TOWARDS A SOUND UNDERSTANDING OF THE EFFECTIVENESS OF SMOKE DETECTORS IN DWELLINGS

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ABSTRACT

Smoke detectors in residential buildings contribute significantly to fire safety in these buildings. However, there are several examples of residential fires known that, despite the presence and operation of smoke detectors, lead to fatality. This was the reason for the Institute for Safety to investigate the effectiveness of smoke detectors in residential buildings.
In the Netherlands many residential buildings are equipped with smoke detectors. Nevertheless, in only a third of the Dutch residential buildings there is a minimum level of protection by smoke detectors, consisting of a working smoke detector on every floor. In a survey on fatal fires in residential buildings it is found that particularly people with an impaired mobility are victims of fires with working smoke detectors. The mobile victims of fatal residential building fires were mostly sleeping and probably could be saved by a working smoke detector. However, there are doubts whether smoke detectors (only) in the circulation spaces provide adequate protection. Therefore an unique serie of live fire experiments are conducted in a block of furnished two-storey houses. These virtually identical houses were provided with smoke detectors in nearly every room. Temperature, heat radiation, carbon monoxide (CO), oxygen (O_2) and nitrogen oxides (NO_x) were monitored during the experiments. The available escape and rescue times are analysed based on the exceedance of the threshold values for incapacitation and lethality.
In this paper we present the results of the experiments and measures that residents can take to increase the fire safety in their homes. In the experiments it is found that the available escape time is extended considerably by placing smoke detectors in potential fire areas. Also the closing of interior doors has a positive effect on the probability for survival of fire, but has a negative effect on the detection time of smoke detectors in the circulation space. To improve the perceptibility of smoke alarms and to increase the available escape and rescue time a measure is to interconnect the smoke detectors on every floor.

INTRODUCTION

A smoke detector is effective when a fire is detected in an early stage and the (dormant) people present are quickly alerted by the smoke alarm, enabling them to escape in time. Therefore we focus in this paper on the limitations of smoke detectors in residential fires, as well as on suitable measures to improve the effectiveness of present smoke detectors in residential buildings. The limitations of smoke detectors are discussed in the context of detection ability, the ability to wake up people, audibility and correct location of detector. The starting point for the analysis of the effectiveness of smoke detectors on the probability of survival is that the level of fire safety in residential fires is determined by a combination of factors, namely the risk factor (fire features), the environmental factor (building features) and human factors (human features). To this a fourth factor is added, namely the smoke detector features. An example of a fire feature is the location of the fire and the path of the spread of smoke. A relevant building feature can be whether interior doors are closed or open. For the human factors it is relevant whether the person can escape by himself or whether the person is impaired mobile and need to be rescued. The interconnection of smoke detectors can be a relevant smoke detector feature for a fast notification. The influence of these features, amongst others, are investigated in real life experiments. Furthermore, the four factors are found to have an influence on various stages of the escape process, i.e. in the stage of discovery (detection), the stage of warning and the stage escape.

Detection time and nuisance alarms related to type of detector

The literature review has shown that the moment at which the smoke detector is activated, depends on the type of material which is burning, whether it is a smouldering or a flames fire, the location of the fire, and the presence of ventilation. For example experiments [1] show that smoke detectors in the room of fire origin (in these experiments the bedroom), and even those in the circulation space, can detect fire before the threshold values for incapacitation and lethality are reached. Furthermore, it has been shown that the effectiveness of the smoke detectors is depending on the type of alarm (optical or ionizing) and the location to the fire.
By means of experiments it has been demonstrated [2] that in smouldering fires the optical smoke detectors generally responded faster than the ionization detectors. In case of flames fires, ionization detectors responded quicker. It is also found that ventilation, both mechanical as well as natural ventilation, can influence the flow so that the smoke from the fire does not reach the smoke detector quickly. As a result there is a delay in the alarm time.[3]
Based on several studies it is found that most of the nuisance alarms are due to cooking.[4] A possible measure to reduce nuisance alarms is to replace smoke detectors for heat detectors. Therefore, in the live fire experiments we investigate the difference in detection time of both types of detectors.

Audibility and ability to wake up people

When a smoke detector goes in alarm in a different room than where a person is located, there will be a sound volume reduction. For a smoke detector in an Australian residence, with a sound frequency of about 3100 Hz and a sound level of 85 dB(A), a reduction is measured with an average of 36 dB(A) if all the doors are open and an average of 45 dB(A) when the doors are closed.[5] Smoke detectors with a sound frequency of about 3100 Hz and a sound level of 105 dB(A) is the reduction in the situation with the doors closed even stronger, namely 58 dB(A). Also for the lower floor the reduction is stronger than for rooms on the same floor. To decrease the effect of sound reduction in the live fire experiments the measure of interconnected smoke detectors is analysed.
After the smoke detector sounds, the time available to survive the fire can be limited, especially when the victim is in the room of fire origin. In response to the alarm of the smoke detector it is therefore necessary to escape quickly. Besides hearing impaired elderly people more people appear to be vulnerable when it comes to waking up by the alarm of a smoke detector. Several studies [6] [7] [8] [9] [10] [11] [12] [13] [14] show that current detectors are barely able to wake up children, people under the influence of alcohol and people who sleep very deeply.

Fatal residential building fires

An analysis of fatal residential building fires confirms that people cannot be saved in all situations by a smoke detector.[15] The analysis is based on the database of the Institute for Safety on unintentional residential building fires in the Netherlands with civil fatalities due to the fire. In the period from 2008 to 2013 a total of 186 people died in 172 fires. For this paper a selection of residential fatalities is analysed, namely only the cases wherein data is given on the presence and functioning of smoke detectors (n=126 fires). In 33% (n=41) of these fatal fires at least one smoke detector was present. In 24% (n=30) of these cases the detector actually went in alarm, with the result of 33 victims.
A further selection is made, namely of the cases wherein also the extend of mobility of the victim is known (n=118 victims). This concerns 73 mobile victims (62% of 118) and 45 impaired mobile victims (38% of 118). About half of the mobile victims were present in the room of fire origin (n=37; 51% of 73), compared seven out of ten impaired mobile victims (n=31; 69% of 45). In the room of fire origin most of the mobile victims were asleep (n=22; 59% of 37) and most the impaired mobile victims were awake (n=17; 55% of 31). The contrast is larger for victims who were in another room, as three-quarters of the mobile victims were awake (n=27; 75% of 36), compared to six out of ten impaired mobile victims (n=8; 57% of 14). This is the first indication that for mobile victims the awakening by a smoke detector is more relevant than for impaired mobile victims. The second indication is that 42% (n=19) of the

impaired mobile victims deceased in a residential building fire with a sounding smoke detector, compared to only 12% (n=9) of the mobile victims.
Since most of the mobile victims who deceased in the fire had no functioning smoke detector, the assumption is that a sounding smoke detector can decrease the number of fatal fire victims. Nevertheless, some mobile victims with a sounding smoke detector died because of the fire. Therefore in the live fire experiments the alarm times of smoke detectors on several locations, several locations for the room of fire origin and the environmental conditions for escape and rescue in several rooms are investigated. Smoke detectors seem less effective for impaired mobile persons. To reduce this category of victims, additional measures are needed to prevent fire, to extinguish the fire quickly, to restrict the spread of smoke and to make a quick rescue possible. For that reason in the live fire experiments it is investigated if the closing of interior doors is a promising measure to increase the probabilities of rescue.

Coverage, functioning and location

The legal requirement in the Netherlands is that houses built in 2003 or later shall be provided with smoke detectors on each floor of the house in the circulation space, that are powered by the power line. Smoke detectors are not required by law for existing houses, but the general advice is to install at least one smoke detector per floor in circulation spaces (hall way/circulation spaces/landing). The data of '*Woon Onderzoek Nederland 2012*' [Housing Research Netherlands 2012] shows that in the Netherlands approximately 70% of all dwellings has a mounted smoke alarm.[15] That does not necessarily imply that in all these dwellings, the smoke detector actually functions or is mounted on every floor. Fire departments from several regions in the Netherlands have published about their home fire safety inspections, wherein among others the presence, location and operation of smoke detectors is described.[15] Based on the relative mean result of these inspections, it can be concluded that smoke detectors are functioning in about two-thirds (66%) of the dwellings. Through comparing this information with the coverage of 70%, it can be stated that approximately 45% of all homes in the Netherlands have working smoke detectors. Focussing on the location it shows that in about half of the dwellings functioning smoke detectors are installed in the circulation space on every floor. Due to a 70% coverage, it implies that only 35% of the dwellings in the Netherlands has a working smoke detector in the circulation space on each floor. This percentage is relatively low. Moreover, there are doubts whether smoke detectors (only) in the circulation spaces provide adequate protection. Therefore are in the live fire experiments smoke detectors mounted not only in the circulation spaces but also in the room of fire origin and in the other rooms.
The alarm time of smoke detectors at various locations has been studied in earlier live experiments, but these experiments are mainly performed in mock-ups of homes.[1 2 3] The live fire experiments described in this paper, on the other hand, are performed in real (demolition) houses which were inhabited shortly before the experiments and are fully furnished with new furniture. In addition, the main focus in previous research is on the alarm times and most of the experiments are finished as soon as the smoke detectors went into alarm. The current live fire experiments examined not only the detection time of smoke detectors, but also the growth of the fire and the spread of smoke in relation with the available escape and rescue time.

METHODOLOGY

To gain a sound understanding of the factors that influence the effectiveness of smoke detectors, the Fire Service Academy conducted an experimental fire study in a block of identical two storey houses, with identically furnished modern furniture, in a small town district due for demolition. The aim of the experiments was to research the fire spread and tenability in an average Dutch residential building. The live fire experiments started in three different locations, namely in the living (2x) or kitchen (1x) on the ground floor or in the master bedroom (2x) on the first floor. During the experiments the surrounding conditions were measured in the all the rooms in the house, including the hallway and landing. Temperature, heat radiation, O_2, CO and NO_x were monitored in each of the five major rooms during the fire growth and analysed on the tenability limits for people to escape and survive a fire.
The following measures are investigated to improve the effectiveness of present smoke detectors in dwellings.

- Detached smoke detectors in the circulation spaces, instead of no smoke detectors;
- Interconnected smoke detectors in the circulation spaces, instead of detached smoke detectors in circulation spaces;
- Interconnected smoke detectors in all rooms, instead of only in the circulation spaces;
- Heat detectors instead of optical smoke detectors in the room of fire origin;
- Closed interior doors, instead of open interior doors.

Description of the tested house

The live fire experiments were conducted in working class houses that were built in 1931. 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 stairs. Double glazing have been installed at ground floor level (ventilation grilles are present here as well) and the ceilings being finished with plaster-board. 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 ground floor plan includes the living, open kitchen, small hall with bathroom and the stairs to the first floor. The floor plan is about 38 m^2. The first floor includes two bedrooms, landing and stairs to the attic which can be closed by a shutter in the attic floor.
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.

Description of the test design

Fire experiments
The fire experiments were set up such that as many of the options of subsequent comparison as possible were integrated. Among other things, this meant that it should be able to compare the situations of a fire in on the ground floor with a fire on the upper floor, to compare a fire in a large room (living room) with a fire in a small room (bedroom) and to compare a fire with interior doors open with interior doors closed. In Table 1 the setup of the fire experiments is shown.

Table 1. Setup of the fire experiments

Test	Location of start of fire	Object on which the fire started	Hallway door	Bedroom doors	Ventilation
1	Bedroom	Bed	Closed	Both open	Exterior doors closed, both bedroom windows ajar
2	Bedroom	Bed	Closed	Both closed	Everything closed, only bedroom window ajar
3	Living room	Sofa	Open	1 open/ 1 closed	Everything closed, only bedroom window ajar
4	Living room	Sofa	Closed	1 open/ 1 closed	Everything closed, only bedroom window ajar
5	Kitchen	Deep fat fryer	Closed	1 open/ 1 closed	Everything closed, kitchen door open halfway

Measurements (instruments and locations)
During the live fire experiments the temperature, heat radiation, CO, O_2 and NO_x are measured. There was one measurement point per room. An exception was the living room, where because of the size and the geometry of the room the temperature has been measured in two places, approximately in the middle of the front and back of the living room. The temperature is measured at two levels, namely at 50 and

180 centimetres height. The other measurements (CO, NO_x, O_2) are measured at a height of 50 centimetres. The visual image is captured by heat-resistant video cameras.
The houses are equipped with smoke detectors. Each room has at least one optical smoke detector and in most rooms also a thermal detector. In test 2 and 5 a second optical detector was mounted in the landing and in the bedrooms. The detectors are from Sprue Safety Products Ltd. The following types are used:

- Optical smoke detectors type Fireangel WST-630-BNLT with a non-replaceable 3V lithium battery with a lifespan of at least 10 years. The smoke detectors are wireless interconnected.
- Thermal detectors type BRK H380 with a 9 V battery. The smoke detectors are linked via an IFG-100 Wireless Interface Gateway 150m. single trigger operation.

Values for incapacitation and lethality
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.

Table 2 contains the threshold values for the measurements of the live fire experiments.

Table 2. Parameters and threshold values

Parameter	**Values for incapacitation**	**Values for lethality (LD_{50})**
Heat (convection + radiation)	FEDheat ≥ 1	T ≥ 120 ^{0}C at 0,5m height q ≥ 6 kW/m^2
CO	FEDtox ≥ 1 OR 10 min AEGL-2 (CO ≥ 420 ppm)	10 min AEGL-3 (CO ≥ 1700 ppm) 30 min AEGL-3 (CO ≥ 600 ppm)
O_2	$O_2 \leq 13\%$	$O_2 \leq 6\%$
NO_x	10 min AEGL-2 ($NO_x \geq 20$ ppm)	10 min AEGL-3 ($NO_x \geq 34$ ppm)

For the analysis of heat exposure the Fractional Effective Dose (FED) for a 50 percent lethality among the population (FED=1) is used, shown in the Table as 'FEDheat'. The FED is calculated on the basis of temperature and radiation in accordance with ISO 13571 (2012). The FED is exclusively applicable for the determination of the probabilities of escape. For survivability the temperature limit of 120 ^{o}C at victim level (50 centimetre) is adopted.[16] Regarding radiation a limit of 6 kW/m^2 is chosen, because it appears that a person can be exposed to this radiation for just 7 seconds.[17 18 19]
In accordance with ISO 13571 (2012) the FED is also calculated for toxic substances, shown in the Table as 'FEDtox'. The calculation takes into account both the presence of carbon monoxide (CO), hydrogen cyanide (HCN) and carbon dioxide (CO_2). Only the production of CO is measured. Because in the experiments there is an (incomplete) combustion of polystyrene foam, the value for HCN is estimated to be 1% ppm HCN per ppm CO emissions.[1] In addition to the FEDtox, the limit values for CO exposure are determined according to the Committee on Acute Exposure Guidelines (AEGL).[20] For escape the values of AEGL-2 apply, and for survivability the values of AEGL-3 are used.
Based on research [21], the limit of the oxygen (O_2) concentration for escape is set at 13%. The research findings suggest that at a percentage of 12 to 16% there is an increased respiration and heart rate and of a slightly decreased muscle coordination. At a percentage of 10 to 14% abnormal fatigue, impaired respiration and emotional reactions are possible. For survivability the threshold value is set at 6%, since then breathing stops after a few minutes, followed by a heart failure.
For the determination of the threshold values for nitrogen oxides (NO_x) the use of AEGL values is not unusual.[1] AEGL-2 is used as a threshold for escape. Survival is based on the AEGL-3 value. A level of 50 percent lethality among the population is only achieved at very high NO_x values, but an NO_x 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.

RESULTS

Description of fire development

In test 1 flames are visible on the top side of the beddings within a minute. After 1,4 minutes, the smoke layer in the master bedroom reaches to 180 centimetres (from the floor). The room fills up quickly with black smoke and burning (liquid) parts of the matrass and beddings are dripping on the carpet, and it begins to burn. After 2 minutes, the smoke layer reaches the side of the landing up to 50 centimetres (from the floor). There is 75 to 90 centimetres of free space on the window side. There are flames of 1 meter high on the bed. One minute later, the flames reach the ceiling and later the smoke layer starts to ignite at the ceiling. After about 4 minutes, the fire intensity is decreasing. Over time, the density of the smoke layer also decreases. Only the bed is on fire. Because of firefighter interventions the experiment is ended 14 minutes after ignition.

In test 2 within a minute after ignition there are flames of 5 centimetres visible in the corner of the bed where the fire ignited. 2 minutes after the fire started, there is already a clear smoke layer visible in the room and the outgassing of the matrass and beddings is also visible. 4 minutes after the start of the fire the aware markers are barely visible through the thick smoke and flames on the bed are 1 meter height. In the master bedroom there is a rapidly developing fire, though the fire is not fully developed (flash-over). After a rapid increase in temperature to nearly 300°C, the temperature drops rapidly again. The fire was probably tempered by a lack of oxygen. The fire raged a full hour before intervention has been made by the safety crew. At that time, the fire appears to be almost extinguished.

In test 3 the temperature in the living room rises rapidly after igniting the fire in the sofa. Within a minute, the first flames are visible above the sofa. From 1,5 minutes the smoke layer begins to form on the ceiling that builds up quickly. After 2 minutes the smoke layer in the living room reaches to 180 centimetres (from the floor) and has now spread to the hallway and landing. Besides the sofa also the shelf above the sofa is burning. After about 5 minutes, a peak in the temperature in the living room has been reached and as a result of lack of oxygen the temperature drops. At that time, the landing is full of grey and black smoke. For a full hour, the fire ragged and after 61 minutes, the safety crew intervened.

In test 4 after 3,5 minutes the first flames above the sofa are visible. After 4 minutes, a smoke layer starts to build up against the ceiling. 30 seconds later the smoke layer reaches a height of 180 centimetres (from the floor). The entire room is filled with thick black smoke, and the flames on the sofa decrease. After 4,5 minutes, there is getting some smoke through the floor in the master bedroom. About 30 seconds later, this happens also in the baby room. After 7 minutes, the first smoke from the master bedroom flooded in the landing. After more than 58 minutes the safety crew intervened.

In test 5 the fire develops very rapidly after the igniting of the deep fat fryer. Within 2 minutes there is a thick smoke layer at the ceiling of the kitchen, which is beginning to extend into the living room. The fire reaches the first kitchen cupboard within 2 minutes. The fire in the kitchen is raging first in the kitchen cupboards above the sink; after that, the kitchen cupboards under the countertop are also involved in the fire. The smoke is spreading through the floor structure to the bedrooms. During the experiment the fire gets through the plaster ceiling and begins to spread in the roof (of the kitchen) so thick smoke under the tiled roof of the kitchen is pressed out. More than 47 minutes after the start the safety crew started to extinguish the fire as the fire threatened to spread to the roof and affect the adjacent houses.

Description of measurements in general

In Table 3 the results are given for the measurements related to the times when the first detector went into alarm and to the times in which the tenability limits for people to escape and survive a fire were exceeded.

Table 3. Overview of times of alarm, possibility of save escape and rescue possibility

Test-ID	**Room**	**Interior door open (o) or closed (c)**	**Alarm time of first optical smoke detector**	**Alarm time of thermal detector**	**Possibility of a save escape**				**Rescue possibility**			
					Maximum escape time out of room (via landing / hallway)	**Measure 1: detached detectors in circulation spaces**	**Measure 2: interconnected detectors in circulation spaces**	**Measure 3: interconnected detectors, also in room of fire origin**	**Exceedance of limits for survival**	**Measure 1: detached detectors in circulation spaces**	**Measure 2: interconnected detectors in circulation spaces**	**Measure 3: interconnected detectors, also in room of fire origin**
1	Master bedroom (*)	o	00:43	01:40	**02:42**	01:30	01:30	01:59	**02:51**	01:39	01:39	02:08
1	Landing		01:12	NOT	**02:42**	01:30	01:30	01:59	**03:09**	01:57	01:57	02:26
1	Nursery room	o	01:24	03:37	**02:42**	01:30	01:30	01:59	**03:36**	02:24	02:24	02:53
1	Hallway		08:03	N/A	**max**	max	max	max	**max**	max	max	max
1	Living	c	23:31	N/A	**max**	max	max	max	**max**	max	max	max
1	Kitchen		30:58	N/A	**max**	max	max	max	**max**	max	max	max
2	Master bedroom (*)	c	00:35	N/A	**04:04**	00:02	00:02	03:39	**04:07**	00:05	00:05	03:32
2	Landing		04:02	NOT	**37:10**	33:08	33:08	36:35	**max**	max	max	max
2	Nursery room	c	18:22	NOT	**37:10**	33:08	33:08	36:35	**max**	max	max	max
2	Hallway		14:53	NOT	**max**	max	max	max	**max**	max	max	max
2	Living	c	NOT	NOT	**max**	max	max	max	**max**	max	max	max
2	Kitchen		NOT	NOT	**max**	max	max	max	**max**	max	max	max
3	Living (*)	o	01:20	02:21	**04:26**	02:25	02:25	03:06	**14:45**	12:44	12:44	13:25
3	Kitchen		01:59	03:11	**04:26**	02:25	02:25	03:06	**N/A**	N/A	N/A	N/A
3	Hallway		02:01	03:40	**06:09**	04:08	04:08	04:49	**14:09**	12:08	12:08	12:49
3	Landing		NOT(!)	04:45	**05:54**	01:09(!)	03:53	03:53	**14:00**	09:15(!)	11:59	12:40
3	Master bedroom	o	03:07	04:59	**05:54**	01:09(!)	03:53	03:53	**14:54**	10:09(!)	12:53	13:34
3	Nursery room	c	07:21	NOT	**05:54**	01:09(!)	03:53	03:53	**39:48**	35:03(!)	37:47	38:28
4	Living (*)	c	01:35	02:35	**04:36**	02:03	02:03	03:01	**13:48**	11:15	11:15	12:13
4	Kitchen		02:24	03:28	**04:36**	02:03	02:03	03:01	**N/A**	N/A	N/A	N/A
4	Hallway		02:33	50:28	**23:18**	20:45	20:45	21:43	**45:36**	43:03	43:03	44:01
4	Landing		06:53	55:00	**15:57**	09:04	13:24	14:22	**33:51**	26:58	31:18	32:16
4	Master bedroom	o	03:37	59:37	**15:15**	08:22	12:42	13:40	**16:55**	10:02	14:22	15:20
4	Nursery room	c	03:06	N/A	**15:57**	09:04	13:24	14:22	**max**	max	max	max
5	Kitchen (*)		00:10	04:00	**05:30**	0	0	05:20	**N/A**	N/A	N/A	N/A
5	Living	c	01:52	05:58	**16:12**	08:57	08:57	14:20	**22:24**	15:09	15:09	22:14
5	Hallway		07:15	NOT	**25:58**	18:43	18:43	25:48	**47:46**	40:31	40:31	47:36
5	Landing		13:24	N/A	**25:58**	12:34	18:43	25:48	**47:33**	34:09	40:18	47:23
5	Master bedroom	o	06:56	N/A	**25:39**	12:15	18:24	25:29	**47:21**	33:57	40:06	47:11
5	Nursery room	c	07:56	N/A	**25:58**	12:34	18:43	25:48	**47:29**	34:05	40:14	47:19

(*) = Room of fire origin; N/A= not available / not measured;; NOT = no alarm; max = limit not reached till end of test; (!) = calculation based on thermal detector in landing as optical smoke detector was probably defect

In Table 3 the alarm times of the optical smoke detectors and the heat detectors are shown. In test 2 and 5 there were two optical smoke detectors present in some rooms. In test 2 the second optical smoke detector in the master bedroom, which is the room of fire origin, went 44 seconds later in alarm, the time difference in the landing was 35 seconds and in de nursery room it was 5 seconds. In test 5 the time difference in the landing was 20 seconds, in the master room it was 23 seconds and in the nursery room it was 54 seconds.

Also the calculated available times for escape and rescue are presented in Table 3. The calculation is based on the measured times of exceedance of tenability limits, both for incapacitation and lethality. In test 1 the oxygen limit for incapacitation was exceed in all upper rooms. For lethality the limit for radiation was exceeded in the master bedroom (room of fire origin) and for oxygen in the other upper rooms. In the master bedroom (room of fire origin) in test 2 the FEDheat was exceeded for incapacitation and the temperature for lethality. In the other upper rooms only the AEGL limit for carbon monoxide was exceeded for incapacitation. In test 3 the FEDheat was exceeded for incapacitation in the living (room of fire origin) and the kitchen. In the other rooms the oxygen limit for incapacitation was exceeded. For lethality the AEGL limit for nitrogen dioxide was exceeded in living (room of fire origin), hallway, landing and master bedroom. In the nursery room the AEGL limit for carbon monoxide was exceeded for lethality. In test 4 the FEDheat was exceeded for incapacitation in the living (room of fire origin) and the kitchen. In the other rooms the nitrogen dioxide AEGL limit for incapacitation was exceeded. For lethality the AEGL limit for nitrogen dioxide was exceeded in living (room of fire origin) and master bedroom. In the hallway and landing the AEGL limit for carbon monoxide was exceeded for lethality. In test 5 temperature limit for incapacitation living in the kitchen (room of fire origin). The FEDheat cannot be determined as the radiation is not measured in the kitchen. In the living the oxygen limit for incapacitation was exceeded and in the other rooms the AEGL limit for carbon monoxide. For lethality the AEGL limit for carbon monoxide were exceeded in all rooms, except for the kitchen as it was not measured there.

The available times for escape and rescue are first of all calculated for the hypothetical situation in which the (dormant) people are not alarmed by signals other than sound, so they will not wake up in the absence of a smoke detector. Subsequently the available times for escape and rescue are calculated for three measures with the application of smoke detectors. In measure 1 the escape time is defined by calculating the difference between the maximum escape time (theoretically on the basis of the threshold values) and the moment when the smoke detector goes into alarm in the hallway (for escape from the ground floor) or landing (for escape from the first floor). Measure 2 is based on the time at which the smoke detector goes into alarm in the circulation space adjacent to the room of fire origin and measure 3 is based on the time the smoke detector sounds in the room of fire origin.

Interpretation of test results

Measure 1: Detached smoke detectors in circulation spaces, instead of no smoke detectors

In the experiments wherein the fire is ignited in the master bedroom on first floor (test 1 and 2), there is a rapid fire development. After ignition there is no escape possible from the room of fire origin within 2 minutes and 42 seconds in test 1 and 4 minutes and 4 seconds in test 2. Though there is only a possibility to escape or being rescued if the fire is noticed. It took some time before the smoke detector in the landing went into alarm. After the sound of the alarm there is barely no to about 1,5 minutes time left to escape from the room of fire origin. After that the limit for survivability is quickly reached.

The probability that people survive these fires while they are sleeping in the room of fire origin is (very) small. In test 1, in which all the interior doors on the floor were open, the probabilities of escape and survival in the other rooms on the first floor is also (very) small. In test 2 the interior door between the landing and the room of fire origin was closed. Therefore there was considerable time available for escape from the nursery room and the landing after the smoke detector went into alarm. In both experiments the limits for escape and rescue are not reached on the ground floor.

In the experiments wherein the fires started in the living on the ground floor (test 3 and 4) there is about 4,5 minutes time available to escape from the room of fire origin. In the hallway there is 6 minutes (test 3) to 23 minutes (test 4) available for escape. On the upper floor there is less time available. In test 4 there is even about 8 minutes less time available. For the possibility of rescue there is in test 3 about 10 minutes extra time available after the tenability limits for escape are exceeded. Except for the nursery room, where more time is available as the inner door is closed. In test 4 the interior door of the room of fire origin is closed, which lead to a good possibility for rescue from the upper floor. Except for the

master bedroom, where the smoke poured into the room via the floor. These possibilities are only valid if the fire is noticed. However, after the alarm sounds the persons in the room of fire origin have only 2 to 2,5 minutes to escape. On the upper floor is even a maximum of 1 minute (test 3) to 8,5 minutes (test 4) available for escape. Only in test 4 there is a half-minute extra time to escape from the nursery room. In the landing there is about 9 minutes (test 3) to 27 minutes (test 4) available for rescue after the sound of the smoke alarm. As in test 4 the smoke poured into the master bedroom via the floor, there is only 10 minutes available. In the nursery room there is at least 35 minutes time available for rescue in both experiments. This is because the interior door of the nursery room is closed.
The findings show that for persons in the room of fire origin a smoke detector in the joining circulation space is hardly effective when the dimensions of the room are small (bedroom). When the room of fire origin is on a higher floor, there is a very high probability for escape and survival for the persons on the lower floor.

Measure 2: Interconnected smoke detectors, instead of detached ones, in circulation spaces
When the fire starts on an upper floor, and there are no persons present on the higher floors, the interconnection of smoke detectors has no effect. The first smoke detector that goes in alarm, after all, is mounted in the circulation space where people on the upper floor have to escape through. The results of test 1 and 2 confirm this. When the fire occurs on the ground floor the interconnection has also no effect, as it is the location of the first detector that goes into alarm. However, for the people on the upper floors the interconnection has a great effect. It leads to about 2,5 minutes extra time for escape (and rescue) in test 3, about 4,5 minutes extra in test 4 and little more than 6 minutes extra in test 5.
The findings show that the interconnection of smoke detectors is an effective measure for escape (and survival) in cases wherein the fire starts on the ground floor. This is an essential finding as an analysis of fire incidents in residential building reveals that, at least in two Fire Regions in the Netherlands, almost three-quarters of the residential fires start on the ground floor. [15]

Measure 3: Interconnected smoke detectors in all rooms, instead of only in the circulation spaces
By mounting smoke detectors not only in the circulation spaces, but also in all rooms where fire may occur and / or where people can stay dormant, and to interconnect the mounted smoke detectors, a substantial extra time can be achieved for escape (and survival). In the fire experiments was the time increase in the worst case (test 1) half a minute. Since the available escape time without the measure is just 1,5 minutes, the half-minute extension can make the difference between whether or no probability of escape.
The measure also has a substantial impact on the possibility to escape out of fire rooms in cases where the smoke alarm in the adjacent circulation space went in alarm too late. This is the case in test 2 (fire in master bedroom) and test 5 (fire in kitchen). In both experiments the fire room door was closed, so the smoke gases could not come close to the detector fast enough. In test 2 and 5 a smoke detector in the room of fire origin provides not only a time extension of 3,5 minutes, respectively 5,5 minutes, but above all the smoke detector ensures that people present can escape at all.
The measure also has a strong effect when the smoke spreads through the ceiling/floor structure to upper rooms. This is the case in test 4 and 5. There, a smoke detector in the room of fire origin, which is interconnected with smoke detectors in the circulation spaces, results in time gains of almost 5,5 minutes (test 4) and 13 minutes (test 5). In both cases, the available escape time was already substantial with detached smoke detectors, i.e. more than 8 minutes (test 4) and 12 minutes (test 5).
Given the sometimes decisive extra time for escape and rescue that can be achieved, it is highly recommended to mount interconnected smoke detectors in the potential rooms of fire origin, and in rooms where people can stay dormant.

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Given the sometimes decisive extra time for escape and rescue that can be achieved, it is highly recommended to mount interconnected smoke detectors in the potential rooms of fire origin, and in rooms where people can stay dormant.

Measure 4: Closed interior doors, instead of open interior doors
In general, it can be stated that when the door of the room of fire origin is closed, the environmental conditions in the other rooms last longer than when the door of the room of fire origin is open. For example, in the experiment with the fire on the first floor and the door of the room of fire origin open (test 1), the available escape time from the other rooms on the first floor is only 1,5 minutes after the sounding of the smoke detector. While in same situation with a closed door (test 2) this is more than 33 minutes. Also the time saving for the possibilities for rescues is substantial since the threshold values are not achieved with a closed door, while with the door open the available time for rescue is just 1.5 to 2,5 minutes. In the experiments with fire on the ground floor and the door of the room of fire origin open (test 3), the closing the doors of the rooms on the upper floor there is only results in a saving in the time for rescue. Specifically, in the room with a closed door (nursery room) there are 15 minutes extra available for rescue compared to room with the door open (master bedroom). On the other hand, closing the door of the room of fire origin has a negative effect on the alarm time and on the audibility of the smoke detector(s). As shown in Table 3 in the situations with an open door the smoke detector in the adjacent circulation space goes into alarm after about 1 minute (test 1) to 2 minutes (test 3), while in the situations with the door closed the smoke detector goes into alarm after 2,5 minutes (test 4) to about 7 minutes (test 5). So the findings demonstrate that the condition of the doors also influence the moment at which the smoke detector is activated, in addition to the type of material which is burning, the type of fire (smouldering or flames), the location of the fire, and the presence of ventilation as literature already revealed.
Also for (dormant) people present in the room of fire origin the closing of the door has a substantial negative effect. With a closed door the smoke it is found that the detector sound too late to escape (test 2 and 5) or even to be saved (test 2). On the contrary, with the door open there is time to escape for at least 1,5 minutes after the smoke detector sounds (test 1). Furthermore with a wooden floor structure (and possibly other structures with empty spaces and/or small openings) there is a risk of smoke spreading through the ceiling and floor structure when the door of the room of fire origin is closed. This has been observed in test 4 and 5.

Measure 5: Heat detectors instead of optical smoke detectors in the room of fire origin
In total, eight (36%) of the 22 placed heat detectors did not go into alarm. The optical smoke detector, mounted next to the heat detector, did detect the fire, except for the two cases in which the situation in that room has not been threatening up to the end of the experiment. In only two tests (test 3 and 4) the heat detector placed in the circulation space went into alarm. Though it detects the fire (much) later than the optical smoke detector, except for the detector in the landing in test 3 as that detector was probably defect. Therefore, it is not recommended to replace optical smoke detectors in circulation spaces by heat detectors. The alarm time difference between the heat detector and the optical smoke detector in the rooms of fire origin are relatively small as it varies between about 1 minute and 4 minutes. After the sound of the alarm of the heat detector there is about 1 minute to 2 minutes time left to escape. So it gives better results in the room of fire origin compared to detectors the circulation space. In one of the experiments the fire started in the kitchen and a heat detector went into alarm before the tenability limit

for a save escape was exceeded. In literature it is found that an optical smoke detector in a kitchen often leads to nuisance alarms. Only in these situations it is recommended to make use of heat detectors, although it detects a fire in a later stadium than optical smoke detectors do. In other situations heat detectors are even strongly discouraged for residential buildings, in particular in circulation spaces.

DISCUSSION

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

CONCLUSION

A smoke detector is effective when a fire is detected in an early stage and the (dormant) people present are quickly alerted by the smoke alarm, enabling them to escape in time. Though, only in a third of the Dutch residential buildings there is a minimum level of protection by smoke detectors, consisting of a working smoke detector on every floor. Therefore we focused in this paper on the limitations of smoke detectors in residential fires, as well as on suitable measures to improve the effectiveness of present smoke detectors in residential buildings. The literature review has shown that the moment at which the smoke detector is activated, depends on the type of material which is burning, whether it is a smouldering or a flames fire, the location of the fire, the presence of ventilation and of the type of detector. Based on the results of the live fire experiments it is not recommended to replace optical smoke detectors by heat detectors. In literature is also found that the current sound frequency of smoke detectors is not optimal. When a smoke detector goes in alarm in a different room than where a person is located, there will be a sound volume reduction. To reduce it, the smoke detectors on every floor can be interconnected. The live fire experiments revealed that the interconnection of smoke detectors is also an effective measure for increase the time for escape (and survival), especially in cases wherein the fire starts on the ground floor. This is an essential finding as most of the residential fires start on the ground floor. Therefore it is highly recommended to mount interconnected smoke detectors in the potential rooms of fire origin, and in rooms where people can stay dormant. After the smoke detector sounds, the time available to survive the fire can be limited, especially when the victim is in the room of fire origin. Several studies show that current detectors are barely able to wake up hearing impaired elderly people, children, people under the influence of alcohol and people who sleep very deeply. An analysis of the database of fatal residential fires confirms that people cannot be saved in all situations by a smoke detector as in a quarter of the analysed cases the detector actually went in alarm. Frequently impaired mobile persons are victim of fatal fires with sounding smoke detectors. In the live fire experiments therefore the measure of closing interior doors is investigated. The results indicate that when the door of the room of fire origin is closed, the environmental conditions last longer in other areas than when it is open. Closing the doors of other rooms leads to extra time for rescue as in some experiments even the threshold values for lethality are not exceeded in those rooms at all. This is particularly relevant for rooms wherein persons present are sleeping. For persons in the room of fire origin the live fire experiments reveal that a smoke detector in the adjacent circulation space is hardly effective when the dimensions of the room are small (bedroom). When the room of fire origin is on a upper floor, there is a very high probability for escape and survival for the persons in the rooms on the lower floor.

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