Australian Building Codes Board’s Domestic Smoke Alarm Study: Ionisation versus Photoelectric

Prepared for the Australian Building Codes Board
By

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Executive Summary

The present report is developed in response to the Australian Building Codes Board's (ABCB) request to undertake a study on the comparative performance of domestic ionisation and photoelectric smoke alarms.

SCOPE AND FRAMEWORK

The National Construction Code (NCC) permits the use of both photoelectric and ionisation smoke detectors as fire alarms in residential premises.

It appears that there is a growing support within the industry for the use of photoelectric detectors over ionisation detectors. The recent study conducted by Fire & Rescue New South Wales (FRNSW) favours photoelectric alarms.

It is not clear whether there are strong objective grounds to promote the use of one type of smoke alarm over the other.

The present report provides critical analysis of available data, including the FRNSW report, in order to reveal the performance of both types of detectors and their relevance for various fire scenarios. The report also reviews historical fire data in order to evaluate probabilities of major fire causes and scenarios, and to relate this to criterion used to estimate efficiencies of various types of smoke alarms. Data from Australia, New Zealand and the United States is used in the present study.

No solid justification for the preference of photoelectric smoke alarms over ionisation smoke alarms has been found. An extended test program is proposed to conduct a robust comparative study on the performance of both types of alarms.

ALARM TIME ACTIVATION DATA

Table 1 summarises the available data on activation of photoelectric, ionisation alarms as well as dual smoke alarms under two major types of fire conditions, namely flaming and smouldering.

Table 1: Summary of average activation times of different types of smoke alarms in flaming and smouldering conditions

FLAMING FIRE CONDITIONS							
Combustible materials	Room of Fire Origin	Ventilation	Alarm type				Ref.
			Photo	Ion	Dual 1	Dual 2[d]	
Low density foam, polyester	Living room	Door open	133	81	83	88	[1]
Low density foam, polyester	Bedroom	Door closed	122	86	120	95	[1]
Low density foam, cotton	Living room	Door open	240	161	243	127	[1]
High density foam, polyester	Bedroom	Door open	159	107	144	112	[1]
Cotton[a]	Bedroom	Door open	375	136	118		[2][b]
Pine sticks[a]	Living room	N.A.	315	306	262		[2][b]
Sofa	Living room	Door closed	714	516	540		[3][c]
Wooden cabinet	Kitchen	Door closed	750	738	738		[3][c]
Wooden cabinet	Kitchen	Half-open window	840	804	768		[3][c]
Flaming materials	Living room	N.A.	130	73	77		[4][e]
Flaming materials	Bedroom	Door open	78	37	186		[4][e]
Flaming materials	Bedroom	Door closed	84	34	619		[4][e]
Gasoline	Testing room	Natural ventilation	443	159	-		[5]
Average activation time (s)			337.2	249.1	270.0		

SMOULDERING FIRE CONDITIONS							
Combustible materials	Room of Fire Origin	Ventilation	Alarm type				Ref.
			Photo	Ion	Dual 1	Dual 2[d]	
Low density foam, cotton	Bedroom	Door open	1897	1876	2051	1275	[1]
Low density foam, cotton	Bedroom	Door closed	1322	1268	1341	1143	[1]
Low density foam, cotton	Living room	Door open	2715	4042	2691	2393	[1]
High density foam, cotton	Living room	Door open	3045	5367	3462	2758	[1]
Pine sticks[a]	Bedroom	Door open	275	307	242		[2][b]
Pine sticks[a]	Bedroom	Door closed	233	261	209		[2][b]
Paper[a]	Bedroom	Door open	436	504	430		[2][b]
Foam and cotton[a]	Bedroom	Door open	358	362	307		[2][b]
Pine sticks[a]	Living room	N.A.	401	428	318		[2][b]
Foam and cotton[a]	Living room	N.A.	303	525	259		[2][b]
Chair section[a]	Living room	N.A.	293	621	319		[2][b]
Cotton batting	Bedroom	Door closed	1572	1746	1530		[3][c]
Sofa	Living room	Door closed	1062	1920	942		[3][c]
Sofa	Living room	Door closed	948	1608	900		[3][c]
Sofa	Living room	Door closed	756	1038	744		[3][c]
Smouldering materials	Living room	N.A.	3856	4695	4304		[4][e]
Smouldering materials	Bedroom	Door open	2179	3618	3471		[4][e]
Smouldering materials	Bedroom	Door closed	2648	3402	3434		[4][e]
Polyurethane	Testing room	Natural ventilation	362	624	-		[5]

SMOULDERING FIRE CONDITIONS							
Combustible materials	**Room of Fire Origin**	**Ventilation**	**Alarm type**				**Ref.**
			Photo	**Ion**	**Dual 1**	**Dual 2^{d}**	
Upholstery fabric	Testing room	Natural ventilation	425	710	-		[5]
Bedding/Upholstered couch	Different rooms of origin	Doors open/closed various arrangements	1020	2640	1018		[6]
Average activation time (s)			**1242.9**	**1788.6**	**1542.8**		

Consistent with various previous reports, it is found that photoelectric alarms typically respond faster to smouldering fires, while ionisation alarms respond faster to flaming conditions.

These findings, however, are to be considered in the context of probabilities of different fire scenarios. It was found that the study conducted by FRNSW involved disproportionally large number of smouldering scenarios.

Based on the review of historical fire data, undertaken in the course of the present study, an extended testing program is proposed. Table 2 summarises the proposed testing program

Table 2: Summary of proposed testing program

Runs	**Location**	**Fire type**	**Materials**	**Ignition method**	**Conditions**
1	Bedroom 1	Smouldering	Bedding	Cigarette/small electric heater	Bedroom 1 door closed; bedroom 2 door open;
2	bedroom 2	Smouldering	Bedding	Cigarette/small electric heater	Two bedroom doors open
3	Lounge	Smouldering	Upholstered couch	Cigarette/small electric heater	Bedroom 1 door open; bedroom 2 door closed;
4	Bedroom 2	Smouldering	Bedding	Cigarette/small electric heater	Two bedroom doors open
5	Bedroom 2	Flaming	Bedding	LPG gas flame	Two bedroom doors open
6	Bedroom 1	Smouldering	Bedding	Cigarette/small electric heater	Bedroom 1 door closed; bedroom 2 door open;
7	Bedroom 1	Smouldering	Bedding	Cigarette/small electric heater	Two bedroom doors open
8	Lounge	Smouldering	Upholstered couch	Cigarette/small electric heater	Bedroom 1 door open; bedroom 2 door closed;
9	Bedroom 2	Smouldering	Bedding	Cigarette/small electric heater	Two bedroom doors open
10	Bedroom 1	Flaming	Bedding	LPG gas flame	Two bedroom doors open
11	Kitchen	Smouldering	Electrical cable	LPG gas flame or alternative	All room doors open
12	Kitchen	Flaming	Electric equipment	Cartridge heater or alternative	All room doors open
13	Lounge	Flaming	Upholstered furniture	LPG gas flame or alternative	All room doors open
14	Lounge	Smouldering	Upholstered furniture	Cigarette/small electric heater	All room doors open
15	Lounge	Flaming	Papers	LPG gas flame or alternative	All room doors open
16	Lounge	Flaming	Wood chair	LPG gas flame or alternative	All room doors open
17	Kitchen	Flaming	Cooking pan	LPG gas flame or alternative	All room doors open

Runs	Location	Fire type	Materials	Ignition method	Conditions
18	Kitchen	Flaming	Clothing	LPG gas flame or alternative	All room doors open
19	Laundry room	Smouldering	Electric equipment	Cartridge heater or alternative	All room doors open
20	Laundry room	Smouldering	Electric equipment	Cartridge heater or alternative	All room doors open except laundry room door
21	Bedroom 1	Flaming	Pillow	LPG gas flame or alternative	All room doors open
22	Bedroom 1	Flaming	Pillow	LPG gas flame or alternative	All room doors open except bedroom 1 door
23	Bedroom 2	Flaming	Paper	LPG gas flame or alternative	All room doors open
24	Bedroom 2	Flaming	Paper	LPG gas flame or alternative	All room doors open except bedroom 1 door
25	Hall	Flaming	Wood chair	LPG gas flame or alternative	All room doors open
26	Hall	Smouldering	Upholstered furniture	Cigarette/small electric heater	All room doors open
27	Kitchen	Nuisance source	Cooking different foods	Cooking equipment	All room doors open
28	Bathroom	Nuisance source	Steam	Hot shower	All room doors open
29	Lounge	Nuisance source	Smoking cigarette(s)	Lighter	All room doors open
30	Lounge	Nuisance source	Candle(s)	Lighter	All room doors open

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1. BACKGROUND

1.1 Home fires and smoke alarms

Home fires are still a problem in our daily lives. From 2007 to 2011 United States fire departments responded to an average of 1,000 home structure fires every day, and home fires killed an average of seven people per day and caused roughly $28 in damage every second [7]. According to the statistics by Australasian Fire and Emergency Service Authorities Council [8], the residential fire deaths per 100,000 is between 0.07 and 0.41 during 1996-2004, and the figure for New Zealand is a little higher during the same period, that is between 0.10 and 0.70. According to The United States Fire Administration [9], the estimation of residential building fire deaths in United States is between 2385 and 3050 (yearly) from 2003 to 2012. According to Australasian Fire Authorities Council [10], it is known that the time period when most fire fatalities occurred was between the general sleeping times of 8pm-8am (72%) in Australia, and the figure increases to 78% in New Zealand with a peak occurring between midnight-4am (42%). The study [11] indicates that one out of four survived occupants (24.2%) were asleep at the time of ignition, while four out of five fatalities (80.5%) were asleep.

There are many reasons that cause home fires. A statistics [10] shows that in Australia the majority of fires (74%) were caused either by electrical faults, smoking materials or heaters/open fires/lamps, and in New Zealand 56% of fires were caused either by open fires/heaters, kitchen fire/cooking materials or electrical faults. Further, 2972 (40.6%) people were injured as result of fires that originated in the kitchen, 1600 (21.9%) people were injured in fires that started in the bedroom [12]. According to the statistics of home fires [12], in New Zealand, 46.7% of people were injured in fires that started in the kitchen,. A statistics [13] shows that 40% of homes fire were caused by cooking equipment and 18% by heating equipment in United States from 2003 to 2007. A study shows that the cooking equipment is responsible for 31.0% of the whole number of residential fires and 9% of civilian deaths [8]. It is also known that flaming cooking materials are involved in fires more than five times more frequently than any other material [4]. These scenarios are amongst the top five ranked by number of deaths, and amongst the top ten ranked by frequency of occurrence.

Home smoke alarm technology is credited as the greatest success story in fire safety in the last part of the 20th century, as it alone represented a highly effective fire safety technology that come into nearly universal usage in a remarkably short time [4]. A working smoke alarm has been reported to reduce the risk of death from residential fires by from between 50% to 70% [14, 15]. According to estimates by the National Fire Protection Association and the U.S. Fire Administration, U.S. home usage of smoke alarms rose from less than 10% in 1975 to at least 95% in 2000, while the number of home fire deaths was cut nearly in half [4]. The US Fire Administration reports that more than 88% of the homes in United States have at least 1 smoke alarm installed, but 60% of the residential fire deaths occur in homes without an operational alarm [14]. However, the coverage of Australian homes by smoke alarms is still of concern. For example, it is known from the statistics of home fires [12] that the presence of a smoke alarm/detector was determined in 2441 (33.3%) of the cases. Where it was identified that a smoke alarm/detector was present, it was found that they operated in 1811 (74.2%) of the cases and alerted 1406 of the occupants or fire injury victims that there was a fire in their property. Analysis of data from the United States Fire Administration's National Fire Incident Reporting System and the National

Fire Protection Association's fire department survey showed that from 2003 to 2006, no smoke alarms were present in 31% of reported home fires and 40% of home fire deaths [16].

There are basically 3 different types of residential smoke alarm: the ionisation alarm, the photoelectric alarm, and the dual alarm [14]. Ionization and photoelectric alarms operate via different mechanisms, detecting visible, and invisible/fine, products of combustion, respectively [17]. Photoelectric alarms use optical sensors and are more likely to respond to slow, smouldering conditions. Working principle of ionisation detectors is based on a modified theory which includes soot particle charge fraction functionality in addition to the generally accepted particle size and number density dependence [18]. Smoke alarms of either the ionisation type or the photoelectric type consistently provide time for occupants to escape from most residential fires, although in some cases the escape time provided can be short [4]. Table 3 [4] shows the estimates of required escape time for the best and worst case scenarios.

Table 3: Estimates of required escape times for best and worst case scenario [4]

Scenario		Pre-movement Time (s)		Movement Time (s)		Total Escape Time (s)	
		M. Home[b]	Two-Story[c]	M. Home	Two-Story	M. Home	Two-Story
Worse case	Young family at night	55	55	35	35	90	90
	Elderly family at night	80	80	55	60	135	140
Best case	Young couple in kitchen	-[a]	-	5	10	5	10
	Elderly couple in kitchen	-	-	10	15	10	15

Note: a – Best case scenarios neglect any pre-movement activity; actual escape times are likely to be longer than best estimates;

b – Manufactured home; and

c – Two-story home.

Many studies have been conducted to analyse the performance of different type of smoke alarms. Consumers Union [19] tested ionisation and photoelectric alarms in 1994. It found that in a smouldering, smoky fire, the ionization alarms responded in 25 to 35 minutes, whereas the photoelectric models reacted in half that time. A statistical study was conducted to compare the performance of different residential smoke detector technologies when exposed to different fire types by Milarcik et al. [20]. The results showed that ionisation detectors, on average, respond faster to flaming fires, while photoelectric detectors, on average, respond faster to smouldering fires. Bukowski et al. [4] have performed comprehensive real-scale tests on the performance of different type of smoke alarms. They arrived at similar conclusion that ionisation type alarms provide somewhat better response to flaming fires than photoelectrical alarms, and photoelectric alarms provide (often) considerably faster response to smouldering fires than ionization type alarms. Su and Crampton [2] conducted a series of experimental studies in a residential dwelling as well as in a laboratory room to examine the effect of "dead air space" on smoke response. The results showed 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.

Nuisance alarms are also a problem in homes. According to a 1994 study of United States residential smoke alarm use, the leading cause of smoke alarm disconnection was nuisance alarms [14, 21]. The Smoke Detector Operability Survey conducted by the United States Consumer Product Safety Commission [22] reported that about one half of the 1012 respondents indicated they experienced nuisance alarms, with 80% of those attributed to cooking activities, and an additional 6% citing steam from bathrooms. The fact that ionisation alarms produce more false alarms but are slower to respond to smoky fires is not the enigma that it seems [14]. A study [23] showed that in 54% of the non-confined home structure fires and 75% of the home fire deaths in which smoke alarms were present but failed to operate, smoke alarm batteries were missing or had been disconnected.

Currently, Australian National Construction Code's (NCC) performance requirements allows both types of smoke detectors (i.e. ionisation and photoelectric), as well dual (combination) alarms to be used.

There is an apparent drive within the Fire Protection Industry to promote the use of photoelectric alarms over ionisation alarms. Fire Authorities seem to support phasing out ionisation alarms on the basis of their belief that most fire fatalities result from smouldering fires.

There is a concern expressed by the Australian Building Codes Board (ABCB) as to whether promotion of exclusive use of photoelectric alarms is soundly based on available alarm performance and fire statistics data. In particular, with response to the recent study by the Fire & Rescue New South Wales [6], ABCB expressed concerns that

- Research methodology is not robust and is biased towards a favourable outcome for photoelectric alarms, which is reflected in the report; and
- Key deficiencies with the research methodology: 1) Comprehensive literature review needs to be undertaken to inform research methodology; 2) Fire scenario selection needs to reflect the probability of fire starts for incident data, in particular kitchen fires need to be included (which represent the largest proportions of fire incident); and 3) Energy source used for smouldering scenarios is extreme and not representative.

1.2 Aims and objectives

The aims of this study is to conduct a critical review of available data on comparative performance of photoelectric versus ionisation smoke alarms, and develop an objective testing scenarios in order to obtain accurate data on performance of these two types of detectors. This analysis will provide support for undertaking additional testing.

The present study stems from the necessity for ABCB to assess whether the apparent current industry trend towards favouring photoelectric alarms, and associated proposals to eliminate future use of ionisation detectors have sound technical basis.

Recent findings [6] obtained by FRNSW appears to contradict other publicly available reports and research publications. Initial screening of the report [6] by ABCB also pointed out to potential methodology deficiencies in the methodology [6].

This present study aims to answer the following questions:
What is the effectiveness of the two types of smoke alarms (e.g. photoelectric and ionisation) in responding to different fire conditions, based on available statistical data.

What are the key causes and scenarios of fire accidents in residential premises?
What kinds of experiments have been done to test the effectiveness of smoke alarms?

What are the advantages and disadvantages of these smoke alarms in their applications based on their working principles?

An ultimate objective of the study is to propose additional testing using the FRNSW experimental rig to ensure robust evaluation of the effectiveness of ionisation and photoelectric smoke alarms in domestic settings.

1.3 Methodology

Methodology of the present study consists of three major tasks, namely 1) literature review, including FRNSW report, 2) analysis of historical fire data, and 3) development of objective testing scenarios.

1.31 Literature review

An extensive literature review is conducted on working principles and performance of photoelectric and ionisation detectors, key fire incident data and effects of different types of fire on activation of both types of smoke alarms.

Ionisation and photoelectric alarms have different working principles, resulting in the different response time for the same amount and type of smoke. The working principle of these two types of alarms will be analysed to evaluate their application areas, for example, different flammable conditions and types of buildings.

Based on these conclusions, a comprehensive literature review is conducted to analyse the historic testing results on smoke alarms. For the literature review, one of the directions is to address the application areas of these alarms to the flammable conditions (e.g. flaming and smouldering combustion). Another direction is to undertake a statistic analysis on typical fire accidents in homes. It aims to evaluate data on typical fire accidents in homes, which will benefit proposing new experimental designs. Previous experimental designs and methods are reviewed.

1.32 Analysis of historical fire data

The study conducted by FRNSW [6] provides some detailed fire incident data. Additional relevant data will be revealed upon conducting an extensive literature search. We aim to develop classification criteria for fire incidents in such a way that such that these criteria are directly related to expected performance of smoke alarms.

1.33 Development of additional testing scenarios

A new set of experiments is proposed based on the FRNSW existing test rig [6]. The new testing program is proposed based on the above analysis results, including fire scenario design, experimental procedures and data processing. The new methodology will result in a robust evaluation of the effectiveness of ionisation, photoelectric and dual/multi smoke alarms in homes.

Scenarios are tailored to the capabilities of the FRNSW testing facility [6]. Different types of proposed tests reflect the classification of fire accidents developed under the above task.

1.4 Scope of the work

The present report includes a critical literature review of available data on the historical fire data, performances of different types of smoke alarms, and a development of additional testing scenarios which would be used to obtain accurate data on the performance of different types of detectors. The content of the present report is as Scopes of this report is as follows:

Chapter 1: Background. This chapter introduces the background of home fires, causes of home fires and briefly discusses the needs for smoke alarms to be installed in residential premises. Further, it overviews basic operating principles of photoelectric and ionisation smoke alarms, and provides general discussion of previous studies on the efficiency of smoke detectors.

Chapter 2: Literature review. Part I. First part of the literature review makes the analysis of the methodology and key conclusions of the recent FRNSW report. Further, it discusses in more detail the principles of photoelectric and ionization smoke alarm technology. The last section of this Chapter is devoted to the analysis of available fire statistics, with the emphasis on the information that is relevant for the present study. Of particular interest here are major causes of home fires, distribution of fatalities between fires of different types, and analysis of combustible materials involved in fires.

Chapter 3: Literature review. Part II. Second part of the Literature review provides analysis of performances of smoke alarms. Previous experimental tests on the performance of smoke alarms (in particular, ionisation and photoelectric) are reviewed, as well as major conclusions of these studies. Activation times of three types of smoke alarms, namely photoelectric, ionization and combination are directly compared. Discussion of nuisance alarms is also provided in order to understand their reasons, which will allow the probability of nuisance alarms to drop in the future.

Chapter 4: Development of additional testing scenarios. Based on the literature review (including the FRNSW report) on the historical home fire data and previous smoke alarms tests, new additional testing scenarios are proposed to obtain accurate data on the performance of smoke alarms of different types. Quantitative statistical methodology is also proposed for processing the results.

Chapter 5: Conclusion. Major conclusions of the study are presented in this section.

2. LITERATURE REVIEW: PART 1: FRNSW REPORT, SMOKE DETECTORS & HISTORICAL FIRE DATA

2.1 Working principles of smoke detectors

2.1.1 Ionisation smoke alarms

In an ionisation chamber, an electric field is maintained by applying a suitable voltage between two electrodes. A radioactive source situated inside the chamber, usually an alpha-emitter, furnishes the ionization radiation. Under an applied electric field, oppositely-charged ions move resulting in a small current flow between the electrodes. Smoke or aerosol particles, when admitted into the chamber, will cling on to the ions and reduce their mobility. This will in turn result in an overall altered electrical current and an associated change in the output voltage. Figure 1 shows a schematic diagram of the ionisation detector.

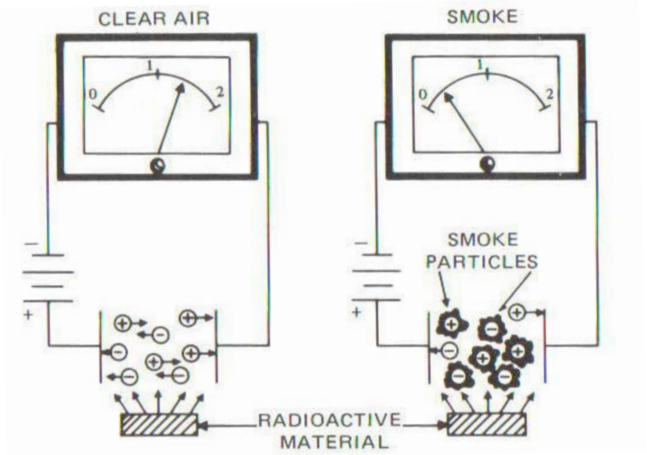


Figure 1: A schematic diagram of the ionization detector

Instead of voltage, generally, a dimensionless variable Y is used which is a linear function of the degree of obscuration [24]:

$$Y = \left(\Delta V/V_0\right)\frac{2-\left(\Delta V/V_0\right)}{1-\left(\Delta V/V_0\right)}$$

Equation 1

where V is the alarm output voltage, and is proportional to the ion chamber current; V_0 is the current of the ionisation chamber filled with clean air; and ΔV is the change in the voltage, i.e. (V_0-V).

The obscuration can be expressed by the following relation [4]:

$$O = \left[1-\left(\frac{I}{I_0}\right)^{\frac{1}{L_f}}\right]\times 100$$

Equation 2

where I is the intensity of the emerging light; I_0 is the initial intensity of the incident light; and L_f is the path length, expressed in feet.

Ionisation detectors generally provide faster response to flaming fire conditions as they are best suited to detect fine particles, from 0.01 to 0.3 microns.

2.1.2 Photoelectric smoke alarms

Photoelectric smoke detectors, on the other hand, operate on a totally different principle as compared to the ionization smoke detectors, i.e. based on light scattering by the interference due to smoke particles. [25]. Photoelectric smoke detectors constitute of a light source, typically a light-emitting diode (LED), and a light receiver such as a photocell, and the latter is arranged at such an angle impeding the reception of any light from the LED. The scattering volume element is defined by the intersection of the viewing angles of the light beam from the LED and the photocell [26]. As smoke particle enter the scattering volume, light from the LED will get scattered and will reach the photosensitive element (i.e. photocell), and this in turn will generate a current. As the smoke concentration in the scattering volume increases, the luminous flux received by the photocell also will increase proportionally. An alarm is triggered as the amount of scattered light reaching the photocell exceeds a pre-set threshold. The signal produced by photoelectric detectors is also sensitive to a number factors, including the physical characteristics of both the detector and smoke including the number concentration, size distribution, shape, and refractive index of the smoke particles as well as the scattering volume and wavelength of light used in the detector [27]. Figure 2 provides a schematic diagram of the photoelectric detector.

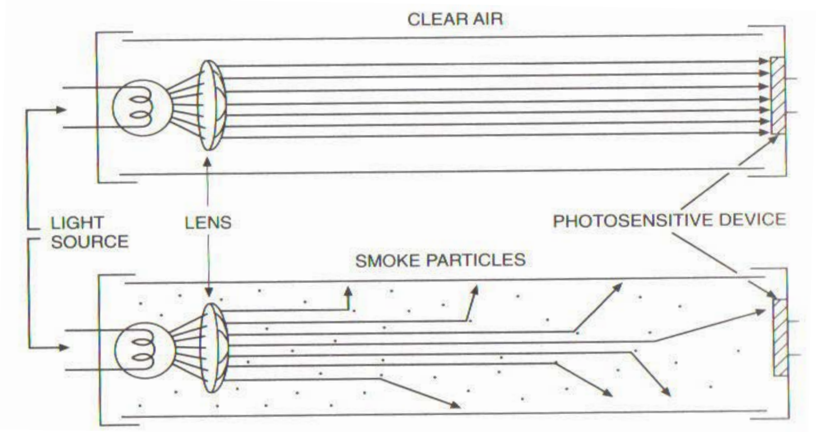


Figure 2: A schematic diagram of the photoelectric detector

Photoelectric alarms generally provide faster response to smouldering fire conditions as they are best suited to detect large smoke particles, from 0.3 to 10 microns, resulting from incomplete combustion.

There are usually two basic methodologies in use for estimating the response of smoke detectors – the Temperature Rise Method and the Optical Density Method (ODM) [28, 29]. The basic principle of the Temperature Rise Method is that the ratio of the optical density (OD) to temperature rise is approximately constant for a given fuel and combustion model. The Optical Density Method consists of directly calculating the smoke concentration at the detector and comparing the smoke level to an alarm threshold for the detector. A summary of previous testing results about optical density alarm thresholds for different types of smoke alarms is provided in [29]. Table 4 shows optical density alarm thresholds for different types of smoke alarms.

Table 4: Optical density alarm thresholds for different types of smoke alarms [29]

Test series	Detector type	Nominal sensitivity (OD/m)	Fire source	ODM alarm thresholds (OD/m)			ODM value at alarm (OD/m)	
Indiana Dunes [30]	Ion	0.0143	Flaming	0.003	0.015	0.090	0.060	0.117
Indiana Dunes [30]	Photo	0.0143	Flaming	0.018	0.045	0.118	0.138	0.237
Indiana Dunes [30]	Ion	0.0288	Flaming	0.003	0.024	0.116	0.081	0.133
Indiana Dunes [30]	Photo	0.0288	Flaming	0.022	0.057	0.118	0.138	0.227
Indiana Dunes [30]	Ion	0.0143	Smouldering	0.032	0.078	0.186	0.111	0.098
Indiana Dunes [30]	Photo	0.0143	Smouldering	0.021	0.040	0.087	0.074	0.111
Indiana Dunes [30]	Ion	0.0288	Smouldering	0.057	0.127	0.186	0.149	0.136
Indiana Dunes [30]	Photo	0.0288	Smouldering	0.033	0.057	0.118	0.082	0.084
Navy [31-33]	Ion	0.0071	Flaming	0.007	0.015	0.044	0.025	0.026
Navy [31-33]	Photo	0.0071	Flaming	0.012	0.028	0.056	0.031	0.026
Navy [31-33]	Ion	0.0186	Flaming	0.011	0.022	0.065	0.034	0.037
Navy [31-33]	Photo	0.0361	Flaming	0.028	0.049	0.057	0.055	0.046
Navy [31-33]	Photo	0.0508	Flaming	0.044	0.068	0.121	0.082	0.049
Navy [31-33]	Ion	0.0071	Smouldering	0.028	0.081	0.116	0.079	0.049
Navy [31-33]	Photo	0.0071	Smouldering	0.028	0.042	0.066	0.061	0.057
Navy [31-33]	Ion	0.0186	Smouldering	0.025	0.090	0.138	0.082	0.057
Navy [31-33]	Photo	0.0361	Smouldering	0.030	0.065	0.076	0.074	0.065
Navy [31-33]	Photo	0.0508	Smouldering	0.063	0.079	0.125	0.093	0.046
FRS [34]	Ion	0.0129	Flaming	0.013	0.025	0.062	0.039	0.039
FRS [34]	Ion	0.023	Flaming	0.006	0.023	0.053	0.032	0.034
FRS [34]	Photo	0.027	Flaming	0.056	0.120	0.165	0.117	0.061
FRS [34]	Photo	0.0295	Flaming	0.034	0.072	0.104	0.069	0.038
FRS [34]	Ion	0.0129	Smouldering	0.098	0.205	0.267	0.212	0.125
FRS [34]	Ion	0.023	Smouldering	0.032	0.094	0.164	0.100	0.074
FRS [34]	Photo	0.027	Smouldering	0.038	0.089	0.160	0.100	0.058
FRS [34]	Photo	0.0295	Smouldering	0.014	0.044	0.136	0.103	0.146

2.2 Fire & Rescue NSW Report

The FRNSW report [6] introduces first the background of smoke alarms, such as the principles of photoelectric and ionisation smoke alarms, smouldering and flaming fires and tenability criteria of incapacitation and death. Then the report analyses the fire historical data attended by FRNSW between 2000 and 2014 for class 1a and 2 buildings. Key elements of the FRNSW study, its results and conclusions are overviewed in this section. Further, deficiencies of research methodology employed by FRNSW are discussed.

Figure 3 (aggregated data from the Report) demonstrates that residential fires happened most frequently in kitchen (25%), and then in the bedroom (18%) and lounge room (13%). The four most probable modes ignition were electrical distribution & appliance (48%), open flame (13%), lighter/match (11%) and smouldering materials (7%). The first ignited materials are usually cooking materials (15%), followed by electrical wire & cable insulation (14%), mattress or bedding (9%), and upholstered furniture (5%).

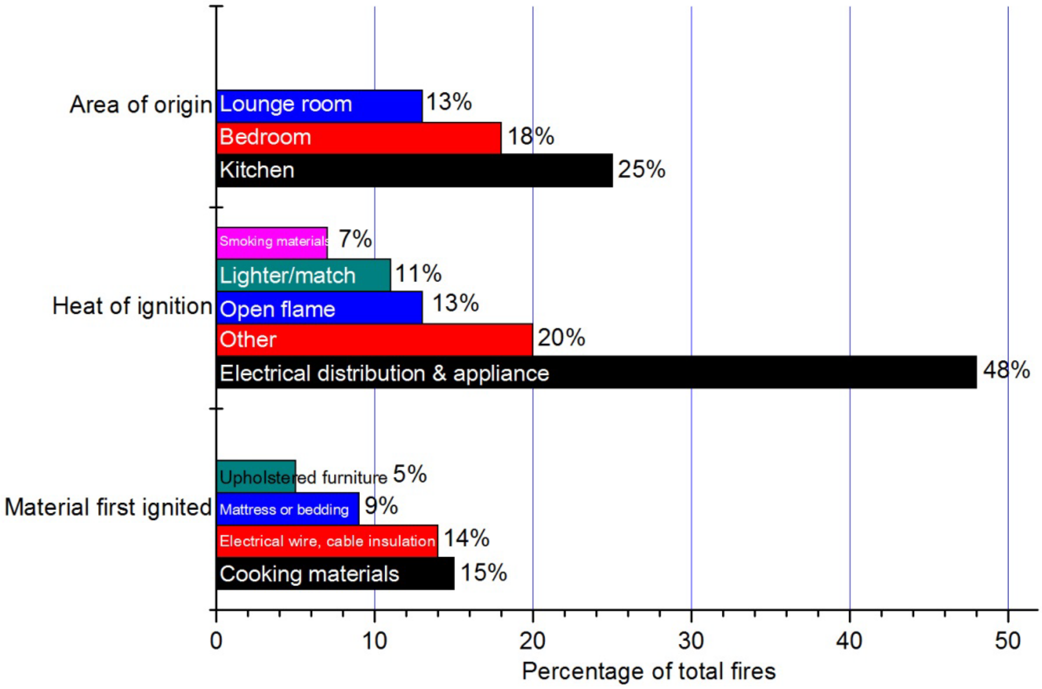


Figure 3: Percentage of total number fires under different situations for class 1a & 2 building during 2000-2014 [6]

Figure 4 shows the percentage of fatal fires under different conditions. It is apparent that fatal fires mostly happened at bedroom (36%), then the lounge room (30%) and kitchen (9%). The percentages by the heat of ignition, from higher to lower, are electrical distribution & appliance (37%), smoking materials (23%), open flame (13%) and lighter/match (12%). Most frequent first ignited material is mattress or bedding (21%), followed by upholstered furniture (15%), electrical wire & cable insulation (6%), and cooking materials (3%).

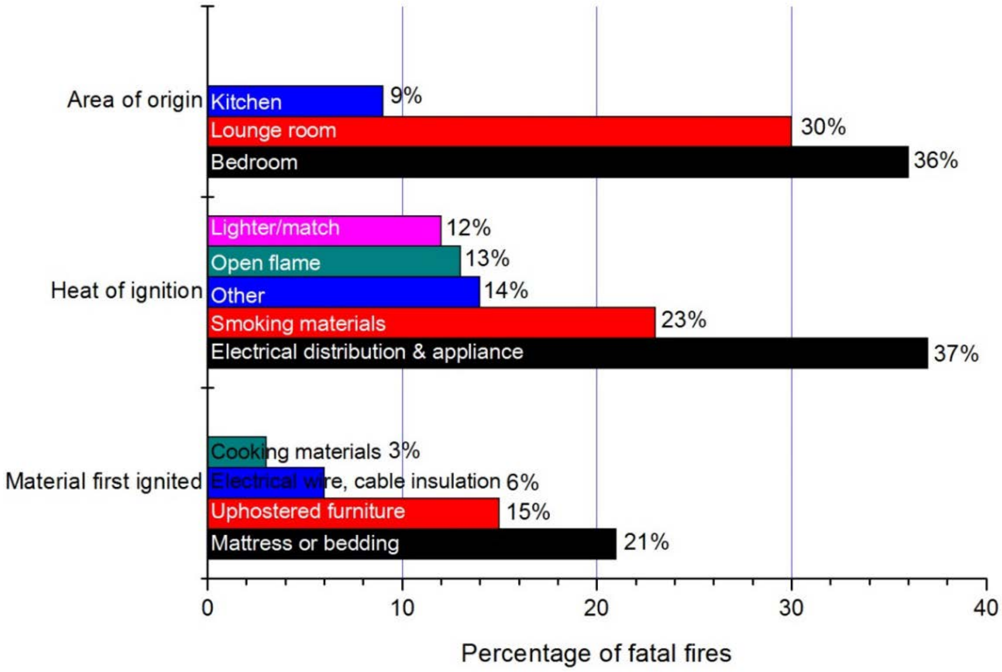


Figure 4: Percentage of fatal fires under different situations for class 1a & 2 building during 2000-2014 [6]

Figure 5 shows the percentage of fatal fires, classified by heat of ignition, in different rooms of origin. Most frequent ignition source in the kitchen is the electrical distribution & appliance (80%), and then lighter/match and open flame have the same percentage of 7%. It is quite interesting that there is no fire caused by smoking materials in the kitchen. In the lounge room, the most frequent ignition sources are smoking materials (43%), followed by electrical distribution & appliance (31%), open flame (10%) and lighter/match (5%). Compared to the situation in the lounge room, the electrical distribution & appliance (38%) and smoking materials (31%) occupy the first two places as ignition sources in the bedroom, and the percentages for lighter/match (15%) are higher than those for the open flame (8%).

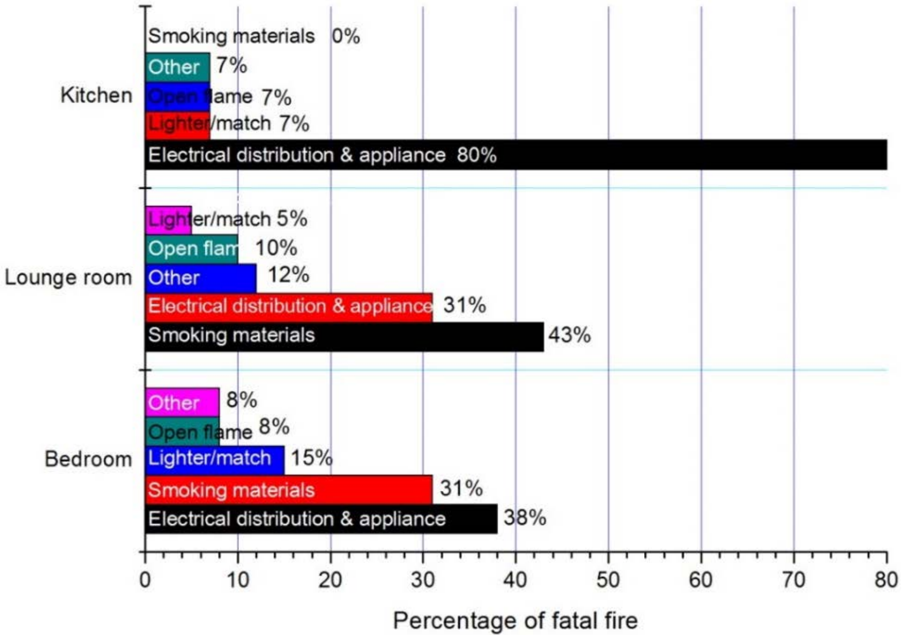
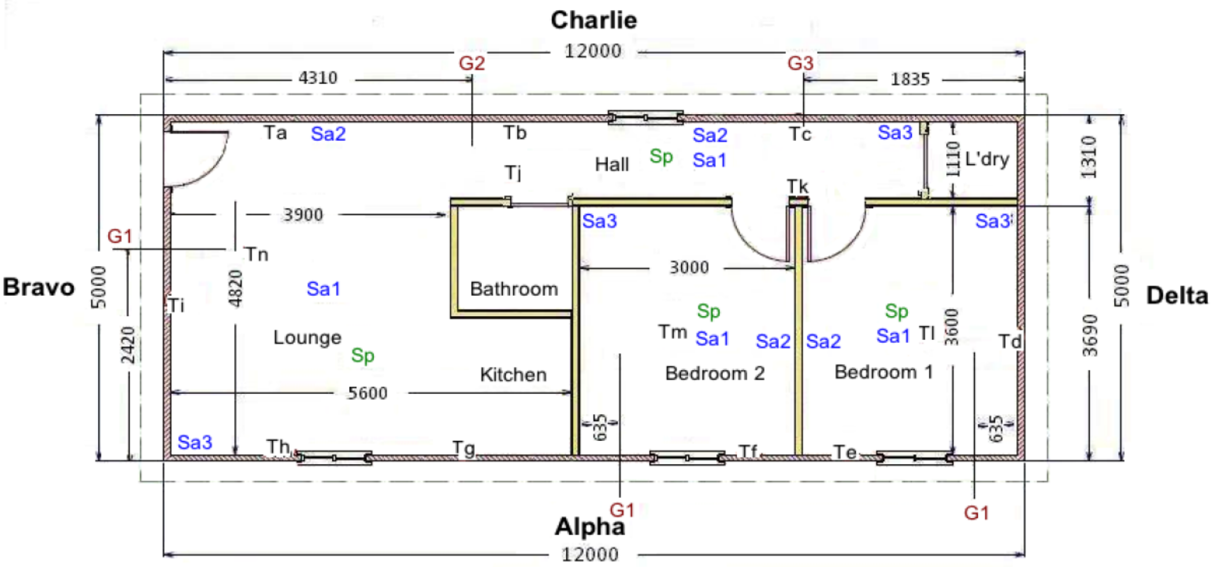


Figure 5: Percentage of fatal fires caused by heat of ignition in different areas of origin for class 1a & 2 building during 2000-2014 [6]

FRNSW used a test rig, simulating residential premises, to perform test burns. The setup was used to test the performance of different types of smoke alarms, such as ionization, photoelectric and combination. Figure 6 shows the layout of the residential test burn setup and the locations of testing equipment. Building structure of the residence was made of radiata pine with 16 mm fire resistant plasterboard lining the internal walls and ceiling. The outside of the building was lined with extra heavy duty premium wall warp and clad with 7.5 mm plywood.



Sa1 - ceiling level smoke alarm location
Sa2 - wall mounted smoke alarm location
Sa3 - dead zone smoke alarm location
G = gas monitoring locations
Sp - sprinkler head

Thermocouple location labelling with corresponding thermocouple numbering. Numbering goes bottom up. For thermocouples Ta-Ti, thermocouples located at floor, 1m, 1.5m and ceiling height. For thermocouples Tj-Tn, thermocouples located at floor, 0.75m, 1.5m and ceiling height.

Ta - 1,2,3,4
Tb - 5,6,7,8
Tc - 9,10,11,12
Td - 13,14,15,16
Te - 17,18,19,20
Tf - 21,22,23,24
Tg - 25,26,27,28
Th - 29,30,31,32
Ti - 33,34,35,36
Tj - 37,38,39,40
Tk - 41,42,43,44
Tl - 45,46,47,48
Tm - 49,50,51,52
Tn - 53,54,55,56

Figure 6: Residence design and equipment locations in the FRNSW tests [6]

A summary of experimental runs, performed by FRNSW, are listed in Table 5. It is important to note that 8 out of 10 runs were carried out under smouldering fire conditions. Two ignition methods were used, including cartridge heater and LPG gas flame. Other conditions included either closed or opened doors 1 and 2.

The focus of the test burns was to analyse smoke alarms in a real home fire environment. Therefore, although testing conditions as per AS3786:2015 were not followed (exact repeatability, all tests starting at 23°C ± 5 °C, test fire room design and structure, fire ignition sources, etc.), all tests simulated real home fires. The tests were undertaken in replica home residence with available bulk furniture from a national furniture chain, and under ambient Sydney conditions.

Table 5: A summary of experimental tests by FRNSW [6]

Runs	Location	Fire type	Materials	Ignition method	Conditions
1	Bedroom 1	Smouldering	Bedding	Cartridge heater	Bedroom 1 door closed; bedroom 2 door open;
2	Bedroom 2	Smouldering	Bedding	Cartridge heater	Two bedroom doors open
3	Lounge	Smouldering	Upholstered couch	Cartridge heater	Bedroom 1 door open; bedroom 2 door closed;
4	Bedroom 2	Smouldering	Bedding	Cartridge heater	Two bedroom doors open
5	Bedroom 2	Flaming	Bedding	LPG gas flame	Two bedroom doors open
6	Bedroom 1	Smouldering	Bedding	Cartridge heater	Bedroom 1 door closed; bedroom 2 door open;
7	Bedroom 1	Smouldering	Bedding	Cartridge heater	Two bedroom doors open
8	Lounge	Smouldering	Upholstered couch	Cartridge heater	Bedroom 1 door open; bedroom 2 door closed;
9	Bedroom 2	Smouldering	Bedding	Cartridge heater	Two bedroom doors open
10	Bedroom 1	Flaming	Bedding	Cartridge heater	Two bedroom doors open

Smoke alarm activation results in the room of origin and the hall are presented in Table 6 and Table 7, respectively. As the fire under flaming condition grew fast in the FRNSW test, there is no big difference among the activation time of the three types of smoke alarms. For example, in the burn 10, activation time for the three types of smoke alarms are 0.87 min in both the places of SA1 and SA2, and all of them did not active in the place of SA3. The only difference for the two flaming test is that the photoelectric smoke alarm activated at 0.17 min, a little early than those of ionization and combination smoke alarms, namely 0.18 min.

Table 6: Smoke alarm activation results in the room of origin [6]

Ignition	Burn #	ROO	Room of Origin (ROO)								
			SA1 P	SA1 I	SA1 D	SA2 P	SA2 I	SA2 D	SA3 P	SA3 I	SA3 D
Smoulder	1	Bed 1	17.35	DNA	15.58	11.5	DNA	13.1	14.65	DNA	12.17
Smoulder	2	Bed 2	DNA	DNA	20.45	27.57	DNA	14.33	26.47	DNA	15.42
Smoulder	3	Lounge	32.08	DNA	26.5	20.3	DNA	14.87	32.03	38.55	31.05
Smoulder	4	Bed 2	12.93	65 .17	11.57	14.33	64.42	12 .45	12.32	12.07	11.07
Smoulder	6	Bed 1	7.55	6.67	5.78	7.35	7.75	5.95	4.48	6.23	4.53
Smoulder	7	Bed 1	14.02	54 .78	55.37	15.98	54.25	15 .98	4.07	53.47	2.55
Smoulder	8	Lounge	33.52	42 .62	38.7	19.5	39.28	9.98	40.88	42.23	38.18
Smoulder	9	Bed 2	7.85	74 .10	7.85	6.32	69.87	6.78	7.85	68.25	7.85
Flaming	10	Bed 1	0.87	0.87	0.87	0.87	0.87	0.87	DNA	DNA	DNA
Flaming	5	Bed 2	0.17	0.18	0.28	0.68	0.68	0.68	0.68	O.68	0.68

It can be also inferred from Table 6 and Table 7 that in the room of origin the combination smoke alarm activated fast in most of the cases that is in 19 out of 24 cases. Photoelectric smoke alarm activated faster than the other two types of alarms in 8 out of 24 cases. No case was found where the first activated smoke alarm was ionisation. The results for the hall area are very much similar to those for the rooms of origin. In 15 out of 24 cases, combination smoke alarm activated faster than the other two types, then followed the photoelectric smoke alarm, namely in 4 out of 24 cases.

Table 7: Smoke alarm activation results in the hall [6]

Ignition	Burn #	ROO	Hall								
			SA1 P	**SA1 I**	**SA1 D**	**SA2 P**	**SA2 I**	**SA2 D**	**SA3 P**	**SA3 I**	**SA3 D**
Smoulder	1	Bed 1	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA
Smoulder	2	Bed 2	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA
Smoulder	3	Lounge	22.4	DNA	22.28	19.33	39.57	14.87	16.63	DNA	14.92
Smoulder	4	Bed 2	48.68	66.07	49.07	48.68	66.07	48.68	16	16.17	15.1
Smoulder	6	Bed 1	DNA	DNA	DNA	DNA	DNA	13.03	12.47	DNA	12.3
Smoulder	7	Bed 1	49.87	55.37	43.17	51.27	55.37	22.45	15.68	54.95	14.17
Smoulder	8	Lounge	26.72	4.12	DNA	21.97	40.12	19.97	24.8	42.1	24.73
Smoulder	9	Bed 2	55.85	74.33	15.05	56.08	72.68	52.5	12.8	72.35	12.2
Flaming	10	Bed 1	DNA	DNA	DNA	DNA	DNA	DNA	0.68	0.68	0.68
Flaming	5	Bed 2	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68

The FRNSW report also provides mean values of activation times for the two types of detectors in various rooms of fire origin. Only smouldering fire scenarios are considered in the statistical analysis. These mean activation times (in minutes) are 17.03 for photoelectric alarm, and 44.19 for ionisation alarm. Similar results for the Hall location are 32.19 (photoelectric) and 57.55 (ionisation). These are average figures across the number of tests. There was no possibility to evaluate Standard Deviations at each fixed location as each type of the test was not repeated. There were no statistical analysis on flaming conditions provided in the view of extremely limited number (two only) tests at such condition.

Some key conclusions can be extracted / quoted from the FRNSW report:

- The investigators admit that “the area of research is too broad to draw definite conclusions based on a single test study”.
- Nevertheless, they conclude (based primarily on average response times) that, across the range of burns and placement locations, ionisation alarms were significantly inferior to their competitors (photoelectric and dual detectors)
- Photoelectric and dual photoelectric/ionization alarms still fell short of the arbitrarily applied yet reasonable expectation of 90% activation in the home fire scenarios tested.
- The focus of the study was on hallway alarm activation. The findings, although preliminary, clearly demonstrated that smoke alarms did not provide effective notification for safe egress when located in hallway only. When room of fire origin alarms were included, the results still fall short of acceptable levels.
- “Aerosol density measurements were not taken, thereby limiting data comparison to the AS3786 test standard. However, the fact that all alarms used met the standard, yet such low percentages of smoke alarms provided safe egress, the question must be raised as to whether smoke alarm test standards should require conditions to be maintained with regard to heat and toxic gases, rather than focusing on aerosol density. Or, if aerosol density has been derived around tenability limits, then perhaps this threshold needs to be reviewed. This would be a

difficult challenge to meet, as different home furnishing materials provide different time to loss of tenability, dependent also on the type of fire occurring".

- The results suggest that alarms operate in fires where fatalities still occur, due to them not alerting the occupant. There are a range of possibilities as to why such fatalities have occurred, including the possibility that the occupant had been already incapacitated due to toxic smoke inhalation.
- "The failure of smoke alarms to respond within tenability and safe egress limits raises the important question of whether or not smoke alarms are performing as desired in the modern home. Although much research has been done to show activation rates and that alarm positions and types are comparable and statistically equivalent, relatively less work has focused on the need for smoke alarms to provide safe egress. Without providing safe egress, activation time becomes irrelevant".

The present study focuses on objective quantitative procedure to compare performance of ionisation and photoelectric detectors. For this point of view, several major drawbacks of research methodology employed by FRNSW have been identified:

- Number of tests is too limited for a meaningful statistical analysis of a very complex phenomenon with multiple factors and uncertainties.
- Repeatability. Experimental runs were not repeated for each of the scenarios, which may have had an influence on the final outcome on the performance of different types of smoke alarms. No Standard Deviations could be established for the results of each of the tests.
- Literature review with respect to various fire initiation conditions and scenarios is too limited. The research methodology must have been informed by the comprehensive literature review.
- There is a severe imbalance in the testing program, even at a glance, between smouldering and flaming fire conditions. The proportion of tests (8:2 ratio between smouldering and flaming scenarios) is not realistic. This is further confirmed by the analysis of the present study conducted in the Section 2.3.

  An example of important fire conditions that have been excluded by such a methodology are kitchen fires. The FRNSW report itself states that 25% of total fire happened in the kitchen (Page 26) and that 15% of all the fires start from cooking materials (Page 27).
- With only two tests under flaming conditions, no statistical analysis could be performed on these scenarios. With a negligible number of tests, flaming conditions, effectively, have been excluded from the consideration altogether. This inevitable predetermined the final outcome being in favour of photoelectric alarms. Therefore, the major conclusion of the FRNSW study on the comparative performance of the two types of detectors cannot be considered as soundly justified.
- Energy supply provided to initiate smouldering fire scenarios (cartridge heater) seems excessive compared with a large number of smouldering fires starting from a burning cigarette. This potentially produced another skew in the data towards faster responses of photoelectric alarms.
- It seems that for flaming conditions fire heat release rate increased too fast, resulting in a very close results of performance for the three types of smoke alarm. The details can be seen in Table 6 and Table 7 of the Report. There is a concern that under more modest fire growth rates ionisation detectors could respond faster, which was not picked up by the FRNSW study. The energy output of the LPG burner used to initiate flaming scenarios should be reduced.

2.3 Analysis of historical fire data

In the view of the working principles of smoke detectors, in order to evaluate their statistical performance in real fires. A detailed analysis of flaming fire frequencies versus smouldering fires frequencies is required. A very important factor which also need be considered is fire fatality, i.e. whether fatalities occur in one type of fire conditions more often than in the other.

In principle, the criteria which is needed to classify fires with regard to photoelectric/ionization alarms response may be proposed in the following manner:

weighted frequency of flaming fires = (number of flaming fires without fatalities + number of flaming fires with fatalities x fatality weight) / (total number of fires) (on per year basis)

weighted frequency of smouldering fires = (number of smouldering fires without fatalities + number of smouldering fires with fatalities x fatality weight) / (total number of fires) (on per year basis)

Fatality weight is a factor attached to the importance of fire loss in a fire, i.e. 10.100, etc. (The methodology to determine a precise reasonable value for this factor is outside of the scope of the present study).

This approach would provide fatality-weighted frequency distribution

$$(f,s) \quad 0 \le f \le 1,\, 0 \le s \le 1;\; s + f = 1$$

Equation 3

where f refer to flaming fire frequency, and s refer to smouldering fire frequency.

It also possible to further separate fires resulting in non-fatal injuries, it assign it yet different weighting.

In principle, smoke alarm testing should be arranged in such a way that the test scenarios reflect the frequency distribution (1)

Unfortunately, available fire statistics data do not allow the distribution (1) to be derived confidently.

Typically, fire statistics reveals the following major data:
- total number of fires
- number of deaths
- number of injuries
- causes of fires (by the type of materials first ignited, types of materials involved, area of fire origin, etc.)

Although Australian fire data is obviously of the paramount importance, and extended set of data may be obtained when international statistics is taken into account. Data from the United States and New Zealand is also considered in the present study. There is strong evidence [6, 35] that Australian data is comparable to the international statistics. Therefore, analysis of extended (international) data set is justified in the context of the present study.

In general, fire statistics data, especially obtained from the number of different countries, is rather non-uniform, and consistent statistical analysis is difficult to perform until the data is in some way harmonised in a way suitable for algorithmic processing.

The key findings from various literature sources are summarised, however, below

Australia-wide report on residential fire fatalities by Australasian Fire and Emergency Service Authorities Council [10] provides data on the rate of fatalities for the financial years from mid-1996 to mid-2004. It demonstrates (Table 8) the rates for Australia varying overall from 0.1 to 0.7 per 100,000 persons per year. No consistent trend is evident over time.

Table 8: Number of residential fire deaths per 100,000 in Australia and New Zealand [10]

	Deaths per 100,000	
Year	**National**	**New Zealand**
1996-1997	0.25	0.70
1997-1998	0.12	0.54
1998-1999	0.41	0.60
1999-2000	0.31	0.31
2000-2001	0.30	0.44
2001-2002	0.30	0.67
2002-2003	0.37	0.60
2003-2004	0.07	0.10

Similar data (Table 9) on injuries in residential fires in Australia [8] showed that injuries per year in the period from mid-1999 to mid-2006 ranged from 4.37 to 6.03 per 100,000 persons per year.

Table 9: Fire injuries in New Zealand [8]

	Injured persons per 100,000	
Year	**Australia**	**New Zealand**
1999/2000	4.37	4.88
2000/2001	4.81	4.43
2001/2002	5.17	7.55
2002/2003	5.56	7.09
2003/2004	6.03	6.73
2004/2005	5.81	6.29
2005/2006	5.47	5.9

More detailed data on residential fires in Australia are available from several sources.

Fire and Rescue NSW (FRNSW) in their recent report [6] provides analysis for the fires in classes 1a and 2 buildings which it attended to between 2000 and 2014.

For the purpose of the present study the following detailed breakdowns [6] are important to consider:

- Percentages of fires by the area of origin (fatal fires vs total)
- Percentages of fires by the form of heat of ignition (fatal fires vs total)
- Percentages of fires by the form of material first ignited (fatal fires vs total)

These are presented in Figure 7,Figure 8 and Figure 9 respectively.

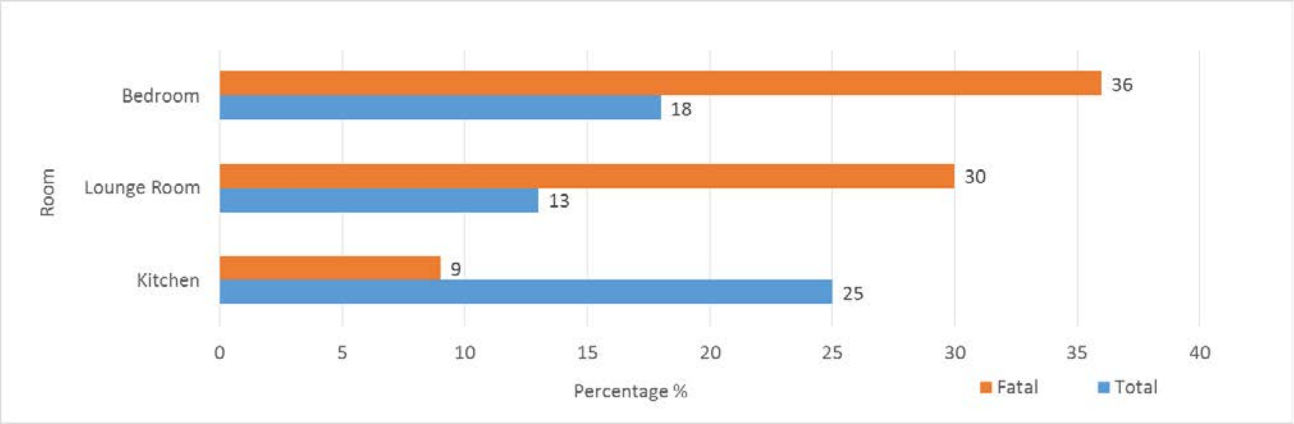


Figure 7: FRNSW: Percentages by Area of Origin, Total Fires vs Fatal Fire, 2000-2014, Class 1a & 2 Buildings [6]

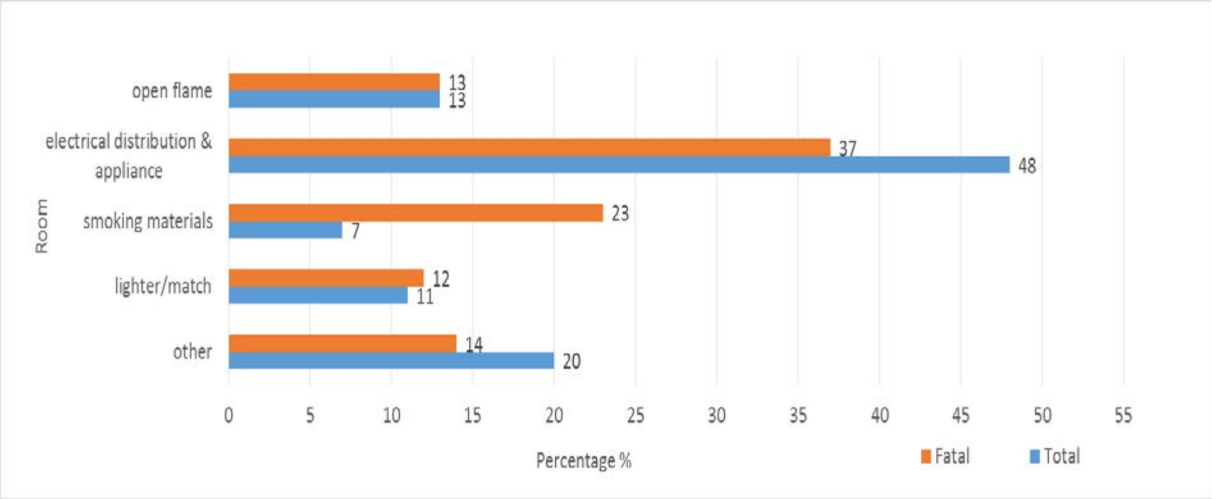


Figure 8: FRNSW: Percentages by Form of Heat of Ignition, Total Fires vs Fatal Fires, 2000-2014, Class la & 2 Buildings. Modified from [6]

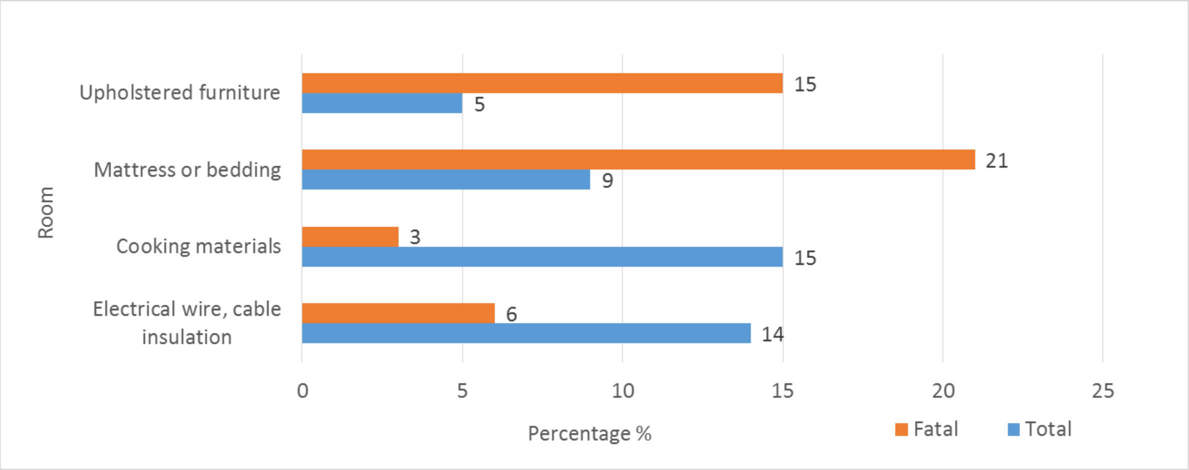


Figure 9: FRNSW: Percentages by Form of Material First Ignited, Total Fires vs Fatal Fires, 2000-2014, Class Ia & 2 Buildings [6]

Major findings of FRNSW informed design of their testing program and consequently final conclusions of their report. They found (Figure 7) that majority of home fires resulting in fatalities originated in either lounge room (30%) or bedroom (36%). Much less (9%) of fatal fires originated in the kitchen area. It should be noted that data on 25% of fatal fires is missing from Figure 7, i.e. it cannot be established with confidence where these fires originated.
With respect to the Form of heat of Ignition, the major scenarios that need be considered are electrical distribution / appliance malfunction, and the smoking materials **Figure 8**.

Further, FRNSW considered materials first ignited (Figure 9). The proper figure to look at, from the fatality point of view, will be percentage of fatal fires started from either mattresses, bedding or upholstered furniture. It is clear from Figure 9 that this figure is actually 36%. Such materials are considered by FRNSW as burning most likely in smouldering mode, with majority of ignitions occurring from smoking materials.

Even based on assumption that any fire involving mattresses, bedding or upholstered furniture would be a smouldering fire (which is obviously overestimation), the percentage of fatalities occurring from smouldering fires cannot exceed 36% (within the statistical FRNSW data set). This is consistent with further reference on p. 29 [6] which puts the figure to 25%. Although we agree with FRNSW that this shows that “reasonable percentage of these fatal fires may have begun by means of smouldering combustion”, “reasonable” actually means only around quarter of fatal fires.

This finding cannot be seen as a justification for severe bias in the FRNSW testing program towards smouldering fires (8 smouldering scenarios out of 10 tests).

It is important to analyse alternative statistical data to derive some further conclusions on the likely ratio between flaming and smouldering fires.

Various forms of fire statistical data are available from [11] (Australian data), [36] (Australia), [35] (Australia, NZ, US), [4] (US), [23] (US), [16] (US), [9], [13], [37], [38].

Further Australian fire statistics is provided by [11].
Percentages of survived versus fatal residential fires by *type of materials ignited, form of materials ignited, form of heat ignition, ignition factor*, adopted from this report, are presented in Table 10, Table 11, Table 12, and Table 13.

Table 10: Percentages of survived versus fatal accidental residential fires by type of materials ignited [11]

Type of Materials Ignited	Survivors% (n)	Fatalities% (n)
Plastic	35.3 (60)	3.0 (4)
Cooking oil	16.5 (28)	3.0 (4)
Fabric/ fibre/ rayon/ cotton, finished goods	17.1 (29)	61.3 (81)
Wood	5.9 (10)	8.3 (11)
Fat/ grease	4.7 (8)	0.8 (1)
Paper and treated paper	2.9 (5)	8.3 (11)
Food	2.4 (4)	0 (0)
Natural or LPG gas	2.4 (4)	6.0 (8)
Other (i.e., natural gas, LPG gas, petrol, grain, petroleum distillate, methyl ethyl ketone, turpentine, kerosene)	5.3 (9)	9.1 (12)
Total	100.0 (170)	100.0 (132)

Table 11: Percentages of survived versus fatal accidental residential fires by form of materials ignited [11]

Form of Materials	Survivors % (n=175)	Fatalities % (n=161)
Cooking materials	25.1 (44)	1.9 (3)
Appliances	18.3 (32)	3.7 (6)
Electrical wiring/cable	9.7 (17)	0.6 (1)
Bedding/ blanket/ sheet/ comforter	5.7 (10)	20.5 (33)
Wearing apparel not on a person (not specified)	2.9 (5)	6.2 (10)
Ceiling covering/ surface	2.9 (5)	0.6 (1)
Insulation	2.9 (5)	0 (0)
Upholstered couch/ chair	2.9 (5)	13.0 (21)
Cabinetry	2.9 (5)	4.3 (7)
Paper/newspaper	2.3 (4)	14.3 (23)
Structural component finish not classified	2.3 (4)	5.0 (8)
Non-upholstered chair/ bench	2.3 (4)	1.9 (3)
Gas or liquid (accelerants)	2.3 (4)	2.5 (4)
Mattress/ pillow	1.7 (3)	7.5 (12)
Rubbish/ trash/ waste	1.7 (3)	3.1 (5)
Curtain/ blinds/ drapery/ tapestry	1.7 (3)	1.9 (3)
Floor covering surfaces (e.g., tiles/carpet/rug/ flooring and stairs)	0.6 (1)	7.5 (12)
Wearing apparel on a person	0	23.6 (38)

Other (e .g., perfume, wheat packs, plastic containers and toys)	7.3 (13)	3.1 (5)
***Note the cumulative percentage is not 100% as multiple forms of material ignited were possible**		

Table 12: Percentages of survived versus fatal accidental residential fires by form of heat ignition [11]

Form of Heat Ignition	Survivors % n	Fatalities % n
Heat from gas fuelled equipment	19.8 (34)	9.1 (15)
Unspecified short circuit arc	20.3 (35)	8.5 (14)
Heat from properly operating electrical equipment	18.6 (32)	16.4 (27)
Heat from improperly operating electrical equipment	12.2 (21)	1.8 (3)
Candle	5.8 (10)	6.1 (10)
Lighter/ match	5.2 (9)	6.1 (10)
Arc from faulty contact/ loose connection/ broken conductor	4.7 (8)	0 (O)
Heat from overloaded equipment	4.1 (7)	1.8 (3)
Heat from cigarette or discarded materials	2.9 (5)	41.5 (68)
Open fire	1.2 (2)	2.4 (4)
Heat from liquid or solid fuel/ powered equipment	2.9 (5)	5.5 (9)
Other (i.e., friction, open flame/ cutting torch operation)	2.3 (4)	17.1 (28)
Total	100.0 (172)	100.0 (164)

Table 13: Percentages of survived versus fatal accidental residential fires by ignition factor [11]

Ignition Factors	Survivors % (n=175)	Fatalities % (n=154)
Electrical failure	35.4 (62)	12.3 (19)
Unattended cooking	18.9 (33)	3.2 (5)
Combustibles too close to heat	14.9 (26)	28.6 (44)
Lack of maintenance/worn out	8.0 (14)	0(0)
Children playing with ignition source	6.9 (12)	1.9 (3)
Other cooking related	5.1 (9)	1.9 (3)
Discarded cigarettes or other materials	2.9 (5)	45.1 (74)
Overloaded (electrical)	3.4 (6)	1.3 (2)
Misuse of materials ignited	0 (0)	8.4 (13)
Others (i.e., open fire, design fault, lightning, improper start up/shut down procedures)	6.9 (12)	7.8 (12)
Total	NA*	NA
Note.* indicates the cumulative percentage is not 100% as multiple ignition factors were possible.		

These data provides important information potentially shading the light on percentage of fatalities resulting from smouldering vs flaming fires. Although exact figures cannot be obtained explicitly from the tables, estimations based on some reasonable assumptions are possible.

Analysis of materials leading to fatal accidents (Table 11) allows those with the potential to support smouldering fires to be identified. These are upholstered items, bedding, mattresses, and some floor coverings (such as carpets). Estimation based on the data from Table 11 shows that maximum number of fatalities resulting from smouldering fires is about 78, out of 161 total fatalities. Therefore, smouldering fires contribute to about 46% of total fatalities number.

Similar estimation based on the US data from Table 14 (number of fatalities by leading items first ignited) provide the figure of about 34%.

Table 14: Non-confined home structure fire deaths by leading items first ignited and smoke alarm status: 2003 to 2006 annual averages [16]

	Present and operated			Present but did not operate			None present		
	Civilian deaths			Deaths			Deaths		
	#	%	Deaths per 100 fires	#	%	Deaths per 100 fires	#	%	Deaths per 100 fires
Upholstered furniture	220	22%	7.6	110	18%	12.8	310	28%	9.1
Mattress or bedding	180	18%	3.5	100	16%	6.4	150	13%	3.1
Flammable or combustible liquid or gas, or pipe, hose, duct or filter	90	9%	2.8	40	6%	5.6	60	6%	1.7
Clothing	80	8%	2.2	40	6%	3.3	40	3%	1.3
Unclassified furniture or utensil	60	5%	2.1	30	5%	4.7	80	7%	3.4
Structural member or framing	50	4%	0.7	40	6%	1.8	50	4%	0.6
Cooking material , including food	40	4%	0.3	30	5%	1.0	30	3%	0.5
Multiple items first ignited	30	3%	2.4	20	3%	4.8	40	4%	1.9
Electrical wire or cable insulation	30	3%	0.5	10	2%	0.6	50	4%	0.9
Floor covering rug, carpet, or mat	30	3%	1.4	50	8%	9.1	50	4%	1.7
Cabinetry	30	2%	0.9	10	2%	1.9	20	2%	1.1
Interior wall covering, excluding drapes	20	2%	0.7	20	3%	2.6	60	6%	1.6
Rubbish, trash or waste	20	2%	1.0	20	3%	3.3	20	1%	0.6
Unclassified structural component or finish	20	2%	1.0	20	3%	3.2	50	4%	1.4
Magazine, newspaper or writing paper	20	2%	1.3	10	1%	2.0	20	1%	1.1
Unclassified soft goods or wearing apparel	20	2%	1.0	10	2%	2.3	30	2%	1.7

Note: Percentages were calculated from the number of deaths with each smoke alarm status. Confined fires, which tend to be minor, were excluded from the calculations of deaths per 100 reported fires.
Source: NFIRS 5.0 and NFPA survey

US data on statistics on the causes of home fires (Figure 10) suggests that cooking and heating equipment combined result in more deaths than smoking materials (39% and 25%, respectively).

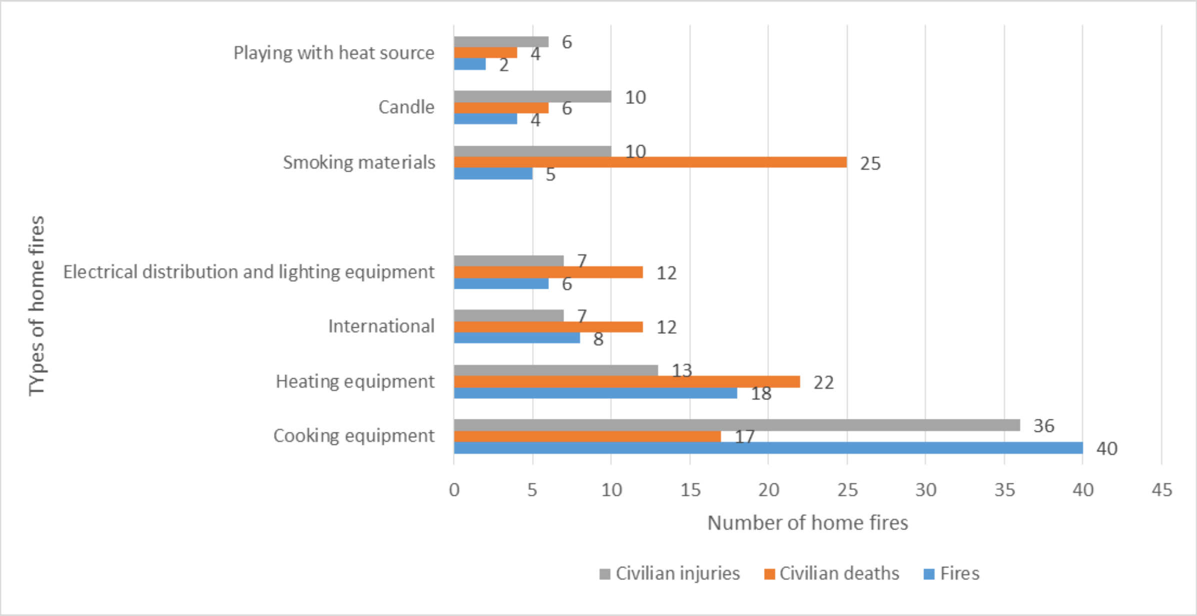


Figure 10: Leading causes of home fires, United States, 2003-2007 [13]

Similar set of data available online [37] (Table 15) indicates a ratio between deaths resulting from flaming fires to deaths resulting from smouldering fires of about 40/23.

Table 15: Major causes of residential fires, civilian deaths and injuries in the United States from 1999-2002 [37]

Major cause	**Fires**	**Civilian deaths**	**Civilian injuries**
Cooking equipment	121, 000 (31.0%)	290 (9%)	4,510 (28%)
Heating equipment	60,000 (15.4%)	360 (12%)	1,330 (8%)
Intentional	41,000 (10.5%)	620 (20%)	1,770 (11%)
Open flame, ember, or torch	34,000 (8.8%)	260 (9%)	2,250 (14%)
Electrical distribution equipment	32,000 (8.3%)	240 (8%)	1,000 (6%)
Smoking materials	22,000 (5.7%)	720 (23%)	1,820 (11%)
Appliance, or air conditioning	22,000 (5.7%)	70 (2%)	700 (4%)
Other heat source	18,000 (4.6%)	190 (6%)	780 (5%)
Exposure	16,000 (4.0%)	30 (1 %)	90 (1 %)
Child playing	13,000 (3.2%)	220 (7%)	1,320 (8%)
Natural causes	6,000 (1.5%)	10 (0%)	60 (0%)
Other equipment	5,000 (1.2%)	40 (1 %)	230 (1%)
Total	**390,000**	**3,050**	**15,860**

Similar assessments are possible from the data presented in Table 16 [9].

Table 16: Leading causes of residential building fire deaths in U.S. during 2003-2012 [9]

Year	Smoking	Intentional	Other, unintentional, careless	Cause under investigation	Electrical Malfunction
2003	500	280	430	210	380
2004	510	270	420	200	370
2005	520	350	410	205	305
2006	490	250	380	180	295
2007	480	310	390	250	300
2008	390	310	420	270	390
2009	370	280	410	260	290
2010	360	280	420	250	290
2011	310	250	380	350	290
2012	340	310	300	290	205

Death number resulting from “other unintentional” fires is quite comparable with the number of smoking fire deaths and has outnumbered them in some recent years. When combined with deaths resulting from “electrical malfunction”, the figure becomes higher that supposed number of smouldering fire deaths.

When considering detailed breakdown of fire deaths causes [9] (Table 17, Table 18, Table 19 and Table 20)

Table 17: Trend of residential building smoking fires in U.S. during 2003-2012 [9]

Year	Estimate of Fires	Estimate of Deaths	Estimate of Injures	Estimate of dollar loss ($millions)
2003	8900	500	1025	308.2
2004	9000	505	1050	318.4
2005	8700	510	1025	358.9
2006	9700	485	1150	367.7
2007	8900	470	950	293
2008	8300	390	950	352.4
2009	7000	360	900	375.3
2010	7600	350	950	301.3
2011	7800	305	1050	302.6
2012	9600	330	800	348.1

Table 18: Trend of residential building electrical malfunction fires in U.S. during 2003-2012 [9]

Year	Estimate of Fires	Estimate of Deaths	Estimate of Injures	Estimate of dollar loss ($millions)
2003	26400	360	900	1.1
2004	27000	350	900	1.1
2005	28500	310	1125	1.3
2006	30000	290	1000	1.2
2007	30500	295	1175	1.1
2008	29100	380	1075	1.3
2009	24700	280	1150	1.2
2010	26100	280	1050	1.1
2011	26800	280	1200	1
2012	20200	210	900	0.8

Table 19: Trend of residential building heating fires in U.S. during 2003-2012 [9]

Year	Estimate of Fires	Estimate of Deaths	Estimate of Injures	Estimate of dollar loss ($millions)
2003	61000	155	675	421.7
2004	60600	200	650	350.8
2005	54200	220	625	347.3
2006	53600	175	575	357
2007	54400	175	700	287.1
2008	53300	145	600	363.4
2009	50200	160	550	322.5
2010	46800	145	575	342.8
2011	43700	180	550	289.2
2012	45200	195	775	421

Table 20: Trend of residential building open flame fires in U.S. during 2003-2012 [9]

Year	Estimate of Fires	Estimate of Deaths	Estimate of Injures	Estimate of dollar loss ($millions)
2003	23700	310	1875	832
2004	23100	295	1600	861.7
2005	22900	240	1600	961.8
2006	22300	205	1475	817.4
2007	20900	245	1475	730.4
2008	19400	210	1325	1099.5
2009	16200	170	1125	853.3
2010	16800	200	1150	636
2011	17000	195	1300	617
2012	18200	175	1100	631.5

It appears that, for example, in 2012 580 deaths had flaming fire as a likely cause (electrical malfunction, building heating, open flame), while fires that likely went through smouldering stage resulted in 330 deaths, by comparison.

Further data from the US Fire Administration [38] is presented below in Figure 11. Again, it is clearly seen that electrical fires, combined with other causes result in more deaths compared to fires started by smoking.

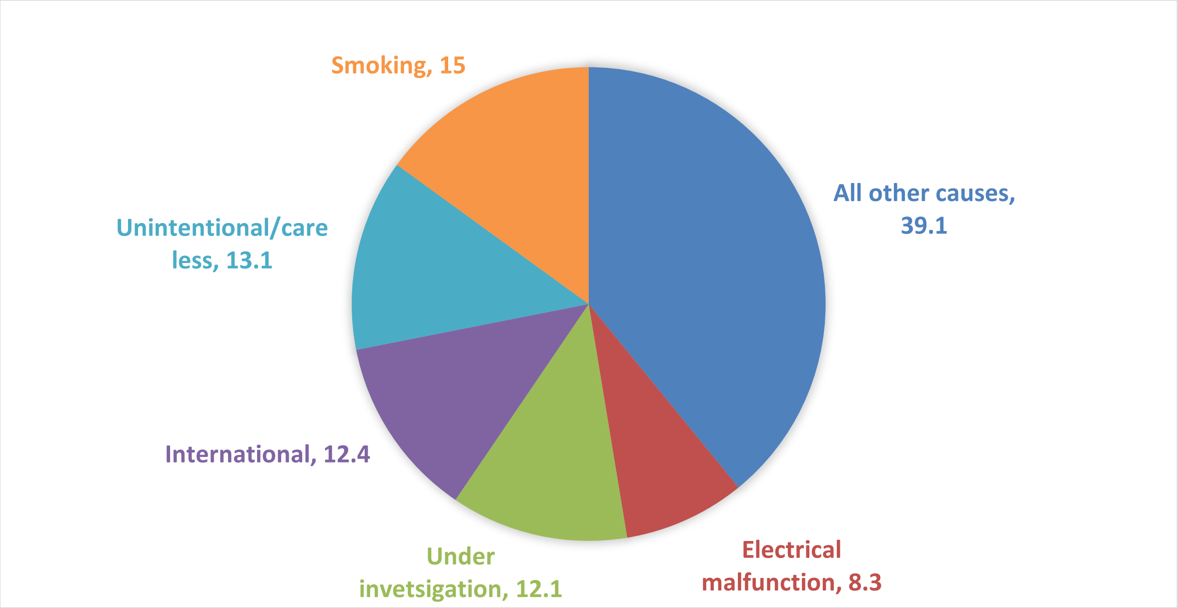


Figure 11: Causes of fatal residential building fi res in U.S. in 2012 [38]

Study by NIST, Table 21 [4] allows direct comparison between number of deaths in smouldering and flaming fires to be made.

Table 21: Top fire scenarios ranked by frequency of occurrence, 1992-1996 [4]

Location	**Fire Type**	**First Item Ignited**	**Frequency**
Ranked by Frequency of Occurrence			
Kitchen	Flaming	Cooking Materials	81 905
Bedroom	Flaming	Mattress	15914
Kitchen	Flaming	Wire /Cable	7499
Bedroom	Smouldering	Mattress	6437
Kitchen	Fast Flaming	Cooking	5134
Bedroom	Flaming	Wire / Cable	4551
Kitchen	Flaming	Interior Wall Covering	4271
Living Room	Smouldering	Upholstered Furniture	4060
Living Room	Flaming	Upholstered Furniture	3715
Living Room	Flaming	Wire / Cable	3481
Ranked by Number of Deaths			
Living Room	Smouldering	Upholstered Furniture	372

Bedroom	Smouldering	Mattress	251
Bedroom	Flaming	Mattress	249
Living Room	Flaming	Upholstered Furniture	160
Kitchen	Flaming	Cooking Materials	142
Kitchen	Flaming	Clothing	79
Living Room	Flaming	Wire / Cable	61
Living Room	Flaming	Interior Wall Covering	51
Bedroom	Flaming	Clothing	51
Kitchen	Flaming	Structural Member Framing	50

It is seen from Table 21 that smouldering fires caused 623 fatalities while flaming fires caused 844 fatalities.

It should also be taken into account that cooking fires are top ranked as causes of fire injuries [9, 35, 38].

In the absence of the ways to produce more precise estimation, it is proposed that flaming and smouldering fires are considered as resulting, statistically, in approximately equal number of fatalities.

This balance is reflected in the extended testing program proposed in the Section 4.2

3. PERFORMANCES OF SMOKE ALARMS

3.1 Previous tests on smoke alarms

In the recent years, questions were raised about the efficacy of some smoke alarm technologies, whether their numbers and locations in homes still represents the optimum configuration, and if multi-sensor designs (as are becoming popular for commercial fire alarm systems) might perform better or produce fewer nuisance alarms [4]. Table 22 shows a summary of previous experimental tests on the performance of smoke alarms.

Table 22: A summary of previous experimental tests on the performance of smoke alarms

Experiments	Year	Materials	Ignition method	House	Results
Cleary [1]	2014	Cotton, polyester	Gas-flame ignition tube	Two-level structure	It was observed that dual alarms with equivalent or higher sensitivity settings performed better than individual photoelectric or ionization alarms over a range of flaming and smouldering fire scenarios. Over a range of ionization sensor settings examined, dual alarm response was insensitive to the ionization sensor setting for initially smouldering fires and fires with the bedroom door closed, while dual alarm response to the kitchen fires

Experiments	Year	Materials	Ignition method	House	Results
					was very sensitive to the ionization sensor setting.
Thomas and Bruck [39]	2010	Burning ethanol, braided wick, heptane, decalin, smouldering wood, wood cribs, smouldering towel and polyurethane foam	Flaming and smouldering	Full-scale card board house	The type of detector technology used appears to have a relatively minor influence on alarm activation time compared with other factors, such as door and fire of origin.
Mealy et al. [40]	2009	Cotton batting, Sofa, Wooden cabinet	Flaming and smouldering	Apartment-style enclosure	Smouldering fires only posed threats under specific conditions and after hours. In general, all of the smoke alarm technologies provided sufficient time to escape the fires before untenable conditions.
Su and Crampton [2]	2009	Wood, paper, polyurethane foam, cotton flannel and upholstered furniture	Flaming and smouldering	Residential dwelling and laboratory room	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.
Mealy et al. [3]	2009	Cotton batting, Sofa, Wooden cabinet	Flaming and smouldering	Full-scale enclosure	The tests demonstrate that the most hazardous conditions developed during the flaming fire scenarios. In general, all of the smoke alarm technologies provided sufficient time to escape the fires before untenable conditions.
Bukowski et al. [4]	2007	Upholstered furniture; mattress; cooking materials.	Flaming, smouldering and cooking	Manufactured; two-storey	Both common residential smoke alarm technologies (ionisation and photoelectric) provided positive escape times in most fire scenarios with the ionisation type reacting earlier to flaming fires and the photoelectric type reacting earlier to smouldering fires. Similar trends are seen for the two-story home tests.
Gottuk et al. [5]	2002	Smouldering wood, flaming fabric and cooking fumes	Flaming, smouldering and cooking	A 49m^3 test room	The results show that improved fire-detection capabilities can be achieved over standard smoke detectors by combining smoke measurements with CO measurements in specific algorithms. False alarms can be reduced while increasing sensitivity (i.e. decreasing the detection time for real fires). Alarm algorithms utilizing ionization detector smoke measurements proved to be more effective than measurements from photoelectric detectors. As expected, the

Experiments	Year	Materials	Ignition method	House	Results
					ionization detectors were better at detecting flaming fires, and the photoelectric detectors were better at detecting smouldering sources.
Meland and Lonvik [41]	1991	Bedding	Flaming and smouldering	Three storey building	During smouldering fires it is only the optical detectors that provide satisfactory safety. With flaming fires the ionization detectors react before the optical ones. If a fire were started by a glowing cigarette, optical detectors are generally recommended. If not, the response time with these two types of detectors are so close that it is only in extreme cases that this difference between optical and ionisation detectors would be critical in saving lives.
Johnson and Brown [42]	1986	Hardboard, artificial smoke	Flaming and smouldering	A typical brick dwelling	Ionization detectors usually provided adequate escape times only when smoke travel from the source room to the rest of the dwelling was restrained by small door openings, since it then took longer for visibility to be lost. Photoelectric detectors were generally more effective than ionization detectors, as expected for smouldering conditions, and when located in the hallway provided adequate escape times for most conditions of size and location of smoke source.
Harpe et al. [43]	1977	Sofa section, chair, innerspring mattress, rocker	Flaming and smouldering	Two-story brick structure	Although the photoelectric detectors in general respond better to a smouldering fire, and ionization type detectors in general respond better to a flaming fire, the time difference between these detectors are minimal when compared on an escape time and lifesaving potential basis.
Bukowski et al. [30]	1975	Chair, sofa, mattress, stove, electric motor, extension cord, cord under carpet	Flaming and smouldering	Two-story brick structure	A residential smoke detector of either the ionization or photoelectric types with small lag time would provide more than adequate lifesaving potential under most real residential fire conditions when properly installed.

Almost all the previous tests in Table 22 are real-scale houses. While some tests used laboratory testing room, Su and Crampton [2] used both real-scale and laboratory tests, and Thomas and Bruck [39] utilized the constructed house in a large scale fire testing facility. The houses used for tests included bedroom, kitchen and living room. For example, Cleary [1] used a 15.8 m long and 4.9 wide house, which was wood-framed with interior walls and ceiling covered with gypsum wall board. The tests were taken under different fire location (living room or bedroom) and ventilation (bedroom door open or closed). Thomas and Bruck [39] constructed the house used cardboard with the doors and windows cut out, and opened or shut as required for each case tested. Su and Crampton [2] performed the tests in a bungalow (93.0 m^2), which had two bedrooms, one bathroom, a kitchen, a living and dining room on the main floor. Mealy et al. [3, 40] used an apartment-style enclosure (41.8 m^2) comprised of four inter-connected rooms to test the performance of smoke alarms.

Some multiple storey buildings were also selected to conduct the experiments. Two story brick structures were used to test the performance of smoke alarms by Harpe et al. [43]. Meland and Lonvik [41] carried out the tests in a room on the ground floor of a three story building. The ground floor is about 17 m^2 with a ceiling height of about 2.5 m. Bukowski et al. [4] conducted their tests in the actual homes with representative sizes and floorplans, utilized actual furnishings and household items for fire sources, and tested actual smoke alarms sold in retain stores. Two different geometries of residential structures were used for the tests: manufactured home geometry (84.7 m^2) representing an apartment, condominium or small ranch house, and two-story home with three brick-clad bedrooms (139 m^2). In the experiments performed by Gottuk et al. [5], a 49 m^3 test room was used, with natural ventilation provided through a 38 cm × 30 cm duct.

All the tests have considered both flaming and smouldering conditions. A two-level screening experimental design was developed to examine the sensitivity to fabric flammability (a slow burning cotton or a fast burning polyester), polyurethane foam density (low density, 21 kg/m3 or high density, 29 kg/m3), considering flaming or initially smouldering fires [1]. Different smoke source were used in Thomas and Bruck's experiments [39], such as burning ethanol, braided wick, heptane, decalin, smouldering wood, wood cribs, smouldering towel and polyurethane foam. The fuel packages used in Su and Crampton's experiments [2] included woo, paper, polyurethane foam, cotton flannel and upholstered furniture. Bukowski et al. [4] tested three types of combustion conditions, including smouldering, flaming and cooking conditions.

In some experiments [42], a white and highly light-scattering artificial smoke produced by smoke machine, specifically a paraffin oil mist, was used considered to be comparable to smoke from smouldering materials. The artificial smoke was produced at three widely different rates chosen to be representative of those observed in laboratory tests of materials: low smoke produced by one machine at its lowest rate, considered qualitatively similar to that produced from polyurethane foam upholstered furniture smouldering after contact with a lighted cigarette; medium smoke produced by one machine at a rate comparable to a large smouldering source such as a polyurethane foam upholstered lounge chair; and high smoke produced by two machines at their highest settings, considered comparable to the rate of smoke production from highly smoke producing wall linings after flaming ignition.

For the same type of fuel, both smouldering and flaming fires may occur under different ignition scenarios. In the tests performed by Mealy et al. [3, 40], of the seven tests conducted with smoke alarm in place, there were three flaming ignition scenarios and four smouldering ignition scenarios, including cotton batting, sofa and wooden cabinet. In the tests, two types of sofa were successfully in developing self-sustaining smoulder and flaming fires. And from the tested taken by Gottuk et al. [5], the polyurethane and cotton fabric showed both flaming and smouldering combustion.

These tests included several types of smoke alarm. In the Cleary's test [1] photoelectric, ionization, and dual photoelectric/ionization alarms were co-located at multiple locations to facilitate comparisons of each alarm type, and different designs for the same type of alarm. In Thomas and Bruck's [39] tests, each room was fitted with two ionization alarms, two photoelectric alarms and one duel (ionization and photoelectric) alarm. In the tests by Mealy et al. [40], smoke alarm clusters consisted of 3 ionization, 3 photoelectric and 2 dual sensor alarms from three manufactures. Besides the above mentioned smoke alarms, Bukowski et al. [4] also tested the CO alarms under smouldering fire scenarios and the closed-door flaming mattress. Gottuk et al. [5] tested the performance of CO smoke alarm and showed that improved fire-detection capabilities can be achieved over standard smoke detectors by combining smoke measurements with CO measurements.

Some tests also considered the transition from smouldering to flaming combustion. For example, Cleary [1] included fires with smouldering to flaming transition times varying from 81 to 182 min. Smouldering chairs were allowed to transition to flaming with no artificial inducement in 11 out of 12 smouldering tests. It was noticed that all smoke alarms activated prior to transition to flaming in all tests, consequently disturbances from an open door may affect the smoke transport prior to alarm activation. Su and Crampton [2] considered fire sources such as pine sticks, cotton, paper, foam, chairs, which transitioned from smouldering conditions to flaming conditions in a range of 68-854 s.

The repeatability was considered in some of the previous tests. Cleary [1] replicated each experimental configuration three times. Bukowski et al. [4] considered the test matrix to perform sufficient replicates to allow estimates of experimental uncertainty and repeatability.

3.2 Activation time

Most home smoke alarms use ionisation or photoelectric sensor technology, alone or in combination, to detect a fire. Ionisation smoke alarms activate when smoke reduces the flow of current between charged electrodes, whereas photoelectric alarms activate when smoke reflects light beams. Both technologies are effective in most fire scenarios; using their combination offers the best protection. Ionisation alarms are less expensive than photoelectric alarms, which contributes to ionisation alarms being the most widely used [13].

It is largely known from previous studies that ionisation smoke alarm is more sensitive to flaming condition while photoelectric smoke alarm is more sensitive to smouldering condition [4, 30, 41, 43]. Slow, smouldering fires, such as those from cigarettes igniting a mattress or couch, are the types quite often associated with residential fire fatalities, yet the ionisation alarms that are found in 87% of US homes are more sensitive to flaming-type fires [14].

Although fire growth rate has generally increased in modern homes, both photoelectric and ionisation smoke alarms seem capable of giving warnings early enough to provide the necessary escape time in most scenarios. However, some concerns have been separately raised about whether ionization smoke alarms actually do operate early enough in smouldering fires and whether photoelectric do operate early enough in flaming fires [23].

Table 23 shows a summary of the performance of smoke alarms under flaming condition. The average activation time of ionisation smoke alarms is 249.1 s, which is considerably smaller when comparing to that of photoelectric smoke alarms, namely 337.2 s. The performance of dual smoke alarms is between the two, namely at 270 s.

Table 24 shows a summary of the performance of smoke alarms under smouldering condition. As expected, the photoelectric smoke alarm (average activation time of 1254.3 s) is more sensitive to the smouldering fire, comparing to the ionisation smoke alarm (1746.1 s). The performance of dual smoke alarm is between these two types, which show an average activation time of 1569.2 s.

Table 23: A summary of the performance of smoke alarms under flaming condition

Combustible materials	Fire of origin	Ventilation	Alarm type				Ref.
			Photo	Ion	Dual 1	Dual 2[d]	
Low density foam, polyester	Living room	Door open	133	81	83	88	[1]
Low density foam, polyester	Bedroom	Door closed	122	86	120	95	[1]
Low density foam, cotton	Living room	Door open	240	161	243	127	[1]
High density foam, polyester	Bedroom	Door open	159	107	144	112	[1]
Cotton[a]	Bedroom	Door open	375	136	118		[2][b]
Pine sticks[a]	Living room	N.A.	315	306	262		[2][b]
Sofa	Living room	Door closed	714	516	540		[3][c]
Wooden cabinet	Kitchen	Door closed	750	738	738		[3][c]
Wooden cabinet	Kitchen	Half-open window	840	804	768		[3][c]
Flaming materials	Living room	N.A.	130	73	77		[4][e]
Flaming materials	Bedroom	Door open	78	37	186		[4][e]
Flaming materials	Bedroom	Door closed	84	34	619		[4][e]
Gasoline	Testing room	Natural ventilation	443	159	-		[5]
Average activation time (s)			337.2	249.1	270.0		

Note: [a] Combustion transitioned from smouldering to flaming conditions. The condition was considered as smouldering combustion if all the smoke alarms activated before the transition;

[b] In this reference, only the smoke alarms positioned in the fire of origin are included;

[c] In this reference, only the activation time of smoke alarms in the closest room to the room of fire origin are shown;

[d] The dual smoke alarms (dual 2) are from different manufactures with the previous one (dual 1);

[e] A configuration of every level plus bedroom is selected in this table. It is following the National Fire Alarm Code released in 1993, requiring smoke alarms in every bedroom for new construction in addition to the every level location.

Table 24: A summary of the performance of smoke alarms under smoldering condition

Combustible materials	**Fire of origin**	**Ventilation**	**Alarm type**				**Ref.**
			Photo	**Ion**	**Dual 1**	**Dual 2**[d]	
Low density foam, cotton	Bedroom	Door open	1897	1876	2051	1275	[1]
Low density foam, cotton	Bedroom	Door closed	1322	1268	1341	1143	[1]
Low density foam, cotton	Living room	Door open	2715	4042	2691	2393	[1]
High density foam, cotton	Living room	Door open	3045	5367	3462	2758	[1]
Pine sticks[a]	Bedroom	Door open	275	307	242		[2][b]
Pine sticks[a]	Bedroom	Door closed	233	261	209		[2][b]
Paper[a]	Bedroom	Door open	436	504	430		[2][b]
Foam and cotton[a]	Bedroom	Door open	358	362	307		[2][b]
Pine sticks[a]	Living room	N.A.	401	428	318		[2][b]
Foam and cotton[a]	Living room	N.A.	303	525	259		[2][b]
Chair section[a]	Living room	N.A.	293	621	319		[2][b]
Cotton batting	Bedroom	Door closed	1572	1746	1530		[3][c]
Sofa	Living room	Door closed	1062	1920	942		[3][c]
Sofa	Living room	Door closed	948	1608	900		[3][c]
Sofa	Living room	Door closed	756	1038	744		[3][c]
Smouldering materials	Living room	N.A.	3856	4695	4304		[4][e]
Smouldering materials	Bedroom	Door open	2179	3618	3471		[4][e]
Smouldering materials	Bedroom	Door closed	2648	3402	3434		[4][e]
Polyurethane	Testing room	Natural ventilation	362	624	-		[5]
Upholstery fabric	Testing room	Natural ventilation	425	710	-		[5]
Average activation time (s)			**1254.3**	**1746.1**	**1569.2**		

Note: [a] Combustion transitioned from smouldering to flaming conditions. The condition was considered as smouldering combustion if all the smoke alarms activated before the transition;

[b] In this reference, only the smoke alarms positioned in the fire of origin are included;

[c] In this reference, only the activation time of smoke alarms in the closed room to the fire origin are shown;

[d] The dual smoke alarms (dual 2) are from different manufactures with the previous one (dual 1);

[e] A configuration of every level plus bedroom is selected in this table. It is following the National Fire Alarm Code released in 1993, requiring smoke alarms in every bedroom for new construction in addition to the every level location.

A set of full-scale apartment fires with both flaming and smouldering fire scenarios were used to assess the performance of various smoke alarm technologies by Mealy et al. [3]. Individual smoke alarm response times are presented in Table 25 for each test and location within the enclosure. It is evident that in general, for the smouldering fire scenarios, the combination alarms responded the earliest, with photoelectric alarms providing a slightly slower response, and ionisation alarms responding the slowest. On average, combination alarms responded 270 s sooner than photoelectric alarms and 822 s faster than ionisation alarms for the smouldering fire scenarios. In the flaming fires, the ionisation alarms were generally the quickest to respond, with the combination alarms lagging only slightly behind and the photoelectric alarms responding the slowest. In these scenarios, the ionisation alarm responded on average 13 s sooner than combination alarms and 67 s faster than photoelectric alarms.

Table 25: Smoke alarm activation times from source initiation [3]

Alarm ID	1I	2I	3I	1P	2P	3P	1D	2D	1I	2I	3I	1P	2P	3P	1D	2D
Smouldering Batting	Fire location: bedroom															
Cluster Location	Dining Room								Living Room							
Time to Activation	1578	1836	1824	1476	1704	1530	1320	1740	3756	4080	4434	2868	2796	4056	2568	2520
Smouldering Sofa	Fire location: living room															
Cluster Location	Dining Room								Bedroom							
Time to Activation	2322	1518	DNA	942	1086	1152	930	954	2700	1314	DNA	1020	1410	3696	1020	1140
Smouldering Sofa	Fire location: living room															
Cluster Location	Dining Room								Bedroom							
Time to Activation	1542	960	2322	924	960	954	876	918	1746	858	2520	924	1002	1284	942	744
Smouldering Sofa	Fire location: living room															
Cluster Location	Dining Room								Bedroom							
Time to Activation	852	N/P	1218	738	750	786	828	660	1554	N/P	2184	864	1056	906	846	N/D
Flaming Sofa	Fire location: living room															
Cluster Location	Dining Room								Bedroom							
Time to Activation	498	498	552	708	708	720	528	552	582	570	624	738	726	732	642	576
Flaming Cabinet	Fire location: kitchen															
Cluster Location	Living Room								Bedroom							
Time to Activation	720	648	720	750	666	708	750	666	780	708	732	732	738	774	744	726
Flaming Cabinet	Fire location: kitchen															
Cluster Location	Living Room								Bedroom							
Time to Activation	780	774	786	828	762	780	852	N/D	828	786	798	858	N/P	822	768	N/D

Note: DNA – Did not activate;
N/P – Alarm not present at this location during test;
N/D – Activation could not be determined due to malfunction.

Thomas and Bruck [39] tested the time of activation of smoke alarms in four houses. Table 26 shows the proportion of alarms that did not activate at rall in the tests. While there was a minor difference between the manufacturers, the major difference was observed between the ionisation and photoelectric alarms, with the photoelectric alarms not activating much more frequently. The other major difference was between the two storey house and the other houses which were all single storey. This difference is principally due to the smoke alarms in the lower storey not activating when the room of fire origin was on the second floor. There was a weak trend to a greater proportion of non-activations in the larger houses compared with the smaller houses and in the more compartmented houses compared with the more open plan houses.

Table 26: Proportion of smoke alarms of each type and manufacturer that did not activate [39]

House	11	12	P1	P2	D2
1	20%	15%	48%	40%	12%
2	17%	20%	37%	30%	25%
3	41%	40%	50%	46%	39%
4	8%	5%	27%	29%	12%
Average	22%	20%	41%	36%	22%

Su and Crampton [2] conducted a series of experimental studies in a residential dwelling as well as in a laboratory room to examine the effect of “dead air space” on smoke-alarm response. Table 27 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 the 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.

Table 27: Experiments in the dwelling and the results [2]

Test		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Bedroom-1 door		Open	Close*	Open	Open	Open	Close*	Close*	Open	Open
Bedroom-2 door		Open	Close	Open	Open	Open	Open	Open	Open	Open
Fire origin		Bed room 1	Bed room 1	Bed room 1	Bed room 1	Bed room 1	Bed room 1	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	61	4	479	1113	1107	862
	11 (i)	276	220	132	427	325	1117	1109	568	824
	12 (i)	264	218	134	440	307	1120	11	10	656
	13 (i)	272	216	137	4	19	308	111	1	1109
	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

Test		1	2	3	4	5	6	7	8	9
	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	921	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	144-1	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

*Bedroom 1 door opened at 1353 s in Test 2 and 1080 s in Tests 6 and 7. Notes , d fpr dual, i for ionization and p for pholelectric smoke alarms. NA for not accurate smoke alarms.

Cleary [44] analysed the data from two full-scale residential smoke alarm fire test series to estimate the performance of dual sensor photoelectric/ionisation alarms as compared to co-located individual photoelectric and ionisation alarms. The NRC Canada tests [45] that used solid combustible sources all started out as smouldering fires with most transitioning to flaming at some time during each test. Likewise, the cooking oil fire produced smoke from the heated oil before igniting. Alarm sensitivities were not measured prior to testing, thus there is no information on relative sensitivity between ionisation, photoelectric or dual alarms. There were 54 instances where a set of alarms were co-located during the 13 individual tests. The average alarm time and standard deviation (SD) for each type of alarm are given in Table 28. The dual alarm responded 616 s faster on average than the ionisation alarm, and 72 s faster on average than the photoelectric alarm.

Table 28: Average alarm times for NRC Canada Test Series [44, 45]

Alarm type	Average alarm type (s)	Standard deviation (SD) (s)
Ionization alarm	1205	1102
Photoelectric alarm	666	537
Dual alarm	587	450

The NIST test series [4] were also analysed by Cleary [44]. There were 92 instances where a set of alarms were co-located during the 30 fire tests. The average alarm times and standard deviations for the ionisation, photoelectric, and dual alarm configuration are shown in Table 29. On average, all three dual alarm configurations provide faster average alarm times compared to the photoelectric, or ionisation alarms at any one of the three ionisation sensor sensitivities. Considering the instances when the ionisation alarm (at a sensitivity setting of 4.3%/m) responded first, the dual alarm on configurations (from high to low sensitivities) activated 89 s, 67 s, and 47 s faster on average than the photoelectric alarms. Conversely, considering the instances when the photoelectric alarms responded first, the dual alarm configurations (from high to low sensitivities) activated 535 s, 523 s, and 518 s faster on average than the ionization alarms.

Table 29: Average alarm times for the NIST test series [4, 44]

Alarm type	Average time to alarm (s)	Standard deviation (s)
Ionization (2.6%/m)	1929	2104
Ionization (4.3%/m)	1981	2132
Ionization (5.9%/m)	2006	2138
Photoelectric	1755	1915
Dual I (2.6%/m)	1702	1945
Dual 2 (4.3%/m)	1720	1936
Dual 3 (5.9%/m)	1730	1929

Note: Italicized entries highlight sensitivity settings used in the NIST report analysis

The situation for flaming and smouldering fires in the NIST test series [4] were also analysed by Cleary [44]. There were 36 instances of co-located alarms during initially flaming fires. Table 30 gives the mean, median and standard deviation of the alarm times for initially flaming fires with the bedroom door opened. The dual alarm configurations yielded faster average alarm times than the photoelectric alarm and average alarm times nearly equivalent to the ionisation alarms. Table 31 gives the mean, median and standard deviation of the alarm times for initially smouldering fires with the bedroom door opened. The dual alarm configurations yielded much faster average alarm times than the ionisation alarms and average alarm times nearly equivalent to the photoelectric alarm. Table 32 gives the mean, median and standard deviation of the alarm times for the cooking fires. The dual alarm configurations yielded faster average alarm times than the photoelectric alarm.

Table 30: Alarm time statistics for the NIST test series of initially flaming fires [**4**, **44**]

Alarm type	Average time to alarm (s)	Median alarm time (s)	Standard deviation (s)
Ionization (*2.6%/m*)	107	107	35
Ionization (*4.3%/m*)	113	113	36
Ionization (*5.9%/m*)	118	118	36
Photoelectric	143	149	33
Dual I (*2.6%/m*)	105	107	29
Dual 2 (*4.3%/m*)	109	112	30
Dual 3 (*5.9%/m*)	114	115	29

Note: Italicized entries highlight sensitivity settings used in the NIST report analysis

Table 31: Alarm time statistics for the NIST test series of initially smoldering fires [4, 44]

Alarm type	Average time to alarm (s)	Median alarm time (s)	Standard deviation (s)
Ionization (2.6%/m)	4228	4213	1282
Ionization (4.3%/m)	4281	4242	1343
Ionization (5.9%/m)	4296	4244	1350
Photoelectric	3656	3753	1558
Dual I (2.6%/m)	3652	3749	1554
Dual 2 (4.3%/m)	3653	3751	1555
Dual 3 (5.9%/m)	3653	3751	1555

Note: Italicized entries highlight sensitivity settings used in the NIST report analysis

Table 32: Alarm time statistics for the NIST test series of kitchen fires [4, 44]

Alarm type	Average time to alarm (s)	Median alarm time (s)	Standard deviation (s)
Ionization (2.6%/m)	774	704	406
Ionization (4.3%/m)	954	849	402
Ionization (5.9%/m)	1080	992	342
Photoelectric	922	867	166
Dual I (2.6%/m)	725	704	309
Dual 2 (4.3%/m)	845	830	269
Dual 3 (5.9%/m)	904	866	189

Note: Italicized entries highlight sensitivity settings used in the NIST report analysis

A series of 24 full-scale experiments was conducted to examine the effects of alarm type, alarm location, fabric type, polyurethane foam density, ignition scenarios, and room configuration, on smoke alarm performance by Cleary [1] in a two-level, fractional factorial design of eight experimental configurations. Alarm times for only two of the three configuration 7 trials were averaged in Table 33. It is evident that photoelectric alarm responded quicker on average than ionization alarm in two of four smouldering fire configurations. And ionization alarm responded quicker on average than photoelectric alarm in all four flaming fire configurations. It is also indicated that dual alarm D2 had the fastest average alarm time for all four smouldering fire configurations, and responded first in 11 of the 12 trials. And dual alarm D2 yielded faster average alarm times than dual alarm D1 in seven of eight configurations, and was the first dual alarm to respond in 22 out of 23 trials where dual alarms were present.

Table 33: Average alarm times for each configuration for living room tests [1]

	Average Alarm time (s)			
Experimental configuration	**P1**	**I1**	**D1**	**D2**
(1) Smouldering, low density foam, cotton, bedroom, door open	1897 (130)	1876 (201)	2051 (290)	1275 (58)
(2) Smouldering, low density foam, cotton, bedroom, door closed	1322 (279)	1268 (162)	1341 (123)	1143 (244)
(3) Smouldering, low density foam, cotton, living room, door open	2715 (484)	4042 (1308)	2691 (513)	2393 (686)
(4) Smouldering, high density foam, cotton, living room, door open	3045 (605)	5367 (360)	3462 (685)	2758 (1163)
(5) Flaming, low density foam, polyester, living room, door open	113 (12)	81 (12)	83 (17)	88 (16)
(6) Flaming, low density foam, polyester, bedroom, door closed	122 (12)	86 (7)	120 (6)	95 (22)
(7) Flaming, low density foam, cotton, living room, door open[a]	240 (77)	161 (5)	243 (86)	127 (29)
(8) Flaming, high density foam, polyester, bedroom, door open	159 (17)	107 (8)	144 (27)	112 (16)

Note: The number in parenthesis is the standard deviation
[a] Average of two tests

Milarcik et al. [20] conducted a statistical study to compare the performance of different residential smoke detector technologies when exposed to different fire types, such as flaming, smouldering and kitchen fire. Three detector studies were included, such as Dunes 1970s [30, 43], Kemano [45] and Dunes 2000 [4]. Table 34 shows the relative time statistics for the performance of smoke alarms under flaming, smouldering and kitchen conditions. The statistical results indicate that, on average, one detector will react faster to smoke from a flaming fire than the other two detectors under different conditions. For example, under flaming condition, the Common language Effect Size results indicate that there is only a 72% chance that an ionisation detector will activate before a photoelectric detector, and only a 71% chance that a dual detector will activate before a photoelectric detector. Furthermore, there is only a 51% chance that an ionisation detector will activate before a dual detector. The odds represent the ratio for one detector activate faster than the other detector, which is calculated from the Common language Effect Size results. It is demonstrated that ionisation, photoelectric, and dual detectors provide statistically equivalent warning to different types of fires. It was confirmed, as, on average, ionisation detectors performed better for flaming fires, and photoelectric detectors performed better for smouldering fires. Dual detectors were actually better, on average, for smouldering fires than photoelectric detectors and were superior to single-type technologies, when all tests were considered as a whole.

Table 34: Relative time statistics for the performance of smoke alarms [20]

Condition	**Technology**	**Mean**	**Common language effect size with**			**Odds of being faster than:**		
			Ion	**Photo**	**Dual**	**Ion**	**Photo**	**Dual**
Flaming	Ionization	1.16	N/A	72%	51%	N/A	5:2	1:1
	Photoelectric	2.01	28%	N/A	29%	2:5	N/A	5:12
	Dual	1.19	49%	71%	N/A	1:1	12:5	N/A
Smouldering	Ionization	1.66	N/A	32%	30%	N/A	10:21	5:12
	Photoelectric	1.16	68%	N/A	45%	21:10	N/A	5:6
	Dual	1.11	70%	55%	N/A	12:5	6:5	N/A

Kitchen	Ionization	1.33	N/A	66%	60%	N/A	2:1	3:2
	Photoelectric	1.88	34%	N/A	45%	1:2	N/A	5:6
	Dual	1.67	40%	55%	N/A	2:3	6:5	N/A
All tests	Ionization	1.41	N/A	54%	39%	N/A	6:5	5:8
	Photoelectric	1.55	46%	N/A	37%	5:6	N/A	10:17
	Dual	1.15	61%	63%	N/A	8:5	17:10	N/A

Bukowski et al. [4] tested a range of residential smoke alarm technologies in a controlled laboratory test and in a series of real-scale tests conducted in two different residential structures: manufactured home geometry and a two-storey brick home. Table 35 and Table 36 show the average time to alarm for several smoke alarms and fire scenarios in a manufactured home and two-story home, respectively. Three installation criteria were used in the tests: every level; every level plus bedrooms; and every room. The “every level” installation represents the minimum arrangement allowed by code, in which smoke alarms are required outside the sleeping rooms and on each additional story of the home. In 1993 the National Fire Alarm Code was revised to require smoke alarms in every bedroom for new construction in addition to the every level location, which is named as “every level plus bedrooms”. The greatest escape time would be only guaranteed if smoke alarms were required in every room, called “every room”, an arrangement that has never been required in any code. It is indicated that, consistent with prior findings, ionisation type alarms provided somewhat better response to flaming fires than photoelectric alarms, and photoelectric alarms provided (often) considerably faster response to smouldering fires than ionisation type alarms. Smoke alarms of either type installed on every level generally provided positive escape times for different fire types and locations. Also the results demonstrated that adding smoke alarms in bedrooms increased the escape time provided, especially for smouldering fires.

Table 35: Average time to alarm for several smoke alarms and fire scenarios in a manufactured home [4]

Every Level Installation Criterion				
	Photo	Ion	Dual Ion/Photo	Aspirated
Flaming				
Living Room	130	73	77	137
Bedroom	96	61	186	121
Bedroom (door closed)	619	172	630	643
Smouldering				
Living Room	4615	4829	4605	4541
Bedroom	2622	3631	3471	2997
Bedroom (Door Closed)	3442	3428	3434	3446
Cooking				
Kitchen	766	520	912	1172
Every Level + Bedrooms Installation Criterion				
Flaming	Photo	Ion	Dual Ion/Photo	Aspirated
Living Room	130	73	77	137
Bedroom	78	37	186	121
Bedroom (door closed)	84	34	619	643
Smouldering				

Living Room	3856	4695	4304	4541
Bedroom	2179	3618	3471	2997
Bedroom (Door Closed)	2648	3402	3434	3446
Cooking				
Kitchen	764	520	539	1172
Every Room Installation Criterion				
	Photo	Ion	Dual Ion/Photo	Aspirated
Flaming				
Living Room	92	27	77	
Bedroom	78	37	104	
Bedroom (door closed)	84	34	134	
Smouldering				
Living Room	2552	4402	4304	
Bedroom	2179	3618	3429	
Bedroom (Door Closed)	2648	3402	3434	
Cooking				
Kitchen	691	487	539	

Table 36: Average time to alarm for several smoke alarms and fire scenarios in a two-story home

Every Level Installation Criterion				
	Photo	Ion	Dual Ion/Photo	Aspirated
Flaming				
Living Room	107	70	553	553
Bedroom	404	30	404	404
Bedroom (door closed)	186	164	3602	3602
Smouldering				
Living Room	1542	4824	1506	1424
living w/AC	1366	4192	2030	2072
Cooking				
Kitchen	880	1554	898	858
Every Level + Bedrooms Installation Criterion				
	Photo	Ion	Dual Ion/Photo	Aspirated
Flaming				
Living Room	107	70	563	553
Bedroom	98	30	82	404
Bedroom (door closed)	186	164	3602	3602
Smouldering				
Living Room	1542	4824	1508	1424
living w/AC	1338	4192	2030	2072
Cooking				
Kitchen	880	1554	898	858

Every Room Installation Criterion				
	Photo	Ion	Dual Ion/Photo	Aspirated
Flaming				
Living Room	107	70	305	330
Bedroom	98	30	82	404
Bedroom (door closed)	186	164	3602	3602
Smouldering				
Living Room	1542	4824	1508	1424
living w/AC	1338	4192	2030	2072
Cooking				
Kitchen	880	1290	876	828

Overall, the variety of studies is consistent in pointing out to the fact that photoelectric alarms are more efficient to alert to smouldering fires while ionisation alarms are generally more efficient to respond to flaming conditions. This is, of course, expected given the operating principles of the two technologies.

There is no solid evidence to prefer one technology over the other. In essence, **Table 23** and **Table 24** providing the direct comparisons, are most informative. They demonstrate that photoelectric detectors respond to smouldering fires approximately 39% faster (in terms of average activation times), and ionisation detectors respond to flaming fires approximately 35% faster. The two figures are statistically indistinguishable.

The analysis in Section 2.3 demonstrates that available fire data, although not entirely complete satisfactory, seems to indicate that both scenarios are equally important taking into account fire frequencies, as well as death and injuries rates.

If this is indeed the case, then it must be concluded (in line with some of the studies discussed above) that ionisation, photoelectric, and dual detectors provide statistically equivalent warning to different types of fires.
It is also worth noting that some studies conclude that only in extreme cases the difference between photoelectric and ionisation detectors would be critical in saving lives. There are also studies indicating that photoelectric alarms may fail to activate much more frequently than ionisation alarms.

3.3 Nuisance alarm

Nuisance activations interrupt other activities and may lead people to ignore the early warning of a smoke alarm. They are the leading reason for deliberately disabling smoke alarms [46]. In 2003, U.S. fire departments responded to 2,189,500 false alarms and only 7% were to fires [47]. In New Zealand, false alarms accounted for almost 40% of the fire call responses during 1998 and about half of all false alarms came from fire alarm systems [48]. In the United Kingdom, false alarms accounted for about 47% of the fire call responses in 2001, with 27% of all fire calls being false calls “due to apparatus” [49]. In the National Smoke Detector Project, 97% of the devices tested for involvement in nuisance alarm were ionisation-type devices, although they comprised only 87% of all devices in the study [50].

A United States Consumer Product Safety Commission (CPSC) report released in 1994 [51] indicated that while 87% of smoke alarms in United States homes have ionization sensors, 97% of nuisance alarms are reported by those units. A further study in 2000 installed smoke alarms in Alaskan Eskimo homes between 10 and 15 ft from the cooking appliances. This study found that 92% of homes with ionization alarms recorded nuisance alarms while only 11% with photoelectric alarms recorded nuisance alarm. Figure 12 shows the reported fires and false alarms in United States during 1980 and 2003 [46].

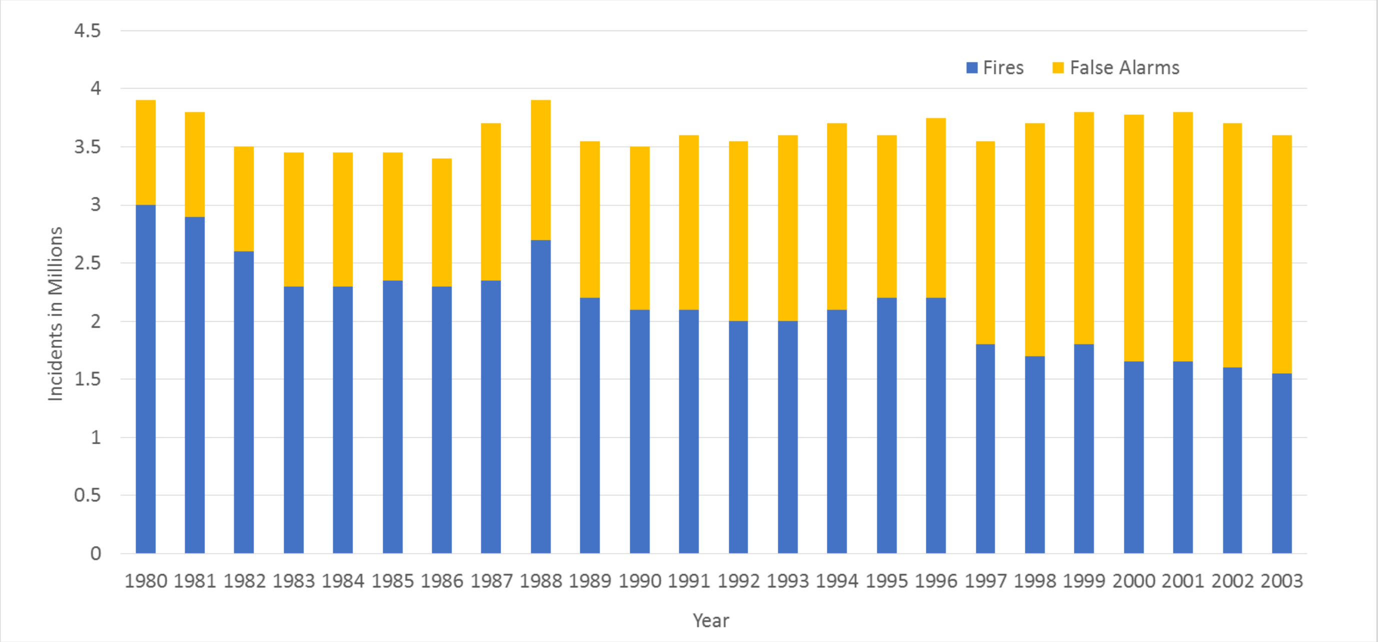


Figure 12: Reported fires and false alarms in United States: 1980-2003 [46]

For United States, Figure 13 shows the reasons that smoke alarm failed to operate in reported non-confined home structure fires during 2003 and 2006 [16, 23, 52, 53]. It is known that power source issues were the leading reason smoke alarms failed to operate, with missing or disconnected batteries being the leading problem. It is also shown that in 62% of the fires in which battery-powered smoke alarms failed to sound, the batteries were missing or disconnected. Dead or discharged batteries accounted for 26% of the battery-powered smoke alarm failures. When hardwired smoke alarms with no battery backup failed to operate, the power had failed, been shut off, or disconnected in 62% of the fires. When hardwired smoke alarms with battery backup failed to operate, 31% of the failures were due to hardwired power failure, shut off, or disconnection; 23% were due to missing or disconnected batteries; and 3% were due to dead or discharged batteries.

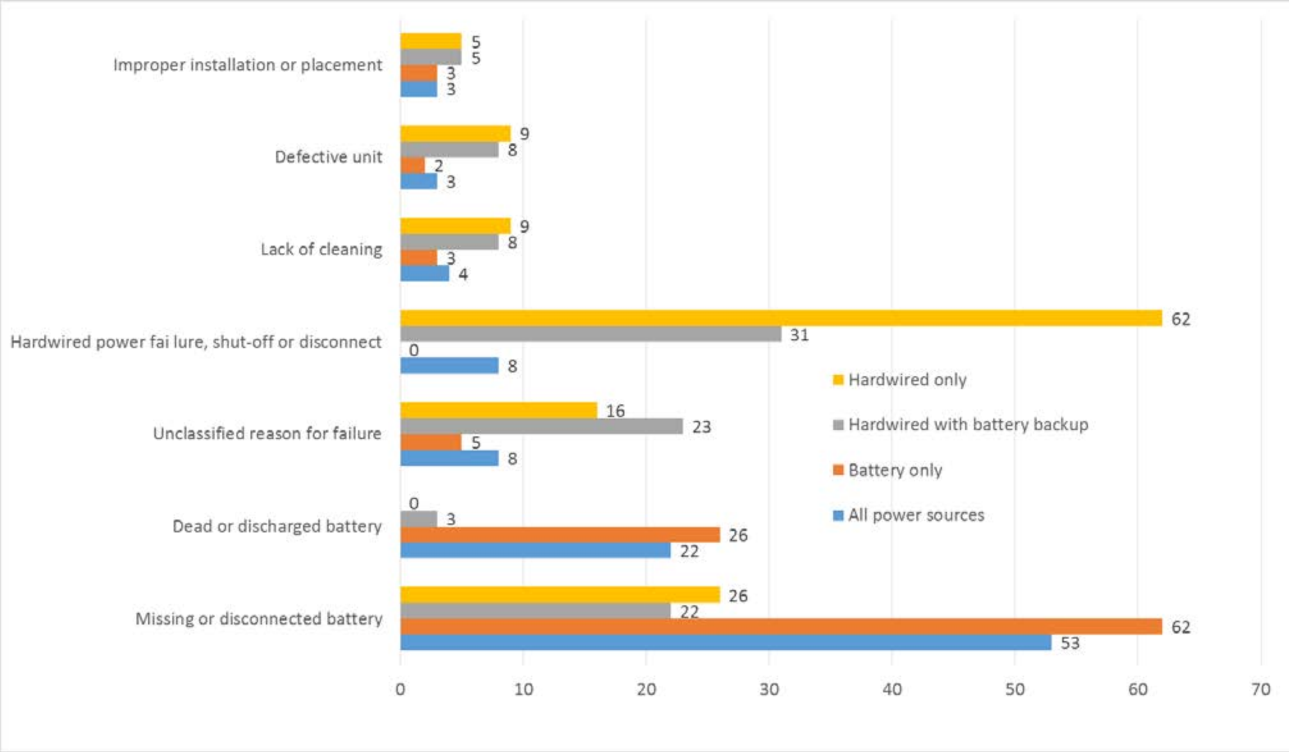


Figure 13: Reason smoke alarm failed to operate in reported non-confined home structure fires: 2003 to 2006 (%) [16, 23, 52, 53]

In New Zealand, the presence of a smoke alarm/detector was determined in 418 (24.6%) of the cases from 1999 to 2006. Where it was identified that a smoke alarm/detector was present, it was found that they operated in 329 (78.7%) of the cases and alerted 230 of the fire injury victims that there was a fire in their property [8]. Where it was possible to determine a reason for the ineffectiveness of smoke alarm/detectors, the most frequently cited reasons are shown in Figure 14.

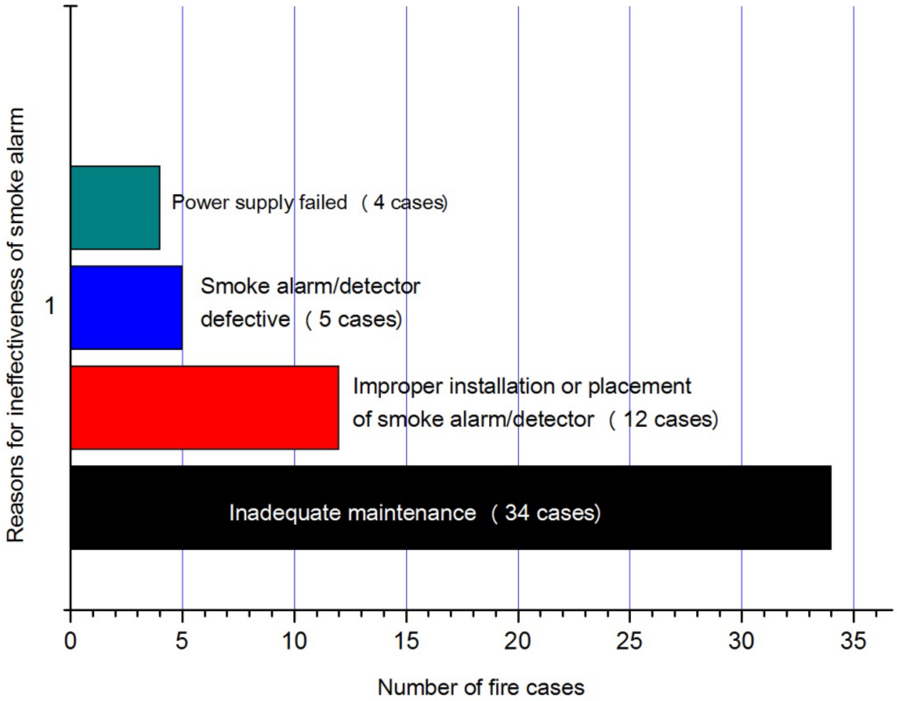


Figure 14: Reasons for ineffectiveness of smoke alarm/detectors in New Zealand during 1999 and 2006

In Australia [8], the presence of a smoke alarm/detector was determined in 2441 (33.3%) of the cases during 1999 and 2006. Where it was identified that a smoke alarm/detector was present, it was found that they operated in 1811 (74.2%) of the cases and alerted 1406 of the occupants or fire injury victims that there was a fire in their property. Where it was possible to determine a reason for the ineffectiveness of smoke alarms/detectors, the most frequently cited reasons were shown in Figure 15.

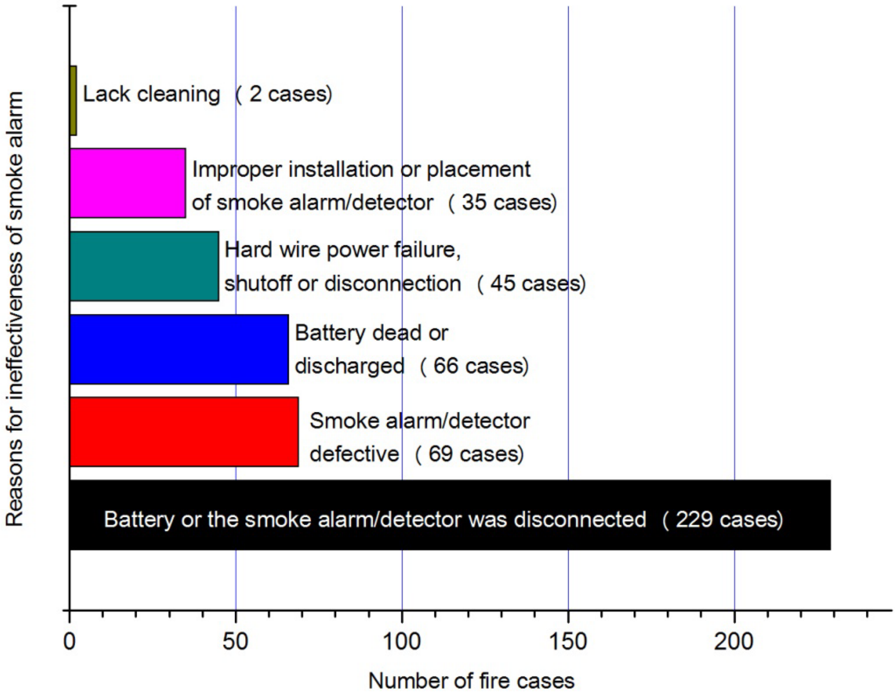


Figure 15: Reasons for ineffectiveness of smoke alarm/detectors in Australia during 1999 and 2006

Table 37 shows a summary of the studies on nuisance alarms. Two types of studies have been identified: direct experimental tests; and field studies. Nuisance alarms in residential settings from typical cooking activities, smoking or candle flames were tested by Bukowski et al. [4]. Fazzini et al. [14] conducted a cohort study of 4 rural Alaskan villages. It was concluded that the incidence of nuisance alarms is much higher in small dwellings using ionisation smoke alarms. The higher rates of alarm disconnection in the homes with ionisation alarms are likely related to the high rate of nuisance alarms in these homes. The use of photoelectric smoke alarms in small dwellings may lead to a lower rate of disconnection and improved survival in the event of fire. Feng and Milke [51] carried out tests to assess the sensitivity of different alarm technologies to a range of common problem scenarios.

Table 37: A summary of studies on the nuisance alarms

Experiments	Year	Method	Results
Feng and Milke [51]	2012	Toast, steam, onion, hamburger, oil, dust	Residential bathrooms and kitchens are the most common locations for nuisance alarms.
Bukowski et al. [4]	2007	Toasting scenarios, frying bacon, frying butter and margarine, frying hamburgers, deep-frying tortillas and French-fried potatoes, broiled and baked/broiled pizza, boiling Spaghetti pasta, candle burning, cigarette smoking	It was observed that ionization alarms had a propensity to alarm when exposed to nuisance aerosols produced in the early stages of some cooking activities, prior to noticeable smoke production. It was stated that the use of a dual photoelectric/ionization sensor alarm that would maintain better overall sensitivity to a variety of fire sources (flaming and smouldering).
Ahrens [46]	2004	Analysis of historical data	When smoke alarm batteries were missing, it was usually because of annoying alarm activations from cooking. One third of alarms cited for nuisance

			activations were located incorrectly. Ionisation devices had a disproportionate share of nuisance alarms.
Gottuk et al. [5]	2002	Wesson oil, toast, cheddar cheese, bacon, propane burner, Kerosene heater, cigarettes, smoking and steam	Cooking aerosols, dusts, tobacco, and aerosol can discharges are examples of sources which cause nuisance alarms. Cooking aerosols and steam (e.g., from a shower) are the most common nuisance alarm sources.
Fazzini et al. [14]	2000	Cohort study of households in 4 rural Alaskan villages	In some rural residence, photoelectric smoke alarms have lower rates of false alarms and disconnection. Homes with ionization alarms had more than 8 times the rate of false alarms as those with photoelectric alarms. Eleven of the ionisation alarms (19%) were disconnected compared with 2 of the photoelectric devices (4%).
Hall [54]	1996	Field study of 80 households	The activities associated with these alarms and the percentage of detectors implicated in said nuisance alarms were: cooking (77%), steam from bathroom (18%), cigarettes (6%), and fireplace/wood stove (4%), other, unknown and chirping (low battery alert) (12%).

Gottuk et al. [5] tested the performance of smoke alarms under various nuisance sources. Table 38 shows the activation time of smoke alarms under different nuisance scenarios. It is evident that in 3 out of 4 cases the photoelectric smoke alarms activate faster than the ionisation smoke alarm. And for the exceptional case that the activation time for ionisation smoke alarm (891 s) is very close to that of photoelectric smoke alarm (818 s).

Table 38: Smoke alarms to different nuisance scenarios [5]

Scenario	Flaming condition	Ventilation	Alarm type	
			Photo	Ion
Toast	Smouldering	Natural ventilation	492	393
Bacon	Smouldering	Natural ventilation	818	891
Cigarettes	Smouldering	Natural ventilation	122	95
Steam	N.A	Natural ventilation	74	73

Feng and Milke [51] used six nuisance sources to assess the sensitivity of different alarm technologies to a range of common problem scenarios. Table 39 shows the probability of activation for each technology to given nuisance source and to the total test series.

Table 39: Total probability of activation for different types of smoke alarm [51]

Technology	Toast	Steam	Onion	Hamburger	Oil	Dust	Total
Dual	100	40	0	60	80	90	62
Ion	100	0	0	80	60	10	42
Photo	100	53	7	0	0	73	39

4. DEVELOPMENT OF ADDITIONAL TESTING SCENARIOS

4.1 Principles of performance testing

To test the performance of different types of smoke alarms, several aspects need be considered in order to obtain an objective outcome, not biased toward any type. It includes the selection of fire sources, ignition methods, areas of fire origin, ventilation conditions, as well as considerations of repeatability, fire growth rates, nuisance alarms and potentially other factors.

The selection of fire sources should represent flaming and smouldering and cooking conditions. A study by Ahrens [16] showed that the leading items first ignited in United States home fires from 2003 to 2006 are, upholstered furniture (22%), mattress or bedding (18%), flammable or combustible liquid or gas, or pine, hose, duct or filter (9%), clothing (8%), unclassified furniture or utensil (5%), structural member of framing (4%), cooking materials including food (4%), etc. Both smouldering and flaming fires may develop from the same type of fuel, depending on ignition scenarios. For example, in the tests performed by Gottuk et al. [5], the polyurethane and cotton fabric demonstrated both flaming and smouldering combustion.

Various ignition methods were used in previous tests. Geiman [25] and Su et al. [45] used an electronic heating element as the source of ignition energy for the tests in both flaming and smouldering ignition. Bukowski et al. [4] utilized different methods for different types of fire. An electric match was chosen to start flaming ignition, a rod made with nichrome wire enclosed in ceramic was used in a smouldering scenario, and cooking condition was produced by a 0.3 m diameter aluminium sauté pan. Butane lighter and torch were used to ignite flaming oily rags, paper, cardboard in the tests [33].

Area of fire origin is also an important influencing factor to test the alarm performance. Common locations for fires to start include kitchen, bedroom, living room and even laundry room. A statistics by Australasian Fire and Emergency Service Authorities Council [8] shows that the majority of injured person in Australia from 1999 to 2006 were in kitchen (2927), bedroom (1600), lounge (843), laundry (204), garage (183), etc. National Fire Protection Association indicated [55] that from 2007 to 2011 in United States cooking equipment represented the leading causes of total fires (43%), followed by heating equipment (16%), intentional (8%), electrical distribution and lighting equipment (6%) and smoking materials (5%). It should be noted that cooking fire is one of the main causes of home fire. It is also indicated in the FRNSW report [6] that 25% of total number of fires for class 1a & 2 building during 2000-2014 started in kitchen, 18% in bedroom and13% in the lounge room.

Ventilation condition is an important factor has influence on the smoke movement, resulting in the variation of alarm activation times. Thomas and Bruck [39] used full-scale model house to conduct the tests with the doors and windows cut out and opened or shut as required for different ventilation conditions. Cleary [1] also conducted tests under different ventilation conditions (bedroom door open or closed). The average activation time of different types of smoke alarms reduced from 1775 s to 1269 s after the bedroom door was closed. Meland and Lonvik [41] indicated that with a flaming fire and open door to the corridor the critical limit for being in the corridor associated with heat stress and reduced visibility was typically reached after 200-240 s, depending on the size of the corridor.

Residential bathrooms and kitchens are the most common locations for nuisance alarms [51]. Bukowski et al. [4] performed nuisance tests in a manufactured home and the selection of sources were based on what are commonly thought to be causes of residential nuisance alarm to mimic expected activities. Feng and Milke [51] tested the performance of smoke alarms under six nuisance sources, such as toast, cooking onions, hamburgers, vegetable oil, steam and cement dust. It is suggested that the tests should be split into a ‘pure nuisance’ phase and an ‘aggressive nuisance’ phase. The threshold obscuration value chosen for separating of the two phases of each test was based subjectively on the average obscuration exceeding 0.15% obscuration per foot, in part accounting for the systematic errors in the optical density meter.

Repeatability was taken care of in some of the previous tests. It was shown that repeated experimental runs are necessary as many tests they showed high standard deviations. Cleary [1] replicated each experimental configuration three times. Bukowski et al. [4] considered the test matrix adequate to perform sufficient replicates to allow estimates of experimental uncertainty and repeatability.

High fire growth rate may be not good to identify the performance of different types of smoke alarms, as if fire progresses too fast the three types of smoke alarm may produce very similar results. To address this issue Su and Crampton [2] considered variety of fire sources such as pine sticks, cotton, paper, foam, chairs, which transitioned from smouldering conditions to flaming conditions over a wide range of times (68-854 s).

4.2 The design of additional testing scenarios

FRNSW study [6] considered 10 different burning scenarios conducted in the FRNSW testing rig, including 8 smouldering scenarios and 2 flaming scenarios. The ignition sources were cartridge heater and LPG gas flame.

Due to the drawbacks of the study described in Section 2.1, extended testing program is proposed. It is assumed that the same FRNSW testing facility will be used for additional tests, shown in Table 40.

Table 40: A summary of additional tests for FRNSW study [6]

Runs	Location	Fire type	Materials	Ignition method	Conditions
1	bedroom 1	smouldering	bedding	Cigarette/small electric heater	Bedroom 1 door closed; bedroom 2 door open;
2	bedroom 2	smouldering	bedding	Cigarette/small electric heater	Two bedroom doors open
3	Lounge	smouldering	Upholstered couch	Cigarette/small electric heater	Bedroom 1 door open; bedroom 2 door closed;
4	Bedroom 2	smouldering	bedding	Cigarette/small electric heater	Two bedroom doors open
5	Bedroom 2	flaming	bedding	LPG gas flame	Two bedroom doors open
6	Bedroom 1	smouldering	bedding	Cigarette/small electric heater	Bedroom 1 door closed; bedroom 2 door open;
7	Bedroom 1	smouldering	bedding	Cigarette/small electric heater	Two bedroom doors open

Runs	Location	Fire type	Materials	Ignition method	Conditions
8	lounge	smouldering	Upholstered couch	Cigarette/small electric heater	Bedroom 1 door open; bedroom 2 door closed;
9	Bedroom 2	smouldering	bedding	Cigarette/small electric heater	Two bedroom doors open
10	Bedroom 1	flaming	bedding	LPG gas flame	Two bedroom doors open
11	Kitchen	Smouldering	Electrical cable	LPG gas flame or alternative	All room doors open
12	Kitchen	Flaming	Electric equipment	Cartridge heater or alternative	All room doors open
13	Lounge	Flaming	Upholstered furniture	LPG gas flame or alternative	All room doors open
14	Lounge	Smouldering	Upholstered furniture	Cigarette/small electric heater	All room doors open
15	Lounge	Flaming	Papers	LPG gas flame or alternative	All room doors open
16	Lounge	Flaming	Wood chair	LPG gas flame or alternative	All room doors open
17	Kitchen	Flaming	Cooking pan	LPG gas flame or alternative	All room doors open
18	Kitchen	Flaming	Clothing	LPG gas flame or alternative	All room doors open
19	Laundry room	Smouldering	Electric equipment	Cartridge heater or alternative	All room doors open
20	Laundry room	Smouldering	Electric equipment	Cartridge heater or alternative	All room doors open except laundry room door
21	Bedroom 1	Flaming	Pillow	LPG gas flame or alternative	All room doors open
22	Bedroom 1	Flaming	Pillow	LPG gas flame or alternative	All room doors open except bedroom 1 door
23	Bedroom 2	Flaming	Paper	LPG gas flame or alternative	All room doors open
24	Bedroom 2	Flaming	Paper	LPG gas flame or alternative	All room doors open except bedroom 1 door
25	Hall	Flaming	Wood chair	LPG gas flame or alternative	All room doors open
26	Hall	Smouldering	Upholstered furniture	Cigarette/small electric heater	All room doors open
27	Kitchen	Nuisance source	Cooking different foods	Cooking equipment	All room doors open
28	Bathroom	Nuisance source	Steam	Hot shower	All room doors open
29	Lounge	Nuisance source	Smoking cigarette(s)	Lighter	All room doors open
30	Lounge	Nuisance source	Candle(s)	Lighter	All room doors open

The following major changes are implemented in the extended testing program: Additional clusters of smoke alarms to be installed in the Laundry room and in the Bathroom (for the purpose of testing response to nuisance alarms).

Equal number of tests is proposed for flaming and smouldering combustion. This reflects analysis on the statistics of causes of fatal fires carried out in the Section 2.3

Test repeatability is required in order to ensure that the results of each tests are statistically stable, and that the Standard Deviations in the alarm activation times can be established in each of the scenarios. Each fire scenario needs be repeated at least three (3) times to confirm the repeatability of testing conditions, including the scenarios already considered in the FRNSW report. Methodology which is to be followed for processing the results is discussed below. It is desirable, if possible, to repeat each of the tests more than three times.

The group of the first ten tests (highlighted in the **Table 40** are the same as in the FRNSW study, but the ignition source in smouldering scenarios is replaced. Energy source used to initiate smouldering scenarios (cartridge heater) is extreme and not representative of real scenarios.   This should be replaced with burning cigarette, match or small electric heater with comparable size and heat output.

Energy output of the LPG gas burner, used to initiate flaming combustion, should also be reduced to consider slower fire growth rates. This will allow more clear distinction between alarms response times to be made.

Selection of materials used as a “first item to ignite” reflect available fire history statistics

Robust statistical methodology, available form some of the previous studies, is suggested to process testing results and discussed below.

- Test of smoke alarms response to naissance sources is suggested. This is an important issue to be considered in the context of evaluating performance of smoke alarms. Frequent nuisance responses are likely to lead to smoke alarms being disconnected or being ignored if activated.

Choice of room of fire origin reflects statistics provided by [4], **Table 8** below.

Table 41: Top fire scenarios ranked by frequency of occurrence, 1992-1996 [4]

Ranked by Number of Deaths			
Living Room	Smouldering	Upholstered Furniture	372
Bedroom	Smouldering	Mattress	251
Bedroom	Flaming	Mattress	249
Living Room	Flaming	Upholstered Furniture	160
Kitchen	Flaming	Cooking Materials	142
Kitchen	Flaming	Clothing	79
Living Room	Flaming	Wire / Cable	61
Living Room	Flaming	Interior Wall Covering	51
Bedroom	Flaming	Clothing	51
Kitchen	Flaming	Structural Member Framing	50

Suitable and robust statistical processing of smoke alarm activation times is proposed [20]. The essence of this methodology is a Common Language Effect Size (CL) statistical method. The CL calculation takes two population distributions (e.g. activation time distributions of alarms of different types) and evaluates the extent of overlap of these distributions.

A normal distribution is created with a mean equal to the difference of the two means, and a standard deviation equal to the root square of the variances of the two populations

$$Z_0 = \frac{|mean_1 - mean_2|}{\sqrt{(\sigma_1^2 + \sigma_2^2)}}$$.

Equation 4

The Z score calculated by the equation (4) is utilised in the normal distribution lookup tables to determine the probability that one type of smoke detector will activate faster than another.

If the value

$$CL = P(Z < Z_0)$$

Equation 5

is close to unity, then one of alarms will activate significantly faster, or in other words will have high Odds

$$Odds = \frac{CL}{CL - 1}$$

Equation 6

of being faster than the other detector. If the CL value is close to zero, then the two technologies have equal odds to activate first.

The proposed testing program represents a minimum set of tests, which seems to be realistic to implement within reasonable time frame and with reasonable resources, using the existing FRNSW testing facility. Much more extensive program can be developed should the demand for it becomes evident.

5. CONCLUSIONS

The present study addresses ABCB concerns that some of the recent studies conducted to compare performance of photoelectric and ionisation smoke alarms may not employ sound technical methodology and may be biased towards favourable outcome towards one type of smoke alarms.

The aims of this study was to conduct a critical review of available data on comparative performance of photoelectric versus ionisation smoke alarms, and propose an objective and representative testing scenarios in order to obtain accurate data on performance of these two types of detectors..

Comprehensive literature review was conducted, included recent FRNSW study [6], as well as a variety of other sources. Both Australian and international (New Zealand and the United States) data was considered.

The literature review has focused on the two major issues:

1) historical fire data for residential premises, and in particular major factors influencing performance of photoelectric and ionisation alarms, and probabilistic distributions of these factors across real fire accidents;
2) review of available studies on comparative performance of photoelectric and ionisation smoke detectors.

With respect to real fire scenarios, it has been established that the two major factors need be taken into account: First is the type of combustion that is flaming or smouldering. This factor is of paramount importance as the two types of smoke alarms under consideration respond in a significantly different way to these two types of combustion process.

The second factor is a statistical number of fatalities occurring in the fires of these two types.

It was concluded that an ensemble of representative fire scenarios for assessing performance of smoke alarms should properly reflect historical distribution of fatalities between various scenarios.

There are uncertainties in the existing fire data which prohibits exact number of fatalities in both types of fires to be calculated. This is reflected primarily by the fact that many reported scenarios cannot be confidently attributed to either flaming or smouldering type, although they can be classifies with a reasonably high degree of confidence.

Based on available data, it has been concluded that number of fatalities in smouldering and flaming fires may, in fact, be comparable.

Based on this outcome, equal importance was assigned to the two types of combustion when developing proposed testing program.

Existing data, reported in various studies, has been found to be consistent with the general perception that photoelectric smoke alarms respond faster to smouldering fires while ionisation alarms respond faster to flaming conditions. This outcome is also consistent with operating principles of the two technologies.

Across the set of experiments, photoelectric detectors responded to smouldering fires approximately 39% faster (in terms of average activation times), and ionisation detectors responded to flaming fires approximately 35% faster. The two figures are statistically indistinguishable.

Given the identified evidence on fire fatalities in the two types of fire scenarios, it is concluded that ionisation, photoelectric, and dual detectors provide statistically equivalent warning to different types of fires.
In line with this conclusion, some reviewed studies conclude that only in extreme cases the difference between photoelectric and ionisation detectors would be critical in saving lives. There are also indications that photoelectric alarms may fail to activate much more frequently than ionisation alarms.
A number of major drawbacks have been identified in the research methodology employed in the FRNSW study [**6**].
Major of these drawbacks are

1) a very limited number of tests absence of tests repeatability;
2) lack of proper review of other existing studies and statistical fire data;
3) Severe imbalance in the testing program, between smouldering and flaming fire conditions, with flaming scenarios being effectively ignored. This include total absence of kitchen fire scenarios.
4) not representative energy sources used to imitate some of the burning scenarios.

It is hard to see how the study [6] can be seen as a benchmark for making major regulatory decisions regarding implementation of domestic smoke alarms. It is just one of many studies on smoke alarm performance, in fact with a very limited coverage of possible fire scenarios.

To address identified deficiencies of the FRNSW research methodology, an extended testing program has been proposed. It reflects outcomes of the comprehensive literature review.

The program consists of 30 tests, with required number of replications. The program also identifies nuisance alarms as an important issue, and proposes relevant testing.

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