Fire research report

Smoke Alarms in Homes: An Analysis

This fire research report provides an exploratory analysis of residential occupancy smoke alarms with regard to their efficiency and ability to provide effective notification for occupant safe egress.

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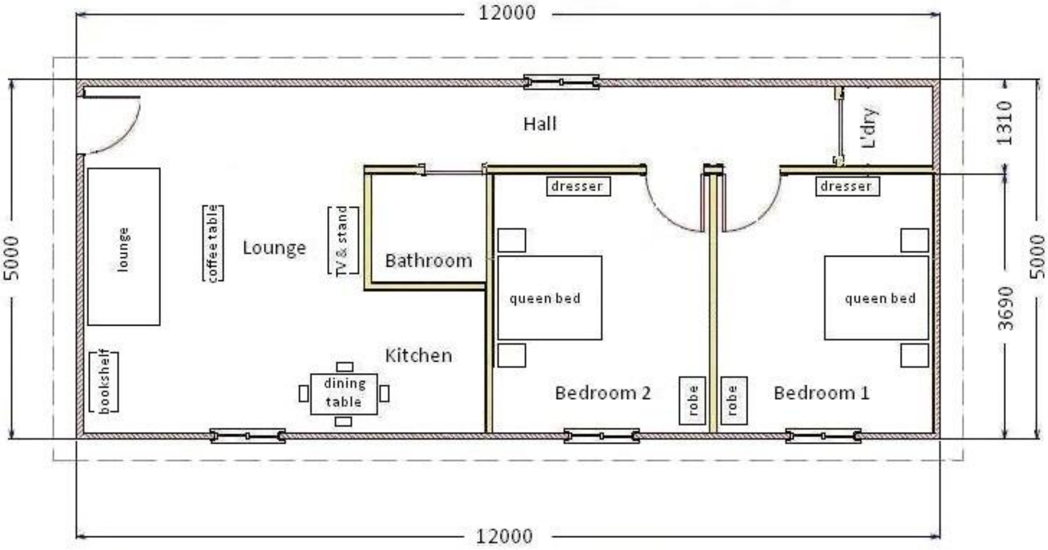
12000
Hall
L'dry
1310
5000
lounge
coffee table
Lounge
TV & stand
Bathroom
dresser
dresser
queen bed
queen bed
3690
5000
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Executive Summary

The homes of today have changed dramatically, and in those changes the risk to toxicity in the event of a fire has increased exponentially. Modern homes are not only larger, but also include petroleum based synthetic furnishings and materials, synthetic carpets, increased possessions, and so on. Building materials have also changed to include particle board, MDF, injected expandable foams, and oriented strand board.

Synthetic materials, although more cost effective, react very differently when exposed to an ignition source. The quantity and type of smoke produced through their combustion is characteristically different from natural fibres, and they release fire energy at an increased rate. Furthermore, furnishings, plastics and paints may contain flame-retardants or smoulder-retardants, but rarely ever do they contain both. These retardants are known to produce increased toxic effects in the time of a fire.

With this heightened inclusion of synthetics over natural fibres, home fires reach levels of tenability loss at much faster rates. Many studies have been undertaken both within Fire & Rescue NSW (FRNSW) and externally that have shown the times to tenability loss due to both toxic gases and heat have significantly decreased in the modern home when compared with a legacy home.

Although research studies have found that there hasn’t been a significant change in the timeframes by which smoke alarms activate, there has been a significant reduction in the time to untenable conditions. This raises concern, as smoke alarms must activate more rapidly in order to provide the same safety measures as when first applied in legacy homes.

Given the upcoming 10 year anniversary (May 2016) of the most recent change in NSW legislation surrounding smoke alarms, the Fire Investigation and Research Unit (FIRU) within FRNSW undertook research to analyse smoke alarms with regard to their efficiency and ability to provide effective notification for safe egress in real fire scenarios.

This research began with a comprehensive literature review regarding types, placements and notification results for a range of smoke alarms in a range of fire conditions. This review also included the analysis of data collected from incidents attended by FRNSW over a nearly 15 year period (Jan 2000-late 2014).

It was found that there were a range of results internationally, some favouring ionisation alarms, some photoelectric, many determining that there were shortcomings with both. Some studies suggested that the type of alarm is less important than the placement, as incorrect placement can result in failure across all alarms.

To delve further into this area of controversy, a comprehensive look at types of fire, materials first ignited, ignition sources, and fatalities was undertaken. International results and data from incidents attended by FRNSW were analysed to produce a series of tables and graphs determining conditions of heightened risk for residential occupancies.

The literature review and subsequent data analysis then shaped the methodology that was utilised to produce real fire environments to study and gain first hand data. The test burns were conducted in a full scale manufactured replica residence, furnished and carpeted, that included the equipment required to determine scientific analysis of time to tenability loss (and therefore the limit to safe egress).

Ten test burns were undertaken across a range of scenarios including type of ignition (smouldering or flaming), material first ignited, room of origin location, and door positioning (open or closed). Furthermore, smoke alarm activation was analysed by positioning 36 smoke alarms (9 in each room, divided into 3 clusters of 3 different types of alarms) throughout the residence. The focus was on hallway alarm activation, in line with NSW legislation requirements; however, the activation of other alarms was also of interest.

The data captured for smoke alarm activation was analysed and then overlaid with the calculated tenability limits and required safe egress times. The findings of this initial exploratory study provide preliminary results of how type of alarm and alarm placement affect safe egress for occupants.

Half of the test burns conducted included an installed residential sprinkler system. These burns (tests 6-10) were conducted under virtually identical conditions to the burns that did not include the sprinkler system (tests 1-5). A comparison between the sprinkler and non-sprinkler system burns was undertaken in order to draw preliminary conclusions on what effect sprinklers may have on residential fire environments.

This study applied conservative limitations for toxicity and safe egress time, considering that any device a residential occupant is relying on should provide a safety measure for those other than only able bodied, alert and functional adults. When considering the increased egress times for the elderly, those with mobility issues, and those who require rescue (ie. children), a required safe egress time (RSET) of 135s was applied. So as not to limit the study, a 120s egress time was also considered, as suggested by multiple international studies. A fractional effective dose/concentration for toxic gases and heat was applied that would support the safe egress of nearly 90% of the population, again, to ensure the majority of people are provided safety measures in the event of a fire.

The findings, although preliminary, clearly showed that smoke alarms are not providing effective notification for safe egress when located only in the hallway. When room of fire origin alarms are also included, the results still fall short of acceptable levels.

When considering only activation percentages for smoke alarms, the best results in the room of origin reach 100% activation across the 10 test burns. The worst results, from hallway alarms, sit at 50%.

Activation data and percentages only provide an isolated look at smoke alarms, and provides no information related to safe egress of occupants when the environment is quickly changing with regard to toxicity, visibility and heat.

When tenability limits with regard to toxic gases, heat and visibility were applied, and an RSET of 120s and 135s was overlaid, the highest performing alarms in the room of origin reached 60% success, the hall's best performers reached only 30%. It's worth noting that in both of these instances, the best performing alarms were located in "dead space" positions, positions not recommended as per NSW legislation, Australian Standards, and the Building Code of Australia.

Excluding those "dead space" alarms reduces the room of origin down to a 50% success rate, and the hall reduced to only a single alarm achieving 10% (the rest were 0%). Across the test fires photoelectric and dual alarms were found to produce statistically superior results, with ionisation alarms clearly inferior in performance.

Further testing and analysis is required to more thoroughly research each of the varying conditions assessed in this research project, therefore ensuring more definitive conclusions. Regardless, these test burns provided enough preliminary information to show cause for concern, the very likely need for change, and the definite need for further testing and analysis to return confidence that smoke alarms provide an effective first line of notification in the event of a real home fire.

1. Background

1.1 Smoke Alarms and Legislation

May 1, 2016 marks ten years since the Environmental Planning and Assessment Amendment (Smoke Alarms) Regulations 2006 (Amendment 2006) came into effect. Amendment 2006 required all new class 1a and 2 buildings to have installed and functional smoke alarms in compliance with Australian Standard 3786 (AS 3786), and existing buildings to be retrofitted to comply with AS 3786. Amendment 2006 came with the caveat that any existing non-compliant smoke alarms could be updated to comply with the standard when they ceased to function or were removed [1].

The minimum requirement for placement and installation of these alarms in NSW in identified building types was laid out in the Environmental Planning and Assessment Regulation 2000 [2] (Regulation 2000). It required that any new buildings in specified building classes be fitted with smoke alarms in any storey of a dwelling that contains a bedroom, fitted in every hallway associated with a bedroom, or the section of the building containing the bedroom and remainder of the building/dwelling if no hallway exists. It also specified that in any storey that does not contain a bedroom, a smoke alarm must be fitted on the travel path of egress.

Neither the Regulation 2000 or Amendment 2006 specified which type of smoke alarm is to be installed (ie. ionisation or photoelectric) but the NSW Government Department of Planning Advisory Note in March 2006 “Smoke Alarms” suggested that smoke alarms should not be located near cooking appliances or bathrooms if possible and refers readers to Fire & Rescue New South Wales (FRNSW) for further information regarding specific types of alarms and installation [1]. The Building Code of Australia [3] suggested something similar in 1996, outlining that if the placement of alarms near cooking appliances or bathrooms cannot be avoided, photoelectric alarms are more suitable near cooking appliances and ionisation alarms are more suitable near bathrooms.

1.2 Smoke Alarms Introduced

There are many types of smoke alarms available including photoelectric, ionisation, dual/multi detection, heat and carbon monoxide alarms, to name a few. This analysis primarily focuses on photoelectric and ionisation smoke alarms as at the time of writing they are the predominant and most cost effective alarms found in residential dwellings (class 1a and 2 buildings) in Australia.

Ionisation smoke alarms are designed using a radioactive material that ionises the air between charged electrodes. The material used is Americium-241, and it emits both alpha rays (absorbed in the detector) and gamma rays (escape from the detector). The Australian Radiation Protection and Nuclear Safety Agency states that the dose of radiation released to occupants is minute when compared with natural background radiation [4]. Ionisation alarms activate when the conductance of air by the electrodes is reduced by smoke particles entering the chamber and limiting the movement capacity of ionised air. If the reduced conductance meets with the preset criteria, the alarm activates. Ionisation alarms are designed to be more responsive to small particles produced during flaming fires. These particles are often termed invisible particles as they are smaller than 1 micron in size [5].

General principle in ionisation alarms [6].

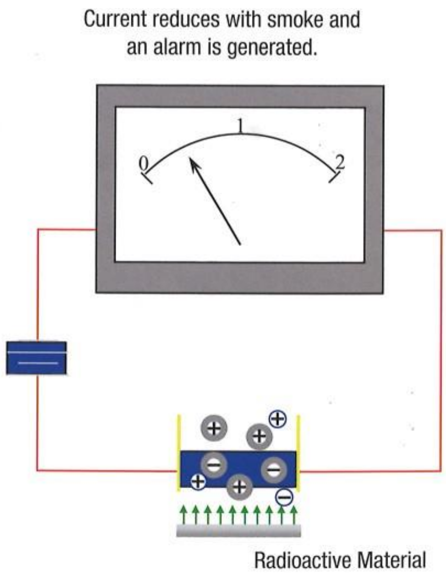

Figure 1: General Principle in Ionisation Alarms

Photoelectric [5] smoke alarms work by means of optical recognition of the presence of smoke. There are two types of optical detectors, light obscuration and light scattering. Light obscuration works on the principle that when particles of smoke enter the light path in the detector, some light is scattered and some is absorbed. The result is that less of the light beam from the transmitter (source) enters the receiver (sensor). If this change meets with the preset criteria, the alarm is triggered. Light scattering detection chambers are arranged so the light source does not normally fall on the photo diode sensor. When smoke enters the chamber, light is scattered by reflection and refraction onto the sensor. If the amount of light falling on the sensor reaches the preset criteria, the alarm is triggered.

General principle in light obscuration photoelectric alarms [6].

Figure 2: General Principle in Light Obscuration Photoelectric Alarms

General principle in light scattering photoelectric alarms [6].

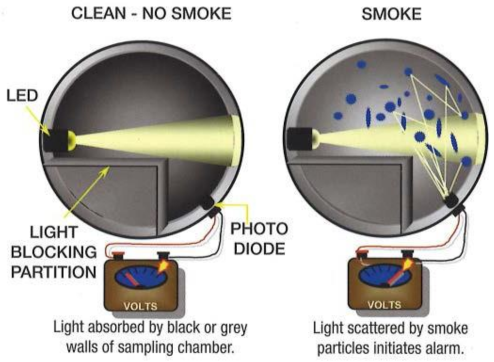

Figure 3: General Principle in Light Scattering Photoelectric Alarms

Optical detectors are more sensitive to visible particles that are larger than 1 micron in size, resulting in their increased sensitivity to smouldering fires. The two optical sensors are grouped as one, photoelectric, in Australian Standards 3786 [7], in the ISO/TS 7240-9 (Test Fires for Fires Detectors) [8], and in all analysed research studies.

1.3 Smouldering and Flaming Fires

Given the sensitivity of different smoke alarms to different types of fires, a brief introduction to smouldering and flaming fires is essential to support a full understanding of the information presented. In this introduction flaming fires refer to well ventilated flaming fires. Vitiated flaming fires (fires burning inefficiently) present significant varied fire profiles depending on their level of inefficiency.

Flaming combustion produces fires that exhibit a visible flame due to the oxidation reaction and heat release occurring in the gas phase surrounding the fuel. These fires produce much higher quantities of small mean sized particles (water (H_2O), carbon dioxide (CO_2), carbon monoxide (CO)) due to more complete combustion [9]. The ratio of CO_2 to CO is in the vicinity of ten to one [10], and in general flaming combustion tends to produce non-irritant smoke [11] (see Section 1.5, Tenability Criteria: Incapacitation and Death, for further information on irritant gases).Typical peak temperatures reached during flaming combustion range between 1500-1800 degrees Celsius, with a heat release of 16-30 kilojoules per gram (kJ/g) [10].

Flaming combustion has the potential to undergo flashover as a transitional state towards a sudden and sustained fully involved compartment fire [12]. For this to occur, all combustible surfaces exposed to thermal radiation pyrolyse, and more or less simultaneously reach ignition temperature resulting in full room involvement [12]. Flashover occurs when the spread of flaming combustion occurs primarily through radiant heat transfer. At this transitionary stage conditions in the compartment are untenable due to thermal effects [13]. If flashover occurs, it is likely to do so when the upper layer (or ceiling layer of buoyant fire gases) reaches or exceeds 600 degrees Celsius [12]. Flashover has been found to occur at a varying range of times (from 1.5 minutes to 10 minutes) depending on conditions present within the compartment and rate of fire growth [12].

Smouldering is a slow, low temperature, flameless combustion that is sustained when the surface of a condensed phase fuel is directly attacked by oxygen [14]. Smouldering fires experience incomplete combustion and produce larger organic by-products, higher quantities of soot, irritant smoke [11], and smaller quantities of H_2O, CO_2, CO than flaming combustion [9]. The ratio of CO_2 to CO is closer to unity in smouldering fires, resulting in increased risk of toxic gas accumulation [10]. Typical peak temperatures in smouldering fires range between 500-700 degrees Celsius, with a heat of combustion around 6-12 kJ/g [10].

It is important not to confuse smouldering combustion with pyrolysis, a non-flaming response of condensed phase organic materials to an external heat source. Pyrolysis involves little or no oxidation and is endothermic (absorbs energy) in the gasification process [14].

Smouldering fires have, in some instances, produced a smoke plume too weak to reach the ceiling of a room [15]. Other studies have found that smoke stratification occurs over time in smouldering fires resulting in less smoke obscuration at the ceiling level and smoke alarms drifting out of alarm [9].

The level of heat flux required to initiate smouldering combustion has been reported as substantially less than required to ignite flaming combustion. As little as 2 kilowatt/meter squared (kW/m^2) has produced smouldering fires in polyurethane foam, whereas $10kW/m^2$ or more is required to produce flaming fires in the same material [10].

Although there is no definitive period of time (nor certainty that transition will occur) smouldering fires can support the transition into flaming fires [10]. This is caused by a spontaneous gas phase ignition supported by the smouldering combustion producing both the gas fuel and heat for transition. Therefore, smouldering combustion presents a risk of resulting in flaming combustion from an original ignition source too weak to directly produce a flaming fire.

Although it is impossible to suggest which type of combustion will result when material is ignited by an external heat source, smoking materials (predominantly cigarettes) are well documented [9, 10, 14, 16, 17, 18, 19, 20] to cause smouldering fires. These fires can develop into flaming fires, depending on the material ignited and environmental conditions.

Cigarette initiated smoulder [14] on cotton mattresses has been found to spread radially at a rate of $6.3\ 10^{-5}$ m/s regardless of the size of the smouldering area. Such fires have been recorded to transition to flaming (at a rate of 2 out of 5) between 65-80 minutes, at which time lethal levels of CO had been reached [14]. Similar studies have been reported using upholstery as the material first ignited, resulting in lethal levels of CO, and a transition to flaming in excess of 2 hours [14].

Materials more prone to a smouldering combustion include cotton fabrics, cotton batting padding, and latex foam padding. Many solid materials are able to sustain smouldering including coal, tobacco, dust, paper, wood, peat, and synthetics (including polyurethane foam) [10].

Fire retardants exist to slow ignition and many more potential retardants have been tested. As yet there are no known retardants that actively and equally slow smouldering and flaming fires. Barrier materials constructed of cotton blends[1] are flame retardant and comply with both cigarette resistance and open flame resistance regulations, but are very bulky and therefore rarely used in upholstered furniture [19].

1.4 Examination of Smoke

When considering an evaluation of smoke alarms an examination of smoke must be considered. The characteristics of smoke particles is dependent on many factors including the mode of combustion, material chemistry and physical make-up of the fuel, humidity, ambient conditions, the movement of smoke, and the availability of oxygen [5].

Once produced, research has shown that as smoke travels away from its source it has a tendency to change in physical property. Research has explained that small particles collide, collect and gather into clusters as they travel away from the source [5, 21, 22]. This results in a decrease in the number of smaller particles, and an increase in the number of larger particles. This has been collectively described as smoke ageing and has been found to impact more significantly on ionisation detectors due to their responsiveness to small particle size/high particle count smoke environments [21, 22].

This phenomenon is also potentially of heightened importance in NSW as residences may contain only a single smoke alarm. Depending on the size and structure of the building, smoke

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[1] Including FR-modacrylic, FR-polyester, and FR-viscose

may have to travel a considerable distance before reaching the alarm, and it is unknown what degree of aging may have occurred over that distance.

In 2007 the Fire Protection Research Foundation undertook a study characterising smoke and its effects on smoke alarms [9]. The study considered the effects and influence of material chemistry, and what this means with regards to smoke alarms. A key finding was that synthetic materials (i.e. polyethylene, polyester, nylon, polyurethane), which are widespread in modern homes, produce higher levels of heat and smoke than their natural counterparts (ie. wood, cotton batting) [9]. Furthermore, the study confirmed that, generally speaking, synthetic materials produce smoke with a larger mean particle size [9].

The results from the smoke characterisation study were consistent with results from other studies whereby the ionisation alarm activated first in most flaming fires, and the photoelectric alarm activated first in most smouldering fires. The results showed that both alarms responded within the 4 minute time limit as set by UL 217 [23] for three flaming fires (Douglass Fir, newspapers and a heptane/toluene mixture), with the photoelectric alarm not responding in the polyurethane foam with cotton/poly fabric flaming fire. Many of the smouldering materials tests reported that the ionisation alarm did not trigger.

In the flaming test scenarios [9] the average time required to activate the ionisation alarm was 123.71s (2.06min) and photoelectric was 187.60s (3.13min). Results [9] showed that the ionisation alarm did not trigger in one scenario (6%), and the photoelectric did not trigger in three scenarios (17%). Neither triggered in the scenario of burning a smaller sample size (100x100x100mm) of polyurethane foam mattress wrapped in cotton/poly fabric.

In the non-flaming test scenarios [9] the ionisation alarm had an average trigger time of 2511.12s (41.85min), but did not trigger in 58% of the test scenarios. The photoelectric alarm had an average trigger time of 2177.37s (36.29min) when only the test scenarios that the ionisation alarm triggered in were counted. Across the full range of test scenarios the photoelectric alarm had an average trigger time of 3273.56s (54.56min), and did not trigger in 16% of the scenarios. Neither alarm triggered in the instance of polyisocyanurate insulation (150x150x120 mm pieces) nor in the mattress polyurethane foam scenario (150x150x50 mm).

The Smoke Characterization Project concluded that the use of combination photoelectric and ionisation alarms be required to maximise the alarm responsiveness across the range of fires.

A research study [22] undertaken by the National Institute of Standards and Technology (NIST) in the USA considered multiple contributing factors to the effectiveness of smoke alarms, including fabric type, foam density, fire location, ventilation and ignition. In this study dual sensor, photoelectric and ionisation alarms were installed side by side at multiple locations to determine effectiveness in activation. The report presents results from the average activation time for each alarm, split into flaming and smouldering fires. Although the focus of this study was to compare the effective alarm times of dual, ionisation and photoelectric alarms, the presented data can be interpreted to compare only photoelectric and ionisation alarms as results are clearly laid out in a table.

The ionisation alarm activated quicker than the photoelectric alarm in all flaming fires by on average 55s with the greatest difference in one test of 79s. In the smouldering fire scenarios, the photoelectric alarm activated on average 893s (15 min) faster than the ionisation alarm. In two smouldering fires the ionisation alarm activated on average 37s quicker, yet in two smouldering fires the photoelectric alarm activated on average 1824s (30 min) quicker.[2]

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[2] This information has been drawn from Table 2 of the study.

1.5 Tenability Criteria: Incapacitation and Death

When considering the situation of a resident being exposed to either a flaming or smouldering fire, time to alarm activation is not the only variable affecting escape. It is important to also consider factors and hazards that affect the local environment, and therefore escape. Although there are multiple factors that can delay a resident's escape, thereby increasing exposure time to hazardous conditions, it is the hazardous conditions that ultimately incapacitate or render an occupant dead. Therefore, the primary focus will be on direct hazards of a fire, with resident actions (which contributes to required safe egress time) being discussed more fully in Section 1.6: Smoke Alarms and Egress. It is important to note that when considering tenability limits with regard to the effective notification of smoke alarms that the time to alarm is less significant than the time between alarm notification and the development of untenable conditions.

The specific condition of any single fire is directly affected by the following: the materials involved in the fire; whether pyrolysation, flaming and/or smouldering is occurring; the location of an individual relative to the fire; the proximity of exits relative to both the individual and the fire; and an individual's susceptibility to the various hazards [24]. Predominantly, fire hazards can be divided into three main groups: asphyxiant gases, irritant gases, and thermal effects [24], with optical density indirectly contributing as a further fire hazard.

When discussing hazards with regard to tenability loss, asphyxiant gases are described in terms of their fractional effective dose (FED). This relates to the time during the course of the fire in which there is a high enough concentration of an asphyxiant toxicant to produce a given effect on the exposed occupant [25]. When FED equals 1, compromised tenability is predicted for half of the population [26]. This is sometimes referred to as the fractional incapacitation dose (FID) [11]. Reference is also made to fractional lethal dose (FLD) [11, 27].

With regard to irritant gases the term fractional irritant concentration (FIC) [11] or fractional effective concentration (FEC) [26] is used, again with reference to fractional lethal dose (FLD) when required. Unless specifically stated in relation to a single gas FED is for cumulative gas concentrations of asphyxiants and FEC is for cumulative concentrations of irritant gases. Each of these will be examined in turn, with relevant equations included.

1.5.1 Asphyxiant Gases

Asphyxiant gases directly affect the central nervous system and the cardiovascular system to an extent [11]. The effect is not a linear condition. Due to natural physiological functions, asphyxiants tend to build up in the brain allowing for normal bodily function up to a point. Once this point is reached, the exposed person will experience rapid deterioration due to tissue hypoxia, followed by unconsciousness and/or death [11]. It is important to note that time to incapacitation due to asphyxiant gases for small children may be half of that for an average adult [11]. This is due to the increased ratio of inhaled volume of air relative to body mass [26]. Furthermore, the elderly (particularly those with cardiovascular issues) are also more susceptible than healthy adults [26].

In fire environments the two main asphyxiant gases are carbon monoxide (CO) and hydrogen cyanide (HCN) [11, 26, 27]. Exposure limits, incapacitation and death for these gases have been determined through a range of studies resulting in clear limits to human survivability [11, 26, 27].

When looking at CO there are a range of equations that are applied to fire environments depending on the test situation and criteria. When only CO concentration and exposure time are known, and a respiratory minute volume (RMV) standard for a 70kg human is applied of 25 L/min for light activity, the following equation (Equation 1 [11]) determines the fractional incapacitating dose. It is important to note that an adult at rest in a fire environment may have a RMV equivalent to light activity due to increased respiration caused by increased levels of carbon dioxide (CO_2) in the air.

Equation 1: Fractional Incapacitating Dose for Carbon Monoxide

$$F_{I_{co}} = \frac{K(\text{ppm CO}^{1.036})(t)}{D}$$

$F_{I_{co}}$ = fraction of incapacitating dose
t = exposure time (min)
$K = 8.2925 \times 10^{-4}$ for 25 L/min RMV (light activity)
D = COHb concentration at incapacitation (30 percent for light activity)

When considering the effects of HCN, which is approximately 20-40 times more potent than CO [11], the time to incapacitation depends on two factors: the rate of uptake and the dose. As HCN does not present a linear projection towards incapacitation, an exponential equation must be used. This is because below thresholds of around 80 ppm of HCN for up to one hour, an exposed person will only experience minor effects; however, between 80ppm and 180ppm, time to incapacitation drops to between 2 and 30 minutes. Above 180ppm incapacitation occurs at less than 2 minutes. The exponential equation (with a regression coefficient of 0.984) for time to incapacitation is shown in Equation 2 [27].

Equation 2: Time to Incapacitation due to Hydrogen Cyanide

$$t_{I_{CN}}(\text{min}) = \exp(5.396 - 0.023 \times \text{ppm HCN})$$

The FID per minute can then be determined by applying the calculation shown in Equation 3 [11], which represents the inverse of Equation 2.

Equation 3: Fractional Incapacitation Dose for Hydrogen Cyanide

$$F'_{I_{CN}} = \frac{1}{\exp(5.396 - 0.023 \times \text{ppm HCN})}$$

When the fractional incapacitating dose is to be determined per minute, it is possible to apply the simplified Equation 4, where CN represents the concentration of cyanide (ppm) corrected for the presence of other nitriles in the gas sample [27].

Equation 4: Fractional Incapacitating Dose for Hydrogen Cyanide, Simplified

$$F_{I_{CN}} = \left[\left(\frac{\exp([CN]/43)}{220}\right) - 0.0045\right] t$$

When considering the uptake of asphyxiants, other factors play a role. For example, as carbon dioxide increases in a fire environment the effect on a human (as mentioned previously) is to increase the rate of respiration. Furthermore, depending on the occupant’s activities, their rate of breathing may be further increased due to activity. The reduction of oxygen (O_2) in a fire environment also directly impacts on survivability by exposing the resident to further levels of hypoxia. Considering the effect of CO_2 and O_2 on tenability, equations for these gases should also be included to determine time to incapacitation and/or death.

The rate of increase by which carbon dioxide stimulates RMV can be as much as 50% with only 3% CO_2 [24], thereby substantially influencing the uptake of other asphyxiant gases. CO_2 is therefore expressed as VCO_2 in order to account for these effects in calculations. Equation 5 [27] represents the calculation when the presence of CO_2 is known with regard to concentration in percentage at resting RMV, and Equation 6 [27] represents the same equation simplified form.

Equation 5: Multiplication factor for Carbon Dioxide (%) induced Hyperventilation

$$VCO_2 = \frac{\exp(0.1903 \times \%CO_2 + 2.0004)}{7.1}$$

Equation 6: Simplified multiplication factor for Carbon Dioxide (%) induced Hyperventilation

$$\mathrm{VCO2} = \exp\left(\frac{[CO_2]}{5}\right)$$

The time to unconsciousness at a constant CO_2 concentration, and the FID (per minute) are shown below in Equations 7 [27] and 8 [11].

Equation 7: Time to Incapacitation due to Carbon Dioxide

$$t_{I_{CO_2}} = \exp[6.1623 - 0.5189 \times \%CO_2)$$

Equation 8: Fractional Incapacitating Dose for Carbon Dioxide

$$F'_{I_{CO_2}} = \frac{1}{\exp(6.1623 - 0.5189 \times \%CO_2)}$$

Oxygen hypoxia, which results from the depletion of O_2 due to fire combustion, has increasing effects on a person depending on the level of decrease ranging from reduced exercise tolerance to rapid deterioration and death. The following equation (Equation 9 [27]) is used to determine time to loss of consciousness, and therefore time to tenability.

Equation 9: Time to Loss of Consciousness due to Oxygen Hypoxia

$$(t_{I_O})\text{min} = \exp\,[8.13 - 0.54(20.9 - \%O_2)]$$

Further to this, the FED calculation is shown by Equation 10 [27], which assumes a per minute time interval.

Equation 10: Fractional Effective Dose due to Oxygen Hypoxia

$$F'_{I_O} = \frac{1}{\exp\,[8.13 - 0.54(20.9 - \%O_2)]}$$

Given the relationships and cumulative effects between CO_2, O_2, CO and HCN, and the FLD of irritant gases (to be discussed shortly), Equation 11 [27] is derived to determine the combined fractional dose equation for asphyxiation.

Equation 11: Combined Fractional Dose Equation for Asphyxiation

$$F_{tn} = [(F_{I_{CO}} + F_{I_{CN}} + \text{FLD}_{irr}) \times VCO_2 + \text{FED}_{I_O}]$$

As asphyxiant gases have cumulative effects in a person's system, over time the total effects of the asphyxiant gases can be summed for each successive minute during the fire [27].

1.5.2 Irritant Gases

There are numerous irritant gases found in fires, including both inorganic and organic irritants. These gases can be separated into sensory irritants affecting the eyes and upper respiratory tract, and pulmonary irritants affecting the lungs [24]. The calculation for each of these irritant gases is simply determined by dividing the concentration of the gas by the known concentration to incapacitate or cause death, (depending on the analysis and application), multiplied by the change in time.

The primary irritant gases include hydrogen chloride (HCl), hydrogen bromide (HBr), hydrogen fluoride (HF), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), acrolein (C_3H_4O) and formaldehyde (HCHO) [11, 26]. The FIC and FLD for irritant gases can be calculated using a known concentrations for incapacitation and death. The following two equations (Equation 12

[11] and Equation 13 [11]) are used to determine FIC and FLD respectively, with the only difference in the calculations being the known concentrations applied. Each of these equations allow for the inclusion of the presence of other known irritant gases. To meet with the criteria of Equation 11, the result of Equation 13 must be used

.

Equation 12: Summation Calculation FIC Irritant Gases

$$\begin{aligned} FIC &= FIC_{HCl} + FIC_{HBr} + FIC_{HF} + FIC_{SO_2} \\ &+ FIC_{NO_2} + FIC_{CH_2CHO} + FIC_{CH_2O} + \sum FIC_x \end{aligned}$$

Equation 13: Summation Calculation FLD Irritant Gases

$$\begin{aligned} FLD_{irr} &= FLD_{HCl} + FLD_{HBr} + FLD_{HF} + FLD_{SO_2} \\ &+ FLD_{NO_2} + FLD_{CH_2CHO} + FLD_{HCHO} + \Sigma FLD_x \end{aligned}$$

Although there are multiple other irritant gases found in fire environments (which can be included in these calculations), the aforementioned seven gases have been selected by toxicologists and approved in standards [26] and handbooks [11, 27] to give a strong indication of tenability limits. There is some discrepancy between handbooks [11, 27] and standards [26] as to what the concentrations of irritant gases are that lead to serious compromised escape and/or incapacitation. This may be due to disagreement between toxicologists that lower limits are too low to be practically applied to real fire environments, with the rebuttal being that the limits are set for within the breathing zone, not close to the fire [11].

Research has shown that asthmatics are particularly susceptible to irritant gases, and even brief exposure can result in bronchoconstriction [26]. This, combined with the measured increased sensitivity of children and the elderly, leads to strong argument of considering an FEC limit of less than 1 in order to increase the survival chances of the those more vulnerable.

1.5.3 Heat Exposure

The third major factor affecting tenability is exposure to heat, which can lead to hyperthermia (heat stroke), body surface burns, and burns to the respiratory tract. In situations where prolonged exposure to convected heat is sustained, yet the temperature is less than approximately 120°C in dry air or 80°C in saturated air, the result is an increase in core body temperature leading to hyperthermia [11]. Figure 4 [28] shows a pictorial description of tolerance time vs temperature in humid and dry environments.

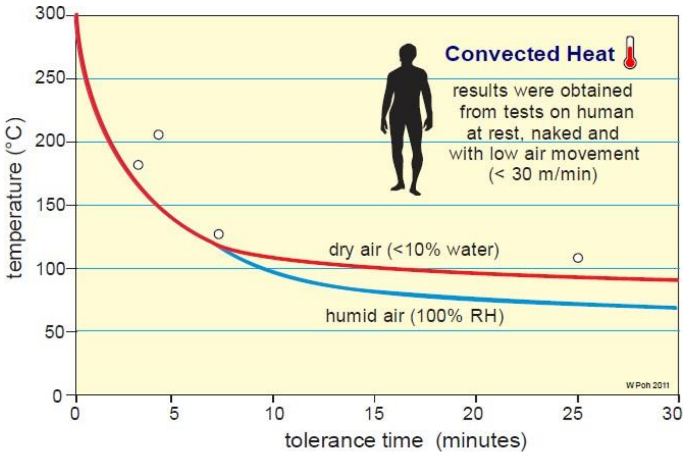


Figure 4: Tolerance vs Time for Convected Heat

At temperatures below these limits, evaporative cooling from perspiration reduces the impact on increased core body temperature. It has also been found that clothing affords a level of protection at temperatures above these limits; however, clothing can reduce tolerance time at lower temperatures by impeding the body's ability to reduce heat through perspiration [11]. When core body temperature reaches 40°C incapacitation can occur due to blurred consciousness and illness. An increase in core temperature to above 42.5°C is fatal unless treated within minutes [11].

Exposure to heat contains the risk of burns to the respiratory tract. When lungs are rapidly exposed to excessive convected heat the result can be a sharp decline in blood pressure, capillary collapse, and potentially circulatory failure [24]. A further potential result of this exposure is a fluid build-up in the lungs [24].

The consequence of exposure to excessive convected heat dramatically increases with humidity. Due to the large, wet surface area of the airways and good blood supply, burns to the respiratory tract are uncommon below the top of the trachea in dry air, even when heat conditions of 350°C or more are met [11]. When steam at 100°C is introduced into the respiratory tract it is possible to cause severe burns down into the deep lung [11].

The equation to determine time to incapacitation for lightly clothed persons due to convected heat is shown in Equation 14 [11, 26] where *T* is the temperature expressed in °C, with the FED per minute for convected heat being the inverse.

Equation 14: Time to Incapacitation due to Convected Heat

$$t_{Iconv} = 5 \times 10^{7} T^{-3.4}$$

Convected heat, along with conducted and radiant heat, influence the effect of a fire on body surface (skin) burns. The threshold of radiant heat for skin is approximately 2.5 kW/m^2 [26]. Below this threshold exposure can be tolerated for 30 minutes or more; however, above this threshold the time to second degree burning, and therefore tenability, decreases rapidly [26]. The equation to determine time to incapacitation due to radiant heat is shown in Equation 15

[24] where *q* is the radiant heat flux expressed in kilowatts per square metre, with the FED per minute due to radiant heat being the inverse.

Equation 15: Time to Incapacitation due to Radiant Heat

$$t_{\mathrm{I,rad}} = 6.9q^{-1.56}$$

With regards to the FED for heat, convected and radiant heat FEDs are directly additive. As time continues in a fire situation the FED for heat is cumulative.

1.5.4 Optical Density

Optical density is a factor that directly affects a person’s egress time and is based on the concept of minimum detectable contrast [26]. This concept estimates that incapacitation has been reached when an occupant is unable to orient themselves due to minimal detectible contrast for distances of 0.5m [24]. At this point, when occupants are essentially unable to distinguish their hand in front of their face, they are likely to become disoriented when engaged in cognitive or motor-skill activities (ie egress) [26].

Although decreased visibility does not directly cause incapacitation or death, it drastically decreases movement times and has also been shown to prevent a person from progressing [11]. Furthermore, increased optical density is invariably due to smoke in a fire environment, which contains toxic gases.

In a non-irritant smoke environment, studies have shown that walking speeds decrease from 1.2m/s in a clean air environment to 0.3m/s when visibility was decreased to 2m [29]. In environments where irritant smoke was introduced, walking speeds reached 0.3m/s (equivalent to moving in total darkness) at a much lower level of optical density [29].

Studies undertaken on fires in buildings show that approximately 30% of people turned back rather than progress through smoke logged environments [29]. Figure 5 [11] shows a visual description of this information.

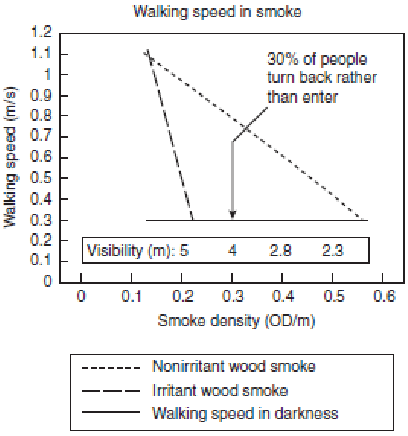


Figure 5: Effects on Walking Speed due to Optical Density

Therefore, although optical density does not directly cause incapacitation, it has an impact on tenability, and should therefore be considered. Equation 16 [11] is used to determine the FEC for smoke when the optical density has been measured.

Equation 16: Fractional Effective Concentration for Optical Density

$$\begin{aligned}\mathrm{FEC}_{\mathrm{smoke}} &= [\mathrm{OD/m}]/0.2 \text{ for small enclosures}\\ &\text{or } [\mathrm{OD/m}]/0.08 \text{ for large enclosures}\end{aligned}$$

Walking speed can also be assessed in irritant smoke based on the FIC (for a single irritant concentration or a mixture of compounds). To determine the fractional walking speed, the following equation [27] can be used for irritant compounds 1 to *n*.

Equation 17: Fractional Walking Speed due to Irritant Effects

$$F_{\mathrm{wvirr}} = 1-[(1-e^{-(x/b)^2})+(-0.2x+0.2)/1.2]$$

F_{wvirr} = Fractional walking speed (1 = normal walking speed 1.2 m/s)

$b = 160$

$x = \mathrm{FIC}$

Equation 17 derives the curve estimating the relationship between fractional walking speed and the FIC for a sensory irritant or a mixture of compounds, as shown in Figure 6 [27].

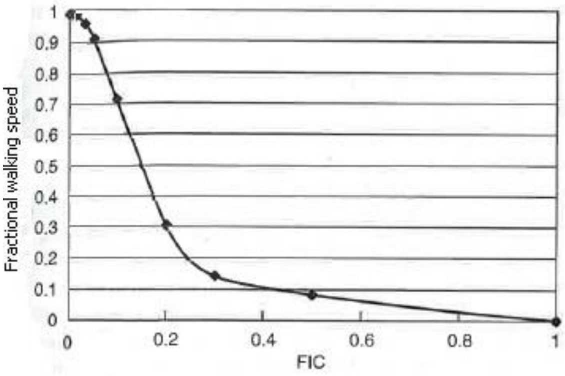
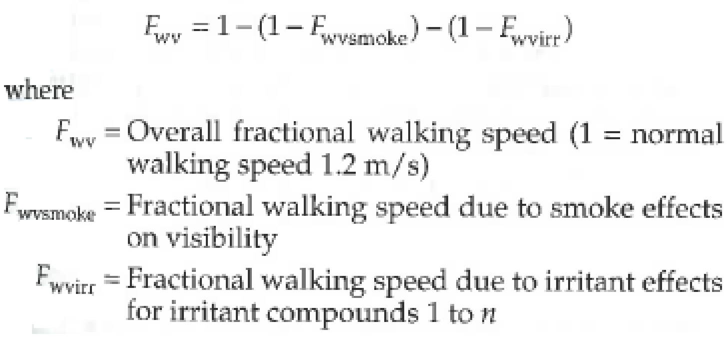


Figure 6: Estimated Relationship between Fractional Walking Speed for Sensory Irritants

Using the results from Equation 17, and in situations where the fractional walking speed due to smoke effects on visibility is known, Equation 18 [27] can be applied to calculate the overall fractional walking speed (whereby 1 is equivalent to the normal walking speed of 1.2m/s).

Equation 18: Overall Effect on Walking Speed to Irritant Smoke Exposure



$$F_{\mathrm{wv}} = 1 - (1 - F_{\mathrm{wvsmoke}}) - (1 - F_{\mathrm{wvirr}})$$

where

F_{wv} = Overall fractional walking speed (1 = normal walking speed 1.2 m/s)

F_{wvsmoke} = Fractional walking speed due to smoke effects on visibility

F_{wvirr} = Fractional walking speed due to irritant effects for irritant compounds 1 to n

1.6 Smoke Alarms and Egress

In the research paper “Full-Scale Residential Smoke Alarm Performance” [30], the National Institute of Standards and Technology (NIST) expands the research discussed in Section 1.4 “Examination of Smoke” to include fractional effective doses (FED), optical density (OD) limits and limits on available safe egress times (ASET). A conservative limit[3] was applied to the FED for toxic gases, heat and optical density. Measured temperature, heat flux and gas concentrations were taken at a height of 1.5m from the floor, and smoke alarms were present in the room of origin.

It was found that in initially smouldering fires, the time to reach the FED toxic gas limit of 0.3 ranged from 4469s-7574s (74min-126min), with an average of 5825s (97min). Initially flaming fires did not reach the FED toxic gas limit in any instances. The time to reach 0.3 FED for heat in initially smouldering fires was within the range of 4977s-10060s (83min-168min), averaging 6227s (104min). In initially flaming fires the range was 269s-1404s (4min-23min), averaging 491s (9min). Finally, the time taken to reach the optical density limit of .25m^{-1} ranged from 1801s-5783s (30min-96min) in initially smouldering fires (averaging 3818s or 64min), and in flaming fires ranged from 206s-1347s (3min-22min), averaging 393s (7min). This research demonstrates that the time to untenable conditions in smouldering fires is much longer than flaming fires.

Using these conservative limits, and applying their results to the results from smoke alarm activation, NIST found that the photoelectric and dual sensor alarms provided a positive egress value in all tests, and the ionisation alarm provided it in 20/24 tests.

NIST research then set a further parameter of an available safe egress time (ASET) time limit of 120s. Under these circumstances, the photoelectric alarm provided safe egress in 10/24 tests, the ionisation alarm provided this in 6/24 tests, and the two dual alarms provided it in 3/23 and 2/23 tests respectively. The ASET parameter is particularly important when considering studies have found that a required safe egress time (RSET) time of 90s[4] [16] will allow most healthy, unimpaired adult occupants to exit, with elderly people or those requiring

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[3] Calculations for these limits are available in the standard [25]. A FED of 1 corresponds to a dose where it is half of the population is expected to become incapacitated.

[4] This value was based around the time taken for sleeping occupants to awaken to the sounding smoke alarm and egress their home.

indirect escape (due to the presence of small children or disabled adults) needing closer to 120s (or in excess of this [31, 32]).

The presence of children in a home can have a significant impact on the time required to safely exit, as studies have shown that rescue remains the most reliable means to evacuate children under the age of 15. A Research Group on Childhood Awakening[5] [33] has reported that children under the age of 15 are unlikely to awaken fully to the current auditory stimulation produced in smoke alarms, and children under the age of 5 are at particular risk due to potential confusional behaviour (including hiding in a closet) if awake when a smoke alarm sounds.

RSET values are calculated by considering several factors: the time from fire ignition to detection; time from detection to notification of occupants; time from notification until occupants take action; time from decision to take action to when evacuation begins; and finally the time from evacuation start to end [34]. Considering this, if adults can self evacuate within 90s (some scenarios have found healthy, unimpaired adults may complete a direct escape as quickly as within 65s), yet some situations require an increased period of time to safely exit (due to the need to provide child rescue or increased mobility issues), an ASET value of 120s may not provide enough time.

Test scenarios in the USA assessed that indirect escape (required when awakening or rescuing other members of the household) may require as much as 135s [31]. In this research, although smoke conditions became untenable with respect to visibility[6], there was only one instance where a smoke alarm failed with regard to toxic gas and heat to support the 135s escape time. This instance was a photoelectric alarm in a flaming fire, and the results showed that the alarm did not provide safe egress time with respect to heat and toxic gas levels.

It is important to note that each of these studies is framed around the 2007 National Fire Alarm Code (2007 NFPA 72) [35] minimum requirements in the United States for alarms in residential occupancies. This required that alarms were present in all sleeping areas, within 6.4m of any sleeping room measured along the path of travel, on every level, with at least one smoke alarm per 46.5m^2 should the floor size exceed 93m^2. The 2007 NFPA 72 required interconnected smoke alarms in all homes, including existing ones.

This is distinctly different from what is currently required in NSW under the Regulation 2000 and Amendment 2006, and therefore consideration must be given with regard to alarm responsiveness should distances between the fire source and smoke alarm be increased (with the potential of closed doors impeding the detection of smoke). This point is further considered in Section 1.12, Fatal Risks in Alarm Placements.

1.7 International Statistics: Structure Fires and Fatalities

The United Stated of America “Home Structure Fires” report outlines a range of USA fire statistics between 2007-2011. The outlined data shows that 7% of fires originating in the bedroom resulted in 25% of civilian deaths, 4% of fires originating in the living room, family room or den resulting in 24% civilian deaths, and 42% of fires originating in the kitchen or

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[5] Paper prepared by a UL working group to address children not awakening to the sound of smoke alarms.

[6] Obscuration, at some level, leads to occupants not being able to visually discern boundaries, and therefore become disoriented even if the surroundings are otherwise known. This can lead to confusional behaviour and compromised tenability. Obscuration alone does not directly compromise tenability; it compromises cognitive and motor-skill activity. [25]

cooking area resulted in 16% of civilian deaths [36]. The report goes on to further show that 70% of victims of fatal fires that originated in the bedroom were located in the bedroom at the time of the incident [36]. These values related to living room/family room/den and kitchen fatalities are 48% and 41% respectively [36].

Through comprehensive data collection the report shows that although upholstered furniture caused only 2% of home structure fires, it was responsible for 18% of the fatalities. Similarly, mattresses or bedding were the cause of 3% of home structure fires, yet 13% of fatalities [36]. Cooking materials caused 29% of the total structure fires, yet only 5% of civilian deaths.

Fire statistics released by the Department of Communities and Local Government in Great Britain show similar findings with regard to the percentages of fatalities for fires started in the bedroom, lounge and kitchen. British statistics[7] [37] show that the highest proportion of fatalities, 45%, were from fires that originated in the lounge room, 29% were from bedroom fires, and 20% were from kitchen fires. This is further broken down into statistics showing the final location of the victim in relation to the fire. In bedroom fires, 35% were found located in the room with 22% outside it. Lounge fires showed 45% were found in the room, with 34% found outside. Kitchen fires resulted in 13% of fatalities being found in the room of origin, with 29% found outside the kitchen.

The British data specific to 2012-2013 shows that although cooking appliances were the cause of 52% of household fires, they only accounted for 12% of fatalities, whereas smoking materials (usually associated with bedroom and lounge room fires) caused 6% of household fires yet 38% of fatalities. Electrical distribution and appliance fires caused 24% of household fires, and 10% of the total fatalities.[8]

A report by the West Australian government examining fatalities due to fires from 2001-2006 further substantiated the findings the USA and Great Britain. The West Australian report showed that smoking materials were responsible for 27% of all fatalities, heating appliances responsible for 21% and electrical distribution and lighting responsible for 15% [38]. West Australia’s data also showed that 40% and 33% of these fatal fires started in the bedroom and living room/lounge respectively.

1.8 FRNSW Statistics: Structure Fires and Fatalities

Data from fires attended by FRNSW between 2000 and 2014 for class 1a and 2 buildings showed comparable findings to the international statistics. The majority of home fire fatalities[9] were from fires that originated in the lounge room (30%) or bedroom (36%). Only 9% of fire fatalities had the kitchen as the area of origin. With respect to total fires attended by FRNSW, 13% originated in the lounge, 18% in the bedroom, and 25% in the kitchen.[10]

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[7] Statistics calculated from Table 12b of Fire Statistics Great Britain 2012/2013. Data range includes the years 2000-2013. NOTE: No explanation is given in the report as to why these percentages do not add up to 100%. It is possible this is due to the inclusion of unreported or unknown data.

[8] Table 2.1: Fatal and non-fatal casualties in accidental dwelling fires by source of ignition, Great Britain, 2012/13

[9] Data collected from the Australian Incident Reporting System (AIRS) via the Strategic Reporting System on October 28, 2014. Includes date range January 1, 2000 – collection date, class 1a and 2 buildings.

[10] Data collected from the Australian Incident Reporting System (AIRS) via the Strategic Reporting System on October 28, 2014. Includes date range January 1, 2000 – collection date, class 1a and 2 buildings.

See Figure 7 for a visual representation of these percentages.

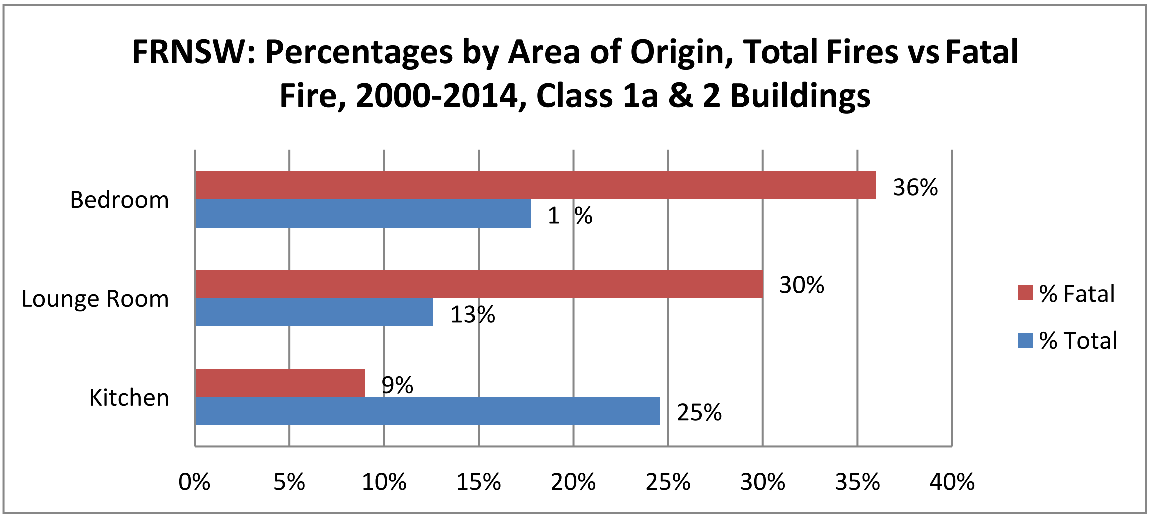

Figure 7: FRNSW Percentages by Area of Origin

When considering the ignition factor[11] involved in total fires vs fatal fires it was found that open flame accounted for 13% of fires in both categories, a lighter or match caused 11% of total fires and 12% of fatal fires, smoking materials accounted for 7% of total fires yet 23% of fatal fires, electrical faults / equipment caused 48% of total fires and 37% of fatal fires. Other causes accounted for 20% of total fires and 14% of fatal fires. Figure 8 illustrates these numbers in a graph.

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[11] Data collected from the Australian Incident Reporting System (AIRS) via the Strategic Reporting System on November 10, 2014. Includes date range January 1, 2000 – collection date, class 1a and 2 buildings.

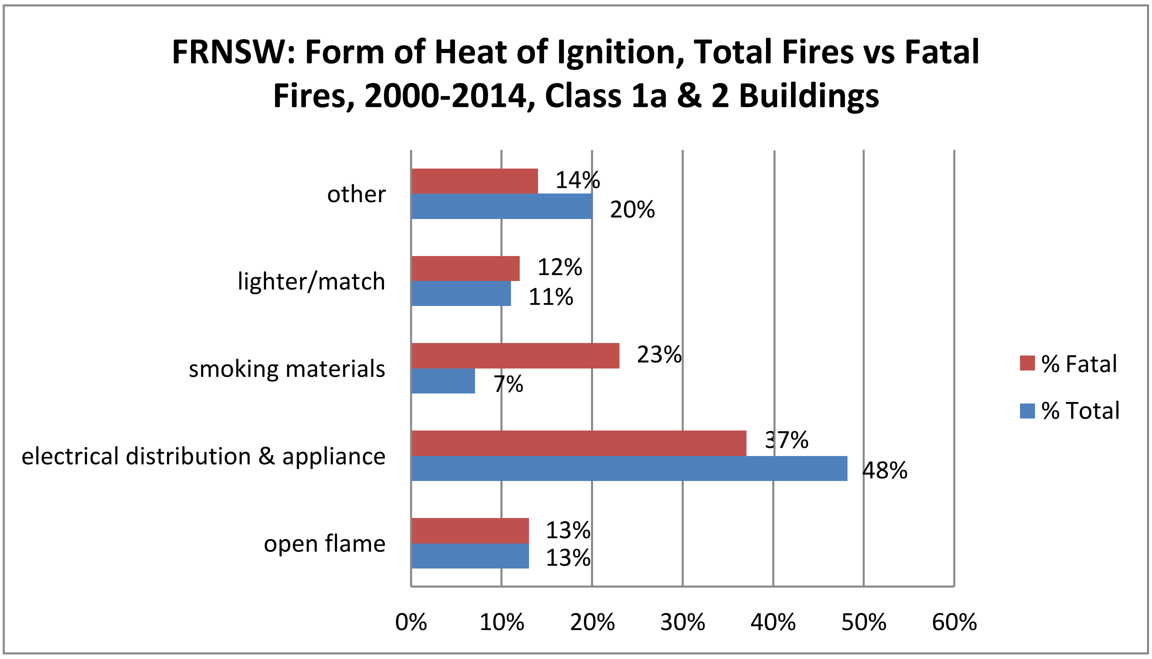

Figure 8: FRNSW Percentages by Form of Heat of Ignition

The data can be further analysed to determine the form of material first ignited in total fires and fatal fires in NSW attended by FRNSW[12].

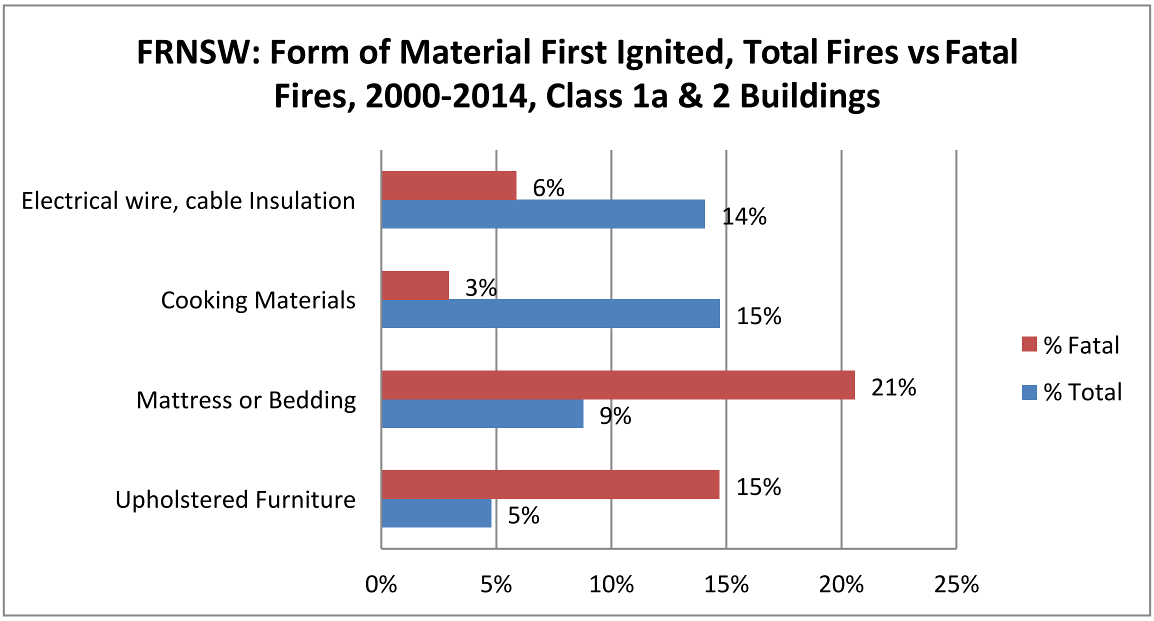

Figure 9: FRNSW Percentages by Form of Material First Ignited

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[12] Data collected from the Australian Incident Reporting System (AIRS) via the Strategic Reporting System on November 10, 2014. Includes date range January 1, 2000 – collection date, class 1a and 2 buildings.

Figure 9 demonstrates that the materials that caused the majority of FRNSW attended structure fires fatalities for class 1a and 2 buildings were not proportionally the cause of the majority of overall structure fires. Although it is impossible to assume what type of fire any given material is likely to cause (flaming or smouldering), it is possible to suggest bedrooms and lounge rooms are most likely to contain mattresses, bedding and upholstered furniture. As mentioned in Section 1.3, "Smouldering vs Flaming Fires", the materials present in these furnishings have an increased propensity to smoulder.

Figure 10 examines at the relationship between form of heat of ignition and area of origin in FRNSW attended structure fire fatalities for class 1a and 2 buildings[13].

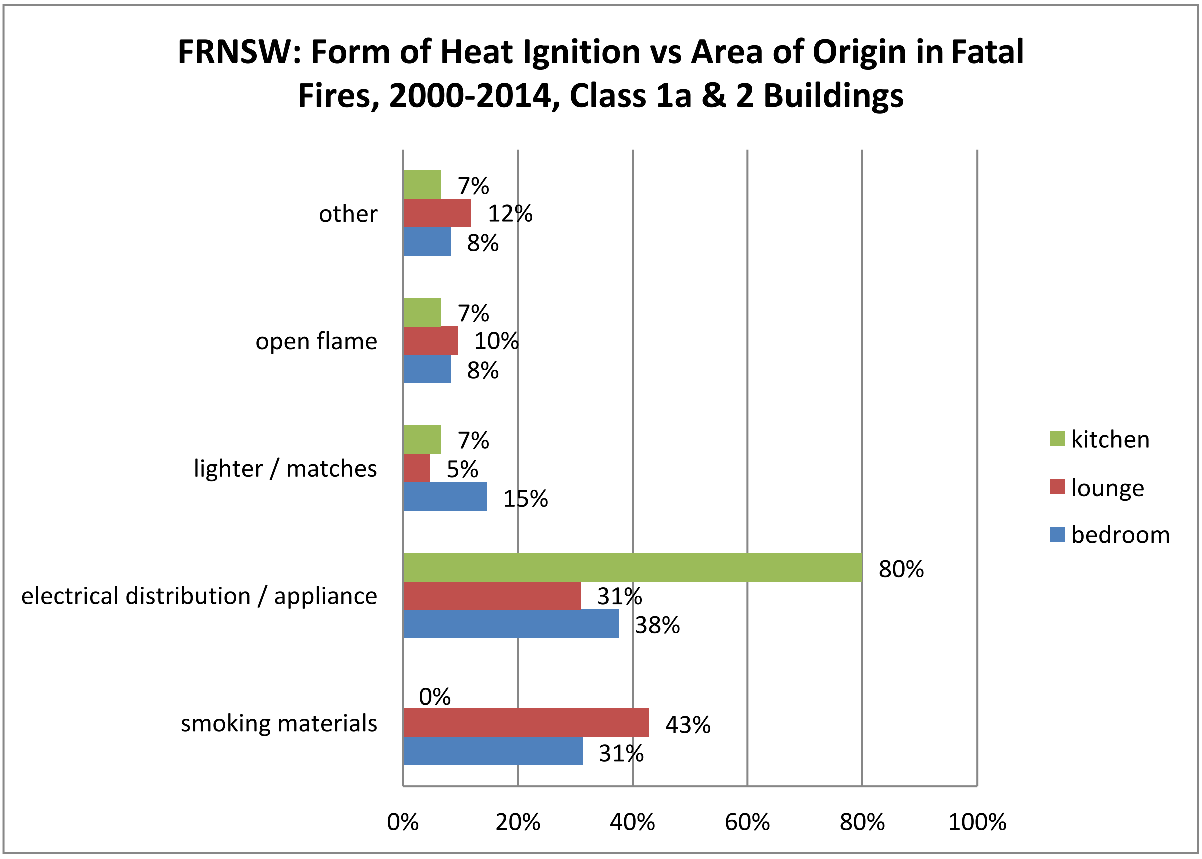

Figure 10: FRNSW Percentages by Form of Heat Ignition vs Area of Origin in Fatal Fires

All incidences of smoking materials (not including lighter or matches) being the form of heat ignition were located in the lounge or bedroom, and further data analysis showed that in 61% of those fires the form of material that first ignited was either bedding, mattress or upholstered furniture.

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[13] Only values for determined causes for heat of first ignition are presented in this table, excluding all cases of "undetermined". Approximately 50% of fatalities in each of the three areas of origin were undetermined for factor of heat of first ignition.

Considering the significant amount of research surrounding the propensity of smoking materials to promote smouldering, and connection between form of heat of ignition and material first ignited, it is possible to postulate that a reasonable percentage of these fatal fires may have begun by means of smouldering combustion. This postulation is supported by research from Norway, which establishes (post statistical analysis) that 25% (considered a conservative value) of fatal fires will start as smouldering, and most likely be ignited by a burning cigarette on upholstered furniture and mattresses[14] [39].

1.9 NSW Households, Smoke Alarms, and Fires

It is interesting to consider whether an increase in smoke alarms over time in NSW can be directly correlated with a decrease in total and fatal fires attended by FRNSW in an equivalent time frame. The Report on Government Services 2014 Volume D: Emergency Management [40] shows that between 2003 and 2013 the percentage of households with a smoke alarm/detector in NSW increased from 72.8% to 92.8% (at a rate of approximately 2.5% per annum, but not as a directly linear increase). Within these years total fires in NSW decreased from 2393 to 2137 (not a linear decrease) and fatal fires slightly decreased (low linear association).

To analyse if a relationship existed between the presence of smoke alarms, fires, and fire fatalities, the associated correlation coefficient[15] was calculated. Between the estimated percentages of smoke alarms/detectors in households and total fire calls attended by FRNSW for the period 2002-2013 the correlation coefficient was calculated to be -0.89. This indicates a moderately strong linear relationship between decreasing number of fires with increasing percentage of households with smoke alarms.

The correlation coefficient between the percentage of smoke alarms/detectors and the number of fire fatalities in the same period is -0.55, indicating a much weaker linear relationship. This is thought to be in part due to the numbers of fire fatalities in fire calls attended by FRNSW being much smaller, and therefore are more likely to be strongly influenced by small unpredictable factors.

1.10 FRNSW: Smoke Alarm Presence in Fire Incidents

Data analysis from the Australian Incident Reporting Scheme (AIRS) has shown that about half of household fires attended by FRNSW had smoke alarms present. Of the total fire calls attended in class 1a and 2 buildings[16], 48% recorded the presence of a smoke alarm, 46% recorded no smoke alarm present, and 6% were recorded as unable to be determined, not applicable, or without information. In total fires with a smoke alarm recorded as present, 65% operated and 43% were recorded to have alerted the occupants.

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[14] In 2005 the smoking rate in Norway was similar to the smoking rate in Australia, 25% vs 23% (Australian source: 4831.0.55.001 - Tobacco Smoking in Australia: A Snapshot, 2004-05, Norwegian source: Norwegian Ministry of Health and Care Services, Norway's National Strategy for Tobacco Control 2006-2010)

[15] A correlation coefficient of +1 shows a direct linear relationship that when one variable increases, the other variable increases also. A coefficient of -1 describes a direct inverse linear relationship. A coefficient of 0 shows no relationship between the two variables.

[16] Data collected from the Australian Incident Reporting System (AIRS) via the Strategic Reporting System on October 28, 2014. Includes date range January 1, 2000 – collection date, class 1a and 2 buildings.

Regarding fatalities in the abovementioned fires, the numbers show a lower proportion of smoke alarms present and alerting occupants. The data shows that 56% of fire fatality incidents had no smoke alarm present, and 44% had an alarm present. Of those fires with an alarm present, 56% were recorded as the alarm having operated, but only 26% of fires with a smoke alarm present were recorded as having alerted the occupants. Figure 11 outlines these percentages visually.

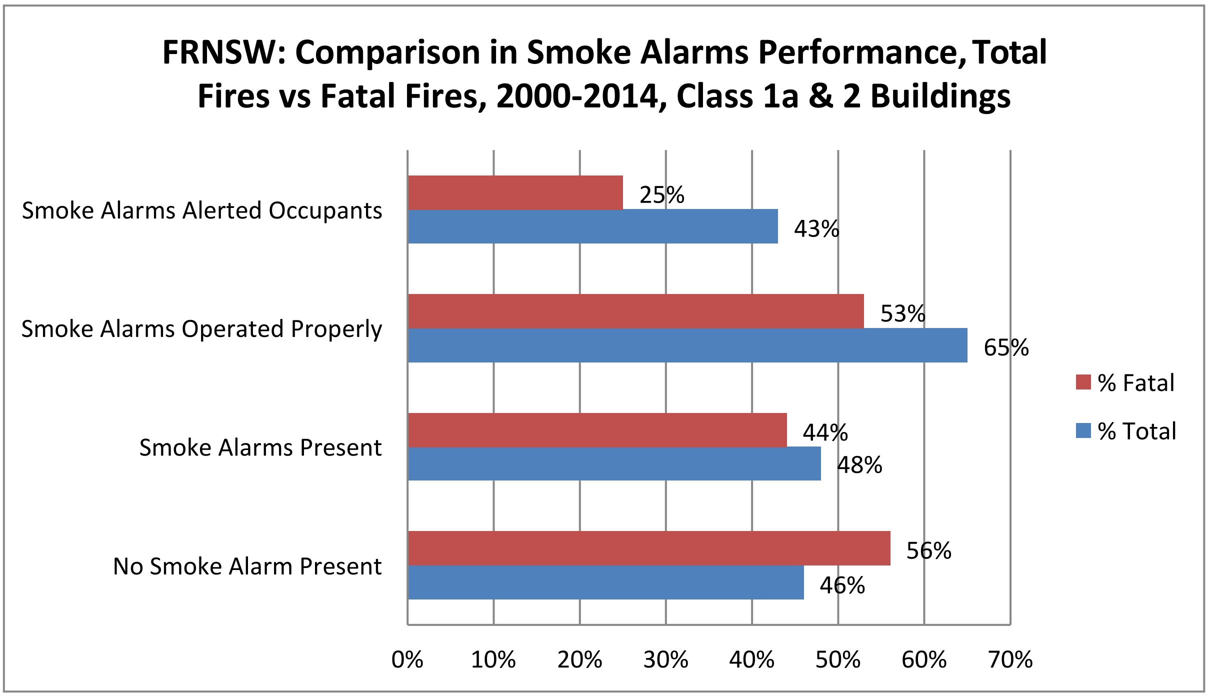

Figure 11: FRNSW Percentages by Smoke Alarms Performance

Figure 11 shows that when the relative percentages of total structure fires and fatal fires are compared, a more tangible difference is noted regarding the performance of smoke alarms. Fatal fires had a lower percentage of smoke alarms present, a lower percentage that operated, and a significantly lower percentage that functioned to alert the occupants.

Considering the area of origin for the majority of fire fatalities in residential dwellings, an analysis of the data was undertaken to determine performance of smoke alarms in kitchens, bedrooms and lounge rooms. This information is displayed in Figure 12.[17]

Figure 12 shows that alarms operated in approximately half of all fatal bedroom and lounge fires. Time frames for these activations are entirely unknown.

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[17] Data collected from the Australian Incident Reporting System (AIRS) via the Strategic Reporting System on October 28, 2014. Includes date range January 1, 2000 – collection date, class 1a and 2 buildings. Where the presence of an alarm was unable to be determined, or the operation of the alarm was deemed "not applicable" were not included in this table.

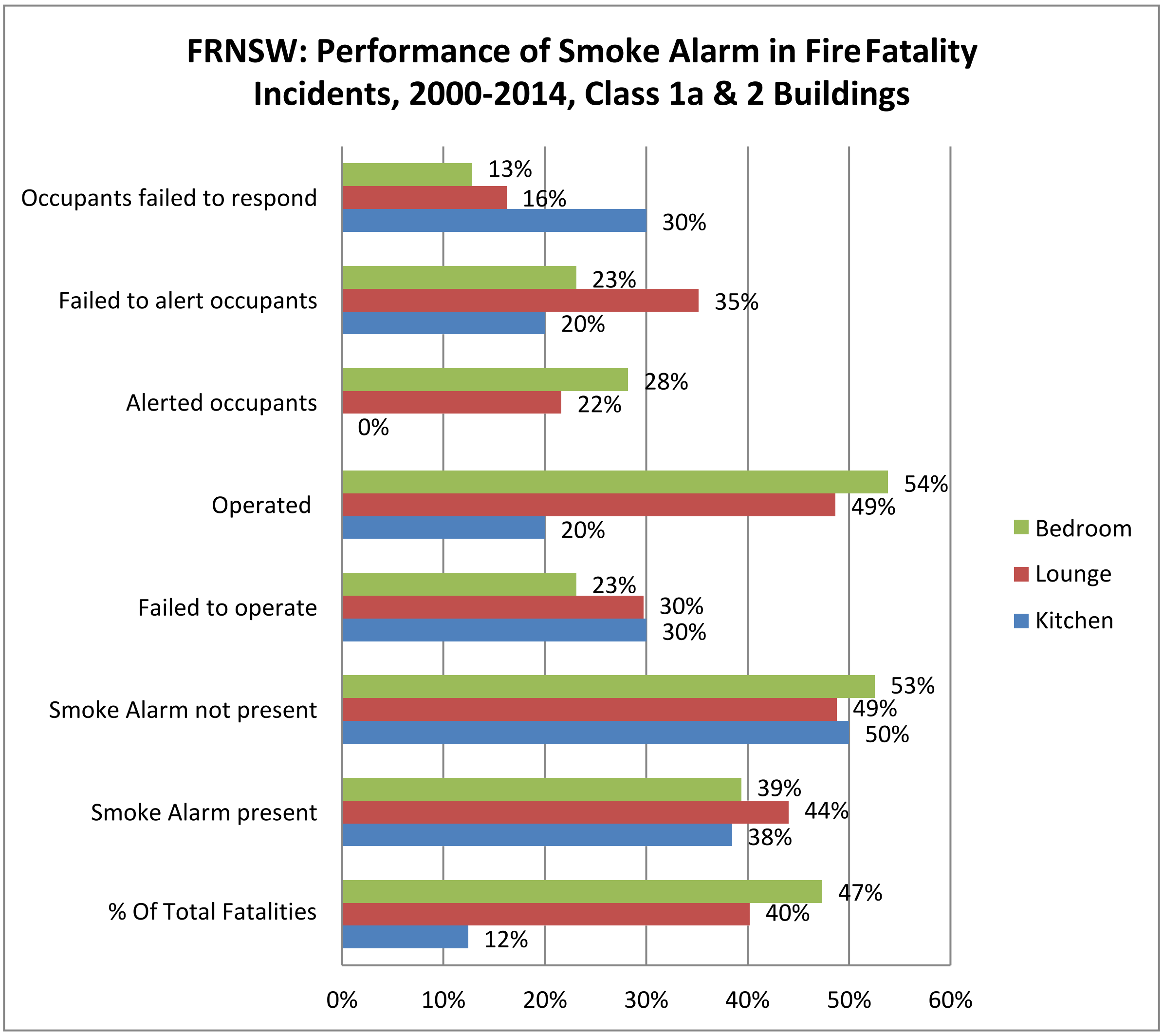

Figure 12: FRNSW Percentages of Performance of Smoke Alarms by Room of Fire Origin

In total structure fires, the ratios of homes with smoke alarms (48%) compared to no smoke alarms (46%) was found to be not representative of the government statistics for NSW discussed in Section 1.9, NSW Households, Smoke Alarms, and Fires. The FRNSW data has produced similar findings to a study undertaken in Norway that examined fatal fires in the period of 1997-2003. Although more than 97% of Norweigian homes had a smoke alarm installed, only 25% of homes that experienced a fatal fire had a working smoke alarm, and 21% had no smoke alarm present (or had a non-functioning alarm) [39]. This may explain why, as mentioned in Section 1.9, there is a much lower correlation between increased smoke alarms in NSW households and fire fatalities.

The USA report on Home Structure Fires [36] may offer a further potential explanation, wherein it states that the vast majority (93%) of unreported fires occur in homes with a smoke alarm, and homes without a smoke alarm are disproportionately likely to need the assistance of the fire department.

This explanation is supported by a recently undertaken Home Fire Safety Checks Program pilot study by the Community Safety Directorate within FRNSW[18]. This pilot study visited 304 homes across 8 specifically selected suburbs due to their risk profile for fires. Of those homes only 38% (111 homes) had a working smoke alarm already correctly installed.

1.11 False Alarms and Their Effects

Numerous laboratory tests and field studies have been undertaken to evaluate the likelihood of various smoke alarms to nuisance, and whether nuisance alarms are less likely to be functional after a given period of time. Conclusions from these reports may provide a potential explanation as to why many properties do not have functional smoke alarms.

Four field studies were considered in this review, three from the USA (Iowa [41], Alaska [42] and Washington [43]) and one from Camden (London), England [44]. The three USA studies examined alarm functionality after a set period of time ranging from 6 months to 42 months post installation, with the British study undertaking a 15 month field study.

Each of the USA studies found that ionisation alarms were far more likely to nuisance, ranging from twice as likely to nearly five times as likely. The Alaskan and Washington studies found that more ionisation alarms were disconnected (19% and 20% respectively) at follow up compared with the photoelectric alarms (4% and 5% respectively). Nuisance alarm was given as the primary reason for disconnection. These two studies placed alarms in varying locations, with the Alaskan study placing alarms on average 4-5m away from both heating and cooking sources, and the Washington study placing alarms throughout the home in accordance with the then current NFPA smoke alarm code. The majority of nuisance alarms were caused by cooking, but nuisance also included low batteries, fireplaces, steam and smoking to a much lower extent. Authors outlined that alarms located closest to the kitchen were twice as likely to nuisance, and had a higher incidence of disconnection.

The Iowa study looked into comparing the two alarms, but also factored in lithium vs carbon/zinc batteries. It found that the alarm most likely to be functional after 42 months was a photoelectric alarm with a lithium battery. This finding was further broken down to show that 6% more photoelectric alarms were functional than ionisation, and 8% more alarms with a lithium battery were functional than a carbon/zinc battery.

The British study addressed battery type (lithium vs zinc) as well as alarm type (photoelectric vs ionisation), and considered whether homes had open plan kitchens. The results at the 15 month follow up study found that nearly half of all installed alarm systems in the households in Camden were not working, 40% of which had been disabled by the tenants. Lithium powered ionisation alarms were the most likely to be working at follow up. Zinc powered photoelectric alarms and ionisation alarms with a pause button were more likely to have experienced low battery warning signals or had their batteries changed. Households with at least one smoker were more likely to have disabled smoke alarms regardless of type, with only 38% of photoelectric alarms and 48% of ionisation alarms still functional. Homes with open plan kitchens were 6% less likely to have a working alarm than enclosed kitchens.

The author of the Washington study addressed potential differences between the USA and British findings, considering that the difference in percentages of houses with smokers could

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[18] Data presented on October 14, 2014 during an update by the Community Safety Directorate for the FRNSW Executive Leadership Team. The pilot program is continuing and numbers are therefore subject to change at any given time and analysis.

be partly responsible. Ambient cigarette smoke may increase the sensitivity of smoke alarms [45], particularly photoelectric alarms. However, as the current smoking rate in England [46] is not substantially higher than that in the USA [47], the effect of cigarette smoke on photoelectric vs ionisation alarms may not be the cause of the difference (although smoking rates in the specific regions and timeframe of the studies are unknown). Other suggested potential differences in the findings were the differences in cooking styles between the countries, a difference in heating sources, the movement of air through the dwelling, and whether wood-burning fireplaces may be present.

The USA based NIST also investigated smoke alarm performance in kitchen fires and nuisance alarms [48]. The study found that smoke alarms may nuisance up to 6m away from the cooking source. Considering this, depending on the layout of a class 1a or 2 building in NSW, smoke alarms (potentially the only smoke alarm in the dwelling) may be placed within 6m of the kitchen and therefore potentially nuisance.

In tests [48] undertaken that included toasting bread, frying bacon, broiling hamburgers, grilled cheese sandwiches, vegetable stir frying, and baking pizza, it was found that dual sensor alarms activated more frequently than similarly placed ionisation and photoelectric alarms. Ionisation alarms were found to activate very early and more to small particulate aerosols prior to noticeable smoke production, and this was suggested as a potential cause of frustration to homeowners. It was found that both ionisation and photoelectric alarms activated at least 10 minutes prior to cooking oil igniting.

Photoelectric alarms showed a significantly reduced incidence of nuisance alarm when placed at varying distances from the cooking source (both stovetop and oven) inside the kitchen, and outside, when compared with ionisation alarms. The NIST research suggested that if alarm placement is required within 6m of a cooking appliance, a photoelectric alarm or alarm with a silencing feature should be installed.

1.12 Fatal Risks in Alarm Placement

The same NIST study [48] also looked at the progression of nuisance alarms to fires within the kitchen, and the activation times for alarms within and outside of the kitchen. Smoke alarms (ionisation, photoelectric and dual sensor) were placed at varying distance between 1.82m and 6.94m from the stove in kitchen fire scenarios. The majority of scenarios resulted in the furthest alarms activating with an ASET value of greater than 120s[19], but two scenarios showed a photoelectric alarm having a ASET value of less than 120s.

This research raises the challenge of placing smoke alarms at a distance from kitchens to prevent nuisance alarms, yet within close enough proximity (within 6.94m) to ensure a positive ASET is provided in the event of a fire.

Studies undertaken in Canada [49], Australia [50] and France [13] have shaped research trials around the placement of smoke alarms and subsequent effects on ASET. The 2003 Canadian Kemano Fire Study [49] examined multiple factors related to home fire safety, including the effect of an intervening door. Some test scenarios had an initially closed bedroom door preventing smoke alarms located outside of the room of origin from activating until the door was opened (one photoelectric alarm activated through the closed door). In the tests that

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[19] An optical density limit of .25 m^{-1} was applied to calculate the available safe egress time (ASET)

maintained an open door for the duration, alarms outside of the room of origin activated, and in some cases activated first.

Australian researchers Bruck and Thomas [50] confirmed that, despite small gaps at the top, bottom and one side of the doors used in their experiments, when the doors were closed (in the absence of an induced pressure difference through mechanical ventilation or external wind), smoke alarms located behind the closed door away from the room of origin did not activate [50].

A 2014 French study [13] examined real scale fire tests in bedroom environments. The study examined (among others) a ventilation controlled fire in a bedroom with a closed door (a bed quilt was the material first ignited). The scenario examined tenability conditions within the room. The fire became ventilation controlled fairly rapidly. Within 3 minutes 30 seconds the hydrogen cyanide (HCN) concentration increased, as did the CO/CO_2 ratio. At 4 minutes tenability limits were reached due to the reduction of oxygen (16%). The photoelectric smoke alarm placed within the bedroom activated at 2 minutes, before conditions became untenable. The photoelectric smoke alarm placed in the corridor behind the closed bedroom door activated at 4 minutes, when tenability limits had already been reached.

These findings present concern for any situation where a fire starts in an enclosed room without an installed smoke alarm, a realistic situation in NSW home environments given current smoke alarm placement requirements.

1.13 Alarm Audibility and Awakening

Given the majority of fatal fires occur between the hours of 12:00am to 6:00am [Figure 14, 36, 51, 52], consideration must be given to the ability of residents to awaken to a sounding smoke alarm. The U.S. Consumer Product Safety Commission (CPSC) [53] published a study in 2005 detailing influencing factors on smoke alarm audibility and awakening. It considered that sleep stage, effects of drugs or alcohol, level of fatigue, time of night, background noise and hearing loss can all impact on a person's ability to detect and respond to the sound of a smoke alarm activating.

The majority of smoke alarms are set to produce a sound volume of 85dBA. The CPSC research [53] presents that an average healthy unimpaired adult with good hearing in a situation of minimum background noise may awaken with an alarm sound as low as 55dBA, with the average requiring 70dBA to awaken. However, the study presents that sounds rarely occur in isolation. A lightweight closed door can reduce alarm volume by 10-20dBA, and an air conditioner (potentially 55-60dBA), traffic, televisions, small appliances, and airplanes can all increase the volume of background noise thereby decreasing the ability for an adult to distinguish and awaken to an activating smoke alarm.

Furthermore, sound travels from room to room in the same manner a person would and is affected by furnishings (drapes, carpets, upholstered furniture) [53]. Sound will be more attenuated in a multi-room home or multi-level home.

Data from the ABS Health Survey 2004-2005 [54] shows that hearing loss increases steadily with age thereby increasing the risk profile not only with respect to RSET values, but also the capability of elderly people to awaken to smoke alarm. Persons 65 and older reported a hearing (partial or complete) loss at a rate of 26% of the population, at 75 years and older the percentage increases to 42%, and by age 85 and over the figure is 54% [55]. Fire fatalities in NSW report a disproportionate number of elderly people aged 65 and over.

The results by CPSC were supported by Australian research undertaken by Thomas and Bruck [50] from Victoria University. Their research showed a significant reduction in sound level behind a closed door, dropping from 85dBA to on average 36dBA, potentially on par with ambient noise levels.

In other research surrounding timely activation and effective notification Thomas and Bruck [56] recommend interconnected smoke alarms in every room of a dwelling. In their research they find that ionisation alarms activate more quickly than photoelectric alarms in the room of fire origin, the adjoining hallway, and the other room in their test building structure. They also found that the ionisation alarm activated more reliably than the photoelectric alarm (96% vs 80% respectively) across the seven tests with the room of fire origin door open.

However, their research showed a significant increase in the amount of time required for the alarm (of either type) to activate in the room of fire origin when compared to the hallway, with the slowest activation in the other (furthest away) room. Furthermore, when the room of fire origin was on the second story, they found that both ionisation and photoelectric alarms only activated approximately 50% of the time in the lower level.

In their concluding remarks, Thomas and Bruck [56] detail that the type of smoke alarm is far less significant when compared with appropriate placement and the interconnection of alarms.

2. Planning FRNSW's Real Fire Scenario Tests

2.1 Considerations

Considering the range of conclusions drawn across the research reports analysed in the literature review, FRNSW determined to undertaken internal testing to gain first hand data to analyse. When planning the test methodology, fatal fires across incidents attended by FRNSW in class 1a and 2 since January 2000 were analysed[20].

Figure 13 provides a visual representation of seasonal percentages for fatal and total fires.

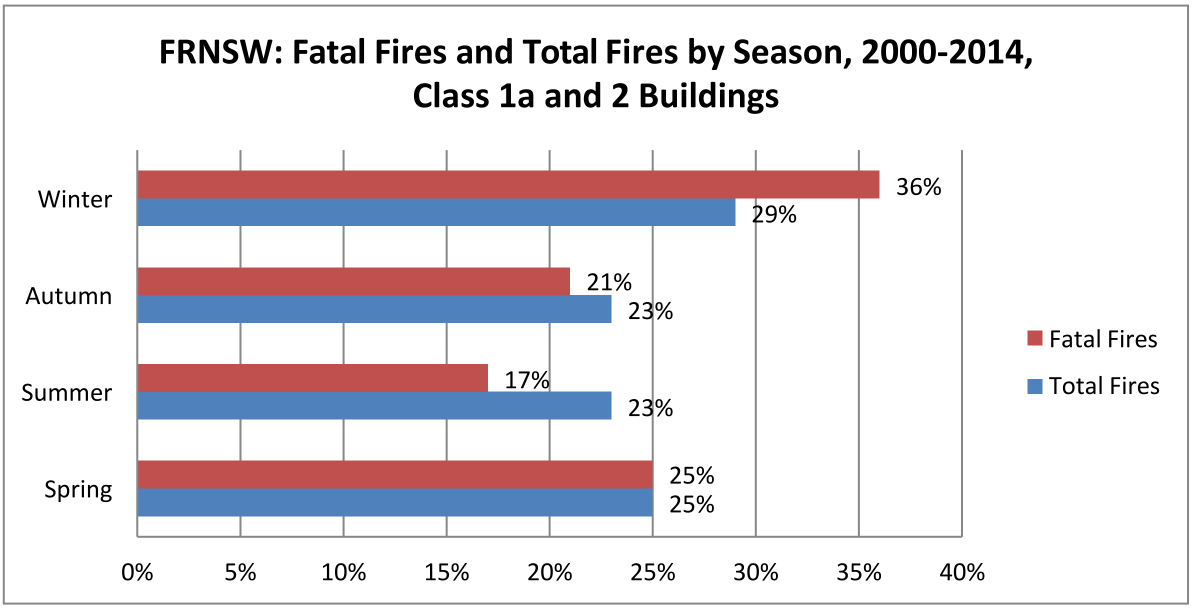

Figure 13: FRNSW Percentages of Fatal Fires and Total Fires by Season

It was found that the highest percentage of both total fires and fatal fires occurred during the months of winter, with 1 fatal fire for every 91 total fires. Table 1 displays the calculated figures of both number of and percentages of total fires per fatal fire by season.

Table 1: Total Fires and Fatal Percentage Fires by Season

	Spring	Summer	Autumn	Winter
Number of Total Fires per Fatal Fire	110	149	126	91
Percentage of Total Fires that include a fatality	.91%	.67%	.79%	1.1%

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[20] Data collected from the Australian Incident Reporting System (AIRS) via the Strategic Reporting System on October 28, 2014. Includes date range January 1, 2000 – collection date, class 1a and 2 buildings.

This percentage of total fires that include a fatality has been worked up as though there is only 1 fatality per fire. A small proportion (6%) of fatal fires in the designated timeframe included more than one fatality. As such, the percentage listed is not an exact figure.

Based off Table 1, winter conditions were considered in the design of the test facility. This resulted in the inclusion of winter bedding materials and a decreased ventilation profile assuming that windows would be closed. Internal temperature readings were taken prior to each burn to determine if they fell within a conceivable range for inside a home in winter.

The time block of the majority of fatal fires was also considered in planning the scenario for the test burns. Global fire service data shows a spike in fire fatalities during typical hours of sleep [36, 51, 52]. This spike was also found when analysing data from fire fatalities attended by FRNSW. Data[21] showed that the highest proportion of fatal fires attended by FRNSW occurred during typical hours of sleep (41% of fire fatalities occurred in the 6 hour block between the hours of 00:00-05:59, and 64% in the 12 hour block between the hours of 20:00-07:59).

Figure 14 displays fire fatalities attended by FRNSW by time of day. Considering the data and resulting figures, the test burns were set up on the premise that the occupant was sleeping at the time of ignition without lights on in the residence.

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[21] Data collected from the Australian Incident Reporting System (AIRS) via the Strategic Reporting System on December 4, 2014. Includes date range January 1, 2000 – collection date, class 1a and 2 buildings.

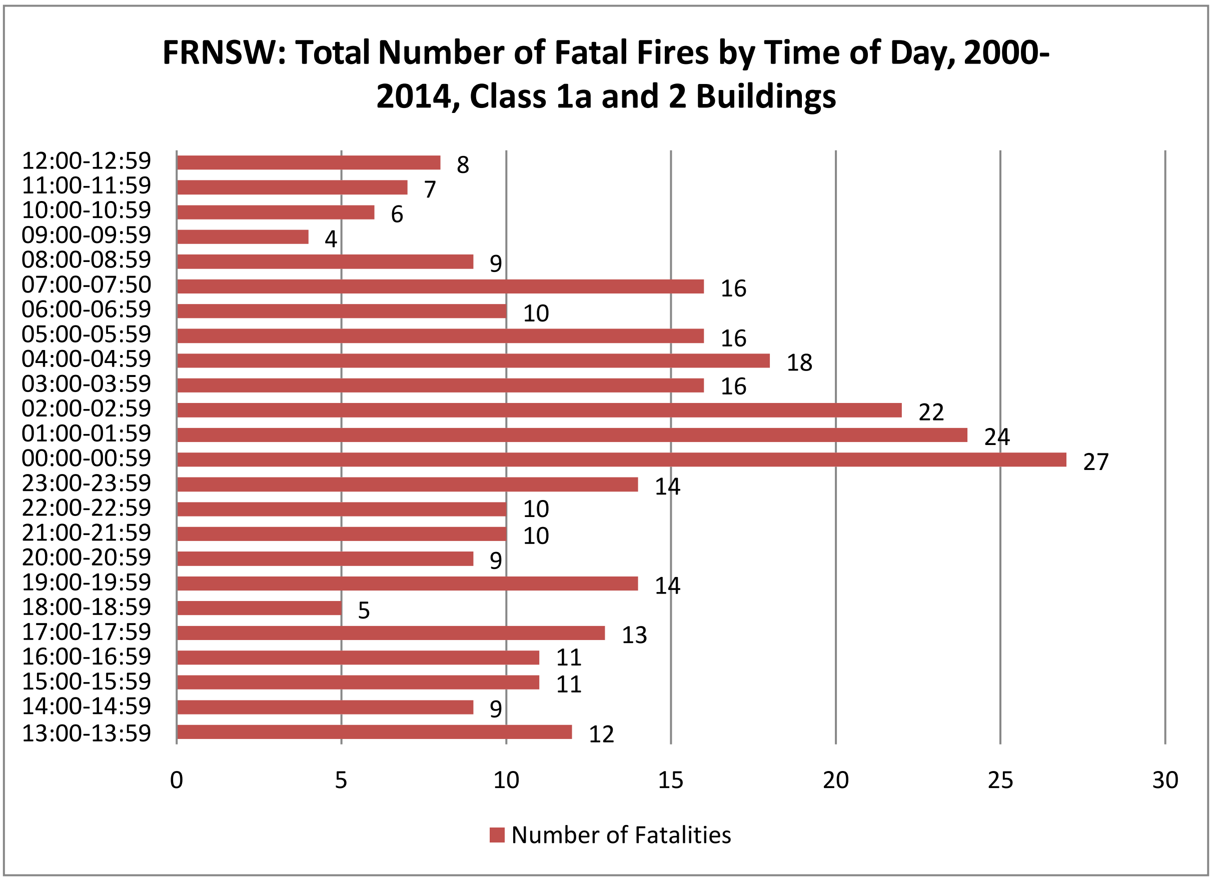

Figure 14: FRNSW Total Number of Fatal Fires by Time of Day

2.2 Focus of Test Burn Scenarios

The focus of the test burn was to determine if the activation of smoke alarms present across a range of positions within the test residence would provide sufficient ASET. Several factors were considered, including tenability limits with regard to heat, toxic gas, and visibility.

To achieve data regarding effective notification and tenability limits, a series of residential test burns were planned. These included smouldering fires, flaming fires, and the same with residential sprinkler systems in place.

NSW legislation currently only requires the following: for smoke alarms to be fitted in any storey of a dwelling that contains a bedroom, fitted in every hallway associated with a bedroom, or the section of the building containing the bedroom and remainder of the building/dwelling if no hallway exists; and that in any storey that does not contain a bedroom, a smoke alarm must be fitted on the travel path of egress. There is no requirement that smoke alarms be hardwired or interconnected.

Australian Standard 1670.6 [57] (AS1670.6) provides further suggestion for the locations of additional smoke alarms to combat dangers of fire sources in bedrooms and behind closed doors. As such, in planning the test burns, FRNSW determined to position a total of 36 alarms in multiple locations throughout the test unit.

AS1670.6 also describes satisfactory locations for alarms with regard to dead air space, ceilings and walls. The dead space is the area in which trapped hot air may prevent smoke from reaching the detector, and therefore theoretically preventing it from alarming. AS1670.6 outlines the positioning of smoke alarms, as per Figure 15 [57].

Considering that International test studies have found smoke stratification can occur at the ceiling level during smouldering fires [9], and that some smouldering fires produce smoke plumes too weak to reach the ceiling [15], and that alarms within the dead space were found to alarm appropriately (and sometimes before those not located in the dead space) [49], it was deemed important to test smoke alarms across on the ceiling, the wall, and in a “dead space” location.

AS1670.6 positions the dead air space as per Figure 15, whereas the BCA considers the dead air space to be a larger region, 300mm by 300mm at a wall ceiling junction, not 300mm by 100mm as per the diagram below.

Considering this, FRNSW determined to place one photoelectric, one ionisation and one dual smoke alarm in each of the following locations: near the centre of the ceiling of each room, in the centre of one wall in each room with the top 300mm from the ceiling, and in the designated “dead space” within 100mm of a wall/wall/ceiling junction

Furthermore, as it is possible that as a bedroom may have no route of egress other than through a connected lounge room[22], it was important to determine whether safe egress (and therefore effective notification) would be provided for the sleeping occupant across a range of fire scenarios.

The situation of a potentially sleeping occupant was planned to be tested by means of both lounge and bedroom fires (door open and closed), and both smouldering and flaming combustion scenarios were considered.

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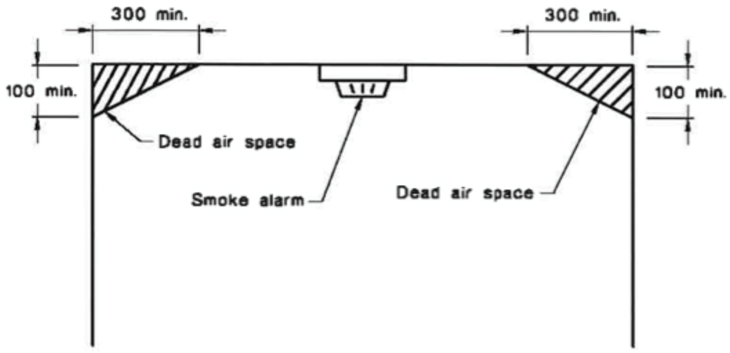
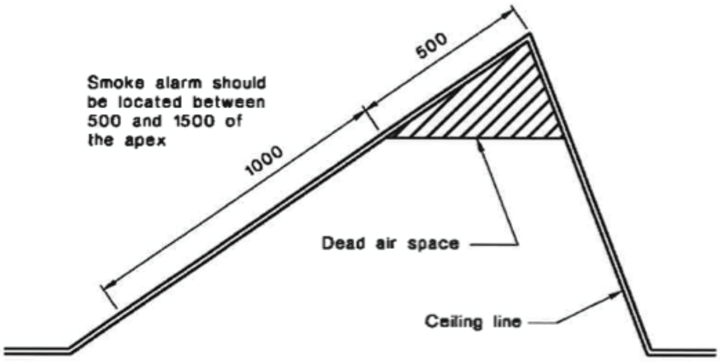
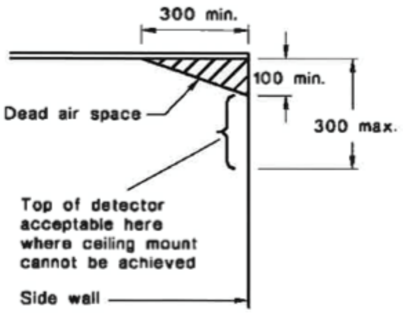
[22] This is considering the possibility of an apartment residence where egress from a window or balcony would result in major injury and likely death due to the height of the fall, and therefore exit through the lounge is the only safe egress route.



(a) Ceiling mount with exposed airflow



(b) Ceiling mount—Sloping ceiling



(c) Ceiling mount not available

Figure 15: Diagrammed Dead Air Space and Correct Smoke Alarm Placement

As children under 15 are unlikely to awaken to the sound of the alarm (see Section 1.6 Smoke Alarms and Egress) it was important to determine if the requisite hallway smoke alarm provided enough warning not only for the sleeping adult to awaken and exit, but also in the event that child rescue were required.

Primarily, considering Regulation 2000, every test burn would focus on whether or not the appropriately positioned ceiling and wall space smoke alarms in the hallway activated within safe egress times. The activation of the alarms in the bedrooms and lounge were of interest to determine if they provided a greater ASET for the residents, and if they had a beneficial effect in the situation of closed doors. Data capture of potential differences in time to alarm was of interest across the different alarm placements.

2.3 Sprinkler System Installation

To round off the testing of smoke alarms and their efficiency in saving lives, residential sprinklers were planned to be included in a series of burns to determine what effect they might provide with regard to safe egress. Sprinkler systems are traditionally designed to prevent flashover in the room of fire origin [58] and beyond, but may also present a safety option during initially smouldering fires.

Much research [36, 59, 60, 61] has been undertaken internationally to analyse the potential benefits of sprinkler systems in residential homes. Further to that, FRNSW's Fire Investigation and Research Unit (FIRU) undertook research and analysis in early 2012 surrounding a recreation of the Quaker's Hill Nursing Home fire that took place in November 2011. The research focused on determining the cause of fire, and also to consider if the result would have been different had sprinkler systems been installed. Since that testing and analysis, NSW legislation has been changed to require the incorporation of sprinkler systems in NSW residential aged care facilities prior to March 2016.

There are multiple variations of sprinkler systems available for installation depending on the class of building involved. As this project is focused around class 1a and 2 buildings, a part 5 residential sprinkler system, in line with AS 2118.5-2008 [58], was included. The part 5 system was deemed an appropriate, effective, practical and economically acceptable design to install.

Rapid response 71°C rated residential concealed pendent sprinklers (with a 59°C rated base plate) were built into the lounge room, both bedrooms and the hallway with location positioning and coverage consistent with the aforementioned Australian Standard (see Figure 19 in Section 2.4, Residential Test Burn Setup and Equipment, for system layout and design).

This type of sprinkler was selected based on the consideration that quicker response time is important in residential occupancies when occupants might be sleeping at the time of ignition, and therefore potentially have less time to respond. Also, being concealed, they provide a more aesthetic safety measure in the instance of a fire.

The provision of water for the sprinkler system was designed to be supplied via a FRNSW pumping appliance running at idle (~300kPa) connected to a 32mm pressure reducing valve. The appliance connection to the manufactured residence was set up via two 38mm fire fighting hoses, with the 32mm pressure reducing valve attached to the external fitting of the manufactured residence to ensure steady and consistent water pressure was applied. This method of water supply was selected over using the local hydrant, which was pressurised via a diesel pump and set off an alarm upon activation.

Figure 16 shows the external fitting for the residential sprinkler system. It was at this attachment point that water supply was connected to the sprinkler system.

Figure 16: Residential Sprinkler System External Fitting

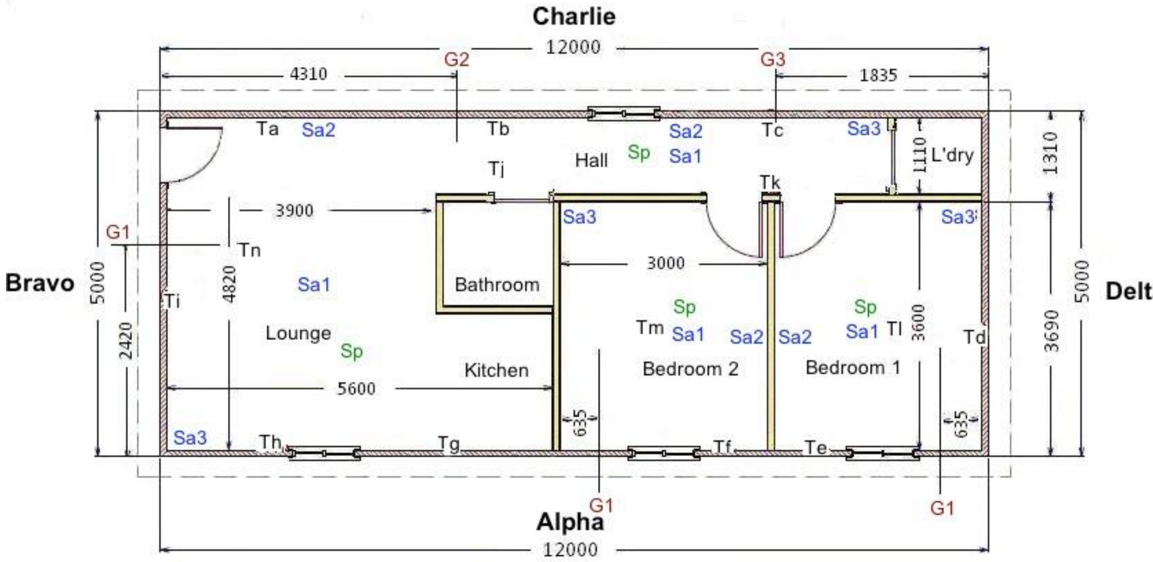
2.4 Residential Test Burn Setup and Equipment

The test burn cell was set up as a two bedroom residence representative of a small terrace or apartment. A hallway connected the two bedrooms and the lounge room. Figure 17 shows the layout of the residence including the location of testing equipment. This was mounted on a purpose built concrete slab at the FRNSW research facility in Londonderry, NSW. The residence was located in an open air environment.

The building structure of the residence was made of radiatia pine with 16mm fire resistant plasterboard lining the internal walls and ceiling. The outside of the building was lined with extra heavy duty premium wall wrap and clad with 7.5mm plywood. The structure contained a solid timber front door and hollow core lightweight internal doors. Aluminium sliding glazed windows were installed, ceiling heights were 2.4m and bulkheads above doors were set at 2.1m. The structure was roofed with a trim deck metal roof to prevent weathering.

Battery powered AS3786 compliant smoke alarms easily available at local DIY and electronics stores were used. Alarms were modified by electronics experts to include a light-emitting diode (LED) connected to the alarm. The signal produced an external visual light indicator on an alarm panel upon activation during the burn scenario. Multiple tests were run to establish that there was no change to the effectiveness of the alarm signalling and activation with the minor modification, and that the LED activated immediately upon alarm signalling. The alarms were then installed in the selected locations with their LED indicators clearly marked on the panel, and a video was set up to record smoke alarm activation.

Each room (including the hallway) was equipped with sets of four type N thermocouples capable of reading temperatures exceeding 1200°C. Each set had a thermocouple placed at floor level, .75m or 1m (depending on location), 1.5m and ceiling level for each room at the locations as specified in Figure 17. The thermocouples were placed close to where a person could be resting/sleeping in each room, on the path of egress in the hallway and lounge, and against the external walls in each room. End probes were inserted through small holes drilled through the linings in the wall and sealed to ensure limited air movement. No thermocouples were placed in direct proximity to the location of the sprinkler pendant.



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 17: Residence Design and Equipment Locations

Each room was set up with mini pinhole cameras. A visual marker at approximately 0.5-1m within each room was selected in order to subjectively measure and determine visual tenability through discernible contrast[23].

Gas analysis was undertaken to measure the variance of CO, HCN, CO_2 and O_2, HCl, HBr, HF, SO_2, NO_2, acrolein, and formaldehyde with regard to tenability, as listed in both the International Standard [26] and the SFPE Handbook of Fire Protection and Engineering [11, 27]. A portable Fourier Transform Infrared (FTIR) Spectrometer was used to simultaneously monitor and analyse the presence of gases (excluding oxygen) in the fire environment. The

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[23] The average distance where people turn back due to smoke density and visibility is 3m as detailed in the SFPE Handbook of Fire Protection and Engineering, and the research by Jin [29]; however, ISO13571 lists a visibility of 0.5m (equivalent to an arm's length) as being the limit for tenability. Given the residence is likely a known environment to the occupant, the distances close to those listed in ISO 13571 were used.

fully transportable unit was equipped with high temperature stinger probes, and was able to function in hot and humid environments.

Gas analysis was undertaken at three locations, as shown in Figure 17. Location “G1” was the mobile gas analysis location that moved to be located directly in the room of origin, in close proximity to the point of origin. Location “G2” and “G3” were stationary gas analysis units that remained in position for the duration of the test burn series.

Oxygen analysis was undertaken at the same locations as the other gases, with a high temperature probe placed in close proximity to the stinger probe for the FTIR. A four head portable gas detector specific to measuring gases in fire environments was used. The range for O_2 was 0-23%.

The residence was thoroughly ventilated and atmospherically tested between each burn scenario ensuring a clean air environment as the baseline. Furthermore, smoke alarms were checked following each burn for evidence of sounding [62], and replaced if it was deemed necessary due to any visual build up of smoke or degradation due to fire conditions.

Ambient conditions were measured by means of a weather station positioned outside of the manufactured residence. The weather station acquired data throughout the test burn, providing information surrounding ambient temperature, pressure and relative humidity.

Modern furniture from a local bulk furniture store chain was purchased to set up the rooms. The two bedrooms were set up in identical fashion using consistent furnishings and materials for comparability. All rooms were carpeted with a polypropylene carpet, except the kitchen space, which was fitted with linoleum. Bedroom, hall and lounge windows were fitted with curtains purchased from a local DIY store. No further wall decorations were present on residence walls.

Figure 18 shows the layout (not to scale) of the residence with regard to the inclusion of furniture.

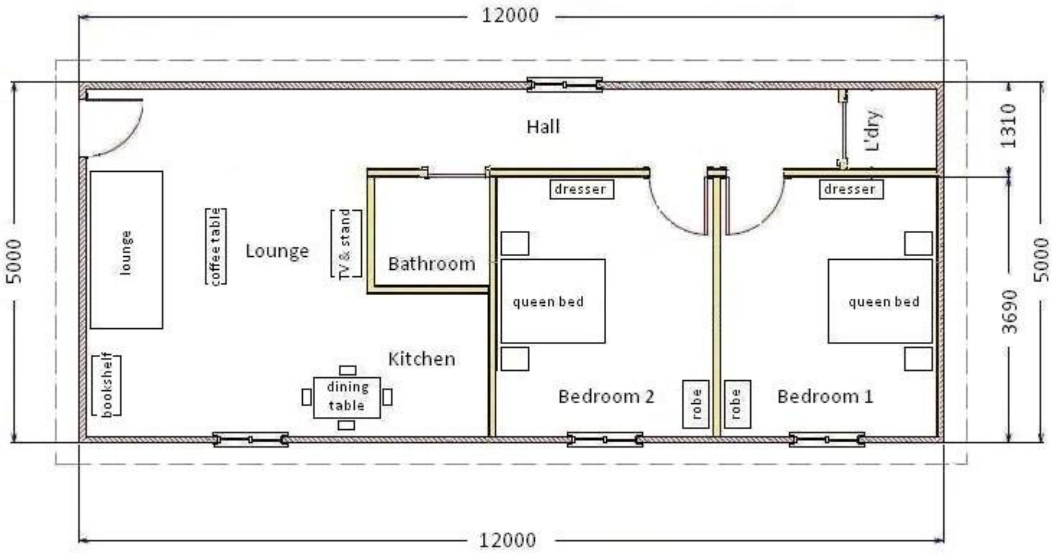

Figure 18 Residence Design Furniture Layout

The part 5 residential sprinkler system was installed as per Figure 19. Sprinkler heads were sealed with 16mm fire resistant plasterboard during test burns that did not require an installed home sprinkler system, and uncovered for latter burns that required the system to function appropriately.

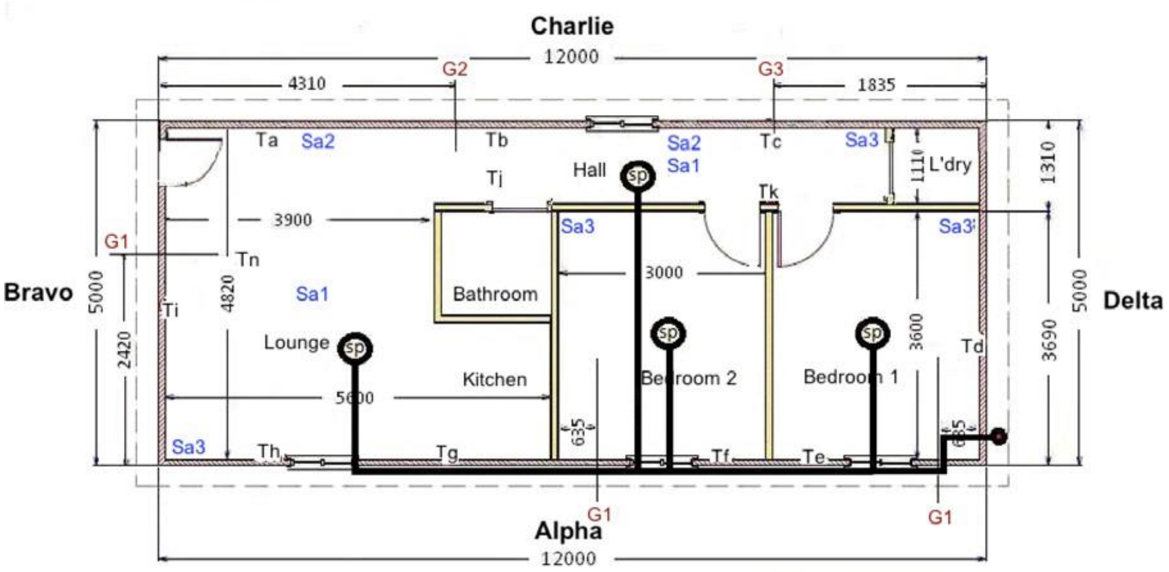

Figure 19: Residence Design Sprinkler Layout

The following equipment was used during the test burn scenarios.

1. Cartridge heater
2. Cartridge heater temperature controller
3. Cartridge heater solid state relay
4. LPG gas flame ignition source
5. 57 thermocouple assemblies
6. 1 x data logger with extension module to capture measurements from the thermocouple assemblies
7. 3 x Multicomponent portable FTIR gas analyser
8. 3 x high temperature stinger probes for gas collection
9. 3 x portable gas analysers for oxygen collection
10. 1 x HD video camera
11. 1 x digital SLR cameras
12. 2 x sports action cameras
13. 1 x USB DVR with 8 channels
14. 26 x CCTV mini pinhole cameras
15. 100 m^2 polypropylene carpet
16. 5 m^2 kitchen linoleum
17. 2 m^2 cotton batting
18. 45 x AS-3786 photoelectric smoke alarms
19. 45 x AS-3786 ionisation smoke alarms

20. 45 x AS-3786 dual ionisation and photoelectric smoke alarms
21. 36 x hardwires for smoke alarms to the alarm control panel
22. 2 x smoke alarm control panels
23. 2 x monitors for viewing the CCTV capture
24. 2 x laptops
25. 2 x handheld transceivers
26. 6 x queen bed frames, PVC
27. 6 x queen bed mattresses, polyurethane foam
28. 8 x bedding pack (2 pillows, quilt and mattress cover)
29. 6 x small clothes wardrobe, melamine, 80x47x178cm
30. 12 x bedside table
31. 6 x three drawer dresser
32. 4 x upholstered 3 seater sofa, 206x85x76cm
33. 3 x television, common flat screen
34. 3 x television stands, melamine, 80x35x37cm
35. 3 x bookcase for lounge, 40x28x202cm
36. 3 x coffee table for lounge room, 90x45x45cm
37. 3 x dining table and chairs, solid rubber wood, 126x89x82cm
38. 6 x (1.5m x 1m) curtains for bedrooms
39. 3 x (2m x 1.5m) curtains for lounge

2.5 Ignition Scenarios

As there are a range of materials available in upholstered furniture and bedding, and a level of unreliability involved in planning test ignition with actual smoking materials [62, 63], an electric cartridge heater was used in place of cigarettes. The 600W, 240V, 2.5 Amp cartridge heater that was used was capable of a maximum temperature of 700°C with a 1mm thermocouple attached to ensure accurate temperature readings were relayed to the solid state relay.

The solid state relay provided a digital temperature control to ensure a steady and reproducible temperature was achieved via the cartridge heater. The solid state relay was capable of switching on and off five times a second to ensure the cartridge heater did not overheat in an open air environment. Sustained smouldering ignition was achieved at approximately 15 minutes with the cartridge heater set to 500°C. Cotton batting sheets (87.5% bleached cotton, 12.5% polypropylene) were used to support sustained smouldering.

Figure 20 presents a visual image of the cartridge heater positioned on bedding material. The metal wire in a more vertical position in this image is an additional thermocouple. This thermocouple was present to measure the ignition temperature at the point of contact with residential furnishings.

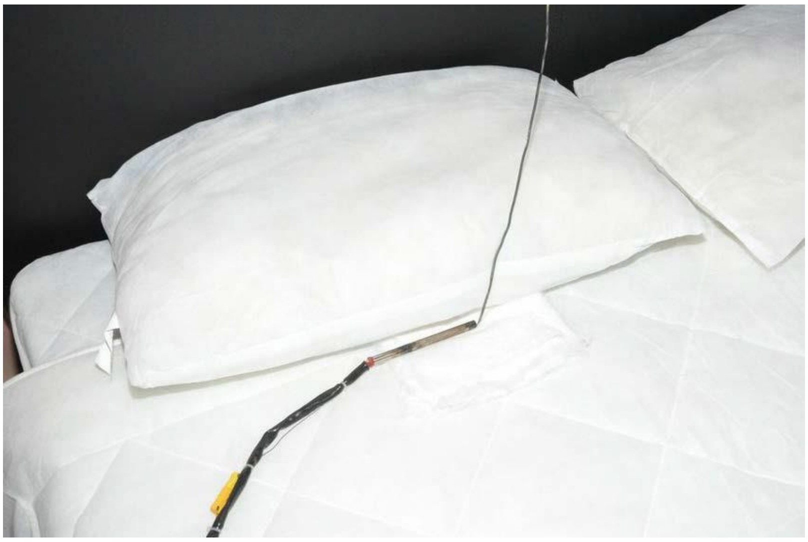

Figure 20: Visual Image of Cartridge Heater Placement on Bedding

Initial flaming ignition test burns were conducted with the same furnishings and a LPG gas flame ignition tube to determine if flaming combustion was produced within a reasonable time period. This was achieved by holding the flame over bedding material and an upholstered cushion for 1-5 seconds and noting results.

Following these initial ignition testing burns, 10 residence burn scenarios were tested with equipment and furnishings as listed and positioned as per Section 2.4, Residential Test Burn Set Up and Equipment. In all test scenarios, analysis began at the moment of ignition (the placement of the cartridge heater or the first moment of application of the LPG gas flame).

Full ventilation and atmospheric monitoring was carried out following each burn scenario to ensure a clean air baseline. Furnishings, materials and instruments were changed when required due to fire or water damage.

Each burn scenario had thermocouples, atmospheric and gas monitoring equipment and video cameras set up as described in Section 2.4, Residential Test Burn Setup and Equipment.

Time and data were captured from burn initiation until test termination, as designed in the test methodology. Specific times were recorded for details such as any changes within the room, and if there were transitionary events in the combustion process (ie. smouldering to flaming).

All burns were undertaken with the residence external door in a closed position except for when the fire fighter was exiting the residence after igniting combustion, or entering to extinguish the fire.

For Burn 5 a small corner of the front door was removed, just large enough to allow a 38mm fire fighting hose to pass through. As there was limited space around the fire fighting hose, it was considered that this did not significantly affect the ventilation profile or air tract movement.

2.6 Test Burn Procedures

Research Burns 1-5, smouldering and flaming combustion

Research Burn 1: **Bedroom 1 smouldering**

- Room of origin: Bedroom 1
- Internal door positioning: **Bedroom 1 door closed, Bedroom 2 door open**
- **Gas measurement height: 1.5m from the floor. G1 positioned in Bedroom 1.**
- Material first ignited: bedding materials
- Form of ignition: cartridge heater
- Form of combustion: smouldering
- **Test deemed concluded:** upon sustained transition of smouldering combustion to flaming, 150 minutes total if hallway alarms don't activate, or 360s (6min) after the slowest hallway smoke alarm activated, whichever was the lesser

Research Burn 2: **Bedroom 2 smouldering**

- Room of origin: Bedroom 2
- Internal door positioning: **Bedroom 1 door open, Bedroom 2 door open**
- **Gas measurement height: 1.5m from the floor. G1 positioned in Bedroom 2.**
- Material first ignited: bedding materials
- Form of ignition: cartridge heater
- Form of combustion: smouldering
- **Test deemed concluded:** upon sustained transition of smouldering combustion to flaming, 150 minutes total if hallway alarms don't activate, or 360s (6min) after the slowest hallway smoke alarm activated, whichever was the lesser

Research Burn 3: **Lounge smouldering**

- Room of origin: Lounge
- Internal door positioning: **Bedroom 1 door open, Bedroom 2 door closed**
- **Gas measurement height: 1.5m from the floor. G1 positioned in Lounge.**
- Material first ignited: upholstered material on the couch
- Form of ignition: cartridge heater
- Form of combustion: smouldering
- **Test deemed concluded:** upon sustained transition of smouldering combustion to flaming, 150 minutes total if hallway alarms don't activate, or 360s (6min) after the slowest hallway smoke alarm activated, whichever was the lesser

Research Burn 4: **Bedroom 2 smouldering**

- Room of origin: Bedroom 2
- Internal door positioning: **Bedroom 1 door open, Bedroom 2 door open**
- **Gas measurement height: 0.75m from the floor. G1 positioned in Bedroom 2.**
- Material first ignited: bedding materials
- Form of ignition: cartridge heater
- Form of combustion: smouldering
- **Test deemed concluded:** upon sustained transition of smouldering combustion to flaming, 150 minutes total if hallway alarms don't activate, or 360s (6min) after the slowest hallway smoke alarm activated, whichever was the lesser

Research Burn 5: **Bedroom 2 flaming**

- Room of origin: Bedroom 2
- Internal door positioning: **Bedroom 1 door open, Bedroom 2 door open**
- **Gas measurement height: 0.75m from the floor. G1 positioned in Bedroom 2.**
- Material first ignited: bedding materials
- Form of ignition: LPG gas flame
- Form of combustion: flaming
- Test deemed concluded: upon full involvement of the room of origin, or 360s (6min) after the slowest hallway smoke alarm activated, whichever was the lesser

Research Burns 6-10, smouldering and flaming combustion equipped with a residential sprinkler system

Research Burn 6: **Bedroom 1 smouldering**

- Room of origin: Bedroom 1
- Internal door positioning: **Bedroom 1 door closed, Bedroom 2 door open**
- **Gas measurement height: 1.5m from the floor. G1 positioned in Bedroom 1.**
- Material first ignited: bedding materials
- Form of ignition: cartridge heater
- Form of combustion: smouldering
- **Test deemed concluded**: upon sustained transition of smouldering combustion to flaming, 150 minutes total if hallway alarms don’t activate, 360s (6min) after the slowest hallway smoke alarm activated, or 60s (1min) after the activation of the sprinkler system, whichever was the lesser

Research Burn 7: **Bedroom 1 smouldering**

- Room of origin: Bedroom 1
- Internal door positioning: **Bedroom 1 door open, Bedroom 2 door open**
- **Gas measurement height: 1.5m from the floor. G1 positioned in Bedroom 1.**
- Material first ignited: bedding materials
- Form of ignition: cartridge heater
- Form of combustion: smouldering
- **Test deemed concluded**: upon sustained transition of smouldering combustion to flaming, 150 minutes total if hallway alarms don’t activate, 360s (6min) after the slowest hallway smoke alarm activated, or 60s (1min) after the activation of the sprinkler system, whichever was the lesser

Research Burn 8: **Lounge smouldering**

- Room of origin: Lounge
- Internal door positioning: **Bedroom 1 door open, Bedroom 2 door closed**
- **Gas measurement height: 1.5m from the floor. G1 positioned in Lounge.**
- Material first ignited: upholstered material on the couch
- Form of ignition: cartridge heater
- Form of combustion: smouldering
- **Test deemed concluded**: upon sustained transition of smouldering combustion to flaming, 150 minutes total if hallway alarms don’t activate, 360s (6min) after the slowest hallway smoke alarm activated, or 60s (1min) after the activation of the sprinkler system, whichever was the lesser

Research Burn 9: **Bedroom 2 smouldering**

- Room of origin: Bedroom 2
- Internal door positioning: **Bedroom 1 door open, Bedroom 2 door open**

- **Gas measurement height: 0.75m from the floor. G1 positioned in Bedroom 2.**
- Material first ignited: bedding materials
- Form of ignition: cartridge heater
- Form of combustion: smouldering
- **Test deemed concluded**: upon sustained transition of smouldering combustion to flaming, 150 minutes total if hallway alarms don't activate, 360s (6min) after the slowest hallway smoke alarm activated, or 60s (1min) after the activation of the sprinkler system, whichever was the lesser

Research Burn 10: **Bedroom 1 flaming**

- Room of origin: Bedroom 1
- Internal door positioning: **Bedroom 1 door open, Bedroom 2 door open**
- **Gas measurement height: 0.75m from the floor. G2 positioned in Bedroom 1.**
- Material first ignited: bedding materials
- Form of ignition: LPG gas flame
- Form of combustion: flaming
- **Test deemed concluded**: 60 (1min) seconds after the activation of the sprinkler system, or 360s (6min) after the activation of the slowest hallway smoke alarm activated, whichever was the lesser

2.7 Limitations of the Test Burn Scenario

There are endless scenarios that could be undertaken in replica real home fire test burns including varying the configuration and construction of the residence, ceiling heights, the position of doors, burning different materials, setting up of individual rooms differently, introducing different furnishings, introducing natural or mechanical ventilation, etc. Ideally each burn would be reproduced identically three times. Due to time and monetary constraints, it was determined to run 10 test burns with variations. However, smoke alarms are designed to function across a range of fire scenarios, and given that every real fire scenario is different, it was conceivable to compare results across test burns.

The test burns were undertaken in ambient autumn conditions. The test environment studied was that of winter conditions, and therefore internal temperature measurements were taken before commencing the burns to determine if the ambient temperature was relative to that of winter. It was assumed that a winter indoor room would be warmer than typical outdoor conditions due to being closed up and having the presence of heaters. The measured external ambient temperature ranges for the test burns ranged from 16-30°C, with the average sitting at 25.6°C.

The internal average temperature for the structure at the start of each burn was 27°C. Although this may have had some effect on the test burns, it was considered within reasonable limits for a warm internal room temperature due to indoor heating in winter, and was not considered to have had a significant effect on results. Furthermore, given the variations in temperatures experienced across NSW in winter, attempt was not made to replicate any one scenario.

The test burns were undertaken with an ambient relative humidity level of that ranged from 19.8-92.2%. As the Sydney region experiences a wide range of relative humidity during winter, the relative humidity was noted prior to each burn scenario, but it was not deemed to be a deviation from the range of what could be experienced in local winter conditions. Furthermore, it was considered that real home fires occur across the range of conditions, not only within specified relative humidity levels.

No assessment was undertaken to establish audibility levels and limitations in any of the test burn scenarios. Much research has been done in this area [53, 56]. For the purpose of these test burns it was assumed that smoke alarms were able to be heard, even behind lightweight doors that are known to diminished volume by 10-20dB [53]. Due to the wide range in variations of background noise in residential dwellings, no attempt was made to replicate any one scenario and measure sound. This research has been undertaken in both Australia and overseas and therefore conclusions from those research studies were considered applicable

There are endless positions for smoke alarm placement. A Canadian [49] study recently examined smoke alarm placement in the “dead zone”, including on the ceiling, the wall, and near corners. As “dead zone” placement was not the primary focus of FRNSW’s residential test burn, it was deemed appropriate to place smoke alarms within one “dead zone”, on the wall in a corner in close proximity to a wall/wall and wall/ceiling junction. No attempt was made to measure activation in alternative placements.

Smoke obscuration affecting visibility was measured by subjective means through using a video camera and visual indicator. Visibility was deemed untenable when it was impossible to discern visual differences in the screen at a distance of 0.5-1m depending on the position of the marker.[24] This could have led to some variance were the test and timing assessment to be repeated. However, as smoke obscuration alone does not directly affect tenability, but rather affects cognitive and motor skill function (which affects egress ability and therefore tenability) it was determined that this method was sufficient. Although research has proven that walking speeds in irritant smoke decreases more significantly with decreases in visibility [29], without scientific measurements of optical density combined with FIC_{irr}, it is impossible to utilise Equation 16 or Equation 18.

Furthermore, as smoke obscuration was not scientifically measured it is impossible to relate the conditions to AS3786:2015 [7] with regard to the aerosol density threshold limits, and whether or not the test burn smoke density fell within the designated standard limits.

No assessment was undertaken to establish the production of various toxic gas asphyxiates or irritants outside of measuring those listed in Section 2.4 Residential Test Burn Setup and Equipment. The primary focus was on toxic gases as described in ISO 13571 [26] and the SFPE Handbook of Fire Protection Engineering [27].

A mass loss analysis was not undertaken during the burn, nor was a room volume analysis. Dimension information was collected should room volume analysis be required in future; however, for the purpose of this study it was not deemed a focus.

Due to equipment limitations, no data pertaining to radiant heat was collected. As such the FED for radiant heat could not be calculated, and the summation and cumulative effects of radiant and convected heat (respectively calculated by adding FED convected and radiant heat each minute, and then summing that result over each minute of the test burn) was not calculated. The tenability limits for FED convected heat and cumulative convected heat were

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[24] The smoke obscuration model (as listed in ISO 13571) is based on the ability to discern minimal detectable contrast. This concept estimates that a mass concentration threshold of .6gm^{-3} has been reached when an occupant cannot see beyond .5m, and above this tenability is likely to be compromised. When occupants are unable to see their hand in front of their face they are likely to become disoriented when engaged in cognitive or motor-skill activities (ie egress). This is the reason for placing an object to determine visual tenability at 50cm in front of the mini pinhole camera as the determining distance compromised tenability.

included in the calculation, but it must be considered that tenability may have been reached at an earlier stage had radiant heat been included.

Although the function of the installed sprinkler system was of great interest during burns 6-10, it was not the main focus of the project. As such, thermocouples were not positioned directly next to the location of the sprinkler head more specifically measuring the local temperature at activation. The result of this limitation is that recorded sprinkler activation temperatures show greater variance than expected, and are less exact than desired.

As no two real home fires are alike, the assessment of a range of fire scenarios was deemed appropriate. Although it is unlikely that the results obtained in this study will be directly reproducible, it does serve as an exploratory look into a range of factors affecting home safety, focusing around the activation of smoke alarms within tenability limits and safe egress timeframes.

3. Results and Discussion

3.1 Introduction to Analysis, Calculating Tenability Limitations

It is impossible to entirely predict the wide range of variables involved in real home fires; including human, building and fire behaviour. As such, FIRU determined a methodology based around increased risks of fire fatality due to time of day and seasonal statistics, built a structure representative of a 2 bedroom terrace or apartment with a single path of egress through the lounge room, and furnished the structure with bulk low cost furnishings available at local furniture chains.

The single path of egress was based around the possibility of security bars on the windows of a terrace house, or the apartment being on a level too high for safe egress through a window. To limit the variability of human behaviour, it was considered that the residential occupant was sleeping in the room of origin (ROO) or a bedroom when the ROO was the lounge room, was awoken by the smoke alarm, and began movement towards egress within a reasonable period of time. It was not assumed that the occupant would suffer any incapacitating psychological effects with regard to fire.

In order to consider the more vulnerable members of society, including the elderly, children, asthmatics, and those with reduced physical or mental abilities, conservative tenability limits were applied. As an FED or FEC of 1 equates to the statistical analysis to 50% of the population having compromised tenability, an FED or FEC criteria of 0.3 reduces this value to 11.4% of the population being susceptible [27]. There is no criteria limit low enough to ensure 100% of the population would be safe. As such, the limit of 0.3 was used when assessing tenability limits to ensure a greater proportion of the population would be considered in calculations.

Concentration limits for irritant gases with regard to incapacitation were applied as per the SFPE Handbook of Fire Engineers [27]. The Australian Technical Specification regarding life safety [25] directs readers to use ISO 13571 [26]; however, this international standard does not list concentrations for irritant gases with regard to impaired egress or fatality, nor does it provide more specific calculations for the combined effects of irritant and asphyxiant gases. As such the values listed the SFPE Handbook of Fire Engineers [27] were used exclusively in order to maintain consistency across the calculations.

A conservative required safe egress time (RSET) was also applied to consider that indirect escape may be required, and to consider the potential range of human behaviour including awakening from sleep, time to recognition, attempts at fire fighting, rescuing or alerting others, and finally exiting. As discussed in Section 1.6, Smoke Alarms and Egress, an available safe egress time (ASET) of 120s may not provide enough time for indirect escape, especially when children and/or less mobile individuals are involved.

As such, to support a broader segment of the population and include time for indirect escape, both egress of 120s and the more conservative RSET of 135s [31] were applied relative to the activation of smoke alarms in both the room of origin and the hallway.

To determine tenability limits Equations 1 (CO), 3 (HCN), 5 (VCO_2), 11 (asphyxiant) and 14 (convected heat) were used. Equations 11 and 14 were then summed per minute duration of the fire in order to determine the cumulative effects of asphyxiation and heat on an occupant.

Unfortunately the gas analysis equipment for measuring O_2 failed for each test burn. The result of this was that an O_2 value of 20.9% had to be included in all asphyxiation calculations, resulting in the time to loss of tenability being increased. Although it is a natural occurrence for oxygen to decrease in a fire environment, without having an indication of the rate of decrease, it was determined to present that no change in oxygen had occurred.

The FTIR analysis equipment used was not able to measure samples at exact 1 minute intervals, as required by the equations that were applied to determine tenability limits. The equipment did measure within 1-2 seconds above 60 seconds (excluding the G2 gas analyser that was closer to 70s intervals during Burn 5), and therefore it was deemed permissible to round this down to 60 seconds for ease of equation application.

Equations 12 and 13 were used to determine the tenability limits with regard to irritant gases, applying the gas concentration standards from the SFPE Handbook of Fire Protection Engineering [27] with regard to impaired escape, incapacitation and death.

3.2 Test Burn Results and Discussion

Burns 1-5 were structured to measure time to tenability loss in smouldering and flaming fire environments in a residential occupancy based on FRNSW and international statistics for fire fatalities. These were considered around sleeping variations of bedroom doors (open and closed), and fires starting on both bedding materials and on the upholstered lounge.

Following the initial 5 burn scenario, a further 5 test burns were undertaken with near identical methodology, excluding two burns (7 and 10) which occurred in Bedroom 2 instead of Bedroom 1 (as in burns 2 and 5). This was changed to limit time loss in moving room of origin located gas analysis equipment.

Test burns 6-10 were equipped with a residential sprinkler system; however for burns 6, 8 and 9 the sprinklers were pressurised by a FRNSW pumping appliance running on idle (approximately 300kPa), without the specified 32mm pressure reducing valve. This was due to a delay in parts supply, and due to other time constraints on the research project, the test burns could not be delayed.

With the sprinkler system not being supplied with the ideal pressure of 50kpa at the sprinkler head, it can be assumed that resultant droplet size from sprinkler activation would not be ideal, nor would discharge density or coverage provided by the spray pattern. These deviations from ideal would therefore reduce the efficiency of the sprinklers to control and suppress the fire.

For burns 7 and 10 (burn 7 was delayed for 24 hours), the pressure reducer had been fitted and the sprinkler systems functioned at ideal pressure as designed.

As mentioned previously, without the location of a thermocouple directly next to the sprinkler pendant, limited information can be drawn with regard to the exact temperature of sprinkler activation. As the results show, in Burns 6-10, this is likely to have presented a level of inaccuracy that could not be overcome. Also, without additional thermocouples on the ceiling between the sprinkler pendant and the fire it was difficult to comment on directional heat movement across the ceiling. As such, the temperature recorded by the thermocouple closest to the fire on the ceiling may not provide an accurate assessment of the temperature at the sprinkler pendant.

All test burn scenarios took place with the bedroom window shut as to simulate a winter fire environment. Furnishings and equipment were replaced as needed between burns to ensure a more reproducible testing environment.

3.2.1 Burn 1, Smouldering Bedroom Fire, Door Closed, 1.5m Monitoring Height

Burn 1 was designed as a test burn to simulate an occupant falling asleep with a burning cigarette. This occupant slept with the bedroom door closed. The gas and temperature measurements were taken at a height of 1.5m, considering the occupant awakening to the smoke alarm and standing up to exit. The test scenario was concluded at 150 minutes as no hallway smoke alarms activated, and no transition from smouldering to flaming fire occurred.

Table 2: Burn 1 Ambient Conditions

Burn 1	Start	End
Date	3/03/15	
Times	8:19:10	10:49:00
Ambient Temperature	16.6°C	24.5°C
Relative Humidity	92.2%	52.1%
Air Pressure	1011.1	1011.1

The following graph, Figure 21, shows a visual analysis of the data, plotting the fractional effective dose/concentration against time duration into the test burn. As can be noted, FEC 0.3 incapacitation due to irritant gases reached in the 22nd minute.

Due to a failure in power to the FTIR analyser the exact moment of incapacitation due to cumulative asphyxiant effects is unknown. Through considering a steady upward trajectory in the data, it is graphically extrapolated to have occurred between 35 and 61 minutes (closer to 35 min).

Based on the that extrapolated trajectory, the closest recorded data point exceeding FED 0.3 cumulative asphyxiation is 61min 35sec into the test burn. Heat and visibility were not found to have significantly influenced tenability, as they both remained within tenability limits.

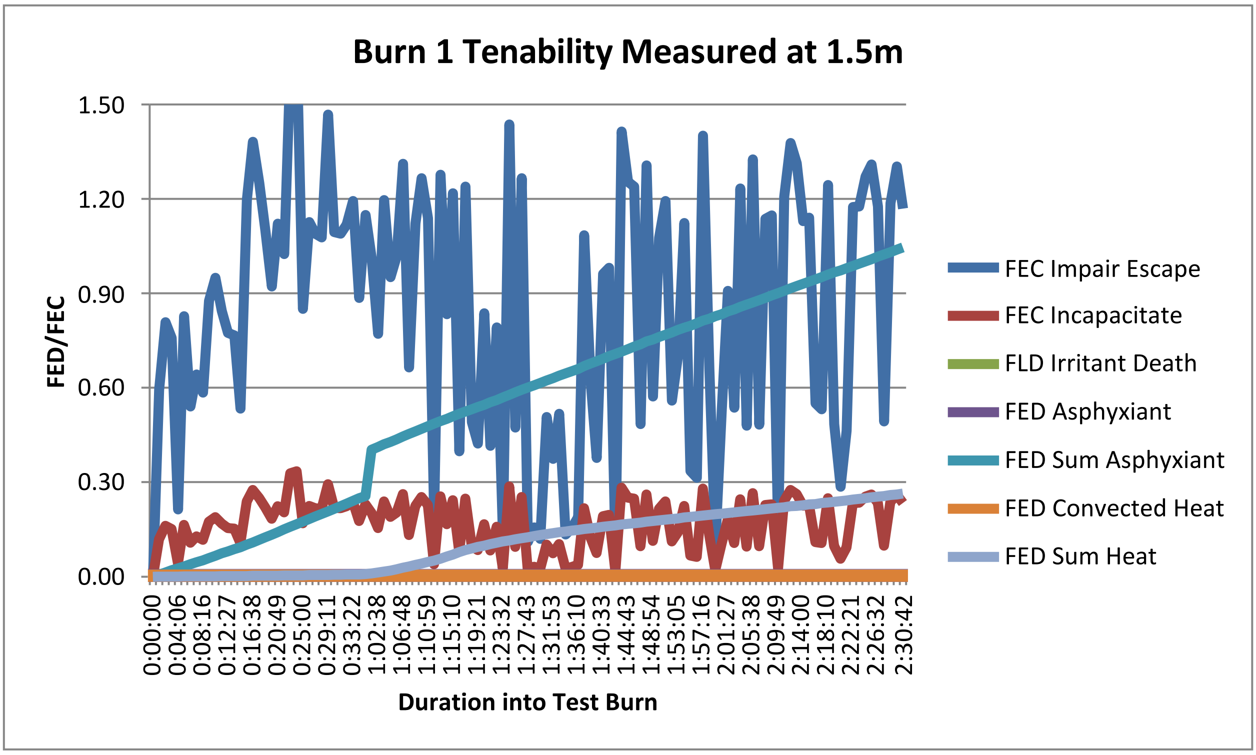


Figure 21: Burn 1 Graphical Analysis of Tenability

The following table shows the absolute time to smoke alarm activation in the room of origin and the hallway, wherein BD1 is bedroom 1, SA1 refers to the ceiling alarms, SA2 refers to the wall space alarms, SA3 is the dead space alarms.

Table 3: Burn 1 Smoke Alarm Activation Times

BD1 SA1 P 17m21s	BD1 SA1 I DNA	BD1 SA1 D 15m35s	BD1 SA2 P 11m30s	BD1 SA2 I DNA	BD1 SA2 D 13m6s	BD1 SA3 P 14m39s	BD1 SA3 I DNA	BD1 SA3 D 12m10s
Hall SA1 P DNA	Hall SA1 I DNA	Hall SA1 D DNA	Hall SA2 P DNA	Hall SA2 I DNA	Hall SA2 D DNA	Hall SA3 P DNA	Hall SA3 I DNA	Hall SA3 D DNA

DNA = Did Not Activate

As can be noted from Table 3, no hallway alarms activated. It is assumed that this was due to the door being closed, therefore preventing smoke from exiting the bedroom and activating the hallway alarms.

Overlaying data as shown in Figure 21 it can be seen that no hallway alarms activated within FEC 0.3 incapacitation, but all three bedroom dual and photoelectric alarms activated prior this tenability level being reached. In this scenario no bedroom ionisation alarms activated.

All bedroom photoelectric and dual alarms activated prior to the FED 0.3 cumulative asphyxiant incapacitation, and all also activated within RSET 120 and 135s. Due to the low temperature profile of this smouldering burn and the ambient temperature conditions, increased time was likely required for the smoke plume to reach the ceiling smoke alarms [15]. Smoke stratification was noted at different points throughout the burn.

The considered result of Burn 1 is that the majority of sleeping occupants (assuming awakening upon alarm sounding) escaped based on bedroom photoelectric and dual alarm activation. Based only on hallway alarm activations and/or bedroom ionisation alarm activation it is possible to deduce that 11.4% of the population would have been incapacitated, and potentially over 50%, as the FED sum asphyxiant continued beyond FED equal to 1.

On analysis of the ceiling temperature within the room of origin, bedroom 1, the temperature did not reach a level that could have potentially activated a sprinkler system, had one been installed.

3.2.2 Burn 2, Smouldering Bedroom Fire, Door Open, 1.5m Monitoring Height

Burn 2 was designed to simulate an occupant falling asleep with a burning cigarette. Unlike the scenario in Burn 1, this occupant slept with the bedroom door open. The gas and temperature measurements were taken at a height of 1.5m, considering the occupant awakening to the smoke alarm and standing up to exit. The test scenario was concluded at 60 minutes due to cessation of the smoulder.

Table 4: Burn 2 Ambient Conditions

Burn 2	Start	End
Date	3/03/15	
Times	12:44:00	13:44:36
Ambient Temperature	24.4°C	26.2°C
Relative Humidity	62.9%	62.8%
Air Pressure	1009.3	1008.3

The following graph, Figure 22, shows the visual analysis of the data collected in this test burn scenario, again plotting fractional effective dose/concentration against time duration into the test burn.

In this test scenario tenability was lost due to FEC irritant gases impaired escape within 5 minutes, FEC irritant gas incapacitation occurred within 15 minutes, and FED sum asphyxiant gases occurred in the 37th minute. Neither heat or visibility reached the level of tenability loss, and where therefore not limiting factors in escape.

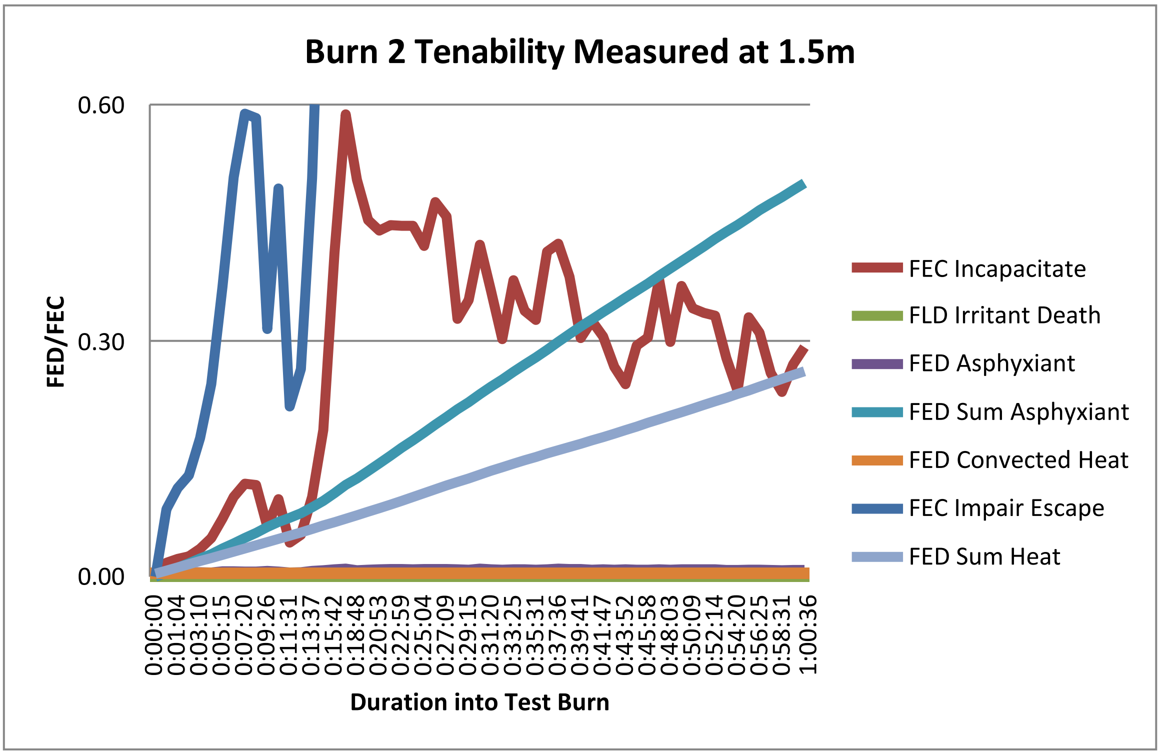


Figure 22: Burn 2 Graphical Analysis of Tenability

The following table shows the absolute time to smoke alarm activation in the room of origin and the hallway, wherein BD2 is bedroom 2, SA1 refers to the ceiling alarms, SA2 refers to the wall space alarms, SA3 is the dead space alarms.

Table 5: Burn 2 Smoke Alarm Activation Times

BD2 SA1 P	BD2 SA1 I	BD2 SA1 D	BD2 SA2 P	BD2 SA2 I	BD2 SA2 D	BD2 SA3 P	BD2 SA3 I	BD2 SA3 D
DNA	DNA	20m 27s	27m34s	DNA	14m 20s	26m 28s	DNA	15m 25s
Hall SA1 P	Hall SA1 I	Hall SA1 D	Hall SA2 P	Hall SA2 I	Hall SA2 D	Hall SA3 P	Hall SA3 I	Hall SA3 D
DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA

DNA = Did Not Activate

As in the scenario of Burn 1, no hallway smoke alarms activated. This test burn scenario was ended due to the cessation of the smoulder at 60 minutes; however, within the test burn duration both FEC and FED 0.3 incapacitation conditions were met.

As no hallway smoke alarms activated, it is possible to assume that 11.4% of the population were incapacitated; however, without a transition to flaming, and with cessation of the smoulder, it is impossible to deduce what lasting effect this could have had on the health and wellbeing of the occupant. It is sufficient to note that some degree of rescue is likely to have been required.

Only two smoke alarms, the wall and dead space dual alarms, activated within FEC 0.3 tenability limits. Neither of these two alarms provided an RSET of 120s or 135s, and so in this test burn scenario all alarms failed to provide the occupant with sufficient safe egress time.

Upon analysis of the ceiling temperature in the room of origin, had a sprinkler system been fitted it would not have activated as temperatures did not increase to the level at which the sprinkler system was rated.

3.2.3 Burn 3, Smouldering Lounge Fire, 1.5m Monitoring Height

Burn 3 was designed to simulate a cigarette fire on a lounge. In this scenario it was considered that a person went to bed whilst the cigarette initiated smoulder in the lounge. As passing through the lounge provided the only path of egress regardless of the location of the occupant during the scenario, loss of tenability within the lounge was considered.

Table 6: Burn 3 Ambient Conditions

Burn 3	Start	End
Date	3/03/15	
Times	15:00:00	15:50:25
Ambient Temperature	28.9°C	35.8°C
Relative Humidity	52.7%	50.1%
Air Pressure	1007.3	1006.8

In Burn 3 gas and temperature monitoring was conducted at a height of 1.5m. The following graph, Figure 23, plots FEC/FED against time duration into the test burn. In this test scenario it can be easily noted that irritant gases were produced at a significantly increased rate when compared with Burns 1 and 2, with FEC 0.3 incapacitation reached within 5 minutes of the ignition of smoulder; followed closely by FEC irritant incapacitation equal to 1.

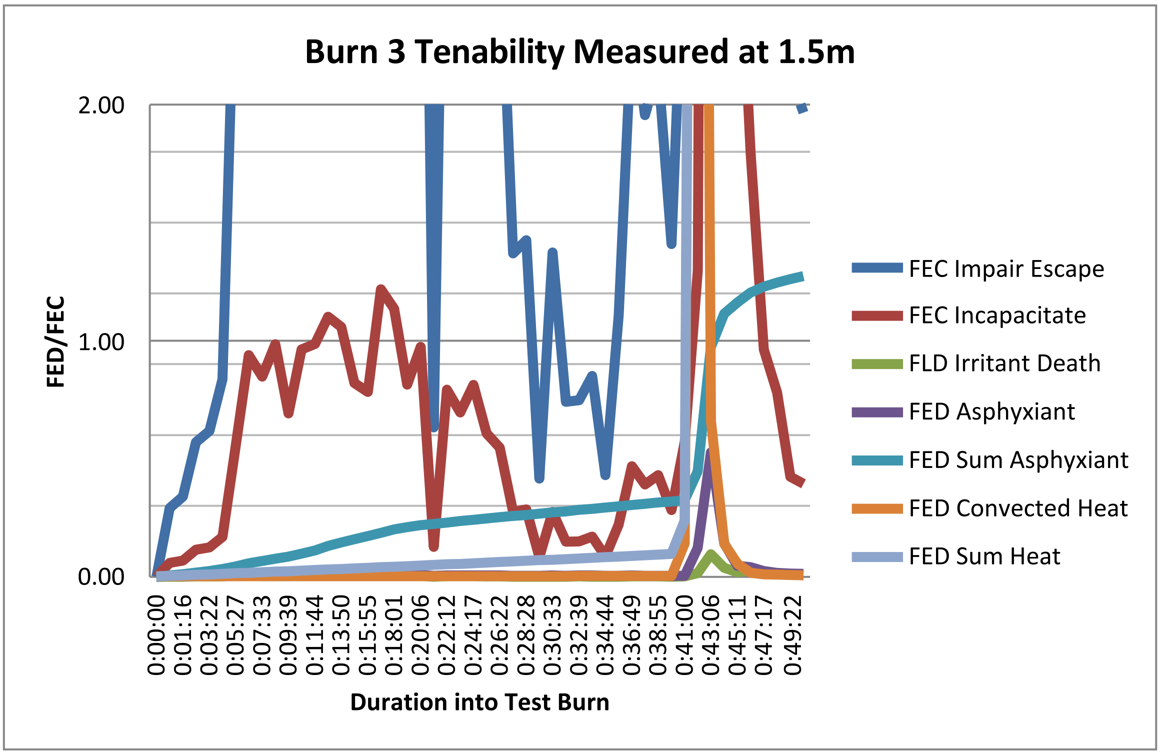


Figure 23: Burn 3 Graphical Analysis of Tenability

This fire scenario also created significantly more heat and transitioned into a flaming fire 39 minutes and 45 seconds into the test burn. Although this transition officially marked the end of the test scenario, the fire was not immediately extinguished and as such developed into a more substantial fire. Further important data was captured post transition.

Between 41 and 42 minutes into the test burn the fractional effective dose due to heat rose from 0.3 to over 9, indicating immediately fatal conditions due to convected heat. Heat data was taken from wall thermocouples in this instance, rather than from the thermocouple located next to the fire. This was due to a malfunction of the Tn thermocouple tree as well as the Ti wall thermocouple tree (see Figure 17), and therefore the data collected at Ta, further from the actual fire, was utilised. It is likely that tenability would have been lost earlier had data from Tn or Ti been available, but as Ta was on the path of egress, it was deemed a suitable point.

Considering the data obtained at Ta, 1.5m height, the following tenability conditions were met based around times into the burn. With transition occurring 39:45 into the fire, by 41:07 FED 0.3 convected heat was met. By 41:12 FED 1.63 was reached, with the cumulative heat FED equal to 2.32. By 41:18 (just prior to extinguishment) FED 4.49 was reached, producing a situation wherein the environment has reached a level of immediate incapacitation and ensuing fatality to anyone entering the room unequipped with protective fire fighting clothing and equipment.

Furthermore, there was a sharp increase at 41 minutes from FED sum asphyxiant from 0.32 to over FED 1 three minutes later. FED irritant gases spiked from 0.57 at 41:00 to 13.15 at 43:06. Considering that fire was completely extinguished by 42:00, this delayed spike in irritant gases is likely due to the cooling and settling of heated gases into the breathing zone, further exemplifying that fire environments remain dangerous post extinguishment once the obvious flaming danger has been eliminated.

At 43 minutes and 6 seconds into the burn (15:43:06) the fractional lethal dose for irritant gases reached 0.1, indicating that 1.1% of the population may die if they were to enter this environment post extinguishment of the fire without appropriate breathing apparatus. Figure 24 shows six images outlining the transition of the smouldering fire into a flaming fire, which had affected half of the lounge chair within a two minutes (times listed below each image).

39 min 34 sec: smoulder

39 min 45 sec: transition

40 min 06 sec: flaming

40 min 40 sec: increased flaming

41 min 05 sec: FED heat 0.3 incapacitation exceeded

41 min 18 sec: at extinguishment, FED 4.49 heat

Figure 24: Burn 3 Smoulder to Flaming Transitionary Photos

As previously stated, the following table shows the absolute time to smoke alarm activation in the room of origin and the hallway, wherein L is Lounge, SA1 refers to the ceiling alarms, SA2 refers to the wall space alarms, SA3 is the dead space alarms.

Table 7: Burn 3 Smoke Alarm Activation Times

L SA1 P	L SA1 I	L SA1 D	L SA2 P	L SA2 I	L SA2 D	L SA3 P	L SA3 I	L SA3 D
32m05s	DNA	26m30s	20m30s	DNA	14m52s	32m05s	38m33s	31m03s
Hall SA1 P	Hall SA1 I	Hall SA1 D	Hall SA2 P	Hall SA2 I	Hall SA2 D	Hall SA3 P	Hall SA3 I	Hall SA3 D
22m24s	DNA	22m17s	19m20s	39m40s	14m52s	16m38s	DNA	14m55s

DNA = Did Not Activate

In Burn 3, no smoke alarms located within the manufactured residence activated within FEC of 0.3 or 1, indicating that not only 11.4% of the population was statistically incapacitated, but over 50% were incapacitated. As no alarms activated within irritant incapacitation tenability limits, therefore none allowed the RSET of 120s or 135s.

As mentioned, this test scenario was shaped around an occupant leaving a smouldering cigarette on the lounge, and then going to bed. Although this occupant was therefore remote from the actual fire, and egress was only via the lounge, the data shows that less than 50% of remote occupants escaped of their own accord based around smoke alarm activation times.

FEC 0.3 incapacitation was noted in the G3 gas analysing position, located outside the bedroom doors, 20 minutes into the fire. This indicates smoke movement and travel. As there was no gas analyser present in either bedroom it is impossible to say exactly when incapacitation may have affected the sleeping bedroom occupant, but it is likely there would have been some effect. Four alarms (three hallway and one lounge) activated within this G3 measured incapacitation limit of 20 minutes; however, if an occupant were to have awoken and entered the lounge to assess the situation, that person may have been immediately overcome by irritant gases.

In Burn 3 visibility was lost, but not until after the transition to a flaming fire. Upon assessment of the Ta thermocouple at the ceiling height it was noted that sprinkler temperature activation was reached at 40 minutes and 41 seconds, 56 seconds after the flaming transition. Although this provides no indication that a sprinkler would have activated exactly at that time, it does present the question as to what effect a sprinkler may have had on tenability. Tenability due to heat was lost by 1 min 20 sec post transition, with the fire becoming immediately fatal due to heat by 1.5 minutes following the flaming transition.

3.2.4 Burn 4, Smouldering Bedroom Fire, Door Open, 0.75 Monitoring Height

Burn 4 was designed as a relatively identical test fire scenario to Burn 2; however, in this situation the gas and heat monitoring occurred at 0.75m from the floor. The reason for the change in height for monitoring was for the following reasons:

- To determine what effects could be felt directly on a sleeping occupant at sleeping height,

- To determine if there is an increase in egress time if a person crawls out of a fire scenario rather than walks

This test burn scenario was ended immediately upon transition from a smouldering fire into a flaming fire in just under 67 minutes.

Table 8: Burn 4 Ambient Conditions

Burn 4	Start	End
Date	4/03/15	
Times	12:18:10	13:25:16
Ambient Temperature	27.8°C	27.7°C
Relative Humidity	55.3%	57.2%
Air Pressure	1007.4	1006.1

In this fire scenario, two hallway alarms and seven bedroom alarms activated within designated tenability limits, also providing an ASET of both 120s and 135s. These included the photoelectric and dual alarms on the ceiling and wall in the bedroom, and all three alarms in the dead space. They also included the photoelectric and dual alarms in the dead space in the hallway. This result shows that staying low in a fire scenario rather than standing and walking towards the exit increases available egress time.

In Burn 4 tenability was not compromised by heat or visibility within the time frame of the test. The transition of the smouldering fire to the flaming fire occurred when the smoulder had burned through the mattress (13:25:00, 66 minutes and 50 seconds into the test fire). At this point, when the smoulder reached the wooden bed slats, the forward propagation of the smoulder burn is likely to have significantly increased with improved oxygen flow [10] and increased heat resulting in a transition to flaming upon reaching the timber slats. The flaming fire began under the mattress at the timber slats and quickly began to increase in size. It was extinguished within seconds using a CO_2 extinguisher. Figure 25 shows an image of the flaming fire occurring immediately prior to extinguishment.

Figure 25: Burn 4 Smoulder to Flaming Transition

Tenability was lost at 0.75m with regard to FEC 0.3 incapacitation at 21 minutes into the fire. Cumulative FED asphyxiant tenability was lost approximately 40 minutes into the fire, over 25 minutes prior to transition of the fire from smoulder to flame.

Although data was not collected, it is likely that some similarities may have been shown, for example an increase of toxic gases due to the transition from smouldering to flaming as were noted in Burn 3. This is based off the marked spike in irritant gases just prior to flaming transition and the fact that increased temperature would have been recorded due to the flaming fire. Although remaining in small quantities during the test burn time frame, carbon monoxide (CO) and hydrogen cyanide (HCN) were both beginning a steady increase in the final 10 minutes of the test burn.

In this test scenario no direct comment can be made as to what tenability was like at 1.5m, beyond an assessment of convected heat (which still remained within tenability limits at the cessation of the test burn upon transition to flaming). No comparison has been made to tenability loss at 1.5m in Burn 2. Although both burns occurred in the same room with the same furnishings, fire ignition sequence, and door open scenario, the two fires progressed quite differently and were therefore less comparable. This variance in fire progression, although expected as no two fires are identical, introduces too great a degree of change for direct comparison.

Figure 26 shows a graphical analysis of the results from Burn 4.

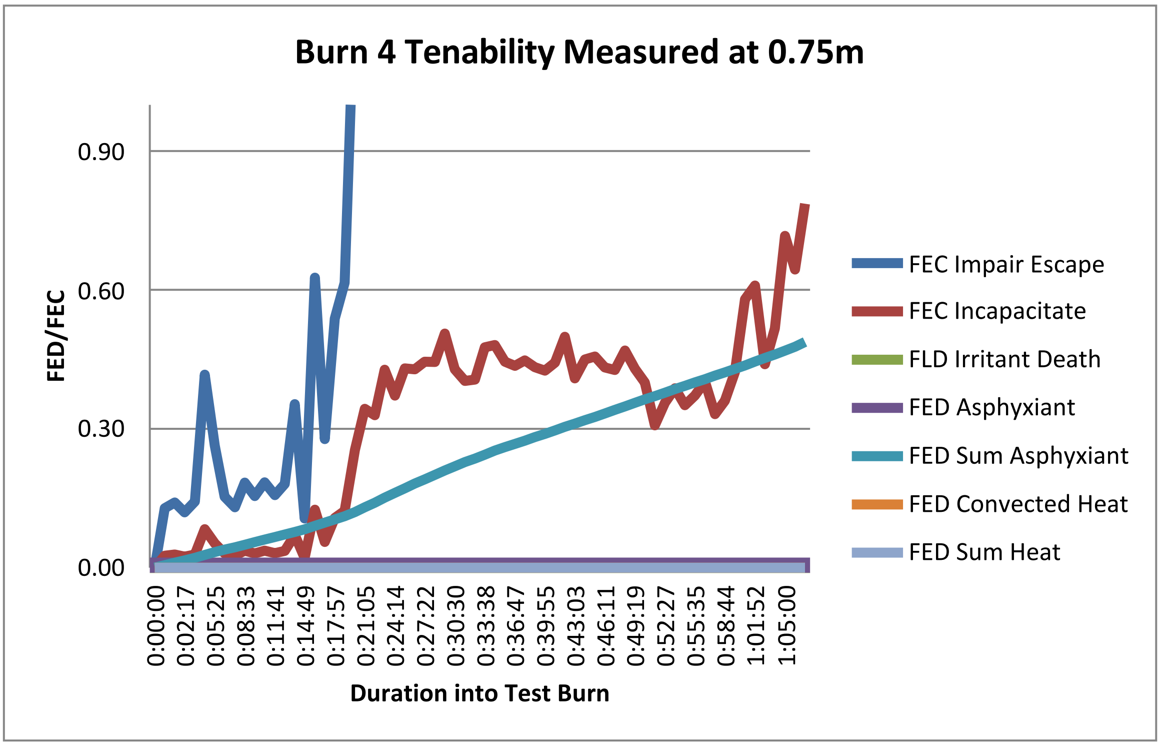


Figure 26: Burn 4 Graphical Analysis of Tenability

As previously stated, the following table shows the absolute time to smoke alarm activation in the room of origin and the hallway, wherein BD2 is Bedroom 2, SA1 refers to the ceiling alarms, SA2 refers to the wall space alarms, SA3 is the dead space alarms.

Table 9: Burn 4 Smoke Alarm Activation Times

BD2 SA1 P	BD2 SA1 I	BD2 SA1 D	BD2 SA2 P	BD2 SA2 I	BD2 SA2 D	BD2 SA3 P	BD2 SA3 I	BD2 SA3 D
12m56s	65m10s	11m34s	14m20s	64m25s	12m27s	12m19s	12m4s	11m04s
Hall SA1 P	Hall SA1 I	Hall SA1 D	Hall SA2 P	Hall SA2 I	Hall SA2 D	Hall SA3 P	Hall SA3 I	Hall SA3 D
48m41s	66m04s	49m04s	48m41s	66m04s	48m41s	16m00s	66m10s	15m6s

DNA = Did Not Activate

In this fire scenario seven of the smoke alarms in the room of origin activated within tenability limits and within an ASET of 120s or 135s. The two that did not were the ceiling and wall ionisation alarms. Two alarms in the hallway activated within tenability limits and overlaid safe egress times, but both (the photoelectric and dual alarm) were located in the dead space, which is not a location suggested for smoke alarms by either the BCA or in AS1670.6 (see Section 2.2, Focus of Test Burns). As such, excluding the dead space alarms, no ionisation alarms within the room of origin activated within tenability and egress limits, and no hallway alarms activated within those limitations either.

The test was terminated before further data on ceiling heat could be collected. Therefore no comment is available as to when the rated temperature for sprinkler activation may have been reached.

3.2.5 Burn 5, Flaming Bedroom Fire, Door Open, 0.75 Monitoring Height

Burn 5 was the first of two flaming fires undertaken in the manufactured residence. It was designed to progress to full room involvement; however, the burn had to be extinguished prior to reaching such a stage due to the potential major loss of the sections of the residence and furnishings/equipment.

Therefore, this burn only progressed until there was substantial flame on the bed, windows in both the room of origin and hallway were broken due to heat, and flames were beginning to exit the window and bedroom door.

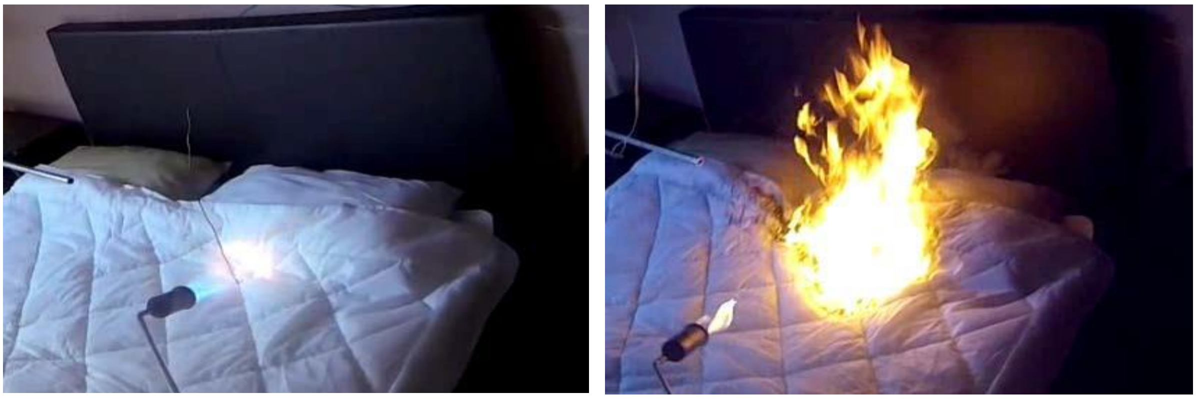
Although data captured continued, the fire was extinguished after 1 minute and 51 seconds (15:24:36).

Table 10: Burn 5 Ambient Conditions

Burn 5	Start	End
Date	4/03/15	
Times	15:23:45	15:28:46
Ambient Temperature	30.0°C	29.9°C
Relative Humidity	50.0%	50.6%
Air Pressure	1004	1004.1

Burn 5 began with the ignition of bedding materials by a LPG gas flame. The gas flame was held over the bedding materials for 5 seconds, igniting a sustained flaming fire.

Figure 27 shows the ignition and resultant flame.



Ignition flame

Resultant flaming fire

Figure 27: Flaming Ignition LPG Gas Torch

This scenario was designed to measure at 0.75m. Measuring at a lower height where someone could be sleeping or attempting to crawl to exit was of interest, too see what degree of egress time might be available in such a scenario.

Given the known movement of gases and heat it was safe to assess that tenability would have been lost sooner at 1.5m (convected heat FED 0.3 was reached at 15:24:44, 59 seconds into the burn, and 16 seconds prior to tenability loss at 0.75m)

Figure 28 shows images taken during the test burn of the fires progress, extinguishment, and bedroom damage post fire. As can be seen from these images this was a relatively small and confined fire that burnt through the bedding, the top layer of the mattress, and the bed head. The fire did not spread beyond these items of furnishing.

Although the flames and heat were large due in part to the ignition sequence of 5 seconds, the actual extent of the fire was relatively small in comparison to full room involvement. When interpreting the data it is important to remember this.

35 sec: Flaming

37 sec: Flaming

1 min 51 sec: Extinguishment

Damage to bedroom observed during residence ventilation

Figure 28: Burn 5 Images, Fire, Extinguishment, Damage

Gas and heat monitoring continued post extinguishment. Gas levels and heat reduced post extinguishment; however, due to the cumulative effects of heat and asphyxiant gases, those FED measurements continued to rise throughout the monitoring time frame of this test burn.

For this fire scenario, two graphs are included, one showing the tenability with respect to gases captured at G1, and the second showing the gases captured at G2 (the sample probe positioned furthest from the fire).

Although the graphs in Figures 29 and 30 do not show the exact time to loss of tenability due to convected heat, from thermocouple data collected it is known that FED 0.3 incapacitation convected heat at 0.75m occurred 75s into the fire, and FED 1 convected heat occurred 96s into the fire. The graph shows the cumulative effects of convected heat as projecting above FED 1.2, and was recorded to exceed FED 1.9 within the timeframe of the test burn.

What is interesting to note is that although irritant gases spiked higher in the room of origin, asphyxiant gases were found to be higher at a greater distance from the fire.

It was an unfortunate oversight to retain the 1 minute monitoring of gases during this flaming fire. It is due to this oversight that important information regarding the exact time to incapacitation may be lost. Many data points within heat changes are excluded from the graphs due to time monitoring constraints in matching data, and this raises questions about what information was lost in the gas monitoring due to the expedited changes occurring in a flaming fire. Ideally gas samples would have been taken at a maximum of 20s intervals during Burn 5.

When considering the temperature on the ceiling in Bedroom 2, it is possible to deduce the time at which a sprinkler system may have activated, had it been present. Considering the ceiling temperature exceeded 71°C (recorded as 84.2°C) at 15:24:12, 27 seconds into the fire scenario, it presents an interesting argument surrounding whether tenability limits would have been reached had a residential sprinkler system been present.

Figures 29 and 30 show the data as discussed from the two gas sampling points G1 and G2, the room of origin and the hallway/lounge locations respectively.

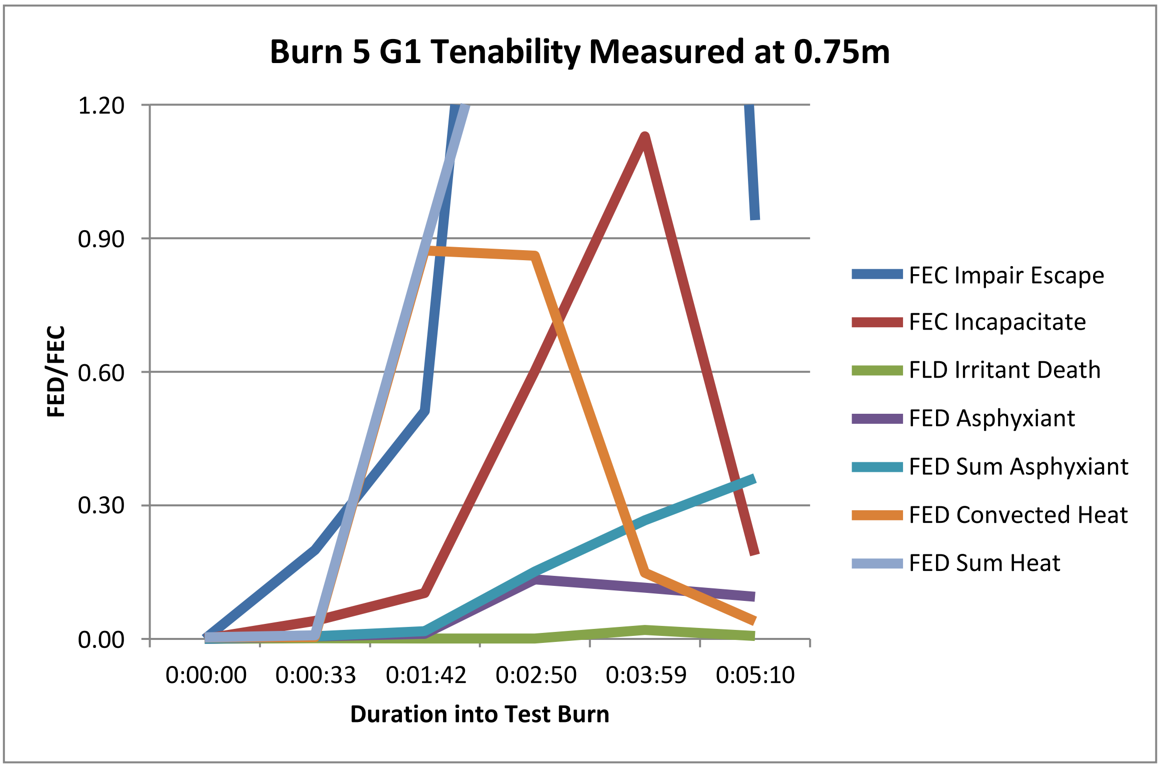


Figure 29: Burn 5 G1 Graphical Analysis of Tenability

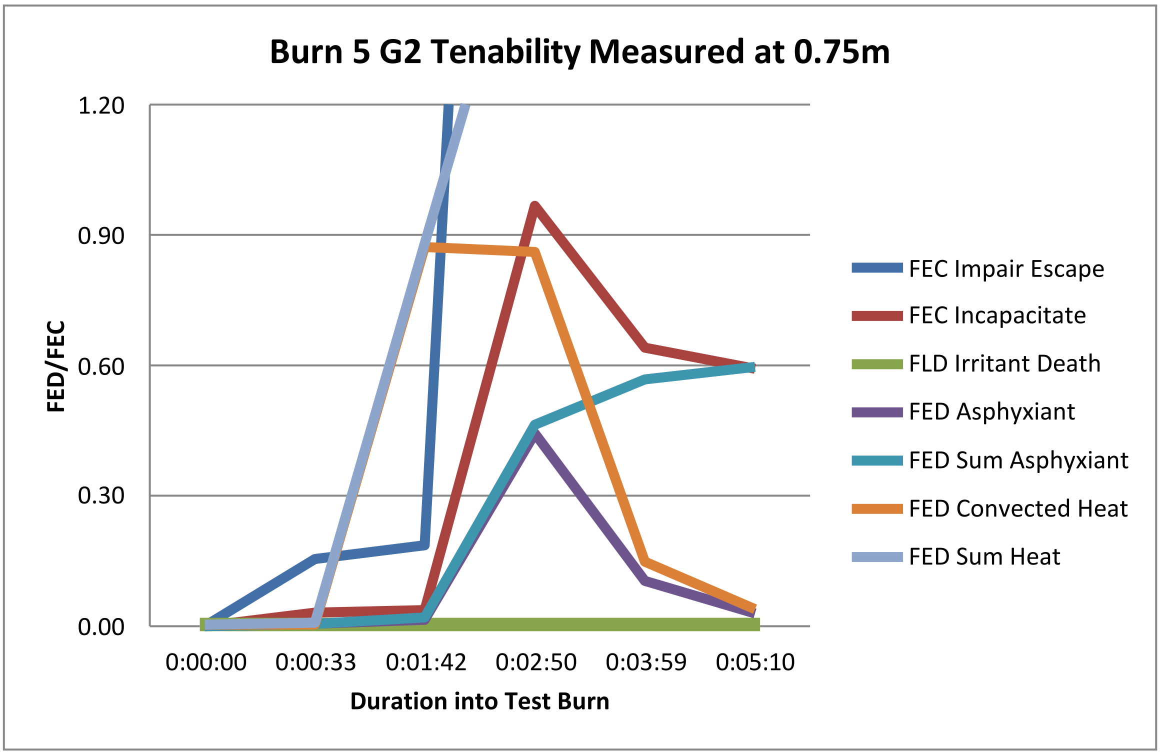


Figure 30: Burn 5 G2 Graphical Analysis of Tenability

As previously stated, the following table shows the absolute time to smoke alarm activation in the room of origin and the hallway, wherein BD2 is Bedroom 2, SA1 refers to the ceiling alarms, SA2 refers to the wall space alarms, SA3 is the dead space alarms.

Table 11: Burn 5 Smoke Alarm Activation Times

BD2 SA1 P 10s	BD2 SA1 I 11a	BD2 SA1 D 14s	BD2 SA2 P 41s	BD2 SA2 I 41s	BD2 SA2 D 41s	BD2 SA3 P 41s	BD2 SA3 I 41s	BD2 SA3 D 41s
Hall SA1 P 41s	Hall SA1 I 41s	Hall SA1 D 41s	Hall SA2 P 41s	Hall SA2 I 41s	Hall SA2 D 41s	Hall SA3 P 41s	Hall SA3 I 41s	Hall SA3 D 41s

DNA = Did Not Activate

Assessment of the activation of smoke alarms shows that all alarms activated, both in the room of origin and in the hallway. It also shows that, although the room of origin alarms on the ceiling were 27-31s faster than the others, all remaining smoke alarms activated simultaneously at 41s.

What activation does not show is that, given the information regarding tenability loss due to convected heat FED 0.3 incapacitation, none of the alarms activated within the ASET of 120s or 135s, including the fastest acting alarms in the room of origin.

3.2.6 Burn 6, Smouldering Bedroom Fire, Door Closed, 1.5m Monitoring Height

As mentioned in the introduction of Section 3.2, Test Burn Results and Discussion, Burn 6 was designed in line with Burn 1. It was set up as though an occupant fell asleep with a cigarette burning on bedding materials, with the bedroom door shut. The residence, including the room of origin, was equipped with a part 5 residential sprinkler system. As mentioned, Burn 6 was not equipped with the specified 32mm pressure reducing valve.

Table 12: Burn 6 Ambient Conditions

Burn 6	Start	End
Date	5/03/15	
Times	11:23:45	12:10:17
Ambient Temperature	25.6°C	26.9°C
Relative Humidity	30.1	28.5
Air Pressure	1003	1002.9

The test burn was concluded approximately 46.5 minutes into the test fire as the smoulder had ceased. There was no sprinkler activation.

In Burn 6, the limiting factor to incapacitating occupants was irritant gases, which reached FEC 0.3 at exactly 11 minutes into the test burn scenario.

Heat and visibility were not limiting factors, and the heat at the ceiling did not reach sprinkler activation temperatures during the time frame of the test burn. Figure 31 shows a graphical analysis of the tenability results, and Table 13 shows the smoke alarm activation times in the room of origin and hallway.

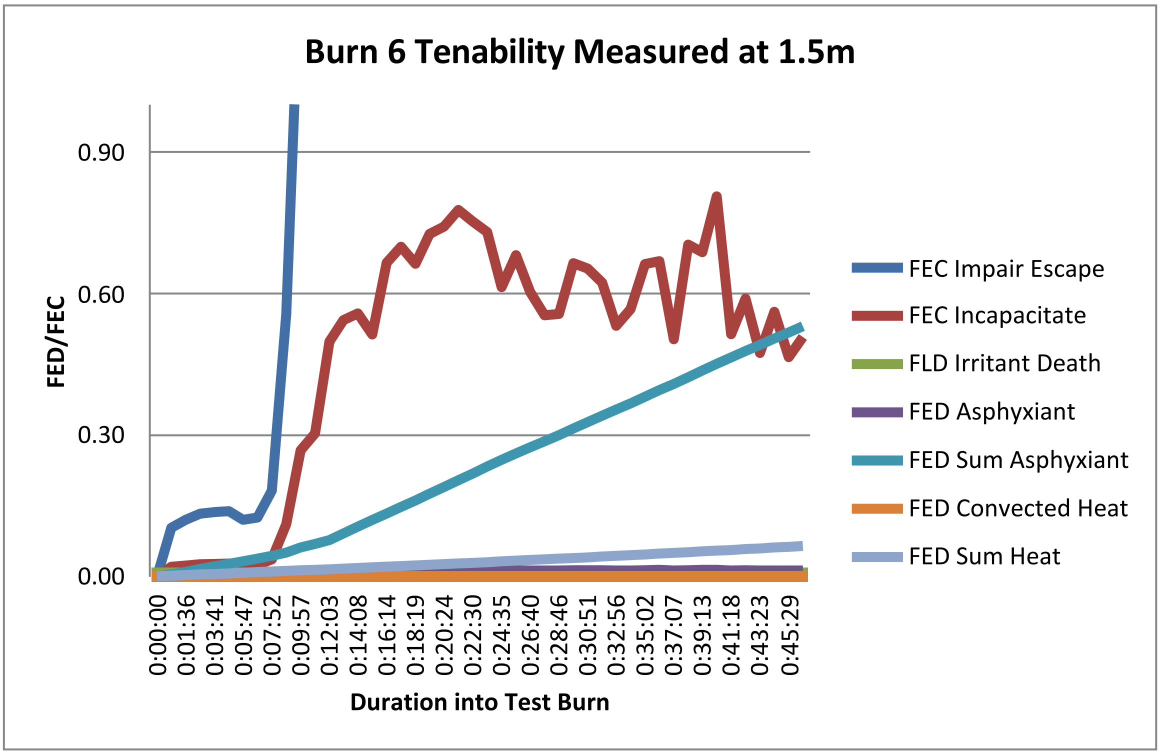


Figure 31: Burn 6 Graphical Analysis of Tenability

As previously stated, the following table shows the absolute time to smoke alarm activation in the room or origin and the hallway, wherein BD1 is Bedroom 1, SA1 refers to the ceiling alarms, SA2 refers to the wall space alarms, SA3 is the dead space alarms.

Table 13: Burn 6 Smoke Alarm Activation Times

BD1 SA1 P	BD1 SA1 I	BD1 SA1 D	BD1 SA2 P	BD1 SA2 I	BD1 SA2 D	BD1 SA3 P	BD1 SA3 I	BD1 SA3 D
7m33s	6m40s	5m47s	7m21s	7m45s	5m57s	4m29s	6m14s	4m32s
Hall SA1 P	Hall SA1 I	Hall SA1 D	Hall SA2 P	Hall SA2 I	Hall SA2 D	Hall SA3 P	Hall SA3 I	Hall SA3 D
DNA	DNA	DNA	DNA	DNA	13m02s	12m28s	DNA	12m18s

DNA = Did Not Activate

All bedroom 1 alarms activated within the tenability limit, and provided a positive result when a safe egress time of 120s and 135s were overlaid on alarm time.

No hallway alarms activated within tenability limits as measured in the bedroom. Only a single hallway alarm that was positioned as per BCA and AS1670.6 instruction (see Section 2.2, Focus of Test Burns) activated, the dual alarm located on the wall. The other two hallway alarms that activated were located in the dead zone.

3.2.7 Burn 7, Smouldering Bedroom Fire, Door Open, 1.5m Monitoring Height

Burn 7 was designed in line with Burn 2, surrounding the circumstances of someone falling asleep in bed with a burning cigarette, with both bedroom doors left open. Gas and heat measurements were taken at 1.5m, and the material first ignited was bedding by means of a cartridge heater. This burn is not a direct comparison with Burn 2 as the time of day was different, ambient conditions were different, and the room first ignited was different. The burn was run in an equivalently laid out bedroom 1 instead of bedroom 2, as initially planned.

In Burn 7 the pressure reducer had been connected resulting in sprinkler activation at the ideal pressure for a home residence. This burn was run out of sequence, and was undertaken on the day following Burns 6, 8 and 9.

Table 14: Burn 7 Ambient Conditions

Burn 7	Start	End
Date	6/03/15	
Times	9:55:30	10:54:40
Ambient Temperature	21.0°C	22.3°C
Relative Humidity	33.6%	27.3%
Air Pressure	1003.3	1003.1

FEC 0.3 incapacitation was reached at 13 minutes and 11 seconds. FED 0.3 cumulative asphyxiant gas was reached at 50 minutes and 48 seconds in the room of origin. Asphyxiant tenability was reached more quickly at a greater distance from the fire, with G2 in the hallway lounge position noting FED 0.3 cumulative asphyxiation at 38 minutes and 38 seconds. G2 was positioned on the path of egress from the bedroom.

The smouldering fire transitioned into a flaming fire at 10:50:00, 54 min and 30 sec into the fire. At 10:50:37, 55 minutes and 7 seconds in the burn, 37 seconds after the transition of smouldering to flaming, the sprinkler activated with the closest recorded temperature of 94.6°C. This activation did not occur within tenability limits of FEC 0.3 irritant or FED 0.3 cumulative asphyxiant incapacitation; however, its activation would have prevented further likely injury due to the heat and toxic gases from flaming fires (see Burns 3 and 5).

For the duration of sprinkler activation the FED/FEC limits for toxic gases and heat remained low. Visibility was lost, but untenable conditions were not met. The sprinkler was run for 60 seconds, and then manually shut off in order to preserve the test environment from excess water. Within minutes of sprinkler shut off the flaming fire returned and there is a spike in irritant gases and an increase in asphyxiant gases and convected heat. Although it is impossible to conclusively determine if this spike would have reached levels untenable to life had the fire continued and not been manually extinguished, when comparing the fire scenario to others wherein the flaming fire continued, it is highly likely.

Figure 32 displays images captured during Burn 7.

16 seconds post flaming transition

Immediately at sprinkler activation 1 second post sprinkler activation

Figure 32: Burn 7 Images, Transition, Sprinkler Activation, 1 Second Post Sprinkler Activation

It would be useful to run further testing of similar scenarios allowing the sprinklers to run for longer to more fully suppress the fire and determine the ongoing effect on tenability. Figure 33 provides a graphical analysis of the recorded data, showing the spike in irritant gases, and the increase in convected heat and asphyxiant FEDs.

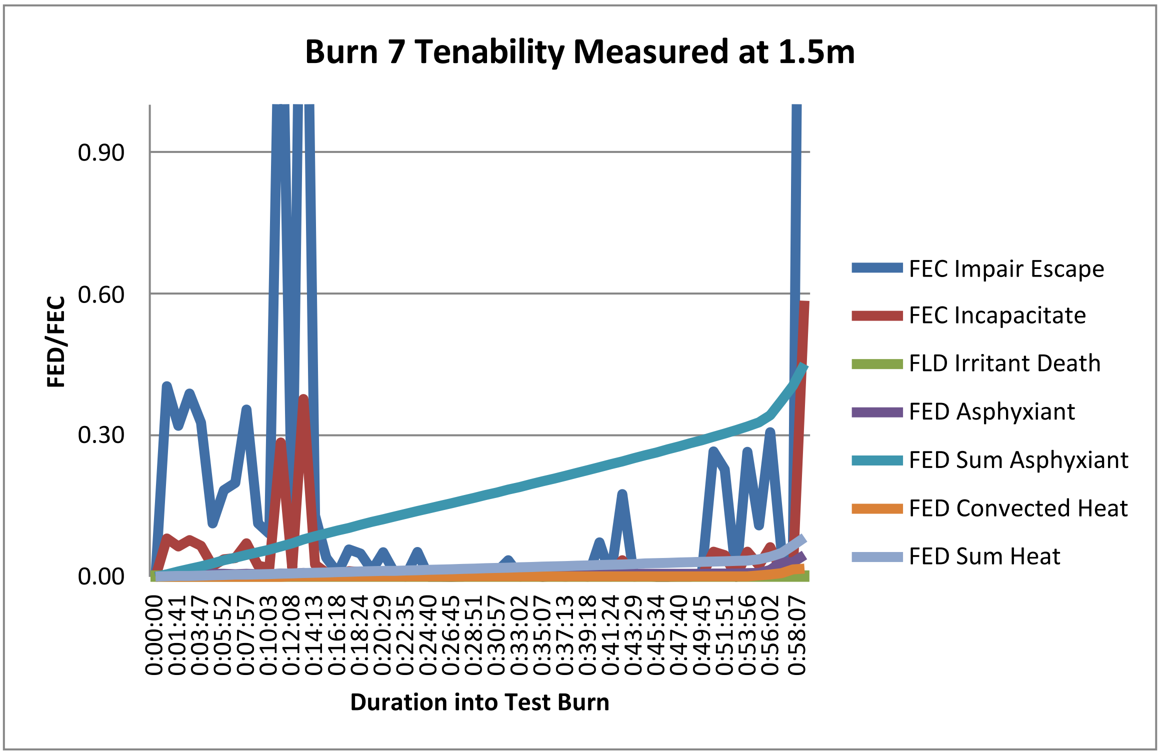


Figure 33: Burn 7 Graphical Analysis of Tenability

As previously stated, the following table shows the absolute time to smoke alarm activation in the room of origin and the hallway, wherein BD1 is Bedroom 1, SA1 refers to the ceiling alarms, SA2 refers to the wall space alarms, SA3 is the dead space alarms.

Table 15: Burn 7 Smoke Alarm Activation Times

BD1 SA1 P	BD1 SA1 I	BD1 SA1 D	BD1 SA2 P	BD1 SA2 I	BD1 SA2 D	BD1 SA3 P	BD1 SA3 I	BD1 SA3 D
14m01s	54m47s	55m22s	15m59s	54m15s	15m59s	4m04s	53m28s	2m33s
Hall SA1 P	Hall SA1 I	Hall SA1 D	Hall SA2 P	Hall SA2 I	Hall SA2 D	Hall SA3 P	Hall SA3 I	Hall SA3 D
49m52s	55m22s	43m10s	51m16s	55m22s	22m27s	15m41s	54m57s	14m10s

DNA = Did Not Activate

In the instance of Burn 7 only two smoke alarms activated within the tenability limit FEC 0.3 in the room of origin. These were the photoelectric and dual alarms within the dead space in the room of origin. Both of these alarms also provided a safe egress time of both 120s and 135s.

No alarms within the hallway activated within tenability limits due to irritant gases, nor did any that were appropriately positioned (in line with the BCA and AS1670.6, see Section 2.2, Focus of Test Burns) in the room of origin.

3.2.8 Burn 8, Smouldering Lounge Fire, 1.5m Monitoring Height

Burn 8 was a similar test scenario to Burn 3 with the exception of time of day, ambient conditions, and the installation of a residential sprinkler system. Gas and heat measurements were taken at 1.5m, and the material first ignited with an upholstered sofa by means of a cartridge heater.

In Burn 8 the sprinkler system ran at idle pressure (not ideal) from the FRNSW pumping appliance.

Table 16: Burn 8 Ambient Conditions

Burn 8	Start	End
Date	5/03/15	
Times	13:56:05	14:45:44
Ambient Temperature	29.0°C	28.7°C
Relative Humidity	25	25.2
Air Pressure	1003	1002.7

This smoulder burn transitioned into a flaming fire at 14:43:18, 47 minutes and 13 seconds into the burn. Although visibility was lost 1 minute and 30 seconds post flaming transition, it was not the limiting factor with regard to tenability. Nor was convected heat.

Sprinkler activation occurred at 14:45:04, 1 minute and 46 seconds after the flaming transition. The Tn ceiling thermocouple recorded steady temperature increase post transition, with the recorded temperature at sprinkler activation of 103.2C.

Prior to the sprinkler activating the Tn ceiling thermocouple recorded a temperature exceeding 150°C. It is unknown why the sprinkler did not activate at an earlier time given the high recorded ceiling temperatures and relative proximity of the ceiling thermocouple to the sprinkler head. What is considered is that the fire was fast growing resulting in a high rate of temperature increase at the ceiling level.

Figure 34 displays an image showing the relative distance between the Tn ceiling thermocouple and the sprinkler head.

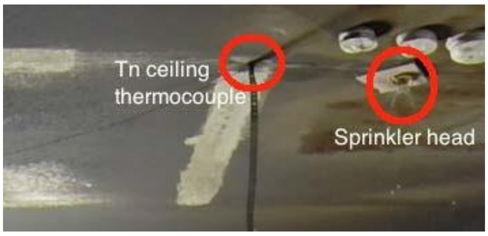


Figure 34: Burn 8 Tn Ceiling Thermocouple and Sprinkler Head Proximity

Regardless of any potential delay in sprinkler activation, the fire was observed to be contained and suppressed. The sprinkler was manually shut off after 41 seconds of activation in order to reduce water damage impact on the residence.

The remainder of the fire was extinguished using a 38mm fire fighting hose. Figure 35 shows images captured during Burn 8, including transition, fire growth, and fire reduction post sprinkler activation.

47 min 13 sec: transition of smoulder to flame

48 min 52 sec: flaming fire just prior to sprinkler activation

49 in 27 sec: sprinkler has reduced and contained the fire

Figure 35: Burn 8 Images, Transition, Flaming, Sprinkler Activation

Due to the movement of the smoke the gas analyser, G2, in the hallway lounge position measured FEC 0.3 incapacitation tenability limits prior to the gas analyser in the lounge room, G1. Tenability loss with respect to egress from the bedrooms can therefore be taken as 10 minutes and 28 seconds due to G2 being positioned directly in the path of egress from the bedrooms.

G1 measured tenability limits due to irritant gases, FEC 0.3 incapacitation, at 15 minutes and 40 seconds. FED incapacitation 0.3 due to cumulative asphyxiation was measured at 32 minutes and 23 seconds, both of which occurred prior to the transition of the smouldering fire to flaming.

Figure 36 shows the graphical analysis of tenability conditions from the G1 probe in the lounge room. It can be noted that although there was a spike in the FED for convected heat and irritant gases at the time of transition from smouldering to flaming, untenable conditions did not progress towards fatal conditions due to fire suppression by the sprinkler.

Although, as in Burn 7, it is impossible to determine the longer term trend with regard to gas analysis as there were only two gas samples taken post transition, it appears that there is a decrease in irritant gases post sprinkler reactivation. The data collected for heat analysis is more clear, showing a definitive increase at the time of flaming, and a definitive decrease post sprinkler activation.

It can therefore be concluded that although an occupant may have been incapacitated by the smouldering fire, tenability limits of death were not reached prior to (or during) sprinkler activation, and therefore the sprinkler may have saved the occupant’s life.

This conclusion is based on the results with regard to tenability loss obtained in Burn 3, where there was no sprinkler activation and the environment progressed towards near immediate death prior to external fire fighter extinguishment.

With the activation of the sprinkler and the containment of the fire, it is unlikely that an occupant would have suffered increased injury due to the dangers of being incapacitated in proximity to a flaming fire.

Figure 36 provides a visual graphical display of the tenability results for Burn 8.

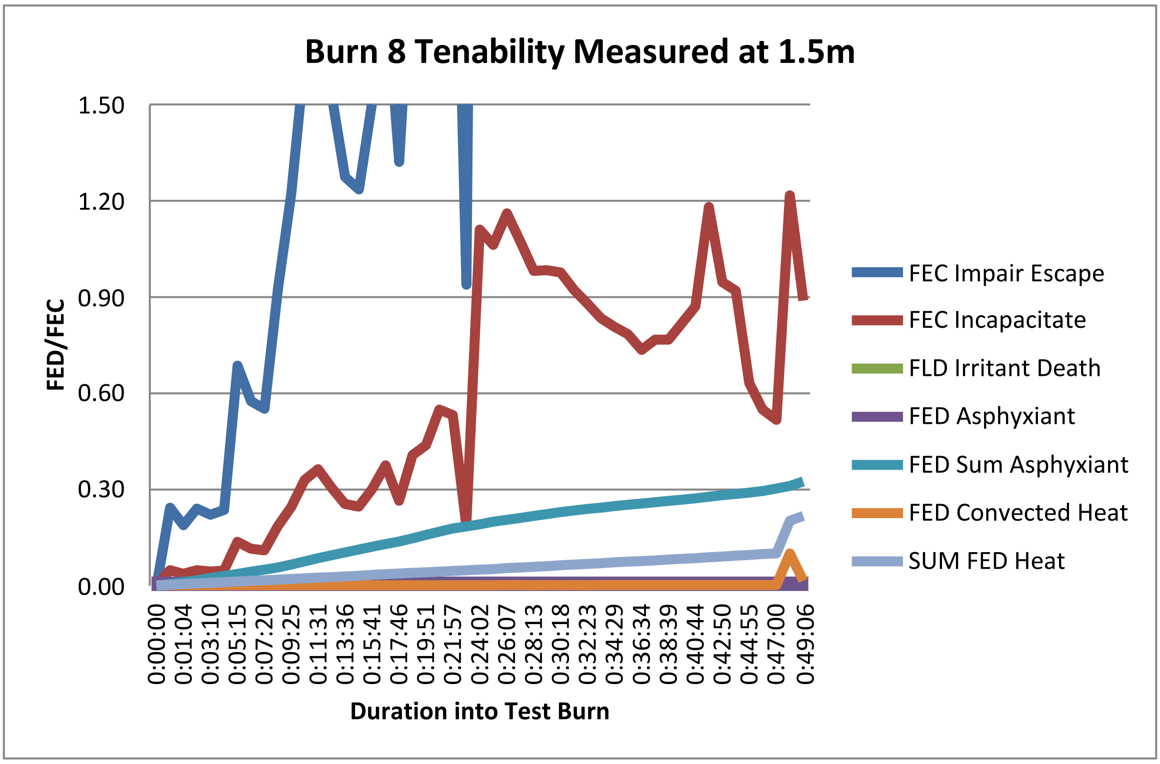


Figure 36: Burn 8 Graphical Analysis of Tenability

As previously stated, the following table shows the absolute time to smoke alarm activation in the room or origin and the hallway, wherein L is Lounge, SA1 refers to the ceiling alarms, SA2 refers to the wall space alarms, SA3 is the dead space alarms.

Table 17: Burn 8 Smoke Alarm Activation Times

L SA1 P	L SA1 I	L SA1 D	L SA2 P	L SA2 I	L SA2 D	L SA3 P	L SA3 I	L SA3 D
33m31s	42m37s	38m42s	19m30s	39m17s	9m59s	40m53s	42m14s	38m11s
Hall SA1 P	Hall SA1 I	Hall SA1 D	Hall SA2 P	Hall SA2 I	Hall SA2 D	Hall SA3 P	Hall SA3 I	Hall SA3 D
26m43s	40m07s	DNA	21m58s	40m07s	19m58s	24m48s	42m06s	24m44s

DNA = Did Not Activate

With regard to smoke alarm activation within tenability limits, only a single alarm within the room of origin activated within the G2 FEC 0.3 incapacitation of 10 minutes and 28 seconds due to irritant gases. This smoke alarm did not provide sufficient egress time when 120s and 135s RSET were overlaid on the smoke alarm activation time.

This is an important consideration in the situation where there may have been an occupant sleeping in the bedroom, who was awakened to the sound of the alarm. Upon entering the region of the G2 gas analyser, the lounge end of the hallway, that occupant may have been overcome by the irritant gases (11.4% of the population), thereby rendering that occupant incapacitated. As such it was deemed that no alarms activated within tenability limits.

3.2.9 Burn 9, Smouldering Bedroom Fire, Door open, 0.75m Monitoring Height

Burn 9 was a similar test scenario to Burn 4 with the exception of time of day, ambient conditions, and the installation of a residential sprinkler system. Gas and heat measurements were taken at 1.5m, and the material first ignited was bedding by means of a cartridge heater. As with Burn 4, the interest to consider tenability at 0.75m was based off the following:

- To determine what effects could be felt directly on a sleeping occupant at sleeping height,
- To determine if there is an increase in egress time if a person crawls out of a fire scenario rather than walks

In Burn 9 the sprinkler system ran at idle pressure (not ideal) from the FRNSW pumping appliance without the inclusion of the 32mm pressure reducing valve.

Table 18: Burn 9 Ambient Conditions

Burn 9	Start	End
Date	5/03/15	
Times	16:32:00	17:49:59
Ambient Temperature	24.7°C	22.1°C
Relative Humidity	43.9%	45.6%
Air Pressure	1003.5	1004.8

In Burn 9 tenability limits were first reached, FEC 0.3 irritant incapacitation, at 42 minutes and 34 seconds at G3, the gas analyser positioned directly outside the bedroom doors. Within bedroom 2, tenability due to irritant incapacitation 0.3 was reached at 53 minutes and 56 seconds. Incapacitation time limits due to cumulative asphyxiation ranged from 44 minutes and 55 seconds at G3 (bedroom hallway position) to 47 minutes and 47 seconds at G2 (hallway lounge). G1 in the bedroom recorded cumulative asphyxiation incapacitation FED 0.3 at 47 minutes and 39 seconds.

At 17:48:22, 76 minutes and 22 seconds into the test burn, the smouldering fire transitioned to a flaming fire. This transition was quickly followed by the activation of the bedroom sprinkler system at 17:48:38, 16 seconds post the transition into a flaming fire. The sprinkler activated with the closest recorded temperature of 75.9°C.

Visibility was lost at 17:45:00, 73 minutes into the fire; however, this was not a limiting factor in egress, nor was convected heat.

As with the previous burns there is a noted increase in irritant and asphyxiant gases post the transition from smouldering fire to flaming, and at the time of sprinkler activation. Again, the spike is likely due to the transition of the fire from smouldering to flaming. Sprinkler activation suppressed the fire towards extinguishment.

Figure 37 provides a graphical analysis of these results.

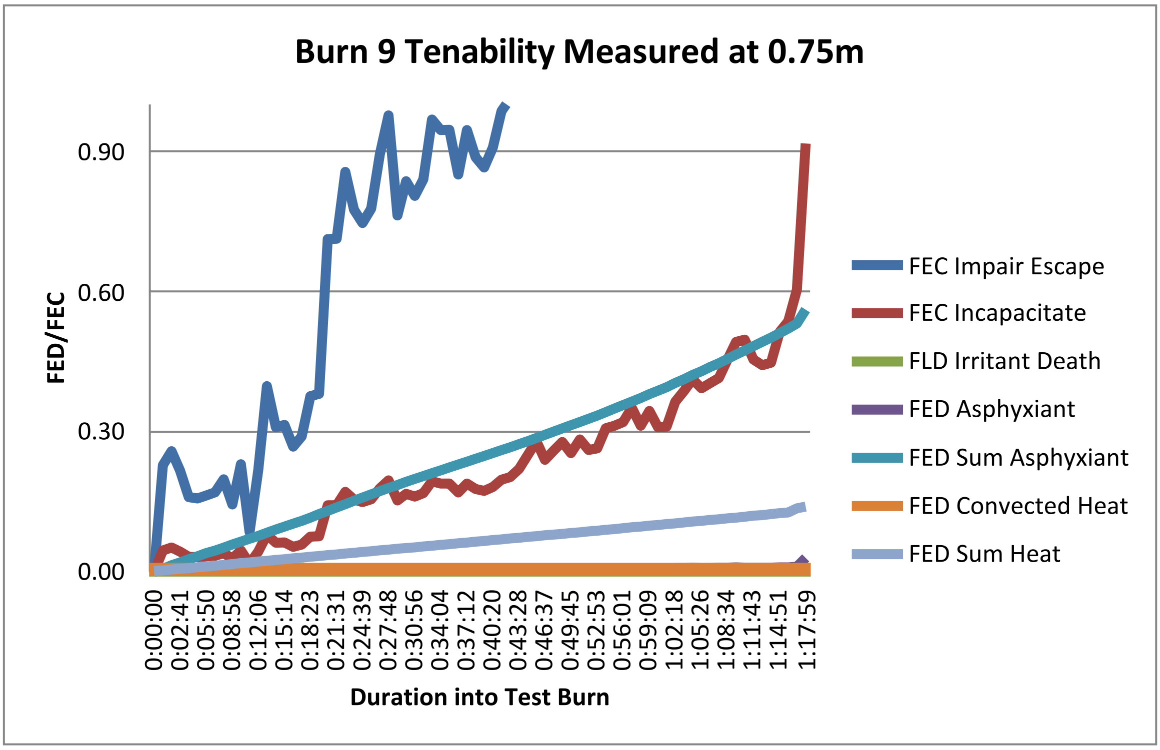


Figure 37: Burn 9 Graphical Analysis of Tenability

As previously stated, the following table shows the absolute time to smoke alarm activation in the room or origin and the hallway, wherein BD2 is Bedroom 2, SA1 refers to the ceiling alarms, SA2 refers to the wall space alarms, SA3 is the dead space alarms.

Table 19: Burn 9 Smoke Alarm Activation Times

BD2 SA1 P	BD2 SA1 I	BD2 SA1 D	BD2 SA2 P	BD2 SA2 I	BD2 SA2 D	BD2 SA3 P	BD2 SA3 I	BD2 SA3 D
7m51s	74m6s	7m51s	6m9s	69m52s	6m47s	7m51s	68m57s	7m51s
Hall SA1 P	Hall SA1 I	Hall SA1 D	Hall SA2 P	Hall SA2 I	Hall SA2 D	Hall SA3 P	Hall SA3 I	Hall SA3 D
55m51s	74m20s	15m3s	56m5s	72m41s	52m30s	12m54s	72m21s	12m12s

DNA = Did Not Activate

In Burn 9, six of the bedroom alarms (all photoelectric and dual) activated both within tenability limits FEC 0.3 incapacitation, as well as providing sufficient safe egress time (120s and 135s). No bedroom ionisation alarms activated within tenability limits.

Three hallway alarms activated within the FEC 0.3 tenability time limit of 42 minutes and 34 seconds, each providing sufficient warning for the designed RSET times. Two of the alarms that activated within safe egress time in the hallway were positioned in the dead space (photoelectric and dual), leaving only a single appropriately positioned alarm with regard to BCA and AS1607.6 advice, the dual alarm on the ceiling, activating within tenability limits.

3.2.10 Burn 10, Flaming Bedroom Fire, Door open, 0.75m Monitoring Height

Burn 10 was a similar test scenario to Burn 5 with the exception of time of day, ambient conditions, igniting bedding in Bedroom 1 instead of Bedroom 2, and the installation of a residential sprinkler system. Gas and heat measurements were taken at 1.5m, and the material first ignited was bedding by means of a LPG gas flame. In Burn 10 the flame was only held over the bedding material for 2 seconds, igniting a smaller initial fire than was seen in Burn 5.

In Burn 10 the sprinkler system ran at ideal pressure having had the 32mm pressure reducer added prior to this test burn.

Table 20: Burn 10 Ambient Conditions

Burn 10	Start	End
Date	6/03/15	
Times	13:23:30	13:25:04
Ambient Temperature	27.7°C	27.8°C
Relative Humidity	19.8%	20.8%
Air Pressure	1000.7	1000.7

In Burn 10 the sprinkler activated 62 seconds post ignition and extinguished the fire. Tenability limits were not reached with regard to toxic gases, heat or visibility at any stage in the test burn. The sprinkler activated at 13:24:32, with the closest recorded ceiling temperature of 105.5°C.

Given the fast activation of the sprinkler system in Bedroom 1, and the noted observation that the fire was completely extinguished by 120s post ignition (18 seconds post sprinkler activation), it is likely that tenability was maintained due to the presence of the sprinkler, rather than due to the slightly smaller initial flame. Had a larger initial flame been produced it is possible that the temperature would have increased more rapidly, potentially setting off the residential sprinkler at an earlier time.

As only two flaming fires test scenarios were undertaken with different ignition durations of time there are limited conclusions that can be drawn in comparing the tenability limits and safe egress times; however, as an individual burn it is clear that the sprinkler system provided safe egress in the event of this flaming fire. Post ignition the fire grew, but was quickly controlled and then extinguished by means of the residential sprinkler system.

Figure 38 shows a graphical analysis of the tenability levels in Burn 10.

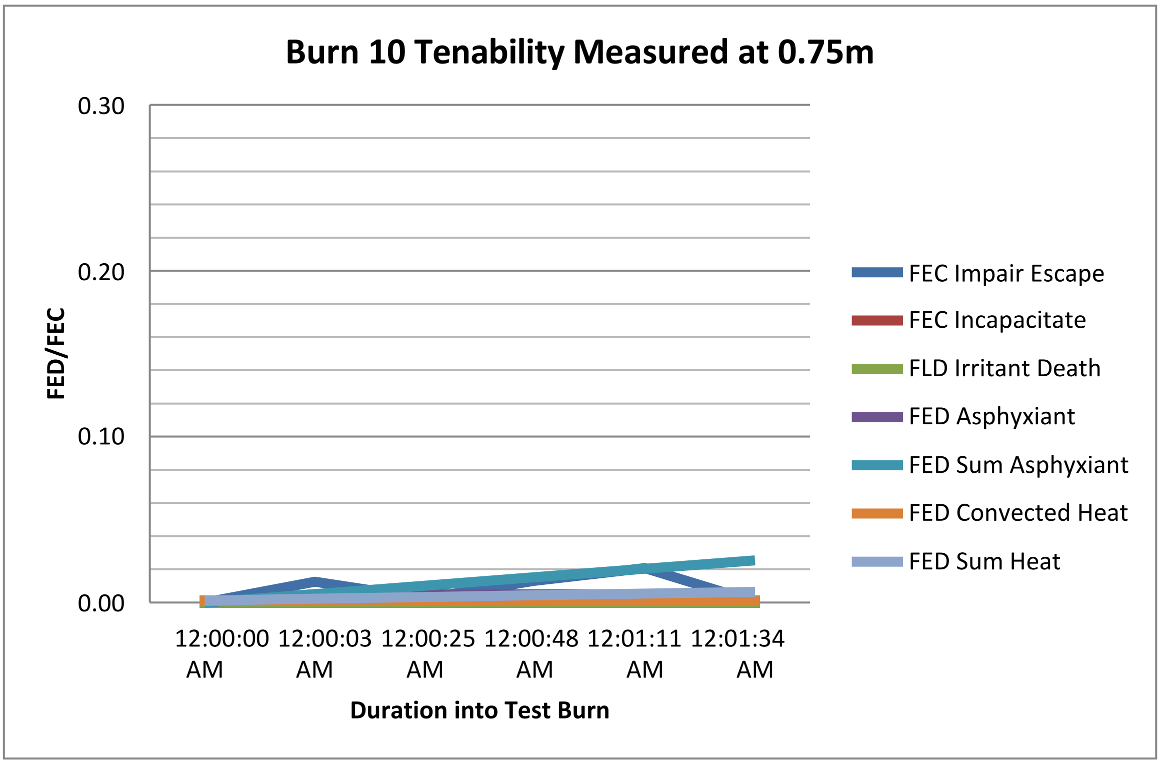


Figure 38: Burn 10 Graphical Analysis of Tenability

As previously stated, the following table shows the absolute time to smoke alarm activation in the room or origin and the hallway, wherein BD1 is Bedroom 1, SA1 refers to the ceiling alarms, SA2 refers to the wall space alarms, SA3 is the dead space alarms.

Table 21: Burn 10 Smoke Alarm Activation Times

BD1 SA1 P	BD1 SA1 I	BD1 SA1 D	BD1 SA2 P	BD1 SA2 I	BD1 SA2 D	BD1 SA3 P	BD1 SA3 I	BD1 SA3 D
47s	8s	47s	27s	27s	DNA	18s	18s	18s
Hall SA1 P	Hall SA1 I	Hall SA1 D	Hall SA2 P	Hall SA2 I	Hall SA2 D	Hall SA3 P	Hall SA3 I	Hall SA3 D
DNA	DNA	DNA	DNA	DNA	DNA	41s	41s	41s

DNA = Did Not Activate

As tenability limits were not reached at any stage during this test burn, all alarms that activated did so within tenability limits, and within the designated safe egress times. The data of activation shows that even with sufficient smoke produced from an active flaming fire that burned for 62 seconds prior to sprinkler activation, seven smoke alarms did not activate. One of these alarms, the wall positioned dual alarm, was in the bedroom. Six of these alarms were positioned in the hallway.

Given there was no loss of tenability it is impossible to definitively conclude what results may have occurred without a residential sprinkler system; however, given the results of Burn 5, and data collected in the smouldering fires that transitioned, it is likely that tenability would have been quickly lost had the sprinkler system not contained, and in this instance extinguished, the fire.

Furthermore, it was surprising to note that seven alarms did not activate in the flaming fire, given Burn 5 had a 100% smoke alarm activation rate. Again, given there were only two flaming fire scenarios this variance could be due to any number of reasons, and it is impossible to draw definitive conclusions.

More testing based around flaming fires, smoke alarm activation, and residential sprinkler systems is needed.

3.2.11 Overall Test Burn Analysis

Across the smouldering fires it is interesting to consider the number of burns that transitioned into a flaming fire. The smouldering fires, at a rate of 100%, produced levels of irritant and/or asphyxiant gas that resulted in incapacitation at 0.3 FEC and/or FED. Although there were variables across the test burn scenarios, a result of FED and or FEC 0.3 at 100% is significant.

The smouldering fires within these test parameters did not result in tenability levels remotely close to death. However, if a smouldering fire is likely to transition into a flaming fire, this drastically increases the risk of fatality to the occupant already incapacitated by the smouldering fire.

As such, further analysis was undertaken considering the smouldering fires, and their transition to flaming. It was also of interest to determine if smouldering fires were able to set off residential sprinkler systems on their own, or only after flaming transition occurred.

Table 22: Smouldering Fire Transition and Sprinkler Activation

	Burn 1	Burn 2	Burn 3	Burn 4	Burn 6	Burn 7	Burn 8	Burn 9
Transition	N	N	Y	Y	N	Y	Y	Y
Time to Transition (minutes)	NA	NA	40.10	66.83	NA	54.50	47.22	76.37
Sprinkler Activation Time	NA	NA	NA	NA	DNA	55.12	48.98	76.63
Closest Recorded Ceiling Temperature at Activation °C	NA	NA	NA	NA	NA	94.6	103.2	75.9
Time from Transition to Sprinkler Activation	NA	NA	NA	NA	NA	0.61	1.77	0.27

NA = Not Applicable

Table 23: Summary Results from Table 23

% Transition	62.5%
Average Time to Transition (minutes)	59.36
% Sprinkler Activation	75.0%
Average Sprinkler Activation Temperature °C	91.2
Average time from Transition to Sprinkler Activation (minutes)	0.88

The data shows that 62.5% of the smouldering fires transitioned into flaming fires. Considering that within each of these, based on smoke alarm activation times and gas analysis results showing that FEC/FED 0.3 incapacitation was reached prior to effective notification, 11.4% of the population was considered incapacitated prior to the transition. Therefore, without external intervention from a fire service resulting in the rescue of the occupant, there is the increased possibility of loss of life.

There are of course many factors involved when considering whether the fire service may have been notified and saved the occupant prior to transition and possible death; however, when considering residential occupancy fires, automated notification to the fire service does not necessarily exist. Therefore, without a neighbour or another resident who was not incapacitated making a call, there is the possibility that notification may not have occurred in a timely fashion.

The average time to transition of a smouldering fire to a flaming fire was 59.36 minutes. A further discussion in relation to smoke alarm activation time, percentage activation, and egress time will be undertaken in the following section, Section 3.3, Smoke Alarm Comparison and Analysis.

What was notable across the 5 smouldering fires that transitioned into flaming fires was that there was a significant spike in toxic gases and heat closely following the transition.

Of the smouldering fires with residential sprinkler systems installed, 75% resulted in sprinkler activation. Although this seems a reasonable percentage of activation, it is important to remember this is based off four test burns and activation only occurred when the smoulder transitioned to a flaming fire. The result therefore still qualifies as an exploratory study in sprinkler activation during smouldering fires.

The average time post transition to sprinkler activation was 0.88 minutes (53 seconds). When the ceiling thermocouple data was analysed in Burns 1, 2, 4 and 6 it was noted that the temperature at the ceiling did not reach 71°C, the rated temperature for the installed residential sprinklers. Burn 4 may have resulted in sprinkler activation due to flaming transition; however, the fire was extinguished prior to growth.

It is important to consider that the sprinklers that did activate did so at a recorded temperature higher than what the sprinkler was rated to. In some instances this may be due to the sprinkler head not being positioned exactly next to the thermocouple. As no thermocouple was placed directly next to the sprinkler head, temperatures may be inaccurate. Furthermore, without the presence of thermocouples across the ceiling to determine the directional movement of heat, it is impossible to know if the heat rose and spread directly towards the position of the sprinkler, or away from it.

As flame growth is not a linear function, heat release from the fire could have spiked in momentary hits, rather than due to sustained levels of increase. If the ceiling thermocouple recorded at the moment of a momentary spike, the temperature could have been recorded as higher than was actually sustained at that time.

The temperatures at the ceiling at the time of sprinkler activation are within 5 seconds of activation. As thermocouple data was collected at 5-6 second intervals, the exact temperature at the exact moment of sprinkler activation is not known in all instances, so temperatures (and therefore the average temperature) may be inaccurate by up to 4-5 seconds, and therefore may be inaccurate potentially upwards of 10°C.

As there were only three accounts of sprinkler activation in the smoulder to flaming fire transition scenarios there are too few data points to determine if this is a reliable range in temperature for activation. Regardless of discrepancies in time and temperature of activation, the three sprinklers activated well within tenability to life conditions in the room of fire origin, which may otherwise have been lost due to the flaming fire transition.

The preliminary conclusion that can be drawn from this information is that although sprinkler systems do not put out smouldering fires, they do appear to provide substantial protection for incapacitated occupants in the instance of a transition from a smouldering to a flaming fire, and they do appear to both suppress and contain the flaming fire.

More research needs to be done in this specific area to draw a definitive conclusion, though the data achieved in this study provides enough information to draw reasonable early conclusions.

With regard to the potential of sprinkler systems cooling hot toxic fire gases and pushing them down onto an occupant, at this stage not enough data exists to conclusively compare the gas spikes in a transition fire from smouldering to flaming, against the same with sprinkler activation. From this exploratory study it does appear that the spike is caused by the transition of the fire, rather than by any potential push down effects of an operating sprinkler.

What was noted in Burn 3, a smouldering lounge fire that transitioned into a flaming fire with no residential sprinkler system present, was that there was a significant spike in toxic gases over 1 minute post fire extinguishment, presumably due to the heated gases cooling and settling. In the instance of Burn 3 the fire developed to a point whereby the environmental conditions were untenable to life. Based on ceiling temperatures it is likely that a sprinkler would have activated far prior to these conditions being met. It is therefore impossible to draw a direct conclusion between high concentrations of toxic gases settling on an occupant with a sprinkler push down effect.

Based on these test fires where the toxic gases were not near a level that could cause death to an incapacitated occupant, the activation of a sprinkler system to quickly contain a flaming fire, that could cause death based on the data acquired, appears to outweigh the possible risk of toxic gas push down. More data is needed before conclusions can be drafn in this area.

Further testing needs to be carried out with flaming fires, both equipped and not equipped with sprinkler systems in order to gain a more substantial set of data to prove or disprove this theory.

No conclusion can be drawn from the flaming fires as there were only two. What can be considered is that there is the potential that a sprinkler system may have retained tenability for longer in Burn 5 had it been present, as it did in Burn 10. This is also based on consideration of the time to activation of sprinklers in transitionary flaming fires. However, as the two initially flaming fire burns contained significant levels of variability within it is impossible to draw definitive conclusions.

It was noted that smoke alarms activated more readily and more quickly across the manufactured residence in flaming burns than in smouldering burns, yet not necessarily within tenability limits. There also still remained a level of non-activation in flaming fires.

3.3 Smoke Alarm Comparison and Analysis

Based around the initial question posed in this research project, whether one type of smoke alarm is faster or more reliable than another across a range of fire scenarios, the following presents a discussion based on the data collected from the ten test burns conducted.

The drawback in analysing the smoke alarm data collected within this study was due to the level of variability between test burns (as is common in real fire test scenarios). Also, there was a limit of 8 smouldering fires and 2 flaming fires. Within those 8 and 2 fires, there was the variance of the presence and lack of sprinklers.

Furthermore, some smouldering fires transitioned to flaming, some did not. In the flaming fires, the ignition sequence varied, therefore resulting in different initial fire sizes. This was complicated by the fact that there were many instances where smoke alarms did not activate. The number of instances of non-activation was too great to consider it could have been simply based around an occasional faulty alarm, especially as each alarm was tested prior to use. Therefore, when alarms failed to activate it considered to have been due to placement, location and type of alarm.

Across the eight smouldering fires, tenability limits were reached in each prior to a transition to flaming, and prior to the activation of any sprinkler systems. As such, these test fires become more comparable, even though they contained variables such as changing the room of origin and varied bedroom door position (open or shut). The two flaming fires contained a greater level of variation, due to different ignition durations, the rapid speed of extinguishment, the fact that only two test burns were undertaken, and the changing presence of a sprinkler system.

Regardless of any of these variables it should be a reasonable expectation, given that NSW legislation only requires a smoke alarm in the hallway, that under any circumstances involving a real home fire situation, hallway alarms will active in a timely fashion with respect to tenability limits and safe egress.

A further reasonable expectation should be that the type of alarm present (photoelectric, ionisation or dual photoelectric and ionisation) should not influence the level of notification given, as no specific type of alarm is given preference in the legislation.

This study serves as an exploratory look into smoke alarm activation based on type of alarm, position within the room, position within the residence (room of origin or hallway) and with regard to tenability and safe egress.

3.3.1 Smoke Alarm Activation Times and Percentages

When considering the activation statistics of smoke alarms, it is easier to compare times when measured across a table. In the following two tables (24 and 25), the first focusing on the room of origin, the second on the hall, DNA stands for did not activate and the blue highlighted squares indicate the alarm within each cluster that was first to alarm.

The ceiling SA1 alarms were considering one cluster, the wall SA2 alarms another cluster, the dead space SA3 alarms the third cluster. All times are given in minutes.

Table 24: Smoke Alarm Activation Results, Room of Origin

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	Burn 1	Bed 1	17.35	DNA	15.58	11.50	DNA	13.10	14.65	DNA	12.17
Smoulder	Burn 2	Bed 2	DNA	DNA	20.45	27.57	DNA	14.33	26.47	DNA	15.42
Smoulder	Burn 3	Lounge	32.08	DNA	26.50	20.30	DNA	14.87	32.03	38.55	31.05
Smoulder	Burn 4	Bed 2	12.93	65.17	11.57	14.33	64.42	12.45	12.32	12.07	11.07
Smoulder	Burn 6	Bed 1	7.55	6.67	5.78	7.35	7.75	5.95	4.48	6.23	4.53
Smoulder	Burn7	Bed 1	14.02	54.78	55.37	15.98	54.25	15.98	4.07	53.47	2.55
Smoulder	Burn 8	Lounge	33.52	42.62	38.70	19.50	39.28	9.98	40.88	42.23	38.18
Smoulder	Burn 9	Bed 2	7.85	74.10	7.85	6.32	69.87	6.78	7.85	68.25	7.85
Flaming	Burn 10	Bed 1	0.87	0.87	0.87	0.87	0.87	0.87	DNA	DNA	DNA
Flaming	Burn 5	Bed 2	0.17	0.18	0.28	0.68	0.68	0.68	0.68	0.68	0.68

DNA = Did Not Activate

Table 25: Smoke Alarm Activation Results, Hall

Ignition	Burn #	ROO	Hall								
			SA1 P	SA1 I	SA1 D	SA2 P	SA2 I	SA2 D	SA3 P	SA3 I	SA3 D
Smoulder	Burn 1	Bed 1	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA
Smoulder	Burn 2	Bed 2	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA
Smoulder	Burn 3	Lounge	22.40	DNA	22.28	19.33	39.67	14.87	16.63	DNA	14.92
Smoulder	Burn 4	Bed 2	48.68	66.07	49.07	48.68	66.07	48.68	16.00	66.17	15.10
Smoulder	Burn 6	Bed 1	DNA	DNA	DNA	DNA	DNA	13.03	12.47	DNA	12.30

Smoulder	Burn7	Bed 1	49.87	55.37	43.17	51.27	55.37	22.45	15.68	54.95	14.17
Smoulder	Burn 8	Lounge	26.72	40.12	DNA	21.97	40.12	19.97	24.80	42.10	24.73
Smoulder	Burn 9	Bed 2	55.85	74.33	15.05	56.08	72.68	52.50	12.90	72.35	12.20
Flaming	Burn 10	Bed 1	DNA	DNA	DNA	DNA	DNA	DNA	0.68	0.68	0.68
Flaming	Burn 5	Bed 2	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68

DNA = Did Not Activate

As can be noted across both tables, the alarms first to activate within the clusters were predominantly photoelectric and dual alarms. Although this information in itself is severely lacking with regard to a safety message, as the time to alarm is less important than the time between alarm activation and tenability limits being reached (including providing enough time for safe egress), the analysis is in with line global discussion surrounding type and placement of alarms. The safety message with regard to safe egress will be further discussed in Section 3.3.2, Smoke Alarm Activation Comparative to Tenability and Safe Egress.

Much of the literature, including a 2008 published paper in Fire Technology [63] that measured the relative time activation and performance of 2600 residential smoke alarms examining data points from four real fire scenario research projects, has been dominated by the discussion focusing only on alarm activation (or relative activation). Therefore, prior to overlaying tenability limitations and safe egress times, an analysis surrounding simply alarm activation times based around alarm type, position within the room, and position in the residence will be provided.

When looking purely at percentage activation during the test burns, inclusive of all 10 test fires, results immediately show that there is a discrepancy between room of origin alarms and hallway alarms. Table 26 shows there is a clear increase in the percentages of alarms that activate (regardless of time) in the room of origin when compared with the hallway. When applying a question of achievement across the alarms, whether they activated 90% of the time or more, the results show that 67% of alarms in the room of origin achieved this, compared with 0% of the hall alarms. No ionisation alarms, in the room of origin or hall, achieved an activation success rate of 90% or above.

When considering that smoke alarms are legislated as a primary source of effective notification in the instance of a residential fire, expecting an activation rate of 90% or above has been considered reasonable.

Table 26: % Activation of Room of Origin and Hall Alarms

	SA1 P	SA1 I	SA1 D	SA2 P	SA2 I	SA2 D	SA3 P	SA3 I	SA3 D
% Activation ROO	90%	70%	100%	100%	70%	100%	90%	70%	90%
% Activation Hallway	60%	50%	50%	60%	60%	70%	80%	60%	80%
% Activation ROO 90% or above	Y	N	Y	Y	N	Y	Y	N	Y
% Activation Hallway 90% or above	N	N	N	N	N	N	N	N	N

The fact that no hallway alarms achieved an activation rate of 90% or above across the test fires raises concern, given hall alarms are the only mandated alarms in a residential occupancy in NSW.

A statistical analysis was run comparing type of alarm and location with respect to room of origin or hallway. In undertaking this analysis, only the smouldering fires were included as the variability within the two flaming fires was too large to provide any strength in comparative analysis.

The average activation time for each type of alarm within each cluster in the room of origin was calculated, followed by a determination of the mean activation for each type of alarm regardless of cluster position. The standard deviation was also calculated. The same process was undertaken with the alarms in the hallway. Tables 27 and 28 below show the results of room of origin and hall respectively. The final column gives an indication of the average time to alarm in that room/hall regardless of type of alarm, with the related standard deviation.

Table 27: Smouldering Fires Average Time to Alarm, Alarm Type and Location, Room of Origin

MEAN	P	I	D	
ROO SA1	17.90	48.67	22.73	
ROO SA2	15.36	47.11	11.68	
ROO SA3	17.84	36.80	15.35	
Mean	17.03	44.19	16.59	25.94
SD	1.45	6.45	5.62	14.36

Table 28: Smouldering Fires Average Time to Alarm, Alarm Type and Location, Hall

MEAN	P	I	D	
H SA1	40.70	58.97	32.39	
H SA2	39.47	54.78	28.58	
H SA3	16.41	58.89	15.57	
Mean	32.19	57.55	25.51	38.42
SD	13.68	2.40	8.82	16.79

From these tables it is clear that the ionisation alarms are inferior with regard to average time to activation. The dual alarms produced better results than the photoelectric alarms; however, they were not statistically different. As such, a photoelectric alarm was just as likely as a dual alarm to activate were a further test fire scenario undertaken.

It is also clear from Tables 27 and 28 that the average time to activation within the room of origin was quicker than the average time to activation in the hallway.

When considering type of detector (photoelectric, ionisation, or dual) and placement (SA1 ceiling, SA2 wall, SA3 dead space) between the room of origin and the hallway in the smouldering fires, the following three tables (Tables 29-31) are produced. In all tables, as before, the times are given in minutes.

It appears from the three following tables that there is a clear difference between room of origin and hall with regard to SA1 and SA2 positioned photoelectric and dual alarms. The ionisation alarms, which were noted in Tables 27 and 28 to be the least efficient alarms, show less difference between room of origin and hall.

Furthermore, from Tables 29-31 it is clear that there is a location effect for photoelectric and dual alarms in the hall; alarms in the dead space position SA3 outperform on average those in positions ceiling SA1 and wall ‘SA2. The same cannot be said for the ionisation alarms in the hall. Conversely, in the room of origin the SA3 position produced the best results for the ionisation alarm, yet the same cannot be said for the photoelectric and dual alarms. These results have been affected due to the high incidence of non-activation of alarms, especially in the hall.

Table 29: Photoelectric Alarms, ROO vs Hall, Cluster Placement

	ROO SA1 P	H SA1 P	ROO SA2 P	H SA2 P	ROO SA3 P	H SA3 P
Mean	17.90	40.70	15.36	39.47	17.84	16.41
SD	10.75	15.06	7.10	17.41	13.71	4.45

Table 30: Ionisation Alarms, ROO vs. Hall, Cluster Placement

	ROO SA1 I	H SA1 I	ROO SA2 I	H SA2 I	ROO SA3 I	H SA3 I
Mean	48.67	58.97	47.11	54.78	36.80	58.89
SD	26.25	14.77	24.89	14.93	23.86	13.31

Table 31: Dual Alarms, ROO vs. Hall, Cluster Placement

	ROO SA1 D	H SA1 D	ROO SA2 D	H SA2 D	ROO SA3 D	H SA3 D
Mean	22.73	32.39	11.68	28.58	15.35	15.57
SD	17.00	16.30	3.74	17.42	12.72	4.66

As mentioned previously, when a study is undertaken based purely on alarm activation time and averages, little is determined with regard to a safety message other than the following:

- Overall room of origin alarms activate statistically quicker than hall alarms
- Ionisation alarms are statistically inferior to photoelectric and dual alarms
- Photoelectric and dual alarms are statistically equivalent

When looking at the alarms in the room of origin, and considering which were the first to activate overall, and which were the first of each type, the following tables are produced.

In Tables 33 and 34 the highlighted orange square indicates the first alarm to activate in the test burn, the green highlighted squared indicates the first alarm of that type to activate. In support of conclusions drawn from Tables 29-31, Tables 32 and 33 show that the ionisation alarms activated both more regularly and quickly in the SA3 position, photoelectric and dual alarms activated equivalently in the SA2 and SA3 positions.

Table 32: Fastest Activation by Cluster, Room of Origin

Ignition	Burn #	ROO	SA1 P	SA1 I	SA1 D	SA2 P	SA2 I	SA2 D	SA3 P	SA3 I	SA3 D
Smoulder	Burn 1	Bed 1	17.35	DNA	15.58	11.50	DNA	13.10	14.65	DNA	12.17
Smoulder	Burn 2	Bed 2	DNA	DNA	20.45	27.57	DNA	14.33	26.47	DNA	15.42
Smoulder	Burn 3	Lounge	32.08	DNA	26.50	20.30	DNA	14.87	32.03	38.55	31.05
Smoulder	Burn 4	Bed 2	12.93	65.17	11.57	14.33	64.42	12.45	12.32	12.07	11.07
Smoulder	Burn 6	Bed 1	7.55	6.67	5.78	7.35	7.75	5.95	4.48	6.23	4.53
Smoulder	Burn7	Bed 1	14.02	54.78	55.37	15.98	54.25	15.98	4.07	53.47	2.55
Smoulder	Burn 8	Lounge	33.52	42.62	38.70	19.50	39.28	9.98	40.88	42.23	38.18
Smoulder	Burn 9	Bed 2	7.85	74.10	7.85	6.32	69.87	6.78	7.85	68.25	7.85
Flaming	Burn 10	Bed 1	0.87	0.87	0.87	0.87	0.87	0.87	DNA	DNA	DNA

Flaming	Burn 5	Bed 2	0.17	0.18	0.28	0.68	0.68	0.68	0.68	0.68	0.68

DNA = Did Not Activate

In the hall, overall the SA3 dead space position was found to alarm the quickest and most frequently across the 10 test burns for the dual and photoelectric alarms. The ionisation alarms showed similar results regardless of cluster position.

Table 33: Fastest Activation by Cluster, Hall

Ignition	Burn #	ROO	SA1 P	SA1 I	SA1 D	SA2 P	SA2 I	SA2 D	SA3 P	SA3 I	SA3 D
Smoulder	Burn 1	Bed 1	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA
Smoulder	Burn 2	Bed 2	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA
Smoulder	Burn 3	Lounge	22.40	DNA	22.28	19.33	39.67	14.87	16.63	DNA	14.92
Smoulder	Burn 4	Bed 2	48.68	66.07	49.07	48.68	66.07	48.68	16.00	66.17	15.10
Smoulder	Burn 6	Bed 1	DNA	DNA	DNA	DNA	DNA	13.03	12.47	DNA	12.30
Smoulder	Burn7	Bed 1	49.87	55.37	43.17	51.27	55.37	22.45	15.68	54.95	14.17
Smoulder	Burn 8	Lounge	26.72	40.12	DNA	21.97	40.12	19.97	24.80	42.10	24.73
Smoulder	Burn 9	Bed 2	55.85	74.33	15.05	56.08	72.68	52.50	12.90	72.35	12.20
Flaming	Burn 10	Bed 1	DNA	DNA	DNA	DNA	DNA	DNA	0.68	0.68	0.68
Flaming	Burn 5	Bed 2	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68

DNA = Did Not Activate

3.3.2 Smoke Alarm Activation Comparative to Tenability and Safe Egress

When time to tenability loss and safe egress time requirements are overlaid on smoke alarm activation times, a stronger message with regard to effective notification is determined. Absolute and relative activation times for smoke alarms are only useful indicators when safe egress is already ensured.

As mentioned in Section 3.1 Introduction to Analysis, based off the literature review, the fact that FEC 0.3 irritant impaired escape was met near instantly in all test fire scenarios, and that indirect escape may be required, the required safe egress time (RSET) times of 120s and 135s for safe egress have been overlaid on smoke alarm activation.

Upon analysis it was found that there was no difference in activation of alarms with regard to 120s or 135s, as no alarms activated within that 15s period of time difference. Therefore, all results presented below can be taken as either 120s or 135s safe egress success or failure with regard to activation.

To determine success with regard to RSET, the calculation was based off the time at which 0.3 FED or FEC incapacitation was first met, plus 135s to ensure safe egress. Tables 34 and 35 below have labels of “y” and “n” present showing whether or not that alarm in that test burn provided sufficient egress as required prior to tenability limits being reached. Table 34 is for the room of origin, Table 35 is the hall.

Note that the boxes highlighted in green did not activate, yet tenability limits were not reached within the time constraints of the test burn. It is impossible to guess whether those alarms would have activated had the sprinkler not so efficiently extinguished the fire; however, as no activation was recorded those alarms were given an “n” with respect to safely providing egress time.

As previously considered with regard to activation, it was expected that alarms would provide safe egress at a rate of at least a 90%, thereby providing a high confidence factor that smoke alarms, the primary device occupants in residential premises rely on to provide effective notification in the event of a home fire, would work.

Table 34: RSET Overlaid on Smoke Alarms, Room of Origin

			Room of Origin (ROO) 135s ASET								
Ignition	Burn #	ROO	SA1 P	SA1 I	SA1 D	SA2 P	SA2 I	SA2 D	SA3 P	SA3 I	SA3 D
Smoulder	Burn 1	Bed 1	y	n	y	y	n	y	y	n	y
Smoulder	Burn 2	Bed 2	n	n	n	n	n	n	n	n	n
Smoulder	Burn 3	Lounge	n	n	n	n	n	n	n	n	n
Smoulder	Burn 4	Bed 2	y	n	y	y	n	y	y	y	y
Flaming	Burn 5	Bed 2	n	n	n	n	n	n	n	n	n
Smoulder	Burn 6	Bed 1	y	y	y	y	y	y	y	y	y
Smoulder	Burn 7	Bed 1	n	n	n	n	n	n	y	n	y
Smoulder	Burn 8	Lounge	n	n	n	n	n	n	n	n	n
Smoulder	Burn 9	Bed 2	y	n	y	y	n	y	y	n	y
Flaming	Burn 10	Bed 1	y	y	y	y	y	n	y	y	y
Total Percentage RSET Escape			50%	20%	50%	50%	20%	40%	60%	30%	60%

Table 35: RSET Overlaid on Smoke Alarms, Hall

			Hall 135s ASET								
Ignition	Burn #	ROO	SA1 P	SA1 I	SA1 D	SA2 P	SA2 I	SA2 D	SA3 P	SA3 I	SA3 D
Smoulder	Burn 1	Bed 1	n	n	n	n	n	n	n	n	n
Smoulder	Burn 2	Bed 2	n	n	n	n	n	n	n	n	n
Smoulder	Burn 3	Lounge	n	n	n	n	n	n	n	n	n
Smoulder	Burn 4	Bed 2	n	n	n	n	n	n	y	n	y
Flaming	Burn 5	Bed 2	n	n	n	n	n	n	n	n	n
Smoulder	Burn 6	Bed 1	n	n	n	n	n	n	n	n	n
Smoulder	Burn 7	Bed 1	n	n	n	n	n	n	n	n	n
Smoulder	Burn 8	Lounge	n	n	n	n	n	n	n	n	n
Smoulder	Burn 9	Bed 2	n	n	y	n	n	n	y	n	y
Flaming	Burn 10	Bed 1	n	n	n	n	n	n	y	y	y
Total Percentage RSET Escape			0%	0%	10%	0%	0%	0%	30%	10%	30%

What is most notable from both of these tables (34 and 35) is that no alarm provided sufficient egress across a range of test scenarios. Focusing on the room of origin, the best-case scenario comes from the activation of the photoelectric or dual alarm, both positioned in the dead space. Across these 10 test burns the best scenario achieved provided for safe egress 60% of the time, with the worst showing only 20% safe egress.

The results across the hall show lower percentages of safe egress provided, with the best case scenario only activating 30% of the time within safe egress limits, the worst five alarms showing a result of 0%.

If flaming fires are removed from this analysis and only smouldering fires are examined the results do not change dramatically. In the hall the best case scenario becomes only 25% activation within tenability and safe egress limits, in the room of origin there is marginal increase to 63% as a best result, still far short of a 90% expected threshold.

If “dead zone” alarms are removed, results from the room or origin reduce to 50% being the best result and 20% worst result. The hall alarms reduce to 10% as the best result (for only a single alarm), and 0% across the others.

Although it is apparent from the methodology that there was a great deal of variation across the 10 test burns: sprinkler systems or no sprinkler systems, varying the room of origin, varying the height of tenability analysis, and changing door position (open or shut) to the room of origin, there should remain a safe assumption that smoke alarms (especially legislated hall alarms) will provide safe egress regardless of the individual fire scenario.

As no two home fires are alike, smoke alarms should be expected to function effectively across a range of scenarios; however, the results show that is not the reality of the situation.

4. Conclusion

The major purpose of this study was to consider smoke alarm activation within the range of issues facing residential occupancies with respect to effective notification and safe egress in the event of a home fire. Due to the wide variety of results and conclusions drawn internationally surrounding smoke alarms and safety, FIRU ran a series of tests to assist in the determination of appropriate safety messages for FRNSW.

Although the area of research is too broad to draw definitive conclusions based on a single test study, this research project has provided a strong exploratory look into the effective notification that a range of smoke alarms provide across a range of home fire scenarios, as well as considering the safety of residential sprinkler systems.

Given the level of variability that needed to be considered it is too early to draw final conclusions; however, enough data was collected and analysed for preliminary conclusions and consideration on where further study is required. Furthermore, much of the data and produced results were found to be in line with the findings from other studies.

It was determined that, across the range of burns and placement locations, ionisation alarms were significantly inferior to their competitors. Photoelectric and dual photoelectric/ionisation alarms provide a statistically greater incidence of safe egress, but fell short of the arbitrarily applied yet reasonable expectation of 90% activation in the home fire scenarios tested.

Given the smoke alarm remains the primary device used within residential occupancies for early notification in the case of a fire, it is reasonable to expect that the alarm will provide at least a 90% success rate with regard to activation within safe egress limits. The results from this study show that even the alarm types and positions performing with a higher level of reliability were poor with regard to providing the notification required for an occupant to exit the residence safely.

This finding is curious when considered in line with the recently published research report by Xiong, Bruck and Ball [64], which analysed the conditions surrounding 177 single fatalities and 183 survivors from accidental fires. The research found that smoke alarms operated at similar rates in survived and fatal fires where the occupant was asleep at the time of ignition. A lingering question remained in the report as to why working smoke alarms could not increase the chance of survival. The FRNSW findings that smoke alarms are failing to provide effective notification within tenability limits could provide an answer.

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 a replica home residence, furnished with readily available bulk furniture from a national furniture chain, and under ambient Sydney conditions.

It is important to consider that although standard testing environments are vital in the development of a testing standard for smoke alarms, real home fires don’t exist within tight parameters of a test standard. They exist across the range of temperatures, humidity, air pressures, home designs, furnishings and ignitions. This raises the question as to whether testing smoke alarms in a sterile situation provides the necessary standard for smoke alarm activation in a real fire environment.

Aerosol density measurements were not taken in the FIRU test burns, 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 FIRU burns took into account the high variability of home fires and worked to maintain elements of consistency in the methodology to provide some level of reliability and comparability between test burns.

Out of ten test burns undertaken only a single burn did not reach tenability limits within the confines of the test burn timeframe. That burn, a flaming fire with an installed residential sprinkler, was extinguished quickly by the sprinkler, thereby maintaining tenability conditions.

Of the other nine burns FED 0.3 irritant gas incapacitation was met in every burn prior to the activation of the vast majority of hall alarms. In no burn did hall alarms comprehensively activate in a timely fashion for safe egress. The best performing hall alarms were in the dead space cluster, and those photoelectric and dual alarms only provided a 30% result of safe egress in fire scenarios (the ionisation alarm was 10%). The next best performing alarm was the dual alarm on the ceiling SA1 position. It provided safe egress 10% of the time.

This result makes sense when compared to the statistics shown in Sections 1.7 (International Statistics: Structure Fires and Fatalities) and Section 1.8 (FRNSW Statistics: Structure Fires and Fatalities), and raises the questions as to whether deaths in bedroom and lounge fires are likely due to incapacitation during a smouldering fire, prior to transition.

The FRNSW statistics in Figures 11 and 12 in Section 1.10, FRNSW: Smoke Alarm Presence in Fire Incidents, show 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 Xiong et al [64] research found that of 177 analysed fatal fires, 14.9% ignited in the kitchen, 35.4% in the bedroom, and 34.3% in the lounge. The top risk factors in fatal fires were found to include: psychotropic and sedative drugs intake; discarded cigarette materials; living alone; aged over 70; sleeping; in the room of fire origin at the time of ignition; and finally alcohol intake. Their research found that cigarette and smoking related materials, known causes of smouldering fires, were the leading ignition factor in fatal fires.

These results show there is a serious issue with the requirement that only a hall alarm be positioned to provide safe egress in the event of a home fire. However, the issue goes beyond hall vs. room of origin (ROO). Although the ROO provided safe egress more readily, it fell far short of the expected 90% result. The best performing alarms, again, were the dead zone SA3 cluster, with the photoelectric and dual reaching 60%. Of the alarms positioned as per the BCA and AS1670, the highest results came from the SA1 P, SA1 D and SA2 P alarms, which only provided safe egress 50% of the time.

The results showing the SA3 as the best performing alarms also raises the question surrounding best placement of alarms for effective notification. Although there are numerous positions which qualify as dead space, and only a single such position was tested in each room, the increased performance of SA3 does suggest that further analysis should be undertaken when determining appropriate alarm placement. Furthermore, due to the risks of smoke stratification in smouldering fires [9], coupled with the risk of the smoke plume not reaching the ceiling due to limited heat [15], further testing should be undertaken focusing on the ceiling smoke alarm position, SA1.

When comparing the results from these test burns to USA results presented in Section 1.6, Smoke Alarms and Egress, some of the USA results show a slightly better outcome regarding safe egress. It must be considered that these results include interconnected alarms in the bedroom and hall as per their domestic standard, and one study included optional lounge room alarms.

Also, many tests only factored in the alarms in the room of origin. Regardless, USA studies, including the “Full-Scale Residential Smoke Alarm Performance” by NIST, found shortcoming when safe egress time was overlaid on smoke alarm activation.

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.

As mentioned previously in this report, the time to alarm is less important from a life safety perspective when compared to the time between alarm activation and tenability limits being reached. With such poor results across the ten test burns, both in the room of origin and the hall, the primary conclusion that can be drawn is that home smoke alarms are failing the public in their preeminent role of providing effective early warning in the presence of smoke or fire [65].

All of these results are based off the assumption that the sleeping occupant both hears and awakens to the sounding alarm. Research has been undertaken detailing that many sleeping occupants may not awaken to a sounding alarm due to closed doors and/or the volume of ambient noise [50, 53]. There is therefore the possibility, as sleeping has been found to be a major risk factor in fatal fires [64], that these results may show a lower performance if audibility and subsequent awakening is also considered.

For each test burn there were 36 alarms present across the manufactured residence, nine in each room. It was found that alarms in unexpected locations activated prior to hall alarms, including in the second bedroom or the lounge when one bedroom was alight.

Although for the analysis of the test burns only the room of origin and hall were focused on, alarms in unexpected locations sometimes activated prior to tenability limits being reached. This both raises and supports the suggestion that home smoke alarms should be present in each room of a residence (bedrooms, lounge and hall) and that they should be interconnected.

What was noted in the four burns that measured tenability limits at 0.75m was that the time to tenability loss was increased when compared with 1.5m. Furthermore, there was a significant increase in the number of alarms that provided safe egress time for occupants. This supports the message that, in the event of a fire, occupants should “get down low and go, go, go”.

When analysing the results of the sprinkler system, a clear preliminary conclusion can be drawn that occupant safety is significantly increased by their presence. In the test fires that contained a developed flaming fire where no sprinkler system was present, fatal conditions to an incapacitated occupant were met, or projected to be met, as smoke alarms did not provide safe egress. In the relative test fires with a sprinkler system installed, tenability limits were contained at incapacitation, and did not progress towards death.

Although the sprinkler systems did not activate within tenability limits with regard to incapacitation, they ensured that the environment of the incapacitated occupant did not worsen. As such, although not serving as a first line of defence early warning device, as is expected of smoke alarms, they provide a considerable measure with regard to occupant life safety.

5. Recommendations

- Fire services' efforts to protect life and property must be focussed on preventing fires in the first instance
- Standard testing procedures for smoke alarms be required to include gas and heat analysis with regard to tenability
- Smoke alarm testing procedures not only be limited to the confines of a standard, but also include real home fire scenarios
- Smoke alarms be required in hallways, bedrooms and lounges
- Smoke alarms be required to be interconnected
- Dual or photoelectric smoke alarms be required to be positioned throughout a residential occupancy
- 10 year lithium batteries be required
- Positioning of smoke alarms be considered, given the low upward heat flux of smouldering smoke plumes, and the test results of faster activation in the dead zone
- Home fire safety messages with regard to planned fast evacuation be pushed due to short time frames available for safe egress
- Fire messages around "get down low and go, go go" continue to be supported to increase safe egress time
- Greater testing on the safety measures of residential sprinklers be undertaken
- Further testing of smoke alarms in real home fire environments be required, using a repeatable methodology for each test, focusing on specific areas of controversy
- Further gas analysis and tenability loss testing to occur in a single room fire at multiple heights to determine toxic smoke movements, the effects of sprinkler activation, and the movement of toxic smoke post extinguishment of a fire
- Gas analysis be tested both during extinguishment, post extinguishment, during ventilation of a fire environment, and post ventilation to further determine risks to health due to any present toxic smoke
- Testing in which room of fire origin progresses to full room involvement be undertaken to determine effects on remainder of residence regarding tenability limits

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