Kemano Fire Studies: part 1: response of residential smoke detectors

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Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/20378519
Research Report (National Research Council of Canada. Institute for Research in Construction); no. RR-108, 2003-04-01

National Research Council Canada   Conseil national de recherches Canada

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KEMANO FIRE STUDIES – Part 1: Response of Residential Smoke Alarms

Research Report 108

Date of Issue: April 2003

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Published by
Institute for Research in Construction
National Research Council Canada
Ottawa, Canada
K1A 0R6

KEMANO FIRE STUDIES – Part 1: Response of Residential Smoke Alarms

By

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ABSTRACT

NRC's Fire Risk Management Program has completed an experimental study of smoke-alarm response in residential dwellings, using the unique opportunity of the Kemano Public Safety Initiative. Working with the Underwriters' Laboratories of Canada, NRC conducted a series of full-scale fire detection experiments in Kemano, a deserted town in northern British Columbia. This study has produced experimental data that can be used to analyze the impacts of type, number and location of smoke-alarms on fire detection time, to improve relevant codes/standards, and ultimately to make better use of current smoke-alarm technology to safeguard Canadians and their homes against fires.

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1.0 INTRODUCTION

Kemano Village was a company town located in northern British Columbia and owned by Alcan Smelters and Chemicals Ltd. This remote village was recently closed as a result of restructured power operations and was donated to the Government of British Columbia's fire services for training of firefighters, fire investigators and for fire studies. This was known as the Kemano Public Safety Initiative (KPSI).

The KPSI provided a unique opportunity to conduct real-scale fire experiments in residential dwellings. Under a partnership with the Underwriters' Laboratories of Canada (ULC), the National Research Council of Canada (NRC) completed a series of fire experiments in 2 houses at the Kemano Village to study the response of residential smoke-alarms.

Smoke-alarms are important and cost-effective fire protection devices in residential dwellings, providing fire detection and evacuation warnings for occupants in case of fires. Statistical data from 1985 to 1995 shows that the fire death rate in Canada has declined by more than 40%, mainly attributed to the use of residential smoke-alarms and the enforcement of relevant codes and standards. However, improving these codes and standards is an ongoing task for the fire protection community. How to maximize the benefit of current smoke-alarm technologies to residential fire safety still warrants further studies.

The objective of this project was to evaluate the performance of current smoke-alarms and explore ways to make better use of current smoke-alarm technology to safeguard Canadians and their homes against fires. The project has produced experimental data that can be used to analyze the impacts of type, number and location of smoke-alarms on occupant warning time. The results of the experiments are documented in this report.

2.0 FIRE EXPERIMENTS

2.1 Experimental Houses

NRC and ULC conducted 13 fire detection experiments in two family dwellings; both employed typical wood-frame construction with common internal materials. Both houses were unheated and the ambient temperature was around 12°C.

One family dwelling was a 1-storey single house (BB-513), as shown in Figure 1 (Approximate square footage: 90 m^2 per floor, 180 m^2 total). This bungalow had 2 bedrooms, a bathroom, a kitchen, a living and dining room on the ground floor and 2 bedrooms, a bathroom, a recreation room and a utility room in the basement. The house was completely carpeted.

The other family dwelling was a 2-storey single house (K1-106), as shown in Figure 2 (Approximate square footage: 140 m^2 total). The 2-storey dwelling had 3 bedrooms and a bathroom on the second floor, a living room, a dining room and a kitchen on the ground floor and a recreation room and a utility room in the basement. The ground floor was carpeted; the stairs and second floor (including bedrooms) were hardwood flooring.

2.2 Fuels and Fire Scenarios

Fire scenarios included flaming and smouldering fires in the bedroom, living room and kitchen. To provide the greatest challenges to the operation of the smoke-alarms, the fires used in the experiments were small and grew slowly, which represented the worst case scenario as far as fire detection was concerned. Fuel packages were prepared using materials representative of common household items that are frequently first ignited in fire incidents. These fuel packages consisted of wood, paper, polyurethane foam, cotton flannel, upholstered furniture and cooking oil.

The wood fuel package was 5 or 10 pine sticks (19 mm x 38 mm x 127 mm each). The paper fuel package was 20 sheets of newspaper (0.50 m x 0.68 m per sheet) folded to a size of 0.165 m x 0.23 m. Polyurethane foam (0.10 m thickness) was cut into round pieces (0.20 m diameter) wrapped with cotton flannel (0.53 m x 0.57 m sheet) to simulate mattress or cushion. The cotton flannel package was a sheet of 0.86 m x 0.86 m folded to a size of 0.215 m x 0.215 m.

Figure 3 shows the fuel packages (wood, paper, foam wrapped with cotton flannel) and ignition source used in some experiments. An electric heating element was used as an ignitor. Ceramic film insulation was used to protect the floor. The fuel package was placed on the ignitor. A perforated metal bucket was used to cover the fuel and ignitor. The holes around the metal bucket controlled the amount of air available for combustion. The smoke came out from the holes on the top of the metal bucket. Figure 4 shows a section of upholstered chair with the ignitor inserted between the cushion and arm. Figure 5 shows a kitchen fire scenario with 450 mL of cooking oil as fuel.

NRC staff manually put out the fire by turning off the ignitor and carefully dropping the fuel package into a bucket of water or using a blanket at the end of each experiment.

2.3 Smoke-Alarms Used

ULC listed smoke-alarms, conforming to CAN/ULC-S531-M87 "Standard for Smoke-Alarms" [1], were installed in the experimental houses. These smoke-alarms included ionization, photoelectric and dual (combination ionization-photoelectric) smoke-alarms powered by batteries. The response times of the smoke-alarms were determined by measuring the current draw through the batteries.

ULC-listed carbon monoxide detectors were also installed in the houses. These CO detectors were designed to continuously monitor for CO and to display the CO level from 0 to 999 ppm. The full alarm will sound (1) in less than 90 minutes at concentrations of 100 ppm, (2) in less than 35 minutes at concentrations of 200 ppm, (3) in less than 15 minutes at concentrations of 400 ppm, (4) immediately at concentrations above 600 ppm.

2.4 Measurement Devices

Various devices were used to measure smoke-alarm response, smoke optical density (smoke obscuration), carbon monoxide concentration and temperature. Experimental data was collected using a data acquisition system.

Figure 6 shows a circuit used to monitor smoke-alarm activation, which was inserted between the positive lead of the battery and the power terminal of the smoke-alarm. The output signal was a current draw through the battery. The current draw should stay at zero when there was no alarm and should change to nonzero when the smoke-alarm actuated, as shown in Figure 7. The response times of all smoke-alarms were recorded.

Six Pulsed 940 Smoke Density Meters, designed and built by NRC, were used to measure the optical density of smoke. Each smoke density meter uses a pulsed, near-infrared light emitting diode (LED) as a light source (940 nanometer) and a pin photodiode and subsequent electronics as a receiver. The smoke density meter operates by sending a beam of light in a direct path from the transmitter through a known distance to the receiver. The distance from the transmitter to the receiver was fixed at 0.60 m for all experiments. Any smoke coming between the light source and receiver reduces the received signal strength since the smoke absorbs and reflects a fraction of the light. The optical density is proportional to the logarithm of the reciprocal of the output signal. All smoke density meters were calibrated using optical filters with known densities at 940 nanometer.

A nondispersive infrared (NDIR) gas analyzer was used to measure the concentrations of carbon monoxide (CO) and carbon dioxide (CO_2). This gas analyzer was designed specifically to measure CO and CO_2 in the frequencies where CO and CO_2 absorb infrared light.

Temperatures in the fire rooms and egress routes were measured using Type K thermocouples (0.038 mm diameter, 26 AWG, $\pm 2.2\,^{o}C$), made of nickel-chromium and nickel-aluminum alloys. Thermocouple (TC) trees consisting of multiple thermocouples were installed in various positions to measure vertical and horizontal temperature distributions in the houses.

Measurement devices also included cameras for audio/video records. Table 1 shows a matrix of fire experiments. A detailed description of experiments in each house is described in the following subsections.

2.5 Experiments in House BB-513

The first round of 9 fire detection experiments was conducted in the bungalow (BB-513) with fires originating in a ground floor bedroom and the living room. A total of 35 smoke-alarms were installed on the ground floor, including 14 photoelectric smoke-alarms, 14 ionization smoke-alarms, 5 dual (combination ionization-photoelectric) smoke-alarms, and 2 carbon monoxide detectors.

2.5.1 Experimental Set-up in House BB-513

Figure 8 shows a plan view of the ground floor, fire locations, smoke-alarms, CO detectors and measurement devices installed in House BB-513. Figure 9 shows snapshots of the experiment set-up in House BB-513. The ground floor had a 2.44 m high ceiling and a 0.42 m lintel above the bedroom doors.

Table 2 shows a cross-reference of all smoke-alarms and measurement devices in House BB-513 and in the data acquisition system. Data Column and Data Channel are the virtual locations of smoke-alarms or devices in the data system. Detector Marker is the shipping label on each smoke-alarm. Detector No. is the smoke-alarm identifier used for all the drawings and figures in this report. In Figure 8, each ionization smoke-alarm is labelled with an "I" in front of its Detector No.; each photoelectric smoke-alarm is labelled with a "P" in front of its Detector No.; each dual smoke-alarm is labelled with its Detector No. only.

2.5.1.1 Smoke-alarm positioning

An ionization smoke-alarm, a photoelectric smoke-alarm and a dual smoke-alarm formed a detector group. Four such groups of smoke-alarms were installed at the ceiling of Bedroom 1 (labelled as P6, 7, I8 in Figure 8), corridor (labelled as I14, 15, P16), foyer (labelled as I18, 19, P20), and the living room (labelled as P26, 27, I28). For each group, the smoke-alarms were spaced 305 mm from each other (centre to centre). The corridor detector group (Detectors I14, 15, P16) outside the bedrooms was at a code-required location [2]. The four groups would produce comparative data for smoke-alarms in these general locations and also provide comparative data for different smoke-alarm types.

Figure 10 illustrates a so-called “dead air space”, the corner space 100 mm from ceiling and wall joints in each direction where smoke may not reach. Theoretically, smoke-alarms should not work in the dead air spaces, and should not be located in these spaces. According to the installation standard [3], smoke-alarms should be located a minimum of 100 mm away from the ceiling-wall joints; wall-mounted smoke-alarms are also limited to a maximum of 300 mm away from the ceiling-wall joints. However, the “dead air space” and its effect on smoke-alarm response had not been adequately defined and addressed experimentally.

In order to study the “dead air space” and its effect on smoke-alarm response, additional photoelectric smoke-alarms and ionization smoke-alarms were strategically installed inside and outside 4 "dead air spaces" in the living room (Detectors P21-P25 and I29- I33) and Bedroom 1 (Detectors P1-P5 and I9-I13), as shown in Figures 8-9. For each of these 4 "dead-air spaces", 2 smoke-alarms were installed at the ceiling with one inside and the other outside the “dead air space"; 3 smoke-alarms were installed on the wall with the top one inside the “dead air space", the mid one in the acceptable region and the low one below the acceptable height. The smoke-alarm spacing indicated in Figure 8 is the distance from the centre of the smoke-alarm. In fact, the bedroom smoke-alarms (Detectors P3, P4, I10, I11) inside the "dead air spaces" had their edge 86 mm from the ceiling-wall joints and the smoke-alarms (Detectors P1, I13) below the acceptable height had their top edge 394 mm from the ceiling. The living-room smoke-alarms (Detectors P23, I31) inside the "dead air spaces" had their top edge 72 mm from the ceiling and the smoke-alarms (Detectors P21, I33) below the acceptable height had their top edge 379 mm from the ceiling. The 2 smoke-alarms in the ceiling "dead air spaces" had their edge 86 mm (Detector P24) and 96 mm (Detector I30) from the walls in the living room. Thus, Bedroom 1 and the living room each had an additional group of 13 smoke-alarms.

A dual smoke-alarm was installed at the ceiling of Bedroom 2 (labelled as 17 in Figure 8). CO detectors were installed on walls above the floor at a 380 mm height in the corridor, 530 mm height in Bedroom 1, and 1090 mm height in the living room.

2.5.1.2 Optical density measurement

Smoke optical density was measured as a function of time using 6 smoke density meters at 3 locations (in Bedroom 1, corridor and the living room), as shown in Figures 8 and 9. Each location had 2 measurement points, one at the ceiling height (150 mm below the ceiling, very close to the grouped smoke-alarms) and the other at eye height (1.68 m above the floor).

2.5.1.2 Carbon monoxide measurement

The CO concentration was measured using the NDIR gas analyzer. The gas sampling port was 1.7 m high either at the door of Bedroom 1 or at the entrance of the living room.

2.5.1.3 Temperature measurement

A thermocouple was placed at the fire source (at the smoke exit holes when the metal bucket was used) to monitor fire development. Another thermocouple was placed underneath the ceramic film insulation that protected the floor.

Temperatures in the living room, corridor and Bedroom 1 were measured using 3 thermocouple trees, as shown in Figures 8 and 9. Each thermocouple tree was installed near the grouped smoke-alarms and the smoke density meters, with thermocouples at heights of 1.22, 1.83 and 2.40 m above the floor (the top one was 40 mm below the ceiling).

2.5.1.4 Experimental procedure

Five experiments were conducted with fire origin in the ground floor bedroom and 4 experiments were conducted with fire origin in the living room. All windows were closed during each experiment. The experiment procedure was as follows:

1. Verification of experiment layout, instrumentation and data acquisition;
2. t = 0 (time zero), starting the electric power to the ignitor, starting the data acquisition system and collecting 2 min baseline data;
3. t = 2 minute, putting the fuel package on the ignitor and covering them with the perforated metal bucket; (except for the upholstered chair fire, see Test 9 section for Steps 2 and 3)
4. Observation of smoke movement and smoke-alarm response;
5. Sending personnel into the house to extinguish the fire and vent the room when all smoke-alarms actuate or at least 20 minute into the experiment; and
6. Ending the experiment.

2.5.2 Results of Experiments in House BB-513

Sound levels of the smoke-alarms were measured at centre and waist height in Bedroom 2, with the Bedroom-2 door closed. The results of sound intensity in decibel (dB) are listed in Table 2. Sound A are the values with the Bedroom-1 door open and Sound B are the values with the Bedroom-1 door closed.

Table 3 shows results of the 9 experiments conducted in House BB-513, including the response of the smoke-alarms at various locations and the maximum change of temperature and CO concentration in the room of fire origin. All test fires started with a smouldering phase and then became a flaming fire. The length of the smouldering stage and the total length of smouldering plus flaming fire are listed in the table for each experiment. The response of the smoke-alarms is presented in the table with the activation time measured from ignition. Although the absolute values for the activation time are given, emphasis should be put on the relative values in order to draw useful conclusions that can be applied to other fire scenarios.

The CO detectors did not produce an alarm in any experiments but they registered the peak CO level that they detected during each experiment. The peak CO levels registered by the CO detectors are shown in the table (for example, NA384ppm; NA means not actuated).

Figures 11-28 show profiles of temperatures at the fire source and on the thermocouple trees, optical densities near Detectors 6–8, 14–16 and 26–28, smoke-alarm response as well as the CO concentration during the fire experiments. Table 4 shows the optical densities of smoke adjacent to Detectors 6–8, 14–16 and 26–28 when these smoke-alarms actuated. Details of the results from each experiment are presented in the following sections.

2.5.2.1 Test 1

All bedroom doors were open throughout this experiment. The test fire was in Bedroom 1, using the fuel package consisting of 5 pine sticks. After a 2-min baseline, the fuel package was put on the electrically-heated ignitor and covered by the perforated metal bucket with all holes open (this point is referred to as ignition hereafter). The fire started with smouldering. Smoke came out from the top holes of the bucket approximately 150 s after the ignition and the 2 smoke density meters in the fire room started to detect smoke production. The 2 smoke density meters in the corridor outside the fire room started to detect the smoke approximately 190 s after the ignition. The 2 smoke density meters in the living room started to detect the smoke approximately 270 s after the ignition. The fire changed from smouldering to flaming 388 s after ignition. The total time of smouldering and flaming was 880 s.

During the smouldering period, the change of temperatures in the house was very small (less than 1°C increase even in the room of fire origin). The maximum temperature rise of 6°C occurred at the ceiling of Bedroom 1 during the flaming period.

The CO concentration measured at the door of Bedroom 1 was 270 ppm at maximum, with the concentration above 100 ppm for 10 minutes and above 200 ppm for 4 minutes. These concentration levels were not high enough nor lasted long enough to trigger the CO detector. The CO detector in the corridor only registered a 24-ppm peak CO level.

All smoke-alarms responded to the fire, with 18 smoke-alarms actuated during the smouldering stage and 15 smoke-alarms actuated during the flaming stage.

Except for Detectors I10 and I14, all smoke-alarms in the 2 bedrooms, corridor and foyer responded when the fire was at the smouldering stage. The 3 dual smoke-alarms in the fire room, corridor and foyer responded within 25 s of each other. An interesting observation was that the photoelectric smoke-alarm in the foyer (Detector P20) provided a fire alarm earlier than Detectors P6 (in the fire room) and P16 (in the corridor).

Detectors I10 and I14 and all living room smoke-alarms responded when the fire developed into the flaming stage. Detector I10 was the last actuated smoke-alarm in the fire room (Bedroom 1). It was mounted in the ceiling "dead air space". However, in the same "dead air space", the wall mounted Detector I11 was among the smoke-alarms giving the earliest warning. In the living room, the wall-mounted smoke-alarms (Detectors P23 and I31) in the "dead air space" had a shorter response time than the smoke-alarms (Detectors P22 and I32) on the wall within the acceptable height.

At the activation of those smoke-alarms that were directly adjacent to the ceiling-mounted smoke density meters, the optical density of adjacent smoke was 0.07-0.28 m^{-1} for the ionization smoke-alarms, 0.05-0.10 m^{-1} for the dual smoke-alarms, and 0.07-0.25 m^{-1} for the photoelectric smoke-alarms. Visibility in the foyer and the living room observed by sight appeared to be sufficient for evacuation purposes throughout the experiment.

2.5.2.2 Test 2

The test fire originated in Bedroom 1, using the fuel package consisting of 5 pine sticks. After a 2-minute baseline, the fuel package was put on the electrically-heated ignitor and covered by the perforated metal bucket with all holes open. The fire started with smouldering. Smoke came out from the top holes of the bucket approximately 130 s after the ignition and the 2 smoke density meters in the fire room started to detect smoke production. The fire changed from smouldering to flaming 390 s after ignition. The total time of smouldering and flaming was 1680 s.

This fire scenario was similar to the one used in Test 1. However, for Test 2, the door of Bedroom 1 was closed for the first 1353 s and was then opened (measured from ignition). The door of Bedroom 2 was closed throughout this experiment.

The fire did not affect temperatures in the corridor and living room until the door to Bedroom 1 was opened. The maximum temperature rise of 6°C occurred at the ceiling of Bedroom 1 during the flaming period and when the door was closed.

All 13 smoke-alarms in Bedroom 1 provided fire alarms when the fire was still at the smouldering stage. The 6 wall-mounted smoke-alarms (Detectors P1-3 and I11-13) and the ceiling mounted photoelectric smoke-alarm (Detector P4) responded to the smouldering fire at times comparable to the 3 ceiling smoke-alarms (Detectors P6, 7 and I8) at the centre of the room, indicating no effect of the "dead air space". The ceiling Detector I10, however, did have a slower response, an indicator of the "dead air space" effect.

With the door of the room of fire origin closed, the smoke-alarms and the smoke density meters in the corridor and the living room did not detect the smoke and fire. There was no visible smoke in the hallway and living room before opening the bedroom door. After the fire room door was opened, all smoke-alarms in the corridor and the living room responded to the fire. Smoke was observed in the living room 24 s after the door was opened. The ceiling-mounted smoke-alarms provided a quicker fire alarm than the wall-mounted smoke-alarms in the living room. However, there was no obvious evidence of the "dead air space" effect.

At the activation of those smoke-alarms that were directly adjacent to the ceiling-mounted smoke density meters, the optical density of adjacent smoke was 0.07-0.18 m^{-1} for the ionization smoke-alarms, 0.07-0.15 m^{-1} for the dual smoke-alarms, and 0.07-0.19 m^{-1} for the photoelectric smoke-alarms. The observed visibility in the foyer and the living room appeared to be sufficient for evacuation purposes throughout the experiment.

The smoke-alarm in Bedroom 2 (Detector 17) did not respond to the fire since the door of Bedroom 2 was closed throughout this experiment. The CO detectors did not produce an alarm. The maximum CO concentration measured at the door of Bedroom 1 was 450 ppm, with the concentration above 100 ppm for 4 minutes, above 200 ppm for 2 minutes, and above 400 ppm for 1 minute. These concentration levels were not high enough nor lasted long enough to trigger the CO detectors. The CO detectors registered a 384-ppm peak CO level in the fire room and a 17-ppm peak CO level in the corridor.

2.5.2.3 Test 3

All bedroom doors were open throughout this experiment. The test fire was in Bedroom 1, using the fuel package of cotton flannel. After a 2-min baseline, the fuel package was put on the electrically-heated ignitor and covered by the perforated metal bucket with all holes open. The fire started with smouldering but quickly changed to flaming approximately 70 s after ignition. The total time of smouldering and flaming was 880 s. The change of temperatures in the house was very small. The maximum temperature rise of 4°C occurred at the ceiling of Bedroom 1 and in the corridor during the flaming period.

The maximum CO concentration measured at the door of Bedroom 1 was 300 ppm, with the concentration above 100 ppm for 9 minutes and above 200 ppm for 3 minutes. These concentration levels were not high enough nor did they last long enough to trigger the CO detectors. The CO detectors registered a 55-ppm peak CO level in the fire room and a 22-ppm peak CO level in the corridor.

Except for 4 photoelectric smoke-alarms (Detectors P5, P24-26), all 29 smoke-alarms in the 2 bedrooms, corridor, foyer and living room responded to the flaming fire. At the activation of the smoke-alarms that were directly adjacent to the ceiling-mounted smoke density meters, the optical density of adjacent smoke was less than 0.01 m^{-1}. Throughout the experiment, there was hardly any visible smoke by sight in the house. The optical density never exceeded 0.014 m^{-1} in the house at the 6 measurement points. Although the optical density adjacent to Detectors P5, P24 and P25 was not measured, the low optical density values in the centre of each room explained why Detectors P5 and P24-26 did not actuate (their normal sensitivity was 0.030 $\pm$ 0.019 m^{-1} or 2.06 $\pm$ 1.30 % per foot).

The response of the ionization and dual smoke-alarms were comparable to the flaming fire, with the dual smoke-alarms slightly quicker than the ionization smoke-alarms at the same locations. With the fire room door open, the time difference between the first smoke-alarm activation in the fire room and the living room was 74 s. The photoelectric smoke-alarms, which did actuate during the experiment, gave a slower response to the flaming fire than did the ionization and dual smoke-alarms.

The wall-mounted photoelectric smoke-alarms provided better response than the ceiling-mounted photoelectric smoke-alarms in both the living room and Bedroom 1. The 2-wall mounted photoelectric smoke-alarms in the "dead air space" (Detectors P3 and P23) were the first of this type in each room to respond to the fire. The 2-wall mounted ionization smoke-alarms in the "dead air space" (Detectors I11 and I31) were among the first in each room to respond to the fire.

2.5.2.4 Test 4

All bedroom doors were open throughout this experiment. The test fire was in Bedroom 1, using the fuel package consisting of newspaper. After a 2-min baseline, the fuel package was put on the electrically-heated ignitor and covered by the perforated metal bucket with all holes open. The fire started with smouldering. Smoke came out from the top holes of the bucket approximately 130 s after the ignition. The fire changed from smouldering to flaming 591 s after ignition. The total time of smouldering and flaming was 880 s.

During the smouldering period, the change of temperatures in the house was very small (less than 1°C increase even in the room of fire origin). The maximum temperature rise of 4°C occurred at the ceiling of Bedroom 1 at the end of the experiment.

The maximum CO concentration measured at the door of Bedroom 1 was 270 ppm, with the concentration above 100 ppm for 8 minutes and above 200 ppm for 4 minutes. These concentration levels were not high enough nor did they last long enough to trigger the CO detectors. The CO detectors registered a 51-ppm peak CO level in the fire room and a 21-ppm peak CO level in the corridor.

All smoke-alarms responded to the fire, with 20 smoke-alarms actuated during the smouldering stage and 13 smoke-alarms actuated during the flaming stage. It was interesting to observe that the smoke-alarm in Bedroom 2 (Detector 17) was the first smoke-alarm to detect the fire that originated in Bedroom 1 and that the smoke-alarms in the corridor and foyer detected the fire earlier than the smoke-alarms (of the same type) in the room of fire origin. The optical density measurements also showed that the smoke density meters in the corridor detected the smoke first.

Looking at the activation times of the smoke-alarms in the living room and Bedroom 1, there was no significant delay in response time for the smoke-alarms installed in the "dead air spaces". In fact, Detectors P3, P4 and I11 were among the first in Bedroom 1 and Detectors P23 and I31 were among the first in the living room to detect the fire.

At the activation of those smoke-alarms that were directly adjacent to the ceiling-mounted smoke density meters, the optical density of adjacent smoke was 0.07-0.19 m^{-1} for the ionization smoke-alarms, 0.06-0.19 m^{-1} for the dual smoke-alarms, and 0.07-0.16 m^{-1} for the photoelectric smoke-alarms. The observed visibility in the corridor, foyer and living room appeared to be sufficient for evacuation purposes throughout the experiment.

2.5.2.5 Test 5

All bedroom doors were open in this experiment. The test fire was in Bedroom 1, using the fuel package consisting of polyurethane foam wrapped with cotton flannel (simulating a mattress and bedding). After a 2-min baseline, the fuel package was put on the electrically heated ignitor and covered by the perforated metal bucket with all holes open. The fire started with smouldering. Smoke came out from the top holes of the bucket and the 2 smoke density meters in the fire room started to detect smoke production approximately 220 s after ignition. The fire changed from smouldering to flaming 757 s after ignition. The total time of smouldering and flaming was 1084 s.

During the smouldering period, the change of temperature in the house was very small (less than 2°C increase even in the room of fire origin). The maximum temperature rise of 4°C occurred at the ceiling of Bedroom 1 during the flaming period.

The maximum CO concentration measured at the door of Bedroom 1 was 350 ppm, with the concentration above 100 ppm for 13 minutes and above 200 ppm for 10 minutes. These concentration levels were not high enough nor did they last long enough to trigger the CO detectors. The CO detectors registered a 95-ppm peak CO level in the fire room and a 43-ppm peak CO level in the corridor.

All smoke-alarms responded to the fire, with 20 smoke-alarms (in the bedrooms, corridor and foyer) actuated during the smouldering stage and 13 smoke-alarms (in the living room) actuated during the flaming stage. Again, it was interesting to observe that the smoke-alarm in Bedroom 2 (Detector 17) was the first to detect the fire that originated in Bedroom 1. The smoke-alarms in the corridor (Detectors P16, 15 and I14) detected the smouldering fire earlier than the central smoke-alarms in the room of fire origin (Detectors P6, 7 and I8, respectively). The differences in activation time between the living room smoke-alarms and Detectors 1-20 were longer in Test 5 than those in Tests 1, 3 and 4.

The optical density measurement also showed that the smoke density meters in the corridor detected smoke first. It also showed that time differences between the smoke density meters detecting the first appearance of smoke in the living room and in Bedroom 1 were longer in Test 5 than those in Tests 1, 3 and 4. At the activation of those smoke-alarms that were directly adjacent to the ceiling-mounted smoke density meters, the optical density of adjacent smoke was 0.14-0.28 m^{-1} for the ionization smoke-alarms, 0.14-0.26 m^{-1} for the dual smoke-alarms, and 0.12-0.30 m^{-1} for the photoelectric smoke-alarms. The observed visibility in the foyer and the living room appeared to be sufficient for evacuation purposes throughout the experiment.

In both the living room and Bedroom 1, there was no significant delay in response time for the smoke-alarms installed in the "dead air spaces". In fact, Detectors P3, P4 and I11 were among the first in Bedroom 1 to detect the fire and all living room smoke-alarms responded in a similar time frame.

2.5.2.6 Test 6

The test fire was in the living room, using the fuel package consisting of 5 pine sticks. After a 2-minute baseline, the fuel package was put on the electrically-heated ignitor and covered by the perforated metal bucket with all holes open. The fire started with smouldering.

The fire changed from smouldering to flaming 234 s after ignition. The total time of smouldering and flaming was 1220 s. The maximum temperature rise at the ceiling of the living room was 4°C during the flaming period.

The door of Bedroom 1 was closed for the first 1080 s (measured from ignition) and was then opened. The door of Bedroom 2 was open throughout this experiment.

The first smoke-alarm that responded to the fire was the dual smoke-alarm in the foyer (Detector 19) while the fire was still in the smouldering stage. All other smoke-alarms responded to the fire during the flaming stage. The dual smoke-alarm in Bedroom 2 (Detector 17) was the second actuated smoke-alarm. Except for Detector P3, all smoke-alarms in Bedroom 1 did not respond to the fire until the door was opened. Detector P3 responded to the fire when the Bedroom 1 door was still closed, with the alarm going on and off a few times.

In the living room and Bedroom 1, the smoke-alarms installed in the "dead air spaces" were among the first in each room to provide a fire alarm, showing no obvious evidence of the "dead air space" effect.

At the activation of those smoke-alarms that were directly adjacent to the ceiling-mounted smoke density meters, the optical density of adjacent smoke was 0.04-0.08 m^{-1} for all 3 types of smoke-alarms. The observed visibility in the house appeared to be sufficient for evacuation purposes throughout the experiment.

The CO detectors did not produce an alarm. The maximum CO concentration measured at the entrance of the living room was 160 ppm, with the concentration above 100 ppm for 4 minutes. These concentration levels were not high enough nor did they last long enough to trigger the CO detectors. The CO detectors registered a 62-ppm peak CO level in the fire room and a 76-ppm peak CO level in the corridor.

2.5.2.7 Test 7

The test fire was in the living room, using the fuel package consisting of 5 pine sticks. After a 2-minute baseline, the fuel package was put on the electrically-heated ignitor and covered by the perforated metal bucket. The fire started with smouldering. This experiment used the same fire scenario as the one used in Test 6, except that the holes around the metal bucket were sealed to limit the amount of air and lengthen the smouldering period. Smoke came out from the holes on the top of the metal bucket. The fire changed from smouldering to flaming 602 s after ignition. The total time of smouldering and flaming was 1230 s. The maximum temperature rise at the ceiling of the living room was 4°C during the flaming period.

The door of Bedroom 1 was closed from the beginning for the first 1080 s (measured from ignition) and was then opened. The door of Bedroom 2 was open throughout this experiment.

All smoke-alarms in the living room, foyer, corridor and Bedroom 2 responded to the fire during the smouldering stage. The foyer detector group was the first that responded to the fire (Detectors I18, 19 and P20). All smoke-alarms in Bedroom 1 did not respond to the fire until the door was opened. There was no significant delay in response time for the smoke-alarms installed in the "dead air spaces". In fact, all smoke-alarms in Bedroom 1 responded to the fire in the same time frame and Detectors P23, P24 and I31 were among the first in the living room to detect the fire.

At the activation of those smoke-alarms that were directly adjacent to the ceiling-mounted smoke density meters, the optical density of adjacent smoke was 0.07-0.21 m^{-1} for the ionization smoke-alarms and 0.05-0.21 m^{-1} for the dual and photoelectric smoke-alarms. The observed visibility in the house appeared to be sufficient for evacuation throughout the experiment.

The CO detectors did not produce an alarm. The maximum CO concentration measured at the entrance of the living room was 220 ppm, with the concentration above 100 ppm for 9 minutes and above 200 ppm for 2 minutes. The concentration levels were not high enough nor did they last long enough to trigger the CO detectors. The CO detectors registered a 57-ppm peak CO level in the fire room and a 68-ppm peak CO level in the corridor.

2.5.2.8 Test 8

All bedroom doors were open throughout this experiment. The test fire was in the living room, using the fuel package consisting of polyurethane foam wrapped with cotton flannel (simulating upholstered furniture). After a 2-minute baseline, the fuel package was put on the electrically-heated ignitor and covered by the perforated metal bucket. The fire started with smouldering. The fire changed from smouldering to flaming 726 s after ignition. The total time of smouldering and flaming was 981 s. The maximum temperature rise at the ceiling of the living room was 3°C at the end of the experiment.

All smoke-alarms responded to the fire, with 26 smoke-alarms actuated during the smouldering stage and 7 smoke-alarms actuated during the flaming stage. Within each group of smoke-alarms (Detectors 6-8, Detectors 14-16, Detectors 18-20 and Detector 26-28), the dual smoke-alarm and the photoelectric smoke-alarm actuated in a similar time frame. The ionization smoke-alarm at the same position took twice as long to actuate. The difference in activation time of the same type of smoke-alarms in different groups was relatively small (compared to the difference between the ionization and photoelectric smoke-alarms in the same group). This indicated that the type of smoke-alarms had a larger impact on smoke-alarm response than the number or general location of the smoke-alarms in this experiment.

The smoke-alarms mounted at the top of the walls were among the first to provide a fire alarm in the living room and Bedroom 1. There was no significant delay in response time for the smoke-alarms installed in the ceiling "dead air spaces" and no obvious evidence of the "dead air space" effect.

At the activation of those smoke-alarms that were directly adjacent to the ceiling-mounted smoke density meters, the optical density of adjacent smoke was 0.07-0.15 m^{-1} for the ionization smoke-alarms, 0.015-0.14 m^{-1} for the dual smoke-alarms and 0.02-0.14 m^{-1} for the photoelectric smoke-alarms. The observed visibility in the house appeared to be sufficient for evacuation purposes throughout the experiment.

The CO detectors did not produce an alarm. The maximum CO concentration measured at the entrance of the living room was 200 ppm, with the concentration above 100 ppm for 6 minutes and at 200 ppm for 2 minutes. The concentration levels were not high enough nor did they last long enough to trigger the CO detectors. The CO detectors registered a 46-ppm peak CO level in the fire room and a 52-ppm peak CO level in the corridor.

2.5.2.9 Test 9

The test fire was in the living room, using a section of an upholstered chair as the fuel (shown in Figure 4). This fuel package had a cushion piece of 0.20 m x 0.30 m x 0.15 m and an arm piece of 0.35 m x 0.30 m x 0.12 m (with a 0.20 m diameter at the armrest). All bedroom doors were open throughout this experiment.

The ignitor was inserted between the cushion and arm at time zero. After a 2-minute baseline, the electrical power to the ignitor was turned on. The fire started with smouldering. In order to control the fire development, the power to the ignitor was turned on and off alternately. The fire was kept in the smouldering mode for 854 s and then changed to flaming. The flame grew to 1.8 m high at one point. The maximum temperature rise at the ceiling of the living room was 30°C. The total time of smouldering and flaming was 982 s.

All smoke-alarms responded to the fire, with 24 smoke-alarms actuated during the smouldering stage and 9 smoke-alarms actuated during the flaming stage. The foyer detector group (Detectors 18-20) produced the quickest response. In each detector group, the ionization smoke-alarm always actuated slower than the dual and photoelectric smoke-alarms at the same position. This indicated that the smoke-alarm type and location had an impact on smoke-alarm response.

In the living room and Bedroom 1, the wall-mounted smoke-alarms always gave quicker response than the ceiling-mounted smoke-alarms (of the same type); the smoke-alarms at the top of the walls (in "dead air spaces") were always among the first (of the same type) to provide a fire alarm. There was no significant delay in response time for the ceiling smoke-alarms installed inside and outside the "dead air spaces" and no obvious evidence of the "dead air space" effect.

At the activation of those smoke-alarms that were directly adjacent to the ceiling-mounted smoke density meters, the optical density of adjacent smoke was 0.08-0.19 m^{-1} for the ionization smoke-alarms, 0.05-0.15 m^{-1} for the dual smoke-alarms and 0.04-0.08 m^{-1} for the photoelectric smoke-alarms. The observed visibility in the house appeared to be sufficient for evacuation purposes throughout the experiment.

The CO detectors did not produce an alarm. The maximum CO concentration measured at the entrance of the living room was 80 ppm, which was not high enough to trigger the CO detectors. The CO detectors registered a 16-ppm peak CO level in the fire room and a 17-ppm peak CO level in the corridor.

2.6 Experiments in House K1-106

The second round of 4 fire detection experiments was conducted in the 2-storey single family house (K1-106) with fires located in the ground floor living room and kitchen. A total of 20 smoke-alarms were installed on the ground and second floors, including 5 photoelectric smoke-alarms, 8 ionization smoke-alarms, 5 dual (combination ionization-photoelectric) smoke-alarms, and 2 carbon monoxide detectors.

2.6.1 Experimental Set-up in House K1-106

Figures 29-30 show a plan view of floor layout, fire locations, smoke-alarms, CO detectors and measurement devices installed in House K1-106. Figure 31 is a snapshot of the experiment set-up in House K1-106.

The ground floor had a 2.50 m high ceiling and a 0.53 m lintel in the dining room and kitchen. The second floor had a 2.44 m high ceiling and a 0.48 m lintel above the bedroom doors. The staircase landing area had a 3.04 m high ceiling.

Table 5 shows a cross-reference of all smoke-alarms and measurement devices in House K1-106 and in the data acquisition system. Similarly, Data Column and Data Channel are the virtual locations of smoke-alarms or devices in the data system. Detector Marker is the shipping label on each smoke-alarm. Detector No. is the smoke-alarm identifier used for all the drawings and figures in this report. In Figures 29-31, each ionization smoke-alarm is labelled with an "I" in front of its Detector No.; each photoelectric smoke-alarm is labelled with a "P" in front of its Detector No.; each dual smoke-alarm is labelled with its Detector No. only.

2.6.1.1 Smoke-alarm positioning

Smoke-alarms were installed in various locations (including code-required locations) on both the ground and second floors in order to study the effect of number, type and location of smoke-alarms on their response time.

Five groups of smoke-alarms were installed at the ceiling of the living room (labelled as I1, 2, P3; I4, 5, P6), staircase landing (labelled as I7, 8, P9), and 2nd floor corridor (labelled as I10, 11, P12; I13, 14, P15). Each detector group included an ionization smoke-alarm, a photoelectric smoke-alarm and a dual smoke-alarm, spaced 305 mm from each other (centre to centre). The five groups produced comparative data for smoke-alarms in these general locations and also provided comparative data for different smoke-alarm types.

An ionization smoke-alarm was installed at the ceiling of every bedroom (labelled as I16, I17, I18). CO detectors were installed at a 0.53 m height on the ground floor wall adjacent to the staircase and at the ceiling in Bedroom 3.

2.6.1.2 Optical density measurement

Smoke optical density was measured as a function of time using 6 smoke density meters at 3 locations (in the living room, staircase landing, and 2nd floor corridor), as shown in Figures 29-31. Each location had 2 measurement points, one at the ceiling height (150 mm below the ceiling, very close to the grouped smoke-alarms) and the other at eye height (1.68 m above the floor).

2.6.1.2 Carbon monoxide measurement

The CO concentration was measured using the gas analyzer. The gas sampling port was 1.7 m high at the entrance of the ground floor staircase.

2.6.1.3 Temperature measurement

A thermocouple was placed at the fire source (at the smoke exit holes when the metal bucket was used) to monitor fire development. Another thermocouple was placed underneath ceramic film insulation that protected the floor.

Temperatures in the living room, kitchen, staircase landing and 2nd floor corridor were measured using 6 thermocouple trees, as shown in Figures 29-31. Each thermocouple tree was installed near the grouped smoke-alarms and the smoke density meters. Each of the ground floor TC trees had 3 thermocouples located 1.22, 1.83 and 2.46 m above the floor (the top thermocouple was 40 mm below the ceiling). Each of the landing and 2nd floor TC trees had 2 thermocouples located 40 and 600 mm below the ceiling.

2.6.1.4 Experimental procedure

Three experiments were conducted with the fire in the living room and 1 experiment was conducted with the fire in the kitchen. All windows were closed during each experiment. The experiment procedure was as follows:

1. Verification of experiment layout, instrumentation and data acquisition;
2. t = 0 (time zero), starting the electric power to the ignitor, starting the data acquisition system and collecting 2 min baseline data;
3. t = 2 minute, putting the fuel package on the ignitor and covering them with the perforated metal bucket; (except for the cooking oil fire, see Test 12 section for Steps 2 and 3)
4. Observation of smoke movement and smoke-alarm response;
5. Sending personnel into the house to extinguish the fire and vent the room when all smoke-alarms actuate or at least 35 minutes into the experiment; and
6. Ending the experiment.

2.6.2 Results of Experiments in House K1-106

Sound levels of the smoke-alarms were measured at the centre of Bedroom 1 and waist height, with Bedroom-1 door closed and all other room doors open. The results are listed in Table 5.

All bedroom doors were open during the 4 fire experiments in House K1-106. Table 6 shows results of the 4 experiments conducted in House K1-106, including the response of the smoke-alarms at various locations and the maximum change of temperature and CO concentration in the room of fire origin. All test fires started with smouldering and then became flaming. The length of the smouldering stage and the total length of smouldering plus flaming are listed in the table for each experiment. The response of the smoke-alarms is presented in the table with the activation time from ignition. Although the absolute values for the activation time are given, emphasis should be put on the relative values in order to draw useful conclusions that can be applied to other fire scenarios.

The CO detectors did not produce an alarm in any experiments but they registered the peak CO level that they detected during each experiment. The peak CO levels registered by the CO detectors are shown in the table (for example, NA77 ppm; NA means not actuated).

Figures 32-39 show profiles of temperatures at the fire source and the thermocouple trees, optical densities near Detectors 4–6, 7–9 and 10–12, smoke-alarm response as well as the CO concentration during the fire experiments. Table 7 shows the optical densities of smoke adjacent to Detectors 4–6, 7–9 and 10–12 when these smoke-alarms actuated. Details of the results from each experiment are presented in the following sections.

2.6.2.1 Test 10

The test fire was in the living room, using the fuel package consisting of 10 pine sticks. After a 2-minute baseline, the fuel package was put on the electrically-heated ignitor and covered by the perforated metal bucket. The fire started with smouldering. The holes around the lower part of the metal bucket were sealed to limit the amount of air to keep the fire smouldering. Smoke came out from the holes on the top of the metal bucket approximately 200 s after ignition. The optical density measurements indicated that smoke moved fairly quickly to the second floor. After the ground floor smoke density meters detected smoke production, the 2nd floor smoke density meters started to detect smoke within 1 minute. The metal bucket was taken off from the fuel 2710 s after ignition. The fire changed from smouldering to flaming 2744 s after ignition. The total time of smouldering and flaming was 2880 s.

During the smouldering period, the change of temperatures in the house was very small (less than 1°C increase even in the room of fire origin). The maximum temperature rise at the ceiling of the living room was 10°C during the flaming period.

All smoke-alarms responded to the fire, with 17 smoke-alarms actuated during the smouldering stage and 1 ionization smoke-alarm actuated during the flaming stage. At each location, the ionization smoke-alarm always responded to the smouldering fire slower than the adjacent dual and photoelectric smoke-alarms. The dual and photoelectric smoke-alarms performed similarly at the same location.

It was interesting to observe that the ionization smoke-alarms in the 3 bedrooms responded to the fire at times much earlier than the ionization smoke-alarms in the 2nd floor hallway and staircase landing. The smoke-alarm in Bedroom 2 (Detector I18) actuated at the same time as Detector I4 downstairs.

At the activation of those smoke-alarms that were directly adjacent to the ceiling-mounted smoke density meters, the optical density of adjacent smoke was 0.08-0.15 m^{-1} for the ionization smoke-alarms, 0.03-0.11 m^{-1} for the dual smoke-alarms, and 0.02-0.11 m^{-1} for the photoelectric smoke-alarms. The observed visibility in the house appeared to be sufficient for evacuation purposes throughout the experiment.

The maximum CO concentration measured at the ground floor staircase was approximately 100 ppm. The CO detectors did not actuate but registered a 77-ppm peak CO level near the staircase on the ground floor and a 66-ppm peak CO level at the ceiling of Bedroom 3 on the second floor. The ceiling CO detector in Bedroom 3 displayed a 33 ppm CO level when the adjacent smoke-alarm activated.

2.6.2.2 Test 11

The test fire was in the living room, using the fuel package consisting of polyurethane foam wrapped with cotton flannel (simulating upholstered furniture). After a 2-minute baseline, the fuel package was put on the electrically-heated ignitor and covered by the perforated metal bucket. The fire started with smouldering. The holes around the lower part of the metal bucket were sealed to limit the amount of air to keep the fire smouldering. Smoke came out from the holes on the top of the metal bucket approximately 240 s after ignition.

The optical density measurement indicated that smoke moved fairly quickly to the second floor. After the ground floor smoke density meters detected smoke production, the 2nd floor smoke density meters started to detect smoke within 1 minute. Note that the sharp spikes in the optical density signals were due to 2 power interruptions to the smoke density meters caused by a bad connection of an extension cord.

The metal bucket was taken off from the fuel approximately 1640 s after ignition. The fire changed from smouldering to flaming 1674 s after ignition. The total time of smouldering and flaming was 1980 s. During the smouldering period, the change of temperatures in the house was very small (less than 1°C increase even in the room of fire origin). The maximum temperature rise at the ceiling of the living room was 4°C during the flaming period.

All the dual and photoelectric smoke-alarms responded to the fire during the smouldering stage. At each location, the dual and photoelectric smoke-alarms performed similarly and responded to the fire much earlier than the ionization smoke-alarm. Two ionization smoke-alarms on the 2nd floor (Detectors I13 and I17) did not actuate. There was no visible smoke (observed by sight) on the 2nd floor throughout the experiment. The other 6 ionization smoke-alarms actuated near the end of the experiment when the fire changed to the flaming mode.

The maximum smoke optical density was 0.16 m^{-1} on the ground floor, 0.08 m^{-1} at the staircase landing, and 0.07 m^{-1} on the second floor. At the activation of those smoke-alarms that were directly adjacent to the ceiling-mounted smoke density meters, the optical density of adjacent smoke was 0.06-0.10 m^{-1} for the ionization smoke-alarms, 0.02-0.13 m^{-1} for the dual smoke-alarms, and 0.02-0.11 m^{-1} for the photoelectric smoke-alarms. The observed visibility in the house appeared to be sufficient for evacuation purposes throughout the experiment.

The maximum CO concentration measured at the ground floor staircase was 140 ppm, with the concentration above 100 ppm for 7 minutes. The concentration levels were not high enough nor did they last long enough to trigger the CO detectors. The CO detectors did not actuate but registered a 72-ppm peak CO level near the staircase on the ground floor and a 53-ppm peak CO level at the ceiling of Bedroom 3 on the second floor. The CO level display on the ceiling CO detector in Bedroom 3 was 40 ppm when the adjacent smoke-alarm activated.

2.6.2.3 Test 12

The test fire was in the kitchen, using cooking oil as the fuel (shown in Figure 5). The ignitor was immersed in 450 mL cooking oil in the cooking pan. The electrical power to the ignitor was turned on at time zero. The fire smouldered slowly. In order to accelerate fire development, a mixture of 25% toluene and 75% heptane was added to the oil pan at 1530, 1680 and 1960 s (each addition was 10 mL). These resulted in temperature spikes measured by the target thermocouple (Figure 36). After each of the first 2 additions of the accelerant, the fire changed to flaming for a short period and then became smouldering again. Only after the 3rd addition of the accelerant, the fire sustained flaming. The fire development, therefore, had 3 flaming periods. The 1st and 2nd flaming periods were very short and the 3rd flaming period was sustained burning. The total time of smouldering and flaming was 2400 s (the fire was put out using a fire blanket at the end of the experiment). The maximum temperature rise at the ceiling of the kitchen was 38°C during the last flaming period.

Before the 3rd flaming period, the optical density was less than 0.02 m^{-1} at the ground floor measurement points and less than 0.01 m^{-1} at the staircase and 2nd floor measurement points. After the start of the 3rd flaming period, smoke moved fairly quickly to the second floor.

During the smouldering period (before the 1st flaming period), only 1 smoke-alarm (Detector 5) responded to the smoke. All other smoke-alarms did not actuate until the fire became flaming. This is desirable since smouldering cooking oil often represents a common nuisance source. Five smoke-alarms responded to the flaming fire during the 1st and 2nd flaming periods. The 12 remaining smoke-alarms responded to the flaming fire during the 3rd flaming period. For the flaming cooking oil, there was very little difference in the response time between the ionization and photoelectric smoke-alarms at each location while the dual smoke-alarm responded to the flaming fire earlier than both the ionization and photoelectric smoke-alarms.

The fact that Detector 5 was the only one actuated during the smouldering period suggested that the sensitivity of this dual smoke-alarm as well as the ionization and photoelectric smoke-alarms need to be determined. Without determination of their sensitivity, it is hard to determine whether this dual smoke-alarm was more sensitive or more prone to the cooking oil nuisance source than the ionization and photoelectric smoke-alarms.

At the activation of those smoke-alarms that were directly adjacent to the ceiling-mounted smoke density meters, the optical density of adjacent smoke was 0.014-0.03 m^{-1} for the ionization smoke-alarms, 0.008-0.01 m^{-1} for the dual smoke-alarms, and 0.014-0.015 m^{-1} for the photoelectric smoke-alarms. The observed visibility in the house appeared to be sufficient for evacuation purposes throughout the experiment. There was very little visible smoke in the three bedrooms (observed by sight) when the bedroom smoke-alarms actuated to the flaming fire.

The maximum CO concentration measured at the ground floor staircase was 30 ppm, which was not high enough to trigger the CO detectors. The CO detectors registered a 21-ppm peak CO level near the staircase on the ground floor and an 11-ppm peak CO level at the ceiling of Bedroom 3 on the second floor.

2.6.2.4 Test 13

The test fire was in the living room, using the fuel package consisting of newspaper (20 sheets). After a 2-minute baseline, the fuel package was put on the electrically-heated ignitor and covered by the perforated metal bucket. The fire started with smouldering. Smoke came out from the holes on top of the metal bucket approximately 160 s after ignition. In order to keep the fire smouldering, the holes around the lower part of the metal bucket were sealed to limit the amount of air from the beginning of the experiment.

All dual and photoelectric smoke-alarms on both floors responded relatively early to the smouldering fire. All ionization smoke-alarms actuated at much later times. At around 3000 s after ignition, 3 holes around the lower part of the metal bucket were opened to allow more air to enter the bucket and to increase the smoke production rate, indicated in Figure 39 by the increase of smoke optical density. Shortly after this, the ionization smoke-alarms on the ground floor and in the 3 bedrooms upstairs actuated at almost the same time. The 2 ionization smoke-alarms in the 2^{nd} floor corridor (Detector I7) and the staircase landing (Detector I10) actuated later than the bedroom smoke-alarms, with the alarm going on and off a few times.

Detector I13 in the 2^{nd} floor corridor did not actuate until the fire became flaming. The metal bucket was taken off from the fuel 4794 s after ignition and then the fire changed from smouldering to flaming. Detector I13 only provided a short alarm and then silenced as shown in Figure 39.

During the experiment, the change of temperature in the house was very small. The maximum temperature rise at the ceiling of the living room was 3°C during the flaming period. The total time of smouldering and flaming was 5080 s.

At the activation of those smoke-alarms that were directly adjacent to the ceiling-mounted smoke density meters, the optical density of adjacent smoke was 0.08-0.09 m^{-1} for the ionization smoke-alarms, 0.03-0.08 m^{-1} for the dual smoke-alarms, and 0.015-0.07 m^{-1} for the photoelectric smoke-alarms. The observed visibility in the house appeared to be sufficient for evacuation purposes throughout the experiment.

The maximum CO concentration measured at the ground floor staircase was 220 ppm, with the concentration above 100 ppm for 40 minutes and above 200 ppm for 1 minute. The concentration levels were not high enough nor did they last long enough to trigger the CO detectors. Although the CO detectors did not actuate, they registered a 152-ppm peak CO level near the staircase on the ground floor and a 132-ppm peak CO level at the ceiling of Bedroom 3 on the second floor.

3.0 DISCUSSION

All test fires in the experiments were limited to small sizes with slow growth rates in order to provide the greatest challenges to the operation of smoke-alarms. Although all test fires started with smouldering then developed into flaming, the length of the smouldering stage was dependent on type and quantity of fuel and amount of available air. The absolute activation times of various smoke-alarms obtained only apply under the experimental conditions of this test program. In order to draw useful conclusions from these experiments that can be applied to other fire scenarios, the following discussion focuses on the relative activation times of the smoke-alarms as well as associate optical densities at their activation.

3.1 Optical Density at Smoke-Alarm Activation

From Tables 4 and 7, it appears that the smoke-alarms in the room of fire origin actuate at higher optical densities than the smoke-alarms in the areas remote from the fire. However, one can see from the optical density profiles that the optical density in the room of fire origin changes much faster than those in the areas remote from the fire. In many cases, it is difficult to make an unambiguous determination of the optical density at which a smoke-alarm actuated in the room of fire origin.

The optical density profiles in the areas remote from the fire generally changed more gradually. Therefore, the activation optical density for a smoke-alarm remote from the fire is more reliably determined. The remote areas where the optical density was measured included the living room for Tests 1-5, the bedroom/corridor for Tests 6-9, and the 2nd floor corridor for Tests 10-13. The activation optical density as determined was 0.001-0.14 m^{-1} for the ionization smoke-alarms, 0.001-0.14 m^{-1} for the dual smoke-alarms, and 0.004-0.12 m^{-1} for the photoelectric smoke-alarms in the remote areas throughout the 13 experiments. The average of the activation optical density over the 13 experiments was 0.065 m^{-1} for the ionization smoke-alarms, 0.043 m^{-1} for the dual smoke-alarms, and 0.046 m^{-1} for the photoelectric smoke-alarms in the remote areas.

The cotton fire (Test 3) had the shortest smouldering time and changed to flaming shortly after ignition. All those smoke-alarms, which were adjacent to the ceiling-mounted smoke density meters, responded to the cotton flaming fire at an optical density below 0.01 m^{-1}, including the smoke-alarms in the room of fire origin.

3.2 Effect of An Intervening Door

Figures 40 and 41 illustrate relative activation times of the smoke-alarms in the 13 experiments. These figures demonstrate the effect of an intervening door on smoke-alarm response in different locations. In Tests 2, 6 and 7, the door of Bedroom 1 was closed initially. The smoke-alarms outside that bedroom did not detect the fire in that bedroom and, vice versa, all smoke-alarms in that bedroom (except Detector P3 in Test 6) did not detect the fire in the living room until the door was opened. Since Bedroom 2 was closed throughout Test 2, the smoke-alarm in this room (Detector 17) did not respond to the fire that was located in Bedroom 1. A closed door can prevent smoke on one side of the door from reaching and triggering a smoke-alarm on the other side of the door.

With the open bedroom door, the smoke-alarms outside the room of fire origin detected the fires at the times reasonably close to the activation times of the smoke-alarms inside the room of fire origin. In some cases, the smoke-alarms outside the room of fire origin detected the fires faster than the smoke-alarms inside the room of fire origin.

3.3 Effect of Smoke-Alarm Type

The experimental data indicated that an increasing smoke-alarm number could shorten fire detection time. However, the smoke-alarm type had a bigger impact than the number of installed smoke-alarms on the fire detection time. At a given location, the dual smoke-alarm generally actuated as quickly as (if not sooner than) the ionization smoke-alarm for the flaming fires and the photoelectric smoke-alarm for the smouldering fires.

Figures 42-44 are bar charts, showing the relative difference in response time between the photoelectric smoke-alarm and the ionization smoke-alarm at each location. Specifically, comparisons are made between Detectors P6 v. I8, P16 v. I14, P20 v. I18 and P26 v. I28 in House BB-513 and to compare Detectors P3 v. I1, P6 v. I4, P9 v. I7, P12 v. I10 and P15 v. I13 in House K1-106. For each of these smoke-alarm pairs, the relative difference is calculated using:

$$(t_{photo} - t_{ion}) / [(t_{photo} + t_{ion})/2]$$

where t_{photo} is the activation time of the photoelectric smoke-alarm and t_{ion} is the activation time of the ionization smoke-alarm. A positive bar means that the ionization smoke-alarm responded to fire quicker than the photoelectric smoke-alarm. A negative bar means that the photoelectric smoke-alarm responded to fire quicker than the ionization smoke-alarm.

For the flaming cotton fire (Test 3), the ionization smoke-alarms responded much earlier than the photoelectric smoke-alarms at all these locations. For the flaming cooking oil (Test 12), there was very little difference in response times between the ionization and photoelectric smoke-alarms.

For the pine, foam and paper smouldering scenarios, the difference in response times between the photoelectric and ionization smoke-alarms was bigger for the 2-storey house than for the 1-storey house. In most cases, the photoelectric smoke-alarms responded faster to the smouldering fires than the ionization smoke-alarms.

3.4 Effect of “Dead Air Space”

Part of this experimental study was designed to address the so-called “dead air space”, where it was assumed difficult for smoke to reach, and its resulting effect on smoke-alarm response. In Tests 1-9 conducted in House BB-513, the smoke-alarms were strategically installed inside and outside the "dead air spaces" in the living room and Bedroom 1.

Figure 45 is an illustration of the expected response of the smoke-alarms inside and outside the “dead air space”. The position of the bars represents the location of the smoke-alarms on the wall or ceiling. The length of the bars represents the assumed relative activation time of the smoke-alarms. According to the “dead air space" concept, the 2 ceiling-mounted and 2 wall-mounted smoke-alarms that were installed less than 100 mm from the ceiling and wall joints would have difficulty detecting the smoke. The 2 wall-mounted smoke-alarms that were more than 300 mm below the ceiling-wall joints would also have difficulty detecting the smoke (i.e. longer detection time).

Surprisingly, however, some smoke-alarms installed in the “dead air spaces” were among the first to detect fires in the experiments. Figures 46-54 show the relative activation times of the 26 smoke-alarms installed in the living room and Bedroom 1. Each smoke-alarm is identified in the figures by its Detector Number. Each bar indicates an actuated smoke-alarm. If a bar is absent at a Detector Number, that smoke-alarm was not actuated in the fire experiment. The length of each bar represents the activation time of the smoke-alarm relative to that of a reference detector. The dual smoke-alarm (Detector 15), which was installed in the corridor at a code-required location, is taken as the reference detector and its relative activation time is set as 1 for Tests 1, 3-5 and 8-9.

The bedroom door was initially closed in Tests 2 and 6-7. In order to separate the effect of the “dead air space” from that of the intervening door, 2 dual smoke-alarms are used as the reference independently. Therefore, for Tests 2 and 6-7, Detector 15 is taken as the reference only for the living room smoke-alarms while Detector 7 at the centre of the bedroom is taken as the reference for the bedroom smoke-alarms. For clarity, the symbol ⑦ is used in the figures when Detector 7 is the reference for the bedroom smoke-alarms; otherwise, Detector 15 is the reference for the bedroom smoke-alarms. Detector 15 is always the reference for the living room smoke-alarms.

Is the "dead air space" still alive? The answer from the experimental data is yes and no for the fire scenarios used in the experiments.

From Figures 46-54, one can see consistently good response for the wall-mounted smoke-alarms located in the so-called "dead air spaces" (Detectors P3, I11, P23, I31). These smoke-alarms responded to the test fires as quickly as, and in approximately half of the cases even faster than those in the recommended positions (compared with the same type wall-mounted Detectors P2, I12, P22, I32 and central ceiling-mounted Detectors P6, I8, P26, I28, respectively).

There were mixed results for the wall-mounted smoke-alarms that were located below the acceptable height (Detectors P1, I13, P21, I33), and for the side ceiling-mounted smoke-alarms in the "dead air spaces" (Detectors P4, I10, P24, I30). In approximately 2/3 of the cases, these smoke-alarms responded as quickly as, or even faster than those in the recommended positions (of the same type on the wall and ceiling).

The unheated condition of the house may have had an effect on the smoke movement and, therefore, on the smoke-alarm response in the "dead air space". Further study is needed to determine to what extent, if any, the temperature in the unconditioned house influenced the results relative to detection in the "dead air space".

3.5 Carbon Monoxide Alarm Threshold for Fire Detection

It is no surprise that the CO detectors did not respond to the fires in all the experiments since these CO detectors were not designed for smoke/fire detection. Nevertheless, these experiments provide a range of values for setting the threshold alarm, should a CO detector be designed as a smoke/fire detector.

In the experiments conducted at Kemano, the CO detectors displayed a reading of 10-40 ppm when the adjacent smoke-alarms were actuated by the test fires. If a CO detector is to be used for fire and smoke detection, it should be designed with an immediate alarm threshold within this range.

4.0 CONCLUSIONS

It is important to reiterate that all test fires in the experiments were controlled to small sizes and grew slowly in order to provide the greatest challenge to the smoke-alarms. The absolute activation times of various smoke-alarms obtained from this study only apply under these experimental conditions. In order to draw useful conclusions from these experiments that can be applied to other fire scenarios, the emphasis should be placed on the relative activation times of the smoke-alarms as well as associate optical densities at their activation.

Since the optical density profiles generally changed more gradually in the areas remote from the fire than in the room of fire origin, the activation optical density for a smoke-alarm remote from the fire was more reliably determined. The activation optical density was 0.01 to 0.14 m^{-1} for the smoke-alarms in the remote areas. The average of the activation optical density over the 13 experiments was 0.065 m^{-1} for the ionization smoke-alarms, 0.043 m^{-1} for the dual smoke-alarms, and 0.046 m^{-1} for the photoelectric smoke-alarms in the remote areas. All those smoke-alarms adjacent to the smoke density meters responded to the cotton flaming fire at an optical density below 0.01 m^{-1}, including the smoke-alarms in the room of fire origin. The observed visibility in the test houses appeared to be sufficient for evacuation purposes in all the experiments.

Smoke-alarms of any type outside the room of fire origin took significantly longer to detect fires if separated from the fire by a closed door. This suggests that additional smoke-alarms may increase protection for these areas separated by a door from those areas protected by the code-required smoke-alarms (i.e., smoke-alarms located in every room provided the best early warning of fires). When the doors were open, the smoke-alarms outside the room of fire origin detected the fires at times reasonably close to (in some cases, even faster than) the activation times of the smoke-alarms inside the room of fire origin. The location of the smoke-alarm in the bedroom could attribute to this observation.

In general, the results of the experiments backed up expectations regarding the effect of smoke-alarm type on fire detection time. Under similar conditions, the smoke-alarm type had a bigger impact than the number of installed smoke-alarms on the fire detection time in these experiments. Combination ionization-photoelectric smoke-alarms responded to each test fire at the same time or sooner than ionization smoke-alarms or photoelectric smoke-alarms alone. At a given location, the dual smoke-alarm generally actuated as quickly as (if not earlier than) the ionization smoke-alarm for the flaming fires and the photoelectric smoke-alarm for the smouldering fires. For the flaming cotton fire, the ionization smoke-alarms responded much earlier than the photoelectric smoke-alarms. For the flaming cooking oil, there was very little difference in response times between the ionization and photoelectric smoke-alarms. For the pine, foam and paper smouldering scenarios, the difference in response times between the photoelectric and ionization smoke-alarms was bigger for the 2-storey house than for the 1-storey house. In most cases, the photoelectric smoke-alarms responded faster to the smouldering fires than the ionization smoke-alarms; the ionization smoke-alarms responded faster to the flaming fires than the photoelectric smoke-alarms.

It was assumed that smoke-alarms would not work in the so-called “dead air space”. Surprisingly, however, some smoke-alarms installed in the “dead air spaces” were among the first to detect the fires in the experiments. The experiments demonstrated consistently good response of the wall-mounted smoke-alarms located in the “dead air spaces”. These smoke-alarms responded to the test fires as quickly as, and in approximately half of the cases even faster than, those in the recommended positions (compared with the same type of wall-mounted and central ceiling-mounted smoke-alarms). Results were mixed for the wall-mounted smoke-alarms that were located below the acceptable height, and for the side ceiling-mounted smoke-alarms in the “dead air spaces”. However, in approximately 2/3 of the cases, these smoke-alarms responded as quickly as, or even faster than, those in the recommended positions (of the same type on the wall and ceiling). The unheated condition of the houses could have contributed to these surprising responses in the dead air spaces. The results relative to detection in the “dead air space” deserve further study to determine to what extent, if any, they were influenced by the temperature in the unconditioned houses.

The CO concentrations in the houses were neither high enough nor lasted long enough to trigger the CO detectors that were designed for prevention of CO poisoning but not for fire detection. Nevertheless, these experiments provide data for setting a fire alarm threshold. Should a CO detector be designed as a fire smoke-alarm, it needs to have an immediate alarm threshold within the range of 10-40 ppm.

The Kemano Public Safety Initiative provided NRC and ULC with a unique opportunity to conduct real-scale fire detection experiments in residential dwellings. This study has produced experimental data that can be used to analyze the impacts of type, number and location of smoke-alarms on fire detection time. This study was also part of an ongoing effort in the fire protection community to maximize the benefit of current smoke-alarm technologies to improve residential fire safety. Between 1985 and 1995, Canada's death rate in fires declined by more than 40 per cent; much of this decline is attributed to the use of residential smoke-alarms and the enforcement of the relevant codes and standards.

5.0 ACKNOWLEDGEMENTS

This study was conducted as a joint research project between the National Research Council of Canada and Underwrites' Laboratories of Canada. NRC/IRC acknowledges ULC's contribution in co-funding this project. NRC and ULC staff also acknowledges the logistic support from the B.C. Office of the Fire Commissioner and Alcan Smelters and Chemicals Ltd.

6.0 REFERENCES

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2. National Building Code of Canada 1995. Canadian Commission on Building and Fire Codes, National Research Council of Canada, Ottawa, 1995.
3. CAN/ULC-S553-M86, "Standard for the Installation of Smoke-Alarms," Underwriters' Laboratories of Canada, Toronto, ON, Canada, 1995 Edition, pp. 1-10.

Table 1 – Matrix of Experiments (May 18-22, 2001)

Test No.	1	2	3	4	5
Test House	BB-513	BB-513	BB-513	BB-513	BB-513
Fire Origin	Bedroom-1	Bedroom-1	Bedroom-1	Bedroom-1	Bedroom-1
Fuel	5 pine sticks	5 pine sticks	cotton flannel	20 sheets of newspaper	polyurethane foam + cotton flannel
Burning Mode	smouldering then flaming	smouldering then flaming	flaming	smouldering then flaming	smouldering then flaming
Test Date	May 18 (4 pm)	May 19 (10 am)	May 19 (1 pm)	May 19 (2 pm)	May 19 (4 pm)

Test No.	6	7	8	9	Audibility
Test House	BB-513	BB-513	BB-513	BB-513	BB-513
Fire Origin	living room	living room	living room	living room	n/a
Fuel	5 pine sticks	5 pine sticks	polyurethane foam + cotton flannel	upholstered chair section	n/a
Burning Mode	smouldering then flaming	smouldering then flaming	smouldering then flaming	smouldering then flaming	n/a
Test Date	May 20 (9 am)	May 20 (11 am)	May 20 (1 pm)	May 20 (3 pm)	May 18

Test No.	#10	#11	#12	#13	Audibility
Test House	K1-106	K1-106	K1-106	K1-106	K1-106
Fire Origin	living room	living room	kitchen	living room	n/a
Fuel	10 pine sticks	polyurethane foam + cotton flannel	450 mL cooking oil	20 sheets of newspaper	n/a
Burning Mode	smouldering then flaming	smouldering then flaming	smouldering then flaming	smouldering then flaming	n/a
Test Date	May 21 (11am)	May 21 (2 pm)	May 21 (4 pm)	May 22 (10am)	May 22

Table 2 – Location of Detector, Measurement Device and Data Storage for Tests 1-9 in House BB-513

Data Column	Data Channel	Detector No.	Detector Diameter (mm)	Detector Marker	Location	Sound A* (dB)	Sound B* (dB)
Col 28	26	1	127	4 p	BR1-W_{door} 18"	78	59
Col 29	27	2	127	5 p	BR1-W_{door} 12"	73	58
Col 30	28	3	127	6 p	BR1-W_{door} 6"	74	69
Col 31	29	4	127	7 p	BR1-C_{door} 6"	71	62
Col 32	30	5	127	8 p	BR1-C_{door} 18"	74	70
Col 33	31	6	127	9 p	BR1-C_{door} 42"	75	58
Col 34	32	7	143	84 i/p	BR1-C mid"	68	58
Col 35	33	8	127	31 i	BR1-C 42"	73	61
Col 36	34	9	127	32 i	BR1-C 18"	76	60
Col 37	35	10	127	37 i	BR1-C 6"	70	61
Col 38	36	11	127	38 i	BR1-W 6"	68	62
Col 39	37	12	127	39 i	BR1-W 12"	68	60
Col 40	38	13	127	40 i	BR1-W 18"	72	63
Col 48	46	14	127	35 i	H-C 12"	84	
Col 46	44	15	143	92 i/p	H-C 18"	82	
Col 47	45	16	127	12 p	H-C 24"	80	
Col 54	52	17	156	95 i/p	BR2-C 29"	102	
Col 52	50	18	127	34 i	E-C 45"	75	
Col 51	49	19	143	91 i/p	E-C 39"	75	
Col 53	51	20	127	10 p	E-C 33"	74	
Col 17	15	21	156	15 p	LR-W 18"	68	
Col 18	16	22	156	14 p	LR-W 12"	62	
Col 19	17	23	156	13 p	LR-W 6"	63	
Col 20	18	24	127	1 p	LR-C 6"	69	
Col 15	13	25	127	2 p	LR-C 18"	62	
Col 16	14	26	127	3 p	LR-C 57"	66	
Col 13	11	27	143	83 i/p	LR-C mid	65	
Col 14	12	28	108	74 i	LR-$C_{fire\ place}$ 52"	66	
Col 12	10	29	108	75 i	LR-$C_{fire\ place}$ 18"	70	
Col 11	9	30	108	73 i	LR-$C_{fire\ place}$ 6"	63	
Col 10	8	31	156	45 i	LR-$W_{fire\ place}$ 6"	62	
Col 9	7	32	156	44 i	LR-$W_{fire\ place}$ 12"	64	
Col 8	6	33	156	43 i	LR-$W_{fire\ place}$ 18"	64	
	camera	34		1 co	hallway		
	camera	35		2 co	fire room		
Data Column	Data Channel			CO Sampling	Location		
Col 55, 56	53			1	fire Rm entrance		
Data Column	Data Channel			Smoke Meter	Location		
Col 41, 61	39			1	BR1 – top		
Col 42, 62	40			2	BR1 – bot		
Col 49, 63	47			3	H – top		
Col 50, 64	48			4	H – bot		
Col 21, 59	19			5	LR – top		
Col 22, 60	20			6	LR – bot		
Data Column	Data Channel			TC	Location		
Col 23	21			1	TCT-BR1-top		
Col 24	22			2	TCT-BR1-mid		
Col 25	23			3	TCT-BR1-bot		
Col 26	24			4	BR1 carpet		
Col 27	25			5	BR1 target		
Col 43	41			6	TCT-H-top		
Col 44	42			7	TCT-H-mid		
Col 45	43			8	TCT-H-bot		
Col 3	1			9	TCT-LR-top		
Col 4	2			10	TCT-LR-mid		
Col 5	3			11	TCT-LR-bot		
Col 6	4			12	LR carpet		
Col 7	5			13	LR target		

* Notes: Sound levels were measured inside Bedroom 2 at centre and waist height with Bedroom-2 door closed: Sound A for open Bedroom-1 door; Sound B for closed Bedroom-1 door.

Table 3 – Results of Experiments in Test House BB-513

Test		1	2	3	4	5	6	7	8	9
Bedroom-1 door		open	close (Note 5)	open	open	open	close (Note 5)	close (Note 5)	open	open
Bedroom-2		open	close	open	open	open	open	open	open	open
Fire Origin		bedroom-1	bedroom-1	bedroom-1	bedroom-1	bedroom-1	Living room	Living room	Living room	Living room
Fuel		5 pine sticks	5 pine sticks	cotton	paper	foam + cotton	5 pine sticks	5 pine sticks	foam + cotton	chair section
Length (s) of Smouldering		388	390	68	591	757	234	602	726	854
Total Length of Burning(s)		880	1680	880	880	1084	1220	1230	981	982
max. ΔT (°C)		6	6	4	4	4	4	4	3	30
maxCO(ppm)		270	450	300	270	350	160	220	200	80
Detector No. and Response Time (s)	1 (p)	220	197	383*	361	287	1189	1195	406	617
	2 (p)	225	205	456*	392	293	1116	1123	428	629
	3 (p)	297	234	197*	387	356	739*	1109	392	587
	4 (p)	315	235	438*	416	344	1116	1115	774	930
	5 (p)	282	302	NA	539	406	1115	1119	640	925
	6 (p)	313	223	403*	521*	461	1112	1115	376	755
	7 (d)	242	209	118	430	307	1102	1103	343	575*
	8 (i)	269	218	122	522	325	1111	1107	760	924
	9 (i)	353	330*	132	601*	428*	1116	1105	818*	922
	10 (i)	409	361	157	614	479	1113	1107	862	926
	11 (i)	276	220	132	427	325	1117	1109	568*	824
	12 (i)	264	218	134	440	307	1120	1110	656	923
	13 (i)	272	216	137	419	308	1111	1109	610	854
	14 (i)	422	1359*	155	377	315	389	606	860	906
	15 (d)	264	1358	136	345	293	337	350	316	541
	16 (p)	337	1377	368*	373	356	297	342	334	376
	17 (d)	297	NA	173	270	273	257	342	369	574
	18 (i)	313	1367	154	428	413*	298	372	529*	644
	19 (d)	267	1370	139	343*	331	234*	275	286	208
	20 (p)	271	1380	432*	328	338	273	281	291	214
	21 (p)	638	1536	533	679	899	405	364	273	240
	22 (p)	570	1468	483	576	843	369	418	280	242
	23 (p)	512	1443	446	505	862	292	357	268	228
	24 (p)	531	1416	NA	753	911	273	372	298	287
	25 (p)	478	1408	NA	712	878	283	522	444	470
	26 (p)	545	1408	NA	787	922	265	374	254	288
	27 (d)	406*	1386	192	637	827	262	318	259*	319
	28 (i)	480	1388	226	686	875	277	383	715	795
	29 (i)	485	1395	226	686	851	307	504	769	869
	30 (i)	555	1444	375	843	932	380	550	810	875
	31 (i)	533	1476	272	671	832	277	383	289	389
	32 (i)	701	1589	341	628	823	271*	360*	279	387
	33 (i)	742	1621	397	780	880	325	388	290	408
	CO^{hall}	NA24ppm	NA17ppm	NA22ppm	NA21ppm	NA43ppm	NA76ppm	NA68ppm	NA52ppm	NA17ppm
	CO^{firerm}		NA384ppm	NA55ppm	NA51ppm	NA95ppm	NA62ppm	NA57ppm	NA46ppm	NA16ppm

Notes: (1) initial temperature 10-14°C, (2) d for dual, i for ionization, p for photoelectric, (3) * time corrected for alarm on and off, (4) NA - Not actuated (5) door opened 1353 s after ignition in Test 2 and 1080 s after ignition in Tests 6 and 7.

Table 4 – Optical Density OD_f (m^{-1}) at Activation of Detectors 6–8, 14–16 and 26–28 in Test House BB-513

Detector →	BR i	Hall i	LivRm i	BR d	Hall d	LivRm d	BR p	Hall p	LivRm p
Test 1	0.17	0.28	0.07	0.07	0.10	0.05	0.25	0.19	0.07
Test 2	0.18	>0.05	0.07	0.15	>0.05	0.07	0.19	>0.05	0.07
Test 3	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Test 4	0.19	0.15	0.07	0.19	0.09	0.06	0.16	0.13	0.07
Test 5	0.28	0.16	0.14	0.26	0.15	0.14	0.3	0.24	0.12
Test 6	0.04	0.065	0.08	0.04	0.04	0.08	0.04	0.04	0.08
Test 7	0.07	0.16	0.21	0.07	0.05	0.21	0.07	0.05	0.21
Test 8	0.07	0.14	0.15	0.015	0.08	0.14	0.02	0.08	0.14
Test 9	0.08	0.14	0.19	0.05	0.12	0.15	0.08	0.04	0.07

Table 5 – Location of Detector, Measurement Device and Data Storage for Tests 10-13 in House K1-106

Data Column	Data Channel	Detector No	Detector Marker	Location	Sound (dB)*
Col 35	33	1	76 i	LRC-77"	58
Col 36	34	2	85 i/p	LRC-64.5"	60
Col 37	35	3	20 p	LRC-52.5"	56
Col 23	21	4	77 i	H1C-44"	72
Col 24	22	5	86 i/p	H1C-32"	66
Col 25	23	6	21 p	H1C-19.5"	71
Col 27	25	7	78 i	LC-53"	72
Col 28	26	8	87 i/p	LC-41"	76
Col 29	27	9	22 p	LC-28.5"	75
Col 32	30	10	79 i	SH2C-25"	76
Col 31	29	11	88 i/p	SH2C-19"	76
Col 33	31	12	23 p	SH2C-13"	75
Col 20	18	13	80 i	H2C-27"	83
Col 19	17	14	89 i/p	H2C-21"	86
Col 21	19	15	24 p	H2C-14.5"	82
	camera	16	48 i	BR3- 43"	66
	camera	17	46 i	BR1- 51"	98
	camera	18	47 i	BR2- 46"	72
	camera	19	1 co	stairs wall bottom	
	camera	20	2 co	BR3 ceiling	
Data Column	Data Channel		CO Sampling	Location	
Col 41, 42	39		1	stairs, 1.66 m ht	
Data Column	Data Channel		Smoke Meter	Location	
Col 18, 45	16		1	H1 – top	
Col 22, 46	20		2	H1 – bot	
Col 26, 47	24		3	L – top	
Col 30, 48	28		4	L – bot	
Col 34, 49	32		5	H2 – top	
Col 38, 50	36		6	H2 – bot	
Data Column	Data Channel		TC	Location	
Col 39	37		1	carpet under fire	
Col 40	38		2	target	
Col 3	1		3	TCT-LR-top	
Col 4	2		4	TCT-LR-mid	
Col 5	3		5	TCT-LR-bot	
Col 9	7		6	TCT-KIT-top	
Col 10	8		7	TCT-KIT-mid	
Col 11	9		8	TCT-KIT-bot	
Col 6	4		9	TCT-H1-top	
Col 7	5		10	TCT-H1-mid	
Col 8	6		11	TCT-H1-bot	
Col 14	12		12	TCT-L-top	
Col 15	13		13	TCT-L-mid	
Col 12	10		14	TCT-SH2-top	
Col 13	11		15	TCT-SH2-mid	
Col 16	14		16	TCT-H2-top	
Col 17	15		17	TCT-H2-mid	

Notes: Sound levels were measured in Bedroom 1 at centre waist height with Bedroom-1 door closed (other open).
For Test 13, TC for carpet under fire in channel 38, TC for target in channel 37.

Table 6 – Results of Experiments in Test House K1-106

Test		10	11	12	13
Bedroom-1 door		open	open	open	open
Bedroom-2 door		open	open	open	open
Bedroom-3 door		open	open	open	open
Fire Origin		living room	living room	kitchen	living room
Fuel		10 pine sticks	foam + cotton	cooking oil	newspaper
Length of Smouldering (s)		2744	1674	1960	4794
Total Length of Burning (s)		2880	1980	2400	5080
max. ΔT (°C)		10	4	38	3
max. CO (ppm) stair-1st-floor		110	140	30	220
Detector No. and Response Time (s)	1 (i)	681	1690*	2037	3121*
	2 (d)	408	329	1642*	447
	3 (p)	418	344	2208	420
	4 (i)	1044	1723	1649*	3246*
	5 (d)	522	396*	867*	538*
	6 (p)	504	371	1607	479
	7 (i)	2017*	1763*	2179	4001*
	8 (d)	574*	468*	1591*	754*
	9 (p)	605*	439	2222	658
	10 (i)	2055*	1756*	2069*	4091*
	11 (d)	700*	537*	1664	1066*
	12 (p)	755	485	2067*	764
	13 (i)	2851	NA	2213	4977*
	14 (d)	577*	483*	2043	826*
	15 (p)	687	580	2214	725
	16 (i)	1166	1810	2257	3330
	17 (i)	1284	NA	2229	3210
	18 (i)	1048	1804	2170	3196
	CO stair	NA 77 ppm	NA 72 ppm	NA 21 ppm	NA 152 ppm
	CO bedroom	NA 66 ppm	NA 53 ppm	NA 11 ppm	NA 132 ppm

Notes:
(1) initial temperature 12-14°C
(2) detector type: d for dual ionization-photoelectric, i for ionization, p for photoelectric
(3) * time corrected time for alarm on and off
(4) NA - Not actuated detectors

Table 7 – Optical Density OD_f (m^{-1}) at Activation of Detectors 4–6, 7–9 and 10–12 in Test House K1-106

Detector →	LivRm ion	Landing ion	2nd floor ion	LivRm dual	Landing dual	2nd floor dual	LivRm photo	Landing photo	2nd floor photo
Test 10	0.15	0.10	0.08	0.11	0.03	0.03	0.11	0.02	0.03
Test 11	0.10	0.08	0.06	0.13	0.02	0.02	0.11	0.02	0.025
Test 12	0.02	0.03	0.014	0.01	0.01	0.008	0.015	0.04	0.014
Test 13	0.09	0.09	0.08	0.08	0.03	0.03	0.07	0.02	0.015

Figure 1. Family dwelling BB-513 for Tests 1-9

Figure 2. Family dwelling K1-106 for Tests 10-13

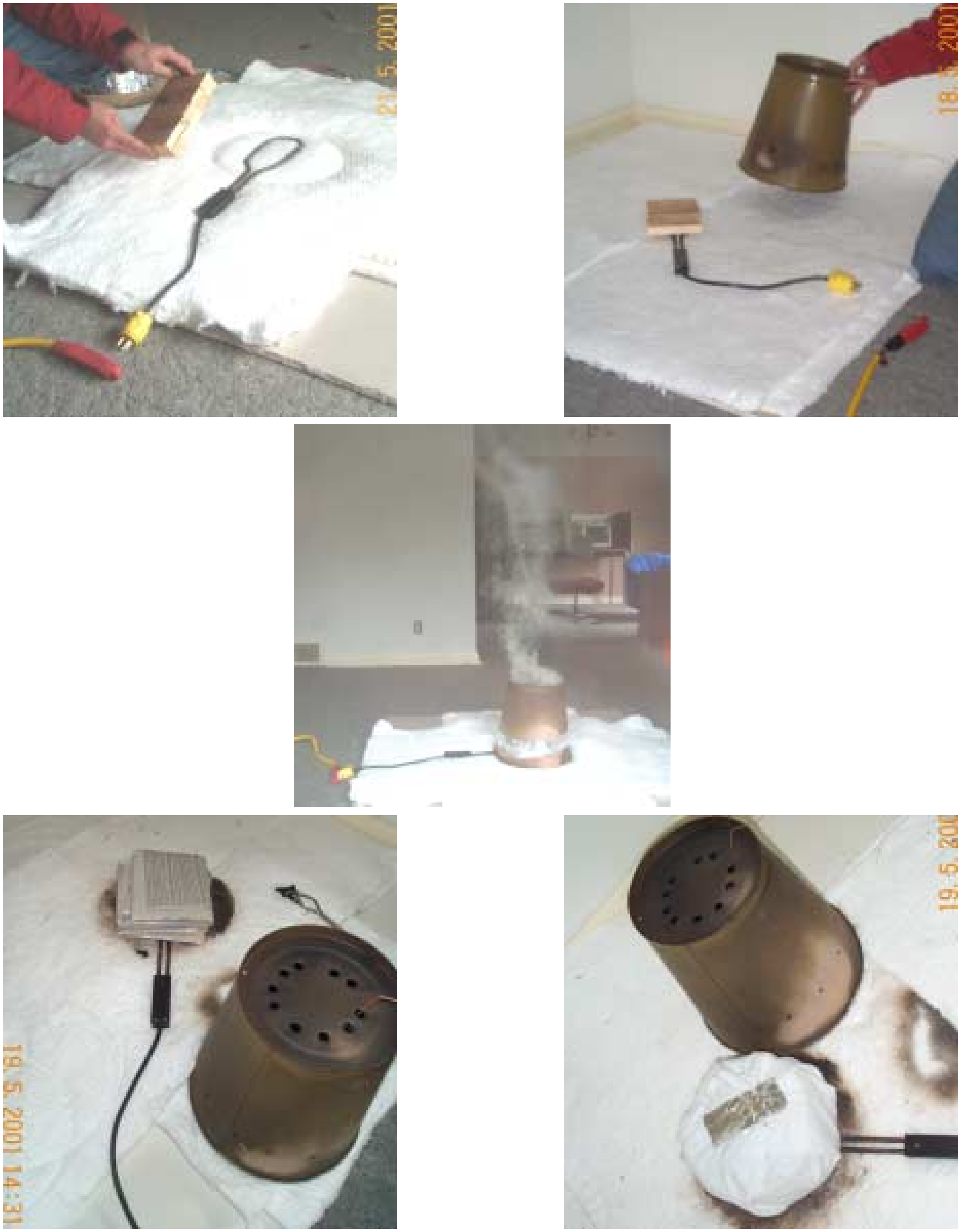


Figure 3. Wood, paper, polyurethane foam wrapped with cotton flannel on an electric igniter, covered by a perforated metal bucket

Figure 4. Section of upholstered chair and an electric igniter

Figure 5. Cooking oil and an electric igniter

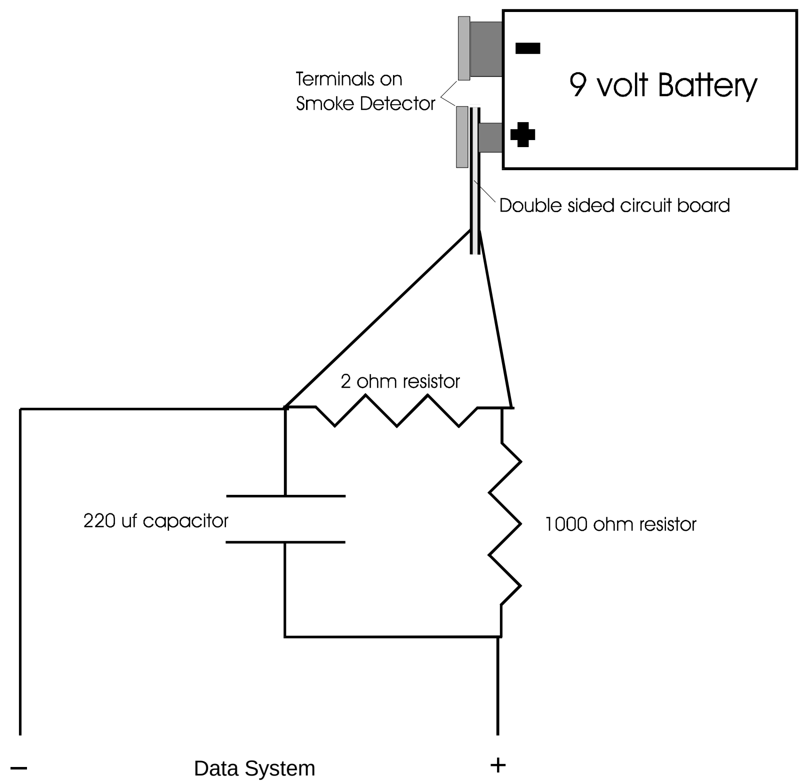


Figure 6. Circuit used to detect smoke detector activation

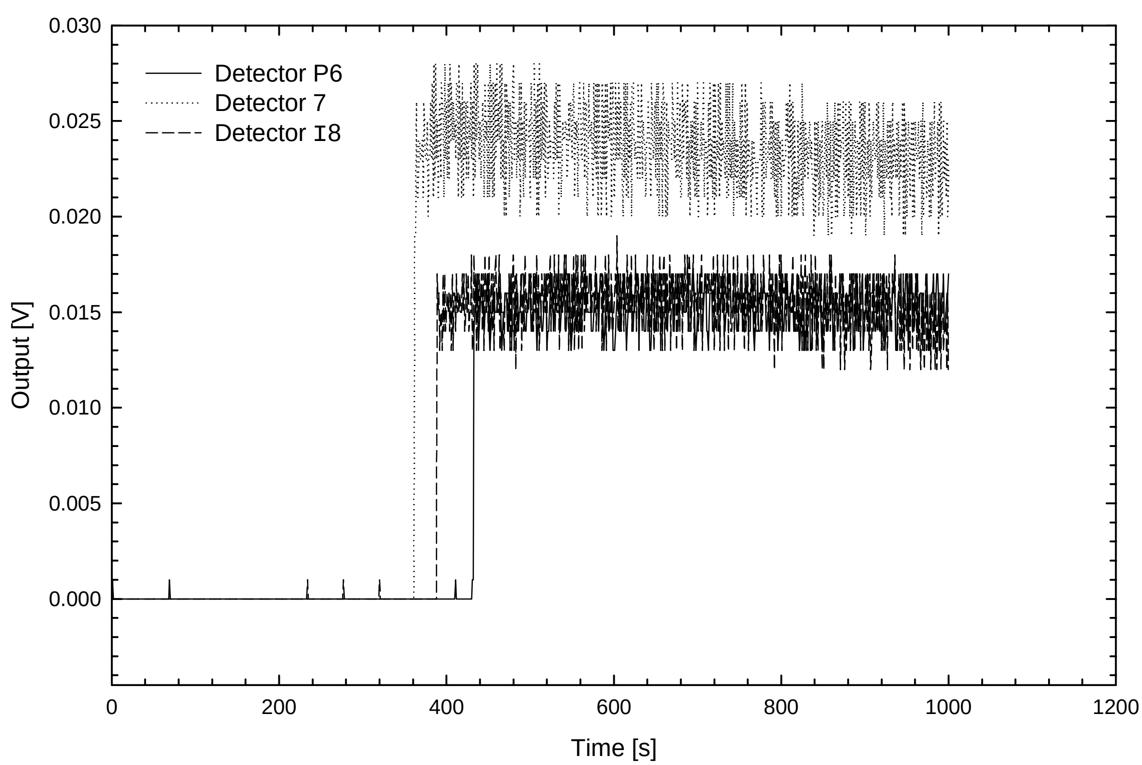


Figure 7. Typical activation signals from smoke detectors

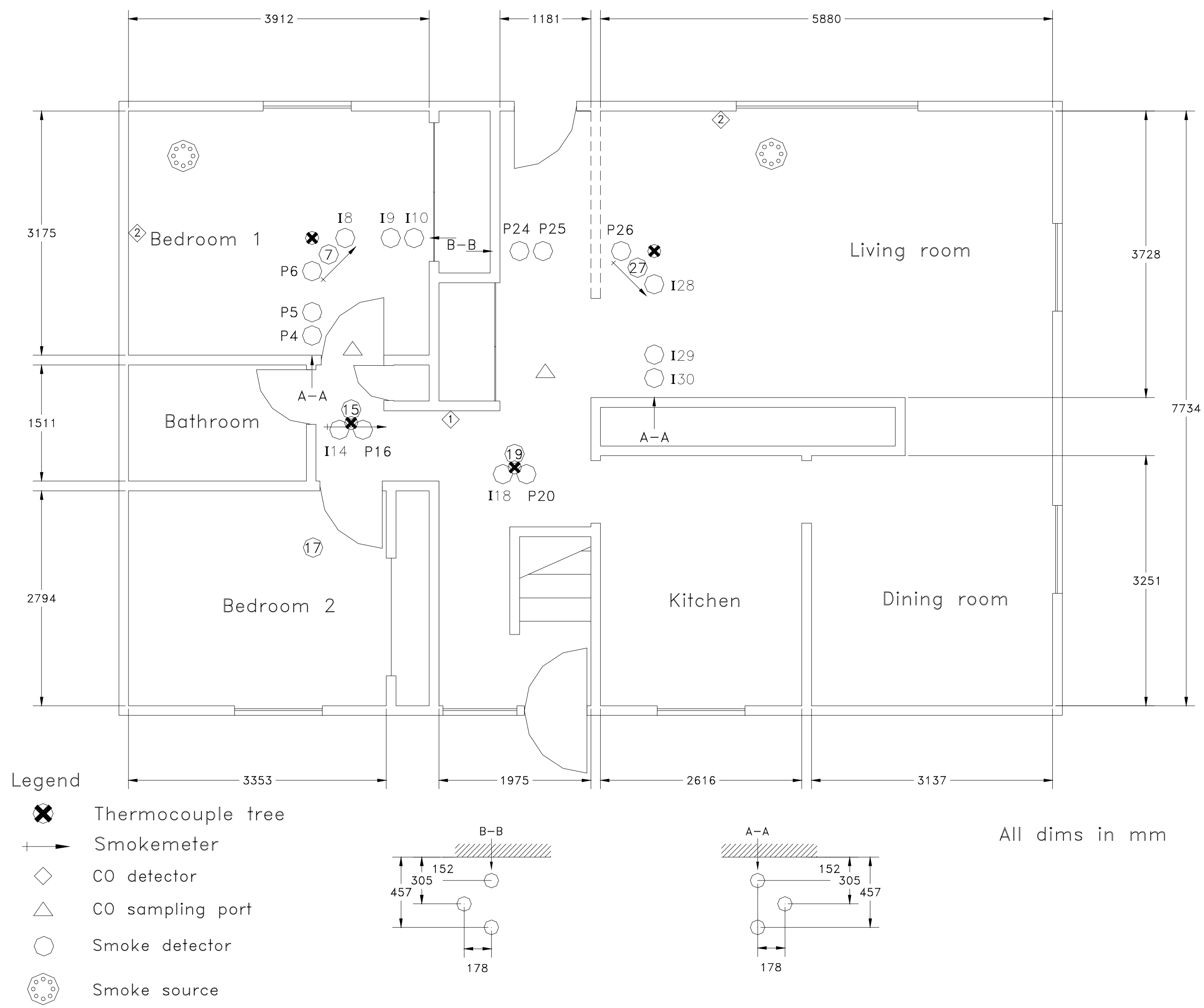


Figure 8a. Ground floor plan of House BB-513 (see 8b for more details)

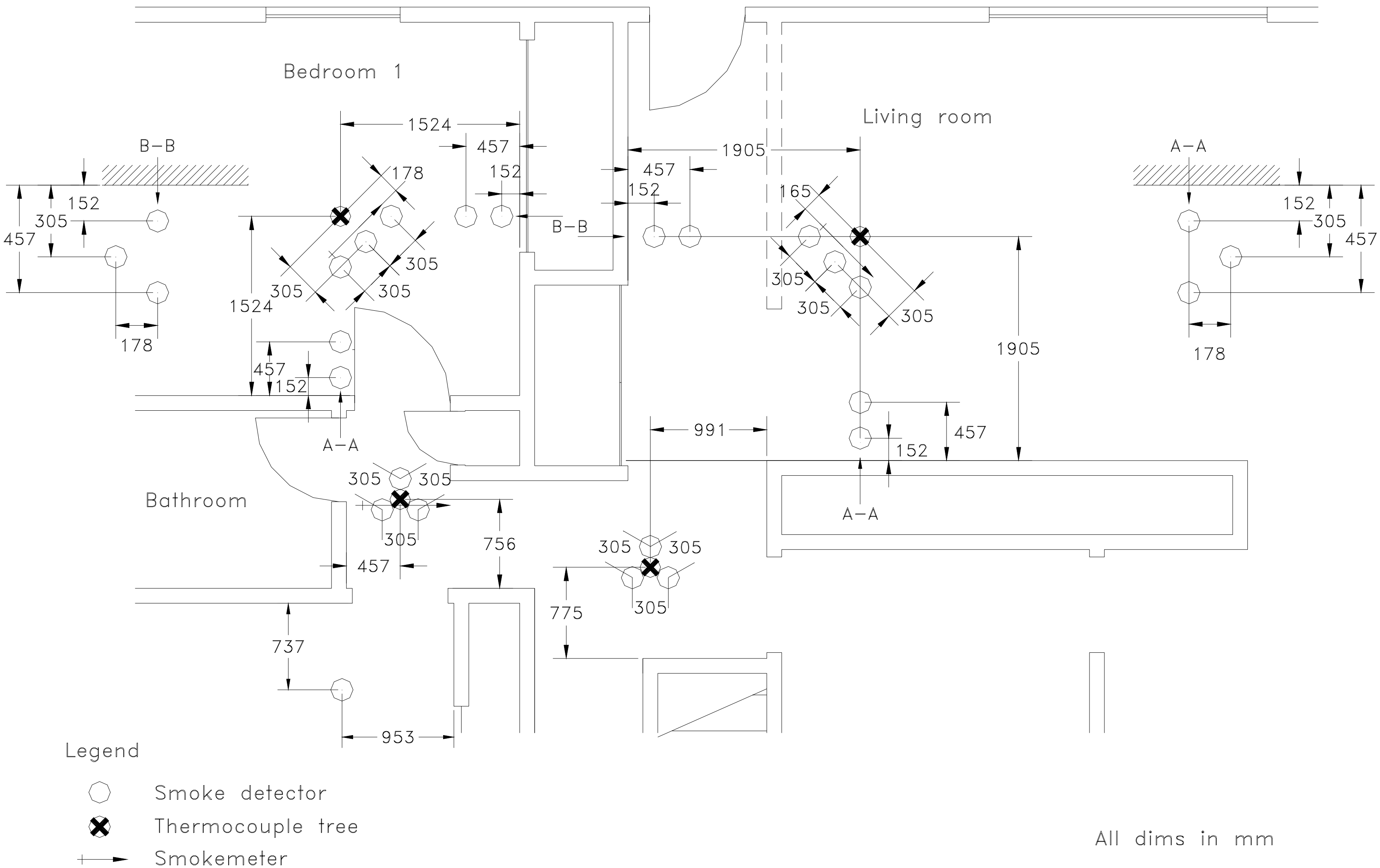


Figure 8b. Ground floor plan of House BB-513 (see 8a for overview)

Figure 9. Snapshots of the experiment set-up in House BB-513

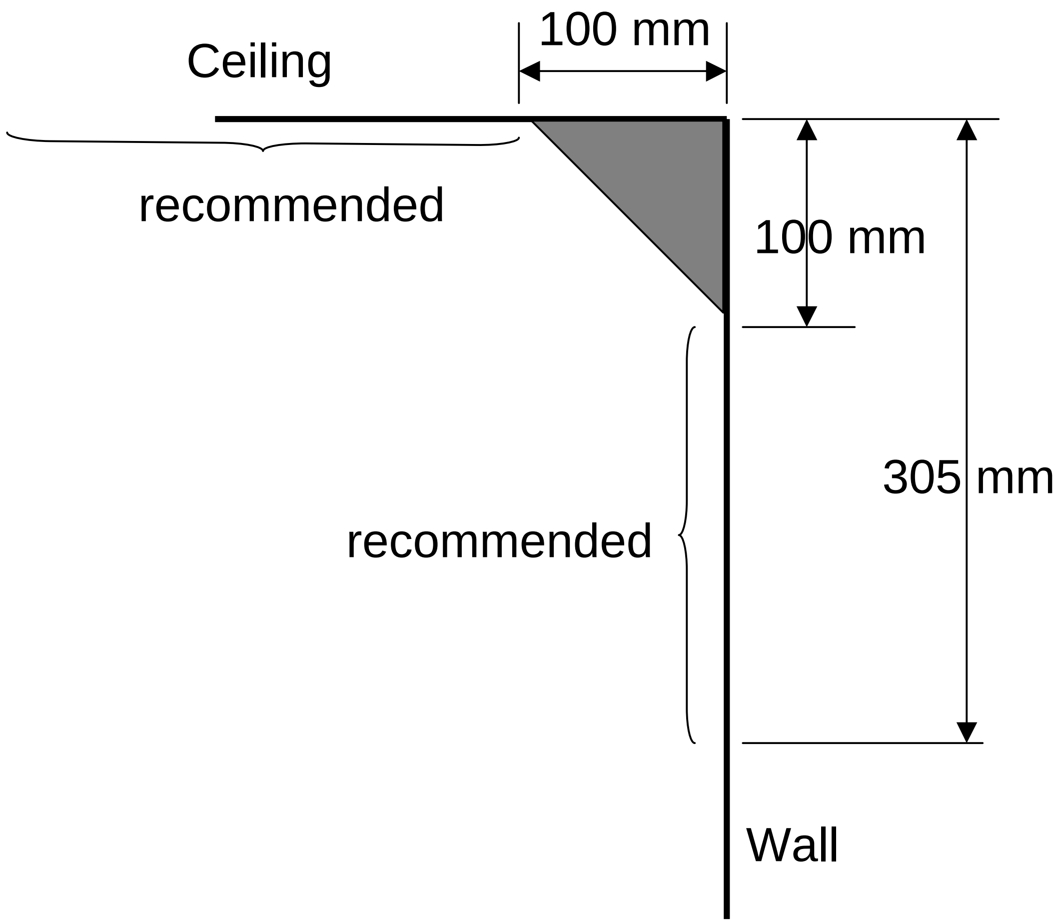
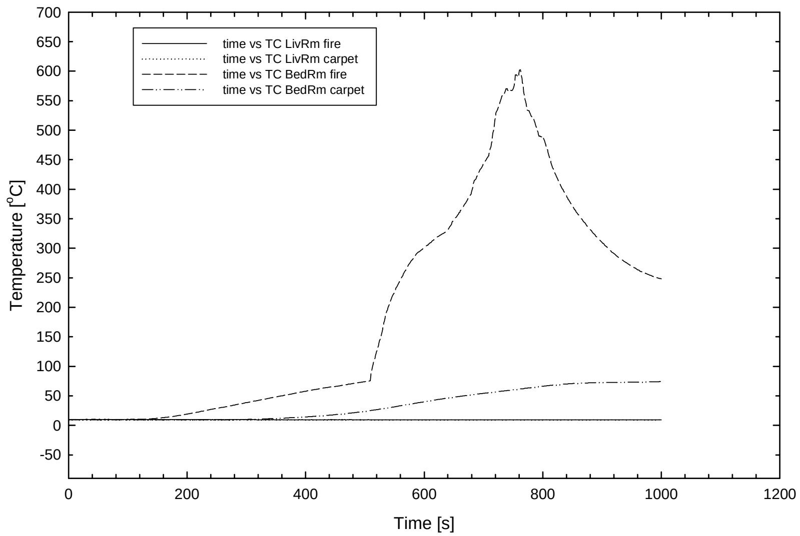
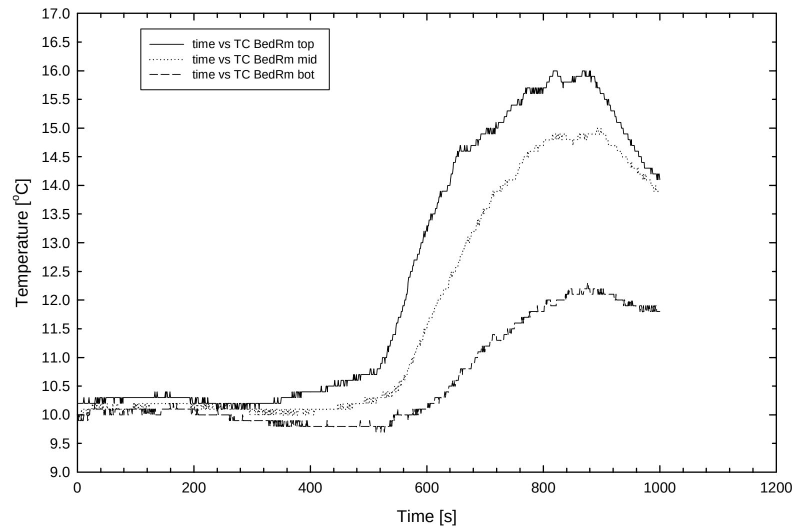


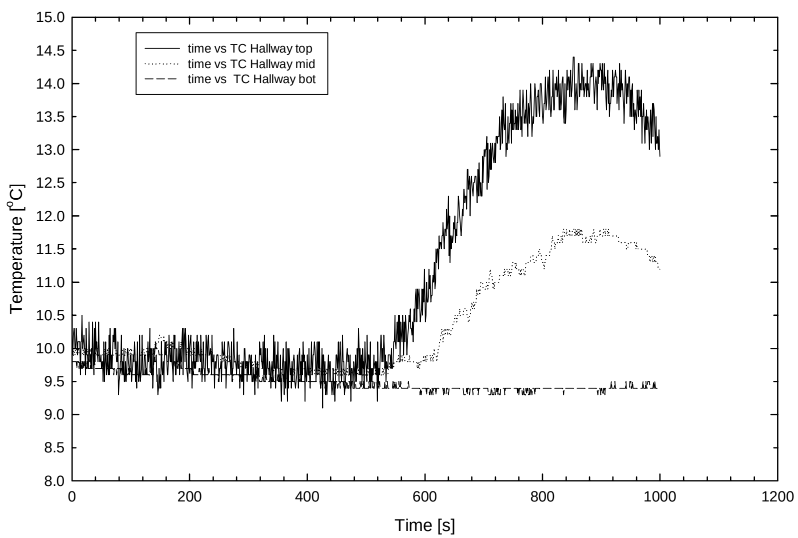
Figure 10. Illustration of so-called “dead air space”



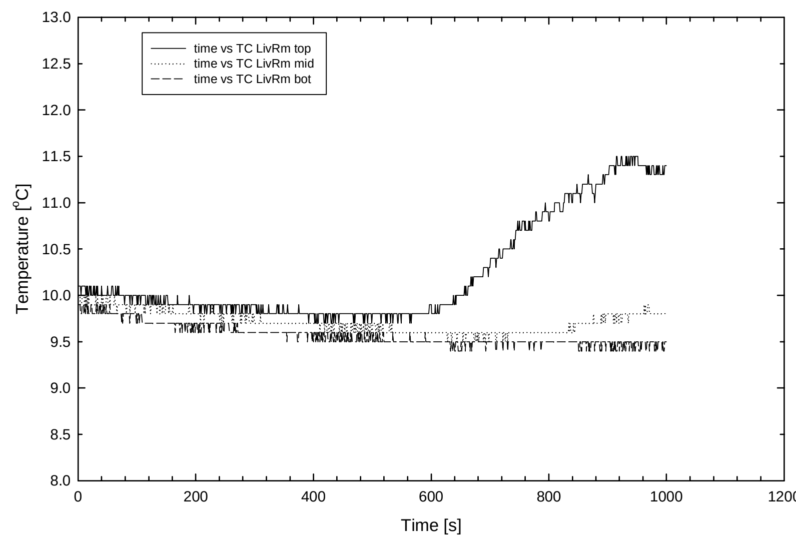
B4128 Test 1 - Target Thermocouples



B4128 Test 1 - Thermocouple Tree in Main Bedroom-1

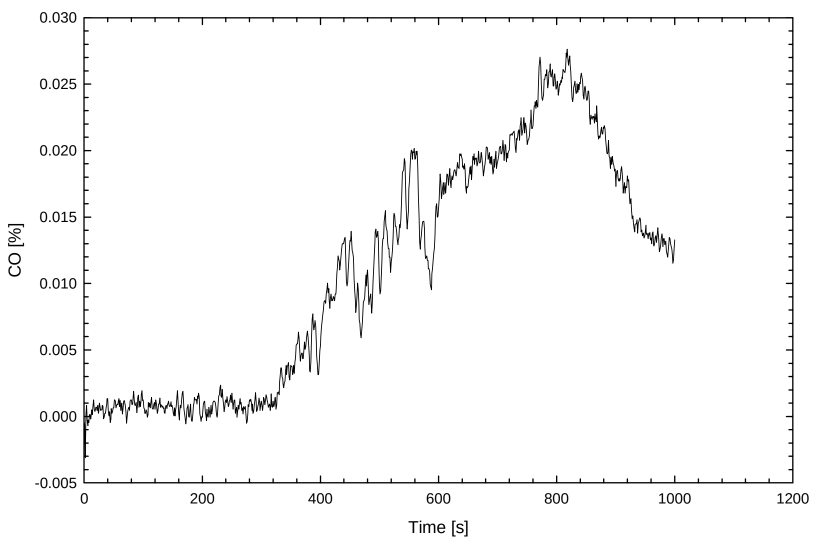


B4128 Test 1 - Thermocouple Tree in Hallway

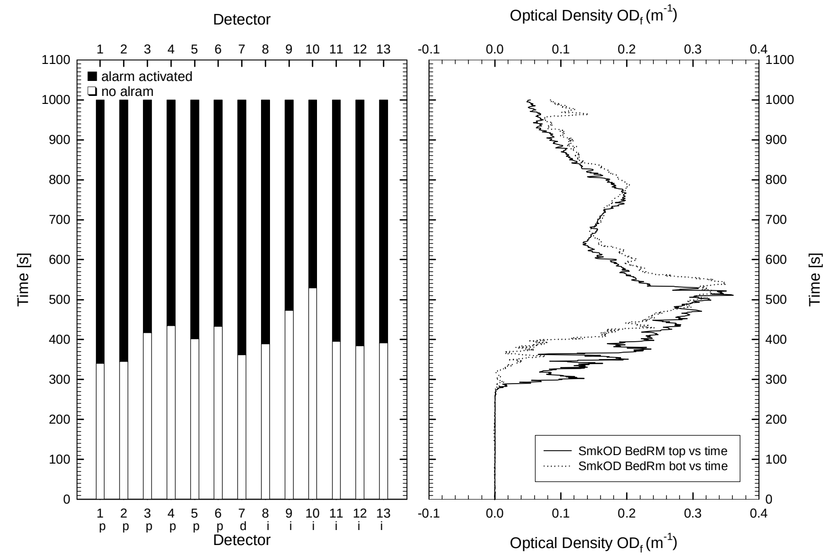


B4128 Test 1 - Thermocouple Tree in Living Room

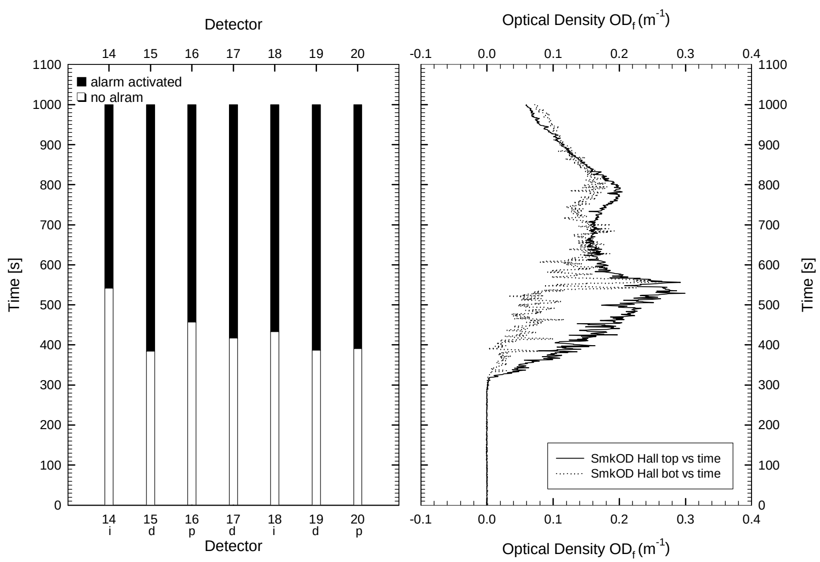
Figure 11. Temperatures at fire source and on TC trees in bedroom, corridor and living room during Test 1



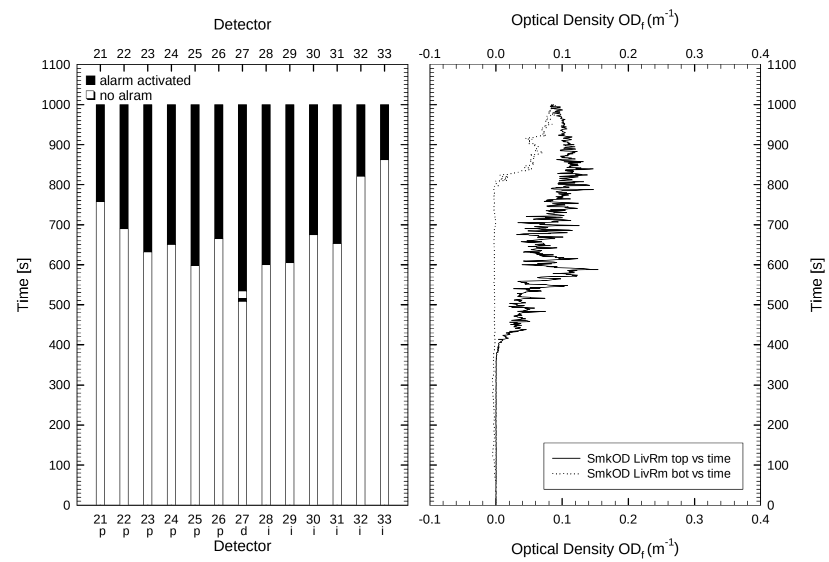
B4128 Test 1 - Carbon Moxide



B4128 Test 1 - Response of Smoke Detectors in Bedroom-1

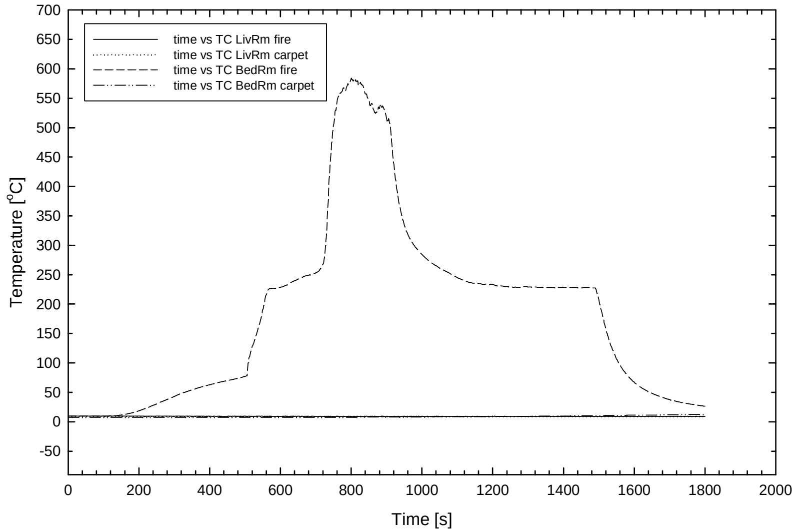


B4128 Test 1 - Response of Smoke Detectors in Hallway, Bedroom-2 and Entrance

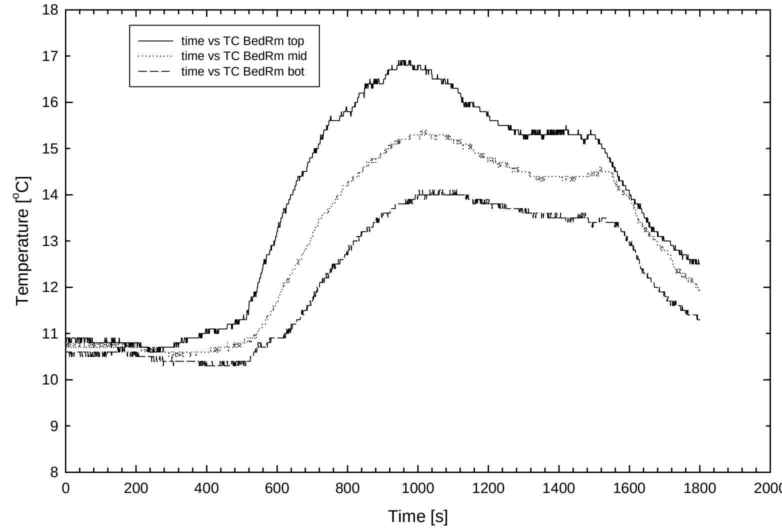


B4128 Test 1 - Response of Smoke Detectors in Living Room

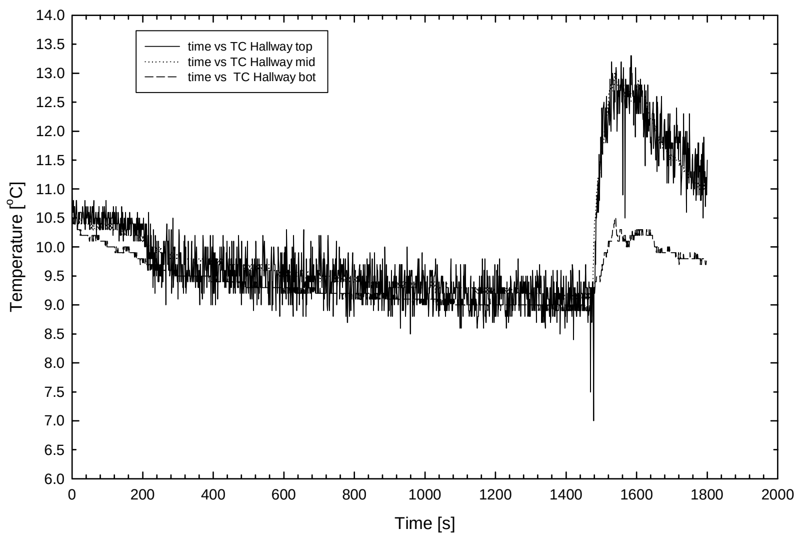
Figure 12. Profiles of CO, optical density (at Detectors 6–8, 14–16, 26–28) and detector response during Test 1



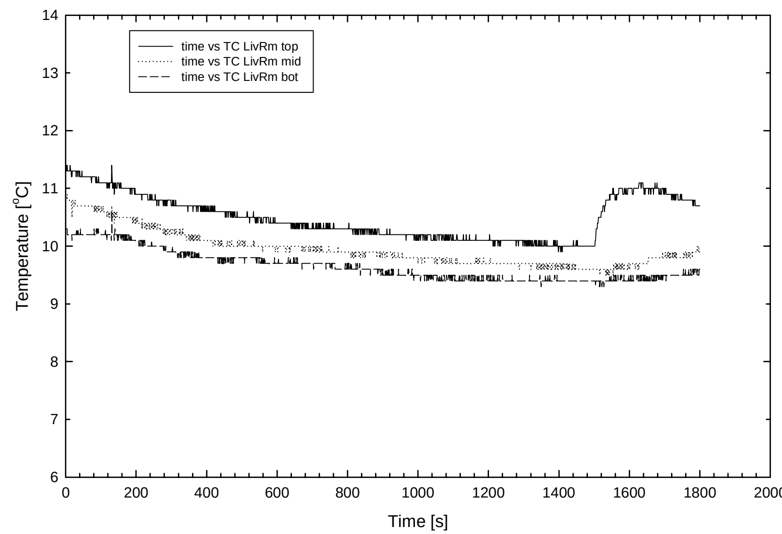
B4128 Test 2 - Target Thermocouples



B4128 Test 2 - Thermocouple Tree in Main Bedroom-1

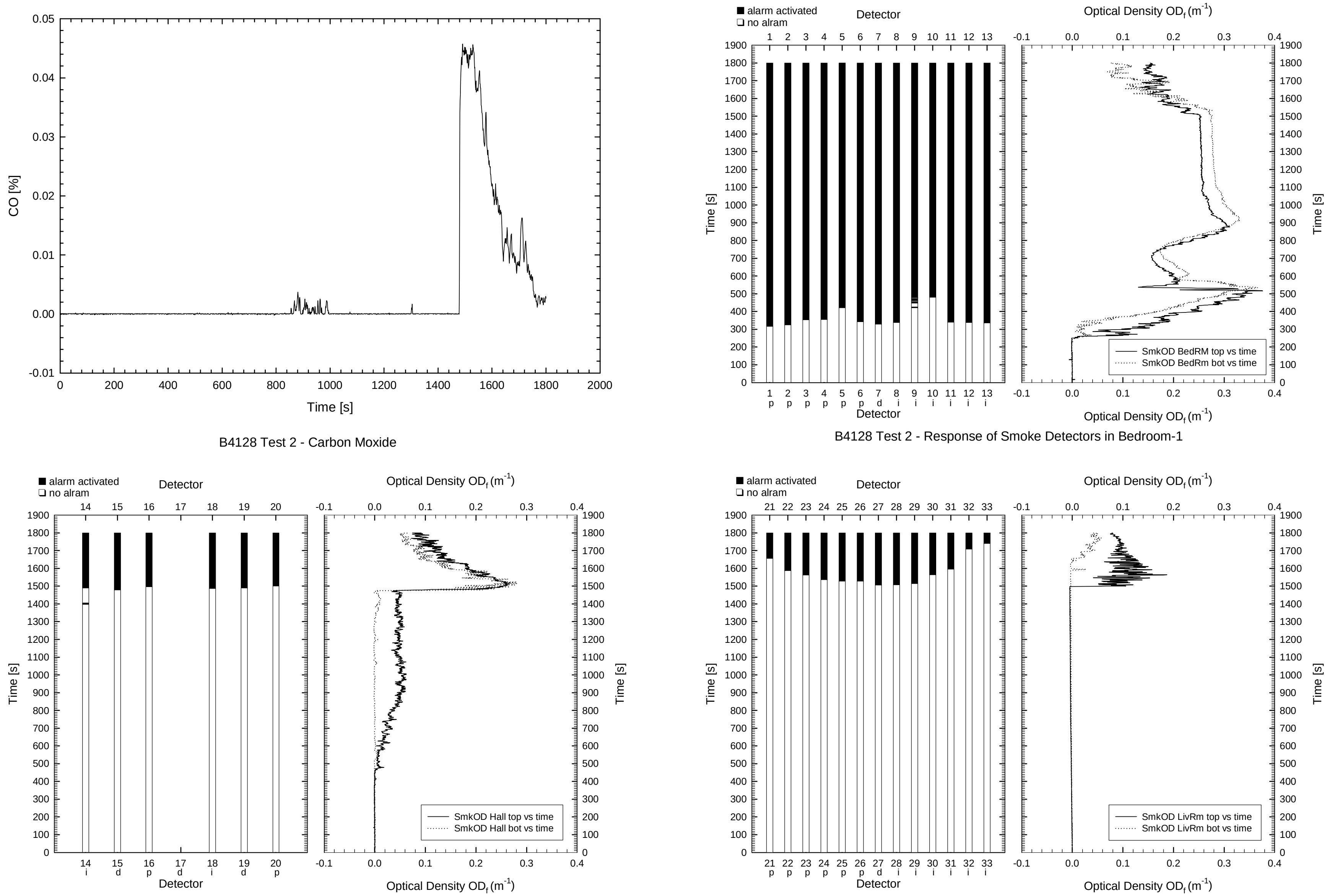


B4128 Test 2 - Thermocouple Tree in Hallway



B4128 Test 2 - Thermocouple Tree in Living Room

Figure 13. Temperatures at fire source and on TC trees in bedroom, corridor and living room during Test 2



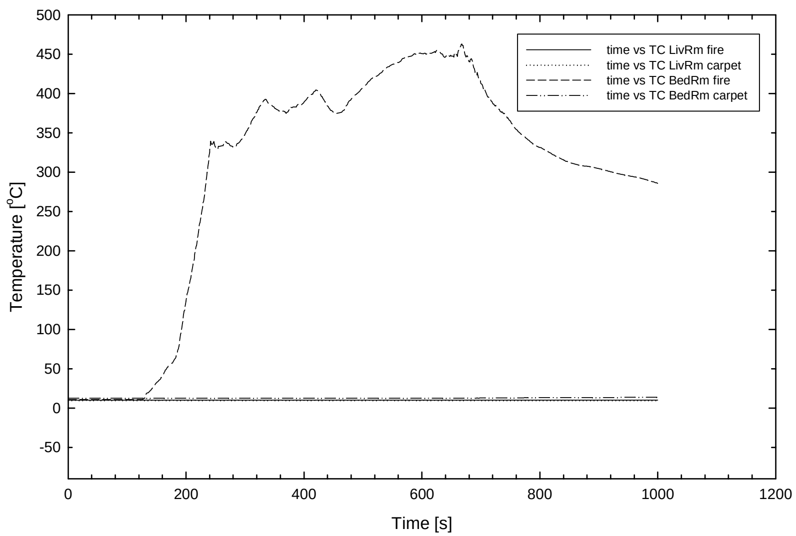
B4128 Test 2 - Carbon Moxide

B4128 Test 2 - Response of Smoke Detectors in Bedroom-1

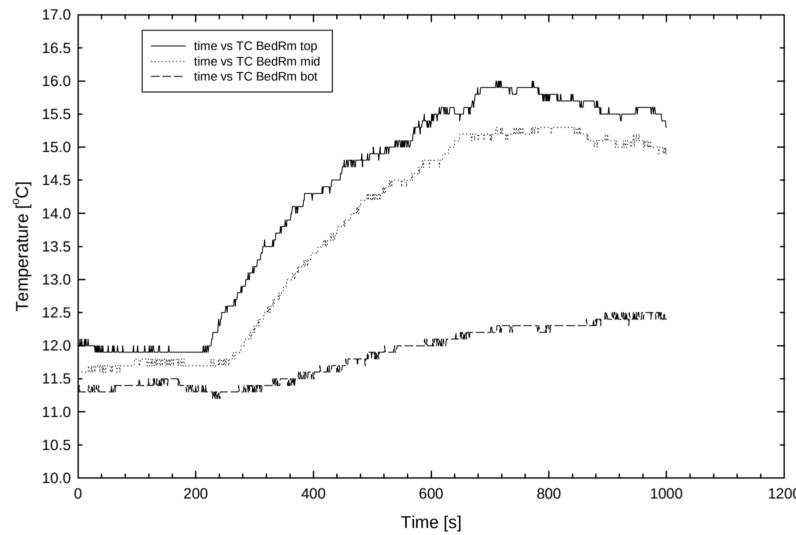
B4128 Test 2 - Response of Smoke Detectors in Hallway, Bedroom-2 and Entrance

B4128 Test 2 - Response of Smoke Detectors in Living Room

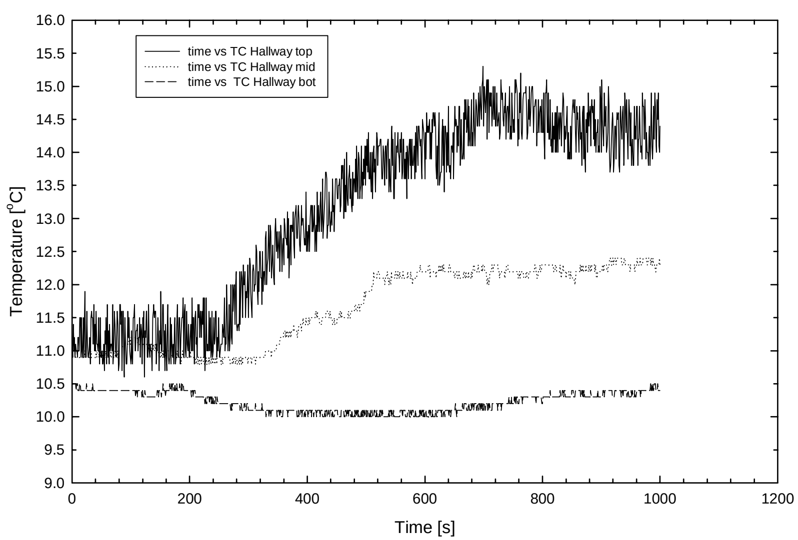
Figure 14. Profiles of CO, optical density (at Detectors 6–8, 14–16, 26–28) and detector response during Test 2



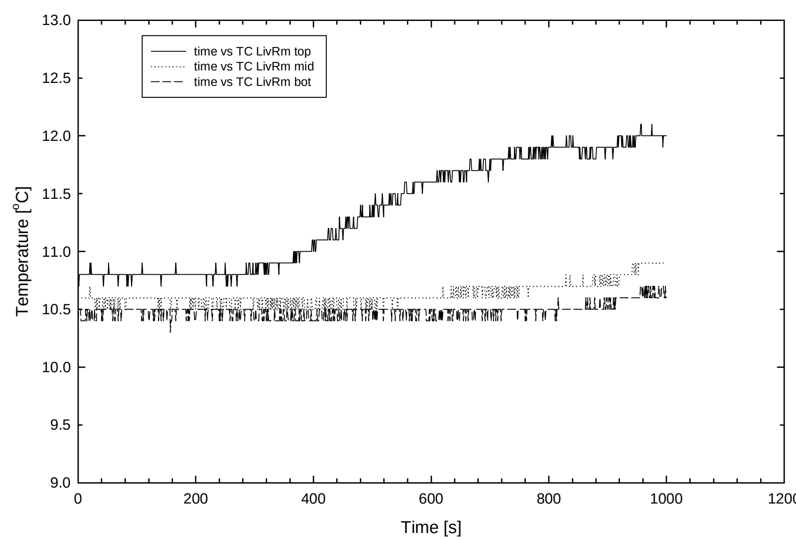
B4128 Test 3 - Target Thermocouples



B4128 Test 3 - Thermocouple Tree in Main Bedroom-1

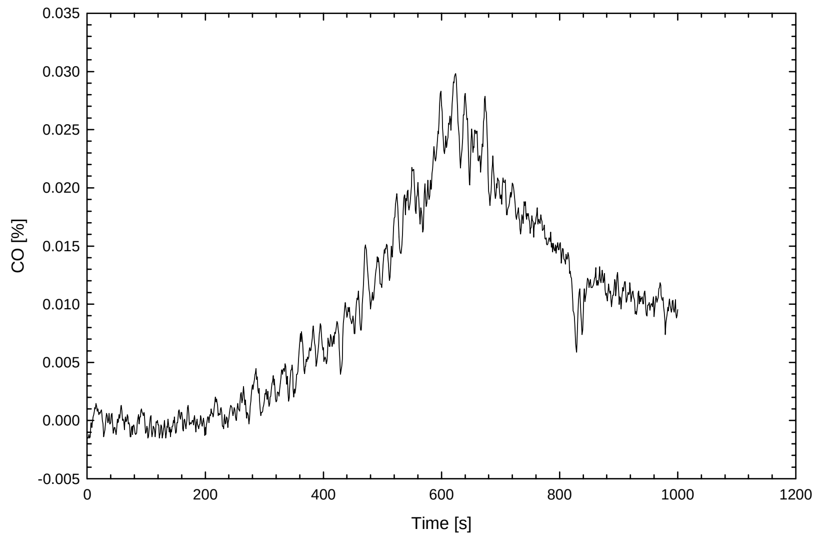


B4128 Test 3 - Thermocouple Tree in Hallway

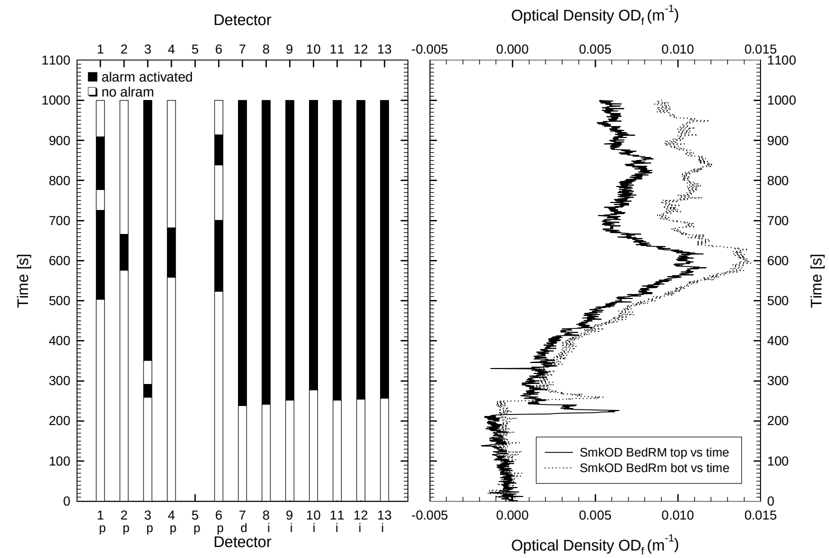


B4128 Test 3 - Thermocouple Tree in Living Room

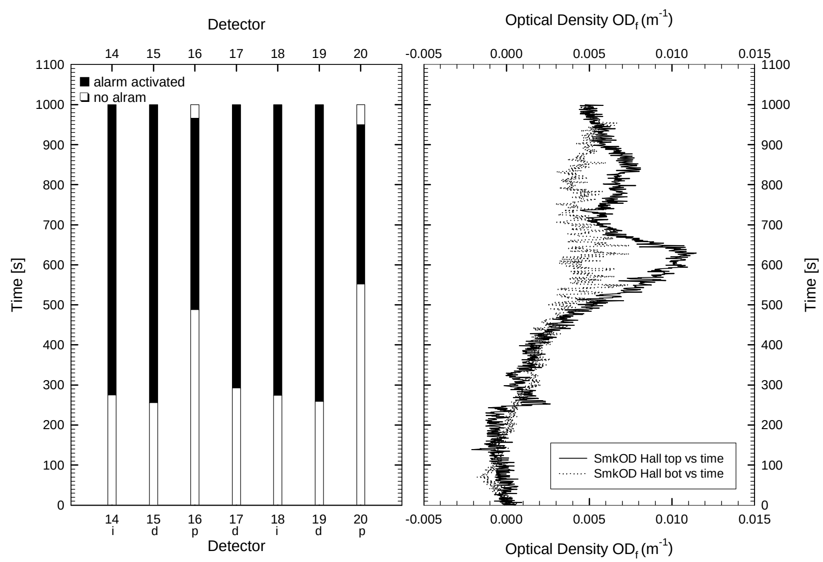
Figure 15. Temperatures at fire source and on TC trees in bedroom, corridor and living room during Test 3



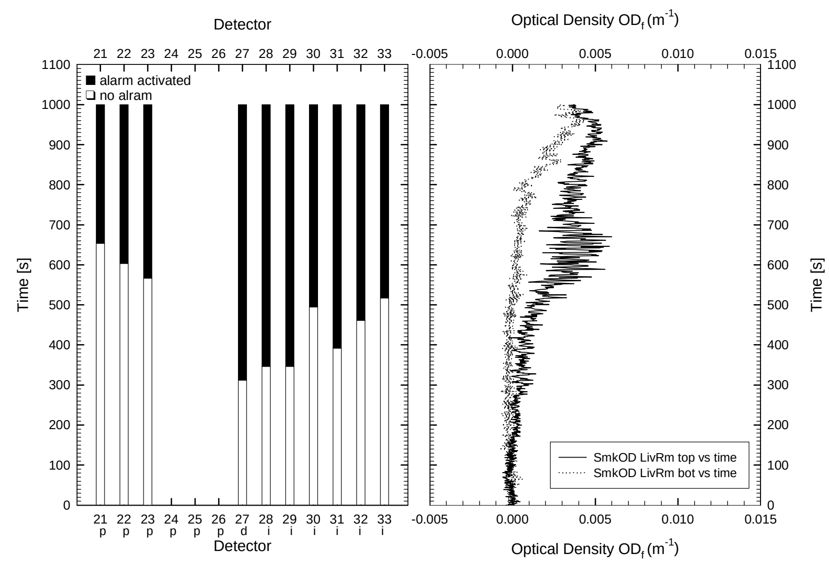
B4128 Test 3 - Carbon Moxide



B4128 Test 3 - Response of Smoke Detectors in Bedroom-1

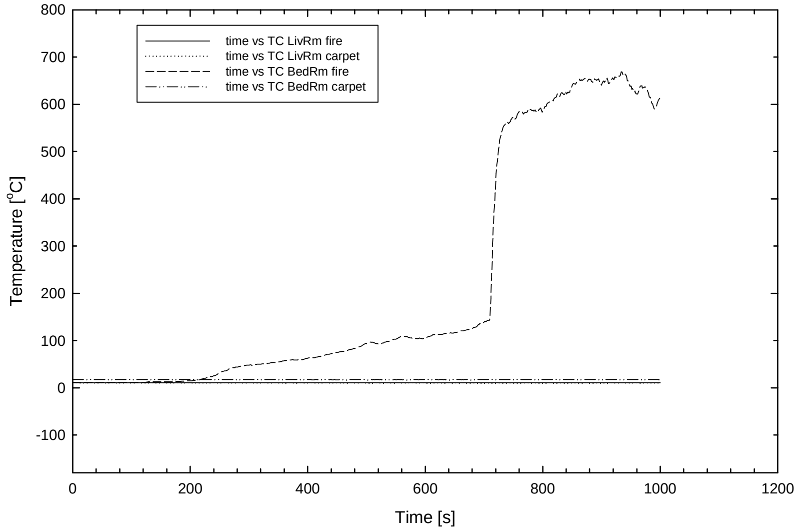


B4128 Test 3 - Response of Smoke Detectors in Hallway, Bedroom-2 and Entrance

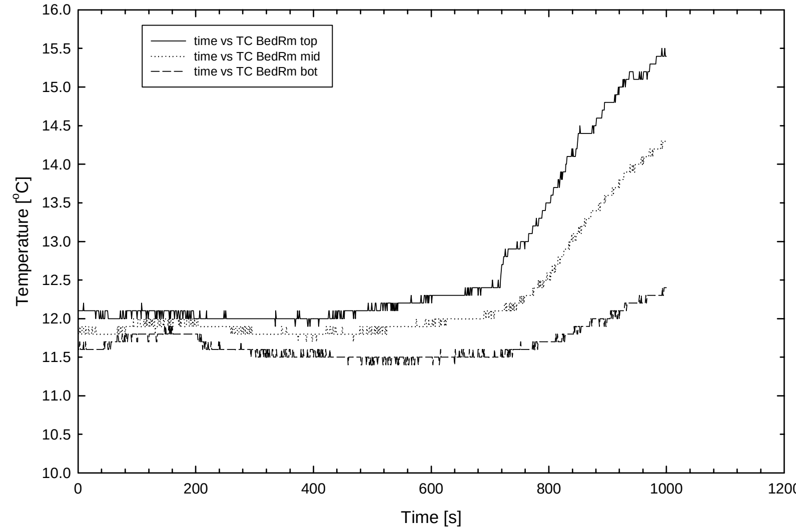


B4128 Test 3 - Response of Smoke Detectors in Living Room

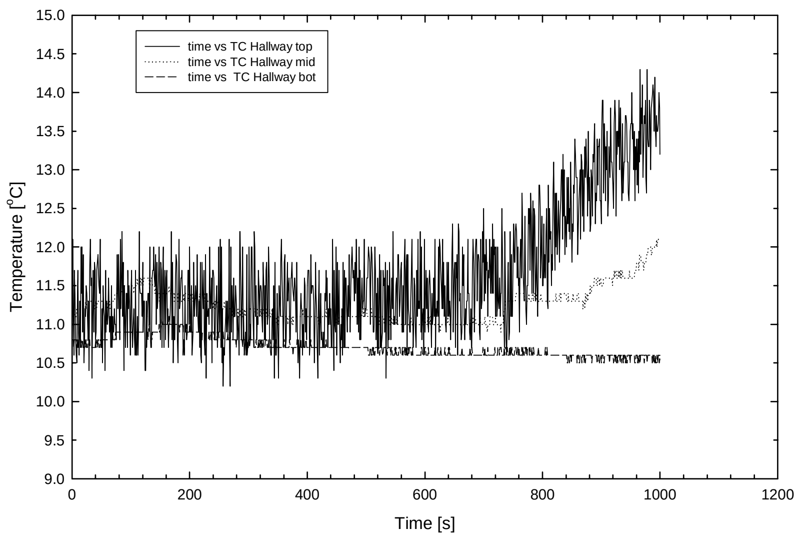
Figure 16. Profiles of CO, optical density (at Detectors 6–8, 14–16, 26–28) and detector response during Test 3



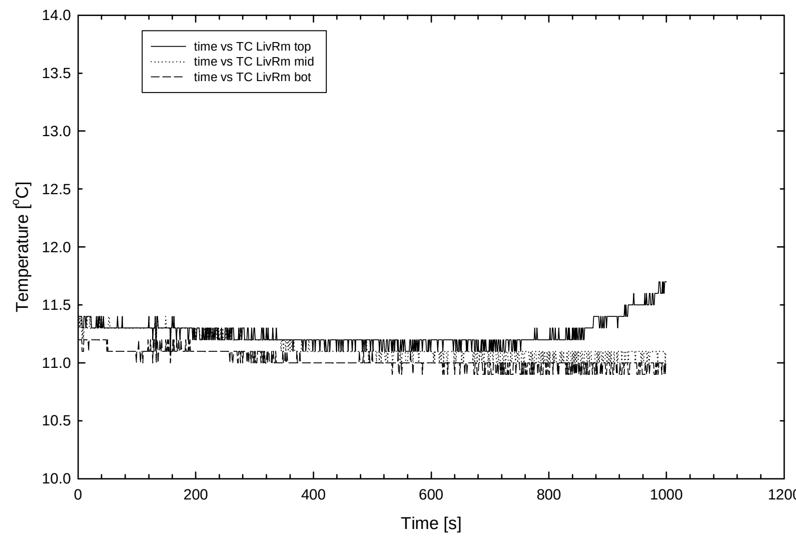
B4128 Test 4 - Target Thermocouples



B4128 Test 4 - Thermocouple Tree in Main Bedroom-1

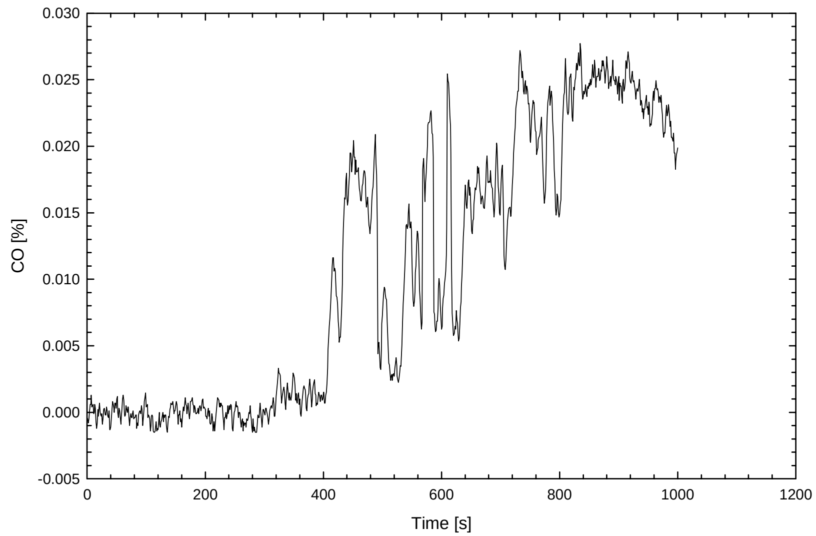


B4128 Test 4 - Thermocouple Tree in Hallway

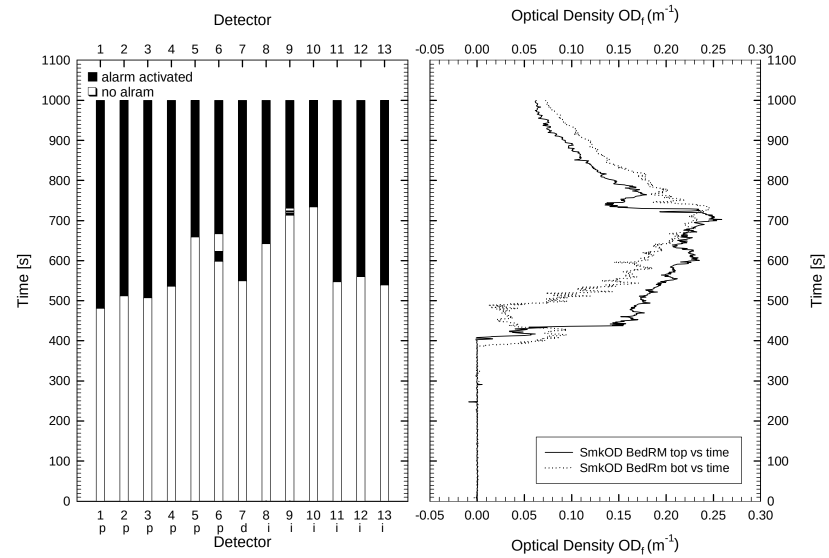


B4128 Test 4 - Thermocouple Tree in Living Room

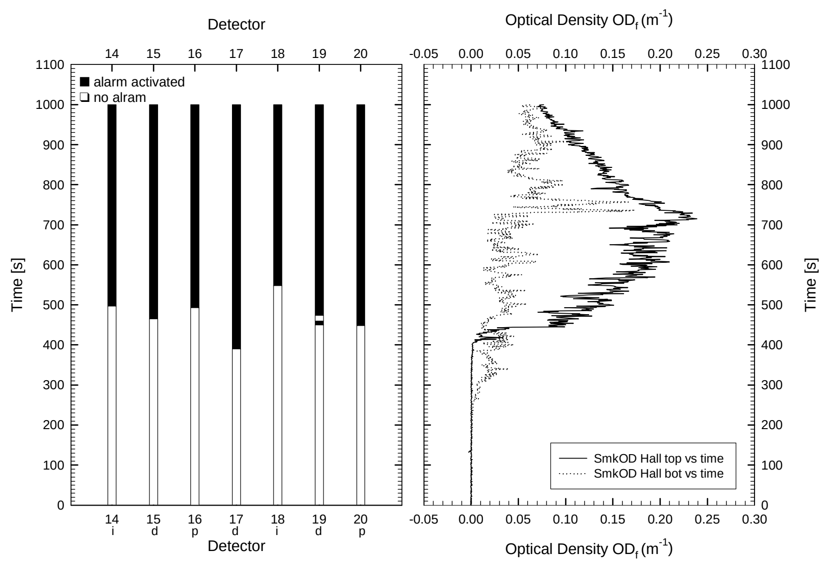
Figure 17. Temperatures at fire source and on TC trees in bedroom, corridor and living room during Test 4



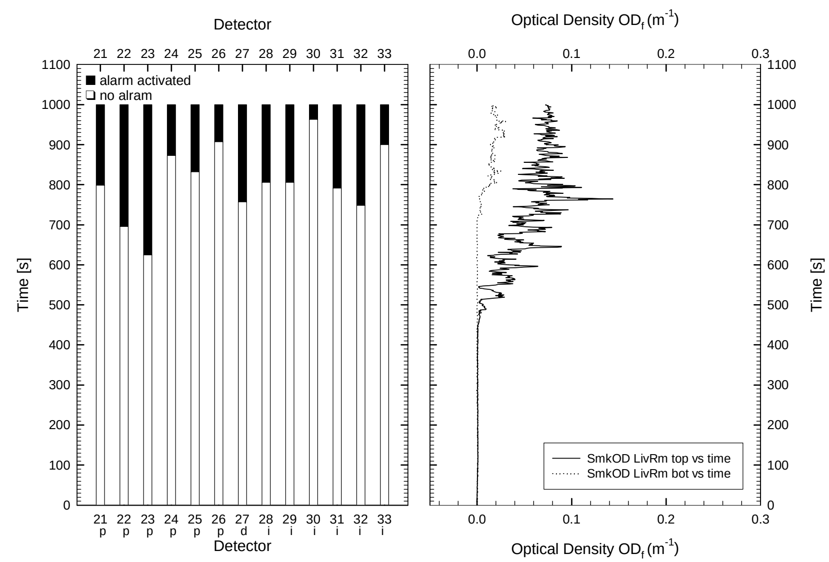
B4128 Test 4 - Carbon Moxide



B4128 Test 4 - Response of Smoke Detectors in Bedroom-1

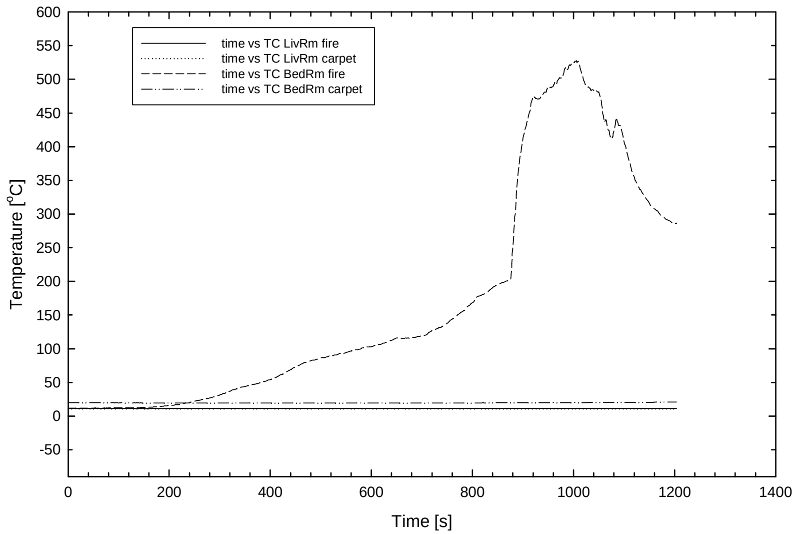


B4128 Test 4 - Response of Smoke Detectors in Hallway, Bedroom-2 and Entrance

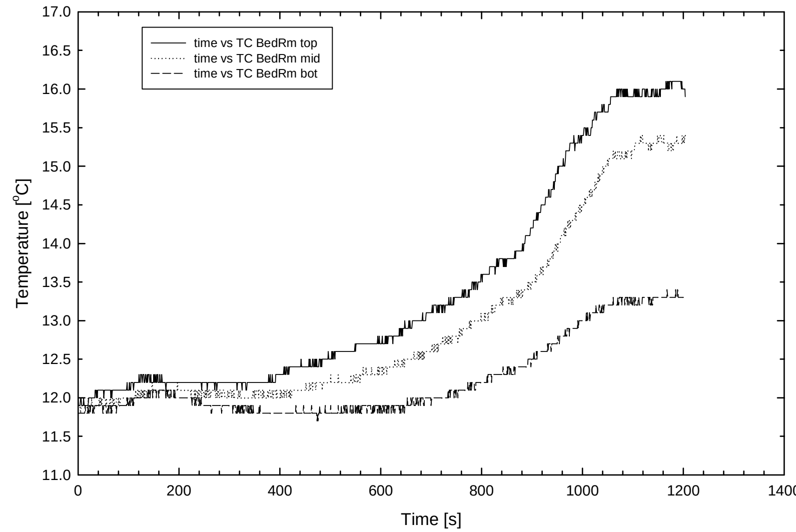


B4128 Test 4 - Response of Smoke Detectors in Living Room

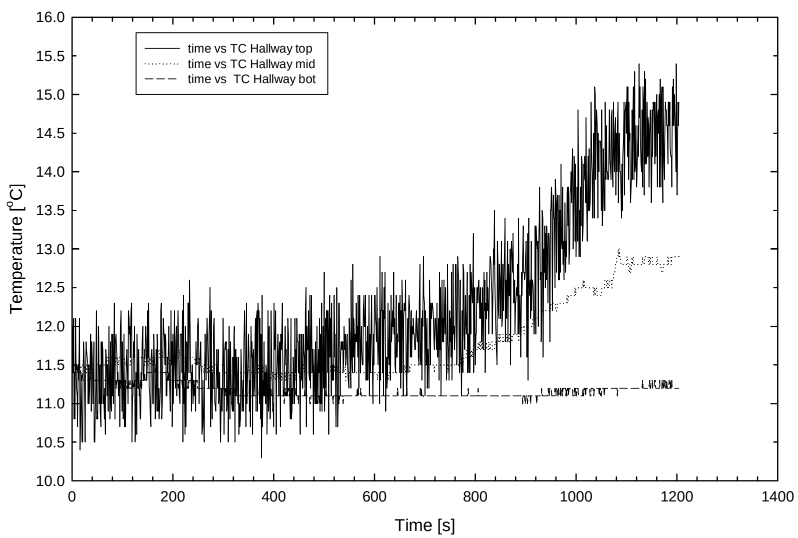
Figure 18. Profiles of CO, optical density (at Detectors 6–8, 14–16, 26–28) and detector response during Test 4



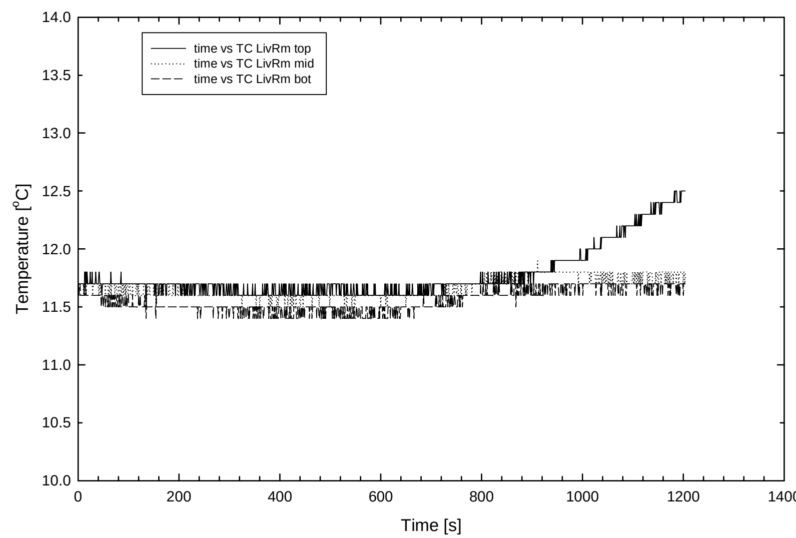
B4128 Test 5 - Target Thermocouples



B4128 Test 5 - Thermocouple Tree in Main Bedroom-1

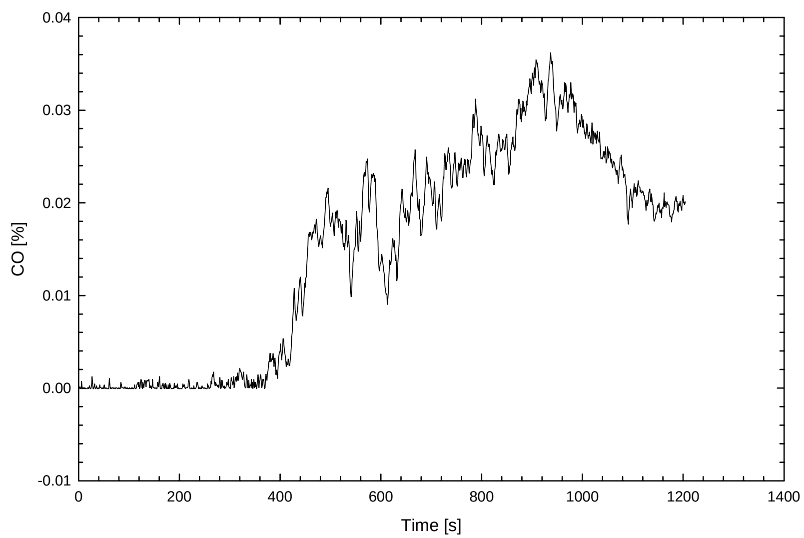


B4128 Test 5 - Thermocouple Tree in Hallway

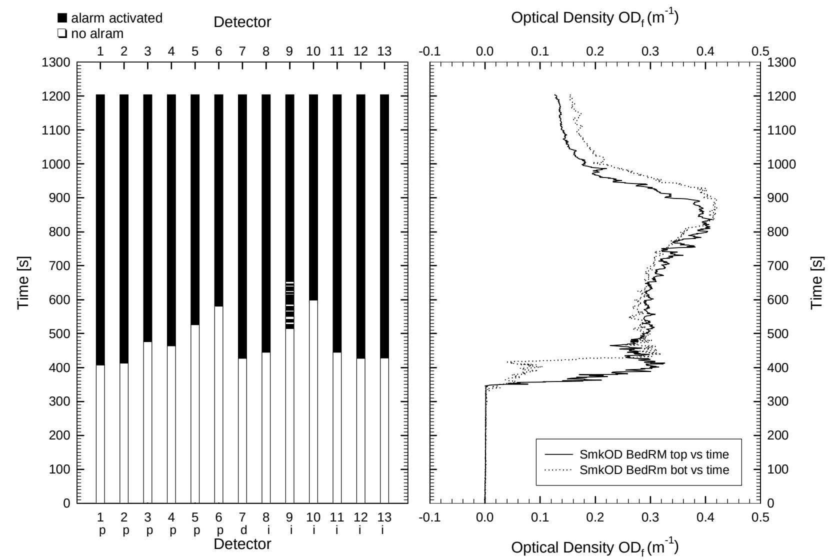


B4128 Test 5 - Thermocouple Tree in Living Room

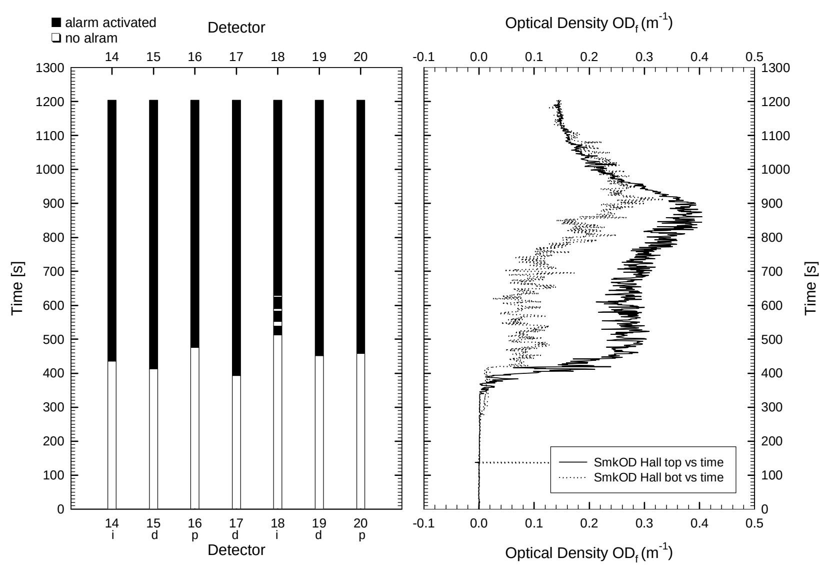
Figure 19. Temperatures at fire source and on TC trees in bedroom, corridor and living room during Test 5



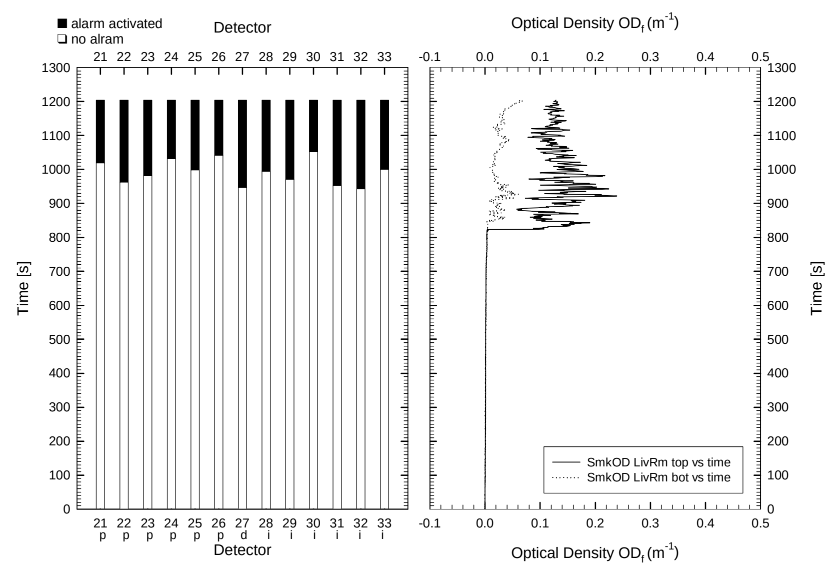
B4128 Test 5 - Carbon Moxide



B4128 Test 5 - Response of Smoke Detectors in Bedroom-1

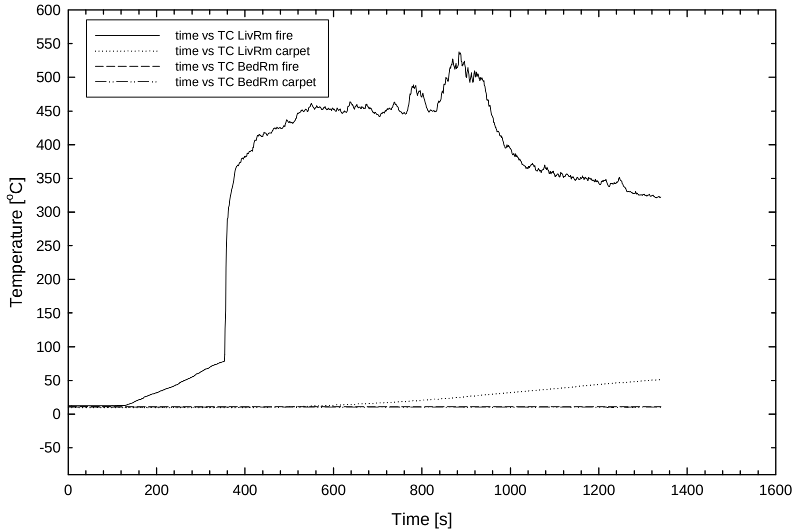


B4128 Test 5 - Response of Smoke Detectors in Hallway, Bedroom-2 and Entrance

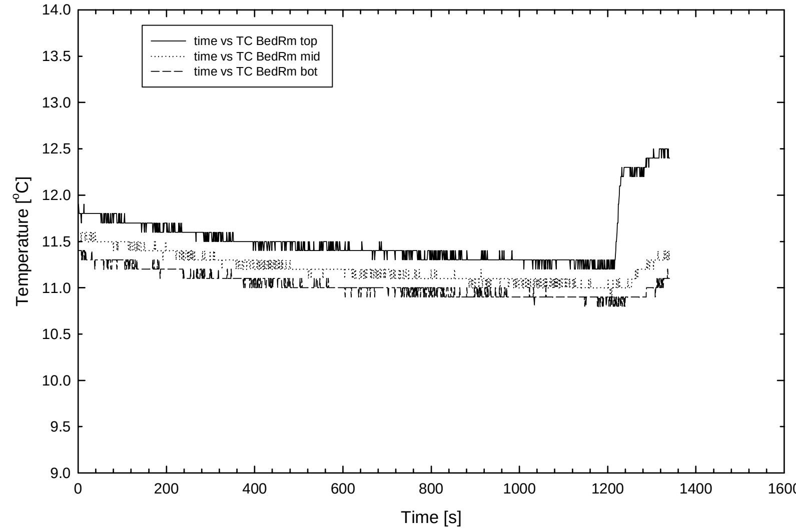


B4128 Test 5 - Response of Smoke Detectors in Living Room

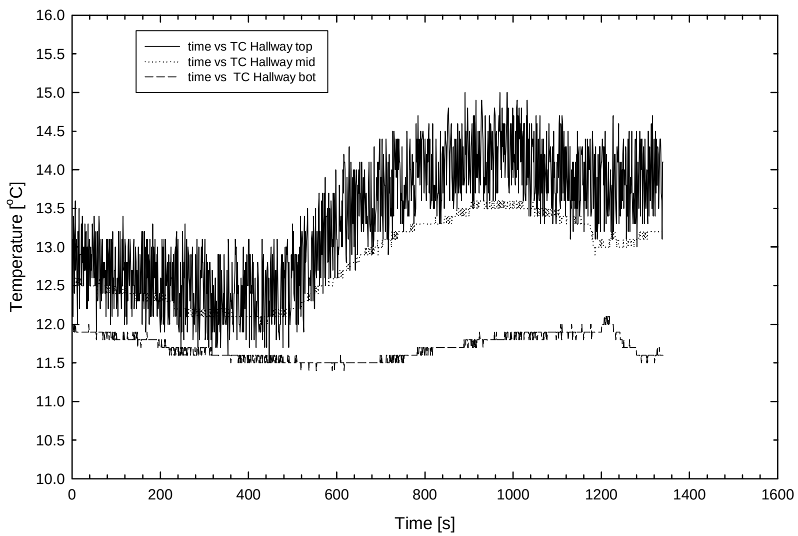
Figure 20. Profiles of CO, optical density (at Detectors 6–8, 14–16, 26–28) and detector response during Test 5



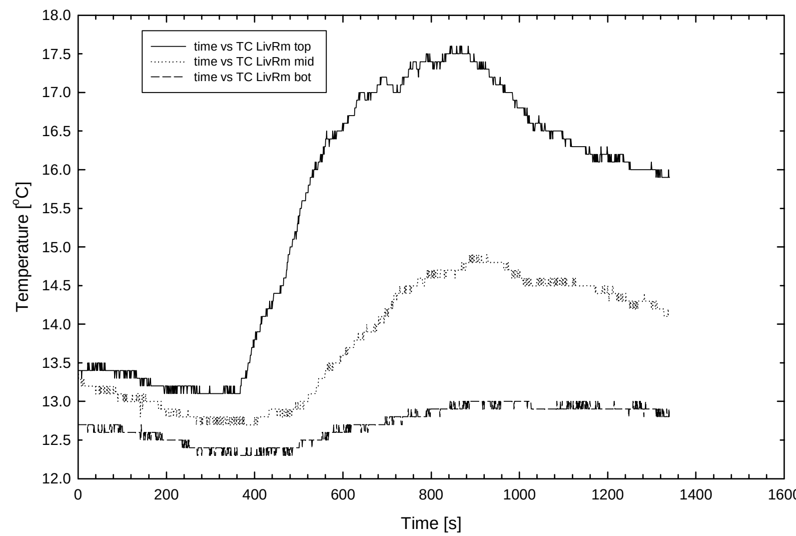
B4128 Test 6 - Target Thermocouples



B4128 Test 6 - Thermocouple Tree in Main Bedroom-1

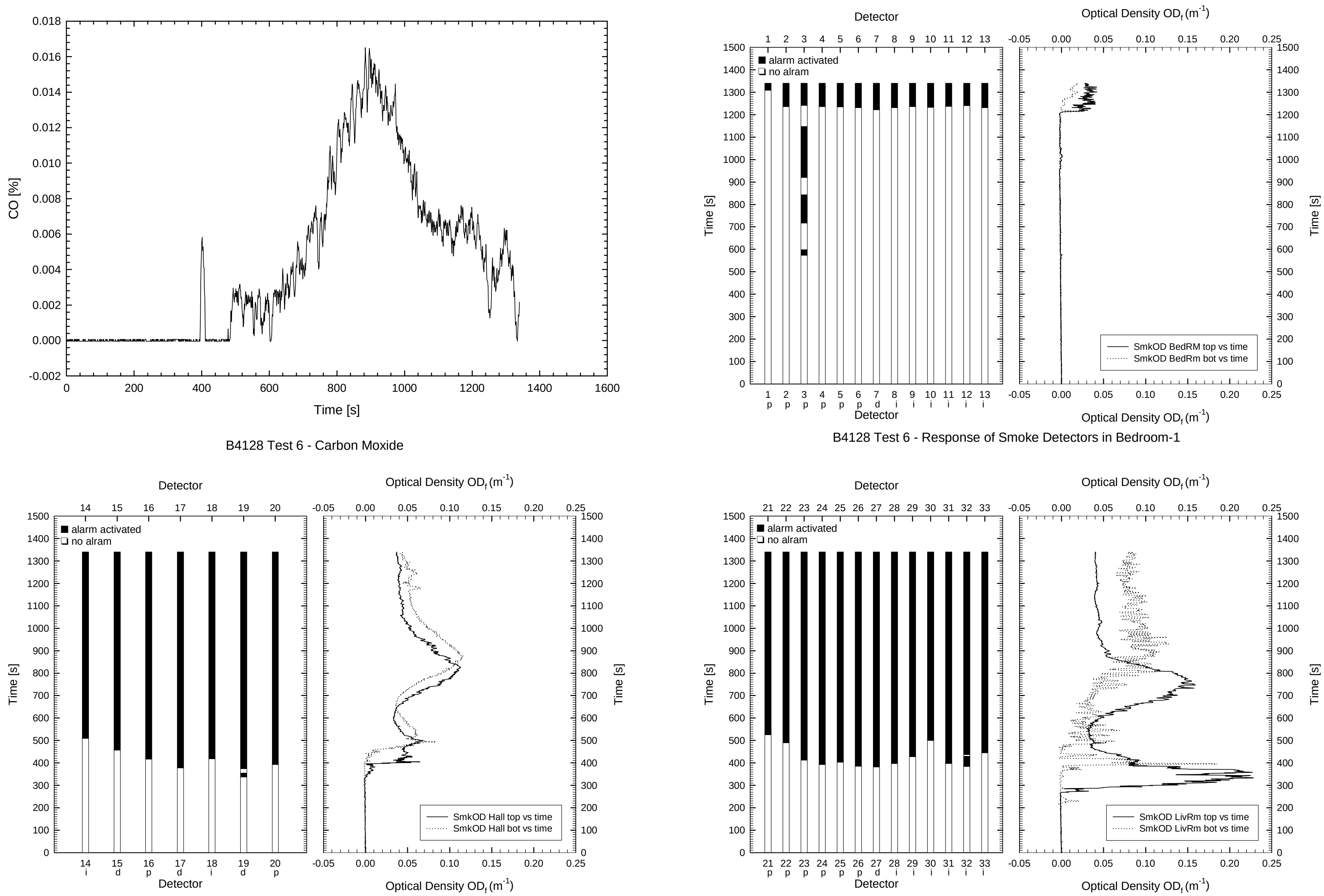


B4128 Test 6 - Thermocouple Tree in Hallway



B4128 Test 6 - Thermocouple Tree in Living Room

Figure 21. Temperatures at fire source and on TC trees in bedroom, corridor and living room during Test 6



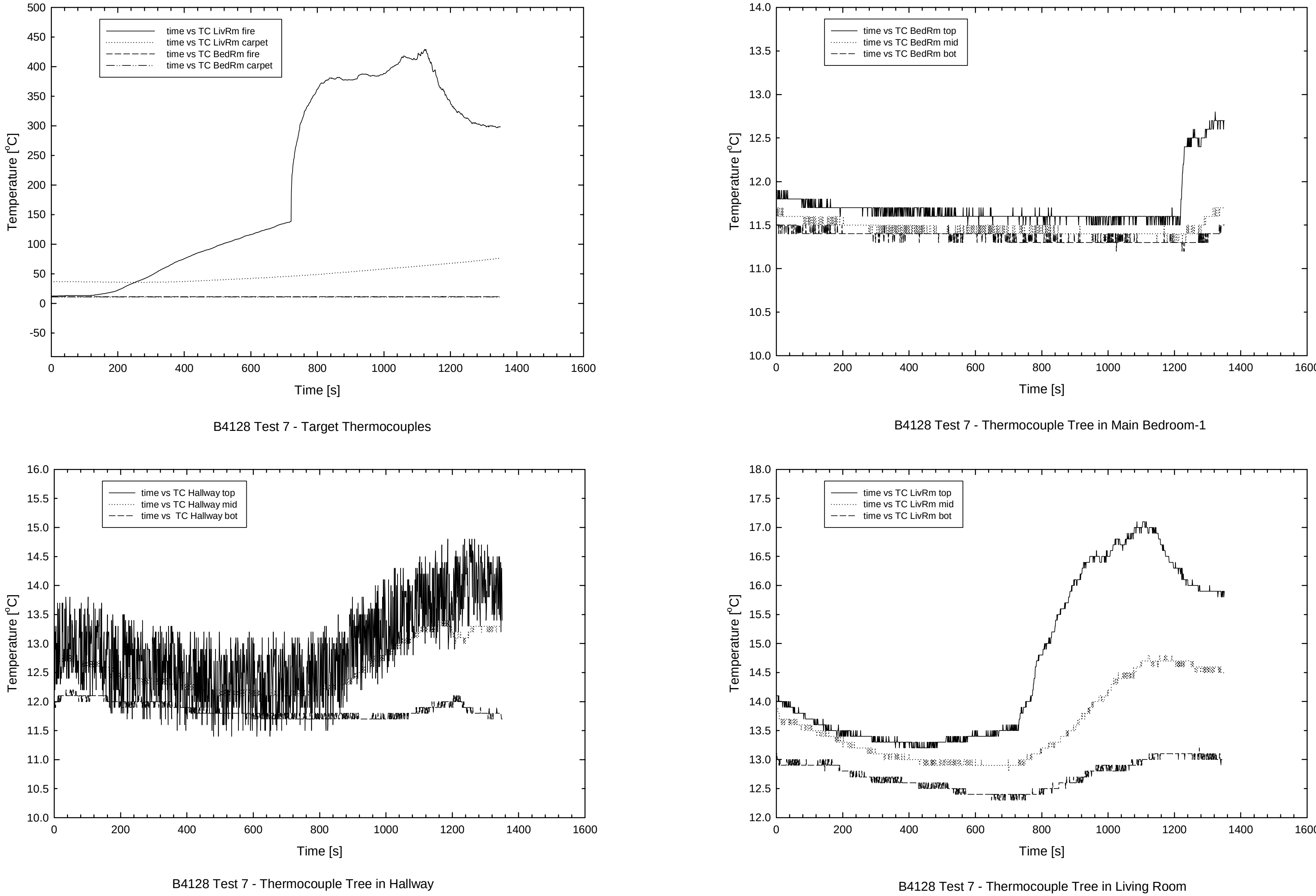
B4128 Test 6 - Carbon Moxide

B4128 Test 6 - Response of Smoke Detectors in Bedroom-1

B4128 Test 6 - Response of Smoke Detectors in Hallway, Bedroom-2 and Entrance

B4128 Test 6 - Response of Smoke Detectors in Living Room

Figure 22. Profiles of CO, optical density (at Detectors 6–8, 14–16, 26–28) and detector response during Test 6



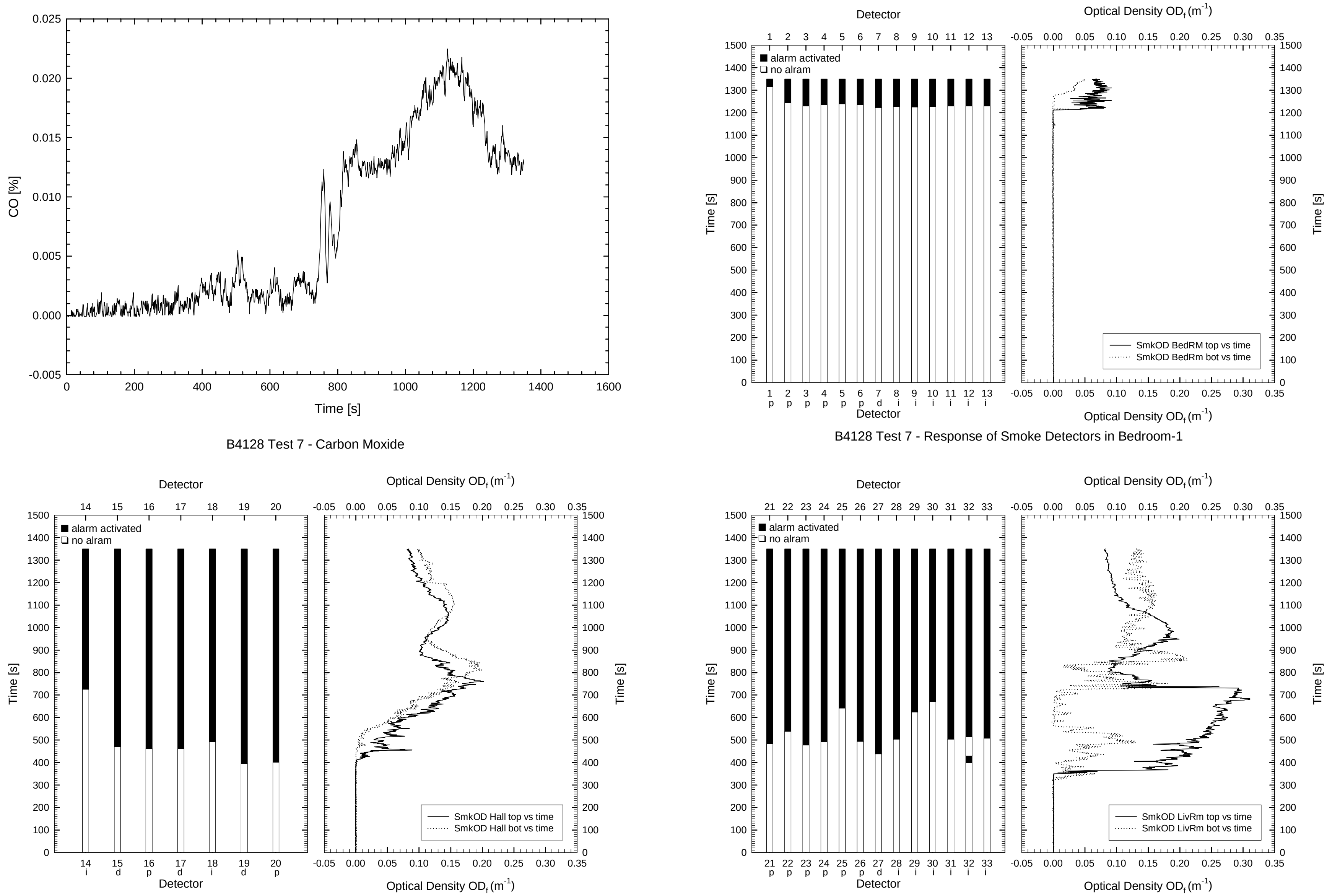
B4128 Test 7 - Target Thermocouples

B4128 Test 7 - Thermocouple Tree in Main Bedroom-1

B4128 Test 7 - Thermocouple Tree in Hallway

B4128 Test 7 - Thermocouple Tree in Living Room

Figure 23. Temperatures at fire source and on TC trees in bedroom, corridor and living room during Test 7



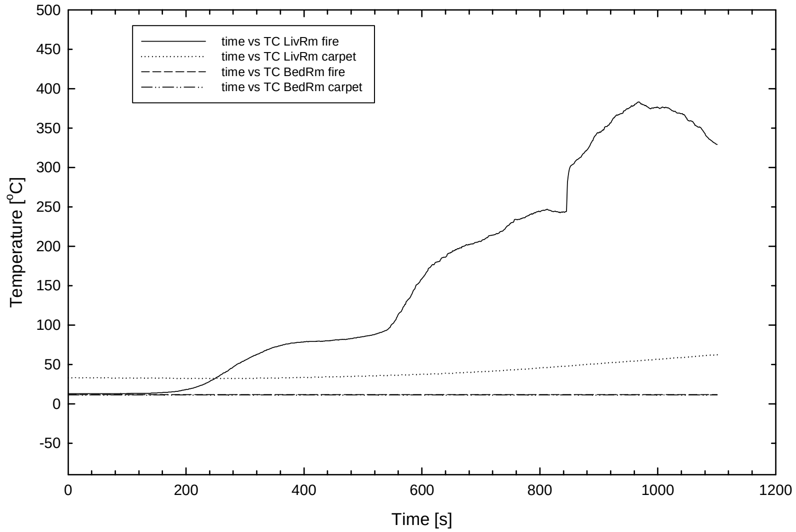
B4128 Test 7 - Carbon Moxide

B4128 Test 7 - Response of Smoke Detectors in Bedroom-1

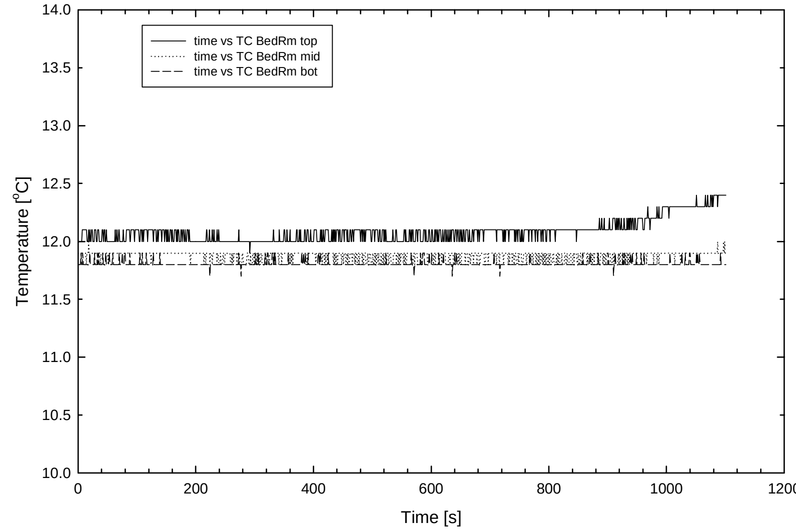
B4128 Test 7 - Response of Smoke Detectors in Hallway, Bedroom-2 and Entrance

B4128 Test 7 - Response of Smoke Detectors in Living Room

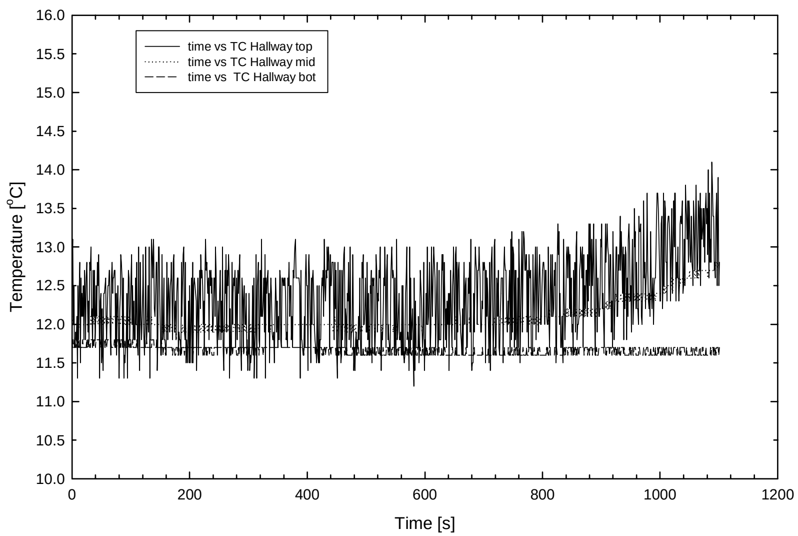
Figure 24. Profiles of CO, optical density (at Detectors 6–8, 14–16, 26–28) and detector response during Test 7



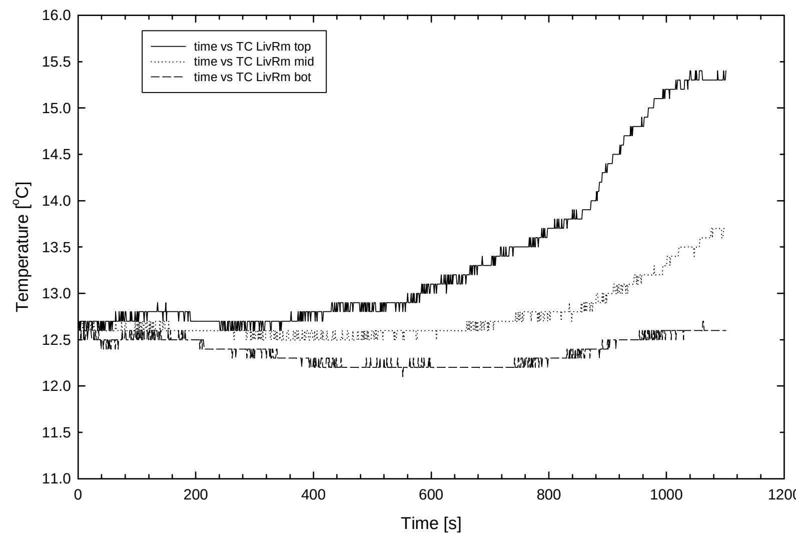
B4128 Test 8 - Target Thermocouples



B4128 Test 8 - Thermocouple Tree in Main Bedroom-1

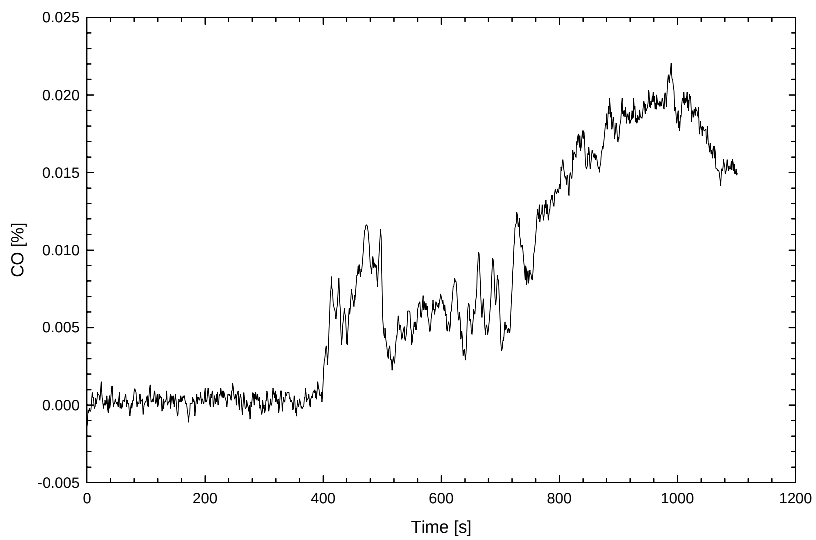


B4128 Test 8 - Thermocouple Tree in Hallway

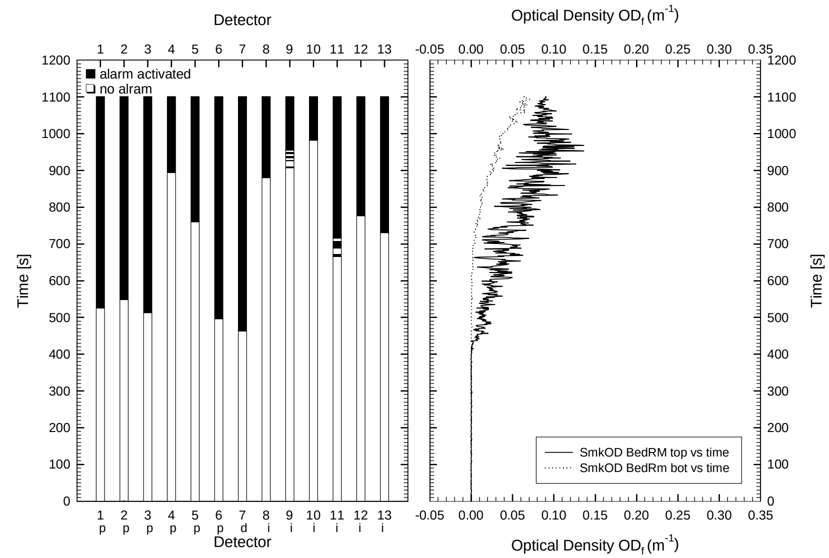


B4128 Test 8 - Thermocouple Tree in Living Room

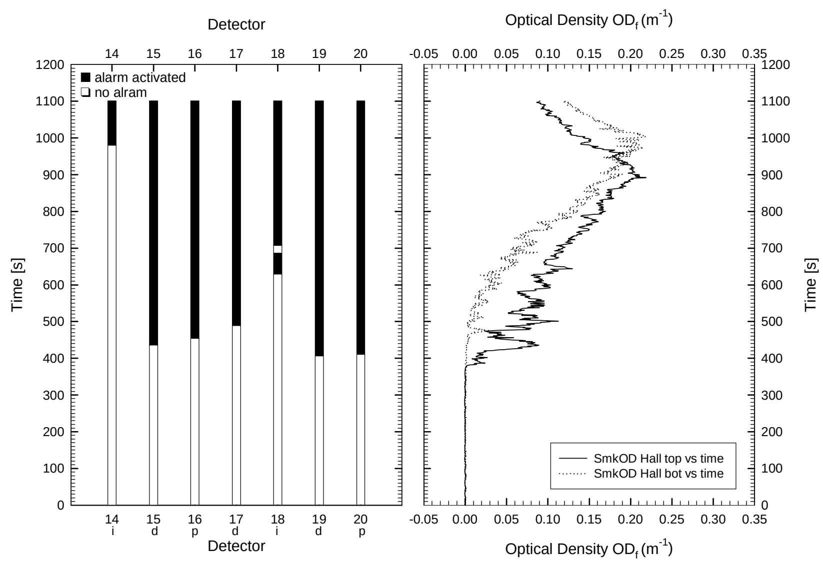
Figure 25. Temperatures at fire source and on TC trees in bedroom, corridor and living room during Test 8



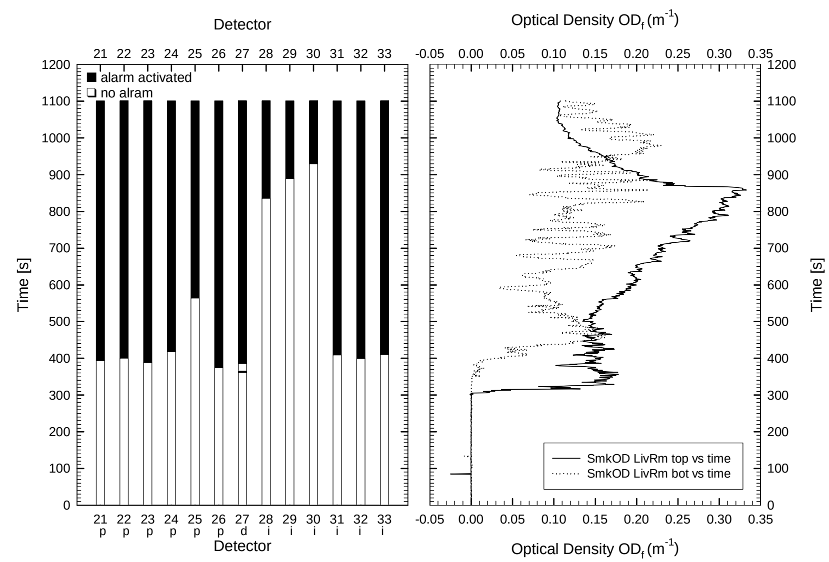
B4128 Test 8 - Carbon Moxide



B4128 Test 8 - Response of Smoke Detectors in Bedroom-1

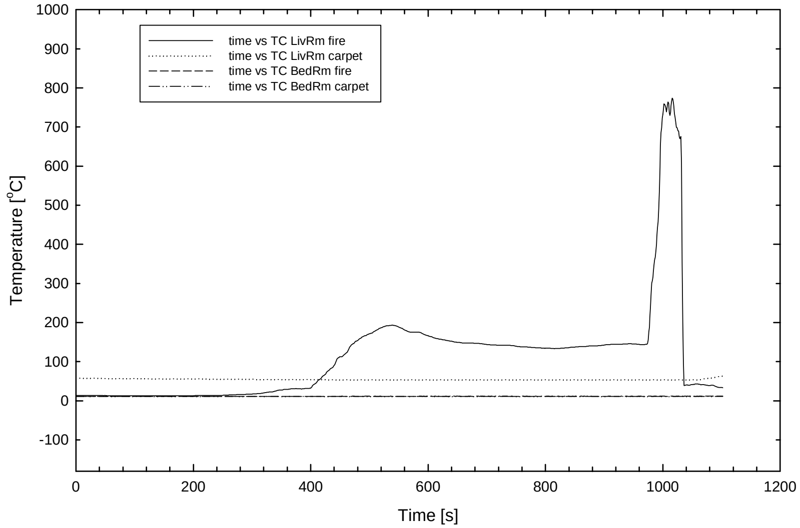


B4128 Test 8 - Response of Smoke Detectors in Hallway, Bedroom-2 and Entrance

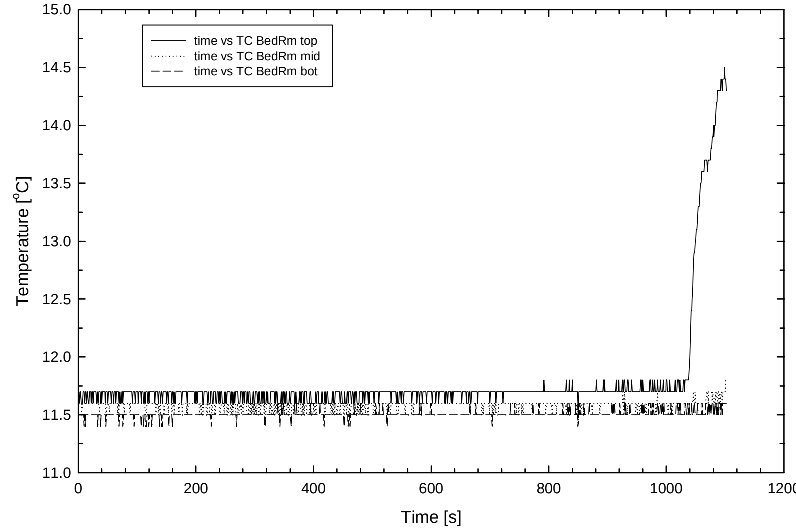


B4128 Test 8 - Response of Smoke Detectors in Living Room

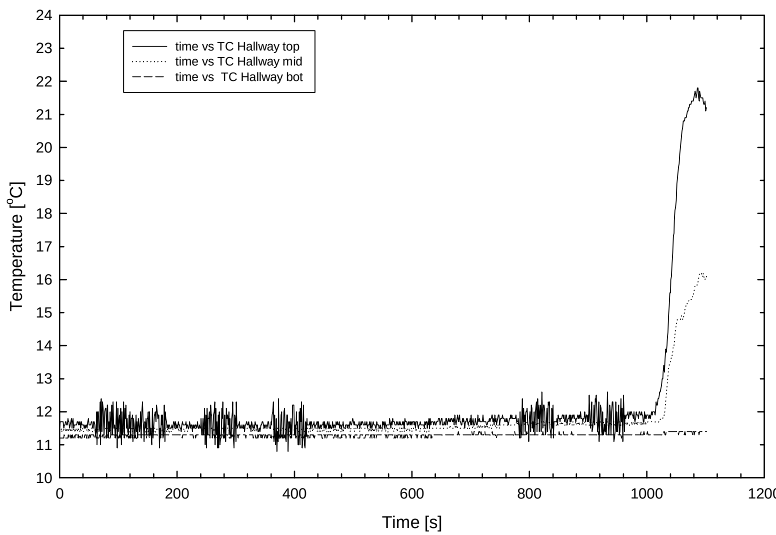
Figure 26. Profiles of CO, optical density (at Detectors 6–8, 14–16, 26–28) and detector response during Test 8



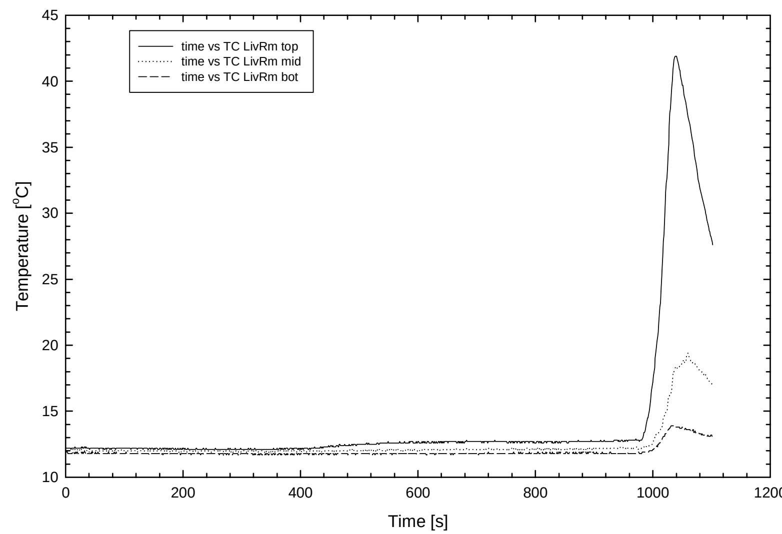
B4128 Test 9 - Target Thermocouples



B4128 Test 9 - Thermocouple Tree in Main Bedroom-1

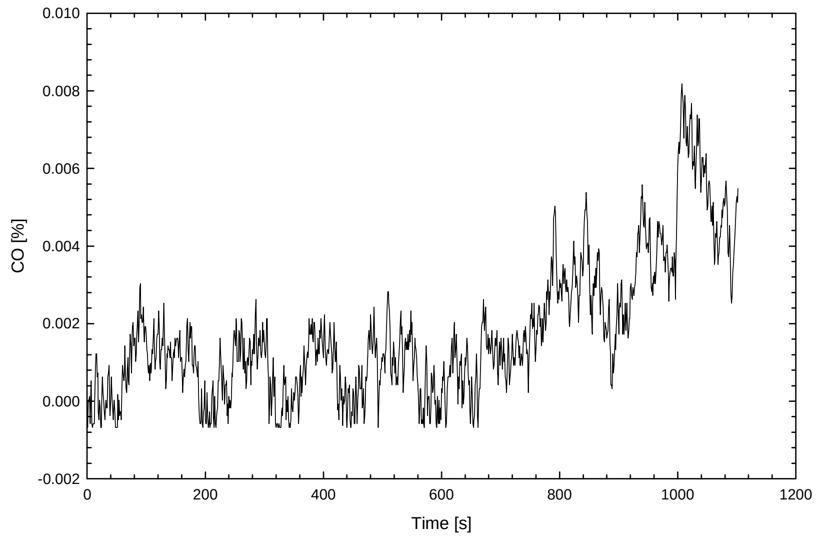


B4128 Test 9 - Thermocouple Tree in Hallway

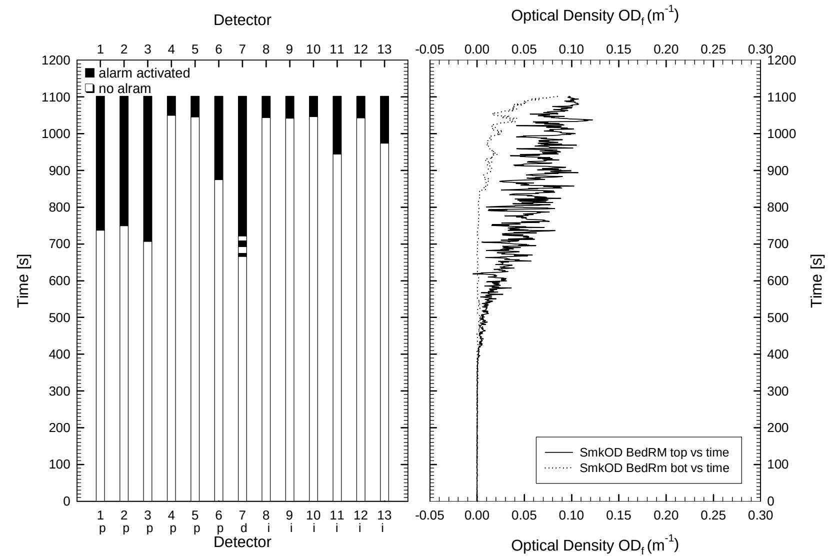


B4128 Test 9 - Thermocouple Tree in Living Room

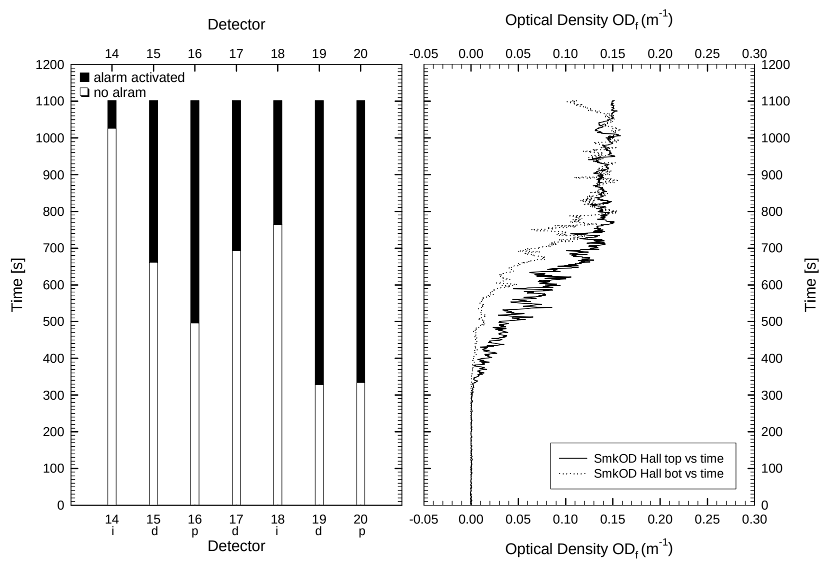
Figure 27. Temperatures at fire source and on TC trees in bedroom, corridor and living room during Test 9



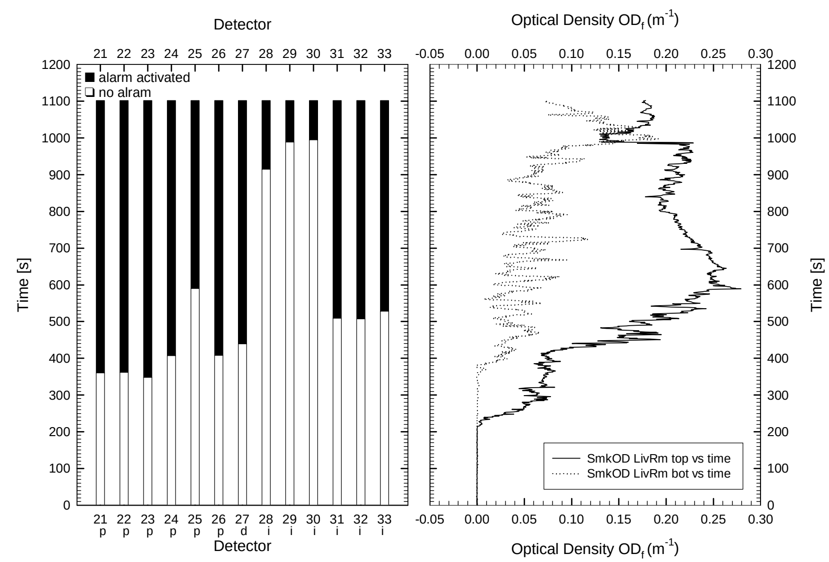
B4128 Test 9 - Carbon Moxide



B4128 Test 9 - Response of Smoke Detectors in Bedroom-1



B4128 Test 9 - Response of Smoke Detectors in Hallway, Bedroom-2 and Entrance



B4128 Test 9 - Response of Smoke Detectors in Living Room

Figure 28. Profiles of CO, optical density (at Detectors 6–8, 14–16, 26–28) and detector response during Test 9

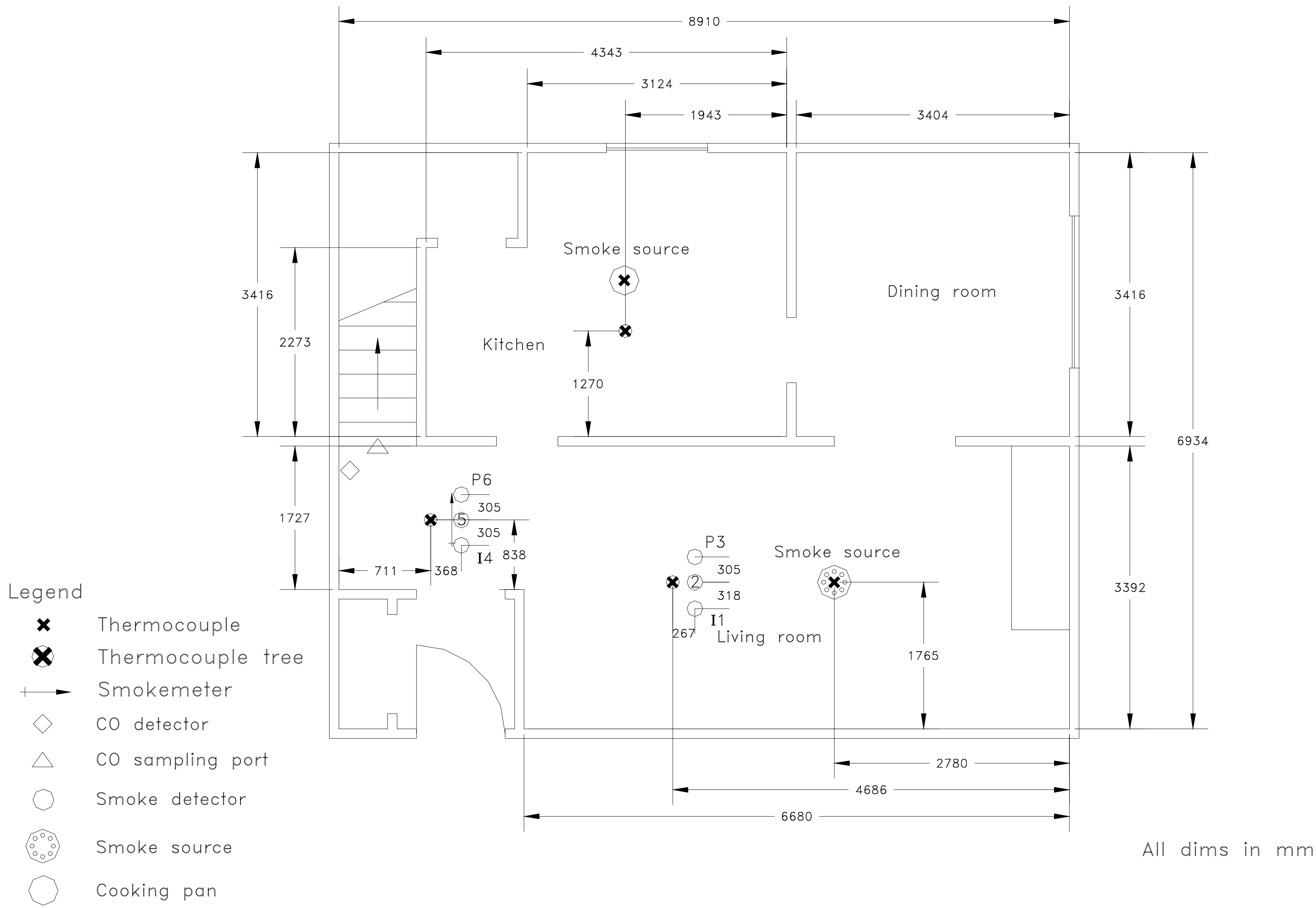


Figure 29. Ground floor plan of House K1-106

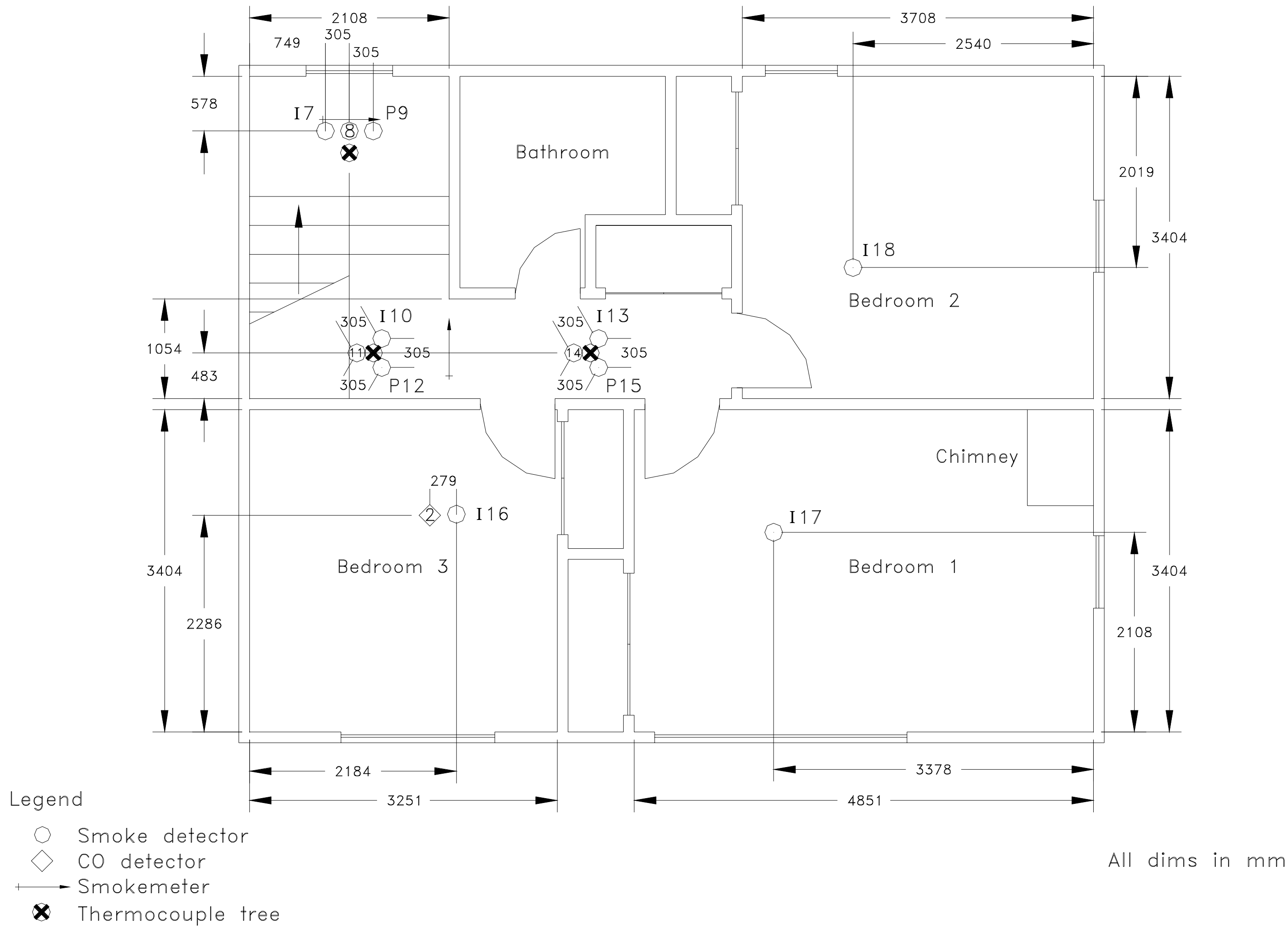
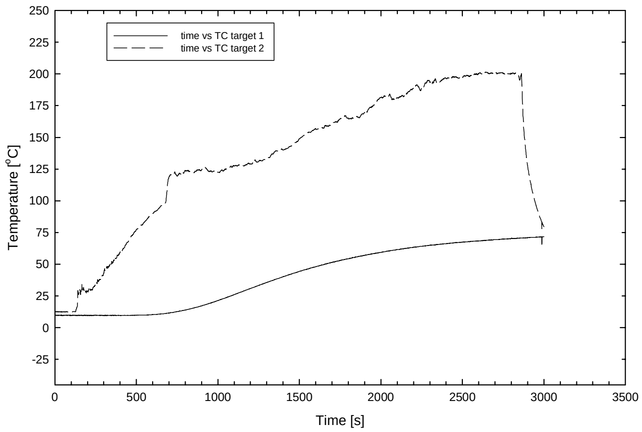


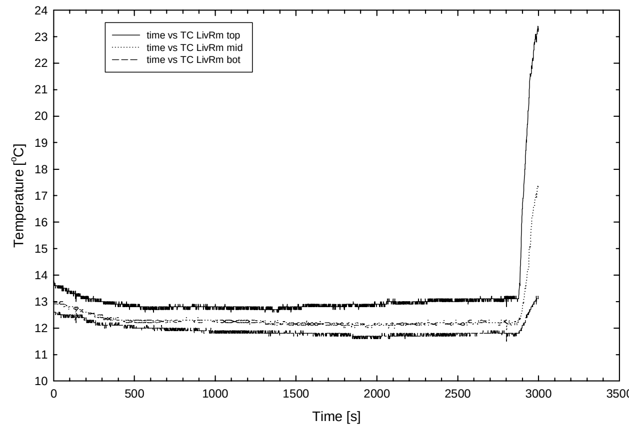
Figure 30. Upstairs floor plan of House K1-106

Living room　　Staircase landing　　2^{nd} floor hallway

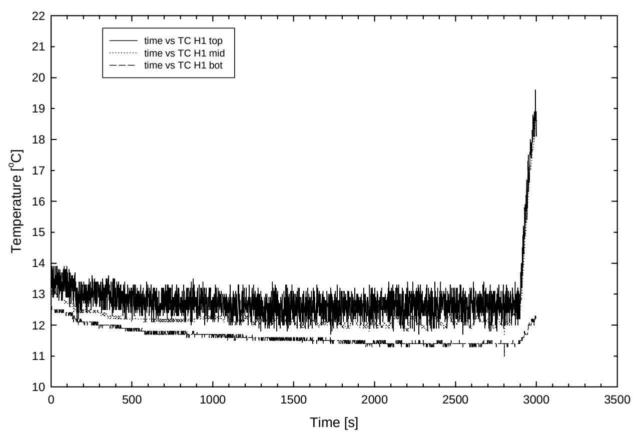
Figure 31. Snapshots of the experiment set-up in House K1-106



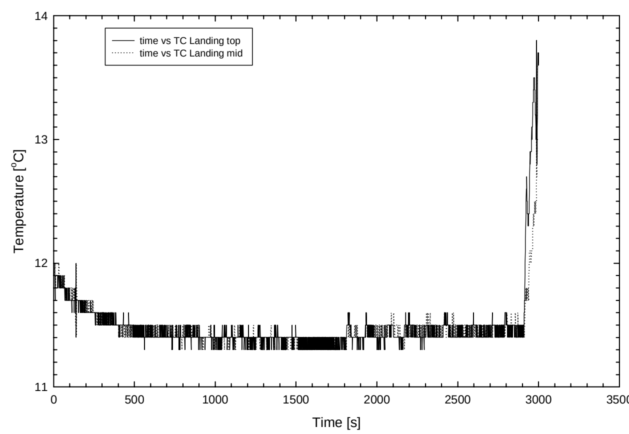
B4128 Test 10 - Target Thermocouples



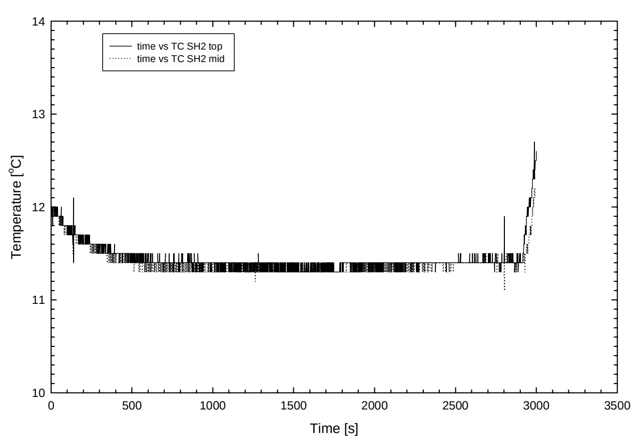
B4128 Test 10 - Thermocouple Tree in Living Room



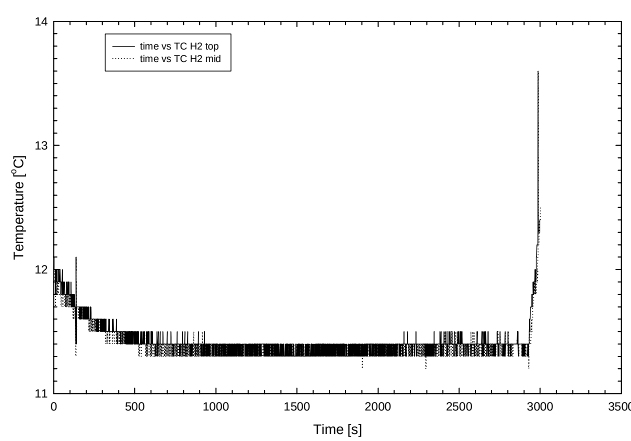
B4128 Test 10 - Thermocouple Tree in Front of Ground-Floor Stairway



B4128 Test 10 - Thermocouple Tree in Stairway Landing

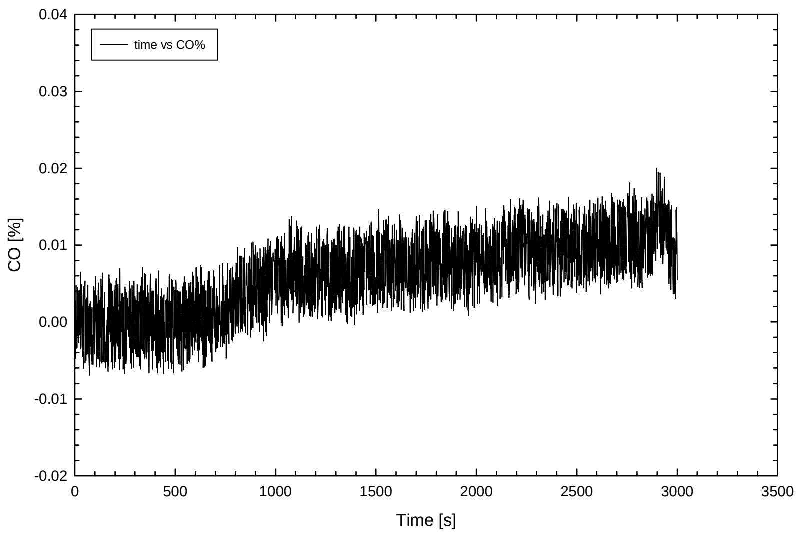


B4128 Test 10 - Thermocouple Tree in Front of 2nd Floor Stairway

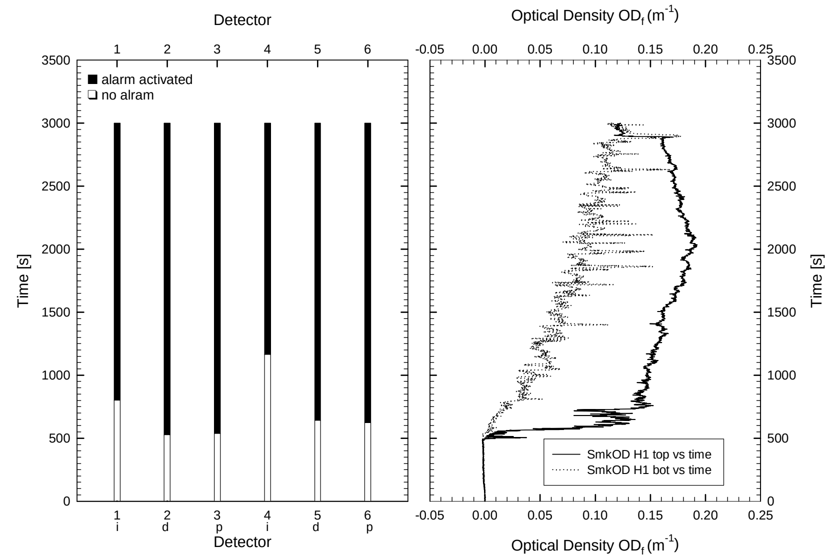


B4128 Test 10 - Thermocouple Tree in 2nd Floor Hallway

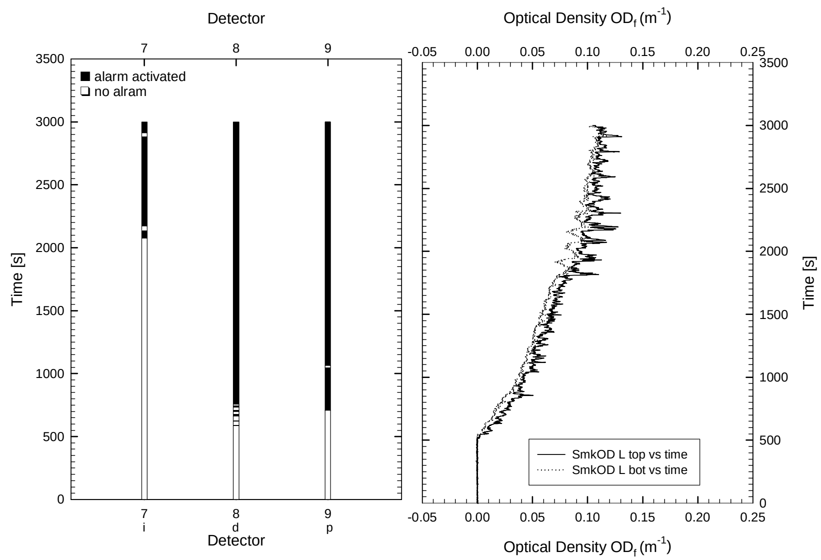
Figure 32. Temperatures at fire source and on TC trees in living room, staircase and 2nd floor corridor during Test 10



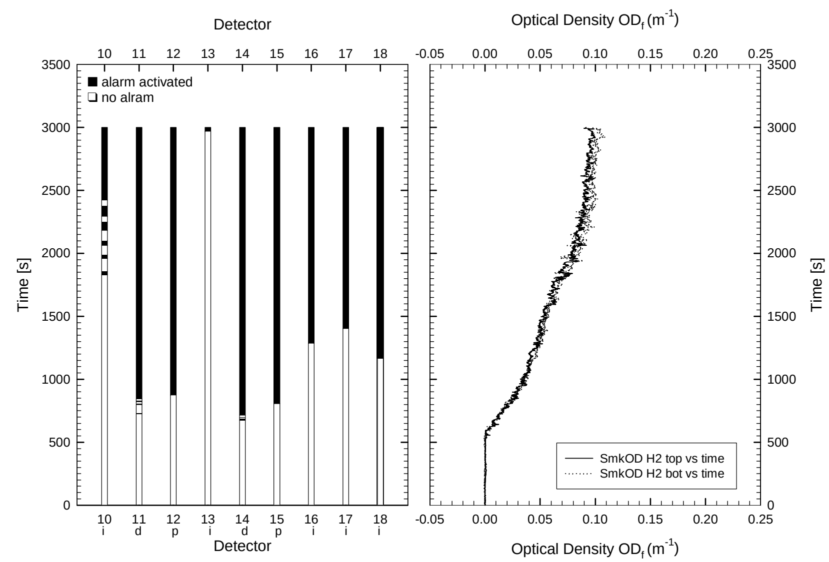
B4128 Test 10 - Carbon Moxide



B4128 Test 10 - Response of Smoke Detectors in Living Room

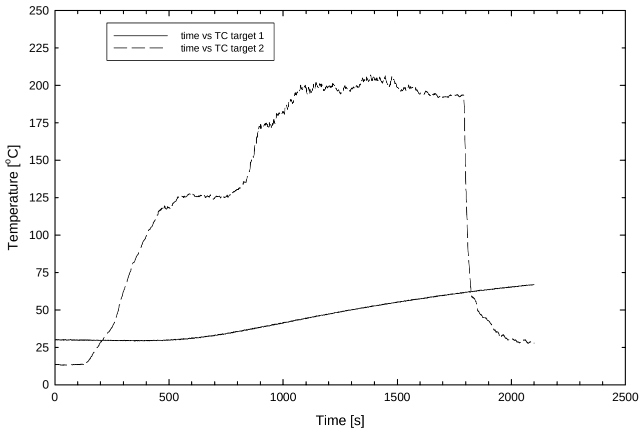


B4128 Test 10 - Response of Smoke Detectors in Stairway Landing

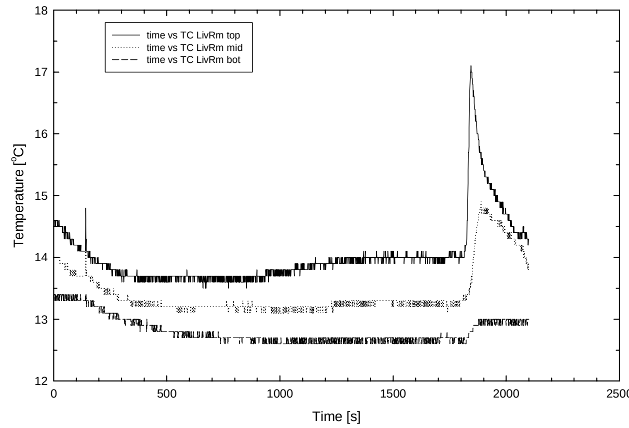


B4128 Test 10 - Response of Smoke Detectors on 2nd Floor

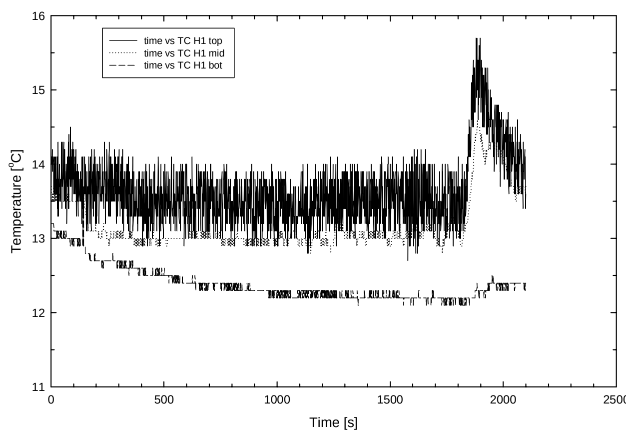
Figure 33. Profiles of CO, optical density (at Detectors 4–6, 7–9 and 10–12) and detector response during Test 10



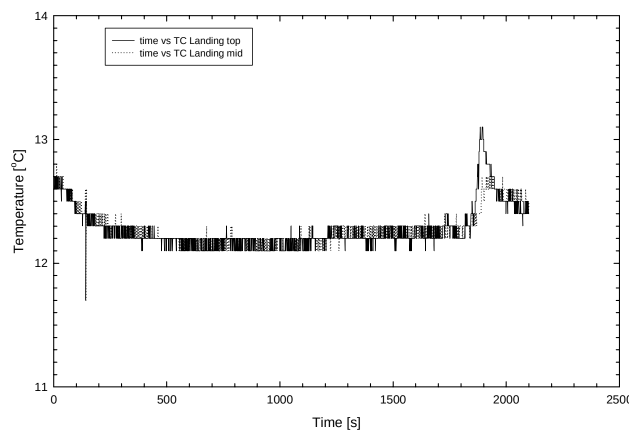
B4128 Test 11 - Target Thermocouples



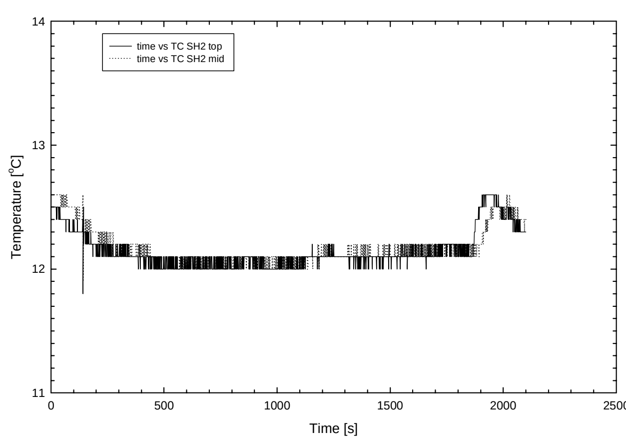
B4128 Test 11 - Thermocouple Tree in Living Room



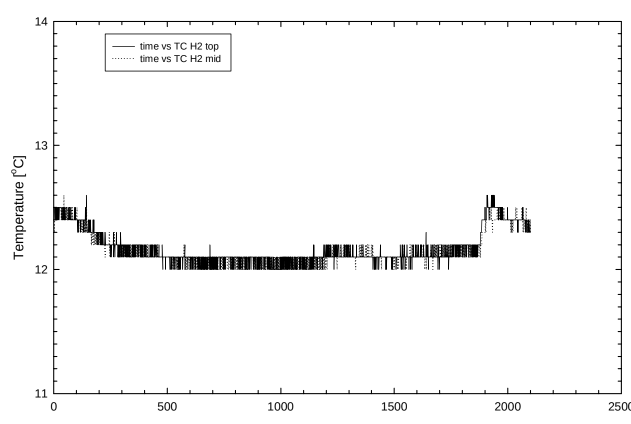
B4128 Test 11 - Thermocouple Tree in Front of Ground-Floor Stairway



B4128 Test 11 - Thermocouple Tree in Stairway Landing



B4128 Test 11 - Thermocouple Tree in Front of 2nd Floor Stairway



B4128 Test 11 - Thermocouple Tree in 2nd Floor Hallway

Figure 34. Temperatures at fire source and on TC trees in living room, staircase and 2nd floor corridor during Test 11

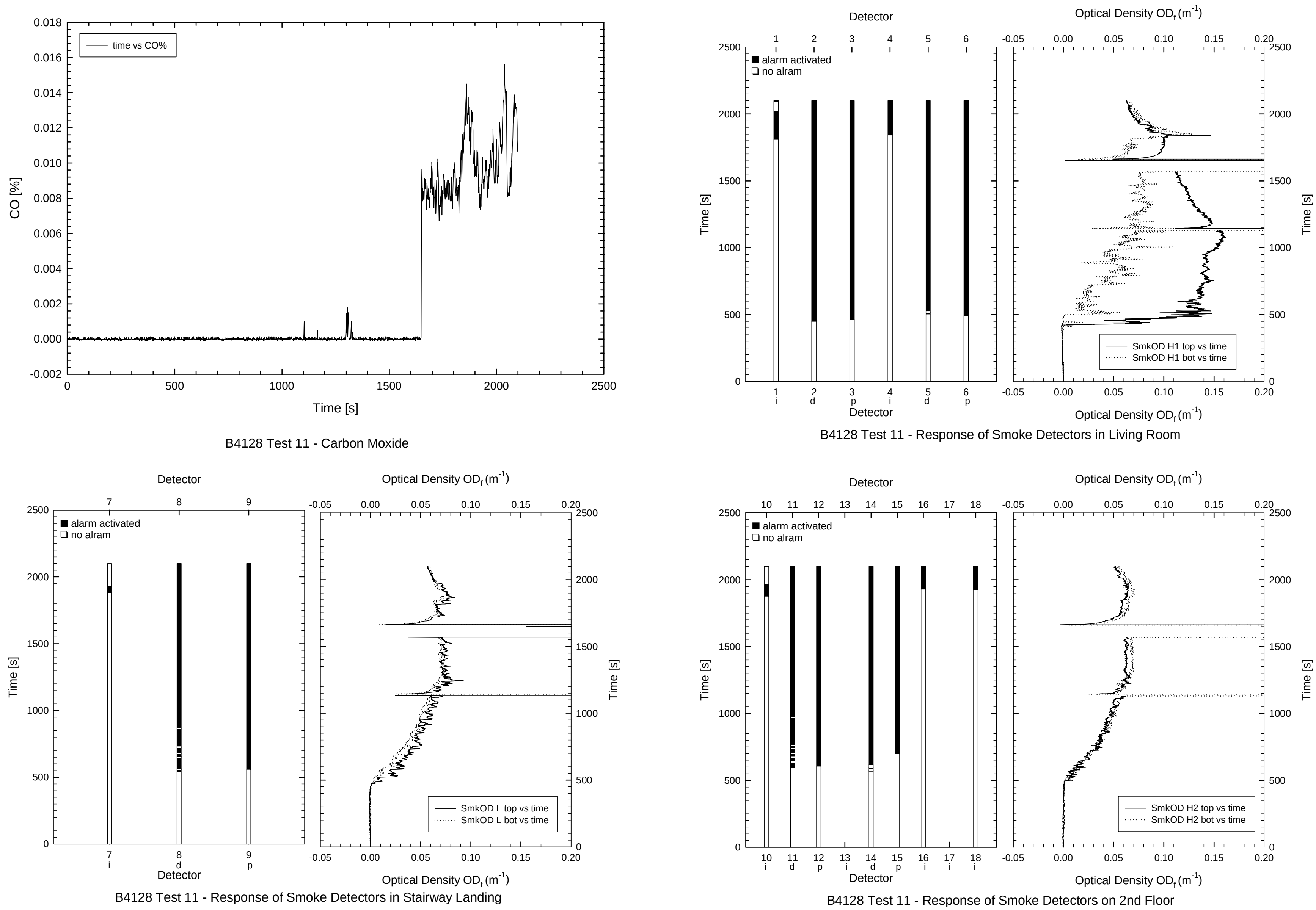
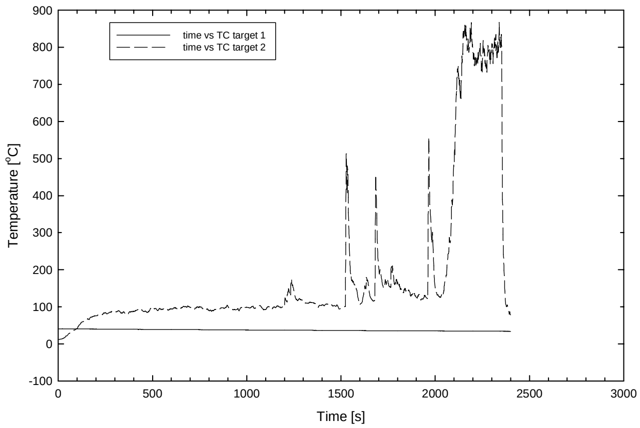
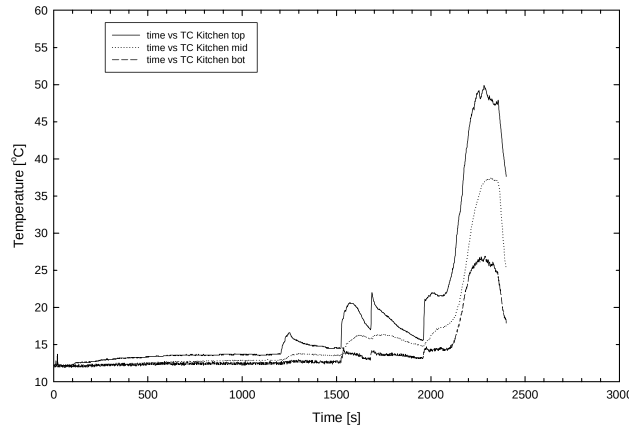


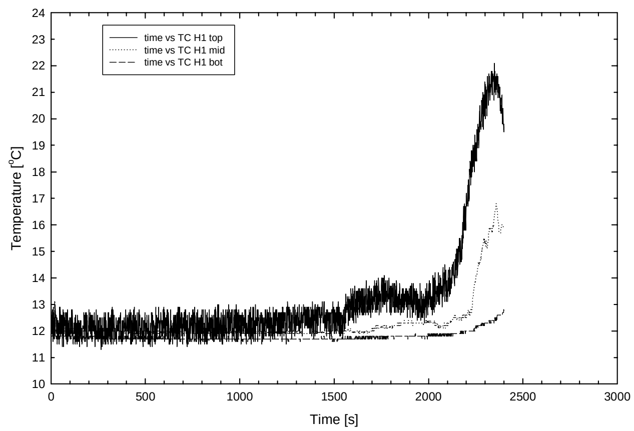
Figure 35. Profiles of CO, optical density (at Detectors 4–6, 7–9 and 10–12) and detector response during Test 11



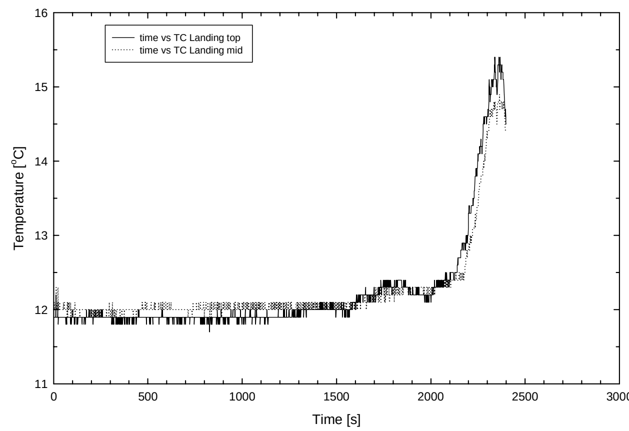
B4128 Test 12 - Target Thermocouples



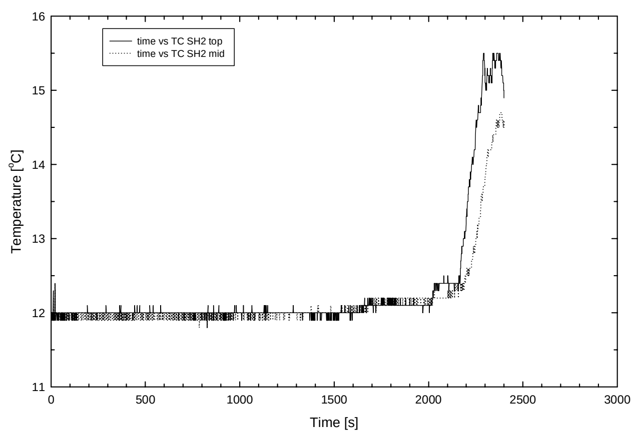
B4128 Test 12 - Thermocouple Tree in Kitchen



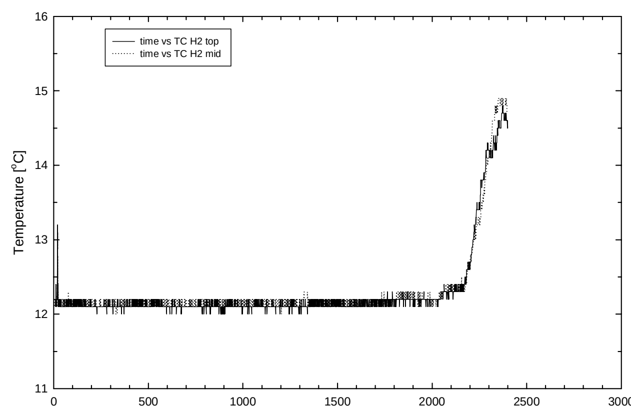
B4128 Test 12 - Thermocouple Tree in Front of Ground-Floor Stairway



B4128 Test 12 - Thermocouple Tree in Stairway Landing

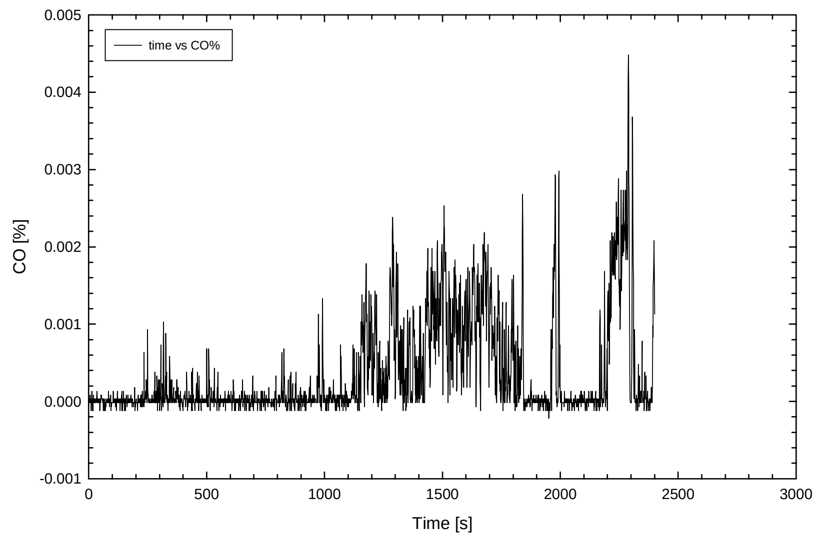


B4128 Test 12 - Thermocouple Tree in Front of 2nd Floor Stairway

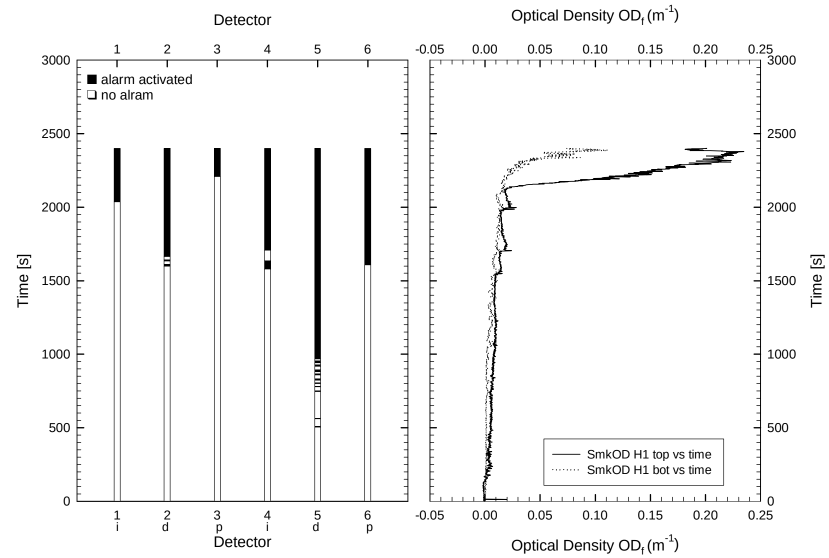


B4128 Test 12 - Thermocouple Tree in 2nd Floor Hallway

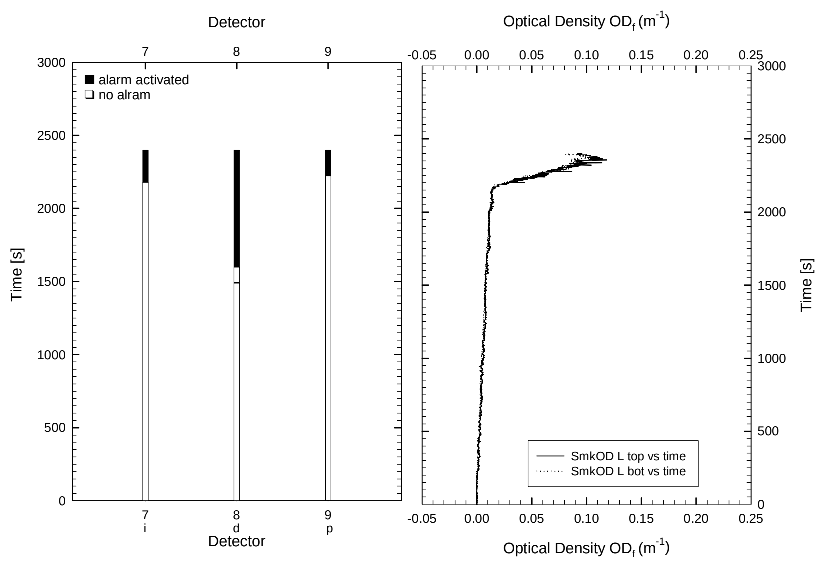
Figure 36. Temperatures at fire source and on TC trees in kitchen, staircase and 2nd floor corridor during Test 12



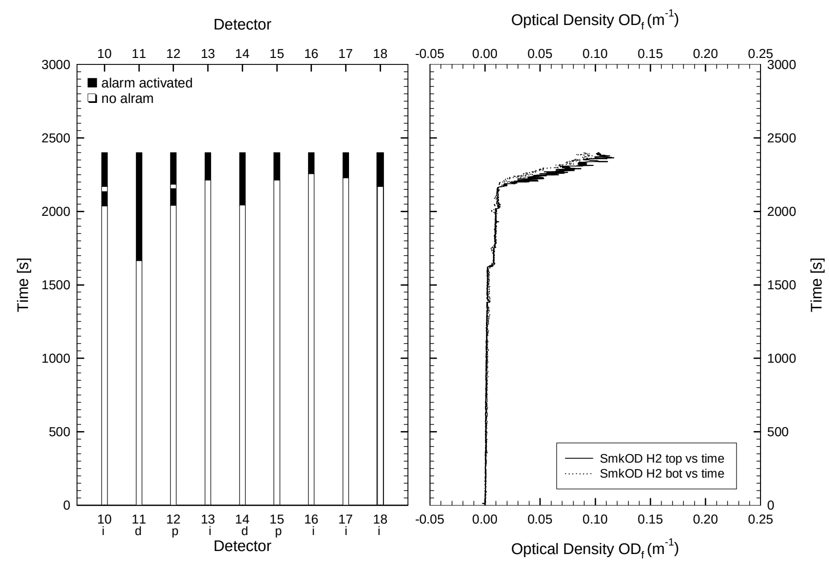
B4128 Test 12 - Carbon Moxide



B4128 Test 12 - Response of Smoke Detectors in Living Room

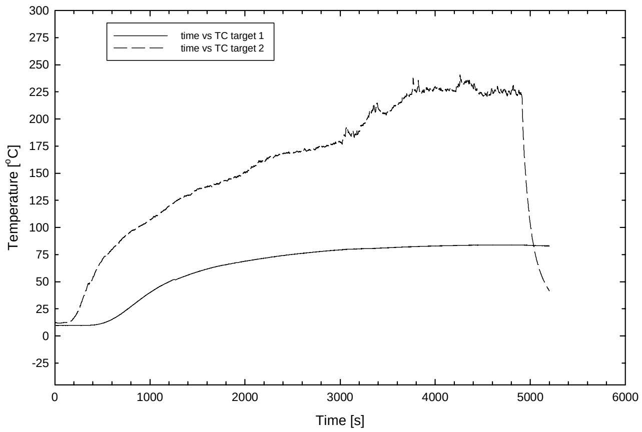


B4128 Test 12 - Response of Smoke Detectors in Stairway Landing

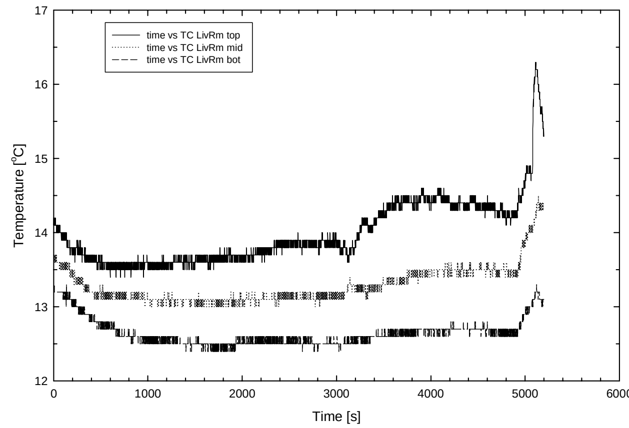


B4128 Test 12 - Response of Smoke Detectors on 2nd Floor

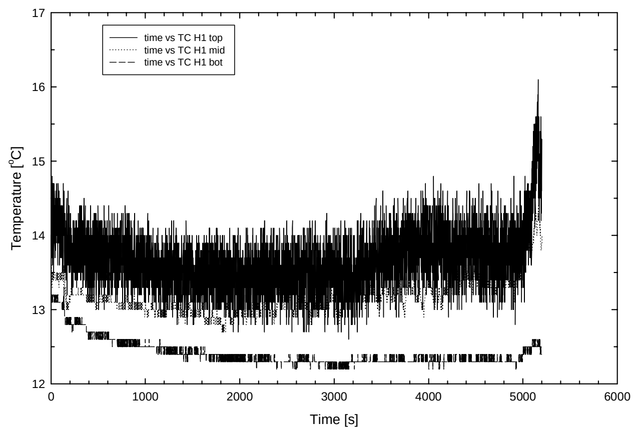
Figure 37. Profiles of CO, optical density (at Detectors 4–6, 7–9 and 10–12) and detector response during Test 12



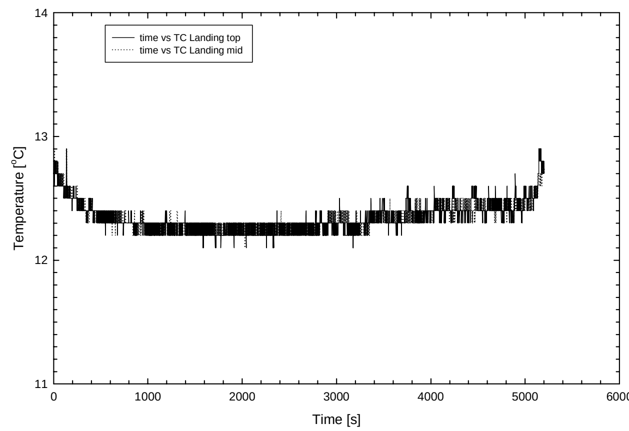
B4128 Test 13 - Target Thermocouples



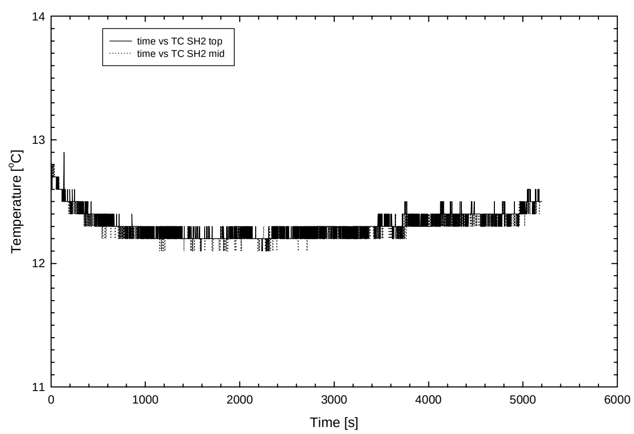
B4128 Test 13 - Thermocouple Tree in Living Room



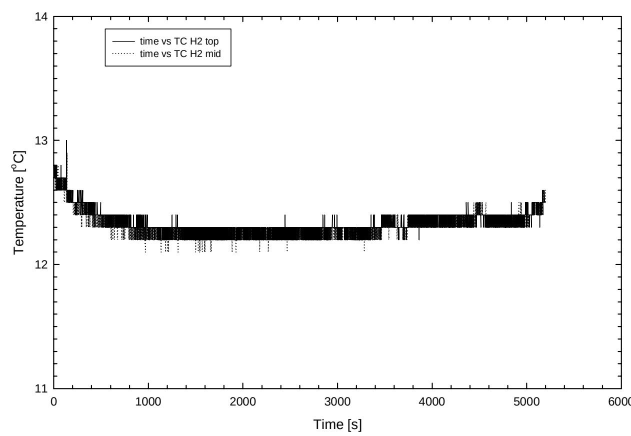
B4128 Test 13 - Thermocouple Tree in Front of Ground-Floor Stairway



B4128 Test 13 - Thermocouple Tree in Stairway Landing



B4128 Test 13 - Thermocouple Tree in Front of 2nd Floor Stairway



B4128 Test 13 - Thermocouple Tree in 2nd Floor Hallway

Figure 38. Temperatures at fire source and on TC trees in living room, staircase and 2nd floor corridor during Test 13

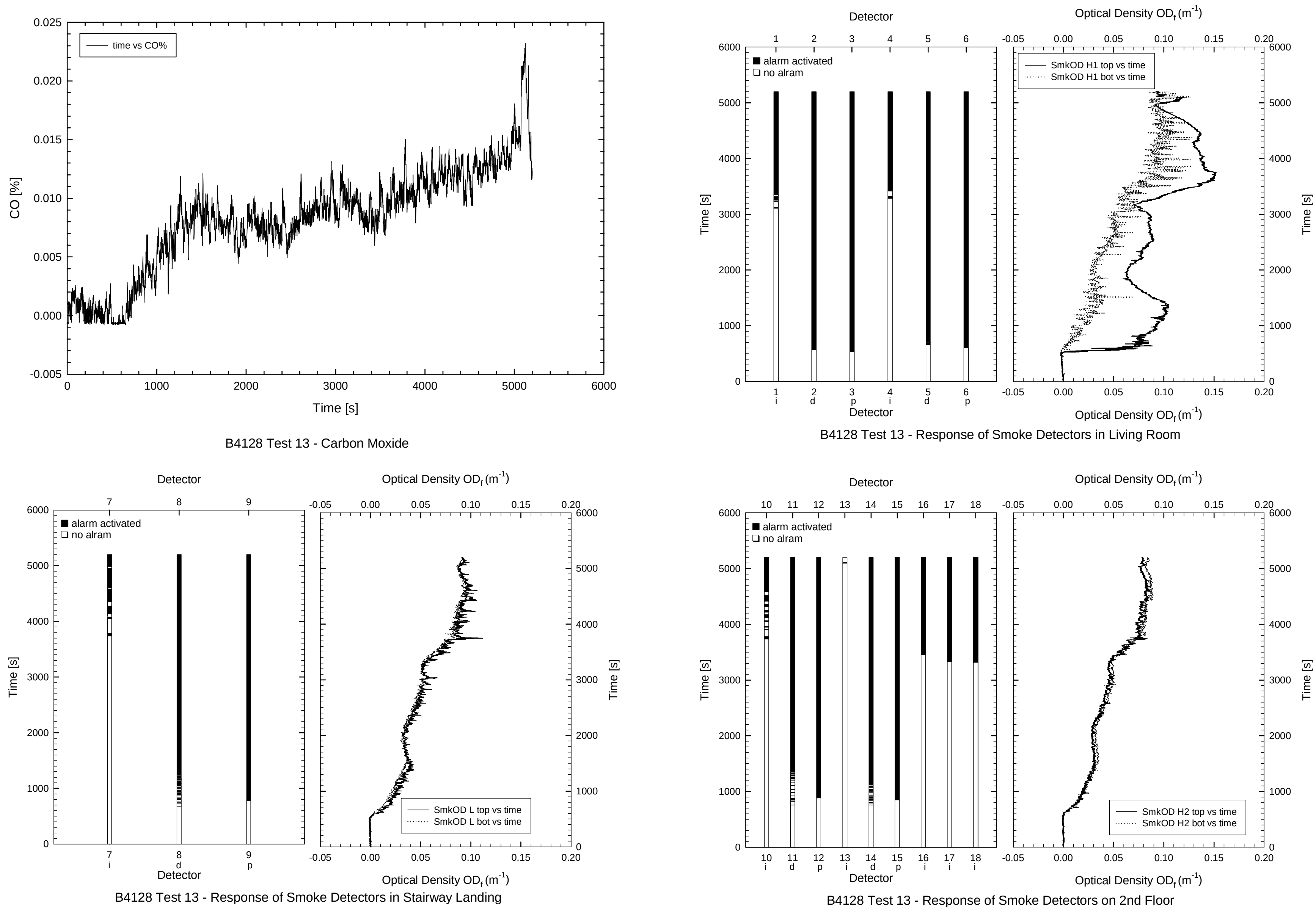
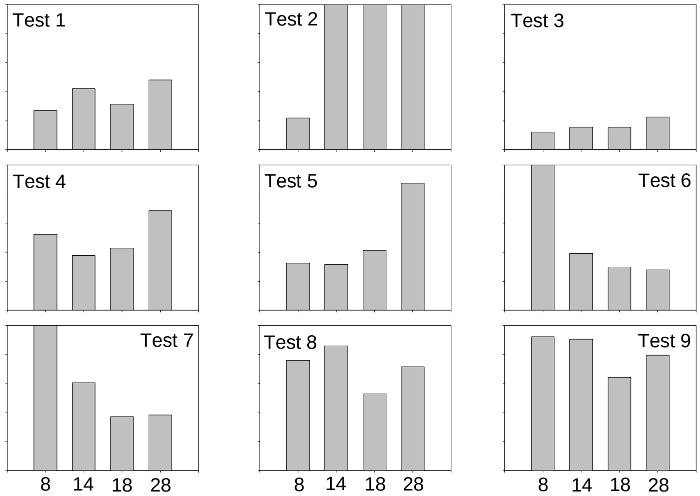
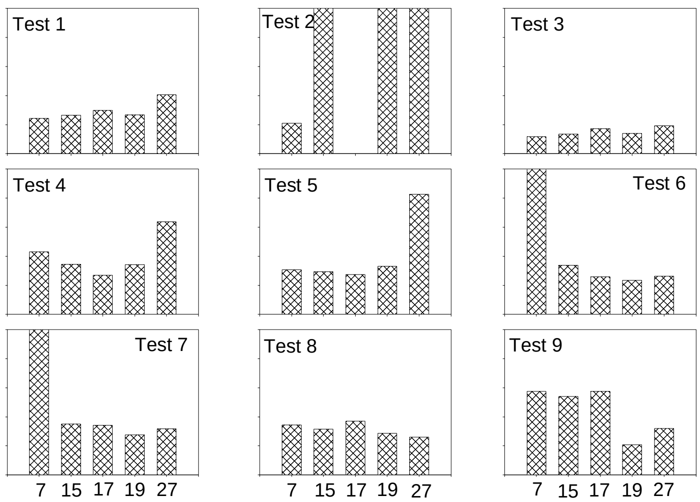


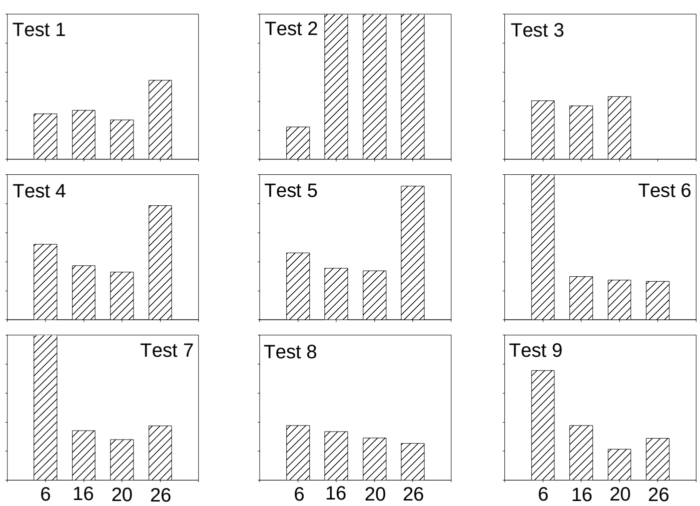
Figure 39. Profiles of CO, optical density (at Detectors 4–6, 7–9 and 10–12) and detector response during Test 13



B513 data on ionization detectors (# 8, 14, 18, 28)

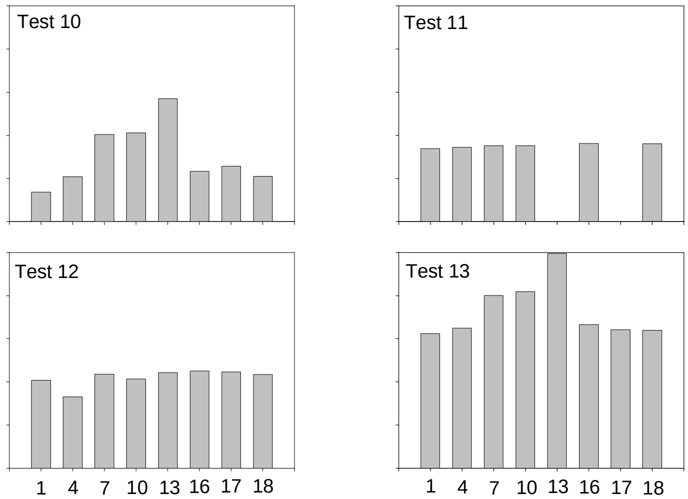


B513 data on dual detectors (# 7, 15, 17, 19, 27)

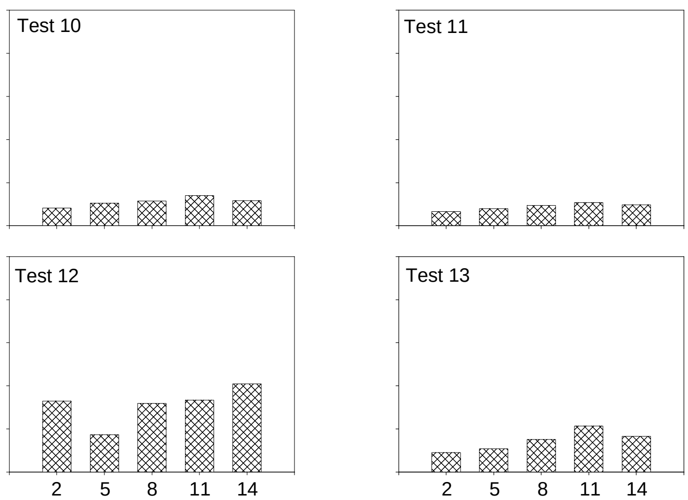


B513 data on photoelectric detectors (# 6, 16, 20, 26)

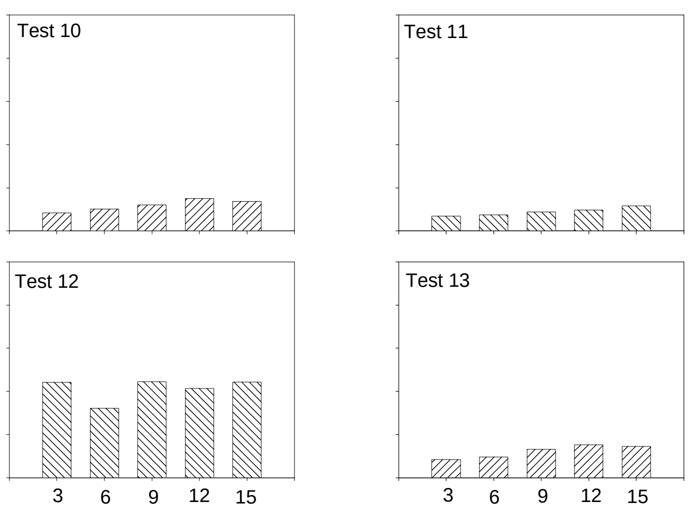
Figure 40. Relative activation times of smoke detectors in Tests 1-9 (Bedroom-1 door closed initially and opened near the end of Tests 2, 6 and 7)



K106 data on ionization detectors (# 1, 4, 7, 10, 13, 16, 17, 18)



K106 data on dual detectors (# 2, 5, 8, 11, 14)



K106 data on photoelectric detectors (# 3, 6, 9, 12, 15)

Figure 41. Relative activation times of smoke detectors in Tests 10-11

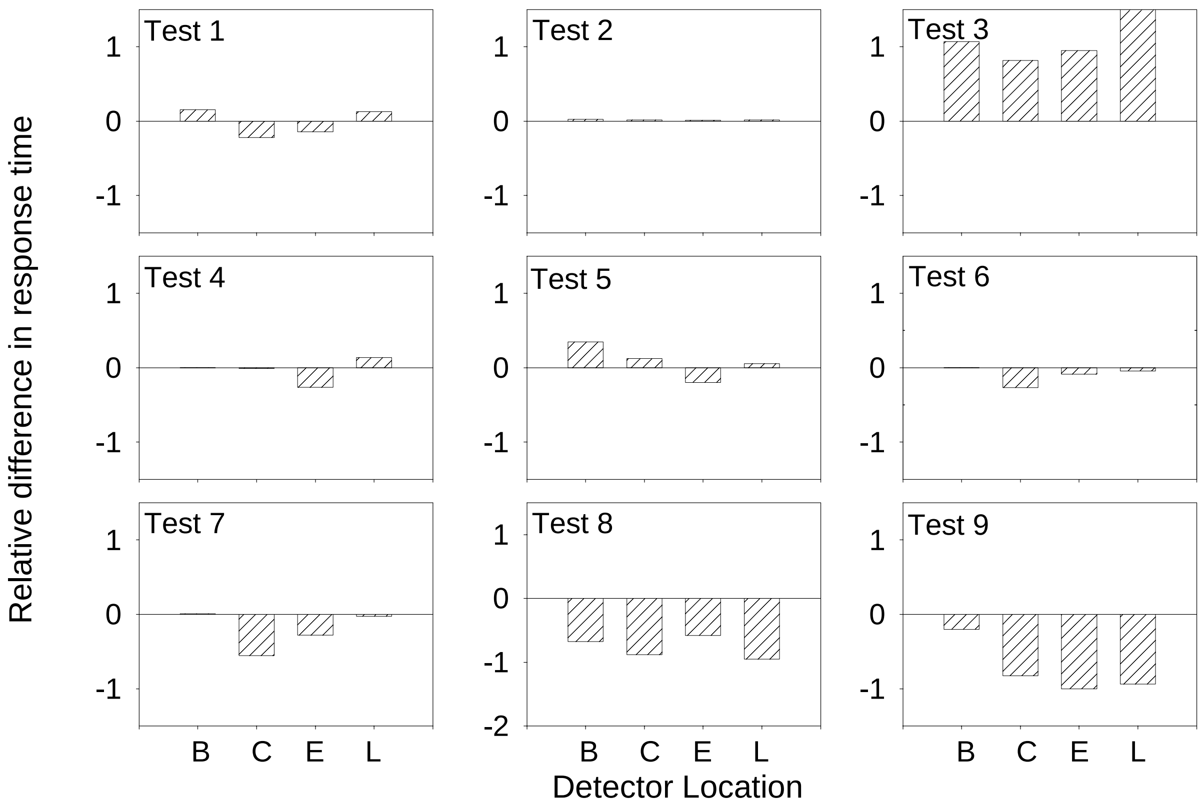


Figure 42. Relative difference in response time between the photoelectric detector and the ionization detector at each given location (B – bedroom P6 v. I8, C – corridor P16 v. I14, E – entrance P20 v. I18, and L – living room P26 v. I28 in House BB-513)

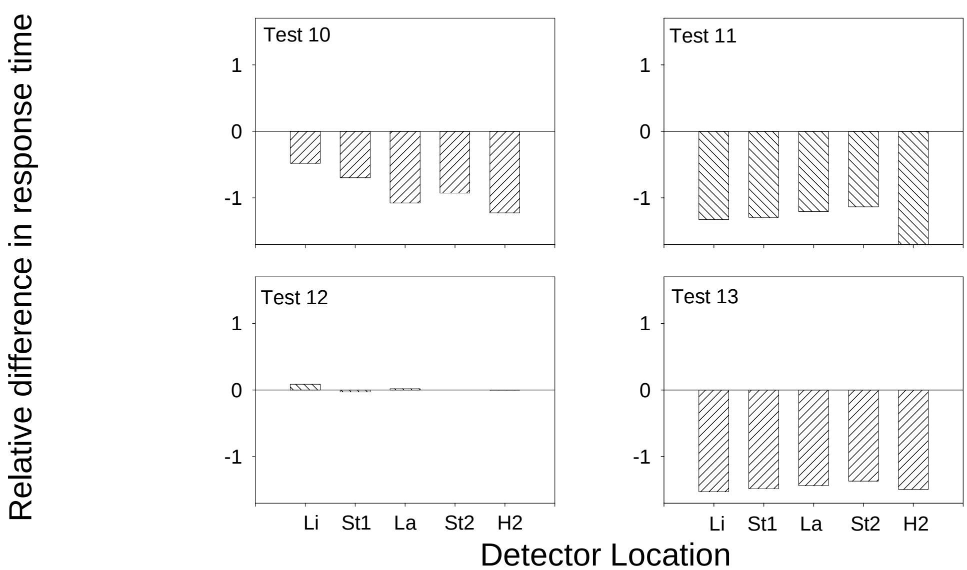


Figure 43. Relative difference in response time between the photoelectric detector and the ionization detector at each given location (Li – living room P3 v. I1, St1 – 1st floor near stair P6 v. I4, La – landing P9 v. I7, St2 – 2nd floor near stair P12 v. I10, and H2 – 2nd floor hallway P15 v. I13 in House K1-106)

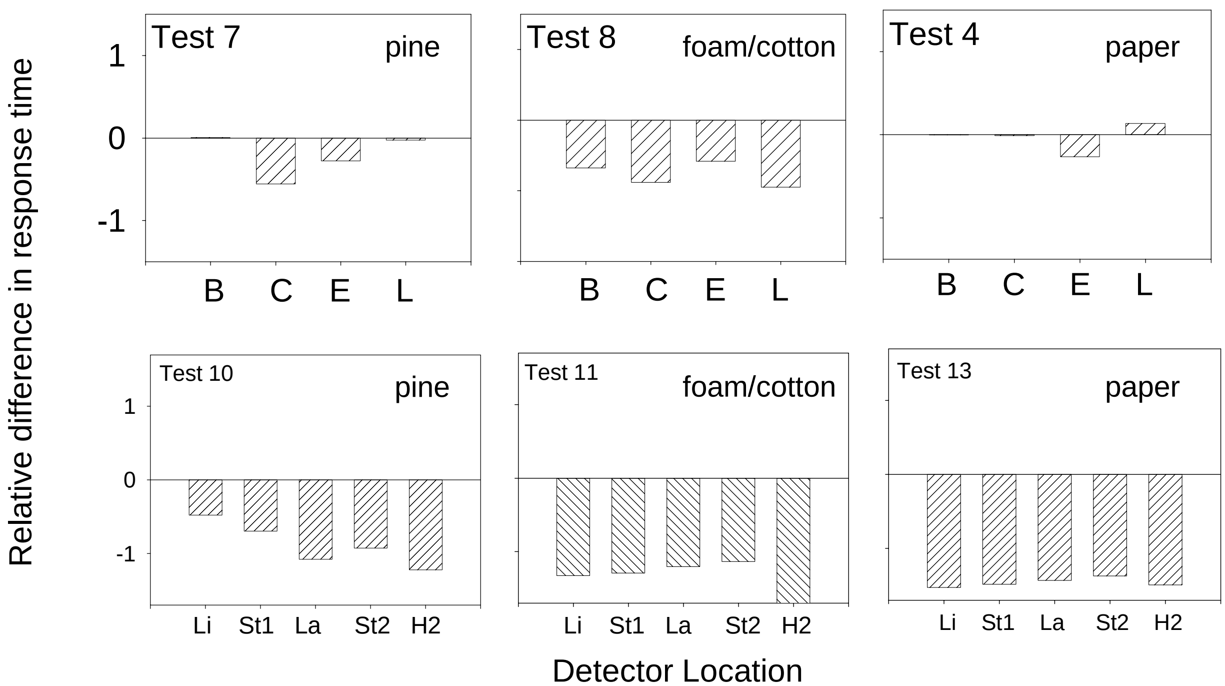


Figure 44. Difference in response time between photoelectric and ionization detectors in 1-storey house BB-513 (B – bedroom P6 v. I8, C – corridor P16 v. I14, E – entrance P20 v. I18, L – living room P26 v. I28) and in 2-storey house K1-106 (Li – living room P3 v. I1, St1 – 1st floor near stair P6 v. I4, La – landing P9 v. I7, St2 – 2nd floor near stair P12 v. I10, H2 – 2nd floor hallway P15 v. I13)

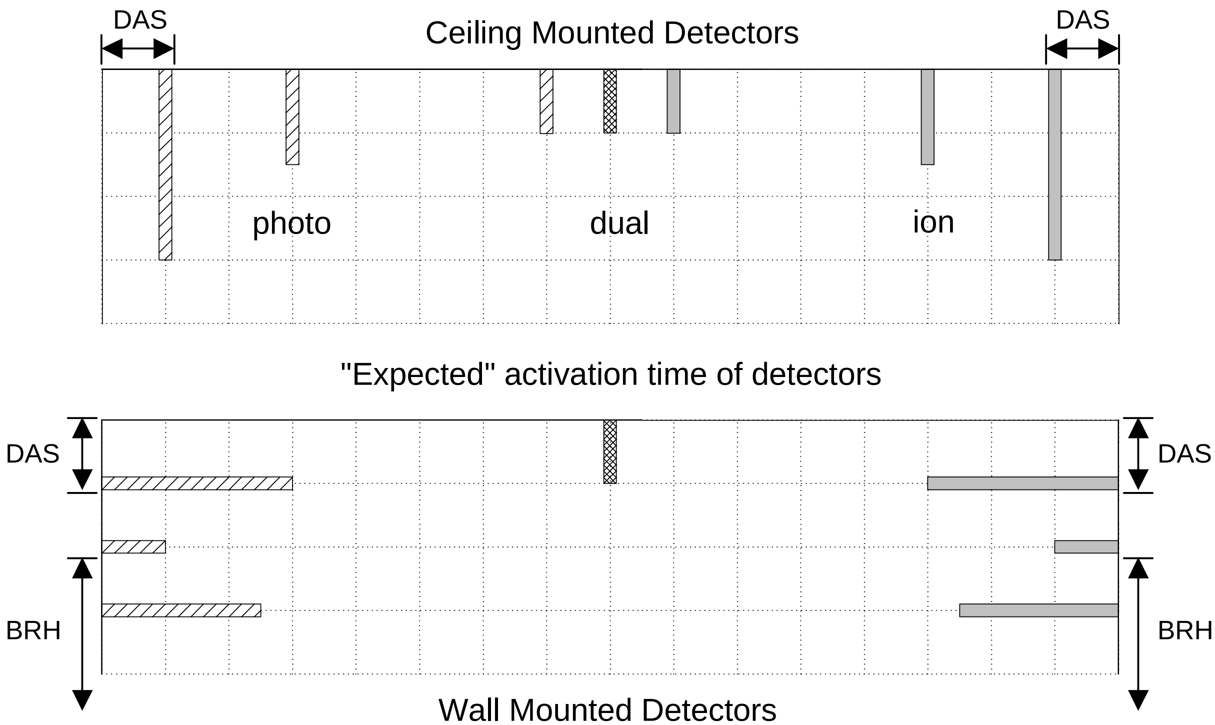


Figure 45. Imaginary response of smoke detectors inside and outside a “dead air space (DAS)" and below recommended heights (BRH)

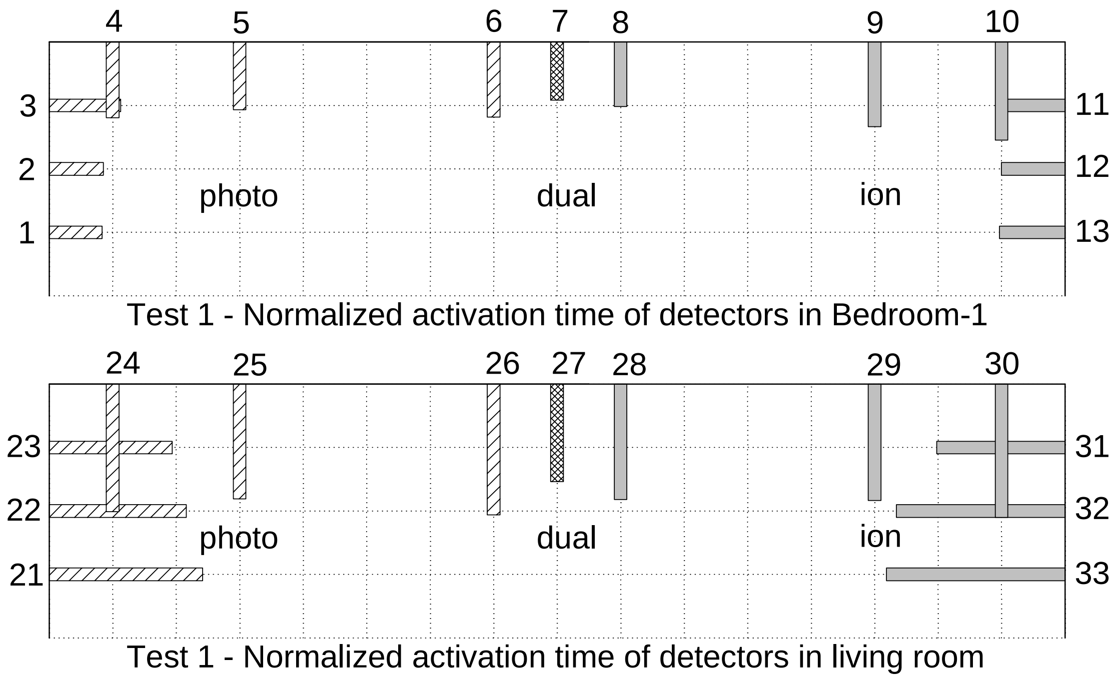


Figure 46. Relative activation times of smoke detectors inside and outside “dead air spaces” and below recommended heights (Test 1)

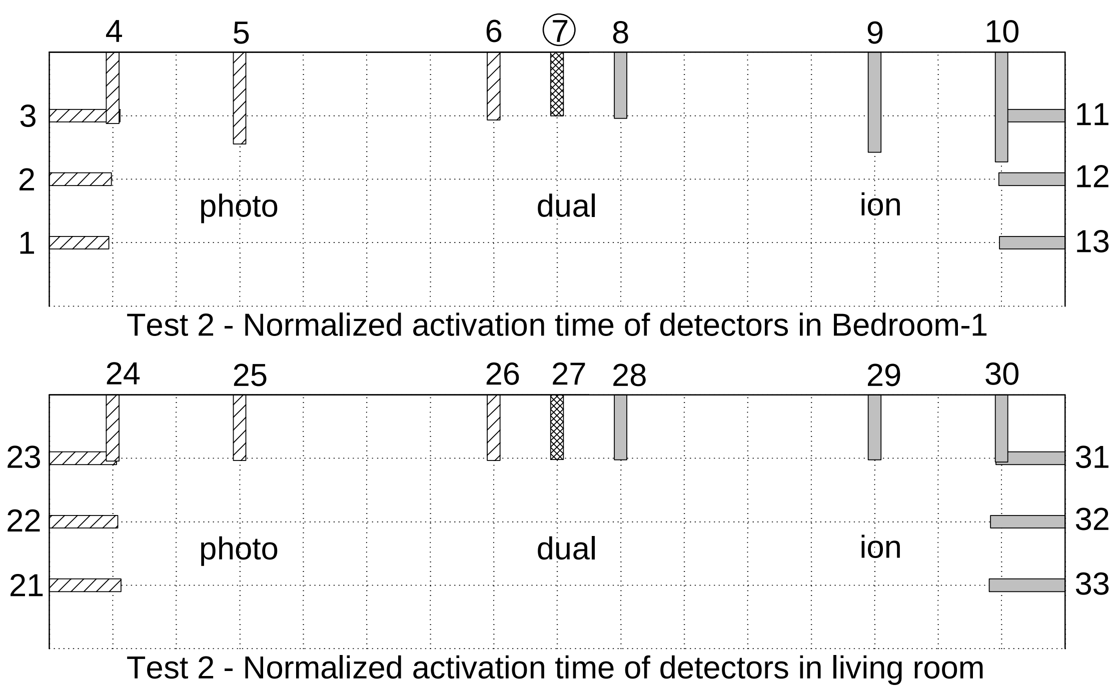


Figure 47. Relative activation times of smoke detectors inside and outside “dead air spaces” and below recommended heights (Test 2)

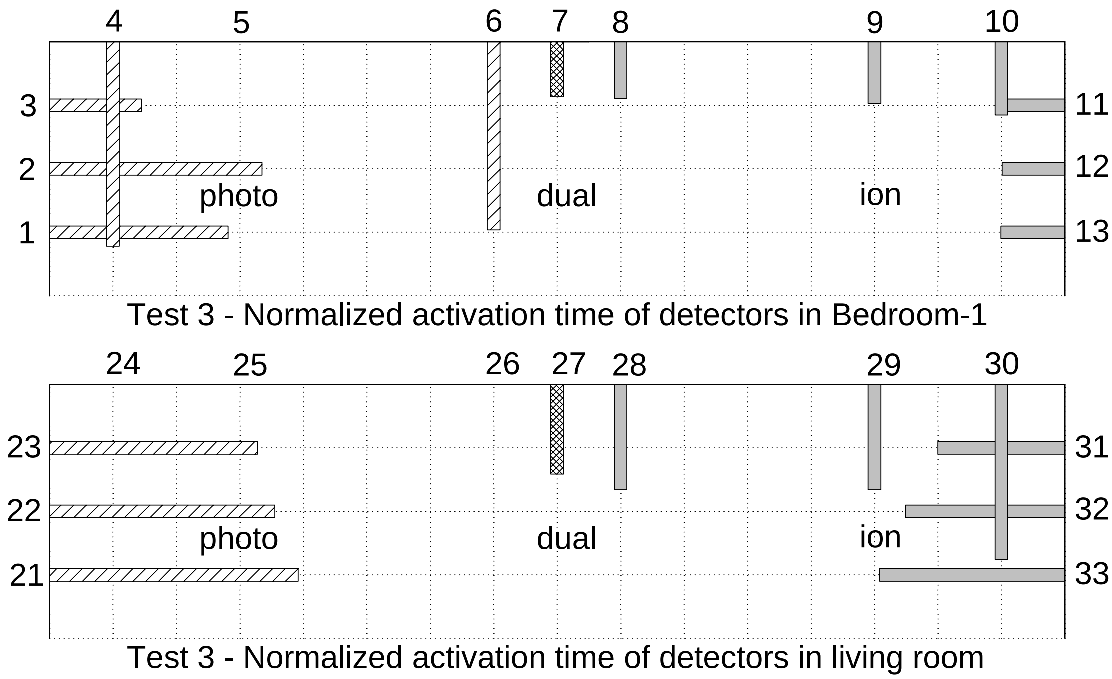


Figure 48. Relative activation times of smoke detectors inside and outside “dead air spaces” and below recommended heights (Test 3)

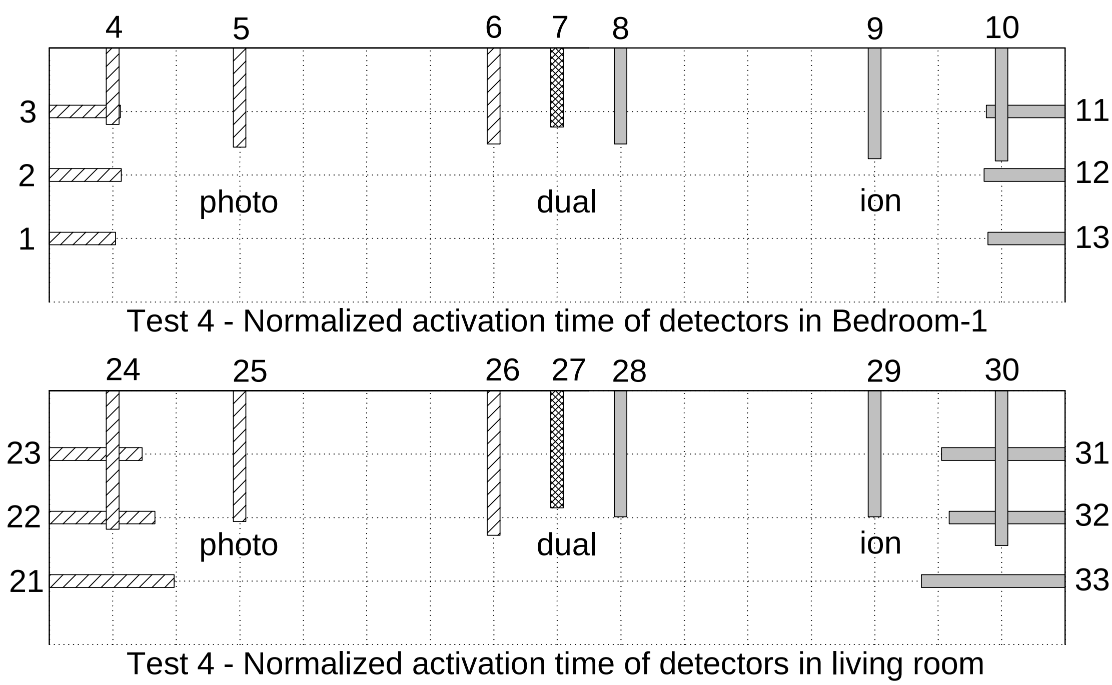


Figure 49. Relative activation times of smoke detectors inside and outside “dead air spaces” and below recommended heights (Test 4)

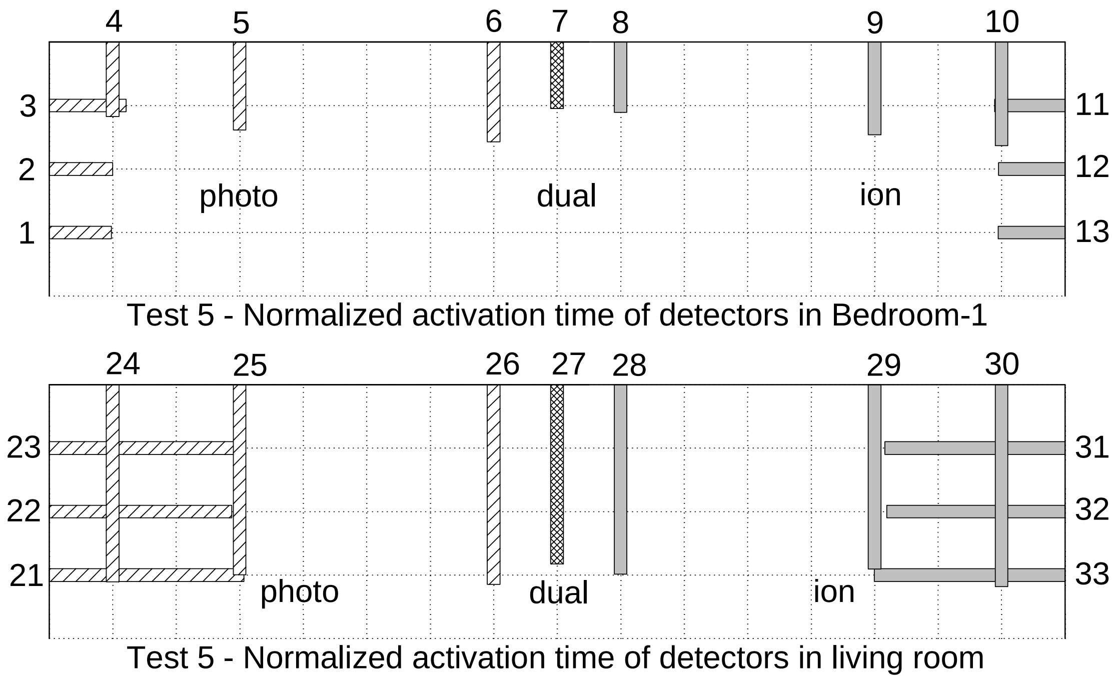


Figure 50. Relative activation times of smoke detectors inside and outside “dead air spaces” and below recommended heights (Test 5)

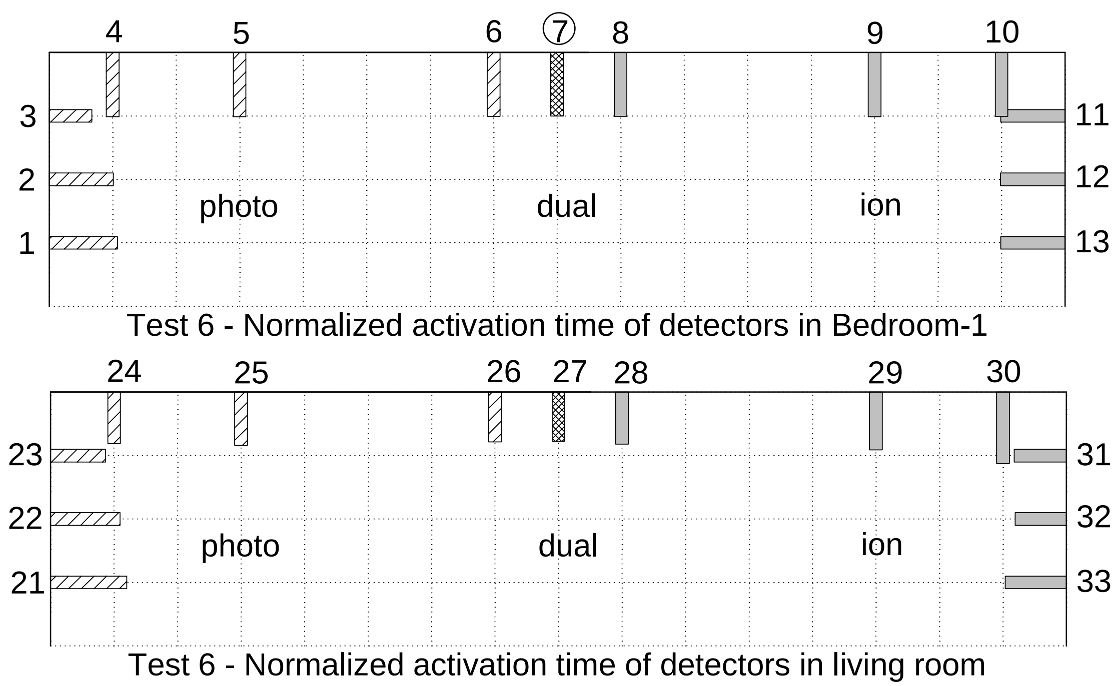
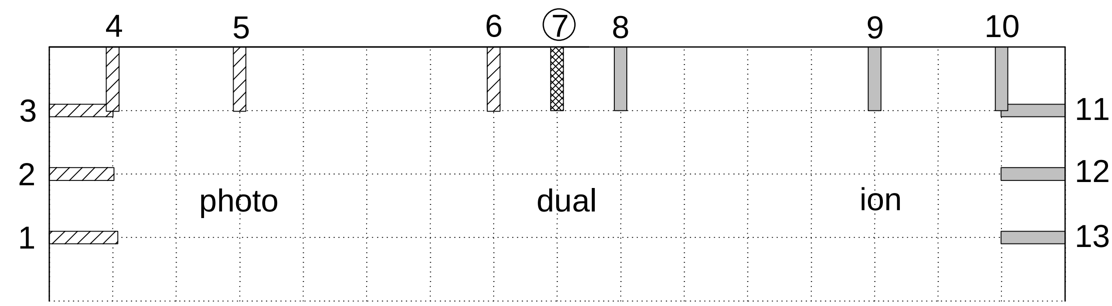
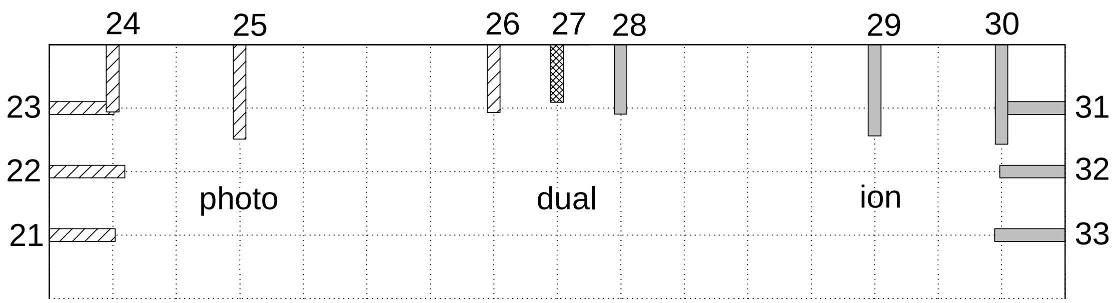


Figure 51. Relative activation times of smoke detectors inside and outside “dead air spaces” and below recommended heights (Test 6)

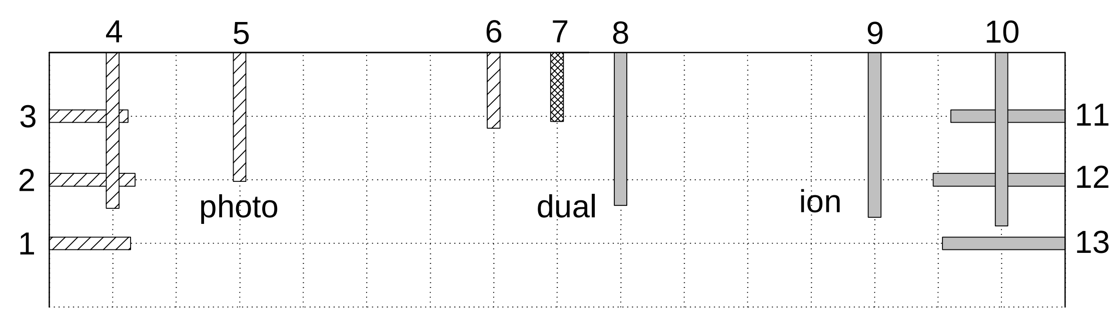


Test 7 - Normalized activation time of detectors in Bedroom-1

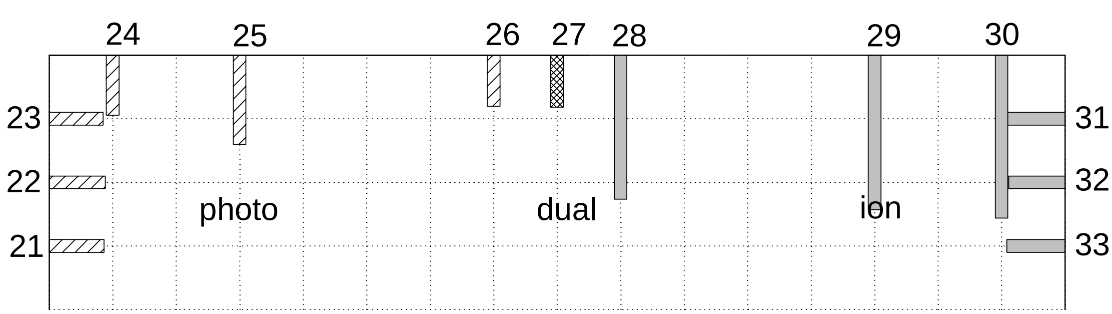


Test 7 - Normalized activation time of detectors in living room

Figure 52. Relative activation times of smoke detectors inside and outside “dead air spaces” and below recommended heights (Test 7)

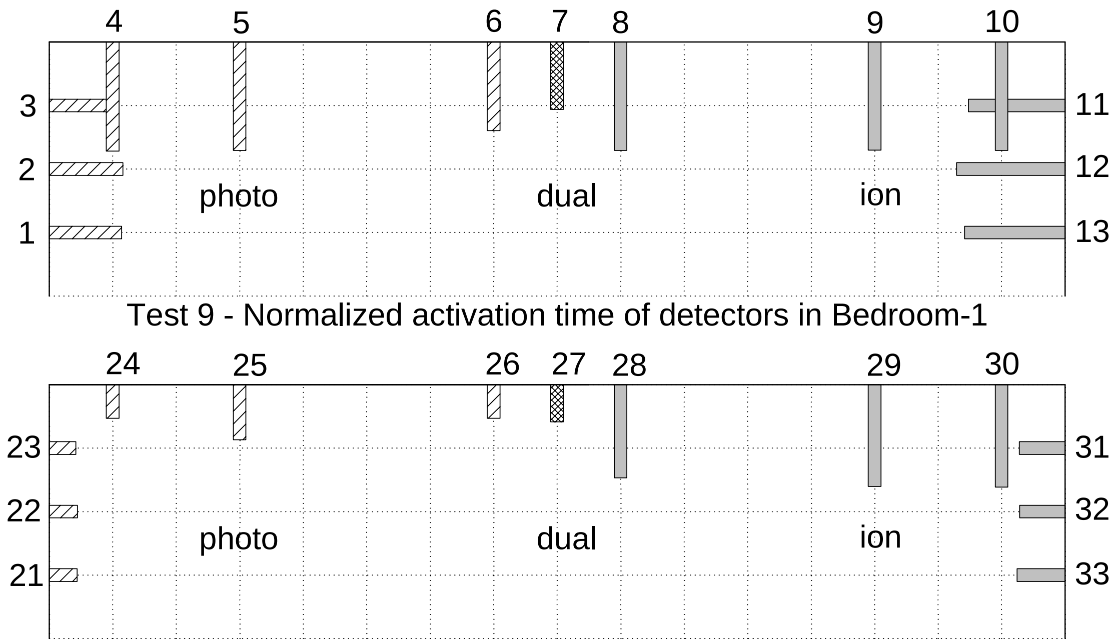


Test 8 - Normalized activation time of detectors in Bedroom-1



Test 8 - Normalized activation time of detectors in living room

Figure 53. Relative activation times of smoke detectors inside and outside “dead air spaces” and below recommended heights (Test 8)



Test 9 - Normalized activation time of detectors in living room

Figure 54. Relative activation times of smoke detectors inside and outside “dead air spaces” and below recommended heights (Test 9)