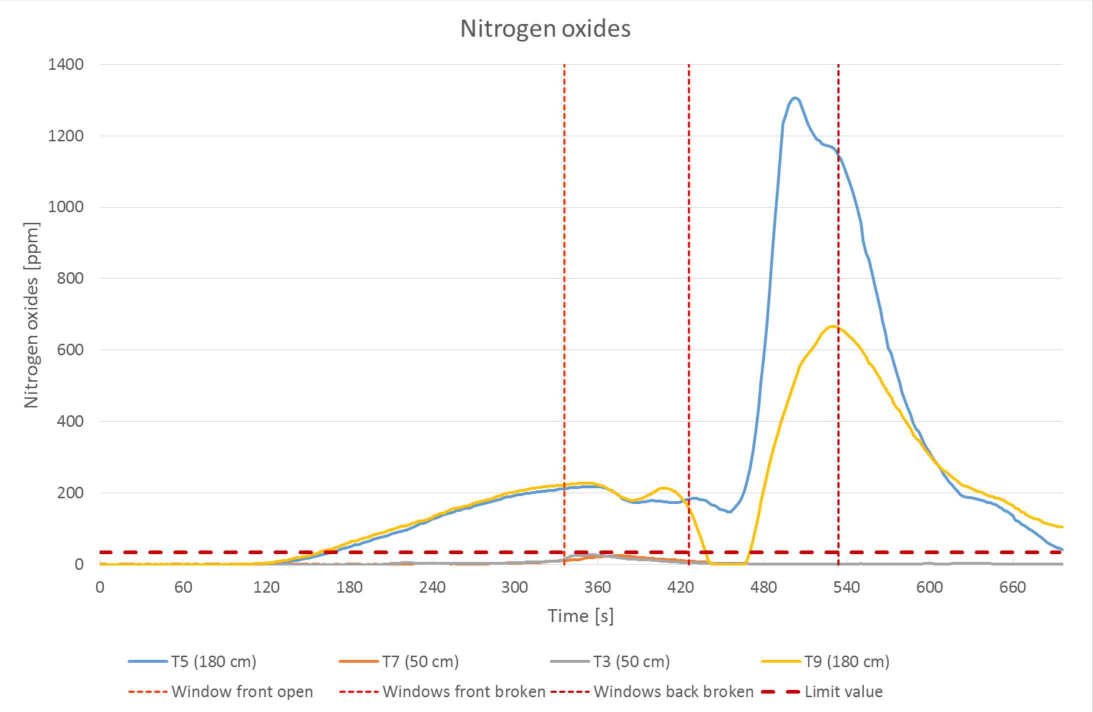

Figure 21: Nitrogen oxides graph

Figure 21 makes clear that both the limit values for escape (10 minutes AEGL-2, $NO_x \geq 20$ ppm at 180 cm) and survivability (10 minutes AEGL-3, $NO_x \geq 34$ ppm at 50 cm) are not exceeded. The value of 20 ppm in the upper layer is exceeded between 2 minutes and the end of the test. Probably the limit value for escape is exceeded if the test lasted longer.

Summery

In table 8 a summary of the results related to the probability of escape and survivability are shown.

Table 8: Summery results test 1 sofa 1

Parameter	Limit value escape (1.8 m) [min.]	Limit value survivability (0.5 m) [min.]
Heat	4 - 5	7 - 8
CO	7 - 8	-
O_2	5 - 6	-
NO_x	-	-

For test 1 the parameter heat is determining.

4.2 Test 2 sofa 2

This section is divided in two sub-sections. In the first sub-section the results from the cigarette test are shown. In the second sub-section the results of the open flame test are presented.

4.2.1 Cigarette test

In figure 22 and 23 pictures are shown on the cigarette test.

Figure 22: Burning cigarette

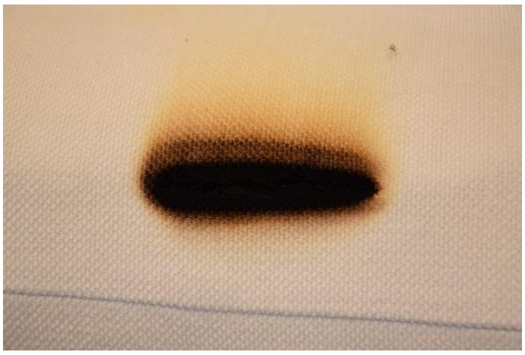

Figure 23: Result

The pictures make clear that the object is not ignited due to a burning cigarette. After the cigarette is extinguished no smouldering appears in the filling or in the top layer of the object. Figure 23 makes also clear that the top layer is not melted away due to the burning cigarette. The object has passed the cigarette test.

4.2.2 Open flame test

In figure 24 to 27 pictures are shown on the open flame test.

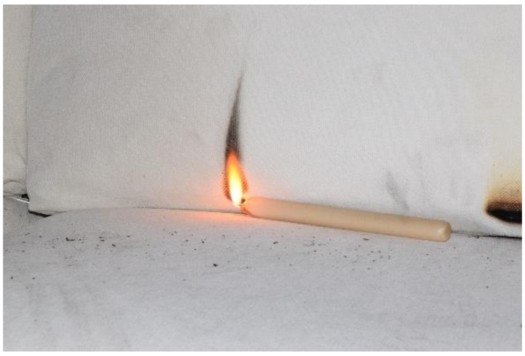

Figure 24: Start open flame test

Figure 25: Fire spread over cushion

Figure 26: Fully developed fire

Figure 27: End of test

The pictures make clear that the object is ignited by a bigger ignition source, such as a candle. The ignition of the object starts within the 20 seconds exposure to the open flame. After ignition of the filling the flame spread over the object is in all directions. The temperatures are high enough to break the windows. This object has failed the open flame test.

In the following figures the results of the measurements related to probability of escape and survivability are shown.

Heat

Figure 28, 29 and 30 show the temperature graph, the radiation heat flux graph and the FEDheat graph.

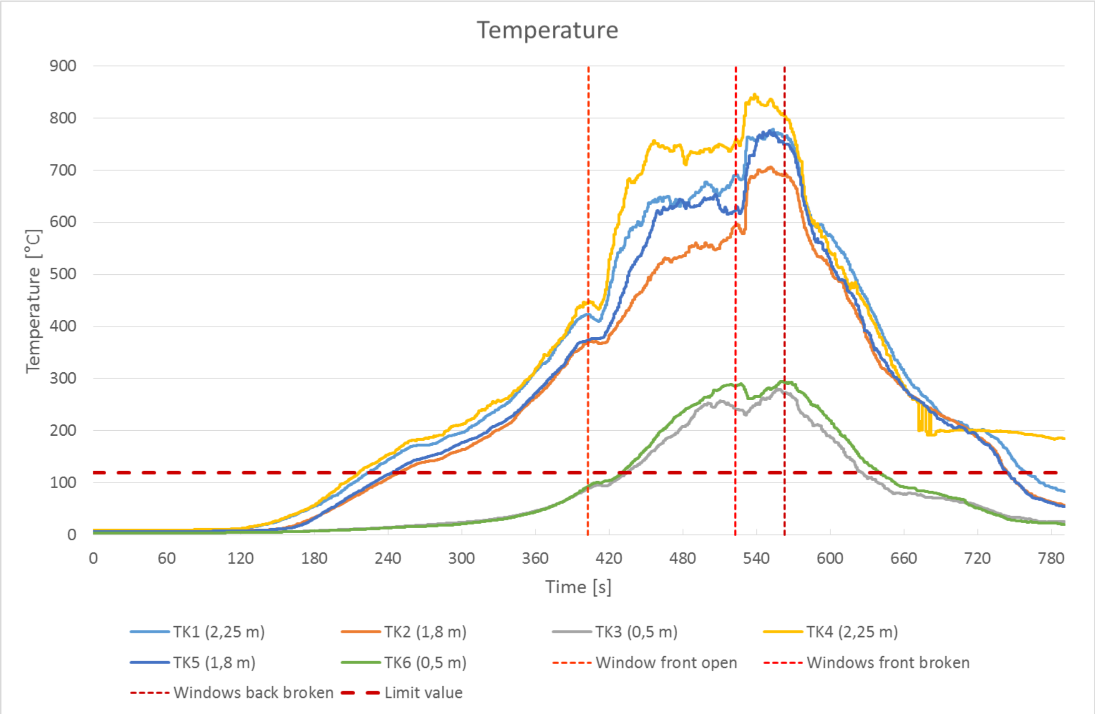

Figure 28: Temperature graph

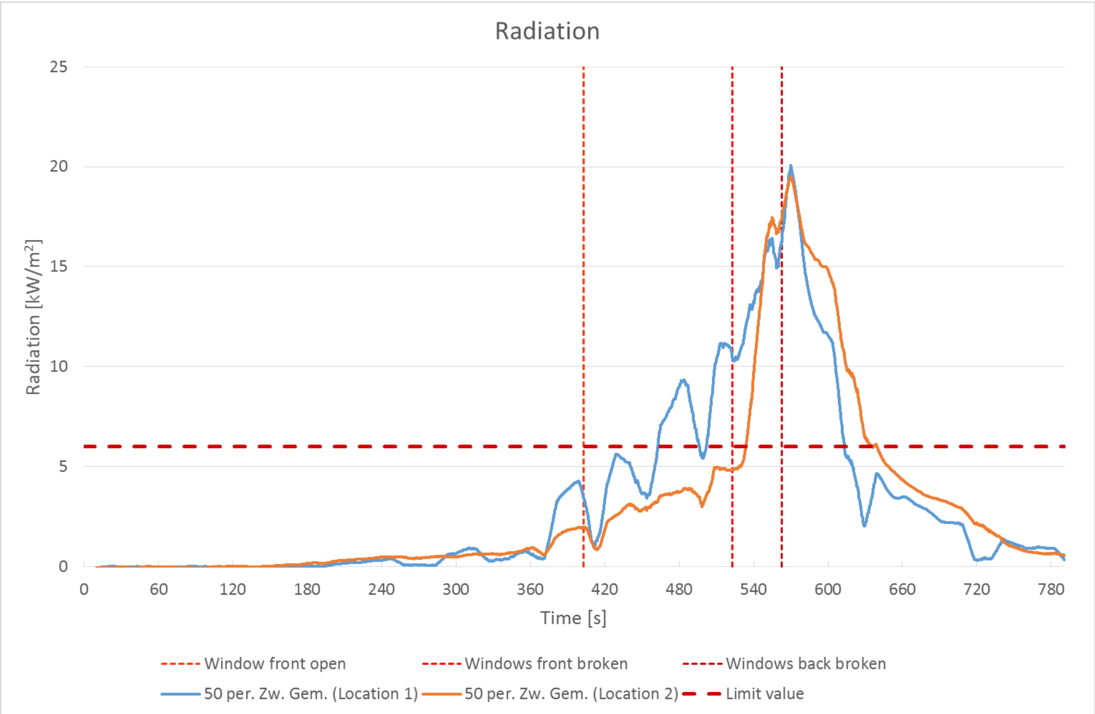

Figure 29: Radiation heat flux graph

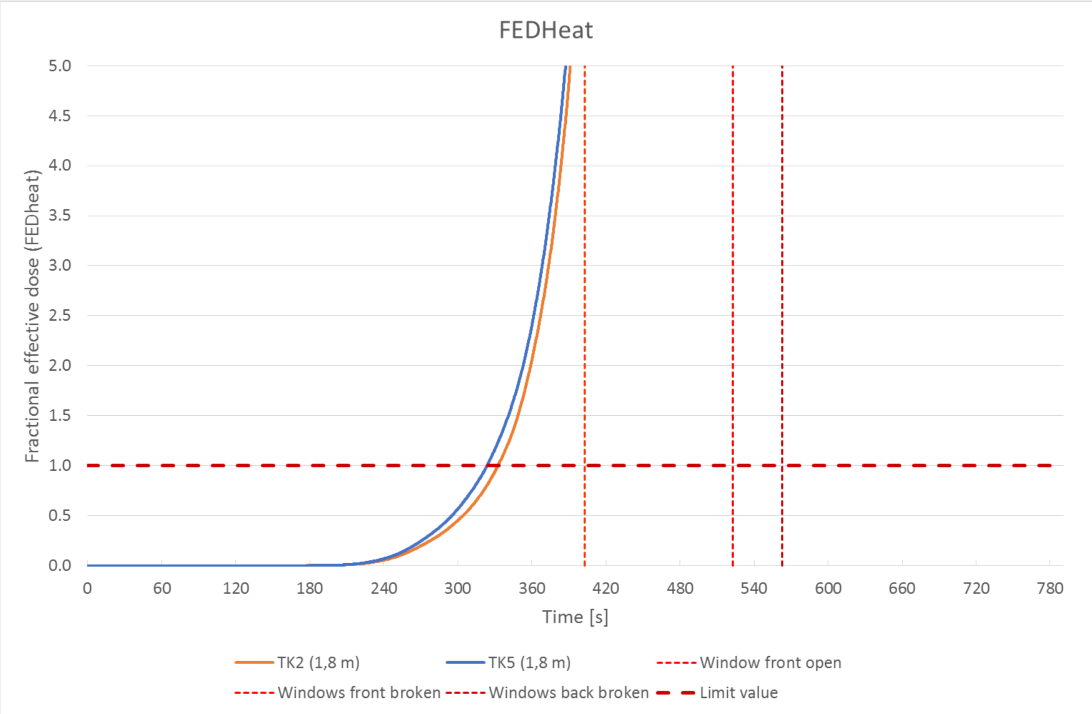

Figure 30: FEDheat graph

Figure 30 makes clear that after 5 to 6 minutes the limit value for escape (FEDheat at 180 cm) is exceeded. Figure 28 makes clear that after 7 to 8 minutes the limit value for survivability (120 °C at 50 cm) is exceeded. Figure 28 also shows that between opening a front window and the breaking of the back windows the temperatures in the upper layer increase to values between 400 °C to 850 °C. These temperatures are high enough to cause a flashover in a fully furnished living room. The radiation heat flux (figure 29) also exceeds the limit value for survivability ($\geq$ 6 kW/m^2 at 50 cm) after 7 to 8 minutes.

Carbon monoxide

Figure 31 and 32 show the carbon monoxide graph and the FEDCO graph.

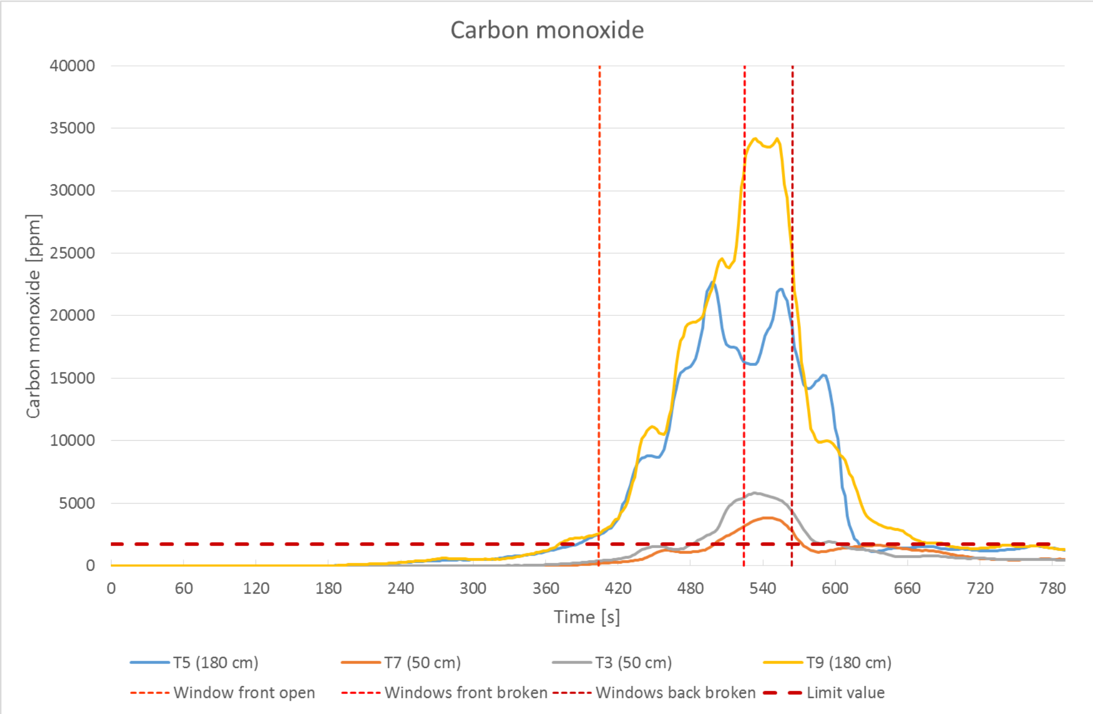

Figure 31: Carbon monoxide graph

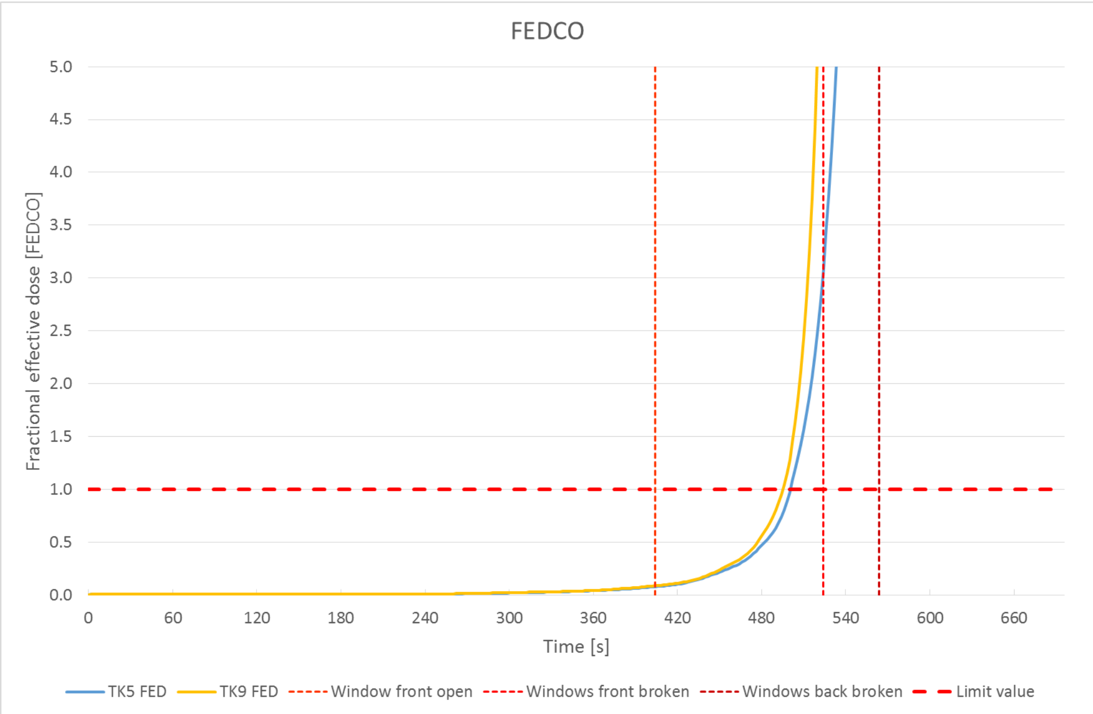

Figure 32: FEDCO graph

Figure 32 makes clear that after 8 to 9 minutes the limit value for escape (FEDCO at 180 cm) is exceeded. The limit value for survivability (10 min AEGL-3, CO $\geq$ 1700 ppm at 50 cm) is not exceeded during the test. The value of 1700 ppm (figure 31) is exceeded between 8 to 10 minutes (2 minutes maximum). In the upper layer carbon monoxide concentration up to 34000 ppm are reached. The carbon monoxide concentration increases after the front window is opened and reaches its peak when the fire is fully developed.

Oxygen

Figure 33 shows the oxygen graph.

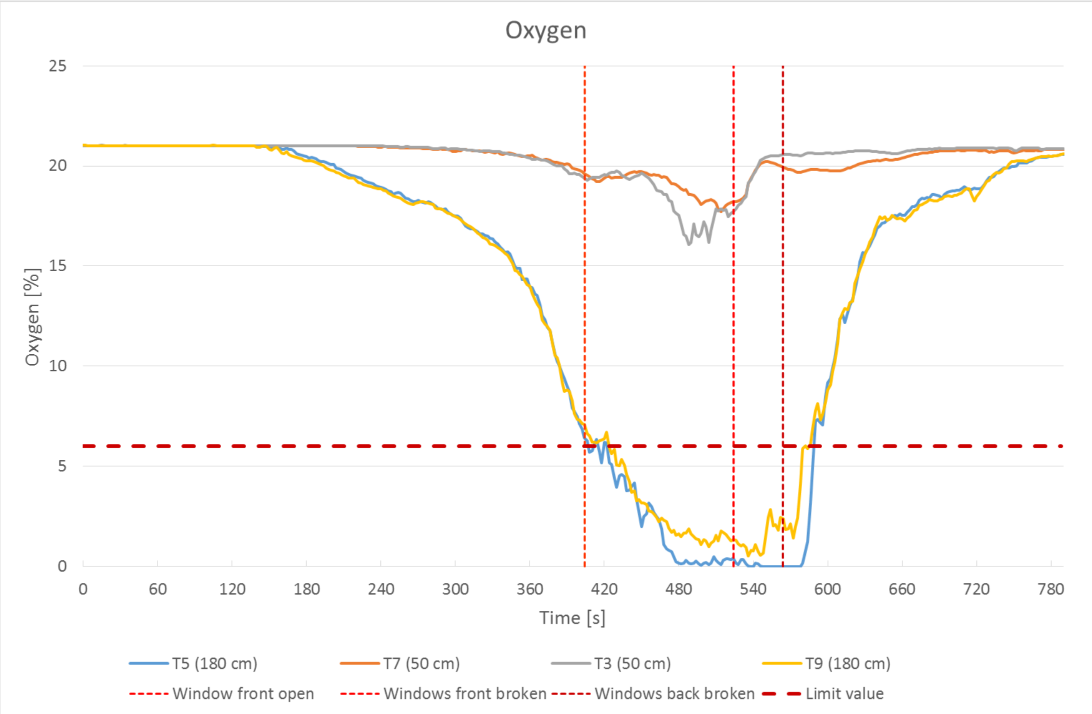

Figure 33: Oxygen graph

Figure 33 makes clear that within 6 to 11 minutes the limit value for escape ($\leq$ 13% at 180 cm) is exceeded. The limit value for survivability ($\leq$ 6% at 50 cm) is not exceeded during the test. After 6 minutes the oxygen concentration in the upper layer decreases rapidly. The same decrease is not visible at 50 cm above the floor.

Nitrogen oxides

Figure 34 shows the nitrogen oxides graph.

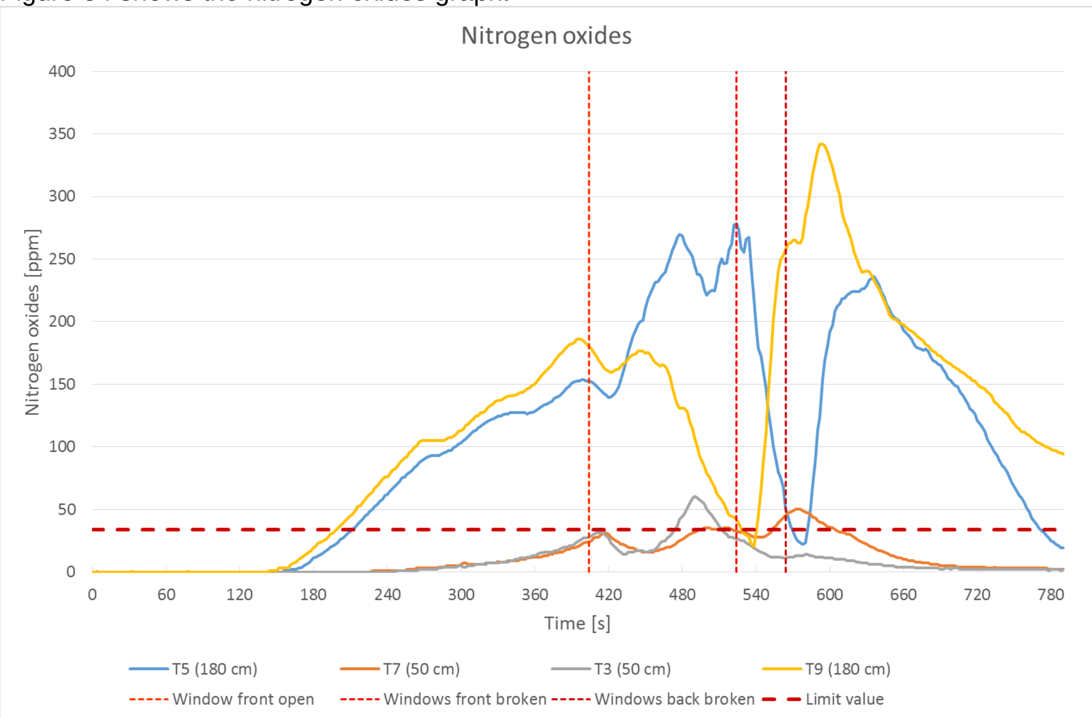

Figure 34: Nitrogen oxides graph

Figure 34 makes clear that both the limit values for escape (10 minutes AEGL-2, $NO_x \geq 20$ ppm at 180 cm) and survivability (10 minutes AEGL-3, $NO_x \geq 34$ ppm at 50 cm) are not exceeded. The value of 20 ppm in the upper layer is exceeded between 3 minutes and the end of the test. Probably the limit value for escape is exceeded if the test lasted longer.

Summery
In table 9 a summary of the results related to the probability of escape and survivability are shown.

Table 9: Summary results test 2 sofa 2

Parameter	Limit value escape (1.8 m) [min.]	Limit value survivability (0.5 m) [min.]
Heat	5 - 6	7 - 8
CO	8 - 9	-
O_2	6 - 7	-
NO_x	-	-

For test 2 the parameter heat is determining.

4.3 Test 3 mattress 1

This section is divided in two sub-sections. In the first sub-section the results from the cigarette test are shown. In the second sub-section the results of the crib 5 test are presented.

4.3.1 Cigarette test
In figure 35 and 36 pictures are shown on the cigarette test.

Figure 35: Burning cigarette

Figure 36: Result

The pictures make clear that the object is not ignited due to a burning cigarette. After the cigarette is extinguished no smouldering appears in the filling or in the top layer of the object. Figure 36 makes also clear that the top layer is slightly melted away due to the burning cigarette. The object has passed the cigarette test.

4.3.2 Crib 5 test
In figure 37 to 40 pictures are shown on the crib 5 test.

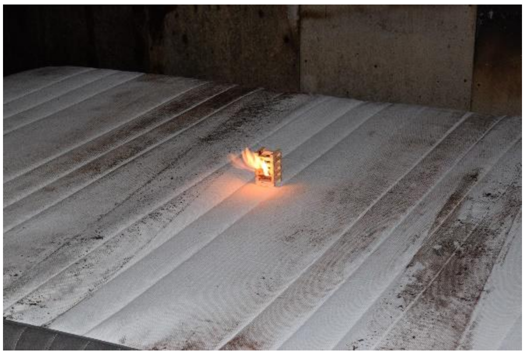

Figure 37: Start crib 5 test

Figure 38: Fire spread over mattress

Figure 39: Windows closed

Figure 40: Fully developed fire

The pictures make clear that the object is ignited by a bigger ignition source, such as a crib 5. The ignition of the object starts well before the crib is burned. After ignition of the filling the flame spread over the object is in all directions. The temperatures are high enough to break the windows. This object has failed the crib 5 test.

In the following figures the results of the measurements related to probability of escape and survivability are shown.

Heat

Figure 41, 42 and 43 show the temperature graph, the radiation heat flux graph and the FEDheat graph.

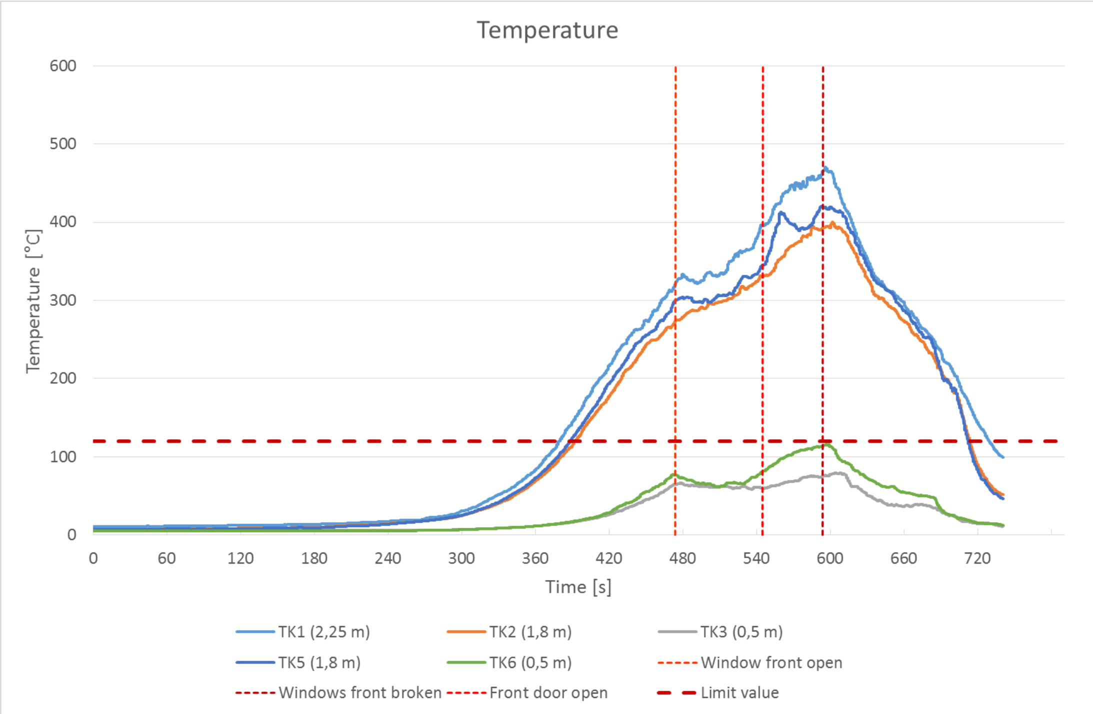

Figure 41: Temperature graph

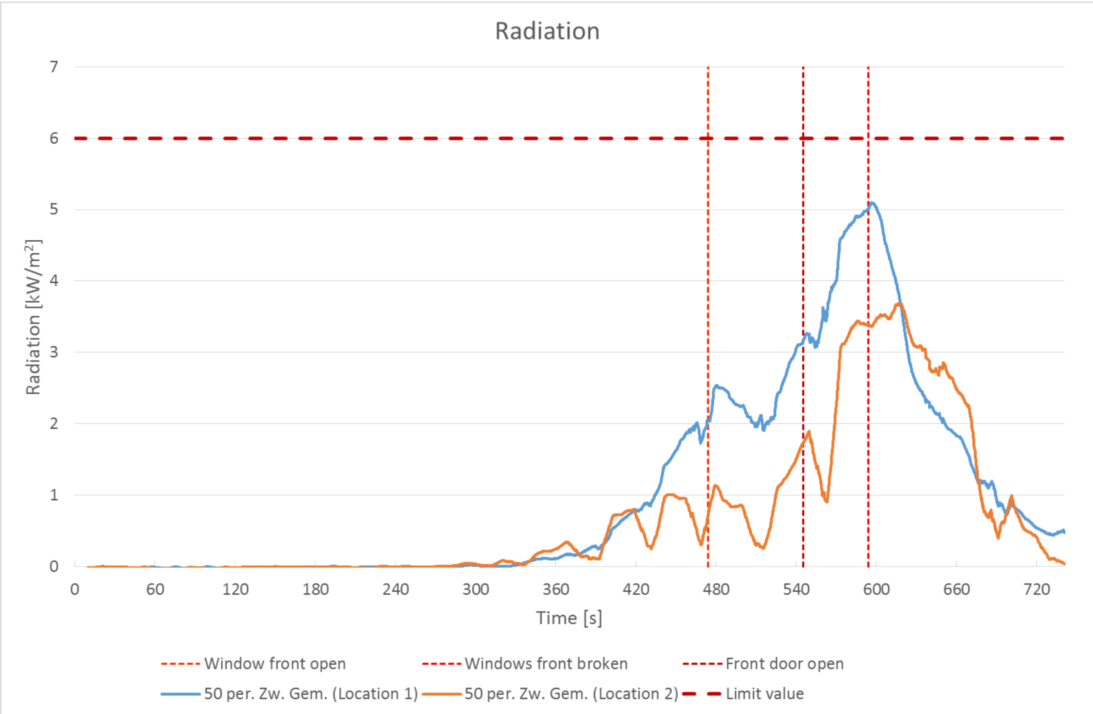

Figure 42: Radiation heat flux graph

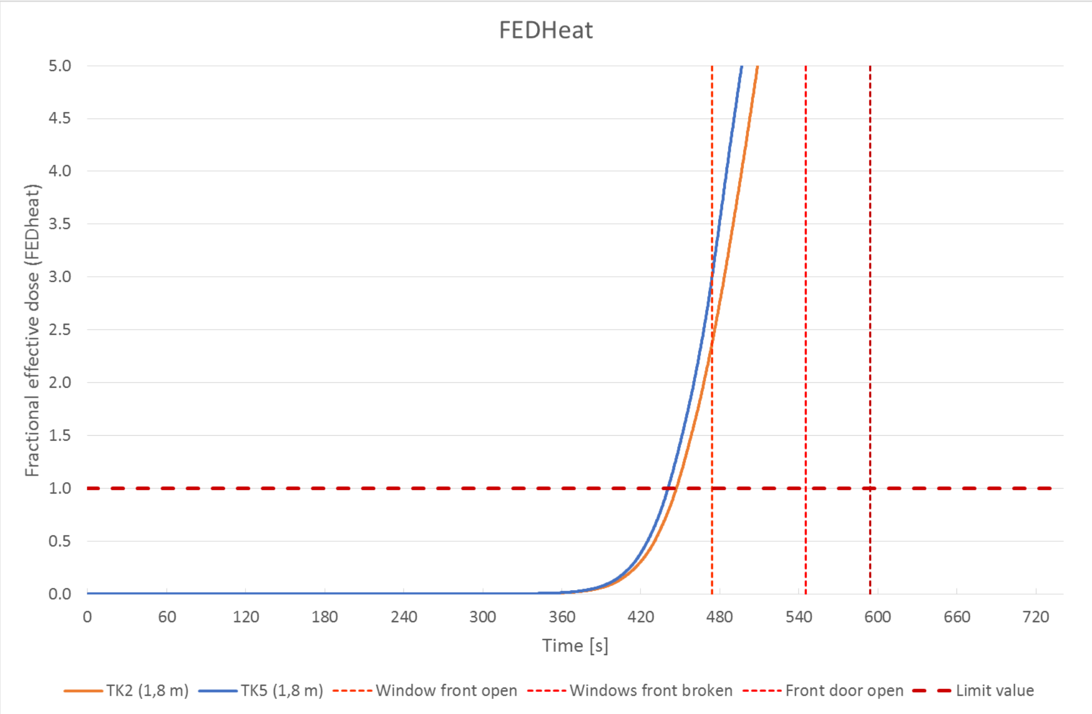

Figure 43: FEDheat graph

Figure 43 makes clear that after 7 to 8 minutes the limit value for escape (FEDheat at 180 cm) is exceeded. Figure 41 makes clear that the limit value for survivability (120 °C at 50 cm) is not exceeded. Figure 41 also shows that after 8 to 10 minutes the temperatures in the upper layer increase to values between 250 °C to 450 °C. These temperatures are probably high enough to cause a flashover in a fully furnished bedroom. The limit value for survivability ($\geq$ 6 kW/m^2 at 50 cm) concerning the radiation heat flux (figure 42) is not exceeded.

Carbon monoxide

Figure 44 and 45 show the carbon monoxide graph and the FEDCO graph.

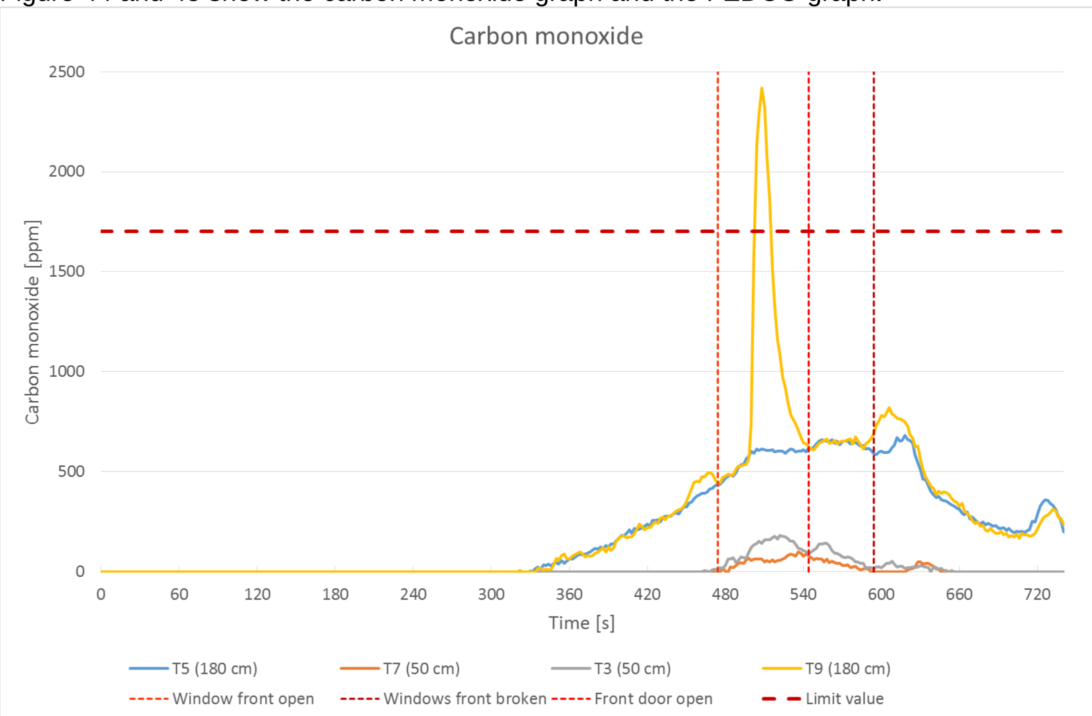

Figure 44: Carbon monoxide graph

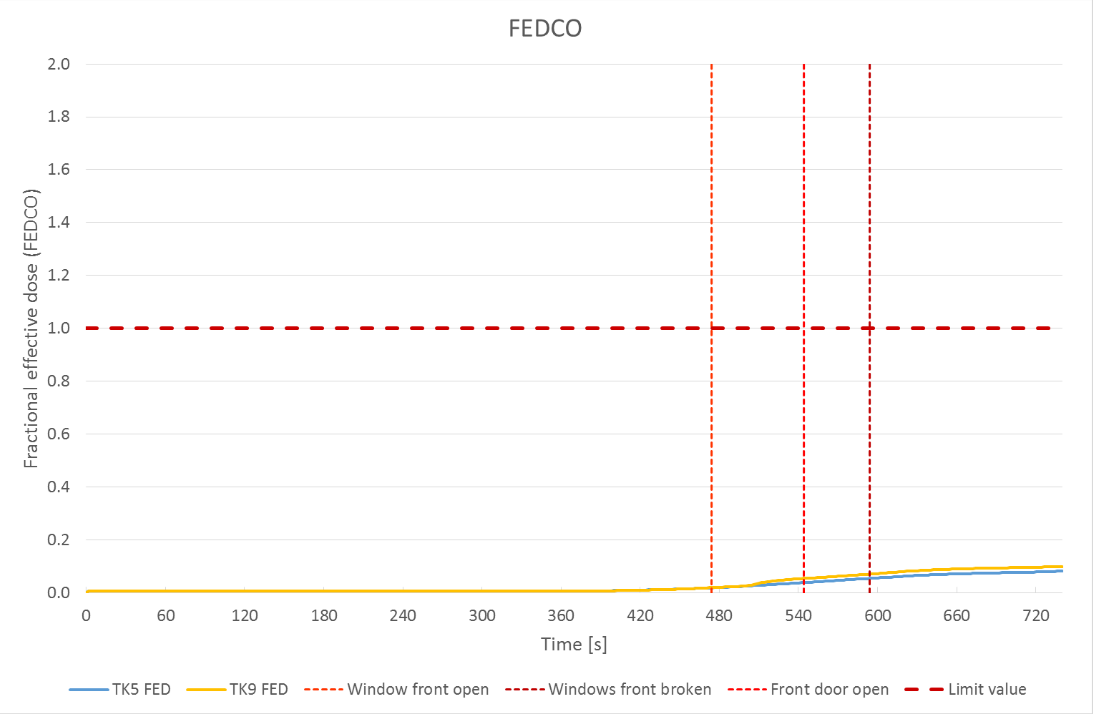

Figure 45: FEDCO graph

Figure 44 and 45 makes clear that both the limit values for escape (FEDCO at 180 cm) and survivability (10 min AEGL-3, CO $\geq$ 1700 ppm at 50 cm) are not exceeded during the test. The value of 1700 ppm is exceeded between 8 to 9 minutes (short peak).

Oxygen

Figure 46 shows the oxygen graph.

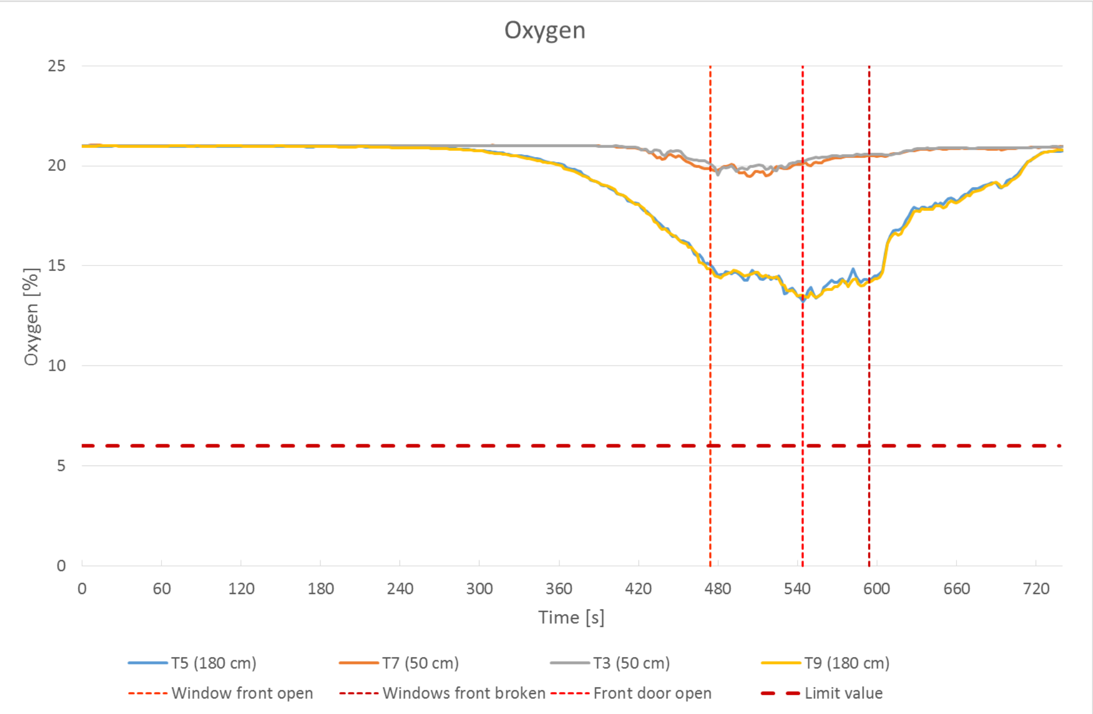

Figure 46: Oxygen graph

Figure 46 makes clear that both the limit value for escape ($\leq$ 13% at 180 cm) and survivability ($\leq$ 6% at 50 cm) are not exceeded during the test. After 5 to 6 minutes the oxygen concentration in the upper layer decreases to approximately 14%.

Nitrogen oxides

Figure 47 shows the nitrogen oxides graph.

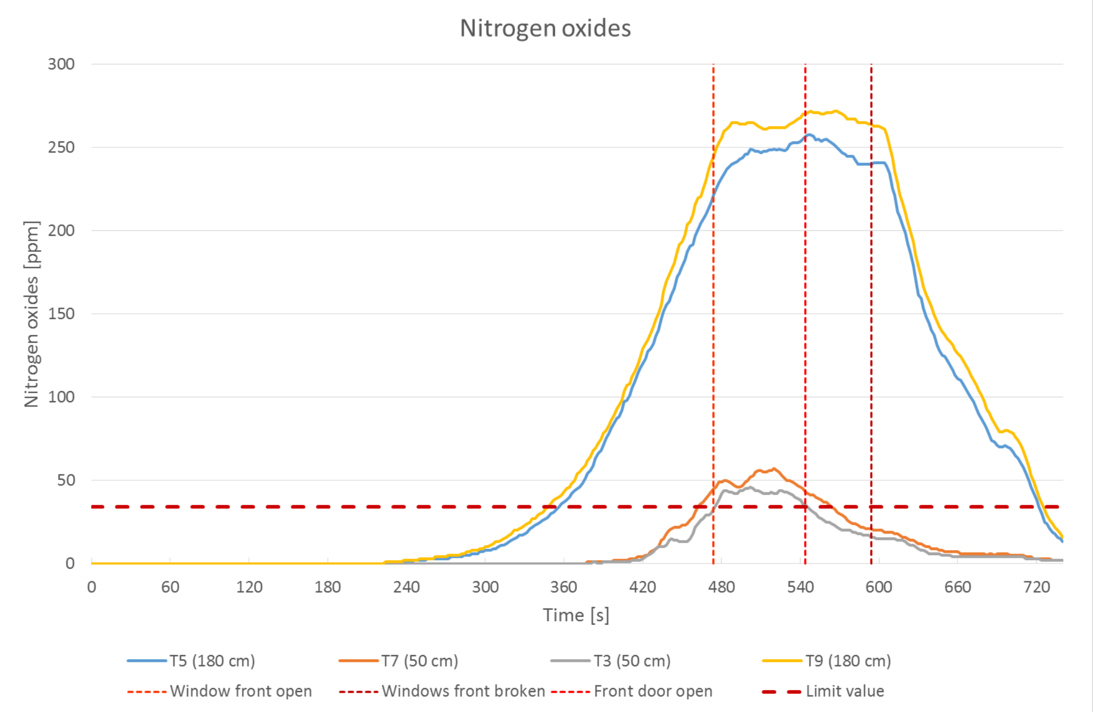

Figure 47: Nitrogen oxides graph

Figure 47 makes clear that both the limit values for escape (10 minutes AEGL-2, $NO_x \geq$ 20 ppm at 180 cm and survivability (10 minutes AEGL-3, $NO_x \geq$ 34 ppm at 50 cm) are not exceeded. The value of 20 ppm in the upper layer is exceeded between 5 to 12 minutes.

Summery

In table 10 a summary of the results related to the probability of escape and survivability are shown.

Table 10: Summary results test 3 mattress 1

Parameter	Limit value escape (1.8 m) [min.]	Limit value survivability (0.5 m) [min.]
Heat	7 - 8	-
CO	-	-
O_2	-	-
NO_x	-	-

For test 3 the parameter heat is determining.

4.4 Test 4 mattress 2

This section is divided in two sub-sections. In the first sub-section the results from the cigarette test are shown. In the second sub-section the results of the crib 5 test are presented.

4.4.1 Cigarette test

In figure 48 and 49 pictures are shown on the cigarette test.

Figure 48: Burning cigarette

Figure 49: Result

The pictures make clear that the object is not ignited due to a burning cigarette. After the cigarette is extinguished no smouldering appears in the filling or in the top layer of the object. Figure 49 makes also clear that the top layer is not melted away due to the burning cigarette. The object has passed the cigarette test.

4.4.2 Crib 5 test

In figure 50 to 53 pictures are shown on the crib 5 test.

Figure 50: Start crib 5 test

Figure 51: Fire spread over mattress

Figure 52: Fully developed fire

Figure 53: End of the test

The pictures make clear that the object is ignited by a bigger ignition source, such as a crib 5. The ignition of the object starts well before the crib is burned. After ignition of the filling the flame spread over the object is in all directions. The temperatures are high enough to break the windows. This object has failed the crib 5 test.

In the following figures the results of the measurements related to probability of escape and survivability are shown.

Heat

Figure 54, 55 and 56 show the temperature graph, the radiation heat flux graph and the FEDheat graph.

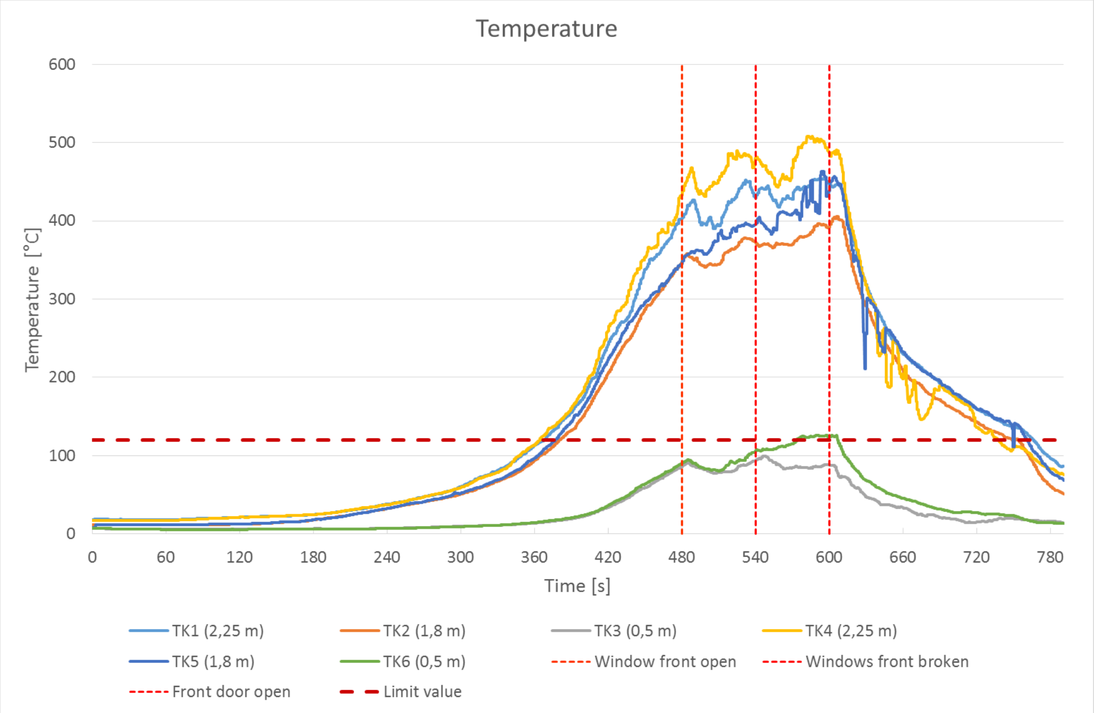

Figure 54: Temperature graph

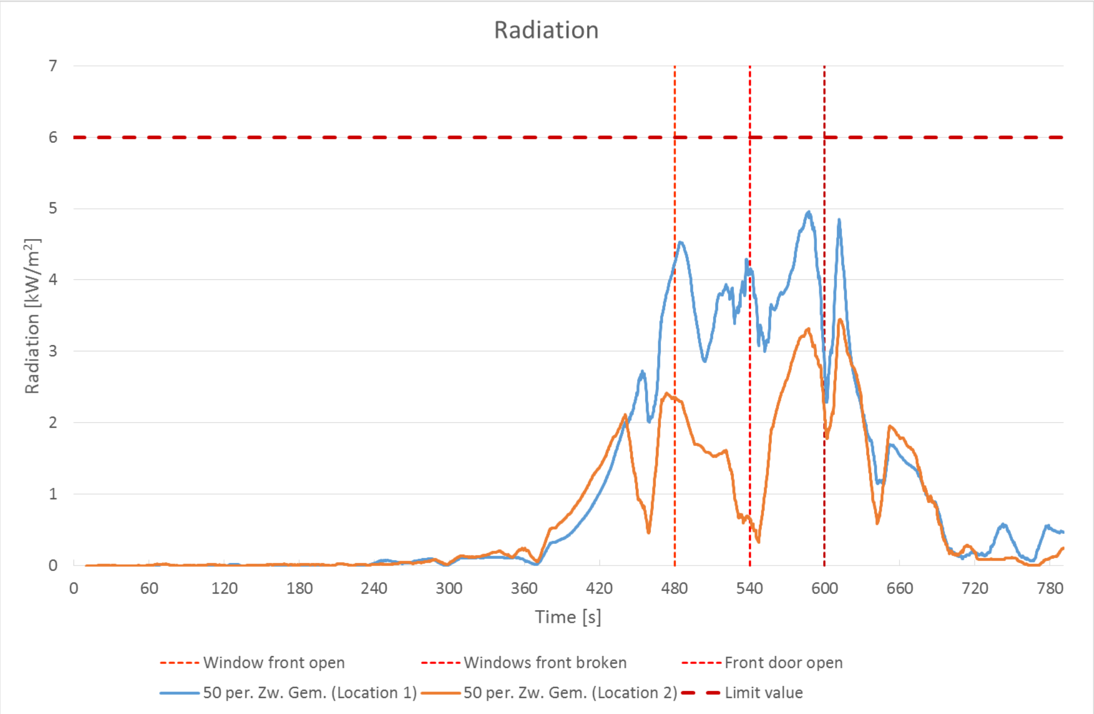

Figure 55: Radiation heat flux graph

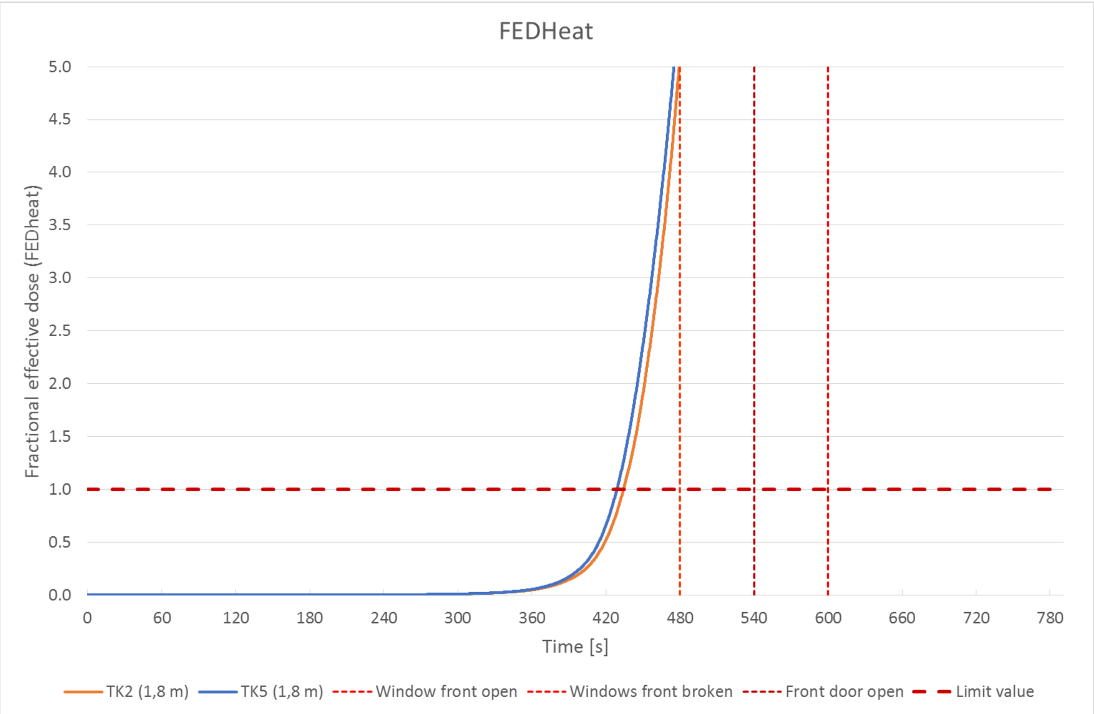

Figure 56: FEDheat graph

Figure 56 makes clear that after 7 to 8 minutes the limit value for escape (FEDheat at 180 cm) is exceeded. Figure 54 makes clear that the limit value for survivability (120 °C at 50 cm) is exceeded after 9 to 10 minutes. Figure 54 also shows that after 8 to 10 minutes the temperatures in the upper layer increase to values between 350 °C to 500 °C. These temperatures are high enough to cause a flashover in a fully furnished bedroom. The limit value for survivability (≥ 6 kW/m² at 50 cm) concerning the radiation heat flux (figure 55) is not exceeded.

Carbon monoxide

Figure 57 and 58 show the carbon monoxide graph and the FEDCO graph.

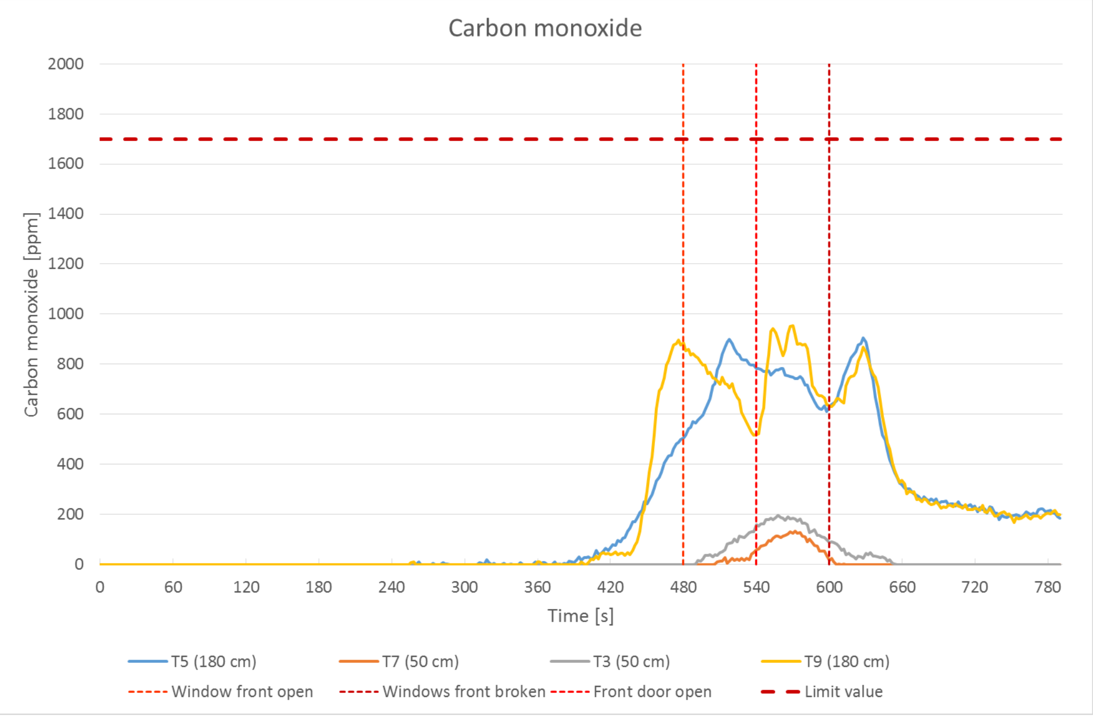

Figure 57: Carbon monoxide graph

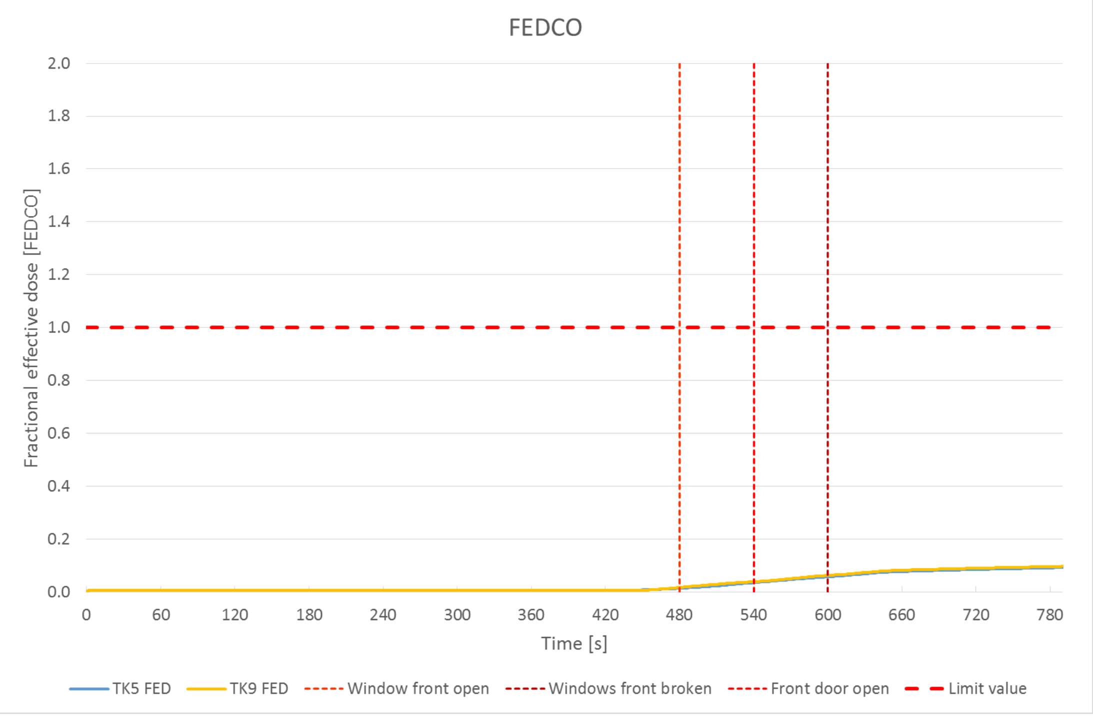

Figure 58: FEDheat graph

Figure 57 and 58 make clear that both the limit values for escape (FEDCO at 180 cm) and survivability (10 min AEGL-3, CO $\geq$ 1700 ppm at 50 cm) are not exceeded during the test.

Oxygen

Figure 59 shows the oxygen graph.

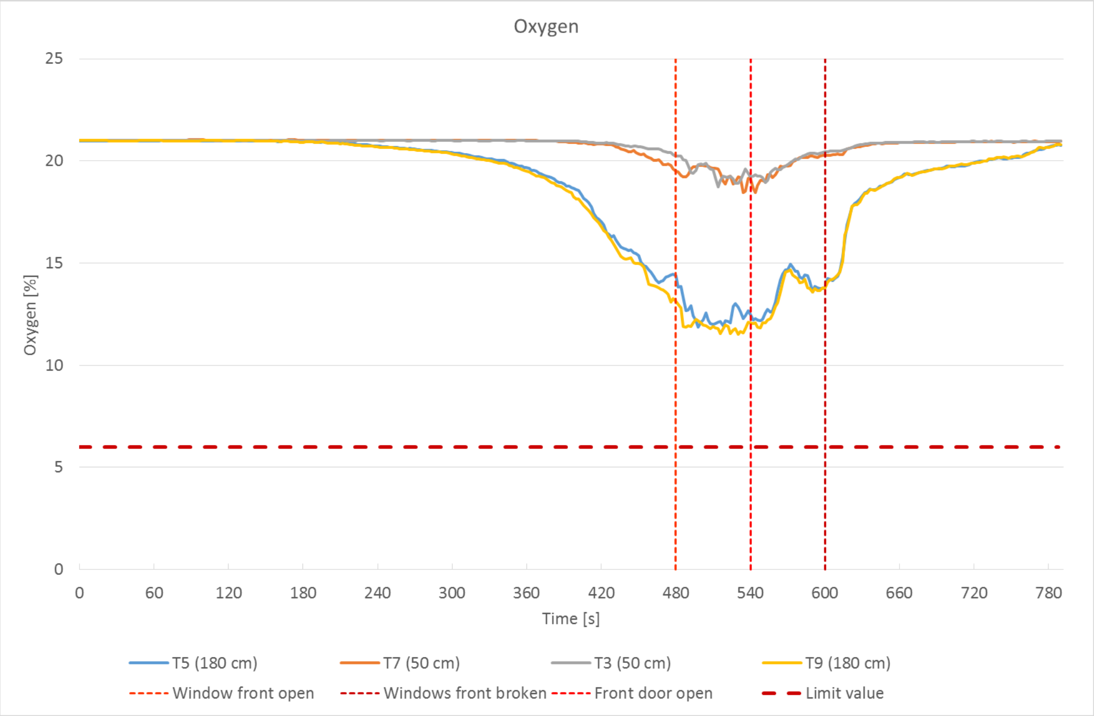

Figure 59: Oxygen graph

Figure 59 makes clear that within 8 to 10 minutes the limit value for escape ($\leq$ 13% at 180 cm) is exceeded. The limit value for survivability ($\leq$ 6% at 50 cm) is not exceeded during the test. After 6 minutes the oxygen concentration in the upper layer decreases.

Nitrogen oxides

Figure 60 shows the nitrogen oxides graph.

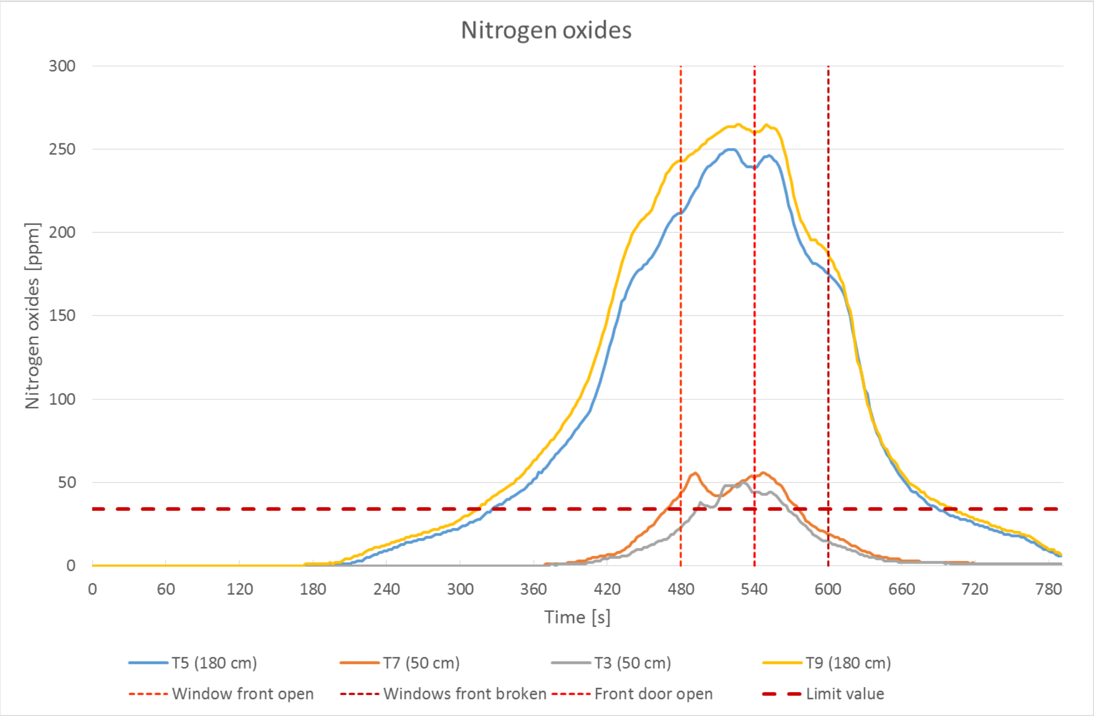

Figure 60: Nitrogen oxides graph

Figure 60 make clear that both the limit values for escape (10 minutes AEGL-2, $NO_x \geq 20$ ppm at 180 cm) and survivability (10 minutes AEGL-3, $NO_x \geq 34$ ppm at 50 cm) are not exceeded. The value of 20 ppm in the upper layer is exceeded between 4 to 12 minutes.

Summery

In table 11 a summary of the results related to the probability of escape and survivability are shown.

Table 11: Summary results test 4 mattress 2

Parameter	Limit value escape (1.8 m) [min.]	Limit value survivability (0.5 m) [min.]
Heat	7 - 8	9 - 10
CO	-	-
O_2	8 - 9	-
NO_x	-	-

For test 4 the parameter heat is determining.

4.5 Heat release rate

During the tests the mass loss rate of the burning objects is measured. From the mass loss rate the heat release rate can be estimated. For the estimation a combustion efficiency of 0.8 and a calorific value of 25 MJ/kg are used. This heat release rate is a rough estimate and not an exact representation. The values in the graph are an indication to assess whether they correspond to known values. In figure 61 the calculated heat release rate of each test is shown.

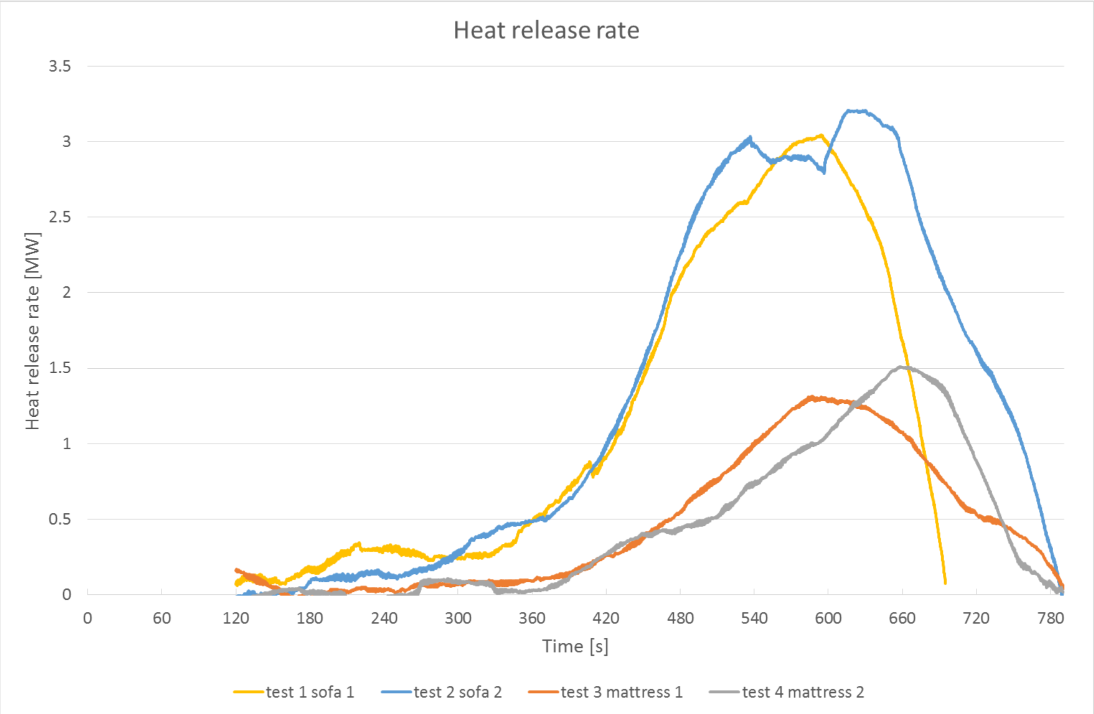

Figure 61: Heat release rate

The peak values for the sofas are between 3 to 3.5 MW. The peak values for the mattresses are between 1 to 1.5 MW. The peak values shown in figure 61 correspond with generally known values.

4.6 Analysis and summary

In table 12 a summary of the tests is presented related on the fire behaviour and resistance to ignition. In table 13 a summary of the tests is presented related on the probability of escape and survivability.

Table 12: Summery results all tests ignition sources

Test	Ignition source	Conclusion
1a sofa 1	Cigarette	Passed
1b sofa 1	Open flame	Failed (ignition within 20 seconds)
2a sofa 2	Cigarette	Passed
2b sofa 2	Open flame	Failed (ignition within 20 seconds)
3a mattress 1	Cigarette	Passed
3b mattress 1	Crib 5	Failed (ignition when crib burns)
4a mattress 2	Cigarette	Passed
4b mattress 2	Crib 5	Failed (ignition when crib burns)

From table 12 it is clear that all objects passed the cigarette test. This was to be expected because upholstered furniture and mattresses from the retailer have specifications that meet the cigarette test described in EN 1021-1:2014 and EN 597-1:2016.

Table 12 also shows that the objects are not able to withstand exposure to a larger ignition source. Once the object is ignited, fire will spread across the object and burn it almost completely.

Table 13: Summary results all tests for probability of escape and survivability

Parameter	Limit value escape (1.8 m) [min.]				Limit value survivability (0.5 m) [min.]			
Test	1b	2b	3b	4b	1b	2b	3b	4b
Heat	4-5	5-6	7-8	7-8	7-8	7-8	-	9-10
CO	7-8	8-9	-	-	-	-	-	-
O_2	5-6	6-7	-	8-9	-	-	-	-
NO_x	-	-	-	-	-	-	-	-

From table 13 it is clear that once the object is burning, heat is the determining parameter for both probability of escape and survivability in the tests. The limit values for the other parameters are exceeded later or are not exceeded during the test.

In addition, it also appears that on survivability level (50 cm above the floor) the conditions stay relatively long below the limit value. Probably this has to do with the breaking of the windows during the tests and the position of the measurement tools. A possible explanation is that after the breaking of the windows a neutral plane in the burning room is formed. Above the neutral plane hot smoke gasses will flow out of the room. Beneath the neutral plane cold clean air enters the room to keep the fire going but also keeps the survivability level relatively clean. This could also explain why on this level no high concentration of carbon monoxide/nitrogen oxides (CO and NO_x) and relatively concentrations of oxygen (O_2) are measured.
From earlier research (Hazebroek, J.C., Groenewegen-ter Morssche, K. Van den Dikkenberg, R., 2015) **it became clear that smoke gases are an important factor for the probability of escape and survivability if the fire room stays closed during combustion (underventilated fires).**

From the results in this chapter it is also clear that the objects produce a lot of heat and smoke during combustion. In addition, it is also clear that temperatures only caused by burning the objects reach values which can cause a fully furnished living- or bedroom to flashover if there is enough oxygen present.
The foam filling seems to be the main contributor to heat and smoke production. The heat production, which is the heat release rate, corresponds with generally known values.

5 Findings

Research question 1:
What is the fire behaviour in a single room environment of the most sold mattresses and upholstered furniture of the retailer when exposed to common test ignition sources such as a cigarette, open flame or crib 5?

Answer research question 1:
From the tests in this study can be concluded that the most sold mattresses and upholstered furniture are able to withstand exposure to a smouldering ignition source such as a cigarette. The same objects aren't able to withstand exposure to a larger ignition source such as an open flame (candle) or a crib 5 (burning papers). Once an object is ignited fire spreads rapidly in all directions and a lot of heat and smoke is produced in a short time (within 10 minutes) during combustion. The heat production from the tested objects is enough to cause a furnished living- or bedroom to flashover, if there is enough oxygen available for combustion. The foam filling seems to be the main contributor to heat and smoke production. The heat production, which is the heat release rate, corresponds with generally known values.

Research question 2:
What is the probability of escape and survivability in a single room environment when only the upholstered furniture (sofa) or mattress is burning?

From the tests in this study can be concluded that once the object is burning, heat is the determining parameter for both probability of escape and survivability. In the test environment the probability of escape (heat) is very low after 4 to 6 minutes when only a sofa is burning and after 7 to 8 minutes when only a mattress is burning. In the test environment the survivability (heat) is very low after 7 to 8 minutes when only a sofa is burning and after 9 to 10 minutes when only a mattress (mattress 2) is burning. For the other mattress (mattress 1) the limit value (heat) isn't exceeded. The limit values for the other parameters (CO, O_2 and NO_x) are exceeded later or aren't exceeded during the tests. There is a big difference between conditions on the escape level (180 cm) and the survivability level (50 cm). This is probably caused by the breaking of the windows during the tests. If the fire room stays closed smoke and smoke gases (CO and NO_x) become an important factor for the probability of escape and survivability and can lead to different conclusions.

6 Discussion

In this chapter some limitations about this study are discussed. These are limitations regarding the scope of the findings and limitations regarding the research method.

The results of this study are of course only valid for the configurations studied in this research and strictly speaking cannot be generalized, except with common sense and caution. There are some limitations that can be mentioned:

- Only 4 objects (two different sofas and two different mattresses) are used in the experiments. It is uncertain if these objects are representative for upholstery. There is also an uncertainty about the results of each object, because the tests per object are not repeated.
- The fire room has the dimensions of a small living room or a large bedroom (22.5 m^2). Different geometry and room dimensions could lead to different results. The material of the enclosure is of influence of the parameter heat. Other materials could lead to different results.
- Although measurements took place at different points (height) and different positions in the fire room, it is uncertain if these measurements give a good representation of average conditions in the fire room at different heights.
- Although ignition sources were chosen and placed with care and the protocol was followed, there could be some (small) differences between tests regarding the method of ignition.
- A limitation of the used methodology (experiments) is that there are always some phenomena or uncertainties in the data that cannot be explained. For example in test 1 the windows broke due to the thermal load. In the other tests plating was used to simulate the (same) window break. The advantage of the chosen methodology is that a good impression can be obtained.
- The limit values used to determine the probability of escape and survivability are arbitrary as mentioned in the report. Other values could lead to different conclusions.
- The estimated heat release rate (HRR) of the objects from the mass loss rate is an uncertainty. As stated before an estimated calorific value and combustion efficiency was used to calculate the HRR. Because those values are estimated the actual HRR of the mattress is probably different. In addition, the heat release rate of the objects will be different from a laboratory environment because the hot gas layer is of influence on the pyrolysis and the lack of oxygen on the combustion.

Taking into account these limitations, the results regarding the fire behaviour, probability of escape and survivability may differ from actual domestic fires. However this study provides a good impression of the fire behaviour of the most sold mattresses and upholstered furniture (sofa) of the retailer and is a good starting point from which improvements can be made to increase the fire safety of furniture and mattresses.

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