# Mapping of gas concentrations, effect of dead-air space and effect of alternative detection technology in smouldering fires

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# Mapping of gas concentrations, effect of dead-air space and effect of alternative detection technology in smouldering fires

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**ABSTRACT**
Eight out of ten fire-related fatalities occur in dwellings. It is a fact that smoke detectors save lives, which emphasizes the importance of every home having a functioning smoke detector. In Norway, smoke detectors in dwellings are mandatory, and recommendations on which detector technology to use and the position of the detectors are given. Smoke detectors should be installed on the ceiling, outside of dead-air space (close to walls).

In this study, ten smouldering fire experiments have been conducted to:

- investigate if smoke detectors with CO sensing can alert residents at an earlier stage than photoelectric smoke detectors, consequently increasing chances of egress and survival for a sleeping person.
- measure concentrations of toxic gases in a room where a smouldering fire occurs and investigate if tenability limits are exceeded when n photoelectric smoke detector is activated.
- investigate if smoke detectors placed within dead-air space are activated at a later stage than smoke detectors placed according to the recommendations.

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# Contents

# Summary

*Background:*
Eight out of ten fire-related fatalities occur in dwellings [1]. It is a fact that smoke detectors save lives, which emphasizes the importance of every home having a functioning smoke detector. In Norway, smoke detectors in dwellings are mandatory, and recommendations on which detector technology to use and the position of the detectors are given.

Smoke detectors should be installed on the ceiling, outside of dead-air space (close to walls).

*Objectives:*
The objectives of this study were:

- to investigate if smoke detectors with CO sensing can alert residents at an earlier stage than photoelectric smoke detectors, consequently increasing chances of egress and survival for a sleeping person.
- to measure concentrations of toxic gases in a room where a smouldering fire occurs and investigate if tenability limits are exceeded when a photoelectric smoke detector is activated.
- to investigate if smoke detectors placed within dead-air space are activated at a later stage than smoke detectors placed according to the recommendations.

*Method:*
Ten experiments with a smouldering fire in a bedroom furnished with a bed were conducted. The fuel for the fire consisted of polyether foam (mattress) and cotton to represent typical furnishings, such as upholstered furniture, mattresses etc.

Nine photoelectric smoke detectors, of three different brands, were used as reference detectors with regards to time to alarm. In addition, 21 combination detectors, with sensors for both CO and light attenuation (optical detection) were used to investigate the spread of smoke and CO in the test room. Gas measurements were made at the head end of the bed.

One of the experiments developed into a flaming fire, and was therefore excluded from further analyses.

*Conclusions:*

- Combination detectors with a CO sensor are activated significantly earlier than photoelectric smoke detectors. This may increase the chances of survival in a smouldering fire.
- Tenability limits for CO can be exceeded at the time a photoelectric detectors is activated. This may be lethal.
- The results show insignificant differences in times to activation for combination detectors placed on walls and on ceiling. This shows uniform spread of CO in the room. Thus CO sensors may be placed at locations more accessible to persons who cannot reach detectors placed on the ceiling.
- The results with regards to differences in time to detection of light attenuation for smoke detectors placed inside and outside of a dead-air space, respectively, were inconclusive.

# Definitions and acronyms

**CO:** Carbon monoxide.

**$CO_2$:** Carbon dioxide.

**Combination detector** is a type of smoke detector that applies multiple detection principles simultaneously, typically photoelectric and ionic, but also a combination of temperature and CO-measurements.

**DiBK:** Norwegian Building Authority.

**DSB:** Norwegian Directorate for Civil Protection.

**Dead-air space:** Area near the transition between wall and ceiling, where it is assumed that there is less air circulation than in the rest of the room.

**Flaming fire:** Combustion process with an open flame, where the fuel is in a gas phase.

**FOBTOT:** Regulation on fire prevention and supervision.

**HBr:** Hydrogen bromide.

**HCl:** Hydrogen chloride.

**HCN:** Hydrogen cyanide , hydrocyanic acid.

**HF:** Hydrogen fluoride.

**$IC_{50}$:** Concentration where 50 % of the exposed population becomes incapable of action.

**$ID_{50}$:** Dose where 50 % of the exposed population becomes incapable of action.

**Ionic smoke detector** is based on the fact that particles found amongst other in smoke, will intercept electric charge carriers in air ionized by a small radioactive source placed in a chamber suitable for the purpose. [2]

**$LC_{50}$:** Concentration where 50 % of the exposed population dies.

**$LD_{50}$:** Dose where 50 % of the exposed population dies.

**NBF:** Norwegian Fire Protection Association.

**NFPA:** National Fire Protection Association. American organization for fire protection and building safety.

**$NO_2$:** Nitrogen dioxide.

**Nuisance alarm:** Alarm from a smoke alarm without there being a danger of fire, typically activated by dust, vapour and similar.

**Photoelectric smoke detector** is based on the fact that particles reflect light when they are illuminated from a small light source inside an otherwise dark chamber. The reflection of particles reaches a light sensitive sensor, which picks up such light as a danger signal and activates an alarm transmitter. [2]

**Smoke detector:** Detector affected by combustion products.

**$SO_2$:** Sulphur dioxide.

**TEK10:** *2010 regulation on technical requirements relating to buildings.*

**Smouldering fire:** Combustion in a solid material without flames and without any emission of light from the combustion zone.

**VTEK:** *Guideline to regulation on technical requirements relating to buildings* (guideline to TEK10).

# 1 Introduction

## 1.1 Background

In 2012 SP Fire Research conducted a study on the research front relating to smoke detectors [3] for the Norwegian Directorate for Civil Protection (DSB) and the Norwegian Building Authority (DiBK). The study presented research conducted between 2000 – 2012 addressing smoke detectors, and also identified the requirements for further research. With basis in the report and its recommendations, our clients wished to have three subjects further explored. The subjects are not directly related to each other, however, they require the same scientific method, which is why it was possible to examine three issues of concern in one and the same test setup.

The first issue to be addressed has to do with the properties of smouldering fires, which are such that it may take a relatively long time before a fire is detected. This is because smouldering fires develop slowly and do not develop much heat. The smoke is not very hot, buoyancy is modest, and the smoke particles are relatively large. Our clients wished to examine whether other detection principles, e.g. CO concentration measurements, might give an earlier alarm than photoelectric smoke detectors.

The second issue of concern has the same background as the one first mentioned. Our clients wished to identify the gas concentration levels accumulated in a room with smouldering fire in the time before a smoke alarm is activated, and to examine whether a person sleeping in a room where such a fire breaks out will have any chance at all of evacuating before incapacitation or death sets in.

The third issue of concerns is related to the recommendation of the Norwegian Fire Protection Association that smoke detectors should not be placed too close to walls or under the ridge [4], in so-called dead-air space. It has been assumed that the smoke circulates less, thereby leading to later detections, in these areas. An American study, further discussed in chapter 2.1, concluded that smoke detectors placed inside dead-air space do not respond more slowly than smoke detectors placed outside the dead-air space. Our clients wished to have equivalent experiments carried out, to verify if we obtained results similar to the American study, and also to examine whether the dead-air space effect was prominent in a typical bedroom.

## 1.2 Objective

The objectives of this project were to:

- examine whether smoke detectors with a CO-sensor may alert dwellers at an earlier stage than photoelectric detectors, thereby increasing the chance of egress.
- identify the level of toxic gases in a room where a smouldering fire breaks out, and examine whether tenability limits to incapacitation are exceeded when a traditional, photoelectric smoke detector is activated.
- examine whether smoke detectors placed in dead-air space respond slower than detectors placed according to the recommendation of the Norwegian Fire Protection Association.

## 1.3 Limitations

This study conducted ten experiments. The fire source was placed on the middle of the bed in four of the experiments, below the bed in three experiments, and on the floor in a corner to the left of the door in three experiments.

All experiments were carried out in a room measuring 8.6 $m^2$, which simulates a small bedroom. The results of this study cannot simply be applied to larger rooms, However, the American study mentioned above [5] conducted experiments in rooms measuring 14.5 $m^2$, 21.4 $m^2$ and 26.6 $m^2$. As far as we know, there does not exist any research on the effect of dead-air space in smouldering fires in rooms larger than 30 $m^2$.

# 2 Hypotheses

## 2.1 Hypothesis A

A combination detector equipped with amongst other a CO sensor would be able to significantly reduce the time to activation, thereby giving persons a better chance of escaping, compared with a photoelectric smoke detector.

H0: A combination detector equipped with amongst other a CO sensor will not significantly reduce the time to activation.

H1: A combination detector equipped with amongst other a CO sensor will significantly reduce the time to activation.

As described in chapter 2.1.3, the smoke produced in a smouldering fire is relatively cold, and as a consequence it may take a relatively long time before the smoke particles reach an photoelectric smoke detector installed on the ceiling. CO is a gas that is present in all fires. CO diffuses faster into the room than smoke particles, which is why a CO detector may be able to alert the dwellers at an earlier stage of the fire than a photoelectric smoke detector. For this hypothesis we wished to quantify how much faster a CO detector responds to the fire, and examine whether this will impact on a sleeping person's possibilities of evacuating the room.

## 2.2 Hypothesis B

Before a photoelectric smoke detector responds to smoke from a smoldering fire, the tenability limits for incapacitation from toxic gases has already been exceeded.

H0: Tenability values for incapacitation from toxic gases have not been exceeded before a photoelectric smoke detector responds to smoke from a smouldering fire.

H1: Tenability values for incapacitation from toxic gases are exceeded before a photoelectric smoke detector responds to smoke from a smouldering fire.

As described in chapter 2.1.3 the smoke produced in a smouldering fire is relatively cold, and as a consequence it may take a relatively long time before the smoke particles reach a smoke detector installed on the ceiling. In the meantime it is possible that the fire will produce such large concentrations of toxic gases, as to incapacitate a person sleeping in the room or cause his/her death, before the detector is activated.

## 2.3 Hypothesis C

Smoke detectors placed in dead-air space respond slower than detectors placed in line with the recommendations.

H0: Smoke detectors placed in dead-air space do not respond slower than detectors placed in line with the recommendations.

H1: Smoke detectors placed in dead-air space respond slower than detectors placed in line with the recommendations.

It is a general perception within fire research environments that the smoke will take longer in reaching detectors placed within than outside dead-air spaces. A study [5] concluded that this may be the case in full scale fires, where there is a turbulent flow of smoke, but that this effect will not apply in the initial phase of a fire. With this hypothesis we wish to verify the results of the mentioned study.

# 3 Theory

## 3.1 Smoke detectors

### 3.1.1 Detection principle

A number of studies have examined which detection principle, e.g. photoelectric or ionic, that is most effective in a smouldering fire and a flaming fire [3]. It appears that photoelectric smoke detectors function best in smouldering fires, while ionic detectors function best in flaming fires. Overall, photoelectric detectors function better than ionic detectors, by virtue of earlier detection in both smouldering fires and flaming fires. This is why the use of photoelectric detectors is described as a pre-accepted performance in VTEK and recommended by NBF.

A study conducted by SP Fire Research shows that ionic smoke detectors are found in 42 % of Norwegian residences, while photoelectric detectors are found in 72 % of dwellings. Additionally, the study shows that 13 % of dwellings have some kind of combination detectors [6].

Recently, combination detectors detecting CO concentrations in addition to e.g. smoke particles (photoelectric), have been introduced in the market. A study in 2005 [7] employed measurements from ionic and photoelectric sensors, CO and temperature sensors as input to algorithms, in which the goal was to reduce the number of nuisance alarms, at the same time as time to detection ought to be at least as short as the time displayed by conventional ionization and photoelectric detectors. Some conclusions of this study were that multisensory algorithms are able to remove a large part of nuisance alarms. Moreover, such algorithms can give earlier, or just as good detection, as conventional detectors. An algorithm using temperature increase rate in combination with measurements from CO detectors and ionic detectors, is a good example of such algorithm.

Dedicated CO detectors have the advantage that they only respond to CO, a gas present in any house fire where incomplete combustion occurs, and that they are not disturbed by dust and water vapour which may lead to nuisance alarms. Since CO diffuses rapidly (spreads inside the room), earlier detection compared to traditional smoke detectors may be obtained, at the same time as the potential for nuisance alarms is reduced.

### 3.1.2 Location of smoke detectors

It may take a relatively long time from when a smouldering fire starts, until a photoelectric smoke detector is activated, and it is not known what concentrations of toxic gasses there are in the room in the time before alarm activation. This is an essential question, since the volume of toxic gases present during the time before the alarm sets off will affect the person's potential for escaping [8]. The location of detectors may therefore be of significance.

In Norway the recommendation is to install smoke detectors on the ceiling, since the smoke, at least in flaming fires, rises to the ceiling. A smoke detector installed on the wall will probably not respond until a layer of smoke has built up from the ceiling and downwards along the wall.

Besides, there are warnings against placing smoke detectors near corners or in the transition between wall and ceiling, because it is assumed that the air in such zones is more stagnant, so that the smoke takes longer in spreading. These areas are called dead-air space. Late detection and fire warning may be a consequence of detectors being placed in the dead-air space.

NBF recommends that smoke detectors be installed on mid ceiling and minimum 50 cm from the wall. If the room has a slanted ceiling, the detector should be placed approximately one meter below the ridge, as shown in Figure 3-1. This is slightly different from the American requirements, which prescribe that there must be minimum 10 cm between a detector installed on the ceiling and the adjoining wall, and maximum 30 cm between detector and ceiling, if it is installed on the wall.

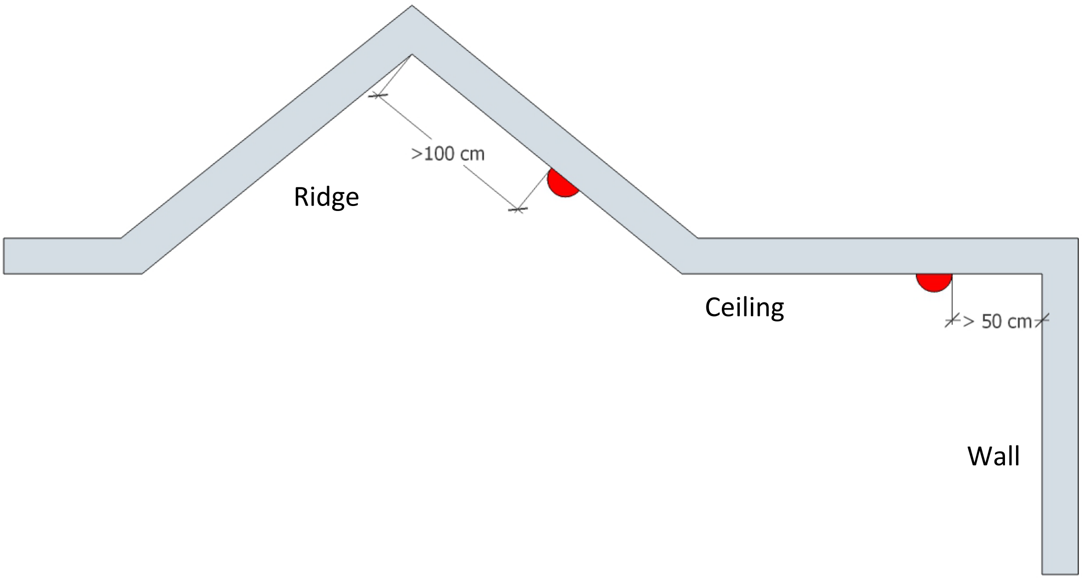



*Figure 3-1 NBF recommends a minimum distance of 50 cm between the smoke detector and the wall, and minimum 100 cm between the ridge and the detector (marked red) if it is installed on a slanting ceiling.*

An American study from 2009 [5] establishes that there is little scientific and experimental proof that dead-air space has a negative effect on smoke detection. In the same study 33 experiments were conducted, both in dwellings and laboratories. The experiments employed both photoelectric and ionic detectors, in addition to combination detectors equipped with both photoelectric and ionic sensors. The experimental setup used in the study  is rendered in Figure 3-2.

*Figure 3-2 From one of the experimental setups examining the effect of dead-air space. Smoke detectors of different brands were installed in different room locations, both inside and outside the zone required in North America. Photo: [5].*

Measurements carried out were time until detection, light attenuation, and temperatures at 12 different points.

The experiments were conducted in rooms of different sizes, 12.4 $m^2$, 21.4 $m^2$ and 26.8 $m^2$ respectively. The smoke detectors were exposed to small, slow-burning fires (smouldering fires), which eventually developed into flaming fires. This was regarded as a *worst case scenario*. Start temperature in the rooms varied between the experiments conducted in the house (10 – 14 °C) and those carried out in the laboratory (approximately 20 °C). Ventilation systems were shut off during the experiments.

The experiments showed that detectors installed in the dead-air space responded just as quickly, and in some cases faster, than detectors installed outside the dead-air space. In this sense, therefore, the experimental studies did not support the recommendation of not installing detectors in the dead-air space. They further showed that the effect of dead-air space may materialize in cases of turbulent gas flows, something that will arise in rooms with a full-scale fire, but this is less relevant, as smoke detectors are supposed to detect fires at an early stage.

### 3.1.3 Factors potentially affecting time to detection of smoke detectors

Various factors impact on the time to detection of a smoke detector. A smouldering fire or flaming fire will impact the volume of smoke differently, as well as the way in which the smoke moves inside the room. In a smouldering fire, which is a relatively cold fire, the smoke is colder than in a flaming fire, and consequently its buoyancy force is smaller. This entails that smoke from a smouldering fire spreads into the entire volume of the room, unlike smoke from a flaming fire, which rises to the ceiling where it forms a smoke layer that gradually becomes thicker. There is also a difference as regards to the properties of smoke in the two types of fire. A smouldering fire produces larger smoke particles than a flaming fire. Photoelectric smoke detectors detect large particles quicker than ionic smoke detectors, which are quicker to detect small particles.

The composition of smoke is affected by the properties of the burning materials. E.g. some plastic products generate smoke with high soot content, while pure wood burns cleaner.

The room's ventilation conditions have an impact on the smoke, both its flow pattern and dilution. Ventilation may lead the smoke away from the detector, consequently increasing the time to detection, but it may also carry the smoke toward the detector, resulting in a shorter time to detection. If the smoke dilutes, the time to detection may increase.

## 3.2 Smoke production in smouldering fires

A smouldering fire is a fire with no flames. Combustion takes place on the surface of the material, and temperature in the combustion zone is low, around 400 °C. Smouldering fires may e.g. arise in materials such as wood, cardboard, paper, and polyurethane foam [9].

The smoke from smouldering fires is typically not dense, and it has a light grey or white colour. The smoke consists of «smoke drops», and average drop size is small [10]. Since the temperature in the combustion zone is low, the smoke is relatively cold and it has little buoyancy force. As a result of these factors the smoke spreads slowly inside a room, and it may therefore take a long time before the smoke reaches a smoke detector installed on the ceiling.

In smouldering fires the decomposition of material components goes slowly, which signifies that it takes a relatively long time before an atmosphere hazardous to humans evolves. Nevertheless, the production of CO per combusted mass is high. In the event of an incomplete combustion, which is the case in smouldering fires, roughly equal volumes of CO and $CO_2$ are produced, so CO is probably a prominent toxic gas in such cases [11].

## 3.3 The effect of toxic gases on humans

### 3.3.1 Toxic substances in fire smoke

Fire smoke can contain a number of toxic substances in different phases – solid particles (soot, fibre), drops (aerosols) and gases. One single material can produce hundreds of toxic gases under combustion, depending on the conditions. Several of these gases may be toxic if concentrations are high enough.

Toxic gases are classified as either narcotic or irritating, depending on how they impact on the organism. Among narcotic gases we find CO, HCN, $CO_2$ and low concentrations of $O_2$. Among irritant gases we find HCl, HBr, HF, $SO_2$, $NO_2$, acrolein, formaldehyde, isocyanate and others.

The human body has four organs that are affected by toxic substances:

- the skin
- the digestion system
- the blood

- the respiration system

Fire smoke impacts on humans through their respiration system. The acute effects are:

- dizziness
- impairment or loss of consciousness
- nausea
- pains in the eyes and upper respiratory passage
- death

Late effects of fire smoke are:

- damage to heart and lungs
- loss of consciousness
- cancer
- chronic bronchia
- increased secrete production from the nose

The likelihood of late effects caused by exposure to low concentrations is assumed to be low.

The effects of exposure of gas concentrations not leading to direct death are:

- reduced evacuation speed
- incapacitation
- reduced mobility
- reduced visibility
- reduced mental capacity
- chronic effects (apply in particular to firefighters)

According to Purser [12] four gases are important in fires: CO, $CO_2$, HCN and reduced oxygen concentration. Of these, CO is the dominant gas. CO will always be present in a residential fire, while the presence of other toxic gases is dependent on which materials are burning. In most victims perishing in fires lethal doses of carboxyl haemoglobin (COHb) were found in the blood [8], [13]–[15]. Heightened concentrations of COHb may suggest that the persons were asphyxiated by HCN in addition to CO. Since HCN is an ordinary smoke gas, it is natural to assume that the person was asphyxiated by HCN through inhaling fire smoke [16].

Some toxic gases may impact on the body's absorption of other toxic gases. One example of such a gas is $CO_2$. $CO_2$ is present in all kinds of fires. $CO_2$ in itself is not toxic in concentrations up to 5 % [11], but at a concentration of 3 % the respiratory minute volume is doubled (a measure of respiration efficiency), and at a concentration of 5 % it is three times as large. This entails that respiration frequency rises, which increases smoke exposure in the lungs, and thereby the absorption of toxic components such as CO.

### 3.3.2 Quantification of toxicity

A dose is the total volume of toxic components that an organism is exposed to (concentration × exposure time). The response is the observed or measured effect, and may constitute different degrees of various symptoms, e.g. death. The dose-response relationship is visualized in a dose response curve, as shown in Figure 3-3.

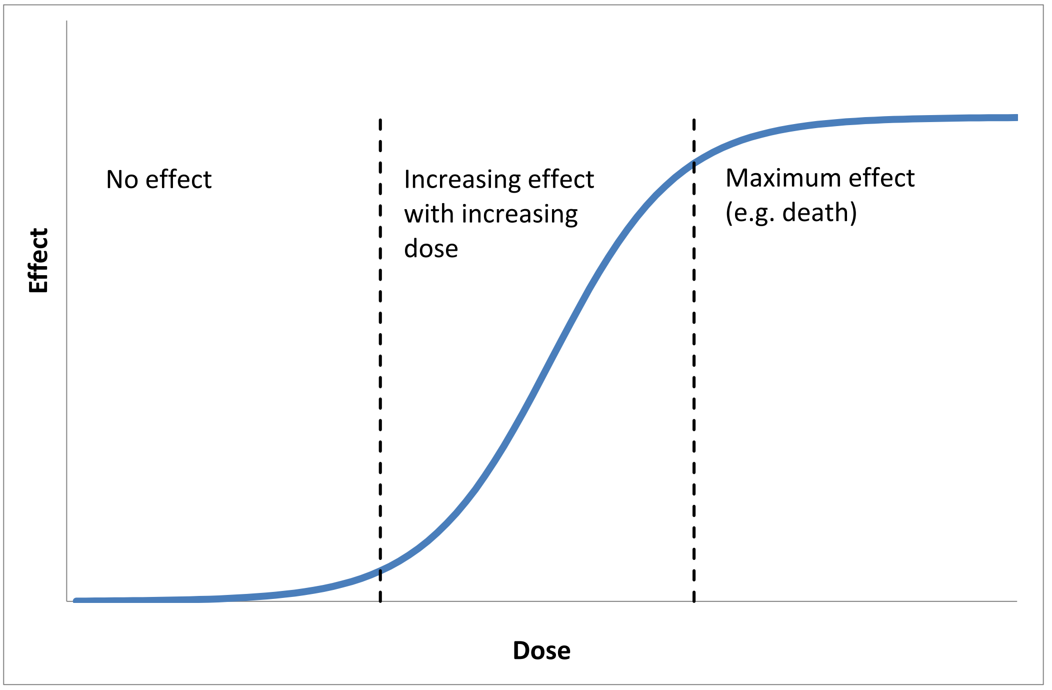


*Figure 3-3 Dose response curve illustrating that the impact of gas on an organism depends on the absorbed dose.*

To quantify the toxicity of various components, the terms $LC_{50}$ and $LD_{50}$ are employed. $LC_{50}$ is the concentration at which 50 % of an exposed population dies. $LD_{50}$ is the dose at which 50 % of an exposed population dies.

### 3.3.3 CO toxicity

CO gas is a particularly important toxicant in a fire smoke because [11]:

- it is always present in a fire, often in high concentrations.
- it causes confusion and loss of consciousness, which reduces and hinders escape.
- it is the prime cause of death in fires.

CO is a narcotic gas which binds to the haemoglobin (Hb) in the blood, forming COHb. Hb binds 200-250 times easier to CO than $O_2$, which means that CO blocks the absorption of $O_2$ into the blood.

CO may give both an acute and delayed effect, but the effect of exposure to low concentrations is slow.

### 3.3.4 Tenability limit values for incapacitation from various gases

In literature multiple values for $IC_{50}$, $LC_{50}$, $ID_{50}$ and $LD_{50}$ are given. For CO, amongst others, Stensaas gives a tenability value for $LC_{50}$ from 5 different sources spanning from 2500 – 8300 ppm [17], however, an accepted $LC_{50}$ value for CO is 5700 ppm [11]. Tenability limits for CO, $CO_2$ and HCN are provided in Table 3-1. Some persons are more sensitive to CO than others, e.g. persons suffering from cardiovascular diseases. Such persons will experience incapacitation at lower doses than healthy persons.

*Table 3-1 Overview of tenability values for incapacitation from various gases [17]. Different sources state different tenability limit values. The table below therefore gives multiple values for some of the gases.*

| Gas | $IC_{50}$ [ppm] | $LC_{50}$ [ppm] | $ID_{50}$ [ppm min] | $LD_{50}$ [ppm min] |
|---|---|---|---|---|
| CO | 1400 – 1700 | 4600<br>5500<br>8300<br>3000<br>2500 - 4000 | 35 000 - 45 000 | 70 000 – 135 000 |
| $CO_2$ | 100 000 | 146 000 | | |
| HCN | 100 – 200 | 110 – 160<br>200<br>135 | 750 – 2500<br>1200 – 2700 | 1500 – 7500 |
| $O_2$ | | 75 000 | | |

# 4 Description of method

## 4.1 Test matrix

Table 4-1 lists the tests carried out in this study, and describes the location of the source of fire in the various tests.

*Table 4-1 Tests conducted in this study. Test 5, marked grey, developed into a flaming fire and was excluded from further analyses.*

| Test number | Location of source of fire |
|---|---|
| 1 | On foot end of bed |
| 2 | On foot end of bed |
| 3 | On foot end of bed |
| 4 | On foot end of bed |
| 5 | Under bed |
| 6 | Under bed |
| 7 | Under bed |
| 8 | On floor, in corner near door |
| 9 | On floor, in corner near door |
| 10 | On floor, in corner near door |

## 4.2 Test room

The tests were carried out in a room measuring 2.4 m × 3.6 m × 2.4 m (w × l × h), which gives a base of 8.6 $m^2$ and a volume 20.7 $m^3$, see Figure 4-1. The test room is defined in the standard ISO 9705 [18]. Such as the standard defines the room, there is a door opening of 0.8 m × 2.0 m (w × h) located in one of the short walls. This door was closed during tests to prevent ventilation. Tests were conducted in such a room in order to enable simple reproduction and repetition of tests at a later stage. The size of the room represents a typical room, typically bedroom, in a dwelling.

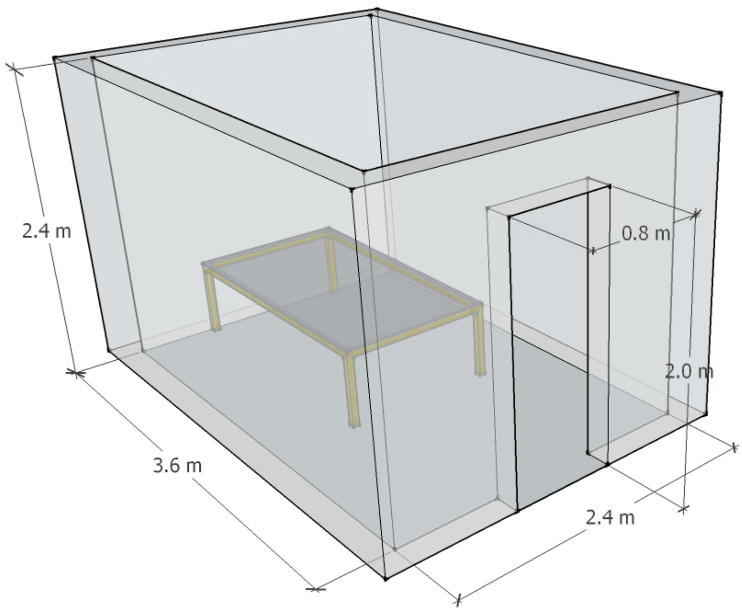



*Figure 4-1 Sketch of test room. The design and dimensions of the room are according to ISO 9705 [18].*

## 4.3 Furnishing

To simulate a bed a horizontal plasterboard measuring 220 cm × 120 cm (l × w) was placed inside the room. The board was mounted on a frame, built from 2" × 2" wooden laths, with its legs elevating 60 cm above floor level. The bed was placed at the middle of the short wall, facing the door.

## 4.4 Source of fire

The combustible material employed in the tests was a polyether mattress segment measuring 70 cm × 50 cm × 10 cm (l × w × h). Figure 4-2 shows the insulated mattress which was packed in ceramic fibre wool to restrict oxygen accessibility.

*Figure 4-2 Mattress segment packed in ceramic wool with the "smouldering fire generator" inside.*

To initiate smouldering fires a device consisting of a resistance wire, approx. 0.9 m long, (0.5 mm diameter and 6.88 Ω/m) which was wound around a 15-cm long ceramic core as shown in Figure 4-3 was made. The device was covered by a layer of cotton before it was placed in the centre of the mattress surface under the ceramic insulation.

(A) (B)

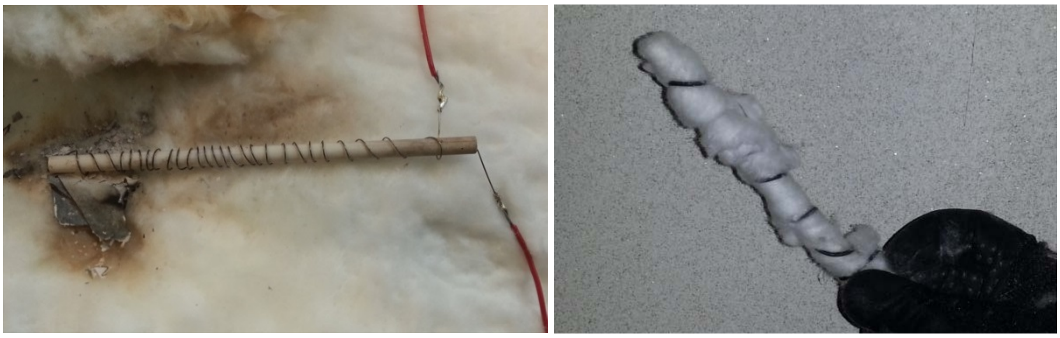


*Figure 4-3 Resistance wire wound around a ceramic core (A) and "smouldering fire generator" ready for use (B).*

At test start the resistance wire was connected to a 12 V voltage source, which gave an effect of approx. 23 W. The voltage was turned off after 10 minutes. A 0.5 mm thick, sheathed thermocouple, type K, was placed next to the device in order to be able to confirm or disprove a smouldering fire start in the closed setup.

In order to ensure dispersion of gases and smoke particles into the room from the same position in each test, the setup was covered by a plywood crate without bottom and with a hole on top (see Figure 4-4). The crate's exterior dimensions were 83 cm × 63 cm × 23 cm (l × w × h), and hole diameter was 51 mm. For the three last tests, where the source of fire was placed in a corner of the room, the crate was modified so that it its bottom became tight, but with the same hole in the top board centre. This was done in order to avoid smoke escaping from the bottom of the crate.

*Figure 4-4 Complete setup of source of fire, where the mattress and smouldering fire generator are covered by a crate with a hole to allow fire smoke and gases to escape.*

# 4.5 Instrumentation

Measurements performed during the tests were time to alarm, gas concentrations, light scattering, and temperatures for each smoke detector. An overview of the instruments employed is found in Table 4-2. The location of measuring instruments and smoke detectors is shown in Figure 4-5 to Figure 4-9.

*Table 4-2 Smoke detectors and instruments employed for gas measurements and logging of data.*

| Manufacturer/brand | Function/type of measurement | Comment |
|---|---|---|
| Deltronic PS 1211 | Photoelectric smoke detector (ON/OFF) | «Model A» (yellow colour in Figure 4-8) |
| Proove JB-S01 | Photoelectric smoke detector (ON/OFF) | «Model B» (blue colour in Figure 4-8) |
| E:Z0 KD-134A/KD-101LB[1] | Photoelectric smoke detector (ON/OFF) | «Model C» (green colour in Figure 4-8) |
| Tyco 830PC 3oTec Triple Sensor Detector | Combination detector with sensors for CO, light scattering and temperature | (Red colour in Figure 4-6 – Figure 4-8) |
| ABB FTLA 2000 | FTIR-measurement of smoke gases | Placed 20 cm above mattress at head end of bed |
| Servomex | Analyser for measuring CO, $CO_2$ and $O_2$ | Placed 70 cm above mattress at head end of bed |
| Hartmann Braun Uras 10E | Analyser for measuring CO and $CO_2$ | Placed 20 cm above mattress at head end of bed |
| Dräger X-Am 5000/5600 | Handheld CO-detector | Placed at head end of mattress, and in source of the smouldering fire[2] |
| Thermocouple Type-K | Temperature gauge | Placed in source of the smouldering fire |
| Agilent, 34972A | Logging system for gas analyser | |
| MZX Tech. | Logging system for combination detectors | |

(A) (B)

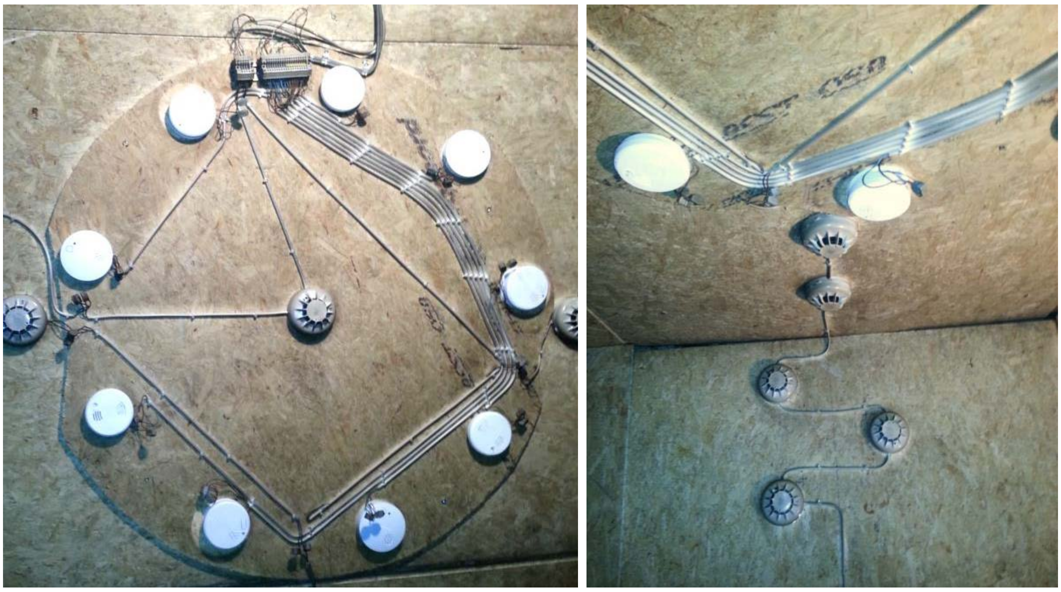


*Figure 4-5 Location of smoke detectors on ceiling (A) and on wall (B). White detectors are photoelectric, and the grey ones are combination detectors.*

[1] KD-101LB was replaced by KD-134A after they were damaged in test 5. KD-101LB was not commercially available within a reasonable period of time. The two other types of photoelectric smoke detectors were also replaced after test 5, but by identical brands.

[2] CO detector at source of fire was not employed after test 5, because it was damaged during this test.

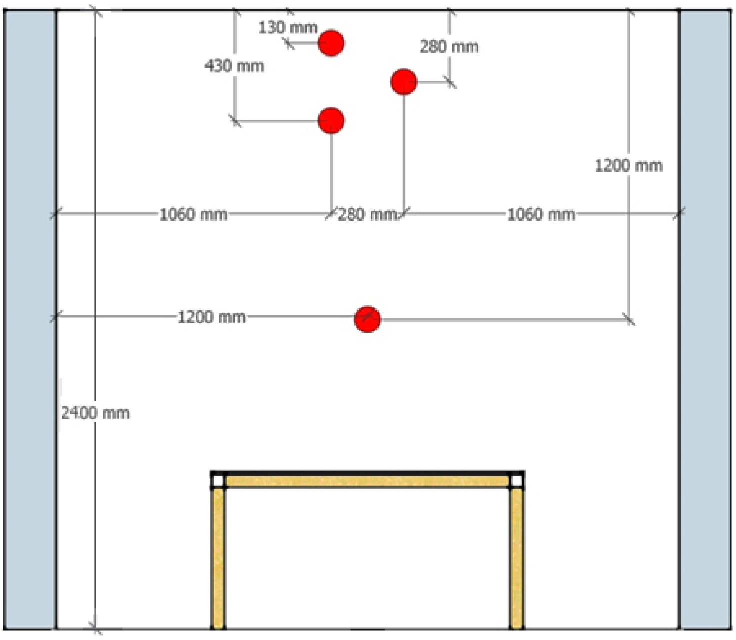



*Figure 4-6 Locations of combination detectors on the room's interior short wall.*

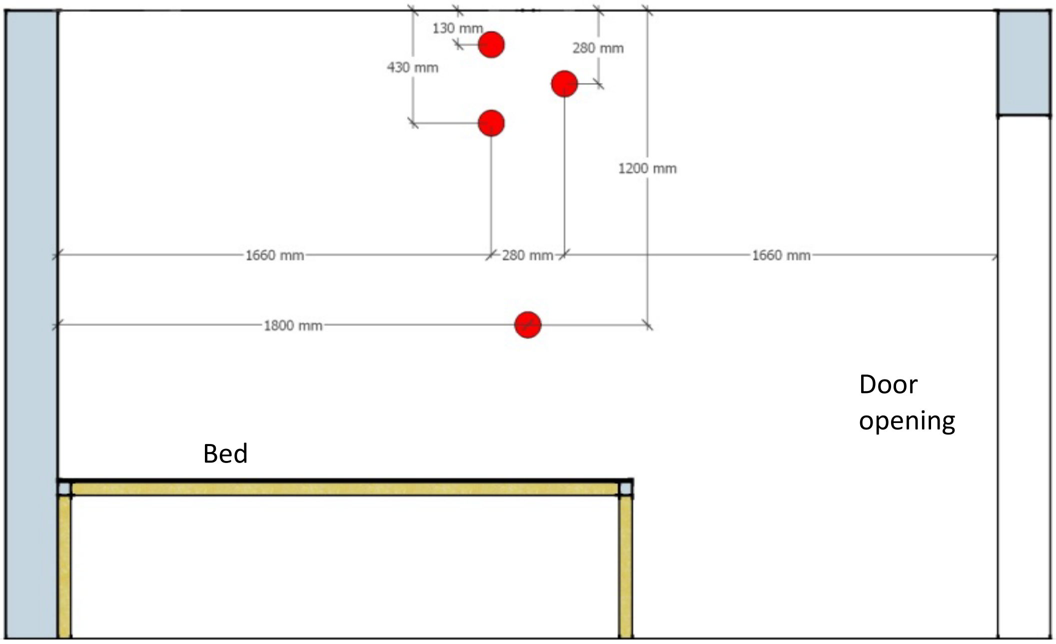



*Figure 4-7 Locations of combination detectors on the two long walls of room.*

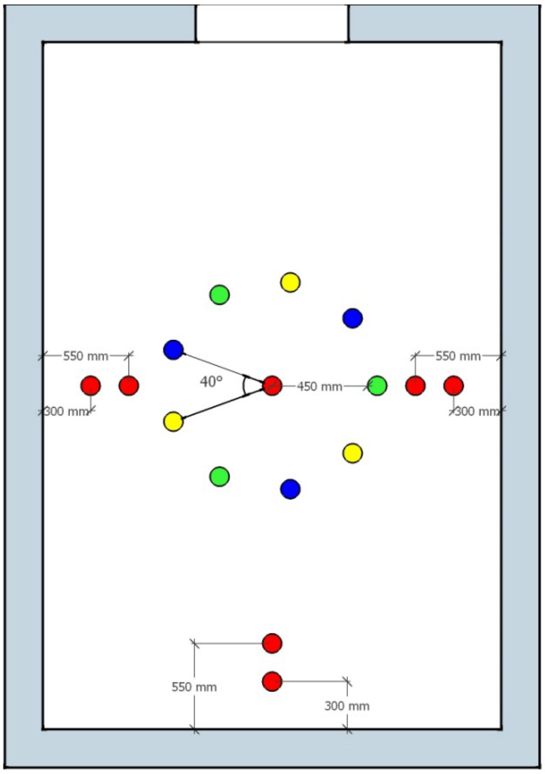



*Figure 4-8 Combination detectors (red) and photoelectric smoke detectors (yellow indicates model A, blue model B and green model C, see Table 4-2).*

In order to represent photoelectric smoke detectors typically found in Norwegian dwellings, brands sold in stores were employed. Three different brands were tested to examine whether the results depend on the type of smoke detectors. The brands are described in Table 4-2 («Model A», «Model B» and «Model C»). Three smoke detectors of each brand were installed.

The photoelectric smoke detectors were placed in a circle centred in mid ceiling. Each detector was placed with a 45-cm interior distance to the centre, and with equal distance (40°) from each other, as shown in Figure 4-8.

To measure the dispersion of smoke and CO in the room, combination detectors were employed. Such detectors have a built-in CO sensor, temperature sensor and light scattering sensor, and provide continuous measurements. They were used to examine whether the location of smoke detectors in the room is significant to detection properties, and whether CO sensors are able to detect an ongoing smouldering fire earlier than photoelectric sensors. Overall 21 combination detectors were installed, of which seven were placed on the ceiling (of which three in dead-air space), 12 on the wall (of which 6 in dead-air space) and 2 on the floor. The locations of combination detectors are illustrated with red markers in Figure 4-6 to Figure 4-8.

All detectors were connected to a logging system, in order to record the point when they were activated.

Extraction of gas for gas measurements was carried out at the head end of the bed, as shown in Figure 4-9. CO, $CO_2$ and $O_2$ concentrations were measured 20 and 70 cm above the bed.

Fourier Transform InfraRed spectroscopy (FTIR) was employed to measure HCN concentrations. These measurements were taken at the head end of the bed as well. The FTIR analyser was calibrated according to ISO 19702:2006 [19]. Extraction of smoke gases was performed at the head end of the test setup, 20 cm above the bed. Prior to the test series the FTIR setup was calibrated against the accredited $CO/CO_2$ gas with known concentration, and before each test a recording of background spectre was made. The FTIR recording was started prior to ignition, and went on continuously throughout the entire test.

*Figure 4-9 Locations of extraction of $CO/CO_2$-measurements and FTIR at the head end of bed.*

A thermocouple was employed to verify ignition in the source of fire. It was placed near the smouldering fire generator.

# 4.6 Data analysis

Statistical differences were examined by applying Mann-Whitney U-test in Statistica version 12 (Dell Software) software. $p \leq 0.05$ was employed as significance criterion with $p \leq 0.01$ being considered highly significant.

To estimate average time to activated alarm for photoelectric smoke detectors, smoke detectors that did not activate were excluded. Test 5 developed into a flaming fire and was therefore excluded from further analyses.

CO measurements were performed 20 cm and 70 cm above the bed mock-up. Both measurements displayed good correlation, but there was considerable noise on the measurement carried out at 20 cm height. For the further analyses measurements taken at 70 cm height were therefore employed.

Noise in the raw data of light scattering measurements was equalized by moving average with an interval of 6 measuring points.

Concentration of HCN was estimated by employing partial multivariate least squares analysis in PAS (Protea Ltd) software. Quality assurance of spectres was made through manual analysis in Horizon MB (ABB) software. Verification of CO measurements conducted by gas analyser and FTIR, FTIR consequently gave a lower value. Estimated correction factors varied. HCN concentration values stated in this report have been corrected by using the lowest correction factor, which was 1.8.

# 5 Results

## 5.1 General considerations

All tests generated a smouldering fire. Test 5 developed into a flaming fire, however, and was consequently excluded from further analysis.

To eliminate sources of error, introductory analyses were carried out, described in section 5.2.

## 5.2 Introductory analyses

### 5.2.1 Comparison of different smoke detector brands

As described in chapter 4.5, nine photoelectric smoke detectors fabricated by three different manufacturers were employed (three detectors from each manufacturer, here named «Model A», «Model B» and «Model C»).

Figure 5-1 shows average time to activation of alarm for the three smoke detector models employed in the ten tests. In test 1, Model 2 was not activated at all. During test 8, 9 and 10 no photoelectric smoke detectors were activated. After the non-activated detectors had been excluded from the data set, there were no significant differences between the different models. Further results are therefore analysed irrespectively of model.

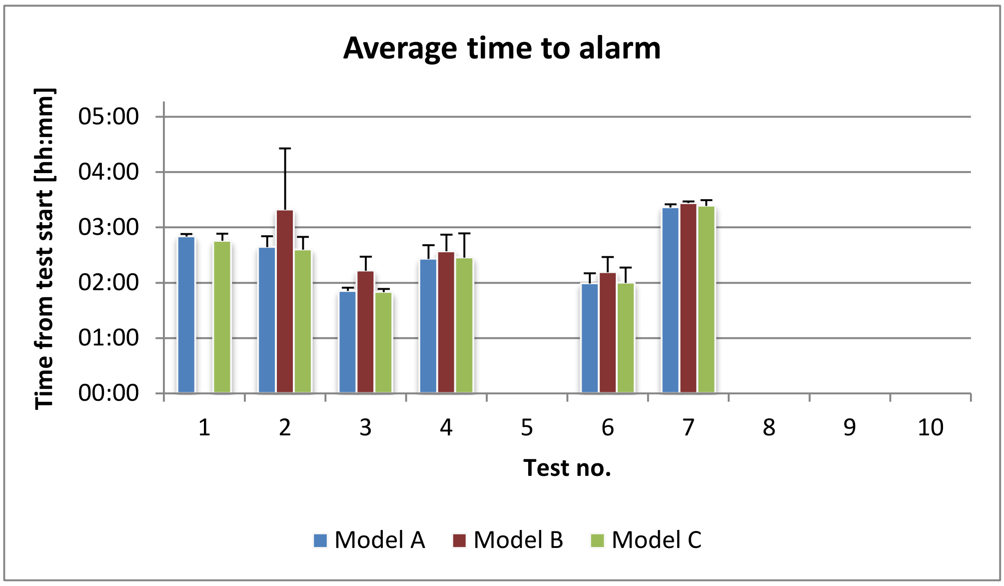



*Figure 5-1 Average time to activation of alarm and standard deviations (N=3 for each column) of the three different models of photoelectric smoke detectors. Model B in test 1, and all three models in test 8, 9 and 10, were triggered during the test time of the respective tests (shown by ÷ in the figure).*

### 5.2.2 Comparison of different CO measurements

There was a high correlation between CO concentrations measured simultaneously in different locations in the room. This was examined by analysing the correspondence between CO concentrations measured by an analyser at the head end of the bed, and by combination detectors installed on the wall and on the ceiling, see Figure 5-2.

Correlation between the CO measurements taken from the head end of the bed and the CO measurements of the combination detectors was quantified at linear regression of all curves. The analysis indicates a high correlation, even though there are indications that CO concentration at the head end was somewhat higher at test start and increased faster throughout the test, than when mounted on the ceiling or on the wall. On average, regression provided the following straight line

$$Y = ax + b$$

where

a = 1.12 ± 0.383
b = 14.09 ± 8.668

Average coefficient of determination of all tests was $R^2 = 0.97 \pm 0.017$.

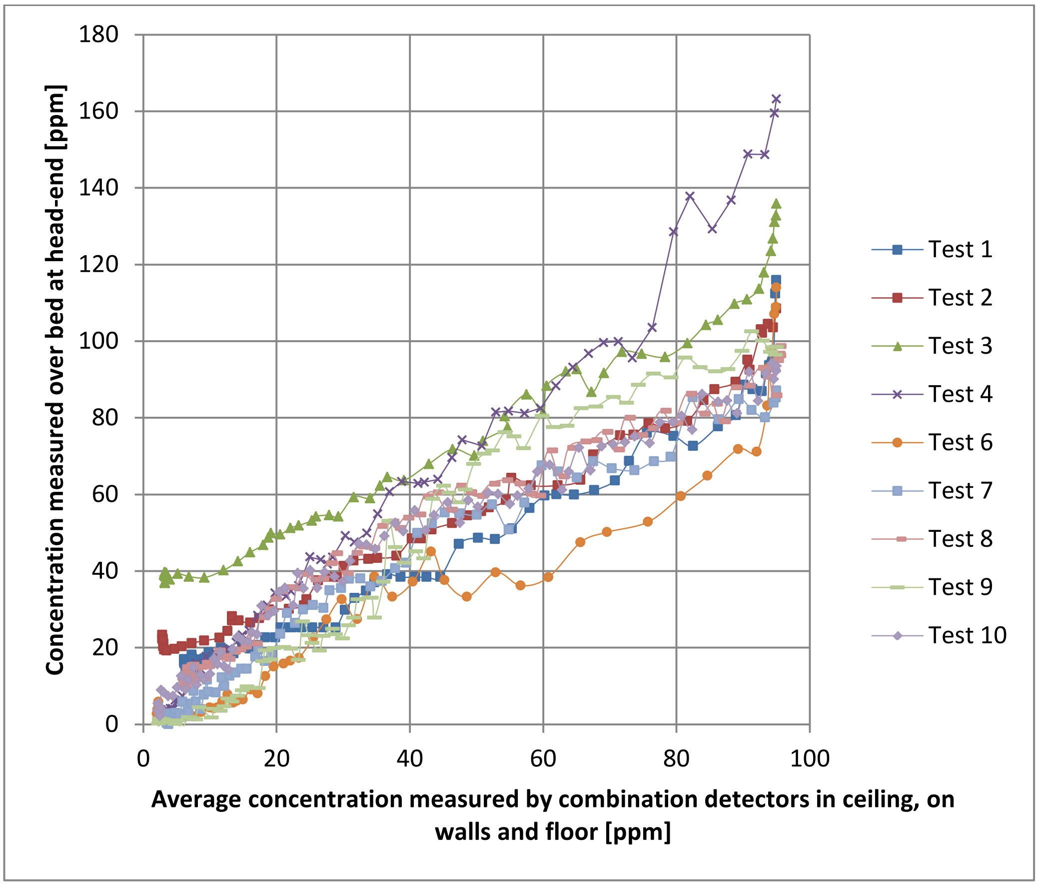



*Figure 5-2 CO concentrations measured by gas analyser at the head end of bed and average concentrations of all combination detectors on wall and on ceiling (N=19) in each test. The points of measurement represent different points in time after each test start. For better visibility, standard deviations of average concentrations are omitted from the graph. The graph shows measurements up to a combination detector saturation value of 99 ppm.*

## 5.3 Comparison of detection principles

### 5.3.1 Alarm activation time of all detectors

Figure 5-3 shows the average time to activation of photoelectric smoke detectors and combination detectors in each test. On average for all tests, the combination detectors were activated 01:42 ± 00:27 [hh:mm] before the photoelectric smoke detectors.

All detectors included in the figure (nine photoelectric detectors and four combination detectors) were placed on the ceiling outside the dead-air space.

Analyses of raw data files from the experiments demonstrate that all combination detectors were triggered at approximately equal levels of CO concentration, which indicates that it is the CO level in the room that triggers the alarm, not the sensor that measures light scattering caused by the smoke.

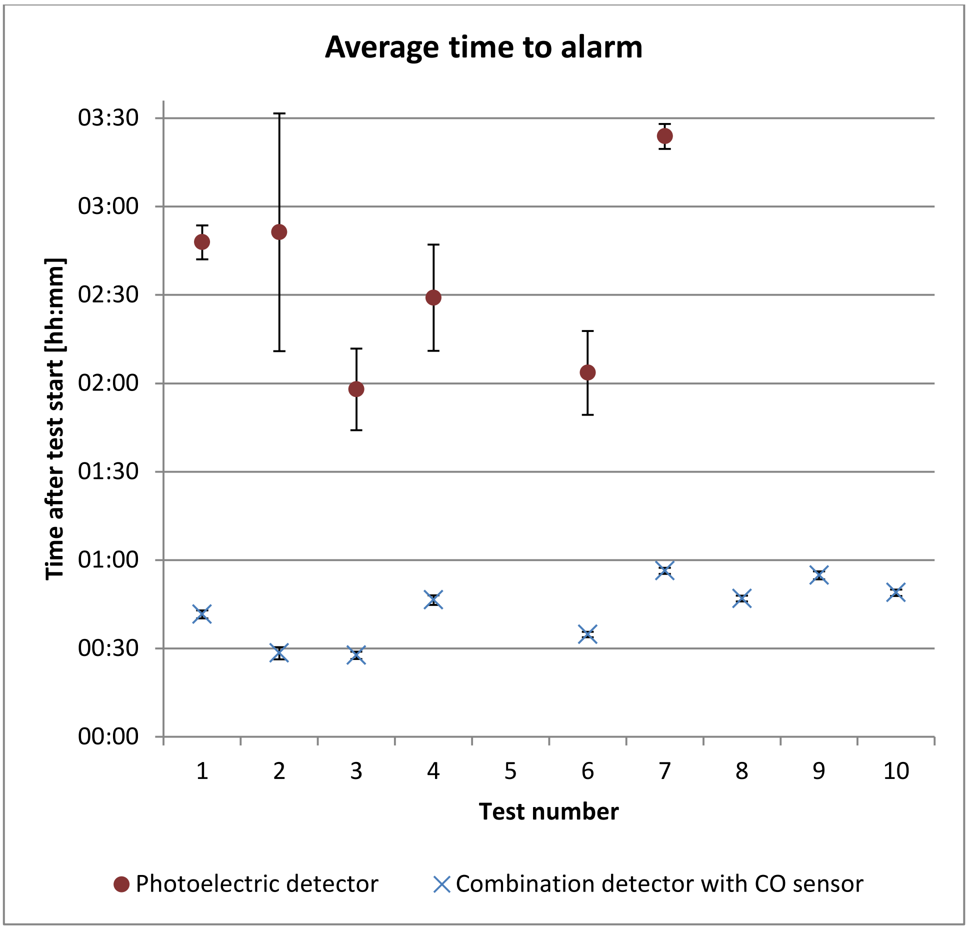



*Figure 5-3 Average alarm activation time and standard deviations of photoelectric detectors (N=9) and combination detectors (N=4). Only combination detectors on ceilings outside dead-air spaces are included. No photoelectric smoke detectors were triggered in tests 8 – 10.*

### 5.3.2 Time to activation when source of fire is located in different places

Figure 5-4 shows the impact of different fire source locations on time to detection for photoelectric detectors and combination detectors respectively. The figure demonstrates that the combination detectors were triggered earlier than the photoelectric smoke detectors. When the source of fire was located on the bed, there was a significant difference between photoelectric detectors and combination detectors in average time to alarm and the shortest average time to alarm. However, when the source of fire was located underneath the bed, only significant difference in average time to alarm was observed. The reason why no significant differences were detected in the shortest time to alarm, was the fact that only two detectors are included in the average. In the last setup, where the source of fire was located in the corner by door, none of the photoelectric smoke detectors alarmed, and it is therefore not relevant to study the differences.

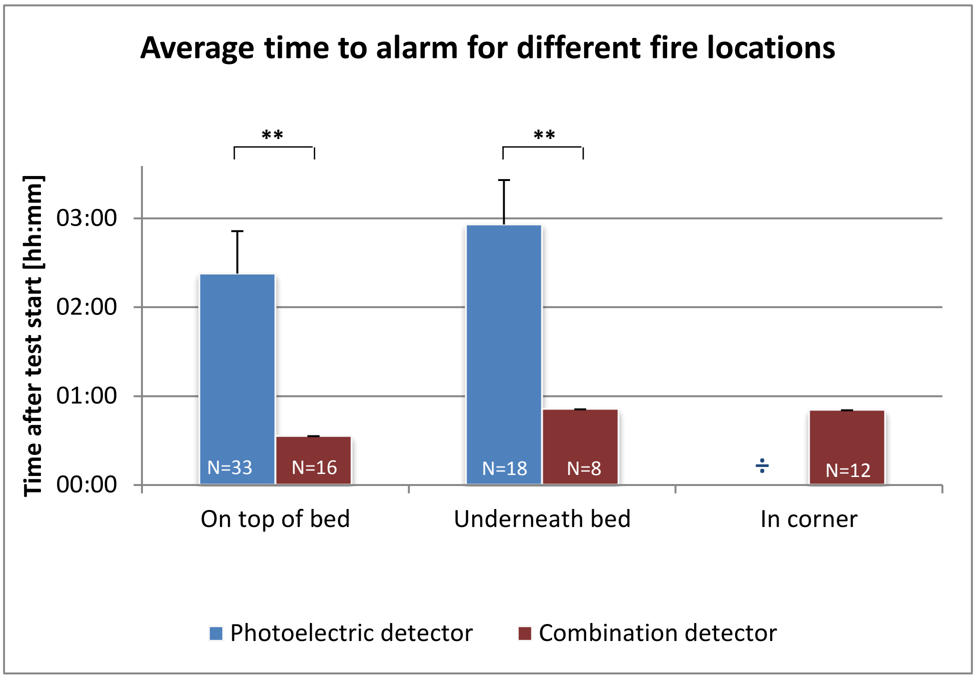



*Figure 5-4 Comparison of time to alarm for photoelectric smoke detectors and combination detectors. The figure shows average and standard deviations of time to alarm. Only combination detectors placed on the ceiling outside dead-air spaces are included, i.e. those mounted closest to the photoelectric smoke detectors. Nine tests are included in the average. When the source of fire was placed on the floor in the corner by the door, no photoelectric smoke detectors went into alarm during the test time (shown by ÷ in the figure). The size of selection (N) is indicated in each column. The degree of significance is shown by ** ($p \leq 0.01$; highly significant).*

## 5.4 Gas concentrations at head height above mattress

The concentration of gases at the head end of the bed was measured during the test to identify the concentrations a sleeping human can be exposed to during a smouldering fire. Based on Purser [12], who states there are four toxic gases prominent in a fire, we have focused on CO, $CO_2$, HCN and low $O_2$ concentration.

Table 5-1 lists results from measurements of gas concentrations at different points of time of activated alarm. CO dose is calculated as the integral of the CO concentration from test start to time for activated alarm. No measurable concentrations of HCN were registered in the period before the detectors alarmed.

*Table 5-1 Measured gas concentrations at the head end of the bed at the time of activated alarm. Values marked in red (and marked by *) in the table lie above the limit for $ID_{50}$. Values below calculated detection limit are shown by «n/a» (not applicable).*

| **Time of measurement** | **Test no.** | **Gas concentration** | | | | |
|---|---|---|---|---|---|---|
| | | $O_2$ [%] | $CO_2$ [ppm] | CO [ppm] | CO dose [ppm min] | HCN [ppm] |
| At shortest time to activation of photoelectric smoke detector | 1 | 20.6 | 1 465 | 576 | 30 859 | n/a |
| | 2 | 20.5 | 1 792 | 733 | 31 384 | n/a |
| | 3 | 20.6 | 1 431 | 502 | 17 855 | n/a |
| | 4 | 20.5 | 1 868 | 639 | 22 690 | n/a |
| | 6 | 20.6 | 1 630 | 643 | 18 985 | n/a |
| | 7 | 20.4 | 2 095 | 993 | ***57 893** | n/a |
| | 8 | | | | | |
| | 9 | | | | | |
| | 10 | | | | | |
| At mean time to activation of photoelectric smoke detector | 1 | 20.5 | 1 565 | 664 | ***37 593** | n/a |
| | 2 | 20.2 | 2 705 | 1 453 | ***63 957** | n/a |
| | 3 | 20.5 | 1 722 | 638 | 24 371 | n/a |
| | 4 | 20.4 | 2 275 | 907 | ***39 325** | n/a |
| | 6 | 20.5 | 2 063 | 933 | 32 547 | n/a |
| | 7 | 20.4 | 2 163 | 1 075 | ***64 184** | n/a |
| | 8 | | | | | |
| | 9 | | | | | |
| | 10 | | | | | |
| At shortest time to activation of combination detector | 1 | 20.8 | 565 | 25 | 587 | n/a |
| | 2 | 20.8 | 509 | 38 | 425 | n/a |
| | 3 | 20.8 | 446 | 53 | 1 121 | n/a |
| | 4 | 20.8 | 472 | 52 | 802 | n/a |
| | 6 | 20.8 | 561 | 35 | 276 | n/a |
| | 7 | 20.8 | 633 | 36 | 515 | n/a |
| | 8 | 20.8 | 588 | 44 | 965 | n/a |
| | 9 | 20.8 | 522 | 30 | 437 | n/a |
| | 10 | 20.8 | 585 | 47 | 902 | n/a |
| At mean time to activation of combination detector | 1 | 20.8 | 581 | 35 | 875 | n/a |
| | 2 | 20.8 | 514 | 42 | 766 | n/a |
| | 3 | 20.8 | 457 | 62 | 1 236 | n/a |
| | 4 | 20.8 | 493 | 61 | 965 | n/a |
| | 6 | 20.8 | 569 | 35 | 315 | n/a |
| | 7 | 20.8 | 641 | 37 | 554 | n/a |
| | 8 | 20.8 | 591 | 46 | 1 019 | n/a |
| | 9 | 20.8 | 524 | 36 | 489 | n/a |
| | 10 | 20.8 | 580 | 46 | 960 | n/a |

Figure 5-5 shows CO concentration at the head end of bed at shortest time to alarm of photoelectric smoke detectors and combination detectors. The CO concentration averaged 18 ± 7 times higher when the photoelectric smoke detectors alarmed than when the combination detectors alarmed. CO concentration measured in the combination detectors at the point of activation was approximately 34 ppm in all the experiments, indicating that it was the CO sensor of the combination detectors that set off the alarm.

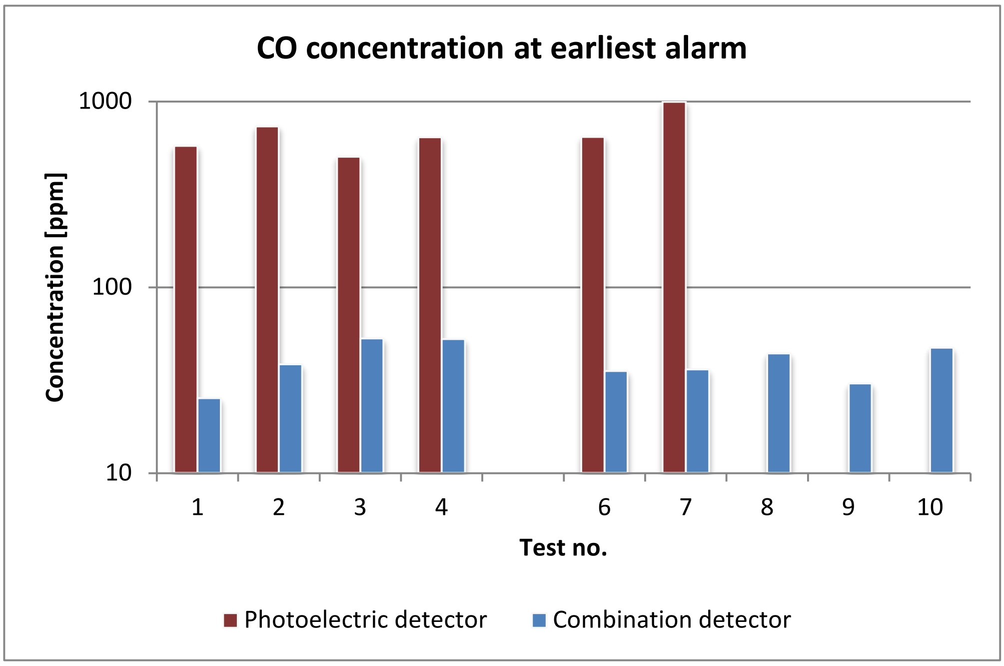



*Figure 5-5 CO concentration measured at head end and on the ceiling and wall at shortest time to alarm for photoelectric smoke detectors and combination detectors. The vertical axis is logarithmic for better visibility. Values are extracted from Table 5-1. Test 5 is excluded as it developed into a flaming fire.*

On average, accumulated CO dose at the time of the first and average alarm of combination detectors provides the following doses:

- 621 ppm×min ± 275 ppm×min

and

- 785 ppm×min ± 294 ppm×min.

Corresponding figures for the first and average alarm of photoelectric smoke detectors are:

- 24 355 ppm×min ± 5 754 ppm×min

and

- 32 081 ppm×min ± 6 113 ppm×min.

## 5.5 Effect of placing smoke detectors in dead-air spaces

### 5.5.1 Enumeration of combination detectors

The location of detectors inside and outside dead-air spaces is outlined in Figure 5-6. To study the effect of the different locations of detectors, light scattering was measured in detectors mounted close to each other and compared in pairs. The detector pairs are listed in Table 5-2.

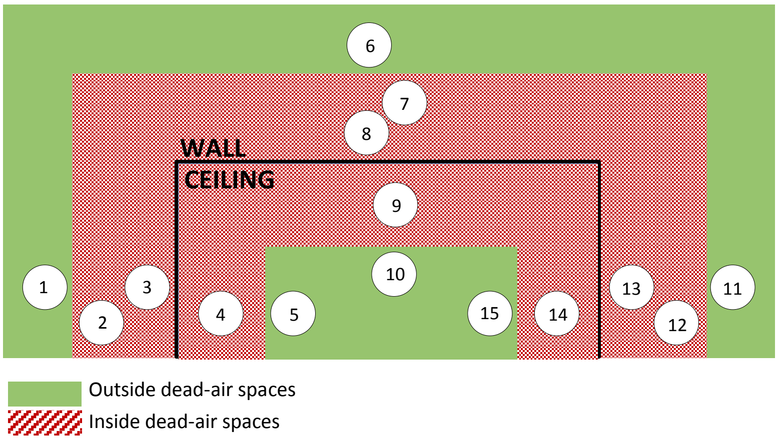



*Figure 5-6 Location of 15 combination detectors inside (red hatched) and outside (green) dead-air spaces, on ceiling (inside black box) and on wall (outside black box). The detectors are numbered to be able to show their location in further analyses.*

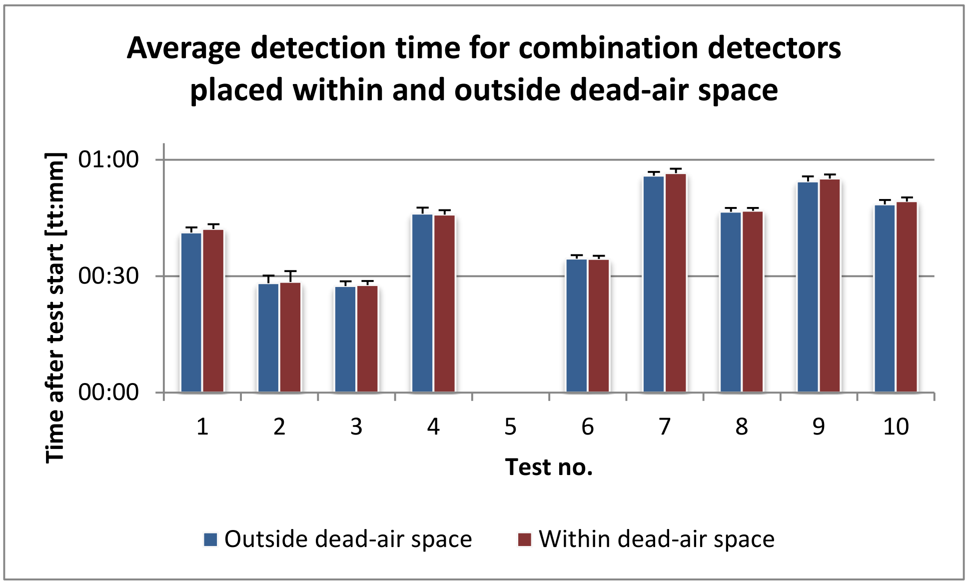
*Table 5-2 A comparison of light scattering for combination detectors in different locations was made by calculating the difference between a selected pair of detectors, as a function of time. The enumeration of the detectors in the table refers to the location in Figure 5-6. The table only lists the detector pairs shown graphically in this report.*

| Detector pair | Detector no. | | Difference in light scattering (LD) | Comparison |
|---|---|---|---|---|
| a | 3 | 1 | $LD_{Detector\ 3} - LD_{Detector\ 1}$ | In and outside dead-air spaces |
| b | 8 | 6 | $LD_{Detector\ 8} - LD_{Detector\ 6}$ | In and outside dead-air spaces |
| c | 13 | 11 | $LD_{Detector\ 13} - LD_{Detector\ 11}$ | In and outside dead-air spaces |
| d | 4 | 5 | $LD_{Detector\ 4} - LD_{Detector\ 5}$ | In and outside dead-air spaces |
| e | 9 | 10 | $LD_{Detector\ 9} - LD_{Detector\ 10}$ | In and outside dead-air spaces |
| f | 14 | 15 | $LD_{Detector\ 14} - LD_{Detector\ 15}$ | In and outside dead-air spaces |
| g | 4 | 3 | $LD_{Detector\ 4} - LD_{Detector\ 3}$ | Ceiling and wall |
| h | 9 | 8 | $LD_{Detector\ 9} - LD_{Detector\ 8}$ | Ceiling and wall |
| i | 14 | 13 | $LD_{Detector\ 14} - LD_{Detector\ 13}$ | Ceiling and wall |

### 5.5.2 Effect of location on time to detection

The location of combination detectors did not seem to have much effect on the time to detection. Figure 5-7 shows that there was no difference in average time to detection for detectors located inside or outside dead-air spaces. The graph also shows that standard deviations were small, which means there was a low variation in time to detection. Only one test identified a significant difference in time to alarm between detectors placed on the ceiling or on the wall.

(A)




(B)

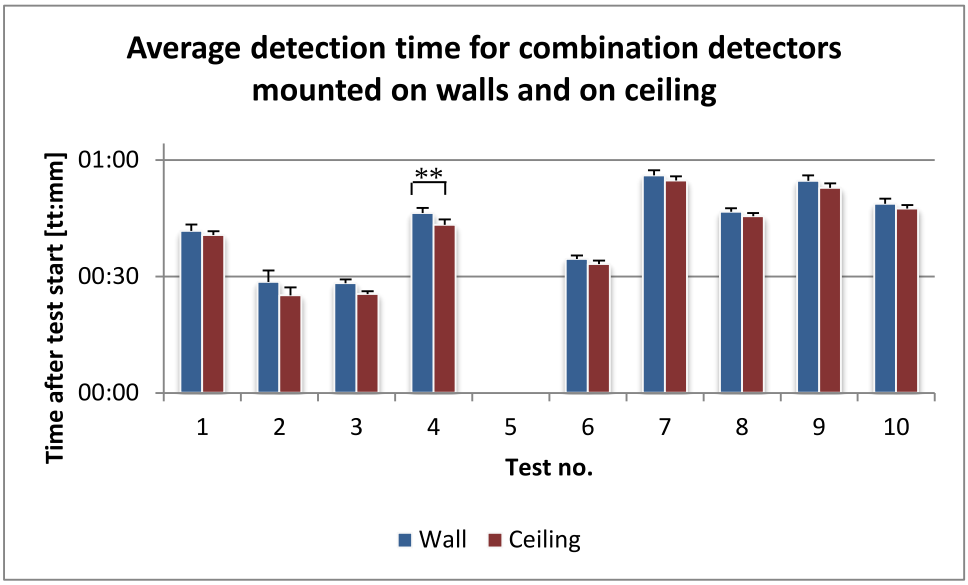


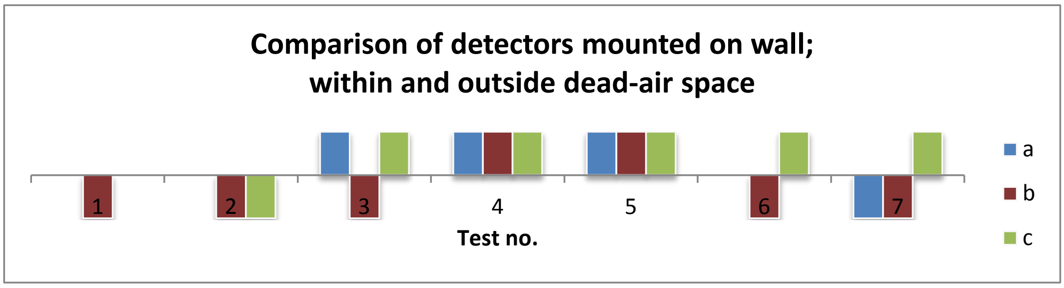

*Figure 5-7 Average time to activation of alarm for combination detectors placed in different positions. (A) compares detectors, both ceiling-mounted and wall-mounted, placed outside and inside dead-air spaces respectively, whilst (B) compares wall-mounted detectors and ceiling-mounted detectors, regardless of whether they are placed in dead-air spaces or not. Significant differences are shown by *) $p \leq 0.05$ and **) $p \leq 0.01$.*

### 5.5.3 Effect of location on photoelectric sensor detection

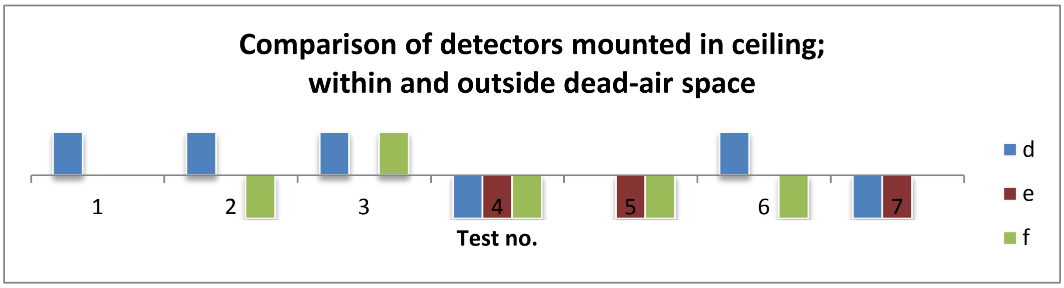
To assess whether there was a difference between measured light scattering at different detector locations, we calculated the difference between the measurement signals of selected pairs of detectors, listed in Table 5-2.

When comparing he detector pairs located inside and outside dead-air spaces respectively, the difference turned out to be randomly negative and positive, which means we did not find a systematic connection (Figure 5-8 A and B). However, the results from comparing detectors placed *inside* dead-air spaces on the ceiling and on the wall, indicate that wall positions provided higher (Figure 5-8 C) and earlier (Figure 5-9) detection than on the ceiling.

(A)




(B)




(C)

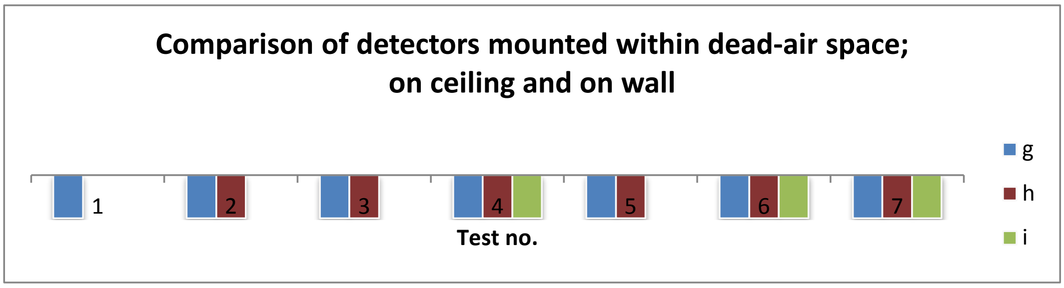



*Figure 5-8 Comparison of measured light scattering from test start to average time to activation for photoelectric smoke detectors, for detector pairs located inside and outside dead-air spaces on wall (A), inside and outside dead-air spaces on the ceiling (B), and on the ceiling and on the wall in dead-air spaces (C). The letters a to i refer to the designation of detector pairs given in Table 5-2. Differences were estimated by calculating the difference in light scattering for the selected detector pairs. Columns above and below the axis itemize the positive and negative differences. Only detector pairs which had a difference in light scattering (difference > 0.1 %/m) are included in the figure.*

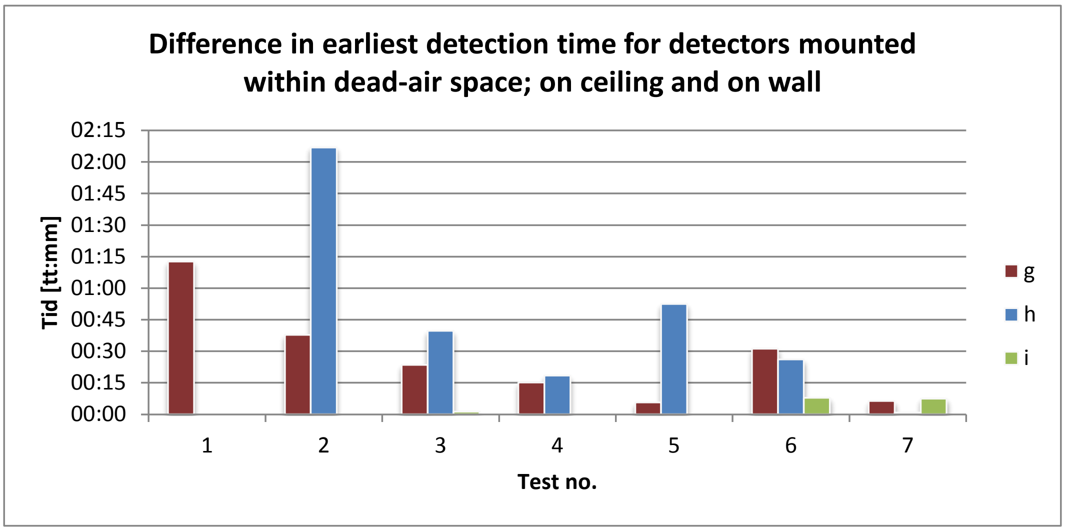



*Figure 5-10 Time difference between first detection of light scattering (light scattering = 0.1) for ceiling-mounted detectors and wall-mounted detectors in dead-air spaces. The letters g to i refer to the designation of detector pairs given in Table 5-2. Positive values show that ceiling-mounted detectors detect light scattering earlier than detectors on walls. Only detectors pairs showing a difference in light scattering (difference > 0.1 %/m) are included in the figure.*

# 6 Discussion

## 6.1 Testing of hypotheses

### 6.1.1 Hypothesis A

Hypothesis A: *A combination detector equipped with amongst other a CO sensor would be able to significantly reduce the time to activation, thereby giving persons a better chance of escaping, compared with a photoelectric smoke detector.*

One of the objectives of the project was to examine whether CO sensors can be activated at an earlier stage than traditional, photoelectric smoke detectors, thus increasing escape time.

Relatively little has happened within the research on domestic smoke detectors the last decade. The market has primarily offered ionic and photoelectric smoke detectors. In recent times, experts have recommended installing photoelectric smoke detectors before ionic, as these generally provide faster time to detection (in both smouldering fire and flaming fires) [3].

Combination detectors have also been introduced, combining several principles of measurement in the same unit. The argument for using these devices used to be that they permit exploitation of the benefits of multiple technologies. This is only partially true, as these technologies are sensitive to nuisance sources, increasing the potential for nuisance alarms. Thus, it is important for these types of smoke detectors to have smart algorithms that weed out and reduce the number of nuisance alarms, at the same time as reducing the time to detection of authentic fires [3], [7].

The experiments of this study employed combination detectors equipped with photoelectric sensors, temperature sensor and CO sensor. The detectors are connected to an alarm central, which analyses the measured values of the various sensors and triggers off an alarm provided certain conditions are met. In all experiments it was the increased carbon monoxide concentration in the room that set off the alarm, long before the photoelectric sensor detected substantial amounts of smoke particles. CO sensors thus seem highly promising in terms of fire detection.

In Figure 5-3 and Figure 5-4, chapter 5.3, it was demonstrated that there was a significant difference in time to alarm between combination detectors and photoelectric smoke detectors. The lapse in average alarm offset time was just below two hours. For a person sleeping in a room with an ongoing smouldering fire, the dose of CO will rise significantly over a two-hour period, which could be fatal.

The recorded CO doses at the point when combination detectors are activated are far below harmful doses, thus one will not be affected by CO. The doses at the point when photoelectric smoke alarms were set off were far higher, implying there is a risk of exceeding $ID_{50}$.

Unlike traditional smoke detectors, CO sensors are not sensitive to dust, water vapour or cooking smoke, reducing the number of nuisance alarms, if not eliminating them altogether. This means that CO detectors may have low alarm limit values without affecting the number of nuisance alarms, as opposed to traditional smoke detectors whose alarm limit value is a balance between early detection and the number of nuisance alarms.

The first CO sensors on the market had a relatively short lifespan, approximately two years. But with time their service life has increased. Some vendors are now advertising with a seven-year life expectancy [20]. Taken into account the recommendation that smoke detectors be replaced every ten years, a service life of seven years should be acceptable.

Results from this study support the notion that a combination detector with a built-in CO sensor may reduce the alarm time, increasing the chance of survival in the event of a smouldering fire.

According to the report *Kartlegging av bruk av røykvarslere i boliger* (English: *Mapping of use of smoke alarms in dwellings*) [6] seniors were less likely than younger people to change the battery themselves. This might be caused by the fact that ceiling-mounted smoke detectors are hard to reach for this age group. We measured little difference in time to alarm between combination detectors placed on the ceiling and on the wall. This means that using a CO detector in a room of equivalent size as employed in these tests, the detector might be placed where it is easiest to reach and maintain for individuals who are not capable of accessing smoke detectors mounted on the ceiling.

### 6.1.2 Hypothesis B

Hypothesis B: *Before a photoelectric smoke detector responds to smoke from a smouldering fire, the tenability limits for incapacitation from toxic gases has already been exceeded.*

The accumulated CO dose at the time when the first photoelectric smoke detector is activated exceeded in one of the experiments (experiment 7) the limit of $ID_{50}$ and was also close to the limit for $LD_{50}$. At the average activation time of photoelectric smoke detectors, the CO dose limit for $ID_5$ was exceeded in four of six valid experiments.

Results show that in the event of a smouldering fire in a bedroom enough CO may be produced to incapacitate a sleeping person *before* a photoelectric smoke detector is activated. Should incapacitation impede evacuation, the dose may also become high enough to cause death.

To calculate HCN concentrations, a correction factor based on the differences of CO concentration measured by a FTIR and a gas analyser respectively was employed.
The correction factor was found to differ from test to test, and it also changed during the course of each test. This study chose to apply the lowest correction factor so as not to overestimate HCN concentrations. This means that we might have underestimated them instead.

### 6.1.3 Hypothesis C

Hypothesis C: *Smoke detectors placed in dead-air space respond slower than detectors placed in line with the recommendations.*

No difference in time to detection was identified between smoke detectors installed inside or outside dead-air spaces. This could mean that the effect of dead-air space is not very conspicuous in rooms of the same size as in this study. The study *An Experimental Examination of Dead-air Space for Smoke Alarms* [5], which conducted tests in larger spaces of different scopes up to 26,8 $m^2$, did not identify any effect of dead-air space either. Maybe even larger rooms are required before the location of smoke detectors in dead-air space will have a significant effect on time to detection.

It has been pointed out that dead-air spaces could be more prominent if there is a smoke flow with large turbulence eddies [5]. Before such a smoke flow occurs, the fire has already developed considerably, and ought to have been detected by a smoke detector.

Perhaps the effect of dead-air space is more prominent in a flaming fire than during a smouldering fire. The study has not explored this possibility.

## 6.2 The study's validity and reliability

### 6.2.1 The test room

The experiments were conducted in a room with an area of 8.6 $m^2$. There are essentially three reasons why a room this size was chosen:

1. The room was meant to represent a standard bedroom.
2. Studies examining the effect of dead-air space were conducted in larger rooms, 12.4 $m^2$, 21.4 $m^2$ and 26.8 $m^2$ respectively, see chapter 3.1
3. This is a standardized room, described in ISO 9705 [18].

The experiments were carried out without ventilation, as this is deemed to be "worst case" in terms of accumulation of gases in the room. In a room with an open window or other ventilation, gas concentrations could dilute, yielding longer time before a person is incapacitated.

A Norwegian bedroom is usually heated during the day and cooled down at night. This may cause thermal gradients in the room, which may affect the dispersion of smoke. In the conducted experiments room temperatures were on average 17.0 °C ± 3.2 °C, which is representative for a bedroom. Lower temperatures *might* result in the smoke needing more time to reach the photoelectric smoke detectors, and that gas concentrations become even higher before the alarm is activated. This has, however, not been examined and it is uncertain how much it would affect time to detection.

### 6.2.2 Source of fire

A non-standardized source of fire was employed. There was a wish for realistic materials to be used, as the study set out to identify *which* gases were formed during the combustion and in *which* concentrations.

The materials of the source of fire, mainly made out of polyether foam and cotton, are representative for upholstered furniture and mattresses, and may provide illustrative gas measurements for smouldering fires in such furniture.

The source of fire was confined in a wooden crate with a hole on the upper side, where the smoke could exit. The purpose was to increase the repeatability of the experiments as the smoke was emitted at the same point in all the experiments.

### 6.2.3 Photoelectric smoke detectors

Three different models of photoelectric smoke detectors were used in the tests. No significant variances in time to detection between the individual types were found.

When the source of fire was placed in the corner by the door, no photoelectric smoke detectors were triggered during the test period. This is believed to be due to the test setup (the bottom of the smoke source was sealed), rather than the smoke detectors, as lower gas concentrations were measured also in these tests.

### 6.2.4 Combination detectors

The combination detectors discussed in chapter 4.5 are non-calibrated instruments. Thus, to measure the quantity of CO concentration, dedicated calibrated instruments were employed. These also served as reference for the CO measurements made by combination detectors.

A total of 21 combination detectors were used. As Figure 5-2 show, coherence of measurements was satisfactory and linearity was good compared with the reference meter (Figure 5-2). This result, together with the assumption that combination detectors have equal sensitivity, means that the detectors provided useful information on relative CO and smoke concentration, and thus on the spread of gas and smoke in the room.

The Tyco Central that the 21 Tyco detectors were connected to, read one detector per second. Each detector was therefore read each 21 seconds, which corresponds to a logging frequency of 0.048 Hz. This must be taken into account when analysing the spread of smoke and gases inside and outside dead-air spaces. Differences in measurement values among two detectors thus had to be recorded with a time interval that was at least equal to the time difference between the readings of the two detectors compared. Apart from this, and considering the fact that the smouldering fire tests lasted for hours, a logging frequency of 0.048 Hz is deemed sufficient.

Initially an attempt was made to perform an analysis of the comparison of light scattering measured inside and outside dead-air spaces at regression between the selected pairs of detectors, both in terms of light scatter values and time to light scatter. This was done in order to calculate differences based on the assumption of a linear connection between the signals from the detectors in each pair. A high degree of linearity was obtained, and a Durban Watson test identified autocorrelation in the measurement series. Attempts were made to compensate for this, but it was concluded that the results were not reliable, and linear regression was therefore rejected as a method.

### 6.2.5 Repeatability

In general it is difficult to control the repeatability of fire tests. Even when using identical test setups in all tests, differences in air currents in the test room, inducted by temperature gradients, may lead to unequal smoke flow between tests. Minor differences in the source of fire may also cause fires to develop in various manners, with corresponding differences in smoke and heat production, which may affect test results.

A smouldering fire is not a stable and repeatable phenomenon. In a smouldering fire it is hard to control the ignition process, which partly derives from the fact that the source of fire is heated by a heating element, and that one does not know whether ignition of the material has been achieved before the heating element is switched off. In some of the experiments, the heating source had to be turned on again to obtain ignition.

These uncertainties appear in the form of different gas concentrations measured in each experiment. In order to account for these uncertainties, this study carried out ten experiments, which ought to have identified the various developments of fire that may be produced within the relevant test setups.

# 7 Conclusions

- Combination detectors equipped with a CO sensor alarm much earlier than photoelectric smoke detctors. This may increase the chance of survival in a smouldering fire.
- There were minor differences in time to detection between ceiling-mounted and wall-mounted combination detectors. This indicates a high level of CO dispersion in the room.
- CO detectors may be installed in a more accessible place for individuals who experience difficulties reaching a smoke alarm mounted on the ceiling.
- Tenability limit values for incapacitation as a result of CO poisoning may be exceeded when photoelectric smoke detectors are triggered. This may at worst be fatal.
- No systematic differences in time to detection were found between smoke detectors placed inside and outside dead-air spaces.
- There was no significant difference in time to alarm between the different brands of photoelectric smoke detectors used in the experiments.

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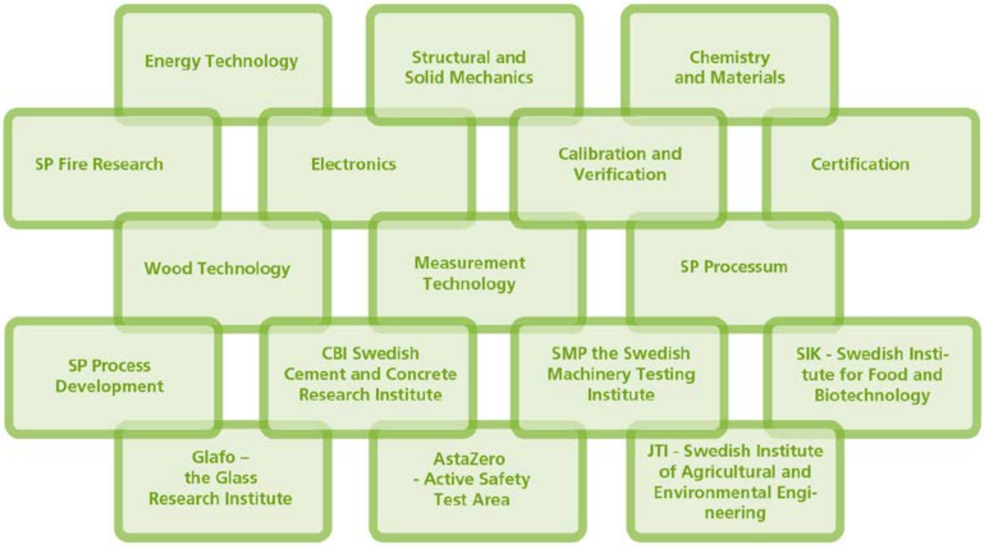



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