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An Experimental Examination of Dead Air Space for Smoke Alarms

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Abstract. North American smoke alarm installation standards and manufacturer's recommendations require that smoke alarms be installed not less than 100 mm from any adjoining wall if mounted on a flat ceiling, and not closer than 100 mm and not farther than 300 mm from the adjoining ceiling surface if mounted on walls. The aim of this prescriptive rule is to avoid installation of smoke alarms in the "dead air space", where it is assumed to be difficult for smoke to reach. However, there was little scientific basis and experimental evidence for this prescriptive rule. A series of experimental studies were conducted in a residential dwelling as well as in a laboratory room to examine the effect of "dead air space" on smoke-alarm response. Small and slow-growing smouldering and flaming fire sources were used to challenge the smoke alarms. The results show that smoke can reach the "dead air space" under the experimental conditions and the smoke alarms installed in the "dead air space" can respond to the fire at times comparable to, and in many cases even earlier than, the smoke alarms installed at conventional locations. There was no obvious evidence of the "dead air space" effect. The prescriptive "dead air space" as currently defined in the standards is questionable as far as early fire detection is concerned when fires are still small and smoke flows caused by the fires are still slow. Performance-based approaches should be used to identify those spaces where smoke may be difficult to reach.

Key words: smoke alarms, fire detection

1.0 INTRODUCTION

Smoke alarms are important and cost-effective fire protection devices in residential dwellings, providing fire and evacuation warnings for occupants in case of fires. For the last 3 decades, North America's death rate in fires has declined by approximately 50%; much of this decline is attributed to the use of residential smoke alarms and the enforcement of relevant codes and standards.

Underpinning this success was the Indiana Dunes tests (1975) of smoke alarms in actual homes

using fire scenarios representative of major fatal fires [1, 2, 3], which became the basis around the world for smoke alarm requirements for residential occupancies. Following this pioneer work, there were continued studies aimed to provide data for use in the improvement of relevant standards and requirements [4-8]. These included investigations of the impact of heating, ventilation and air conditioning (HVAC), performance of smoke alarms in conjunction with heat detectors and sprinklers, as well as computational fluid dynamics studies, to just name a few. The most recent systematic evaluation of smoke alarms in residential fire settings was conducted in 2000-2002 [9].

Although most of the works mentioned above involved wall and ceiling mounted smoke alarms, there was limited information directly related to the so-called “dead air spaces”. North American standards and manufacturers’ recommendations require that smoke alarms be installed not less than 100 mm from any adjoining wall if mounted on a flat ceiling, and not closer than 100 mm and not farther than 300 mm from the adjoining ceiling surface if mounted on walls [10, 11]. The objective of these requirements is to avoid locating smoke alarms in the “dead air space”, where it is assumed difficult for smoke to reach. However, there was little scientific basis and experimental evidence for this prescriptive rule.

In a field study involving hotel fire scenarios, smoke alarms were mounted at various locations including locations on a wall 12 mm below ceiling [6]. The study concluded that the location of the smoke alarms within a room did not appear to be a significant factor in activation times. However, the test data was not documented in the reference [6].

A series of full-scale experiments were conducted to study the effect of dead-air space on smoke alarm response using small and slow-growing smouldering and flaming fire sources. Field experiments were conducted in a residential dwelling (to be demolished) as part of a smoke alarm research project [12]. Further experiments were conducted in a laboratory room. This paper presents results from these experiments.

2.0 EXPERIMENTS IN A DWELLING

2.1 Experimental Set-up in the Dwelling

The family dwelling used for the field experiments was a bungalow, which had 2 bedrooms, a bathroom, a kitchen, a living and dining room on the main floor. It had a basement level below the main floor. The fire detection experiments were conducted on the main floor with a fire originating in a bedroom or the living room. Figure 1 shows a plan view of the main floor. The locations of the fires, smoke alarms and measurement devices are also shown. The main floor had a 2.44 m high ceiling and a 0.42 m lintel above the bedroom doors. All windows and exterior doors were closed during the experiments. Since the normal utility services to the test house had been discontinued, the house was unheated and the ambient temperature was around 10-14°C during the experiments. The experiments were conducted during daylight without additional lighting.

2.1.1 Smoke Alarm Positioning

A total of 33 smoke alarms were installed on the main floor, as shown in Figure 1, including photoelectric, ionization and dual (combination ionization-photoelectric) smoke alarms. Each smoke alarm had an identification number (preceded by a “P” for photoelectric, an “I” for ionization, or no letter for dual). This paper focuses on the smoke alarms installed in the living room and Bedroom 1 since smoke alarms installed in other places were not located in the “dead-air spaces”.

In Bedroom 1, smoke alarms P1-P3 and I11-I13 were mounted on 2 adjacent walls, smoke alarms P4-P6, 7 and I8-I10 were mounted on the ceiling. Smoke alarms were located in 2 “dead-air spaces”. For the smoke alarms mounted on the walls, P1 and I13 were below the required height, P2 and I12 were in the recommended region, and P3 and I11 were inside the “dead air spaces”. For the smoke alarms mounted on the ceiling, P4 and I10 were inside the “dead air spaces”. Figure 2 is a photograph showing the locations of the smoke alarms in Bedroom 1.

Similar smoke-alarm positioning was used in the living room (P21-P23 and I31-I33 on the walls; P24-P26, 27 and I28-I30 on the ceiling). The wall-mounted smoke alarms P21 and I33 were below the required height, P22 and I32 were in the recommended region, and P23 and I31 were inside the “dead air spaces”. The ceiling-mounted smoke alarms P24 and I30 were inside the “dead air spaces”.

As shown in Figure 1, the measurements of the positions of the smoke alarms located in the “dead-air spaces” are from the adjacent ceiling-wall joint to the closest edge of the smoke alarms. All

smoke alarms were randomly oriented with the sensing inlet.

2.1.2 Measurements

The response time of each smoke alarm was monitored using a circuit inserted between the positive lead of the battery and the power terminal of the smoke alarm, which produced a current draw through the battery when the smoke alarm actuated.

Smoke optical density was measured as a function of time using six smoke density meters in Bedroom 1, the corridor and the living room, as shown in Figure 1. Each location had 2 measurement points, one at a height of 2.29 m (150 mm below the ceiling) and the other at a height of 1.68 m above the floor. The ceiling measurement points were just below smoke alarms (P6, 7, I8), (I14, 15, P16), and (P26, 27, I28), respectively. Each smoke density meter used a pulsed, near-infrared light emitting diode as a light source (940 nanometer), aperture and silicon pin photodiode as a receiver with a light-path length of 0.60 m. The light source was pulsed to minimize the affects of ambient light and temperature variations. All smoke density meters were calibrated using optical filters with known densities including calibration at 100% and 0% transmission. (A comparison of the IR light source system with four white and laser light source systems is provided in a separate report [13].)

Temperatures in the living room, corridor and Bedroom 1 were measured using 3 thermocouple trees (Type K thermocouples, 0.038 mm diameter, 26 AWG, $\pm 2.2^{\circ}\text{C}$, made of nickel-chromium and nickel-aluminum alloys). Each thermocouple tree had thermocouples at heights of 1.22, 1.83 and 2.40 m above the floor (the top one was 40 mm below the ceiling). The thermocouple trees were installed near the smoke density meters and smoke-alarms (P6, 7, I8), (I14, 15, P16), and (P26, 27, I28). Additional thermocouples were placed at the fire source to monitor the fire development.

2.1.3 Fuels and Fire Scenarios

In order to challenge the smoke alarms, 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 included wood, paper, polyurethane foam, cotton flannel and upholstered furniture.

The wood fuel package was 5 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. A 0.20 m diameter by 0.10 m thick piece of polyurethane foam was wrapped with cotton flannel (0.53 m x 0.57 m sheet) to simulate a mattress or cushion. The cotton flannel fuel package was a sheet 0.86 m x 0.86 m folded to a size of 0.215 m x 0.215 m. In each experiment, one fuel package was placed on an ignitor (electric heating element). A perforated metal bucket (bottom side up) was used to cover the fuel and ignitor. The metal bucket had holes around the perimeter side to control the amount of air available for combustion. The smoke came out from the holes on the top of the metal bucket. (The floor at the fire location was protected with ceramic fibre insulation underneath the fire source.)

A section of an upholstered chair was also used as a fuel package in an experiment. The fuel package included a cushion piece (0.20 m x 0.30 m x 0.15 m) and an armrest piece (0.35 m x 0.30 m x 0.12 m). The ignitor was inserted between the cushion and armrest.

Table 1 shows the fuel package, fire location and state of bedroom doors in the experiments. Five experiments were conducted with the fire origin in Bedroom 1; four experiments were conducted with the fire origin in the living room. All windows, exterior doors and the bathroom door were closed during the experiments. The door of Bedroom 1 was open during Tests 1, 3-5, 8 and 9. In Tests 2, 6 and 7, the door of Bedroom 1 was closed initially and was opened at the time indicated in Table 1.

2.2 Results of Experiments in the Dwelling

The test fires were limited to small sizes with slow growth rates in order to provide the greatest challenge to the operation of the smoke alarms. The 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. During the smouldering period, the change of temperature in the house was very small in all experiments – less than a 1°C increase in the room of fire origin for experiments with wood, paper, cotton flannel or upholstered chair pieces as the fuel package; less than a 2°C increase in the room of fire origin for experiments with the polyurethane foam. In all experiments, the maximum temperature rise occurred at the ceiling of the room of the fire origin during the flaming period. The temperature rises associated with the activation of the smoke alarms were less than 3°C in all experiments.

Table 1 shows the length of the smouldering phase, the total length of smouldering plus flaming phase, and the response times of the smoke alarms at various locations for each experiment. Except for Test 3 where the cotton flannel fire quickly changed from smouldering to flaming, all other test fires had a relatively long period of smouldering before changing into flaming. Tests 6 and 7 had the same experimental set up except that the amount of air available for combustion was controlled in Test 7 by sealing some of the holes around the metal bucket to lengthen the smouldering period. Since the door of Bedroom 1 was closed initially in Tests 2, 6 and 7, the smoke alarms in the living room did not respond to the fire that was located in Bedroom 1 until the door was opened and, vice versa, most smoke alarms in Bedroom 1 did not respond to the fire that was located in the living room until the door was opened. Figure 3 shows exemplar data plots of temperature and optical density measurements for Test 1. More data plots can be found in a report [12].

2.2.1 Optical Density at Smoke Alarm Activation

The polyurethane foam wrapped with cotton flannel fuel package produced the highest smoke obscuration among all the fuel packages used in the field experiments. The optical density changed more gradually in areas remote from the fire origin than in the fire room. The activation optical densities were determined for smoke alarms P26, 27 and I28 in the living room for Tests 1-5, and for smoke alarms P6, 7 and I8 in Bedroom 1 for Tests 6-9, which were just above the ceiling-mounted smoke optical density meters. The average optical density at activation was $0.076 \pm 0.028 \text{ m}^{-1}$ for the ionization smoke alarms (I8, I28), $0.062 \pm 0.036 \text{ m}^{-1}$ for the dual smoke alarms (7, 27) and $0.068 \pm 0.029 \text{ m}^{-1}$ for the photoelectric smoke alarms (P6, P26). The exception was Test 3 with the flaming cotton flannel fire — for the smoke alarms that actuated during the test, they activated at an optical density below 0.01 m^{-1} .

2.2.2 Effect of “Dead Air Space”

The experiments were designed to address smoke alarm response in the “dead air space”, where it was assumed to be difficult for the smoke to reach. Based on the “dead air space” assumption, the ceiling-mounted and wall-mounted smoke alarms that were installed less than 100 mm from the ceiling and wall joints would have difficulty detecting the smoke; the wall-mounted smoke alarms that were more than 300 mm below the ceiling-wall joints would also have difficulty detecting the smoke.

As shown in Table 1, however, the smoke alarms installed in the “dead air spaces” were among the first to detect fires in most of the experiments. The relative activation times of the 26 smoke alarms located in Bedroom 1 and the living room are shown in Figures 4 and 5. The length of each bar represents the response time of the smoke alarm relative to that of a reference smoke alarm. The dual smoke alarm #15 installed in the corridor, is taken as the reference (its relative response time set at 1) for presentation purposes in this paper. (Note: in order to present all smoke alarms installed in each room on one chart, i.e. to reduce the number of figures, a common reference has to be used. Readers can choose other references to make their own comparisons.) The position of a smoke-alarm identification number represents the location of that smoke alarm (either on the wall or ceiling). Each bar indicates an actuated smoke alarm. If a bar is absent at an identification number, that smoke alarm was not actuated in the experiment. A grid is superimposed over the figures to indicate the scale – each side of the square represents one unit.

As shown in Figures 4 and 5, there was no obvious evidence of the “dead air space” effect for the smoke alarms installed in the “dead air spaces” (P3, P4, I10, I11; P23, P24, I30, I31) or below the required height (P1, I13; P21, I33). In most cases, they responded to the fire as quickly as, or even faster than, some smoke alarms installed in the allowed locations (P2, P5, P6, 7, I8, I9, or I12; P22, P25, P26, 27, I28, I29, or I32) (compared with the same type). Only in a few cases, smoke alarms in the “dead air spaces” had relatively slower response than those in the allowed locations but there was no significant delay in response time.

In Test 3, with the cotton flannel fuel package, the fire quickly changed to flaming and there was hardly any visible smoke throughout the experiment. Four photoelectric smoke alarms P5, P24-26 did not respond to the fire. The maximum optical density was 0.014 m^{-1} in the centre of the fire room (Bedroom 1) and less than 0.01 m^{-1} in the living room. These low optical density values explained why smoke alarms P5 and P24-26 did not actuate (their normal sensitivity was $0.030 \pm 0.019 \text{ m}^{-1}$ or $2.06 \pm 1.30 \%$ per foot). In addition, it is well known that photoelectric smoke alarms are better in detecting smouldering fires. Even under such conditions, smoke alarm P4 mounted in the ceiling “dead air space” responded to the fire as quickly as P6 at the centre of the room while P5 mounted outside the ceiling “dead air space” did not respond.

It is also worth noting that in Test 6, smoke alarm P3 in the wall “dead air space” of Bedroom 1 responded to the living room fire when the Bedroom 1 door was still closed and that all other smoke alarms in Bedroom 1 did not respond to the living room fire until the door was opened.

For the fire scenarios used in these experiments, the results show that smoke can reach the “dead air space” and the smoke alarms installed in the “dead air space” can respond to the fire at times comparable to the smoke alarms installed at conventional locations.

Due to discontinued utility services, effects of the heating and ventilation system as well as lighting were not studied in the field experiments. Operation of lighting devices could induce localized flow. Operation of the heating and ventilation system might change smoke movement and smoke alarm response, depending on the locations of supply and return vents and their proximity to the fire source and smoke alarms.

3.0 EXPERIMENTS IN A LABORATORY ROOM

The family dwelling used for the field experiments was unheated with an initial temperature of 10-14°C. At a normal room temperature of 20°C, the air density would be lower and the smoke might be less buoyant. To determine whether the difference in room temperature would influence the smoke movement to the “dead air space”, a laboratory study was undertaken with an initial room temperature of 20°C. However, this investigation of the ambient temperature effect was limited in terms of the temperature range. A more important objective of the laboratory study was to get measurements further into the “dead air space” since the physical size of the smoke alarms used in the field experiments limited how deep they could be located into the “dead air space”. In this series of experiments, smoke optical density in the “dead air space” was measured.

3.1 Experimental Set-up in the Laboratory

A room of 6.1 m by 3.5 m by 2.4 m high was used in the laboratory tests, which was similar to the size of the living room in the dwelling used for the field experiments. Figure 6 shows a plan and elevation view of the room. The locations of the fire and measurement devices are also shown. A door was left open during the experiments. A 0.25 m lintel was above the door. The initial room temperature was 20°C for each experiment.

3.1.1 Measurements

Smoke optical density in the “dead air space” was measured as a function of time using smoke density meters, which were constructed to suit the measurement in this space. Six smoke density meters were installed on the ceiling 20, 150 and 350 mm from the adjoining wall and on the wall 50, 150 and 350 mm from the adjoining ceiling, as shown in Figure 7. Three of these smoke meters were installed in the “dead-air space” (less than 100 mm from the ceiling and wall joint) or below the required height (farther than 300 mm from the adjoining ceiling surface). This was similar to the positioning of smoke alarms in the field experiments. However, the smoke density meters were installed farther into the “dead air space”. Each smoke density meter consisted of a white light source (light emitting diode), aperture and detector (a silicon pin diode). The light source was pulsed to minimize the effect of ambient light and temperature variations. The smoke density meters were calibrated using various neutral density filters, including calibration at 100% and 0% transmission.

Temperatures were measured at the centre of the room using a thermocouple tree with thermocouples located 100, 500 and 900 mm below the ceiling. Mass loss of fuels was also monitored.

3.1.2 Fuels and Fire Scenarios

Table 2 shows some parameters for the experiments. Similar to the field experiments, a fuel package of pine sticks covered with a perforated metal bucket was used to produce a smouldering fire. The mass loss rate of the pine sticks during smouldering was 0.265 g/s. The maximum temperature rise was 3°C close to the ceiling. The rate of temperature rise was comparable to the field experiments.

A heptane and toluene mixture (75% heptane and 25% toluene in volume) was used as the fuel for flaming fires. The liquid fuel was added to a small pan (200 mm in diameter). The mass loss rate was 0.43 g/s in a test with 25 ml of the liquid fuel and 0.54 g/s in another test with 50 ml of the liquid fuel. The heat release rate was estimated to be 20 kW and 25 kW and the maximum temperature rise measured close to the ceiling at the centre of the room was 6°C and 11°C in these two tests, respectively.

3.2 **Results of Experiments in the Laboratory**

Figure 8 shows optical density profiles measured inside and outside the “dead air space” during

the laboratory experiments. The optical densities measured in the “dead air space” (on the ceiling 20 mm from the joint, on the wall 50 and 350 mm from the joint) were either similar to or greater than those measured at the allowed smoke-alarm locations (on the ceiling 150 and 350 mm from the joint, and on the wall 150 mm from the joint). In the range of optical density up to 0.1 m^{-1} , which is normally associated with smoke alarm activation, there were very little differences in the optical density profiles. The results show that there was no “dead air space” under the experimental conditions and little influence of the ambient room temperature. The prescriptive “dead air space” as currently defined in the standards is questionable.

4.0 DISCUSSION

The experiments were designed to address smoke alarm response in the “dead air space”, where it had been assumed difficult for smoke to reach and not suitable for smoke alarm installation. For the fire scenarios used in these experiments, smoke reached the “dead air space” and the smoke alarms installed in the “dead air space” responded to the fire at times comparable to, or even earlier than, the smoke alarms installed at conventional locations. There was no obvious evidence of the “dead air space” effect from the field experiments and the further laboratory experiments.

A dead-air-space effect may apply to airflow with large-scale turbulent eddies. It is very true that large eddies cannot get into small spaces. However, smoke alarms are expected to detect a fire early when it is still small and its smoke flow is still slow. Smoke alarms should respond to the fire long before it becomes a fully-developed fire. Thus, the behaviour of large-scale eddies may not be relevant for fire detection situations, such as residential smoke alarms under the fire scenarios used in this study.

It must be noted that the experiments were conducted without the operation of HVAC systems. The effect of HVAC systems on smoke flow and smoke alarm response in the “dead air space” was not studied in this experimental study.

5.0 CONCLUSIONS

Avoiding installation of smoke alarms in spaces where it is difficult for smoke to reach is a reasonable fire safety objective to achieve early fire detection. However, the prescriptive rule to stay

away from the “dead air space” as currently defined in the standards is questionable, at least for the experimental conditions used in this study. Performance-based approaches should be used to identify the spaces where it may be difficult for smoke to reach.

6.0 ACKNOWLEDGEMENTS

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7.0 REFERENCES

1. R.W. Bukowski, T.E. Waterman and W.J. Christian, “Detector sensitivity and siting requirements for dwellings,” National Bureau of Standards, Washington, D.C., Report# PB 247 483 (NBS GCR 75-51), 1976.
2. S.W. Harpe, T.E. Waterman and W.J. Christians, “Detector sensitivity and siting requirements for dwellings - phase 2,” National Fire Protection Association, Boston, MA, Report# SPP43A (NBS-GCR 77-82), 1977
3. T.E. Waterman, S.W. Harpe and W.J. Christian, “An engineering approach to the positioning of fire detectors in residences,” Society of Fire Protection Engineers, Boston, MA, SFPE technology report 77-6, 1977.
4. R.H. Kennedy, K.W.P. Riley and S.P. Rogers, “A study of the operation and effectiveness of fire detectors installed in the bedrooms and corridors of residential institutions,” Building Research Establishment, Garston, Watford, CP26/78, April 1978
5. R.W. Bukowski, “Investigation of the Effects of Heating and Air Conditioning on the Performance of Smoke Detectors in Mobile Home,” National Bureau of Standards, Washington D.C., NBSIR 79-1915, October 1979.
6. J.A. Drouin and A.E. Cote, E. “Smoke and heat detector performance: field demonstration test

results,” Fire Journal (Boston), vol. 78, pp. 34-38, 69, Jan. 1984.

7. A.E. Cote, “Field Test and Evaluation of Residential Sprinkler Systems. Part 3,” Fire Technology, Vol. 20, pp. 41-46, May 1984.
8. W.D. Davis, G.P. Forney, R.W. Bukowski, “Developing detector siting rules from computational experiments in spaces with complex geometries,” Fire Safety Journal, Vol. 29, pp. 129-139, 1997.
9. R.W. Bukowski, R.D. Peacock, J.D. Averill, T.G. Cleary, N.P. Bryner, W.D. Walton, P.A. Reneke, and E.D. Kuligowski, "Performance of Home Smoke Alarms Analysis of the Response of Several Available Technologies in Residential Fire Settings", National Institute of Standards and Technology, Gaithersburg, MD, NIST Technical Note 1455, December 2003 (revised March 2006).
10. CAN/ULC-S553-02, “Standard for the Installation of Smoke-Alarms,” Underwriters’ Laboratories of Canada, Toronto, ON, Canada, Second Edition, July 2002.
11. NFPA 72, “National Fire Alarm Code”, National Fire Protection Association, Quincy, MA, USA, 2007 Edition.
12. J.Z. Su, G.P. Crampton, D.W. Carpenter, C. McCartney and P. Leroux, “Kemano Fire Studies – Part 1: Response of Residential Smoke Alarms,” Institute for Research in Construction, National Research Council Canada, Ottawa, ON, Canada, Research Report 108, 2003 (URL: <http://irc.nrc-cnrc.gc.ca/pubs/rr/rr108/>).
13. G.P. Crampton, G.D. Loughheed, “Comparison of Smoke Measurements with Standard and Non-Standard Systems,” Institute for Research in Construction, National Research Council Canada, Ottawa, ON, Canada, Research Report 183, 2004 (URL: <http://irc.nrc-cnrc.gc.ca/pubs/rr/rr183/>)

Table 1 – Experiments in the Dwelling and the Results

Test		1	2	3	4	5	6	7	8	9
Bedroom-1 door		open	close ¹	open	open	open	close ¹	close ¹	open	open
Bedroom-2 door		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		pine sticks	pine sticks	cotton	paper	foam + cotton	pine sticks	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
Smoke Alarm Identification Number 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	

¹ Bedroom-1 door opened at 1353 s in Test 2 and 1080 s in Tests 6 and 7.

Notes: d for dual, i for ionization and p for photoelectric smoke alarms; NA for not actuated smoke alarms.

Table 2 – Experiments in the Laboratory Room

Test	A	B	C
Fuel	heptane-toluene mixture	heptane-toluene mixture	pine sticks
Initial Mass (g)	18.3 (25 ml)	36.6 (50 ml)	133
Combustion Mode	flaming	flaming	smouldering
Mass Loss Rate (g/s)	0.43	0.54	0.265
Maximum Temperature Rise (°C)			
100 mm below ceiling	6	11	3
500 mm below ceiling	3	6	2
900 mm below ceiling	1.5	4	1.5
Duration of Experiment (s)	150	180	515

Captions

Figure 1. Plan view of the test house and experimental set-up.

Figure 2. Locations of the smoke alarms in Bedroom 1.

Figure 3. Exemplar data plots of temperature and optical density measurements at different heights (Test 1).

Figure 4. Relative activation times of smoke alarms with fire origin in Bedroom 1.

Figure 5. Relative activation times of smoke alarms with fire origin in the living room.

Figure 6. Laboratory test room and set-up.

Figure 7. Optical density meters in the laboratory room.

Figure 8. Optical density profiles during laboratory room experiments.

Figure 2. Locations of the smoke alarms in Bedroom 1.

Figure 3. Exemplar data plots of temperature and optical density measurements at different heights (Test 1).

a) Test 1 with pine sticks as fuel in Bedroom 1

b) Test 2 with pine sticks as fuel in Bedroom 1

c) Test 3 with cotton flannel as fuel in Bedroom 1

Figure 4. Relative activation times of smoke alarms with fire origin in Bedroom 1.

d) Test 4 with newspaper as fuel in Bedroom 1

e) Test 5 with polyurethane foam and cotton flannel wrap as fuel in Bedroom 1

Figure 4. Relative activation times of smoke alarms with fire origin in Bedroom 1 (continued).

a) Test 6 with pine sticks as fuel in the living room

b) Test 7 with pine sticks as fuel in the living room

c) Test 8 with polyurethane foam and cotton flannel wrap as fuel in the living room

Figure 5. Relative activation times of smoke alarms with fire origin in the living room.

d) Test 9 with upholstered chair section as fuel in the living room

Figure 5. Relative activation times of smoke alarms with fire origin in the living room (continued).

Figure 6. Laboratory test room and set-up (all dimension in mm).

Figure 7. Optical density meters in the laboratory room.

Figure 8. Optical density profiles during laboratory room experiments.