Practical Assessment of the Dependence of Fire Service Intervention Times on Life Safety

by

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iii Abstract

This research identifies realistic timelines for human survivability during accidental dwelling fires (ADF). It also establishes a time window within which the fire service is likely to affect a rescue of the occupants from ADFs. Through a comparison of these two timelines, the likelihood that the fire service will rescue an occupant before they receive a fatal dose of heat and/or smoke (asphyxiant gases) is established. The dependence of fire service intervention times is also assessed in the context of increasing intervention times resulting from cuts to fire authority budgets.

The results show that an increase in the time taken to affect a rescue will lead to an increase in the number of fatalities and the severity of injuries which occur when the occupants of a dwelling become trapped by (or are otherwise unable to escape from) fire within the property.

Around 80% of all fire deaths and injuries in Great Britain occur in dwellings. This study analyses national and local fire statistics to identify the typical fire situations and common circumstances which lead to fire deaths and injuries. This statistical analysis has been used to inform the carrying out of thirteen large-scale fire experiments. Asphyxiant gas concentrations and compartment temperatures were gathered during these experiments, in order to establish human survival times resulting from the adverse effects of exposure to these. Statistics have also been analysed and a methodology developed to establish fire service intervention times.

Establishing survival times on the basis of an analysis of national statistics constitutes new work within the field of community fire safety. In addition, the author is in a preferential position to establish realistic times for fire service interventions, and there is no evidence that these timelines have previously been developed to this extent or compared to timelines for occupant survival. The findings of this research should be considered by fire authorities as they make important decisions for the development of local fire service resourcing activities in continuing times of austerity.

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vii List of Abbreviations

ADF	Accidental Dwelling Fire
B&B	Bed and Breakfast
BLD	Bedroom, Living and Dining Rooms
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COHb	Carboxyhaemoglobin
DCLG	Department of Communities and Local Government
F&RS	Fire & Rescue Service
FDR	Fire Damage Report
FED	Fractional Effective Dose
FIC	Fractional Irritant Concentration
GB	Great Britain
HBr	Hydrogen Bromide
HCl	Hydrogen Chloride
HCN	Hydrogen Cyanide
HF	Hydrogen Fluoride
HMO	House in Multiple Occupation
IRMP	Integrated Risk Management Program
IRS	Incident Recording System
ISO	International Organization of Standardization
Min	Minutes
NIST	National Institute of Standards and Technology (of America)
NFPA	National Fire Protection Association (of America)
O_2	Oxygen
O_2Hb	Oxyhaemoglobin
PD	Published Document
PPM	Parts Per Million
RMV	Respiratory Minute Volume
ROFO	Room of Fire Origin
RTC	Road Traffic Collision
SFPE	Society of Fire Protection Engineers
UCLAN	University of Central Lancashire
UK	United Kingdom
WMFS	West Midlands Fire Service

viii List of Symbols

C_i	is the average concentration of asphyxiant gas (ppm)
C_t	is the concentration of the species (ppm)
$(C \cdot t)_i$	is the specific exposure dose (ppm·min)
D	is the product exposure dose of a given chemical species (ppm·min)
q	is the radiant heat flux (kw/m^2)
T	is the temperature (°C)
t	is the duration of the exposure (min)
t_{CO}	is the time to compromised tenability for CO (min)
t_{HCN}	is the time to compromised tenability for HCN (min)
t_{Iconv}	is the tenability limit for experiencing pain from convective heat (min)
t_{Irad}	is the tenability limit for experiencing pain from radiative heat (min)
Δt	is the chosen time increment (min)
φ_{CO_2}	is the average concentration of CO_2 (%)
φ_{CO}	is the average concentration of CO (ppm)
φ_{HCN}	is the average concentration of HCN (ppm)
v_{CO_2}	is the frequency factor
X_{FED}	is the fractional effective dose from either heat or asphyxiant gases

Introduction

The author of this thesis (Richard Walker) is employed by WMFS as a Fire Engineer within the Fire Safety Team. Richard has a technical background in his current position, based on the knowledge he gained as a serving firefighter for 8 years and his further academic and vocational learning as a fire safety professional. In his previous employment within the chemical industry, Richard gained an understanding of polymer chemistry both academically and through practical application.

Richard discussed his interest in developing his understanding of the human toxicological effects during domestic fire situations with the Integrated Risk Management Program (IRMP) manager at WMFS. Following this conversation Richard proposed a program of work to further organisational knowledge and develop an evidence based approach to future decision making. He chose to complete this project within the framework of a PhD research programme and received joint support from the Chief Fire Officer and the IRMP manager to do so.

The main aim of this research is to establish the effectiveness of attending fire crews to undertake their duties to help the occupants of a building during a dwelling fire. This will be achieved through the comparison of two timelines. The first timeline will consider human exposure to the effects of heat and smoke in domestic fires and create survival times in these situations. The second timeline will look to establish the time it takes for a fire crew to be mobilised to this type of incident and to have a positive impact on trapped occupants.

The knowledge gained from this research will provide evidence in support of future fire authority decision making in times of austerity, where the grant provided to WMFS from central government is being reduced (currently in the order of 25-30%). This project will focus on the intervention activities carried out by WMFS and will also consider what can be done to prevent fires from starting and to protect people when they do start.

This thesis will identify and review previous publications in this field and will seek to build on these from the perspective of attending firefighting crews. It will also summarise the academically accepted methodologies which will be used to gather and process any evidence gained. A series of experiments will be conducted, with aspects of these experiments being informed by an in-depth statistical analysis which considers data taken from within WMFS and also from data gathered by Department of Communities and Local Government (DCLG) from all national Fire and Rescue Services (F&RSs).

The data gathered during the experimental phase will be used to develop timelines for human survivability in typical domestic fires. This data will then be compared with timelines for F&RS interventions to these fires. This comparison will provide information as to how effective an operational firefighting crew are at rescuing trapped persons and preventing them from becoming fatally exposed to heat and/or asphyxiant gases.

This study supports the findings of other experimental attempts to establish fire survival timelines in domestic fire situations. It also furthers the understanding in this field by developing fire scenarios which are informed by national statistical analyses and through the comparisons between survival and rescue timelines to assess F&RS effectiveness.

0.1 The Challenge for the Fire Service

Over a 4 year period since the spending review in 2010, government funding for each of the 46 F&RSs in England has reduced by between 26-39% [1]. Whilst reductions have been seen by all F&RSs, the metropolitan brigades have seen larger percentage decreases than those serving more rural areas. Of the 6 metropolitan F&RSs, the average funding reduction over this period was 34% and as a result, the number of whole-time firefighters has reduced by 13.5% with retained firefighters reducing by 18.9% nationally [1].

Many F&RSs have adopted new duty systems and resourcing options to minimise the impact that funding reductions has had on their ability to respond to emergency incidents. However, in large cities the closure of fire stations and the reduction in numbers of firefighters has been much publicised. In 2014, London Fire Brigade reduced its number of fire stations and fire engines, each by approximately 10% [2]. Reductions in the numbers of fire crews, fire engines and fire stations has the potential to increase the average response time to an emergency incident [3]. A report issued by the Department for Communities and Local Government showed that average response times to dwelling fires have increased from 6.2 minutes in 2004/05 to 7.7 minutes in 2015/16 [4], see Figure 1.

This represents an average increase of 90 seconds to the incidents where the vast majority of fire injuries and fire fatalities occur. However, it should be recognised that an increase of approximately 30 seconds is attributable to an automated method of recording this data introduced in 2009, which represents an actual increase of about 1 minute over this period. With further reductions in funding expected between 2015 and 2019, further increases in response times are anticipated.

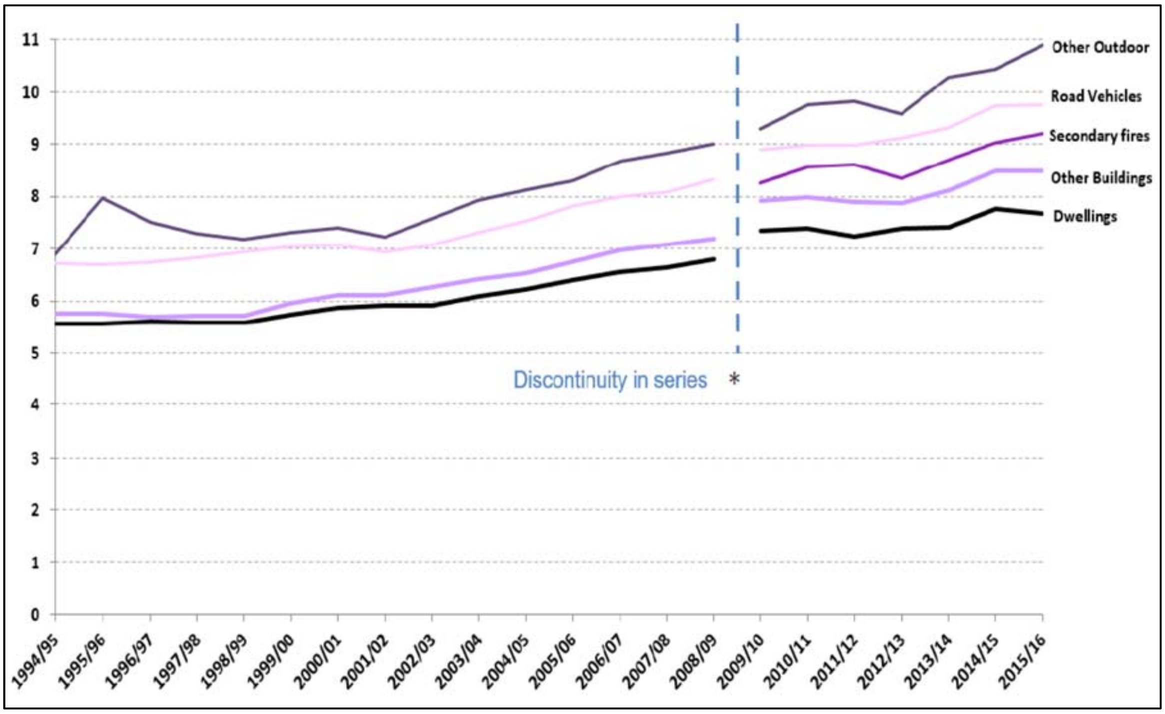


Figure 1 – Average response times by type of fire in England [4]

0.2 Economic Cost of Fire

A national report published in 2011 showed that, in 2008 the economic cost of fires in England alone were £8.3bn and that these were broken down into 3 cost areas [5].

- Anticipation - £3.2bn (cost of fire protection, fire safety training and insurance premiums)
- Consequence - £3.3bn (cost of fatalities and injuries, loss of business and property damage)
- Response - £1.8bn (cost of F&RS resource and capital)

Of the £3.3bn cost as a consequence of fire, £1.4bn of this was directly attributable to the cost of fire deaths and injuries. Whilst F&RSs have a responsibility to protect the members of their communities, any activities to reduce the number of fire deaths and injuries also work in support of the local economy by driving down these costs.

0.3 Preventing Fire Deaths and Injuries

All F&RSs undertake prevention, protection and intervention activities and these are discussed further in Chapter 5. F&RSs conduct these activities because it is recognised that fire deaths and injuries can be prevented as a result of fire service interventions. Better still, fire prevention and fire protection activities will also prevent casualties.

Whilst fire service attendance times have steadily increased since 2004/05, the number of fire deaths and injuries has decreased over the same period. Fire deaths have reduced by 33% and fire injuries by 29% [6]. It is therefore reasonable to suggest that the significant increase in prevention and protection initiatives undertaken by most if not all F&RSs, over this time period, has been the main factor for these decreases.

In addition to those fire deaths and injuries which are preventable by fire service intervention, it is also recognised that some fire deaths are unpreventable by this method. Unfortunately there are some members of our communities whose lifestyle is such that it places them at significant risk from fire. The reality is that, even if these members of our communities lived next door to a fire station, they are unlikely to survive a fire in their homes.

It is not uncommon that these vulnerable persons are some of the most difficult to influence via prevention and protection activities and the only option is for F&RSs to interact with other agencies to identify and help these individuals. This has been one of the biggest challenges to F&RSs in recent times.

0.4 Objectives of this Research

The main objective of this study is to establish the likely impact of an increase in fire service attendance times above current standards and uses data from within the West Midlands to establish these standards. This study will be completed in the context of reductions in funding from central government and also the economic cost of fire.

The study aims to identify the amount of time that people are likely to survive exposure to domestic fire situations, and to compare the point at which fatalities and injuries occur with a reasonable time for a fire service attendance. On the basis of this comparison it should be possible to determine if current intervention times can positively influence the outcome of such an incident.

If it is such that fire deaths and injuries occur well before or well after existing fire service attendance timeframes, then it could be concluded that the time taken to attend an incident bares little influence over the outcome.

If, however, it is demonstrated that deaths and injuries in domestic fires occur at around the same time that a fire service attendance is achieved, then it could be concluded that any future increases in attendance times are likely to cause an increase in the numbers of fire deaths and injuries, with everything else being equal.

0.5 Research Methodology

In order to compare the duration that people can survive a domestic fire with the time of a reasonable fire service attendance, it will be necessary to develop a detailed understanding of these two timelines.

The timeline for survivability will be established by gathering data from a series of large-scale fire experiments conducted within a disused house. In order to gain the best information from these experiments it is important to understand the types of domestic fires which are most likely to cause death or injury to its occupants.

A detailed analysis of statistical data will be undertaken to gain a thorough understanding of those factors, within a domestic fire, which can contribute towards excessive human exposure to heat and smoke. This detailed analysis will cover three main data sources. It will include national fire incident data that is publicly available from government websites.

It will also include a more detailed analysis to understand the combinations of factors which contribute towards the impact on people and this will involve the processing of data that is not publicly available. This data will be requested from the DCLG by the author and will be provided as raw data. It will be processed by the author to gain this more detailed understanding. In addition, the author will also have access to raw data from West Midlands Fire Service and this will also be used for the same purposes.

Once the factors which contribute towards fire deaths and injuries are established by this statistical analysis, they will be used to inform the large-scale experiments. They will influence the internal layout of the premises, the location of the fire and the types of fuel. They will influence the location of the data gathering points and anticipate the actions of occupants on becoming aware of a fire. They will help to establish the benefit of early warning from a domestic fire alarm and the other measures that might help to protect people involved in these incidents.

A series of full-scale fire tests will then be conducted within a disused domestic property. The property will be fitted with various pieces of instrumentation to establish the quantities of heat and the main asphyxiant gases within the fire compartment and elsewhere within the property. This data will be gathered and processed to establish the timeframes after which the occupants of these rooms are likely to receive a fatal exposure or become injured.

Alongside these experiments, data will also be gathered to accurately determine the average fire service attendance time to this type of incident and to consider the window in which the fire service are likely to have a positive impact at a domestic fire.

Finally, the occupant impact timeline and the fire service intervention timeline will be compared. If it can be demonstrated that the occupants of a domestic building, which is on fire, are still alive at the time where the fire service can have a positive impact, then it will be concluded that an increase in fire service attendance times, against current standards, will increase the number of fire deaths and injuries in the UK. This is on the basis that exposure is time dependant.

Chapter 1 - Literature Review

This section aims to give a thorough introduction to all of the recent literature relating to the main areas of this study and to critically review these in its context. This will include an introduction to pyrolysis and combustion and a review of fire toxicity. It sets out a standard approach to assessing fractional effective doses, tenability and toxicological analysis and describes the hazard presented to people from heat and asphyxiant gases.

It further discusses the need to consider data from fire statistics and reviews a number of other large-scale tests which are similar to those planned within this study.

1.1 Pyrolysis, Combustion, Fire and Smoke

Whilst natural fires have occurred on Earth for millions of years, there is evidence to suggest that widespread human use of fire started much more recently, some 50 to 100 thousand years ago [7]. Early humans used fire for cooking, for heating to enable people to live in cooler climates, for protection against attack from wild animals and later for the production of metals etc.

Almost all carbon based polymeric materials, both naturally occurring (e.g. wood) and synthetic materials (e.g. plastics) can undergo pyrolysis and/or combustion. Pyrolysis is the process of simultaneous phase and chemical species change caused by heat. Combustion is a chemical process of oxidation that occurs at a rate fast enough to produce temperature rise and usually light.

A fire in its most simple terms is the chemical reaction between a fuel and oxygen, producing both heat and light energy. As with all irreversible chemical reactions, the reactants (fuel and oxygen) undergo a permanent chemical transformation to yield the products, typical examples of which include carbon dioxide, water and carbon monoxide. The exact types and ratios of products given by these combustion reactions are dependent on the chemical structure of the fuel and the conditions under which the combustion reaction occurs.

In addition to the combustion process, pyrolysis also occurs where heat is applied to combustible materials. The chemical species produced can then either contribute to further combustion or can be released in the gas phase and remain non-combusted. As a result of both pyrolysis and combustion a significant portion of the fuel is converted into an array of chemical species which have a relatively low molecular weight.

These chemical species appear in the gas phase and also as airborne solid and liquid particles. They are buoyant and can be transported within the smoke plume to locations remote from the fire. A non-volatile solid-phase frequently remains, consisting of carbonaceous char and inorganic residue.

In the context of fires within buildings, these chemical reactions can be extremely complex due to both the complexity of the fuels and the chemistry of these combustion reactions. For example, an armchair could consist of three different types of fuel, i.e. a wooden frame with flexible polyurethane foam for padding and a fabric covering such as cotton. As each fuel component pyrolyses it will break down to yield a large number of chemical species [8][9].

This cocktail of chemical species will be carried within the smoke plume as solid, liquid and gas phase particles. A significant number of the chemicals produced during combustion can have an adverse effect upon people exposed to this smoke. As it is accepted that fire smoke is very complex, only a relatively small number of chemical species, which have a significant effect, are generally considered when assessing the toxicity of fire smoke.

1.2 Fire Toxicity

Almost all polymeric fuels contain atoms of carbon and hydrogen and as a result, they are often referred to as hydrocarbon fuels. Many hydrocarbon fuels also contain atoms of oxygen and nitrogen, amongst many others. As a result, the smoke produced during the pyrolysis and combustion processes contains compounds, produced during chemical reaction, which contain these elements.

When people are exposed to fire and smoke they can be adversely affected in one or all of the following three ways and any exposure to heat or smoke can prevent people from safely evacuating from within an affected building [10].

- Heat – exposure to excessive heat can cause burns, where human cells can be irreversibly damaged
- Sensory irritation – where smoke enters the ocular or respiratory tracts, certain chemical species will cause discomfort and pain
- Asphyxiation and hypoxia – exposure to smoke can reduce the natural ability of a human body to breath in and distribute necessary oxygen to all of its organs and cells

This study considers human exposure to heat and focuses on the irritant and asphyxiant effects of exposure to smoke. The rationale for this is detailed in Section 1.5.1.

1.2.1 The Human Respiratory System

The human respiratory system consists of the oral and nasal cavities which act as openings, allowing air to be transferred into and out of the human body. The pharynx, larynx and the trachea collectively make up a pipe which allows and regulates air flow into and out of the lungs. The lungs consist of an array of pipework known as the bronchial tree which enables air to be passed into the alveoli. These small grape like sacks are where gas exchange occurs with oxygen being supplied into the blood and the human waste product of carbon dioxide being removed from it. The diaphragm is a large muscle used to create the necessary pressure difference within the lungs that is required for air to be inhaled and exhaled [11].

1.2.2 The Human Circulatory System

The human circulatory system consists of the heart which acts as a pump for circulating blood to all cells throughout the human body. The arteries and veins act as a network via which oxygenated blood is circulated to all cells and deoxygenated blood returns to the heart. Capillaries are very small blood vessels where gases, nutrients and waste are exchanged with the surrounding cells. Blood is the liquid medium used to transport gases, nutrients and waste material around the body. Gases are primarily transported via their chemical attachment to haemoglobin [12].

1.3 Asphyxiant Effects of Fire Gases

It has been identified that there are four main fire gases [13][14] (used within the asphyxiant-gas model [15]) each of which has the potential to impact upon the occupants of a building who may be exposed to these gases during a fire. It is of significance that a building's structure acts to contain the products of combustion and it is typical for a significant proportion of these harmful fire gases to remain within the building and to increase the extent to which its occupants are exposed. The four gases considered are carbon monoxide (CO), hydrogen cyanide (HCN), carbon dioxide (CO_2) and oxygen (O_2).

The potential for human exposure to these four gases will be determined during the large-scale fire experiments and an assessment of their impact will be made. This analysis will be completed using the fractional effective dose (FED) methodology, as outlined by David Purser and further discussed and developed in a number of studies [16][17][18].

1.3.1 Carbon Monoxide

The stoichiometric combustion reaction of methane with oxygen is given below with the fuel and oxygen being consumed and carbon dioxide and water being produced.

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

CO is a gas that is produced in all hydrocarbon combustion reactions. It is more readily produced in vitiated environments where the availability of O_2, at the location where chemical reaction occurs, is limited as seen below.

$$CH_4 + 1.5O_2 \longrightarrow CO + 2H_2O$$

In Purser's review of the asphyxiant components of fire effluents, he states that there is little doubt that carbon monoxide is the most important asphyxiant agent formed in fires, being one of the main causes of the incapacitation of victims at a fire scene and probably the main ultimate cause of death for fire victims [19].

CO has a toxic effect on humans as a result of its affinity for the 'oxygen sites' on haemoglobin within the blood. The stability of the CO and haemoglobin complex is approximately 250 times greater than that with O_2 and therefore CO occupies the sites needed for O_2 transportation. Additionally, partial conversion of haemoglobin to carboxyhaemoglobin (COHb) causes the O_2 that is bonded as oxyhaemoglobin (O_2Hb) to be more tightly held and it is therefore less available to the body tissues [20].

Thus an individual exposed to CO, loses the ability to efficiently transport O_2 from the lungs to the cells. This action is known as anaemic hypoxia, with hypoxia being an inadequate supply of oxygen to the cell tissues. Anaemic hypoxia specifically refers to hypoxia caused by a reduction in the oxygen carrying capacity of the blood, where both the respiratory and circulatory systems are otherwise functioning as normal.

When the ratio of COHb to O_2Hb approaches 50:50 in the blood, during a fire, this is usually lethal [19]. COHb is stable both in cadavers and also in stored blood samples and can be used, by either a doctor or a pathologist, to give a good indication of the extent to which a victim has been exposed to this asphyxiant gas. In these terms, the ratio of COHb to O_2Hb is given as a percentage COHb. So a measurement of 30% COHb would mean that the haemoglobin in the body was 30% saturated with CO with the remaining 70% being saturated with O_2.

1.3.2 Hydrogen Cyanide

Hydrogen cyanide is also produced in combustion reactions although only from fuels which contain nitrogen. In domestic fires, nitrogen containing fuels typically include upholstered furniture, bedding materials and some clothing. These contain polymers such as polyurethanes, polyamides and polyacrylonitrile as well as natural materials such as wool. HCN has a lethal dose some 25 times smaller than that of CO [20] and where the toxic effects of CO are often slow, HCN intoxication tends to be quite rapid [19].

Increased HCN levels have also been recorded within the blood of fire victims although HCN is not always considered as a significant contributor towards fire fatalities [19]. CO is widely perceived as the most prevalent and dangerous of the combustion products with HCN frequently being overlooked [21]. This is likely to be because HCN has a half-life of only 1 hour within the bloodstream and blood samples are rarely taken within the short time frame required to obtain peak measures of concentration [22]. As a result, the HCN level observed in the blood of fire victims, is often erroneously low.

In support of this argument, it is known that all fires which produce HCN also produce CO with an equivalence between the yields of both [23]. So you would expect to see high concentrations of HCN in the blood of victims where there is also a high concentration of CO, when nitrogenous fuels form part of the combustion reaction.

CO and HCN are both asphyxiant gases. CO suppresses the ability of the human body to transfer O_2 to the living cells, whereas the adverse action of HCN is somewhat different. HCN inhibits the enzyme, cytochrome oxidase, responsible for utilising O_2 within the cells.

This acts to suppress the central nervous system by attacking the mitochondrial cytochrome in the tissues of vital organs, predominantly within the brain and the heart to have a toxic effect and prevent O_2 transfer [17].

1.3.3 Carbon Dioxide

Carbon dioxide is also produced in the combustion process, more prevalently in the earlier stages of the fire where oxygen levels remain high. CO_2 is not recognised as a significant human asphyxiant and does not contribute significantly to toxicity when compared to CO and HCN. However, CO_2 does significantly increase the rate and the depth of breathing in humans [20].

The normal at rest breathing rate of an adult is 12 breaths per minute (min) with the tidal volume of a single breathe typically being in the order of 500 ml. An adult will therefore typically inhale and exhale 6 litres of air every min and this is known as the Respiratory Minute Volume (RMV).

A 2% concentration of CO_2 in air will typically increase the RMV by 50% to 9 litres/min whereas 10% concentrations of CO_2 will increase the RMV by as much as 8-10 times or 48-60 litres/min. As a result of these increased respiratory volumes, the total amount of CO and HCN inhaled is increased at a proportionate level [20].

1.3.4 Oxygen Depletion

The concentrations of CO, HCN and CO_2, within a building increase during a fire, whereas the concentration of O_2 decreases as a result of it being consumed during the combustion process and displaced as the other gases are produced. It is important therefore to recognise that O_2 depletion in a fire can lead to 'low oxygen hypoxia' which can result in motor skill impairment, increased fatigue, loss of consciousness and eventually death [19]. It is generally accepted that the levels of asphyxiant gases will be lethal before O_2 depletion becomes toxicologically significant [24].

1.3.5 Considering the Combined Effects of Fire Gases

The impact on respiration rates at high CO_2 levels has already been discussed however, the question is often posed, 'Are the combined effects of exposure to the asphyxiant gases additive, synergistic or antagonistic?' In order for the effects to be additive, it would be reasonable to expect that if a person had a half of an incapacitating dose of CO and a half of an incapacitating dose of HCN then the combined effects would lead to incapacitation. A synergistic effect is where the combination produces an effect greater than the sum of the individual effects and an antagonistic effect is where the combination has an overall effect which is less than the sum of the individual effects.

The bar chart given in Figure 2 shows the COHb levels found in people who sustained fatal CO poisoning through either fire or non-fire exposures according to Nelson [25]. Non-fire fatalities typically occur through accidental exposure to faulty heating equipment or through deliberate exposure to the fumes from a vehicle exhaust.

The chart shows that, for both fire and non-fire fatalities the highest portion of the population had a percentage COHb in the region of 70-80% at the point where they stopped breathing.

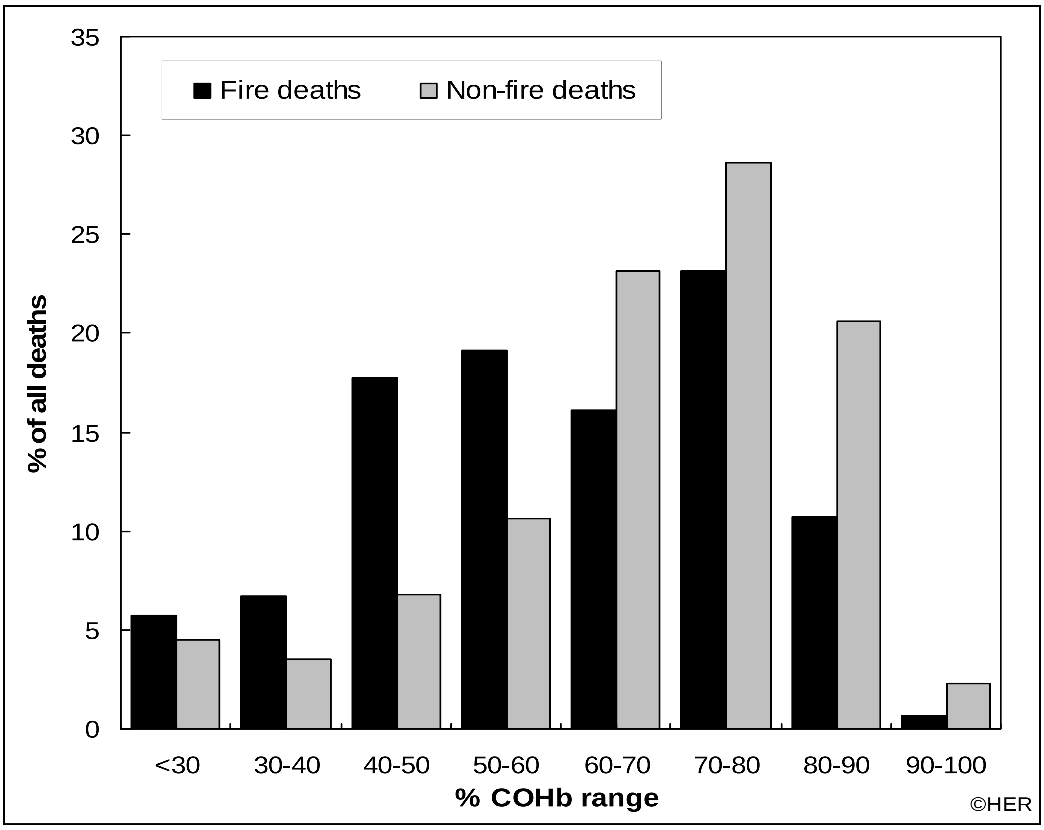


Figure 2 – COHb levels in fire and non-fire deaths [25]

However, there is a subtle difference in the shape of the two curves, in that the majority of non-fire fatalities seem to occur in the region between 60-90% COHb, whereas the majority of fire fatalities occur in the region 40-80% COHb. Clearly the levels of CO found within these people contributed towards their death, but if we consider the typical fuel types for both categories this may help to explain why fire fatalities generally occur with a lower percentage COHb.

Where exposure to fumes from faulty heaters or vehicles leads to a fatality the fuel is generally clean i.e. natural gas, petrol or paraffin and therefore the range of products of combustion can be relatively simple. However, where the fatality occurs as a result of exposure to fire gases, the chemistry can be much more complex, as discussed.

HCN is typically found in domestic fire gases but would not necessarily be expected in non-nitrogenous fuels such as natural gas, petrol or paraffin. It is therefore likely that the inhalation of these other chemical components, alongside the CO, also contributed towards death and a combined effect is observed. Exposure to CO will be a significant factor in determining the survivability of exposure to fire gases but it should also be recognised that other species such as HCN will also contribute significantly.

Both CO and HCN are produced more prevalently as a result of developed flaming combustion [26][27]. These lead to hypoxia in those people exposed to these asphyxiant gases and as such it is assumed that the effects of a combination of these gases are additive. A number of studies have been conducted and the outcome of these suggests that exposure to a combination of these gases does not have a significant synergistic effect and that there is general agreement that their combined effects may be treated as additive [28][29][30].

1.3.6 Human Susceptibility and Variations

Figure 2 also shows that there is quite a significant COHb range resulting in fatality. Both in fire and non-fire situations, some people died as a result of having <30% COHb whereas others were observed to have more than 90% COHb. With this being the case for non-fire situations, where the fuels and burning processes are generally cleaner, it shows that there is a significant variation in human susceptibility to CO exposure.

In practice, few people survive exposure to more than 50% COHb [19], although it is recognised that a number of subgroups are often more susceptible to its exposure. The factors which can make a person more susceptible include alcohol and drugs, age and certain health conditions [19]. There are strong statistical links between fire victims and alcohol or drug use, where both prescription and recreational drugs are included.

An individual's age will also be an important factor, with the very young (ignition likely to be as a result of fire-play [31]) and the elderly (ignition likely to as a result of smoking materials [32]) being the most susceptible subgroups, with a significantly reduced tolerance to asphyxiant gases [33][34]. Particular health conditions can also increase an individual's susceptibility, with asthma sufferers and people with lung conditions such as chronic bronchitis also having a significantly reduced tolerance [19].

1.4 Human Tolerances to Fire Gases

The effects of the significant asphyxiant gases are discussed earlier in Section 1.3 of this thesis. This section continues to summarise the typical concentrations of each of the four gases at which an effect would be likely.

1.4.1 Carbon Monoxide

Inhalation of CO can cause confusion and loss of consciousness and it is the major ultimate cause of human death in fires in Great Britain (GB) [19]. Animal tests conducted by Kaplan demonstrated that exposure to around 7,000ppm (0.7%) of CO for a 5 min period was likely to have an incapacitating effect [35]. Figure 3 shows the typical times to incapacitation for a number of concentrations of CO [36].

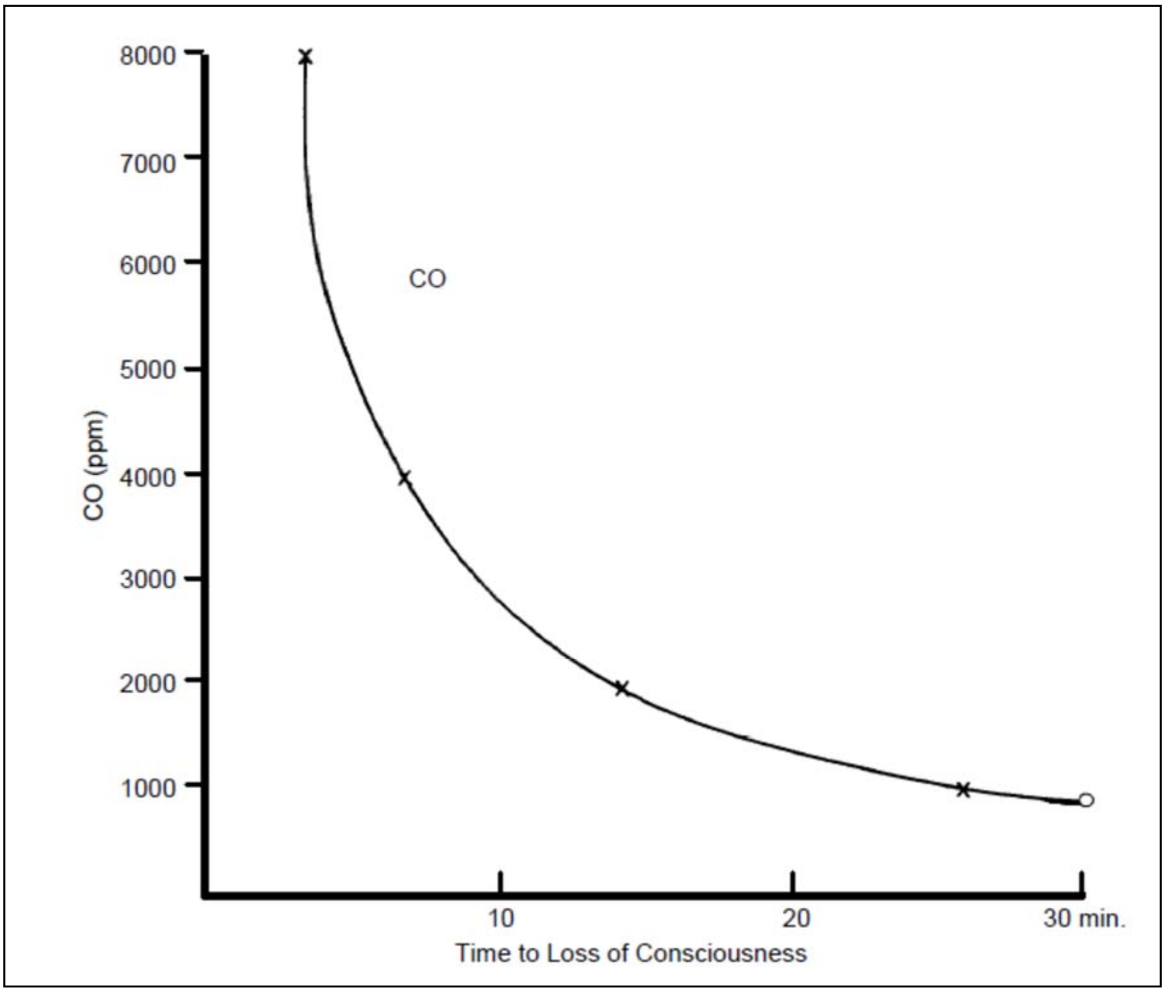


Figure 3 – Time to incapacitation for active monkeys exposed to CO [36]

In general the time-concentration curve may be described as a dose dependency curve (e.g. 8,000 × 4 ≈ 1,000 × 30 ≈ 2,700 × 10).

1.4.2 Hydrogen Cyanide

It is observed that the effect of HCN differs from CO with the transition from hyperventilation to incapacitation occurring much more rapidly, whereas hyperventilation occurs for an extended period, prior to the onset of incapacitation, with CO. Animal tests show the following effect as given in Table 1 [37]: -

HCN Concentration	Toxic Effect
<80 ppm	Minor effects with 60 min exposure, mild background hyperventilation
80-180 ppm	Episode of hyperventilation with subsequent incapacitation within 30min
>180 ppm	Hyperventilation occurs immediately with incapacitation occurring within a few minutes
>300 ppm	Death occurs rapidly

Table 1 – Toxicological effects of HCN on animals [38]

Studies have been conducted and information gathered by Purser [38], to consider the effect of exposure to HCN at different concentrations. A graphical representation of the dose relationship is given in Figure 4 [36]. This representation confirms that exposure in excess of 180 ppm leads to rapid incapacitation. This is equivalent to a level of only 0.02% showing that HCN, which is less prevalent, is 35 times more effective at incapacitating than CO.

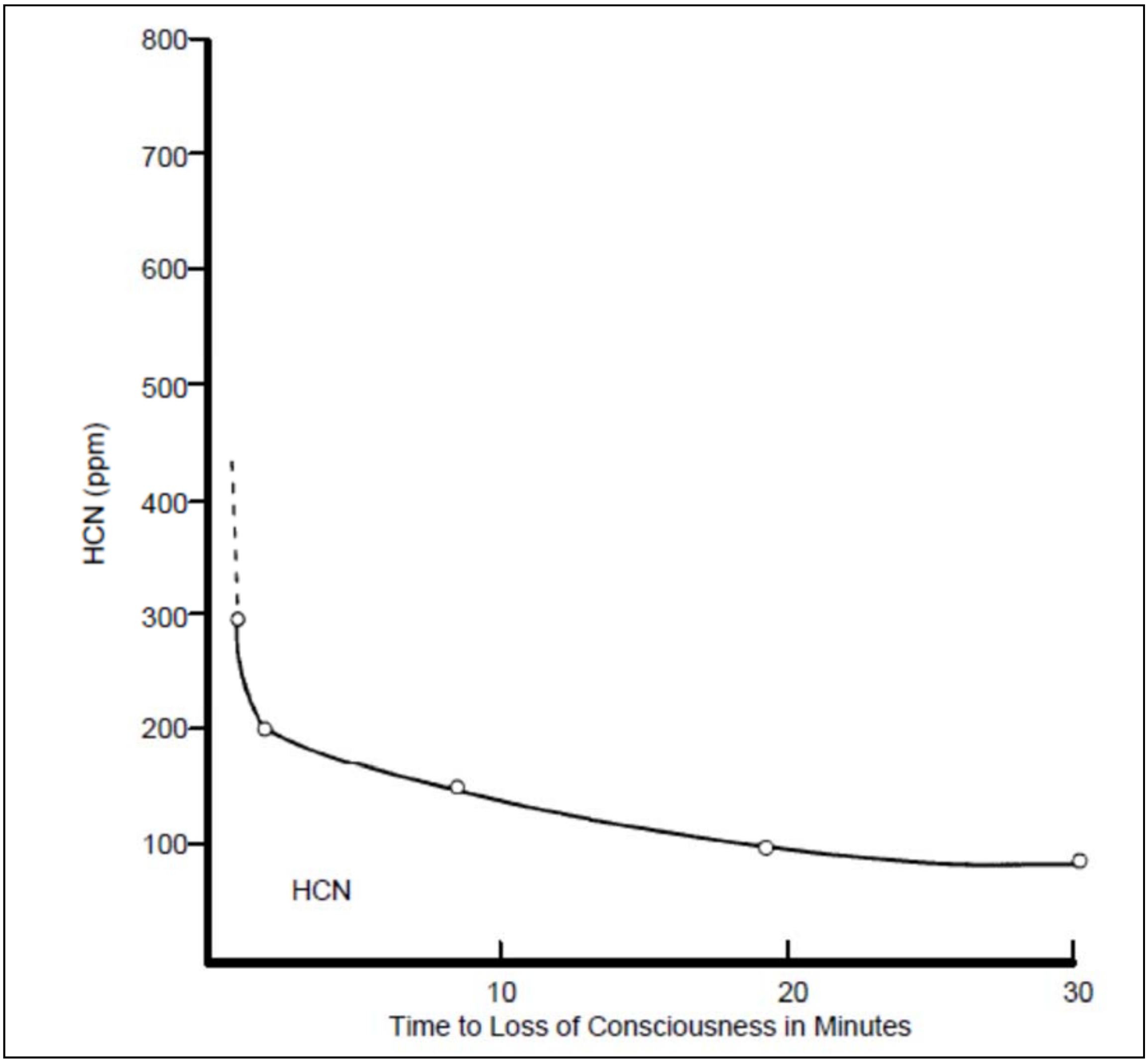


Figure 4 – Time to incapacitation for seated monkeys exposed to HCN [36]

1.4.3 Carbon Dioxide

CO_2 can cause a loss of consciousness at very high concentrations, whilst at lower concentrations it causes a marked increase in the respiratory rate. Table 2 introduces the effects that different concentrations of CO_2 will have on the respiratory rate [38].

CO_2 Concentration	Respiratory Effect
3-5%	Between these concentrations there is an increased degree of respiratory distress with increasing rapid breathing
5-6%	Severely rapid breathing occurs causing huge discomfort and symptoms such as headaches and nausea
7-10%	Severe rapid breathing and symptoms such as dizziness, drowsiness and unconsciousness
10%	At 10% CO_2 a loss of consciousness is expected within 2 min

Table 2 – Respiratory effects of CO_2 on animals [38]

1.4.4 Oxygen Depletion

The concentration of O_2 in normal, breathable air is ≈ 21% by volume. As a victim is exposed to reduced O_2 concentrations, they become susceptible to the effects of hypoxia. Purser has studied these effects and Table 3 is reproduced from these works [38].

O_2 Concentration	Hypoxic Effect
20.9-14.4%	Indifferent phase – only minor effects observed on visual and exercise capability
14.4-11.8%	Compensated phase – slight increase in breathing and heart rates with a reduced ability to perform complex motor skills
11.8-9.6%	Manifest hypoxia – marked increase in breathing and heart rates with loss of critical judgement and muscular control
9.6-7.8%	Critical hypoxia – loss of judgement and comprehension, leading to unconsciousness and eventually death

Table 3 – Hypoxic effects of reduced O_2 concentrations [38]

Typically a fire in an enclosure may have a CO_2 concentration of approximately 5%, CO concentration of 0.25-0.5% and an O_2 concentration approaching 13.5% [39]. CO_2 would trigger hyperventilation at 5% and at 5,000 ppm CO would cause rapid incapacitation. Therefore from a fire effluent toxicity perspective O_2 depletion has not been studied in detail. However, for high altitudes (mountaineering and aviation) O_2 depletion is a serious threat.

Incapacitation times in reduced O_2 environments at altitude is given in Figure 5 [38].

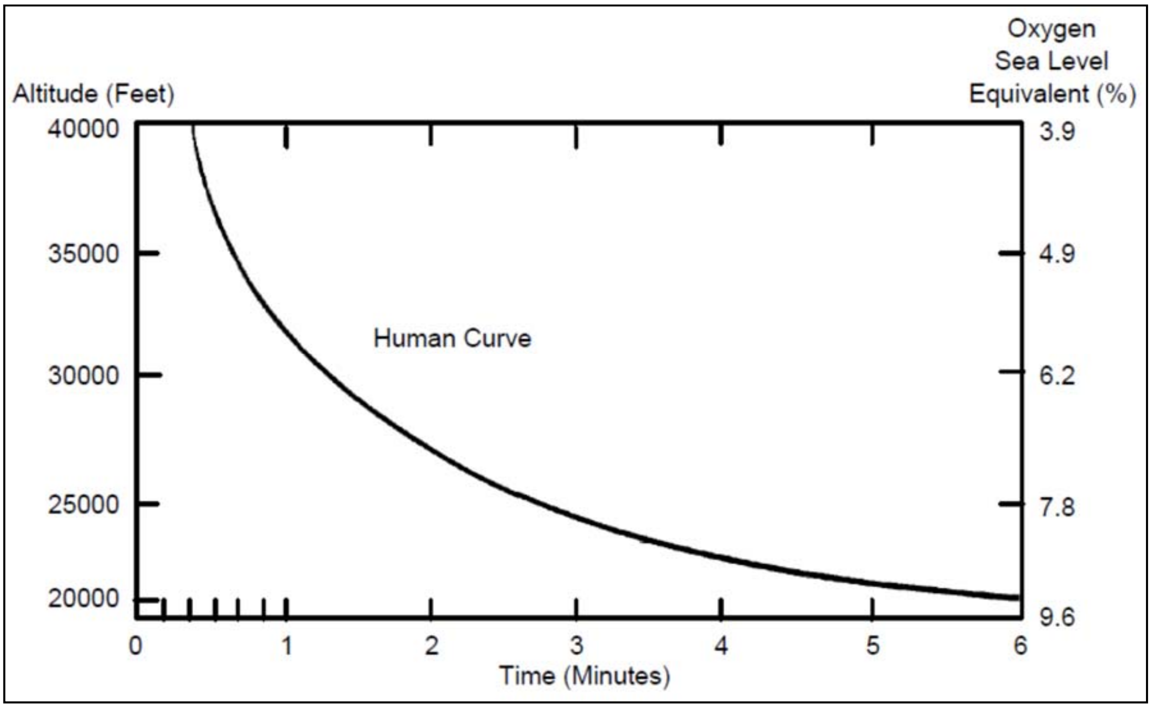


Figure 5 – Time to incapacitation for humans exposed to reduced O_2 levels [38]

1.4.5 Irritant Gases

There are 20 or so identified irritant gases and it is likely that others exist [14]. The 'Irritant' gases include substances such as [40][41]: -

- Hydrogen Halides (HF, HCl, HBr,)
- Acrolein an unsaturated aldehyde (C_3H_4O)
- Nitrogen Dioxide (NO_2)
- Sulphur Dioxide (SO_2)
- Other organo-irritants

These materials cause irritation to the sensory organs and the upper respiratory tract [40]. They inhibit a person’s ability to make their escape, through a range of symptoms including tears, blinking, and severe pain to the eyes, nose and throat, breath-holding and coughing. These gases will not be considered within this analysis as discussed in Section 1.5.1.

In contrast to the asphyxiant gases, the irritant gases are considered to be concentration and not dose dependent [42]. In many cases the irritant gases are considered as secondary, however exposure to these gases can have both behavioural and physiological effects which will impair an individual’s ability to escape and, as a result, cause additional exposure to the toxic gases [43].

1.5 Tenability and Fractional Effective Dose

This section considers the mechanisms by which people are affected when in enclosed spaces during a fire. It outlines the different hazards which prevent safe escape and focuses on the major threats to the occupants of a dwelling when a domestic fire occurs.

1.5.1 Tenability

In buildings which can be occupied by members of the public, tenability is typically considered in the terms of zero exposure to heat and smoke. In public buildings where zero exposure cannot always be avoided, then the design of the building is such that visibility through smoke is maximised, and exposure to convective and radiative heat is minimised. It is widely expected that building design dictates that the adverse effects of a fire on the health and safety of the occupants of public buildings are kept to an absolute minimum.

In domestic properties the old adage still applies ‘An Englishman’s house is his Castle!’ Fire safety legislative requirements placed upon domestic buildings are considerably more relaxed and far less regulated compared with public buildings. The big difference from a human perspective is that the internal layout of a domestic residence is much more familiar. However it is important that there is a recognised methodology for establishing the point when conditions become such that escape is no longer possible and where incapacitation becomes likely [44] and then using this to determine any health effects from exposure [45].

Where fires occur, tenability impairment is considered to arise through a number of mechanisms. These mechanisms are considered within ISO 13571 [15] and the British Standard Published Document PD 7974-6:2004 [42], and they include the following: -

1 Sensory Irritancy – escape can be impaired by the effects of irritant chemical gases in the smoke. They can act upon the eyes and the respiratory tract to cause pain and debilitation.

2 Smoke Obscuration – where the particles contained within the smoke layer obscure human vision to the point where they are unable to navigate their way to an exit.

3 Exposure to Harmful Smoke – extended exposure to the asphyxiant gases contained in smoke will lead to confusion, rapidly followed by incapacitation, loss of consciousness and then death.

4 Exposure to Fire and Heat – clearly this can cause severe pain to any unprotected parts of the human body. It can affect external skin cells, where they are exposed to flames or a heat source through radiative heat transfer and also through skin cells which come into contact with flames or become immersed within a hot smoke layer. Internal skin cells can also be affected through inhalation of hot smoke, particularly in situations where the smoke has a high humidity.

The human impact of each of these hazard mechanisms can be calculated using a Fractional Effective Dose (FED) approach. This approach is discussed further in Section 1.5.2 but put simply, it calculates the amount of harm caused (dose received) within a given time step and then adds these individual doses together until a threshold is reached, at which point an adverse effect is expected to occur. Whilst this approach is not definitive for any given individual, it can identify a time when a person has been exposed to a quantity of heat, smoke or toxic chemical species such that they will have been impacted. The impact is likely to render that person unable to act to help themselves, and they therefore become more vulnerable to further exposure.

By way of an example, if someone is placed in a room where the concentration of carbon monoxide is such that thy inhale 20% of an incapacitating dose over the course of a minute, then they are likely to become incapacitated after a period of 5 minutes, by which time a full dose will be achieved.

The outcome of any exposure will be either a Fractional Irritant Concentration (FIC) or a FED. A FIC will calculate the point at which the concentration of irritant is such that impairment will occur, whereas a FED calculates the point at which an effect occurs with the effect usually being either incapacitation or lethality [38].

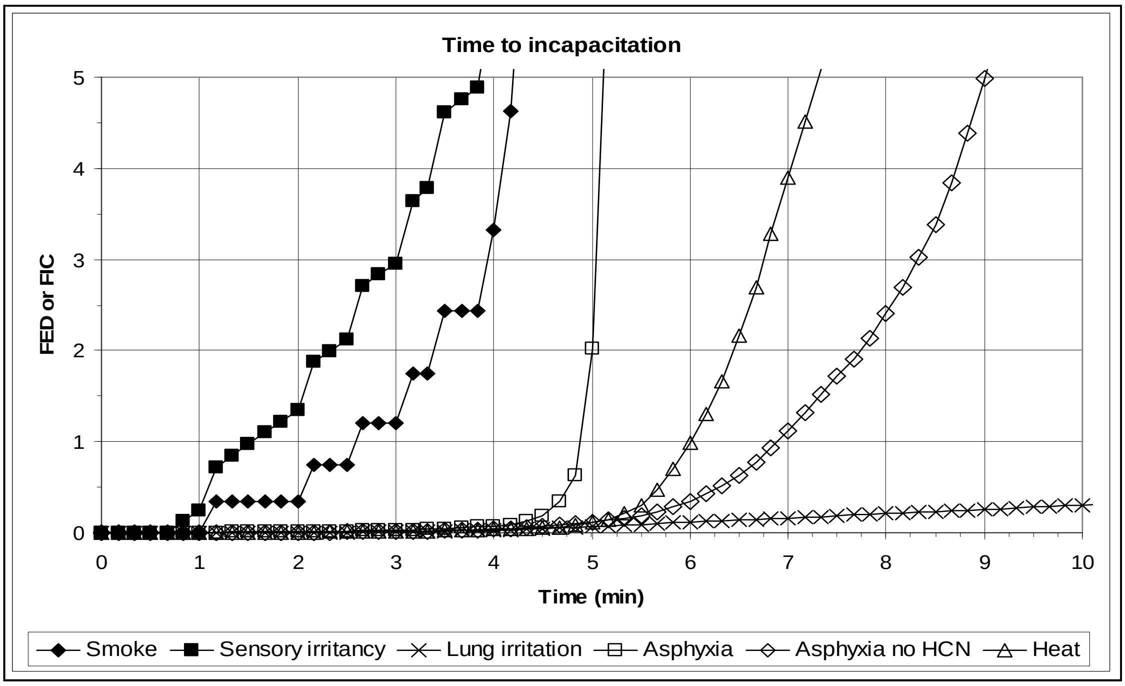


Figure 6 – FED analysis for the occupant of a house during an armchair fire [46]

In Figure 6, a comparison of these hazards is given as an example for the occupant of a domestic house during an armchair fire. The point at which the FIC or the FED equals 1.0, identifies the time at which either irritation or incapacitation occurs.

This figure is discussed further by Purser [46], where it can be seen that after approximately 1.5 min sensory irritancy occurs with smoke obscuration occurring just after 2.5 min. Purser suggests that, whilst smoke obscuration and irritant gases are likely to delay and inhibit escape attempts, they are not likely to be the main cause of collapse or death. He says that the main agents responsible for causing intoxication and loss of consciousness are the asphyxiant gases [23].

F&RS crews are likely to be able to perform a successful rescue on someone who is exposed to irritant gases but the same cannot be said for asphyxiant gas exposure.

Sensory irritation would no doubt be unpleasant and smoke obscuration could increase the time taken to evacuate however, in reality people have an intimate knowledge of the internal layout of their domestic residence. It is entirely conceivable that a person who is blindfolded could, through touch alone, find their way to an exit. It is therefore more likely that people are able to overcome the incapacitating effects of irritant gases over the short escape distances found within a typical domestic property.

Continuing along the timeline in Figure 6, it can be seen that incapacitation due to the asphyxiant gases occurs at around 5 min and impairment resulting from the effects of heat is predicted at approximately 6 min.

1.5.2 Principles of Fractional Effective Dose

FED is a methodology used in the assessment of the hazard of toxic fumes in human exposure to fire smoke. Its basic principle is that 50% of the exposed healthy adult population will become incapacitated at a point where they have received a finite exposure level or an ‘incapacitating dose’ of asphyxiant gases. The point at which an incapacitating dose has been received is therefore calculated with a knowledge of the concentration of asphyxiant gases inhaled against the duration of the exposure [15].

$$\boxed{D = \sum C_t \Delta t}$$

Equation 1 – Human dose calculations

Where: -

D is the product exposure dose of a given chemical species (ppm·min)
C_t is the concentration of the species (ppm)
t is the duration of the exposure (min)

A series of tests was completed on Macaque monkeys in the 1980s, these tests showed a number of findings [47]. Firstly, it showed that these animals were likely to become incapacitated at 30% COHb when active (encouraged to move around in their enclosure) and at 40% when they were at rest. Secondly, it showed that incapacitation occurred when these animals had received a dose of around 27,000 ppm·min CO. This figure was found to be consistent for exposures between 900 - 8,000 ppm equal to 0.09 - 0.80% and is seen to follow Haber's rule. A Macaque monkey has a typical body mass of around 10-15 kg.

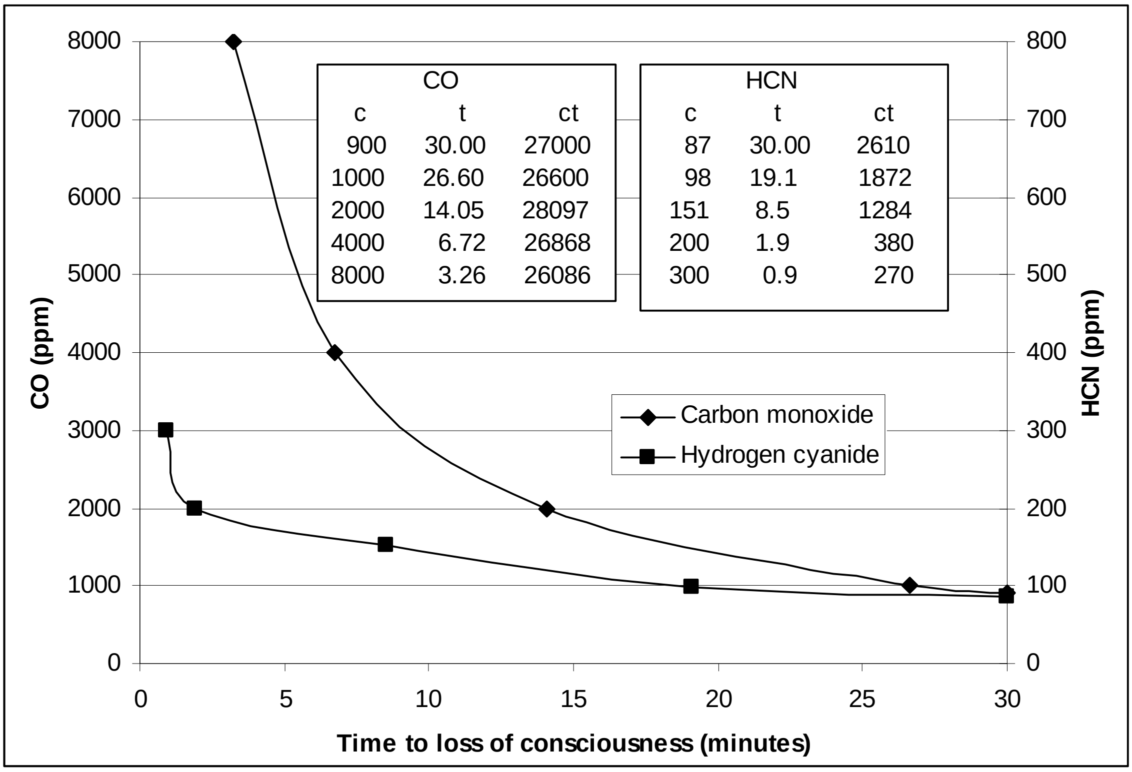
Fritz Haber's rule was developed on the concept that the product of the concentration of a substance (C) and the length of exposure (t) produces a fixed level of effect and ultimately yields a curve similar to the one given in Figure 3 [48].

A second study completed on Baboons showed that the CO concentration required to incapacitate these animals, after a 5 minute exposure, was 6,850 ppm [35]. This represents a product exposure dose of 34,250 ppm·min as calculated in Equation 2. This figure is similar to, but slightly greater than, that for the Macaque monkey and is consistent with the increase in body mass. This figure has now been rounded up to 35,000 ppm·min and adopted as the standard incapacitating dose for humans.

$$\boxed{\begin{array}{l} D = \sum C_t \Delta t \\ D = 6{,}850 \times 5 = 34{,}250\,\mathrm{ppm} \cdot \mathrm{min} \end{array}}$$

Equation 2 – Baboon CO dose calculation

Similar tests were conducted for HCN, however it was established that the product exposure dose for incapacitation is not constant in the same way that it is for CO and does not follow Haber's rule [19]. Instead it is seen that concentrations of around 90 ppm cause incapacitation after a 30 minute exposure, whereas 150 ppm can incapacitate after a couple of minutes. The FED for exposure to HCN, follows an exponential function.



CO		
c	t	ct
900	30.00	27000
1000	26.60	26600
2000	14.05	28097
4000	6.72	26868
8000	3.26	26086

HCN		
c	t	ct
87	30.00	2610
98	19.1	1872
151	8.5	1284
200	1.9	380
300	0.9	270

Figure 7 – Relationship between incapacitation time/concentration for CO and HCN [46]

The data gathered during these two studies is shown in Figure 7 and the difference in the shape of the two curves is clear. For CO, the time to loss of consciousness decreases steadily in proportion to an increase in CO concentrations. In contrast, the time to loss of consciousness with HCN is fairly steady below 150ppm with the times above that level decreasing rapidly. As CO_2 is not recognised as an asphyxiant gas it does not contribute directly towards the calculation for FED, its contributory affects are covered in Section 1.6.1.

1.6 Analysis of the Heat and Asphyxiant Gas Hazard

Human exposure to the life-threatening components of a fire is multi-faceted and it is important at this stage to establish a robust methodology for assessing this risk. ISO 13571 [15] provides such an appropriate methodology. The relevant parts of the standard which are considered as part of this research project will be explored in more detail within this section of the thesis.

The fundamental approach considers time-dependent concentrations of asphyxiant gases and thermal conditions with a view to estimating the time at which occupants will experience an effect. This standard recognises that the guidance can be applied to estimate the time window during which the occupants can be rescued when they are immobilised due to injury, medical condition or entrapment for example [15].

In many texts, incapacitation is considered as an end point however there is some ambiguity surrounding the meaning of this word, for example collapse, unconsciousness and others. ISO 13571 therefore uses the phrase ‘compromised tenability’ to describe an end point as influenced by both physiological and behavioural responses as a result of exposure to fire hazards [15]. Tenability is defined within ISO 13943 [49] as the ability of humans to perform cognitive and motor skill functions at an acceptable level when exposed to a fire environment. Where exposed individuals are able to perform cognitive and motor skills at an acceptable level, the exposure is said to be tenable. Where they cannot, the exposure is said to result in compromised tenability [15].

The time to compromised tenability, within this standard, focusses on four different hazards presented by fire with the hazard being realised first, defining the time to compromised tenability: -

- Asphyxiant fire gases
- Irritant fire gases
- Heat
- Visual obscuration due to smoke

These four different hazards are discussed in Section 1.5.1 and as a result of the assumptions made within this section and the statistical analysis outlined in Section 1.7, it is considered that within domestic fire situations asphyxiant fire gases and heat represent the two greatest hazards.

A main assumption of ISO 13571 is that there are variances in human susceptibility to fire hazards and therefore a logarithmic statistical distribution of these variances is taken. The end point for each calculation represents the point at which 50% of the healthy adult population would experience compromised tenability. Obviously, this means that the remaining 50% would have experienced a level of exposure which were tenable [15].

The standards consider that incapacitating 50% of the occupants is not an acceptable outcome, but based on the log normal distribution and other assumptions, at 0.3×FED approximately 11% would be incapacitated and at 0.1×FED it drops to around 1% being incapacitated.

1.6.1 Asphyxiant Gas Analysis

This analysis considers the asphyxiant fire gases only and within the standard there are two approaches which can be considered. The standard recognises that in cases where the fire effluent composition can be established through gas sampling, the toxic-gas model should be used. Only where this data is unavailable, a more generic approach (mass-loss model) is used whereby an estimation of the concentration of asphyxiant gases is made on the basis of calculations from a known fuel source [15].

The toxic-gas model is used within this analysis and works on the basic principle of taking the exposure dose of each toxicant on a concentration time curve and integrating the area below the curve to establish a dose. When the dose reaches a critical level it is assumed that compromised tenability has occurred.

The toxic-gas model calculates the FED of each asphyxiant gas at each time increment using Equation 3.

$$\boxed{X_{FED} = \sum_{i=1}^{n} \sum_{t_1}^{t_2} \frac{C_i}{(C \cdot t)_i} \Delta t}$$

Equation 3 – Simple model for calculating FED from asphyxiant gases

Where:

C_i is the average concentration of asphyxiant gas (ppm)

Δt is the chosen time increment (min)

$(C{\cdot}t)_i$ is the specific exposure dose (ppm·min)

The dose for compromised tenability of CO was established as 35,000 ppm·min as discussed in Section 1.5.2. The time taken for compromised tenability for CO is given in Equation 4 as the dose divided by the average concentration. The 35,000 ppm·min represents a constant dose at which compromised tenability occurs.

$$\boxed{t_{CO} = \frac{35{,}000}{\varphi_{CO}}}$$

Equation 4 – Time to compromised tenability from CO

Where:

t_{CO} is the time to compromised tenability for CO (min)

φ_{CO} is the average concentration of CO (ppm)

The dose for HCN cannot be represented as a constant as established in Section 1.5.2 and is instead given as an exponential expression which was derived as a best fit for the curve [15]. The time taken for compromised tenability for HCN is given in Equation 5.

$$\boxed{t_{HCN} = 1.2 \times 10^{6} \times \varphi_{HCN}{}^{-2.36}}$$

Equation 5 – Time to compromised tenability from HCN

Where:

t_{HCN} is the time to compromised tenability for HCN (min)

φ_{HCN} is the average concentration of HCN (ppm)

By expanding Equation 3 to consider multiple asphyxiant gases and by including the curves established in Equation 4 and Equation 5, a new formula can be developed to consider the additive effect of CO and HCN. This is given in Equation 6 and is taken from ISO 13571 [15].

$$\boxed{X_{FED} = \sum_{t_1}^{t_2} \frac{\varphi_{CO}}{35{,}000}\Delta t + \sum_{t_1}^{t_2} \frac{\varphi_{HCN}^{2.36}}{1.2\times 10^{6}}\Delta t}$$

Equation 6 – Model for calculating FED with CO and HCN asphyxiant gases

Where:

φ_{CO} is the average concentration of CO (ppm)

φ_{HCN} is the average concentration of HCN (ppm)

Δt is the chosen time increment (min)

It is estimated that the uncertainty given in Equation 6 is ±35% [15].

The only remaining factor to consider is that of hyperventilation bought about by exposure to CO_2, as discussed in Section 1.3.3. As a result of this effect, the formula is further modified to include a factor by which both the concentration of CO and HCN are multiplied. Again this is an exponential function based on an empirical fit to human hyperventilation. Equation 7 accounts for hyperventilation and is accurate to within ±20% [15].

$$\boxed{v_{CO_2} = \exp\left[\frac{\varphi_{CO_2}}{5}\right]}$$

Equation 7 – Model for calculating the hyperventilation factor for CO_2

Where:

v_{CO_2} is the frequency factor

φ_{CO_2} is the average concentration of CO_2 (%)

With the inclusion of the hyperventilation factor, Equation 6 is rewritten as Equation 8: -

$$X_{FED} = \sum_{t_1}^{t_2} \frac{\left(\varphi_{CO} \cdot v_{CO_2}\right)}{35{,}000} \Delta t + \sum_{t_1}^{t_2} \frac{\left(\left(\varphi_{HCN}{}^{2.36}\right) \cdot v_{CO_2}\right)}{1.2 \times 10^{6}} \Delta t$$

Equation 8 – Absolute model for calculating FED for asphyxiant gases

This equation will be adapted into a spreadsheet in order to calculate the FED for each of the chosen scenarios at different locations.

The ISO 13571 model also recognises the impact of O_2 depletion although it does not consider O_2 concentrations above 13% to be of concern [15], this is in accordance with Purser's findings in Table 3.

1.6.2 Heat Exposure Analysis

Of the three types of heat transfer (conduction, convection and radiation), the two main types of heat transfer considered as a hazard to the occupant of a building are convection and radiation. People are exposed to convective heat where they come into contact with the hot smoke layer. They are likely either to be trapped within a compartment and the hot smoke layer descends to the point where people become immersed within it or people have to travel from a level above the fire down through a rising smoke plume.

People are likely to be exposed to radiative heat where they are in the vicinity of flames and are unprotected by a physical barrier such as a wall or a door or they are exposed to heat radiated downwards from within a hot smoke layer.

Exposure to heat can be life threatening in three different ways [15]: -

- Hyperthermia
- Body surface burns
- Respiratory tract burns

For the purposes of considering escape from domestic fires, respiratory tract burns are not considered significant although they have been reported to have an adverse effect on the hospital based recovery of fire victims [50]. Thermal burns to this area of the body, from inhalation of air containing less than 10% by volume of water vapour do not occur in the absence of burns to the skin or the face [50]. When a fire is not suppressed by an automatic sprinkler the water vapour levels are usually low and tenability limits, with regards to skin burns, are normally lower [50].

Tenability limits for both convective and radiated heat exposure are both time dependent. Broadly speaking, convective heat at around 120°C can be tolerated for up to 4 min by unprotected skin and radiant heat of around 2.5 kW/m^2 can be tolerated for around 30 s also on unprotected skin [38].

For convective heat exposure there are two separate calculations which consider tenability for clothed and unclothed skin. For the purposes of this project, the equation for calculating the FED (X_{FED}) for convective heat uses the formula for unclothed skin. This recognises that the head is likely to be unclothed and it also gives a worst case tenability limit.

For unclothed skin the tenability limit is calculated using Equation 9.

$$\boxed{t_{lconv} = (5 \times 10^{7}) T^{-3.4}}$$

Equation 9 – Time to experience pain from convective heat

Where:

t_{lconv} is the tenability limit for experiencing pain from convective heat (min)

T is the temperature (°C)

In order to calculate the FED from convective heat, the reciprocal is taken [15].

$$\boxed{\begin{aligned} X_{FED} &= \sum_{t_1}^{t_2} \left(\frac{1}{t_{lconv}} \right) \Delta t \\ \therefore X_{FED} &= \sum_{t_1}^{t_2} \left(\frac{1}{(5 \times 10^{7}) T^{-3.4}} \right) \Delta t \\ \therefore X_{FED} &= \sum_{t_1}^{t_2} \left(\frac{T^{3.4}}{5 \times 10^{7}} \right) \Delta t \end{aligned}}$$

Equation 10 – Model for FED from convective heat

For radiative heat there are also two calculations, one giving the tenability limit for second degree burns and the other for experiencing pain.

$$\boxed{t_{lrad} = 4.2 \cdot q^{-1.9}}$$

Equation 11 – Time to experience pain from radiative heat

Where:

t_{lrad} is the tenability limit for experiencing pain from radiative heat (min)

q is the radiant heat flux (kw m^{-2})

In order to calculate the FED from radiative heat, again the reciprocal is taken [15].

$$\boxed{\begin{aligned} X_{FED} &= \sum_{t_1}^{t_2}\left(\frac{1}{t_{Irad}}\right)\Delta t \\ \therefore X_{FED} &= \sum_{t_1}^{t_2}\left(\frac{1}{4.2\cdot q^{-1.9}}\right)\Delta t \\ \therefore X_{FED} &= \sum_{t_1}^{t_2}\left(\frac{q^{1.9}}{4.2}\right)\Delta t \end{aligned}}$$

Equation 12 – Model for FED from radiative heat

Bringing together Equation 10 and Equation 12 allows for the calculation of the FED of the additive effects of both convective and radiative heat.

$$\boxed{X_{FED} = \sum_{t_1}^{t_2}\left(\left(\frac{T^{3.4}}{5\times10^{7}}\right)+\left(\frac{q^{1.9}}{4.2}\right)\right)\Delta t}$$

Equation 13 – Model for FED from convective and radiative heat

As with the toxic gas model, the effects of convective and radiative heat are additive. The formula used for FED calculations from heat exposure is given in Equation 14.

$$\boxed{X_{FED} = \sum_{t_1}^{t_2}\left(\frac{T^{3.4}}{5\times10^{7}}\right)\Delta t}$$

Equation 14 – Absolute model for FED from heat exposure

1.6.3 Variances in Human Subpopulations

The methodology given so far in Section 1.6 is based on a dose which effects 50% of healthy adults (animal or human). It is recognised that some human subpopulations are more susceptible to toxic smoke namely children, the elderly and those suffering from chronic conditions such as asthma, for example [38] [51]. Nelson showed that the average COHb levels in the elderly cadavers are lower than in younger adult ones [25]. Purser recognised that there is a distribution in the levels of COHb found in persons who died as a result of exposure to the asphyxiant gas CO [38]. The ISO 13571 model also recognises the impact of O_2 depletion although it does not consider concentrations above 13% to be of concern [38], in accordance with Purser's findings.

Figure 2 shows that victims died with <30% COHb in their blood whereas other victims survived long enough to inhale enough CO to take their blood COHb level in excess of 90%. To allow for variances in susceptibility, to provide a factor of safety and to consider the more vulnerable members of society, PD 7974-6 suggests that a tenability endpoint of 0.3×FED be considered [42]. The same safety factor is also given in ISO 13571 [15]. It should be noted that it is unrealistic to set an absolute safe limit and that some people will suffer compromised tenability and even die as a result of exposure to 0.3×FED or less [52].

Lethality is expected to occur at a point where the values are 2-3 times greater than those for compromised tenability [46]. Two exposure endpoints will be used to estimate the point where lethality occurs, 1.0×FED will be considered as a conservative end point for the vulnerable population (i.e. $0.3\times2.5\approx1.0$) and 2.5×FED will be considered for healthy adults (i.e.$1.0\times2.5\approx2.5$). This methodology and the proposed end points were discussed and agreed as appropriate with D.Purser in a private communication.

1.7 Initial Analysis of Fire Statistics

Data and information is gathered in many fields. When analysed and interpreted, this data can often be used to identify trends and to predict likely future outcomes. In the fire arena, this is very much the case and those who are involved in preventing and responding to fires regularly use fire statistics. In a recent survey of EU member states, into the users of and uses for fire data, responding organisations, such as the F&RSs, were the main user with government departments, insurers, researchers and regulators also using the data [53].

This EU survey also identifies the main use of fire statistics as respondents using data to inform government policy, to raise awareness of trends, to develop strategies to prevent fires and fire deaths and to evaluate F&RS performance.

In the UK, data from fire incidents has been recorded and gathered for many years. Between 1952 and 1973, this data was collated by the Fire Research Station (part of the Buildings Research Establishment), acting as agents for the Home Office, who prepared an annual report of some basic findings [54]. Then in 1980 the Home Office themselves started to report on UK Fire Statistics. Their reports were produced every 5 years and included 10 years of data, e.g. the 1980 report covered the period from 1970-1980 [55]. Traditionally, this data was collated by government officials and a report was produced. These reports focus heavily on the following areas: -

- The incidence of fires – Numbers, geographic location, building types and occupancies, F&RS activities, numbers and methods of rescue, fire size, sources of ignition, causes and fire occurrence times (hours, days, months)
- Human involvement with fires – Number of fatal and non-fatal casualties, nature of injury, casualty details such as age, sex and other sociodemographic groupings, building types and fire and casualty locations within

1.7.1 Background of Fire Statistics

Fire statistics in the UK are based on data received primarily from the Fire and Rescue Services. This data is gathered by each F&RS independently and is then reported to government statistics officers for collation and analysis on an annual basis. Each F&RS will gather data from both its Fire Control centre, where 999 calls are handled and fire appliances are mobilised, and also from Incident Commanders. The Incident Commander is the individual in charge of an incident, who is located at the fire scene, who will need to gather information and report this on their return to the fire station. Further details can then be added as they become available, for example the findings of a pathologist during a post-mortem of a fire victim should also be included.

The statistical reports produced by government officials contain significant amounts of information and analysis. However, they are produced in written form with the raw data not generally being made available for further in-depth analysis. Whilst each F&RS will have internal access to its own raw data, the data sets can be of limited statistical value, for example, a large Metropolitan F&RS may have only 15-20 fire fatalities each year. As a result of these two factors, it is difficult for academic researchers to closely examine the root causes and the factors which contribute to fire fatalities and injuries. The analysis presented within this section of the thesis is based on the government's published data.

1.7.2 Fire Data Report

In 1994 the Fire Data Report (FDR) was introduced. This was initially a paper based report which sought to gather a significant amount of valuable information about primary fires [56]. Primary fires include all fires in buildings, vehicles and outdoor structures or any fire involving casualties, rescues or fires attended by five or more fire appliances [6]. An example of an FDR report is provided in Appendix A.

This method of reporting was used across all of the F&RSs in GB for the next 15 years until a new system was implemented in April 2009. The new system was introduced to address a number of failings raised in an independent review of the Fire Service by Professor Sir George Bain in 2002 (known as the Bain Report 2002) [57]. The new system also recognised the Fire and Rescue Services Act 2004 and its requirement to collect data for special service calls (other incidents attended by a F&RS where there is no fire involved, such as a Road Traffic Collision (RTC)) [58]. The change was also influenced by the introduction of the Integrated Risk Management Program (IRMP) and the introduction of the National Framework [56].

1.7.3 Incident Recording System

In April 2009 the Incident Recording System (IRS) was introduced by the Department for Communities and Local Government (DCLG), with this system currently being used by all F&RSs as of Jan 2017. This new approach replaced FDR with a computer based system which enabled the gathering of more detailed information on incidents attended by an F&RS. This system is capable of extracting information from an incident mobilising system and pre-populating the IRS report.

This should support the Incident Commander to populate the remaining information more efficiently. Table 4 shows the number of questions required to complete an IRS report for a number of different incident types.

	Number of questions asked		Number of incidents		
Incident type	**Total**	**if pre-populated**	**Total per year**	**As % of all incidents**	**Cumulative**
False Alarm	24	4	473,000	39.0%	39.0%
Skip/ refuse fire	29	9	190,000	15.7%	54.6%
Small outdoor fire	29	9	150,000	12.4%	67.0%
Special Service	27	7	100,000	8.2%	75.2%
Primary Car Fire	58	38	84,000	6.9%	82.1%
Primary Fire (dwelling)	75	55	54,000	4.4%	86.6%
Primary Fire with evacuation	85	65	42,000	3.5%	90.0%
RTC	31	11	35,000	2.9%	92.9%
SS -Lift release	27	7	26,000	2.1%	95.1%
Large Outdoor fire	48	28	21,000	1.7%	96.8%
SS - Hazmat	31	11	14,000	1.2%	97.9%
RTC with Casualty and extrication	53	33	12,000	1.0%	98.9%
Primary Fire with casualties	94	74	9,000	0.7%	99.7%
Special Services (with casualties)	46	26	4,000	0.3%	100.0%

Table 4 – Questions required to complete an IRS report [56]

It can be seen that more data is gathered at those incidents which involve casualties. For example a fire in a house which involves a casualty would require 94 questions to be answered, twenty of which could be pre-populated from automatic recording systems within the fire control room and on the fire appliance. This critical data is collected in order to gain a greater understanding of those incidents which impact most upon people. Preventing these types of incidents and responding effectively to them is seen as critical to all F&RSs.

FDR data was originally gathered in calendar years however, since 2000, FDR and now IRS data is gathered in financial years from 1st April to 31st March the following year.

1.7.4 Fatal and Non-fatal Casualties

When considering human survivability in a building fire, statistical data is split into incidents which involved fire related fatalities and incidents where people were injured as a result of being exposed to heat, smoke or both. This section of the thesis explores these interactions and draws upon historical data to identify current trends. It is important to note that this analysis does not include firefighter casualties.

1.7.5 Fatal Casualties

Fire fatalities occur reasonably frequently across GB with some 322 people dying in fire related incidents in the year 2013/14. Recent numbers of fatal casualties are significantly lower than those seen in the 1980s where numbers peaked at around 1,000 people losing their lives to fire every year.

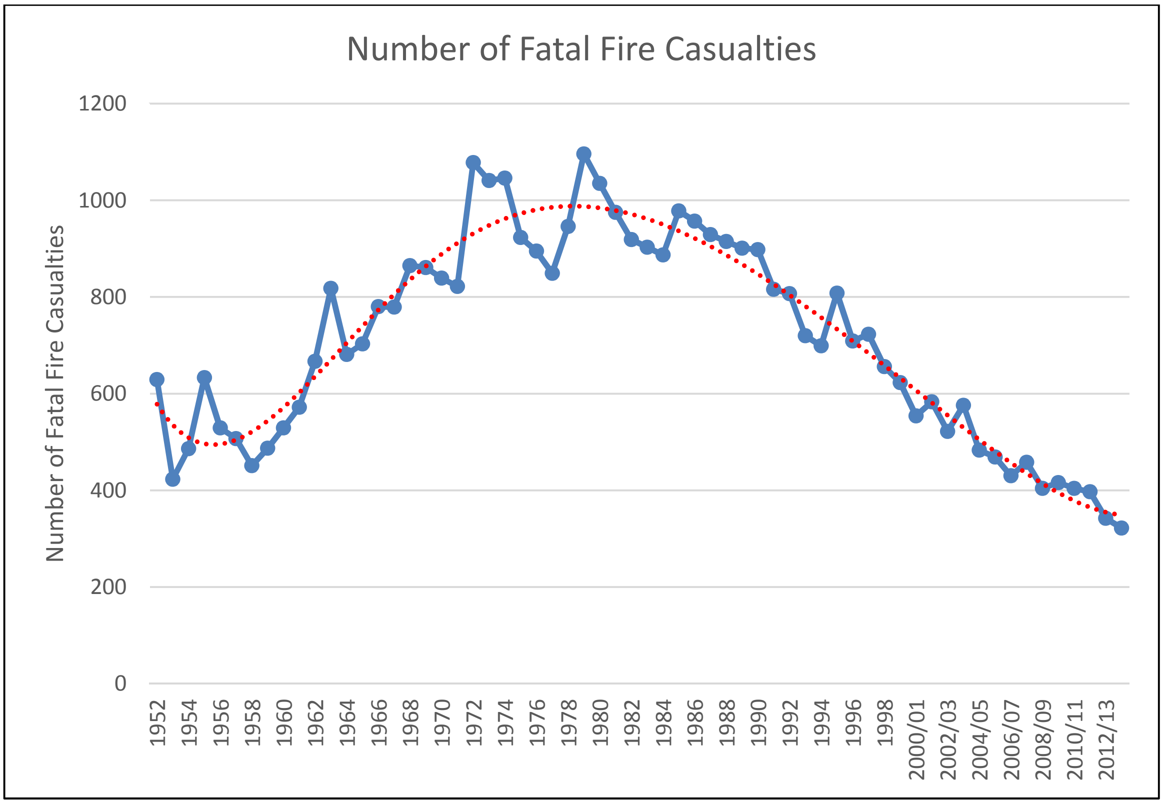


Figure 8 – Fatal casualties from fire 1952-2014

Figure 8 shows the number of fire fatalities each year since 1952. The graph displays actual numbers of fatalities and also shows a red trend line. This trend line illustrates that the number of annual fire fatalities was around 500 people in the early 1950s at which point it rose sharply until the numbers had nearly doubled by around 1980. Since the mid-1980s, the numbers of people dying in fires has dropped steadily such that, in recent years, they are below the 400 mark for the first time since national data was gathered.

The increase in fire fatalities from the 1950s is largely attributed to an upturn in the use of man-made plastics in households. Traditional materials such as wood, cotton, wool and leather gave way to synthetic materials e.g. fabrics and polymeric foams. These man-made materials were not only more ignitable, but when they became involved in fire, released a greater amount of the toxic compounds which adversely affect humans [59].

The decrease in fire fatalities, since its peak in the early 1980s, most likely comes as a result of two factors. Smoke detection became more widely available and more affordable and their use was encouraged by changes to guidance and building regulations. As a result, an increase in smoke alarm ownership from around 8% of households in England and Wales in 1988 to around 78% in 2003 has been seen [6]. Since then, the ownership of a ‘working’ smoke alarm has increased further to 88% in 2012/13 [6].

In addition, the Furniture & Furnishings (Fire) (Safety) Regulations were introduced in 1988 [60]. These regulations were designed to ensure that the flammable components in furniture met stricter regulations in terms of ignitability. Specifically materials should be resistant to ignition sources such as matches and cigarettes. Other factors such as reductions in the use of open flame heating and changes in smoking habits may contribute.

1.7.6 Non-fatal Casualties

In respect of non-fatal fire casualties or 'fire injuries', the trend is slightly different. The number of non-fatal fire casualties was around the 3,000 mark during the mid-1950s and rose steadily until around 1980 at which point a significantly sharper rise started to occur. The number of non-fatal fire casualties peaked at around 18,000 in the late-1990s and has since halved to just above 9,000 in 2013/14 [6].

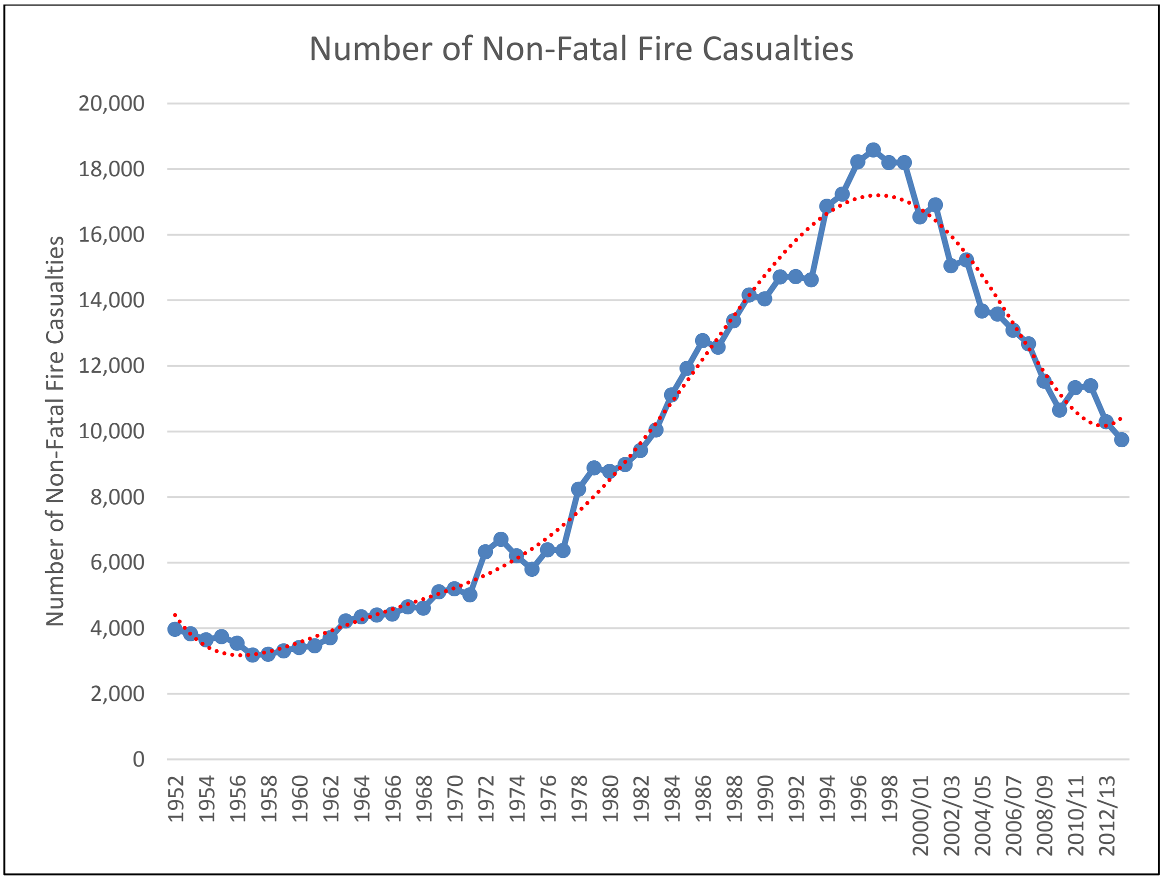


Figure 9 – Non-fatal casualties from fire 1952-2014

Whilst there was a steady rise in the numbers of non-fatal casualties from the mid-1950s, this became somewhat exacerbated by the inclusion of people who received a 'precautionary check-up'. The inclusion of this group within the statistical data set started in 1983 and had not previously been incorporated.

There is no sharp increase from the 1950s as with fatalities, instead there is a delay until the 1970s when an increase is seen. The peak is also later at around 1998 at which point fire fatalities were very much on the decrease. A comparison of the fatal and non-fatal curves is given in Figure 10, note that there are two separate scales on the y-axis.

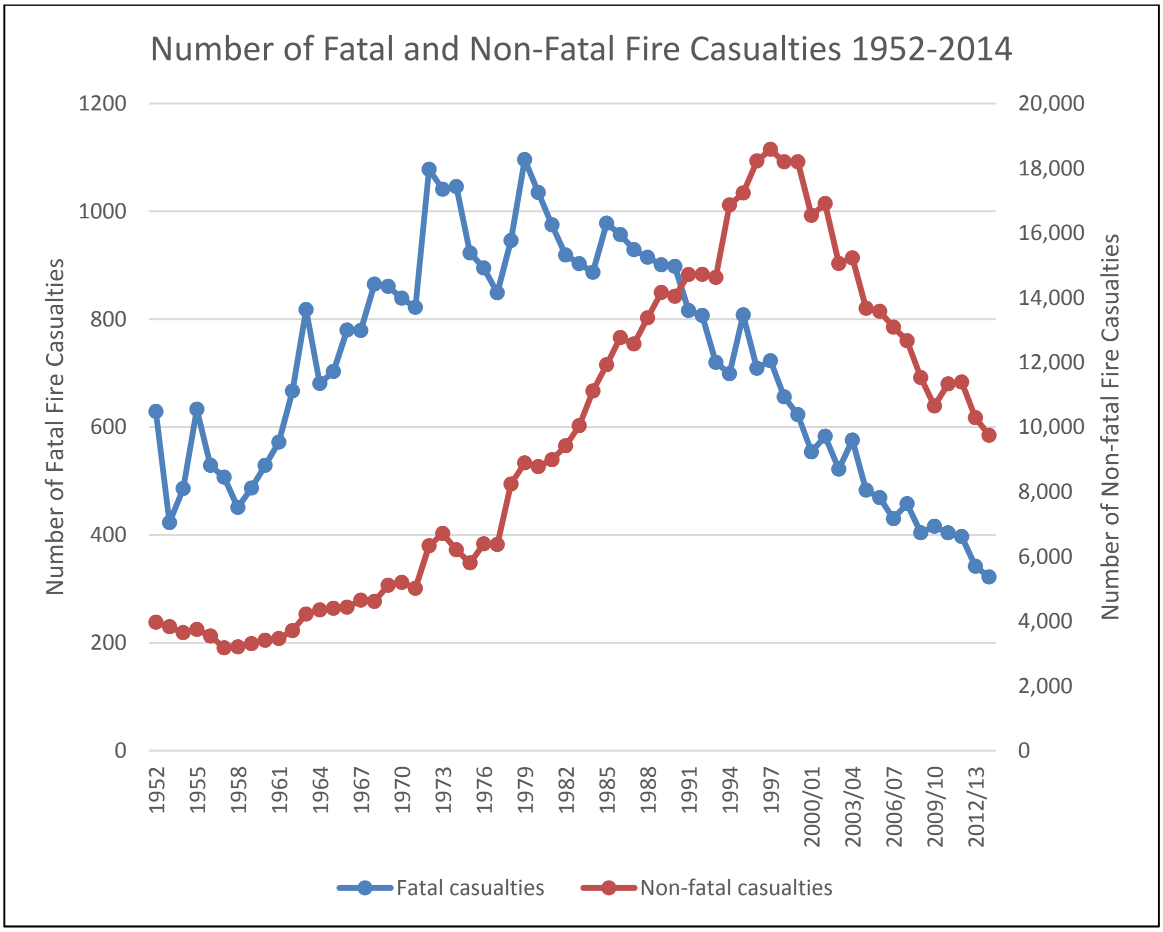


Figure 10 – Fatal and Non-fatal casualty comparison 1952-2014

1.7.7 The Role of the Pathologist

At this point, it is worth understanding the role played by a pathologist, when determining the cause of a fire death. When someone dies and there is evidence to suggest that their death may have been caused by the heat or smoke from a fire it is standard practice for a post-mortem to be conducted. These post-mortems are carried out either by local hospital pathologists or by forensic pathologists as determined by the nature of the fatality.

The role of a pathologist is often limited to establishing if the victim was (i) alive when the fire started and then developed and (ii) if there were any other injuries or circumstances that may have led to the victim dying prior to a fire occurring or preventing their escape.

Funding for post-mortems is restricted and as a result the pathologist is very likely to place more focus on establishing if the fire contributed towards the death rather than specifically looking at the individual effects of either smoke or heat, i.e. the mechanism of the fatality. A pathologist will routinely conduct the toxicological analysis of a victim's blood or organs, looking for drugs (prescription and recreational), alcohol and CO levels. HCN is rarely considered during this process.

In England and Wales, there is a mechanism for investigating sudden, suspicious or unexplained deaths [61]. As a result, the investigation aims to identify three aspects.

- What was the cause of death?
- Was the death a possible homicide?
- Have any public health concerns been identified?

The findings of the pathologist will then be given to a coroner to support their inquest with the aim of providing a verdict that identifies whether the victim was: -

- Lawfully killed
- Unlawfully killed
- Accidental death
- Killed himself/herself
- Open verdict

The strength of a police investigation and the level of suspicion around foul play may also impact upon the extent of the pathological investigation. Where there is a strong suspicion that an unlawful act has been committed, this may lead to a more thorough investigation from a forensic pathologist. This is however costly and as a result many investigations are less comprehensive and carried out by a local authority pathologist.

The author has had a number of conversations with people from within the field of pathology, with the general consensus described herein. An initial post-mortem is almost certain to be conducted by a local authority pathologist unless the police request a forensic investigation. In only a small number of cases, where the cause of death is identified as suspicious, and there is significant interest from the police, will the cadaver be passed to a forensic pathologist for a further and more in-depth post-mortem.

During both types of post-mortem, the primary concern is to establish if the fire contributed towards the fatality or if there was some other natural or unnatural factor involved. Once it has been established that the fire was in some way a contributory factor, the actual mechanism by which the fatality occurred is then of much less significance.

Neither a hospital nor a forensic pathologist is likely to go to any great length to distinguish between a fatality occurring as a result of smoke inhalation and one occurring as a result of exposure to heat. While death causes breathing cessation, burns continue to occur after death. This type of in-depth analysis can be prohibitively costly and unless it is absolutely clear that one or the other does not exist, there is a chance that the cause of death will be given as a combination of exposure to both heat and smoke. As a result, there may be some inaccuracies in respect of the fire statistics that are produced annually by the DCLG.

Whilst there is a desire to establish the cause of death for anyone exposed to fire, there is a question over the validity of the data produced by pathologists as a guideline for developing fire protection systems. Shepherd provides guidance, from qualified pathologists, in an attempt to focus on ways for better protecting people during domestic fires [61].

1.7.8 Initial Statistical Analysis

An initial statistical analysis has been conducted to try to establish the trends that are present in respect of both fatal and non-fatal fire casualties. This data has been extracted from government statistics reports and is based on data provided by the F&RSs. Data has been gathered from Fire Research Station reports from 1952-73 inclusive, Home Office reports from 1980-95 inclusive and annual DCLG reports from 2006 to 2014 inclusive.

This data shows that in the most recently reported year (Apr-13 to Mar-14) there were 322 fatal casualties and 9,748 non-fatal casualties as a result of fire, not including firefighters. This section of the thesis uses data presented by these sources only and does not make any use of raw data. It builds upon the data given previously and identifies both the locations in which fire casualties occur and the nature of any injury sustained for both casualty types.

1.7.9 Fatal Casualties

When fire fatalities occur, two of the important factors that are considered are where the fire occurred and what the cause of death was. Recent fire statistical reports place the location of the fire into one of four categories: -

- Dwellings – residential homes and houses in multiple occupation (HMOs)
- Other Buildings – B&B, halls of residence, offices, shops, factories, public buildings etc.
- Outdoors (Road Vehicles)
- Outdoors (Other) – fields, woodland and derelict vehicles/buildings

Fire location data was not recorded prior to 1970 and before 1981, the two categories of Outdoors (Road Vehicles) and Outdoors (Other) were grouped together as ‘Outdoors’.

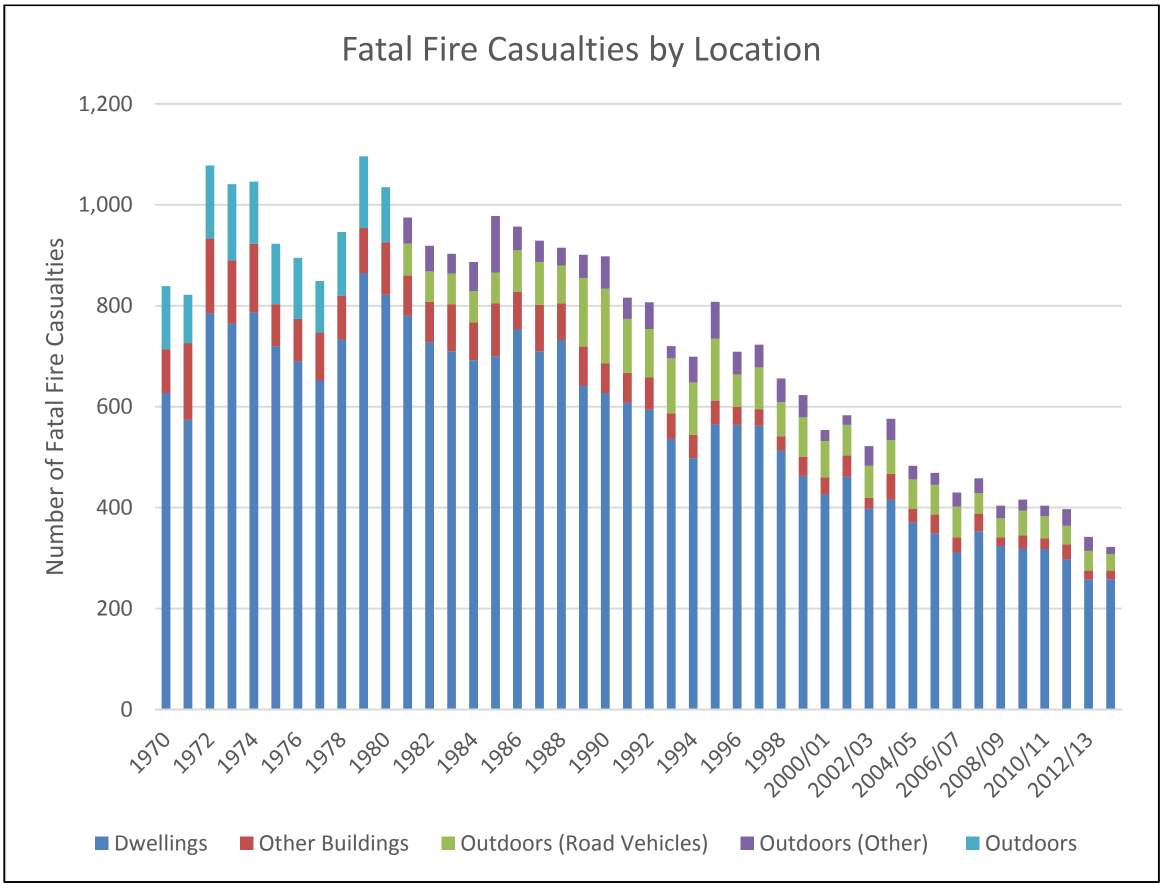


Figure 11 – Fatal casualties by location

Figure 11 shows that the majority of fire fatalities occur in dwellings and account for 77% of deaths over the last ten years. Over the same time period, only 6% of fatalities occurred in other buildings, with 11% in road vehicles and 6% elsewhere outdoors.

The cause of a fire fatality will be approximated by a Fire Officer in the first instance and is usually then confirmed by a pathologist, with the fire statistics being updated where necessary. A fire fatality is categorised as follows: -

- Burns – presumably where there is evidence of severe burns with low levels of COHb, if indeed it is possible to test for COHb levels as a result of the degree of burn damage
- Overcome by gas/smoke – presumably where there are high levels of COHb and little evidence of burns
- Burns and overcome by gas/smoke – presumably where there are severe burns and high levels of COHb and the pathologist considers that both were contributory towards the cause of death
- Other – this causation is often used where there is evidence to suggest that the victim was dead prior to the fire occurring
- Unspecified – where an incident is subject to an ongoing criminal investigation, the coroner may record an unspecified cause and this may not have been subsequently updated

This information should be taken in the context of the role of the pathologist which is discussed in Section 1.7.7. The data for fatal casualties by cause is shown in Figure 12 although no data is presented for 1975 as a result of industrial action taken by F&RSs and in 2009/10 one of the F&RSs failed to provide a completed record to DCLG. Data for these two years is omitted. Figure 12 also identifies the point where fire deaths were reclassified to consider a fatality as a result of a combination of both heat and smoke.

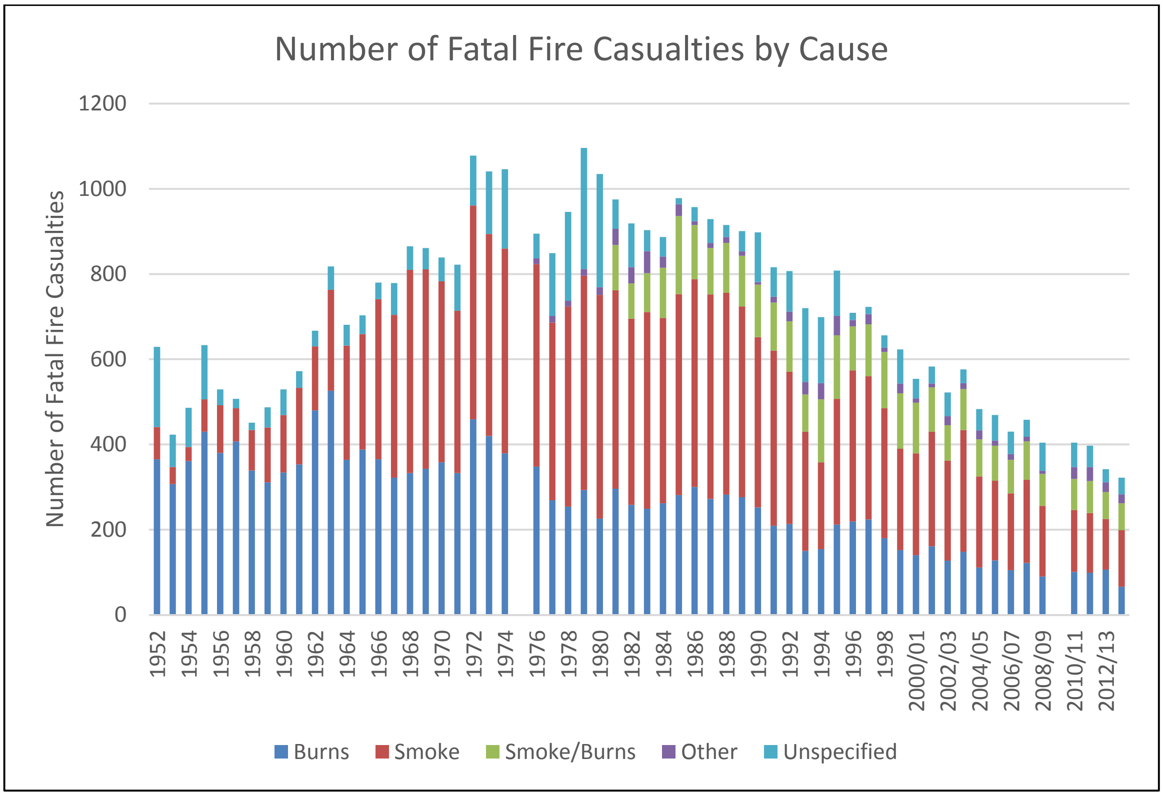


Figure 12 – Fatal casualties by cause

Over the last ten year period of data gathering (omitting 2009/10), it can be seen that smoke inhalation caused 40% of fatal fire casualties with the remainder being burns (25%), a combination of smoke and burns (18%), other (5%) and unspecified (12%). This data is also shown in Figure 13.

If it is assumed that all 'Other' fire fatalities do not necessarily occur as a result of exposure to the fire and that those 'Unspecified' fire fatalities eventually fall proportionately into one of the other three categories, the analysis can be repeated and adapted.

This shows that as many as 48% of fatal fire victims are caused by smoke inhalation alone, 30% are caused by burns and the remaining 22% are either indecipherable between the two or are caused by a combination of the two, see Figure 14.

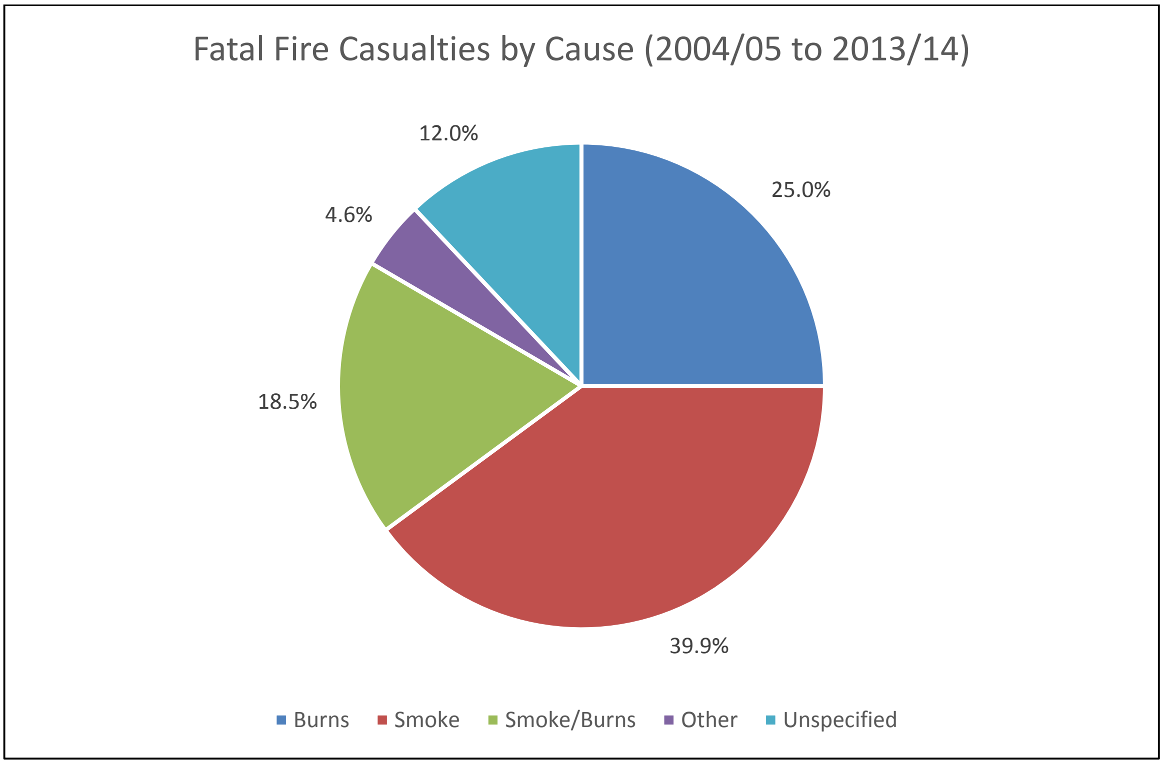


Figure 13 – Fatal casualties by cause (2004/05 to 2013/14)

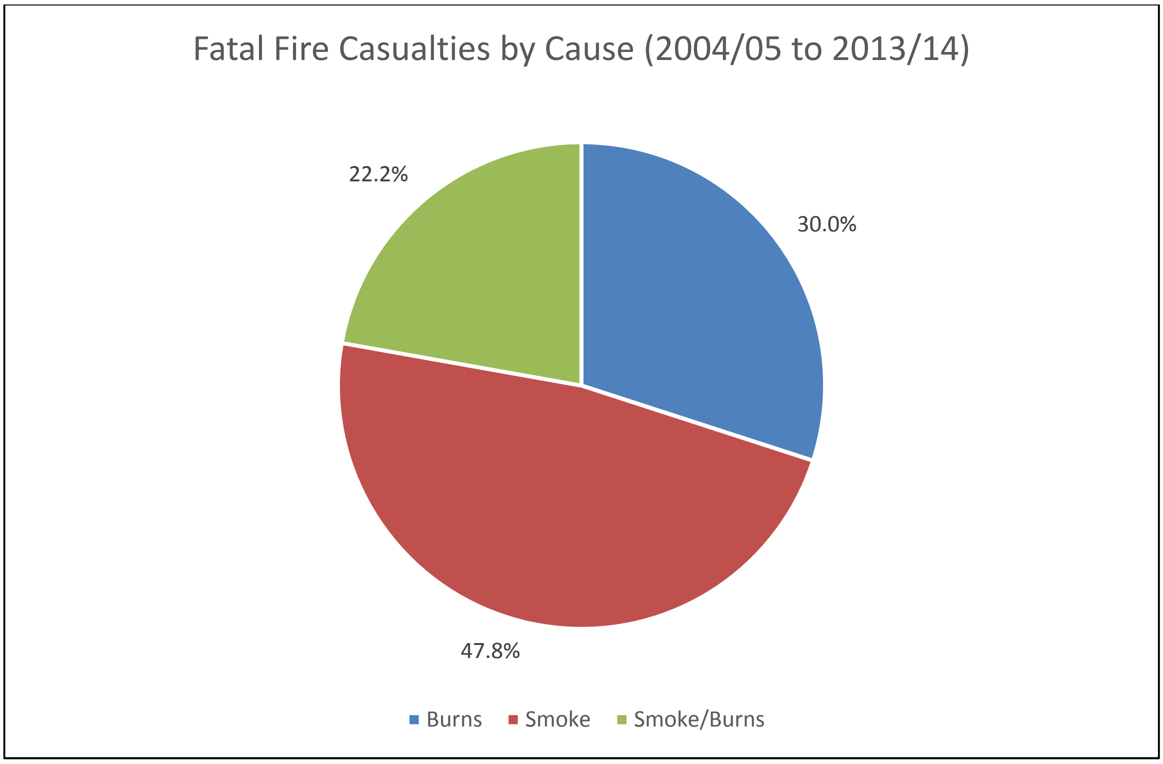


Figure 14 – Fatal casualties by cause adapted (2004/05 to 2013/14)

With the number of fatal fire casualties being reasonably low in statistical terms (generally 500 – 1,000 per annum), there is a potential for significant year-on-year differences. The data has therefore been considered in respect of each grouping as a percentage of the annual total of fatal casualties. This data is given in Figure 15 and shows an initial change (between 1952 and 1980) from injuries being caused by burns towards injuries being caused by smoke.

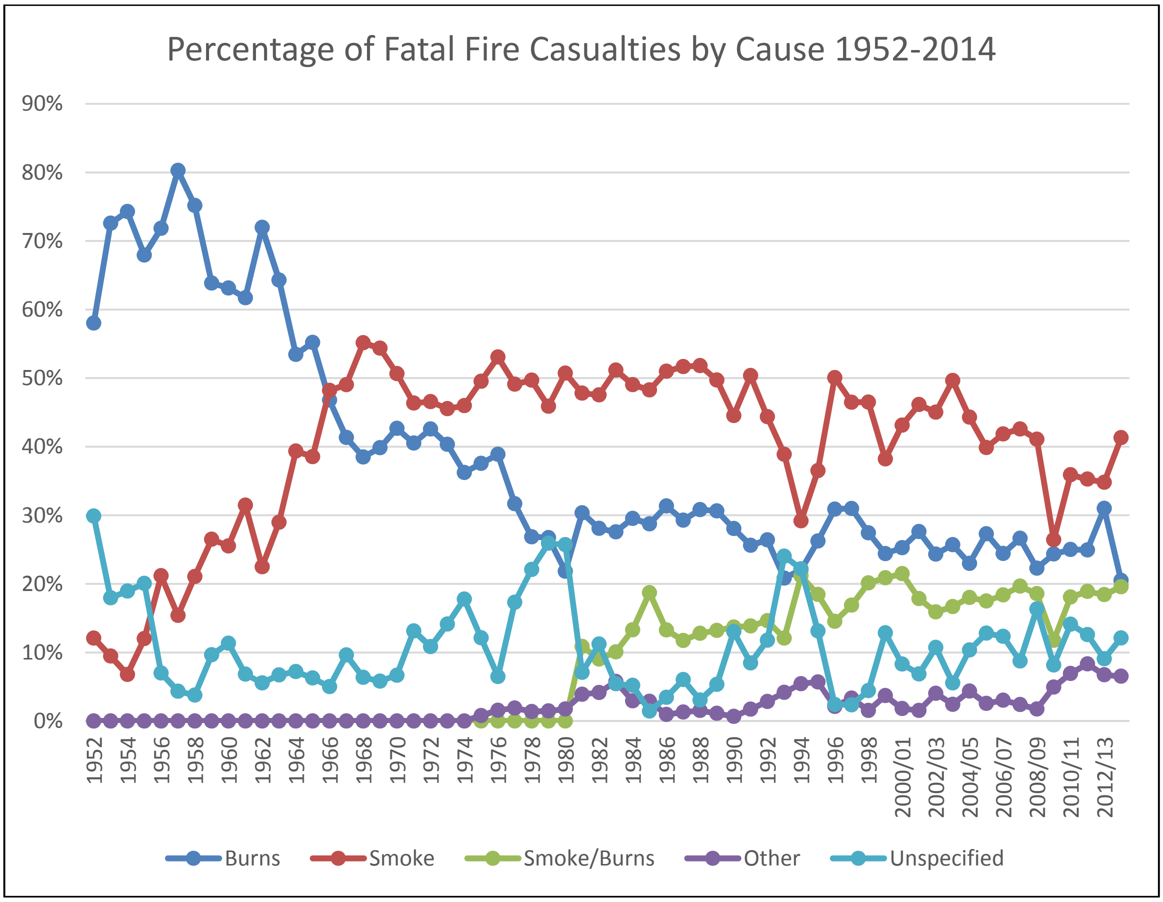


Figure 15 – Percentage of fatal casualties by cause (1952 to 2014)

Within Figure 15, it can be seen that these trends continue up to around 1980 and then the trends change. This is explored further in Figure 16 and Figure 17.

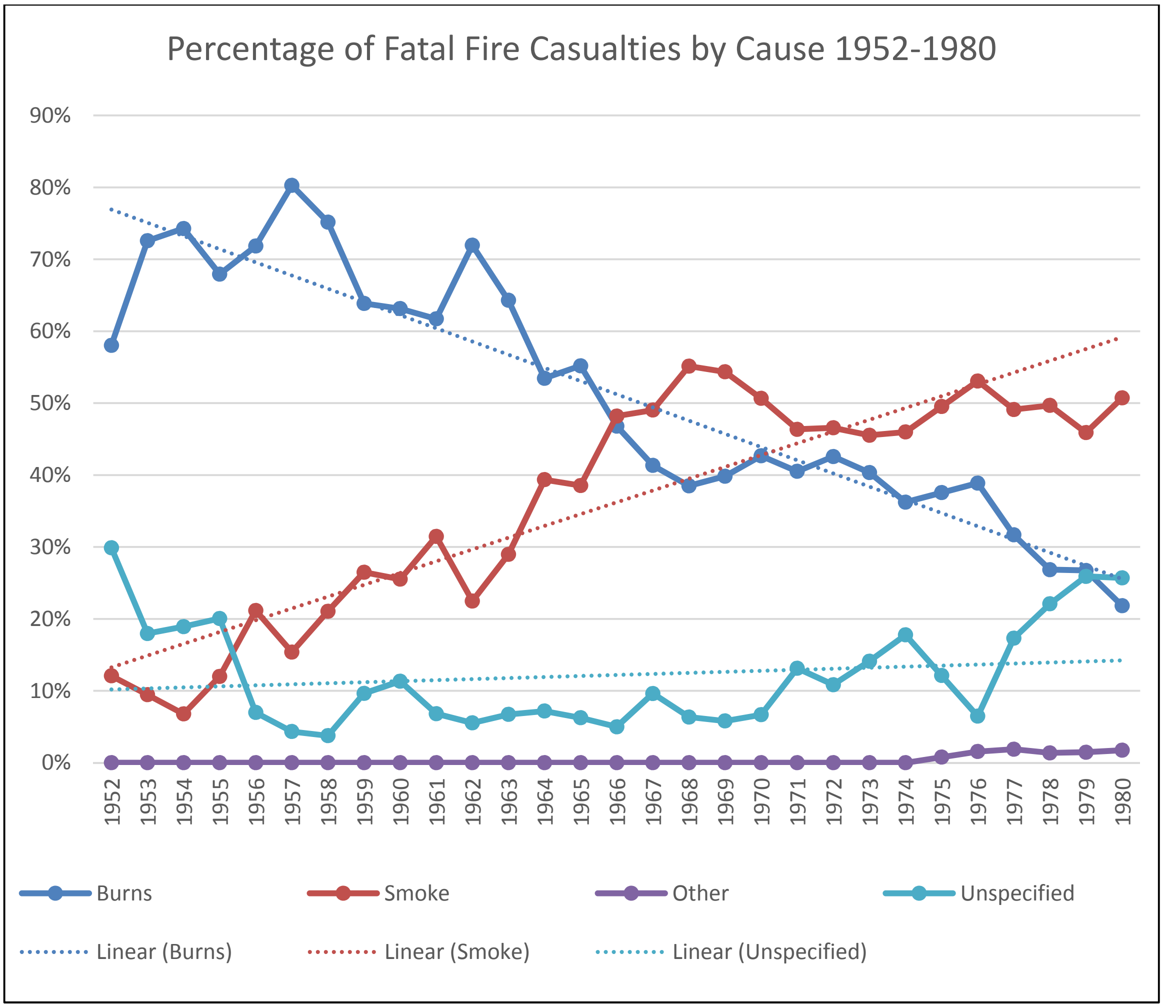


Figure 16 – Percentage of fatal casualties by cause (1952 to 1980)

Between 1952 and 1980, there was a significant change in the recorded cause of fatal fire casualties. In the early-1950s, around 75% of all fire deaths were attributed to burns with around 10% being attributed to smoke inhalation. In the intervening period between 1952 and 1980 the number of fatalities being attributed to burns, fell proportionally to around 25% and fatalities, resulting from smoke inhalation, rose proportionally to around 50%.

As previously discussed, this is most probably as a result of the more widespread use of plastics in households during this time.

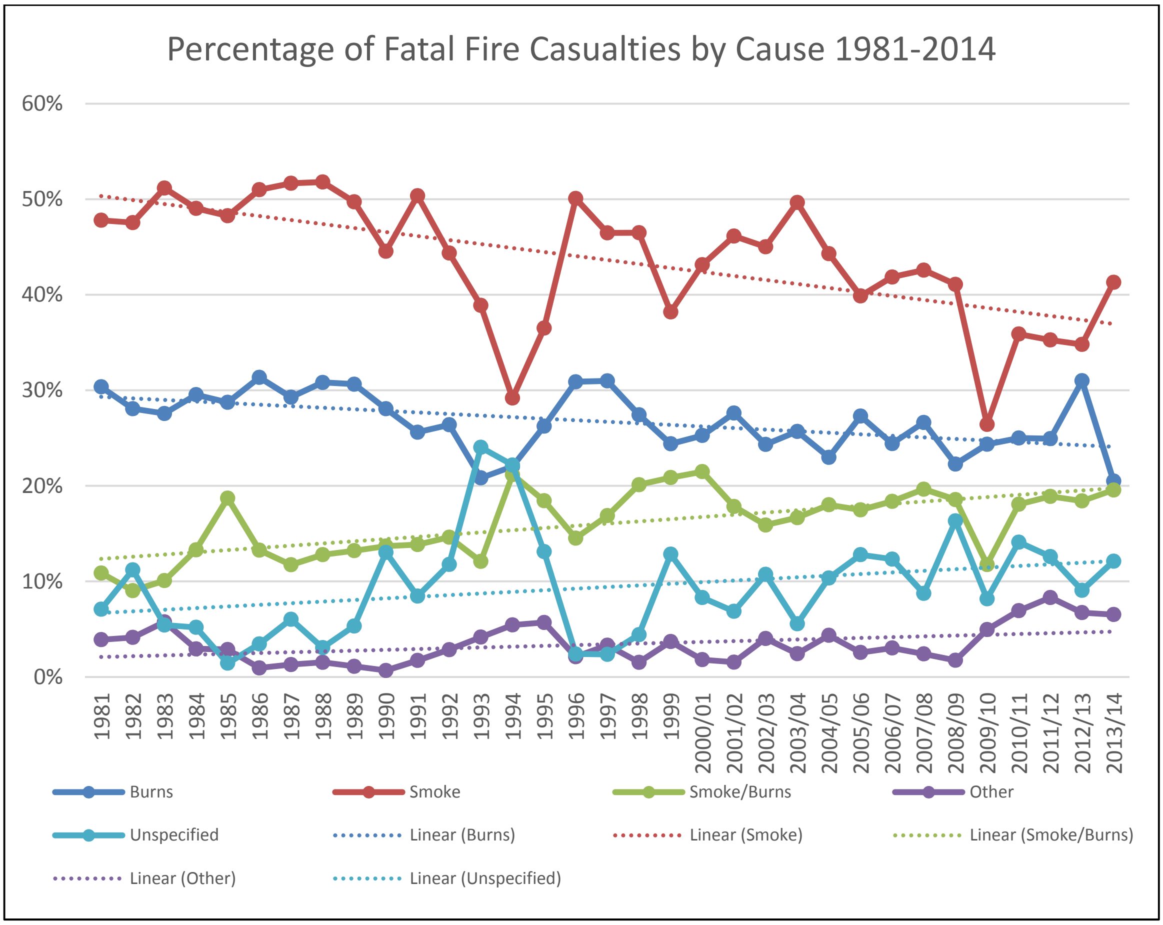


Figure 17 – Percentage of fatal casualties by cause (1981 to 2014)

However, from 1980 to 2014 the trend lines change somewhat, with the two main causes of fire deaths decreasing steadily as a new category is introduced. The new category, which accepts that fire fatalities can occur as a result of a combination of exposure to heat and asphyxiant gases, rises steadily from around 11% in its first year as a recognised category to around 20% by 2013/14.

Whilst the number of 'Other' fire fatalities is generally small and consistent over this time period, the number of 'Unspecified' fire fatalities also increases from around 7% to around 12%. As a result, the number of fire deaths classified as being caused by 'Burns' or 'Smoke' alone steadily decrease but remain proportional to one another.

1.7.10 Non-fatal Casualties

Non-fatal fire casualties have been considered in the same way through an analysis of the locations where these fires occur and also the nature of the injury which occurs. With regards to non-fatal casualties the total number is some 30 times greater than for fatal casualties and so the data set has greater statistical validity.

Fire location data uses the same categories for both fatal and non-fatal casualties and was not recorded prior to 1970. Before 1981, the two categories of Outdoors (Road Vehicles) and Outdoors (Other) were grouped together as 'Outdoors'.

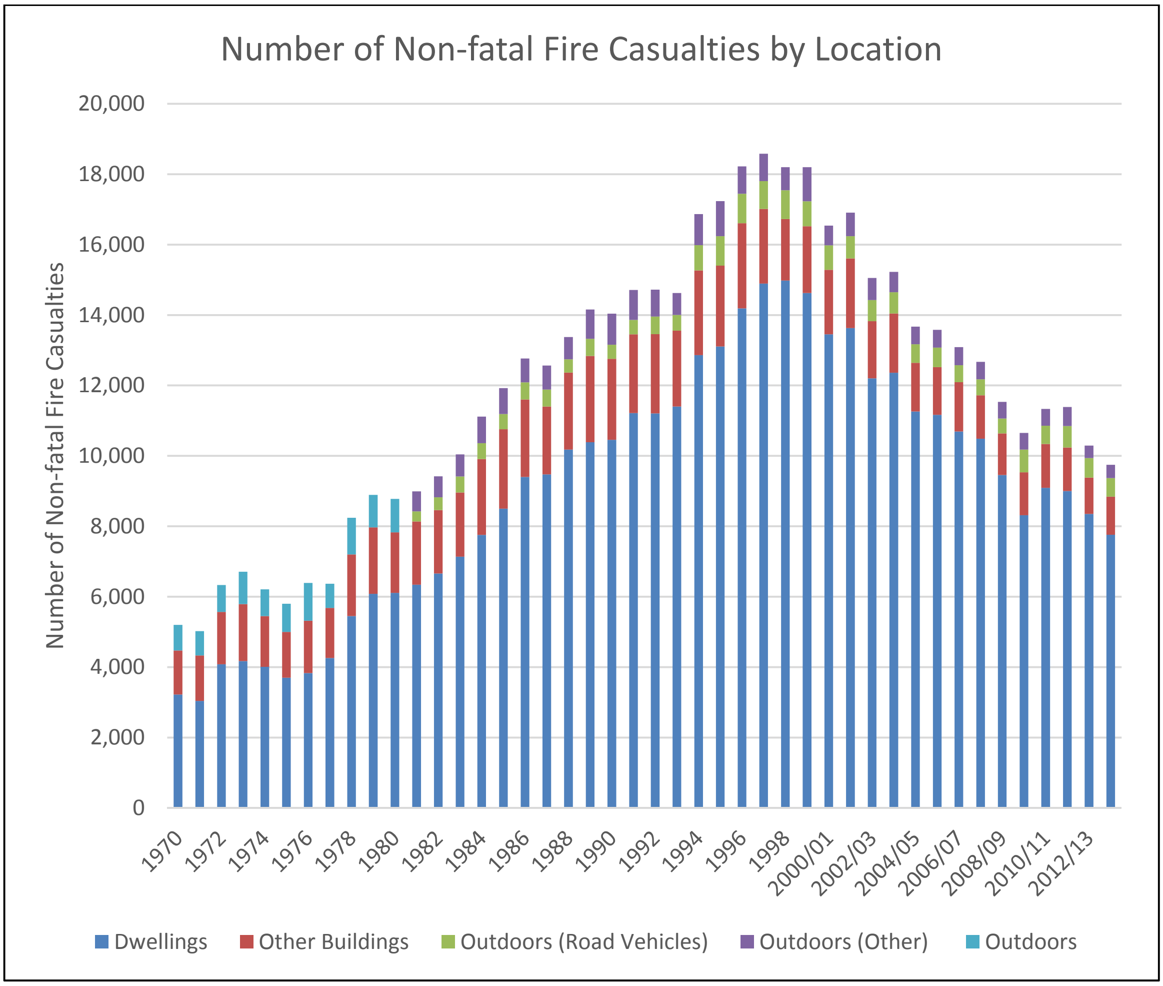


Figure 18 – Non-fatal casualties by location

Figure 18 shows that the majority of fire injuries also occur in dwellings, with the last ten years of data showing that 81% of all fire injuries occur in this location. Over the same time period 10% of injuries occurred in other buildings, with only 5% in road vehicles and 4% elsewhere outdoors. The data for non-fatal casualties by cause is shown in Figure 19 although again, no data is presented for 1975 and 2009/10.

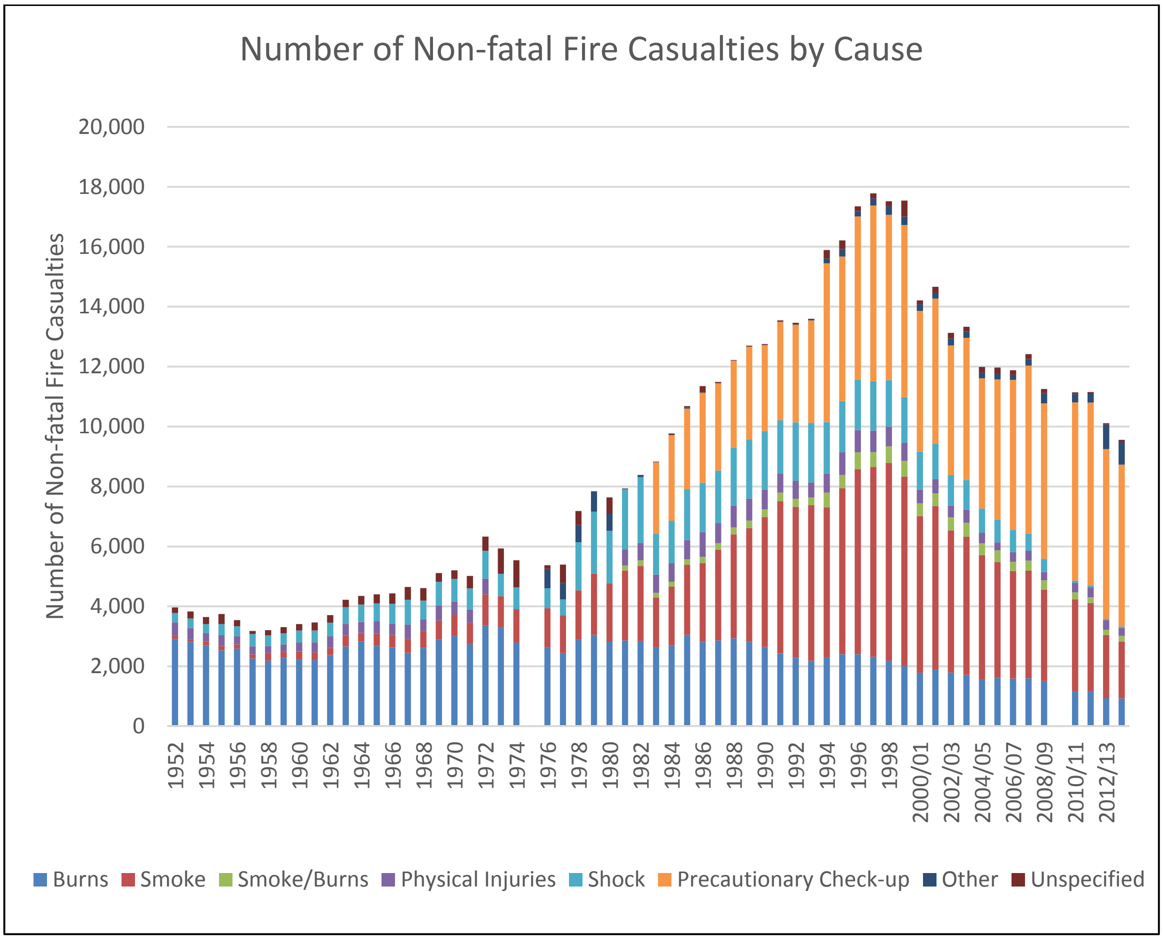


Figure 19 – Non-fatal casualties by cause

Over the most recent ten year period of data gathering (omitting 2009/10), it can be seen that smoke inhalation caused 28% of fire injuries with burns accounting for 12%, a combination of smoke and burns 2%, Other 3% and Unspecified 1%. In addition, physical injuries accounted for 3% and shock for 4%, with a large proportion, some 47% of fire injuries, recorded as having a precautionary check-up only.

1.7.11 Conclusions from the Initial Statistical Analysis

The analysis within this section shows that, over the last ten years, 77% of all fire deaths and 81% of all fire casualties occur as a result of fires within dwellings. In addition, smoke inhalation is the major cause of fatal casualties resulting in 40% of deaths (arguably up to 70%) and is a major contributor to non-fatal casualties resulting in 28% of injuries, over the same time period. In recent times, an increasing number of people are taken to hospital for a precautionary check-up and this is now the main classification for fire injuries with 47% over the last ten years.

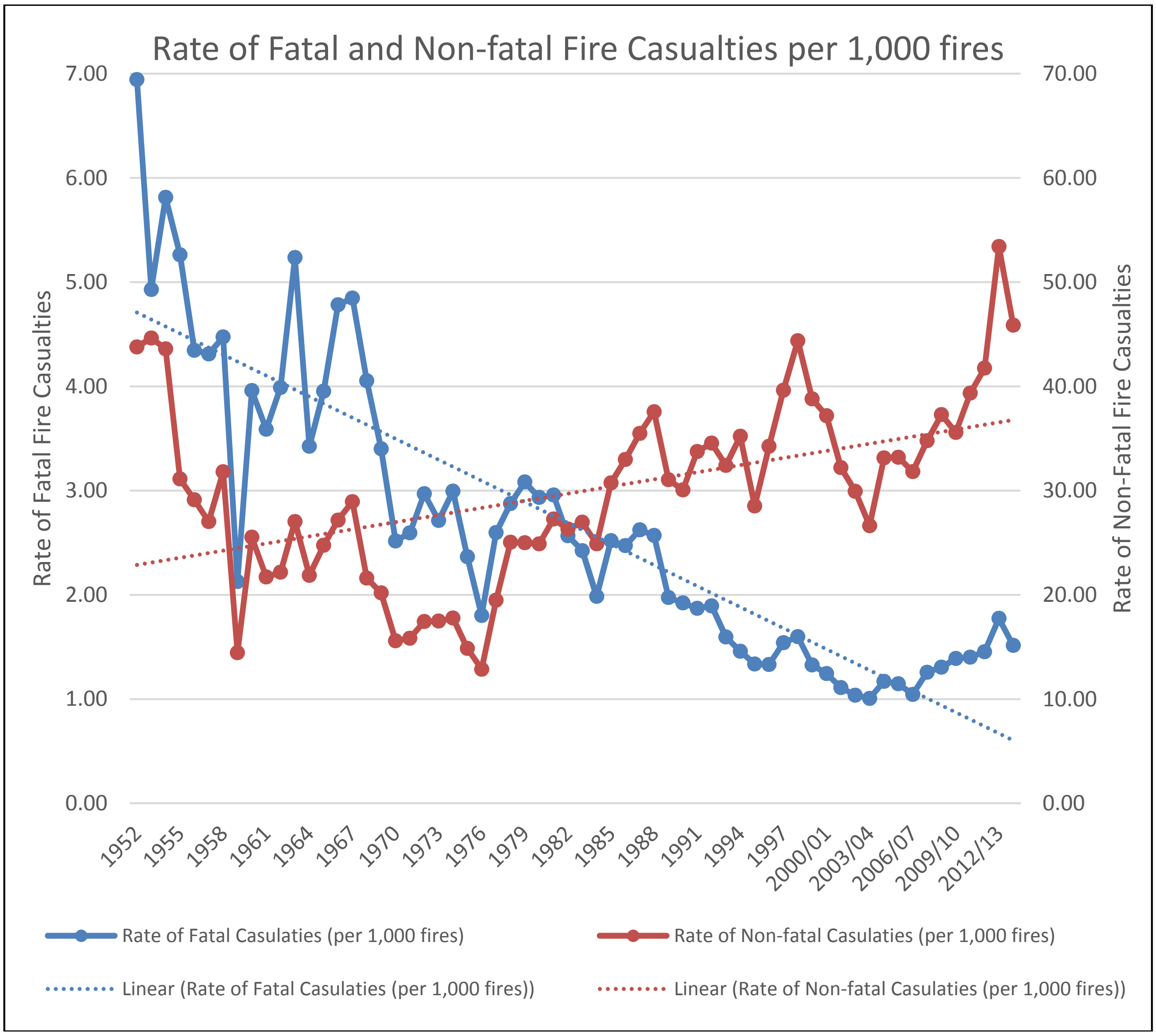


Figure 20 – Rate of fatal and non-fatal casualties (per 1,000 fires)

Figure 20 shows that, since fire statistics were first compiled in the UK in 1952, the rate of fatal casualties per 1,000 fires has dropped steadily from around 5 to around 1.5 in recent times. Conversely, the rate of non-fatal casualties per 1,000 fires has doubled from around 20 to around 40. It can be seen that the rise in injuries can be attributed to the inclusion of precautionary check-ups to some extent with figures rising sharply from 1983 onwards, when this category was introduced.

1.7.12 Victims of Fire

An internal review, conducted by officers from the WMFS, considered fire-related deaths in the region, over a 5-year period. The review concluded that 80% of fatalities occurred with one or more of the following contributory factors [62]. This supports other evidence found [63][64][65]:-

- Persons suffering from social deprivation [66][67],
- Elderly persons,
- Persons with mental or physical disabilities,
- Persons under the influence of alcohol [68].

1.8 Large-scale Fire Tests

This section aims to review the available literature relating to large-scale fire tests that have been conducted on dwellings and consider human exposure to heat and/or asphyxiant gases. A number of separate studies have been identified and each of these are described in the following sub-sections.

1.8.1 The Toxicological Impact of Basement Fires

A study undertaken by Joseph Su of the National Research Council of Canada, aimed to determine tenability conditions in a dwelling with a fire located in the basement [69]. It uses the Canadian system for floor numbering, i.e. the basement is the cellar, the first storey is the Ground Floor and the second storey is the First Floor as seen in Plate 1.

Plate 1 – Internal layout of the test facility [69]

Internal walls and floors were constructed and then external walls were built as shown in Plate 2. The internal layout of the three storeys can be found in Appendix B.

Plate 2 – External layout of the test facility [69]

The aim of Su's research was to establish the sequence of events during a fire within this structure, looking at smoke alarm activation, the onset of untenable conditions and, for a separate study, structural failure of the floor above the basement. Su used uncovered polyurethane foam and wooden cribs as the fuel to simulate a sofa fire in the basement [69]. In all experiments one of the second storey bedroom doors was open and one was closed. There were various experiments with the basement door in the open and closed positions and Su considered tenability from the perspective of both heat and toxic gas exposure.

Smoke obscuration was the first criterion to be met, with visibilities of 1m being reached at the first storey doorway to the basement at around 180 s. Where the doorway to the basement was closed, the escape time from the upper floor was roughly doubled from around 240 s to 500 s.

This test house was typically open plan on the first storey however, photoelectric smoke alarm response times were consistently around 42 s in the room of fire origin (ROFO), around 61 s on the first storey and around 120 s on the second storey with the basement door open. With the basement door closed the response times were identical in the ROFO, they were extended to 79 s on the first storey and to 185 s on the second storey. Where the doorway from the basement to the accommodation is closed, there is a delay in the actuation of the smoke detector however, the extension of the escape times in these scenarios is more than compensatory.

This study claims that untenable conditions were not reached at any time within the second storey bedroom with a closed door [69]. Tenability in the circulation spaces was calculated using the methodology in ISO 13571, although no consideration was given to the effects of HCN as only data for CO and CO_2 were gathered.

Each test was conducted for 500 s in duration (just over 8 min). Where the basement door was open, the worst case conditions on the first storey were, <5% O_2, 45,000 ppm CO and 140,000 ppm CO_2. Where the basement door was closed, worst case conditions on the first storey were, 19% O_2, 10,000 ppm CO and 20,000 ppm CO_2, remembering that this building is unusually open plan, when compared with homes in the UK.

The data presented in Figure 11 of the Su report and reproduced in Appendix C, agrees that CO/CO_2 yield ratios are broadly in the region of 0.20-0.25 [69]. The data described above is brought together in Table 5.

	Basement Door Open	Basement Door Closed
Average Alarm Actuation (s)		
Basement	42	45
First Storey	61	79
Second Storey	120	185
Average Time Available for Escape where FED=1 (s)		
First Storey	230	500
Second Storey	250	500
Average Concentration of Gas on the First Storey		
O_2 (%)	<5	19.0
CO (%)	4.5	1.0
CO_2 (%)	14.0	2.0

Table 5 – Results from the NRC study

1.8.2 Tenability Analysis from the Su Study

A comparison between the time to compromised tenability for heat and asphyxiant gas is given in Table 6. The table is split into open and closed door tests and shows the tenability time for both heat and toxic gas for comparison. Where the basement doorway is closed, it can be seen that in 11 of the 12 tests, the time to compromised tenability from asphyxiant gas occurs before that for heat. Where the basement doorway is open, it can be seen that in the area close to this doorway, a combination of heat and asphyxiant gas compromised tenability occurs, with 5 occurrences as a result of asphyxiant gas and 7 occurrences as a result of heat exposure. Where measurements are taken more remotely from the fire, on the second floor, again it can be seen that in 10 of the 12 tests, the times to compromised tenability from asphyxiant gas occurred before those for heat.

	1st Storey SW Quadrant				2nd Storey Corridor			
	Asphyxiant Gas		Heat		Asphyxiant Gas		Heat	
	0.3	1.0	0.3	1.0	0.3	1.0	0.3	1.0
	Tests with Open Basement Doorway							
UF-01	205	235	230	280	225	255	320	435
UF-03	209	240	205	213	225	247	252	330
UF-04	220	260	207	215	245	280	250	290
UF-05	206	232	220	240	235	260	270	320
UF-06	198	233	202	211	208	241	229	254
UF-07	225	265	192	207	230	275	225	255
	Tests with Closed Basement Doorway							
UF-02	466	679	1086	1196	362	501	1171	1241
UF-08	400	510	482	486	375	510	507	FED < 0.5
UF-09	329	484	786	796	364	504	FED < 0.2	FED < 0.2

Table 6 – Tenability time (seconds) for asphyxiant gas and heat

1.8.3 Toxicological Analysis of an Armchair Fire

A study conducted by David Purser aimed to complete the toxic hazard assessment of a dwelling fire scenario [23]. Test facility consisted of a two-storey rig with an armchair located within the ground floor lounge, the door to the hallway was partially open. This study focused on fire scenarios with limited ventilation. Upstairs were two bedrooms one with a closed door and one with an open door. Kitchen and bathroom doors were closed. Data considered the effect of exposure to both asphyxiant gas and heat.

Data gathered from the test showed an incubation period for the fire of around 2-3 min after which the fire started to grow rapidly. Quintiere recognises that, in the early stages of fire growth, development is slow until a point where the fire starts to take hold [70].

Due to the limited amount of external ventilation to the fire, the peak lounge ceiling temperature was around 350 °C and the fire self-extinguishes at 9 min. The maximum CO concentration in the fire compartment reached 11,000 ppm (1.1%) and peak HCN concentration was measured at 1,100 ppm. The ionisation detector sited in the lounge actuated at around 30 s. Compartment fires are almost always under-ventilated and under these conditions the yield of toxic products would be expected to be much greater [71][72].

There was enough smoke on the first floor landing to actuate the ionisation detector at around 120 s. Temperatures in the open door bedroom peaked at around 9 min at 60 °C. The irritant smoke would become problematic to an occupant situated in the open door bedroom at around 4.5 min and unconsciousness is predicted at around 6.5 min as a result of the asphyxiant gases. The presence of a closed door in the second bedroom would have protected its occupants for more than 20 min.

This information is reproduced in Table 7.

	Lounge Door Open
Average Alarm Actuation (s)	
Lounge	30
First Floor Landing	120
Average Time Available for Escape where FED=1 (s)	
Open Door Bedroom	390
Closed Door Bedroom	>1,200
Maximum temperature (°C)	
Lounge (@9min)	350
Open Door Bedroom (@9min)	65
Peak Concentration of Gas in the Lounge	
CO (%)	1.1
HCN (%)	0.11

Table 7 – Results from the Purser study [23]

This study concluded that: -

- Occupants of the fire room and the open door bedroom would have been at serious risk from the fire.
- The time between detection and loss of tenability was very short (around 2 min) with the fire compartment door open.
- Closing the door of the fire compartment greatly reduces the hazard to the rest of the house.

1.8.4 Tenability Analysis from the Purser Study

Purser’s study concluded that a number of different hazards would be presented to the occupants of the fire compartment (lounge) and he considered the timescales associated with each of these hazards. Two smoke detectors were located within the premises with the lounge detector actuating at around 30 s and the detector on the first floor actuating at around 120 s after ignition. It is worth noting that it is unusual for smoke detectors to be located in rooms which are occupied in domestic premises, and it is more typical to find them in the circulation areas (hallway and landing).

The first hazard faced by the occupant of the lounge is smoke, with Purser’s analysis suggesting that smoke irritancy occurs at around 1.5 min. At this point, the occupants of the lounge are most likely to suffer difficulties in seeing, due to painful eye irritation and may also have some breathing difficulties, with these effects hampering but not preventing escape [23].

Around a minute later, at 2.5 min, the occupant will no longer be able to see the nearest doorway due to the effects of visual obscuration from the smoke. Visibility at this point will be less than 2 m, however, this effect is also unlikely to prevent escape, as the occupant would not be expected to be too disorientated due to the relatively small size of a typical lounge room and the intimate knowledge that the occupant is likely to have [23].

The situation in the lounge becomes much more serious after 5 min where a person exposed to the smoke would be expected to collapse and become unconscious as a result of the combined effects of the asphyxiant gases CO and HCN. Purser suggests that unconsciousness will result largely as a result of the presence of HCN and that if the asphyxiant gas CO is considered alone, unconsciousness would not be predicted for a further 2 min [23].

Exposure to heat is likely to cause compromised tenability for an occupant of the lounge at around 6 min with the effect being burns to any areas of unprotected skin. The FED dose calculations for the times to compromised tenability in the lounge, as derived by Purser, are depicted in Figure 21.

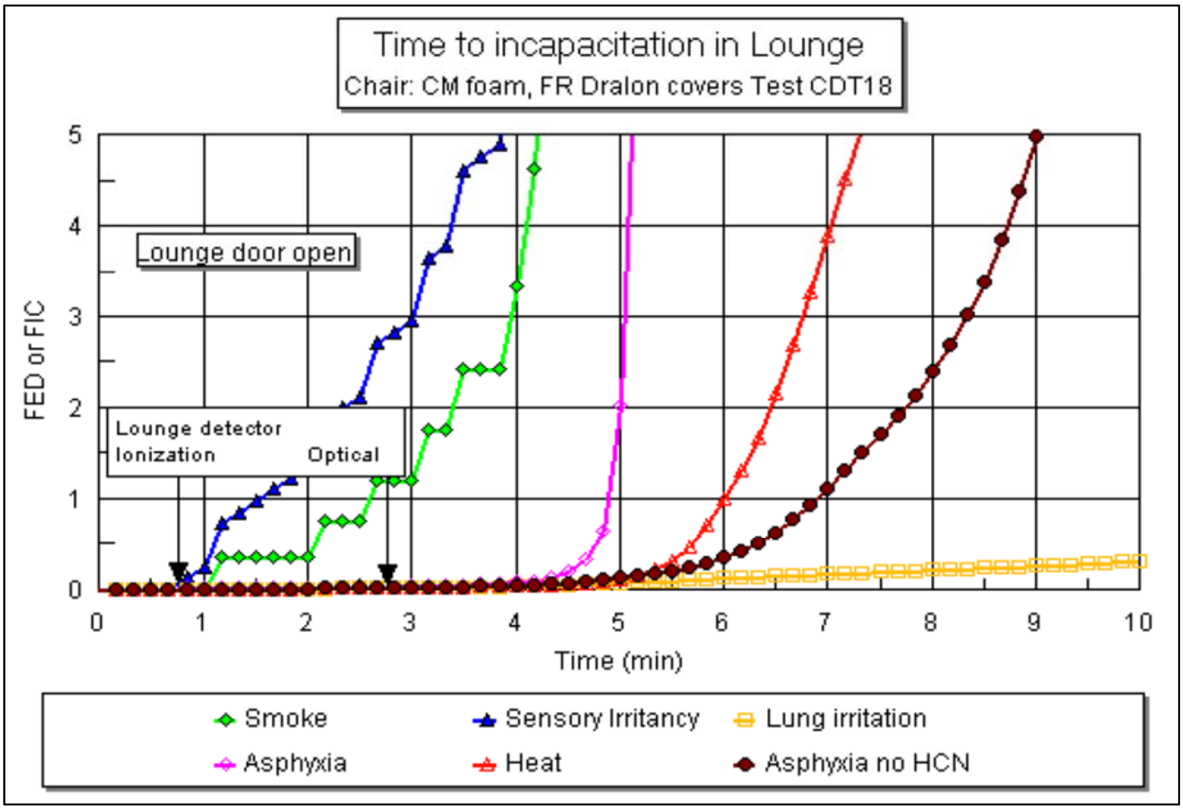


Figure 21 – Time to compromised tenability in the lounge (Purser) [23]

Purser also considers the hazards presented to the occupants of the bedroom with the open door. The hazard of smoke obscuring occupant visibility occurs at around 4.5 min and after this time there is likely to be a delay for people in this room to find their way out of the bedroom and down the stairs [23]. The occupants may well find that they are faced with a situation where they need to make a decision to try to escape via the stair or to close the bedroom door and either wait for a F&RS rescue or escape via a window.

Soreness to the eyes and difficulty with breathing would occur at around 5.5 min. Again this is not likely to prevent an escape but may be a contributory factor in the decision to either evacuate or stay put. Considering the list given in Section 1.7.12, there is a high probability that a significant number would decide not to attempt to self-evacuate in the presence of irritant gases.

At around 6.5 min unconsciousness in the open bedroom occurs as a result of the inhalation of the asphyxiant gases CO and HCN and, as with the lounge, this effect occurs predominantly as a result of HCN [23]. Where the effects of the asphyxiant gas CO are considered in isolation, unconsciousness would be expected at around 9 min.

During these experiments, the temperature in the open bedroom is insufficient to cause compromised tenability. The most likely reason for this is that, as the smoke travels from one room to another it entrains clean air as a result of the turbulent effects of fluid dynamics. This clean air is of a sufficiently low temperature to dilute the hot smoke layer and to significantly reduce its temperature. The effects discussed here are shown as a graph in Figure 22.

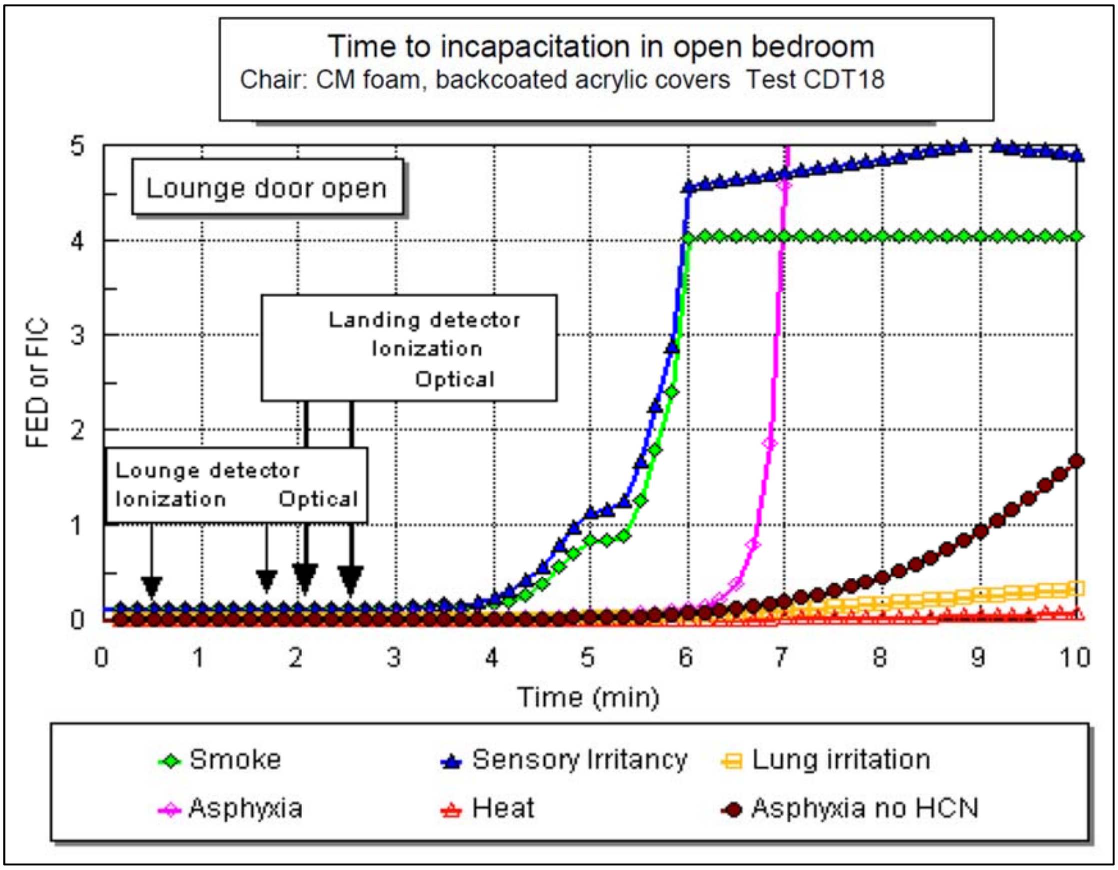


Figure 22 – Time to compromised tenability in the open bedroom (Purser) [23]

Purser also analyses data from within the closed door bedroom and concludes that the occupants of this room would be protected for a period in excess of 20 min [23]. It would still be the case that the occupants may need to decide whether to pass down the staircase or to stay within the bedroom and keep the door closed.

1.8.5 Analysis of Family Home Fire Dynamics

This study was conducted by Stephen Kerber of the Underwriter's Laboratory in the United States [73]. It focused on the effects of active firefighter ventilation activities during a fire but it also gathered information relating to occupant compromised tenability from both heat and toxic smoke in several locations within a domestic home. Using purpose built test rigs with the layout of single and two storey family homes, a series of 15 fires were conducted with various ventilation arrangements.

During this study, fires were ignited in the living room of the single storey accommodation and in the family room of the two-storey accommodation. For the single storey tests, temperature and gas concentration measurements were taken in the fire compartment (living room) and in two nearby bedrooms, one with its door open and one with its door closed. In the two-storey tests, temperature and gas concentrations were also taken in the fire compartment and in the upper storey hallway which was open to the fire compartment on the lower floor.

Temperature and gas concentration measurements were taken at 0.3 m and at 1.5 m from floor level to identify exposure for both an adult in the standing position (1.5 m) and in a crawling position close to the floor (0.3 m). Gas concentrations were recorded for O_2, CO, and CO_2, but notably not for HCN.

These experiments were designed to compare the effects of differing ventilation methods and great emphasis was placed on ensuring that pre-ignition conditions were close to identical for each test. Identical pieces of furniture were burned with their position being reproduced for each test. Ignition was in the same location and ventilation was controlled [73]. Whilst different ventilation methods were used from 8 min after ignition onwards, initial fire development was repeatable for five of the seven single storey tests. With the two-storey tests, initial fire development was also reproducible in six of the eight tests.

1.8.6 Tenability Analysis from the Kerber Study

Tenability was measured at heights of 0.3 m and 1.5 m above floor level in a number of rooms for both heat and toxic gases and the endpoint of both 0.3×FED and 1.0×FED were calculated to consider both the healthy adult population and some of the more vulnerable human subpopulations.

The results of the experiments were averaged across the number of experiments for both single and two-storey accommodation. They clearly showed that, in the fire compartment, exposure to heat was a greater threat than to toxic gas. However, there was insufficient data from those rooms, which were remote from the fire, to draw any conclusions.

A key conclusion from this study was that those who are in the fire compartment or not protected by a closed door were likely receive a fatal dose of heat/smoke prior to arrival of the fire department. However, there is also a likelihood that where persons were more remote from the fire, had the protection of a door and/or were lying at floor level, they would not have suffered fatal exposure to either heat or smoke and it is possible that prompt action from a firefighting crew would save their lives.

1.8.7 $CO:CO_2$ Yield Ratio

The combustion reaction and the chemical yields of CO and CO_2 are dependent on the availability of O_2 and this can be affected by a number of factors (not exhaustive): -

- Orientation of the fuel
- Amount of ventilation
- Air flows near the fire
- Heat output of the fire

Gann reviewed a number of published articles considering the ratios of various species in smoke [74]. For well ventilated fires, $CO:CO_2$ ratios are in the region of 0.02-0.10, in fires with limited-ventilation, this ratio increases to 0.15-0.30. During an analysis he conducted, using a Zone Model, he chose the $CO:CO_2$ ratio to be set at a constant 0.30.

For moderately vitiated combustion, PD 7974-6 indicates that a reasonable $CO:CO_2$ ratio should be around 0.10 [42]. It should also be recognised that CO can further react with O_2 in the plume producing CO_2, where the conditions for reaction are satisfied (typically additional oxygen and temperatures above 625 °C) [75]. Research suggests that the ratio in the plume will change, the further it travels from the fire source [76]. The plume becomes diluted with clean air thus introducing more O_2 and where the plume contains adequate energy, the CO will further react to yield CO_2 thus reducing the ratio.

The Su study does not discuss yield ratios [69], however analysis of the data given within the report and reproduced in Appendix D shows that, where there is reasonable ventilation, the ratio of $CO:CO_2$ is consistently in the order of 0.20-0.25 and where the fire is vitiated the ratio rises to approximately 0.50 [69]. The Purser study does not discuss this either and again approximations of 0.12-0.15 are taken from the data given [23].

1.8.8 Summary of the Conclusions Drawn from the Large-Scale Tests

A number of conclusions can be drawn as a result of comparing these three studies with one another. These conclusions are given below: -

1. **The effect of a closed door** – where two bedrooms are compared, one with its door open and one with the door closed, the difference can be considerable. Closing a door (a typical domestic door not a fire door) can considerably reduce the amount of smoke and gas transferred and this can increase the tenable duration from less than 7 min with an open door to more than 20 min when the door is closed.

2. **Delays in smoke detection with a closed door** – where the door of the fire compartment is closed, this can lead to an extended time to detection where the detector is located outside of that room. These experiments agree that whilst the time to detection is increased, the amount of time available for escape becomes significantly greater and therefore more than compensates for the delay in detector response.

3. **Tenability where heat is compared to asphyxiation from CO only** – where the occupant of a domestic building is located either within the fire compartment or close to it, there is a likelihood that incapacitation will result from exposure to either heat or asphyxiant gas at around the same time. Where the occupant is located more remotely from the fire, the likelihood is that incapacitation from exposure to asphyxiant gases will occur first, however, it is probable that temperatures will also become sufficient to incapacitate.

4. **Tenability where heat is compared to asphyxiation from the combined effects of CO and HCN** – in experiments where both of the two main toxic gases are considered, a loss of consciousness due to smoke inhalation occurs prior to that from heat exposure both within the fire compartment and in other locations remote from it.

5. **Other effects occurring prior to incapacitation** – it is recognised that both visual obscuration and soreness to the eyes and respiratory tract will occur prior to incapacitation, as a result of exposure to smoke. Both of these effects are unlikely to cause a loss of consciousness to an exposed occupant although it may impact upon their decision to evacuate the building or seek refuge.

Chapter 2 - Statistical Analysis of Fire Deaths & Injuries

An initial statistical analysis was carried out in Section 1.7 and showed that people living in GB are 4 times more likely to be injured or killed as a result of domestic fire, compared with fires in other buildings or outdoors. It was also demonstrated that as many as 48% of all fire fatalities occur as a result smoke inhalation alone, with 30% attributed to burns and a further 22% resulting from a combination of smoke inhalation and burns.

Several attempts have been made to identify a typical risk profile for those who are vulnerable of becoming a fire fatality [77][78][79]. In this section a more detailed analysis is described with the aim of further informing the design of the experimental part of this project. This analysis will delve deeper into the national statistical reports produced by DCLG and will also look at raw data (where available from DCLG and WMFS) to focus on the identification of those factors which contribute towards fatalities and injuries.

2.1 Further Analysis of DCLG Published Data

2.1.1 Location

Figure 11 and Figure 18 showed that the majority of fatal and non-fatal fire casualties are exposed to fire and its effluent in their homes. Data taken from the DCLG reports on GB Fire Statistics showed that, over a four year period from April 2010 to March 2014, there were a total of 1,465 fatal fire casualties and 42,763 non-fatal fire casualties. This analysis aims to confirm the main locations where these injuries and fatalities occurred.

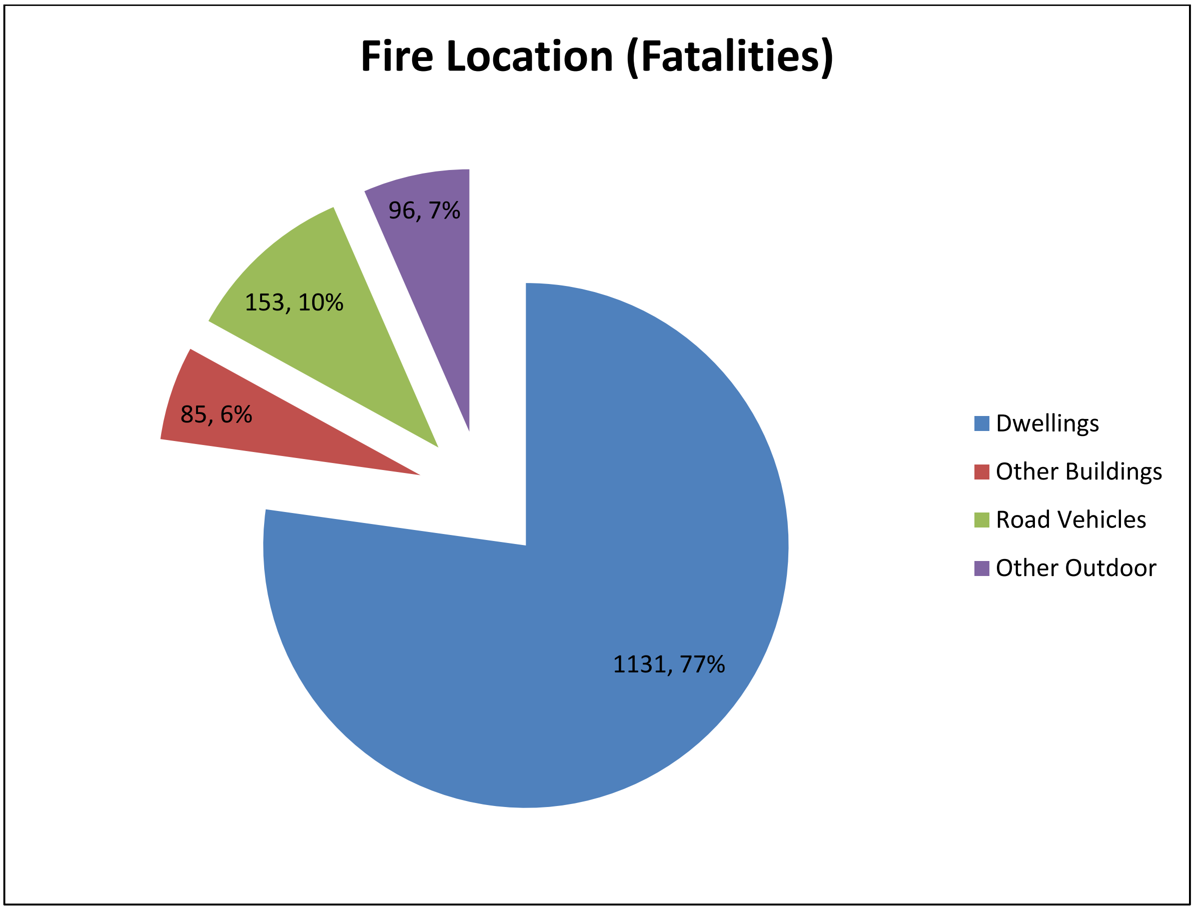


Figure 23 – Fatal casualties by location (Apr-09 to Mar-14)

Of the 1,465 fire fatalities, some 77% of these occur in the home, with 10% occurring in road vehicles, 7% outdoors and 6% in other non-domestic buildings.

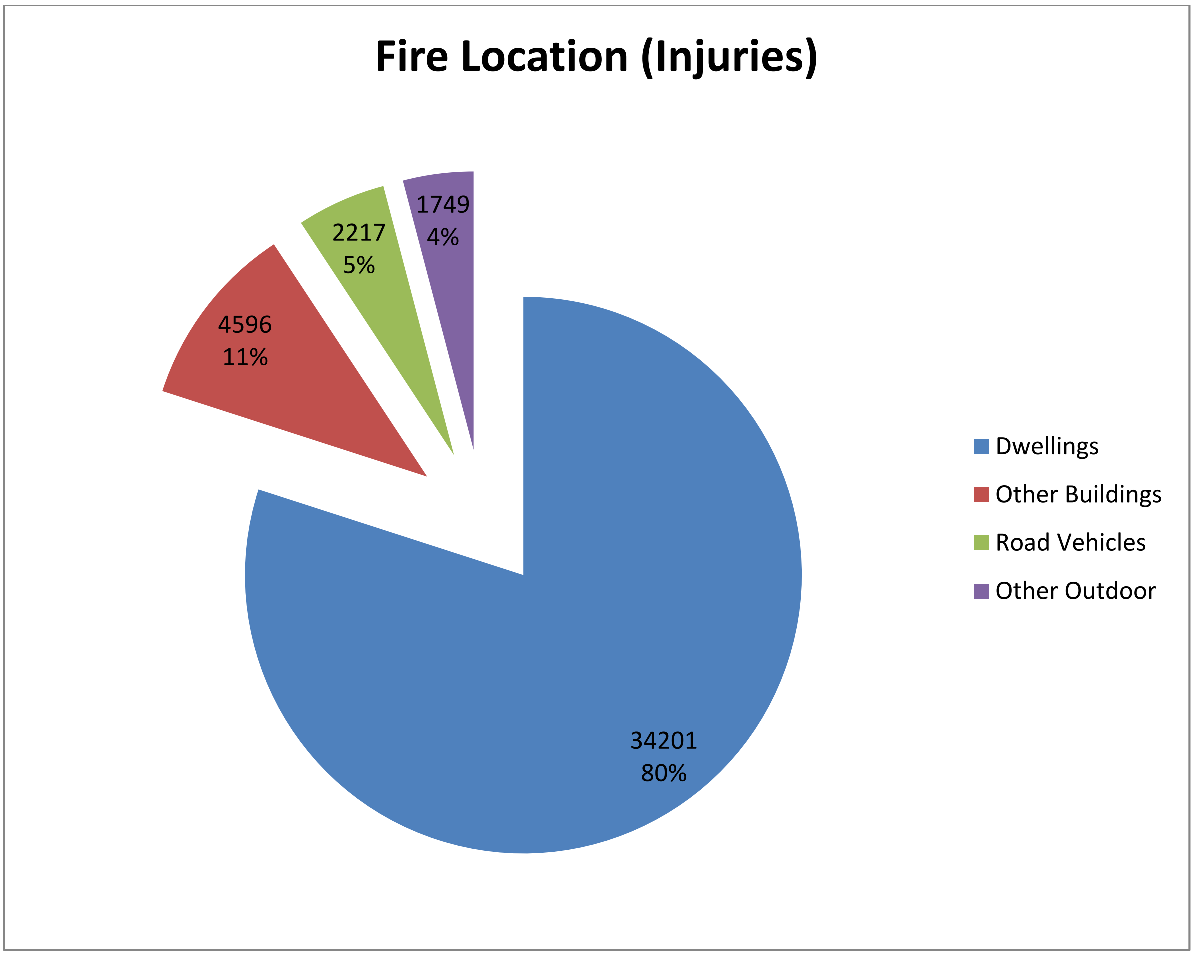


Figure 24 – Non-fatal casualties by location (Apr-09 to Mar-14)

Of the 42,763 non-fatal fire injuries, some 80% of these occur in the home, with 11% occurring in other non-domestic buildings, 5% in road vehicles and 4% occurring outdoors.

In order for this project to have the greatest impact in reducing fire deaths and injuries, a focus will be placed upon fires which occur in domestic premises.

2.1.2 Motive

Only those fatal (1,131) and non-fatal (34,201) casualties which occurred in dwellings are considered when looking at the motive. Fires in dwellings can occur as a result of an accidental cause such as a carelessly discarded cigarette or an electrical fault; or as a result of a deliberate act intended to harm persons or to damage property, for example.

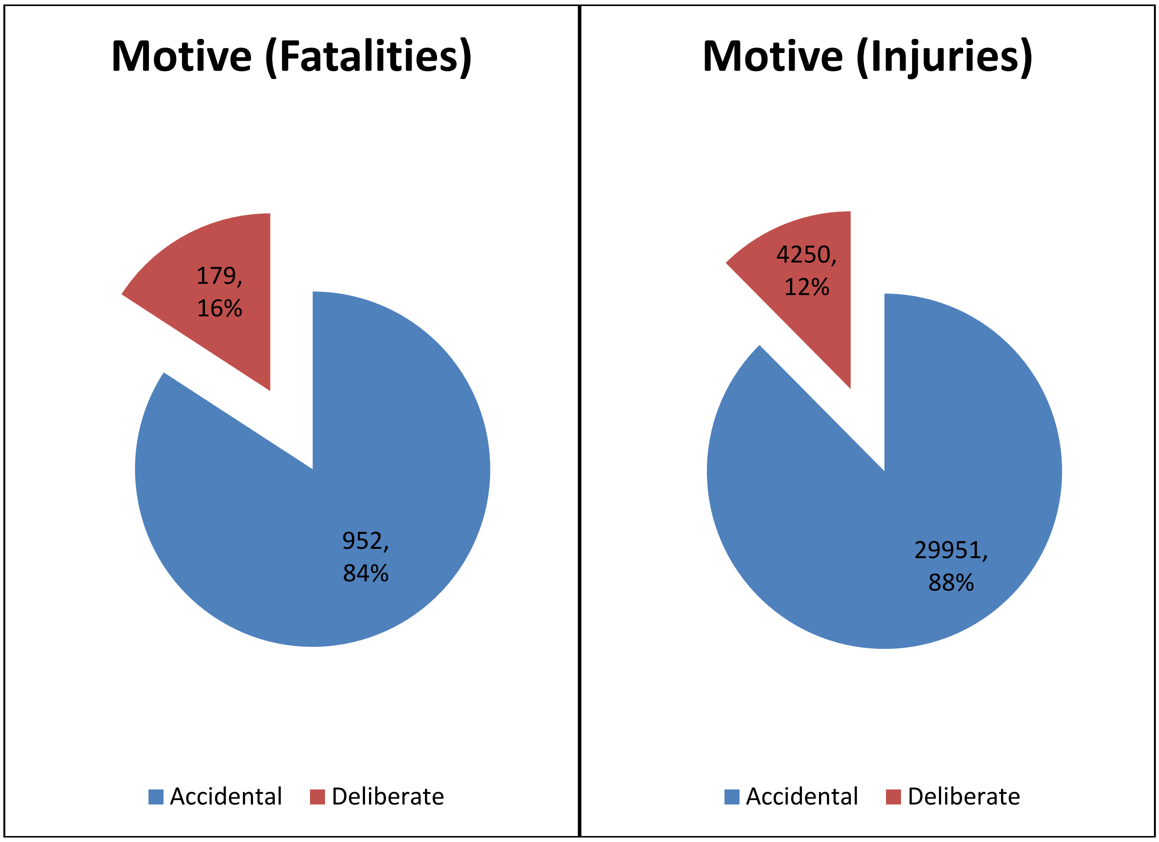


Figure 25 – Fatal and Non-fatal casualties by motive (Apr-09 to Mar-14)

The vast majority of fatal casualties (84%) and non-fatal casualties (88%) occur in fires which are considered to have been caused by accident. This information is well recognised by the F&RSs within GB and significant amounts of preventative and protective action are conducted to reduce the number and severity of ADFs.

2.1.3 Room of Fire Location

Only those fatal (952) and non-fatal (29,951) casualties which occurred in ADFs are considered when looking at the location of the fire. This section identifies the room where the fire started, when it lead to human fatalities and injuries. The casualty may have been within the fire compartment or may have been located somewhere else within the property, this analysis does not refer to the location of the casualty but to the room of fire origin only.

DCLG data identifies the type of room/compartment in which the fire starts and gives 25 different options. Within this analysis, certain room types have been grouped together for simplification. The bedroom, living and dining rooms have been grouped together on the basis that they all contain furniture and furnishings. Halls and stairs are grouped together as are the remaining 16 options, which are grouped as 'Others'.

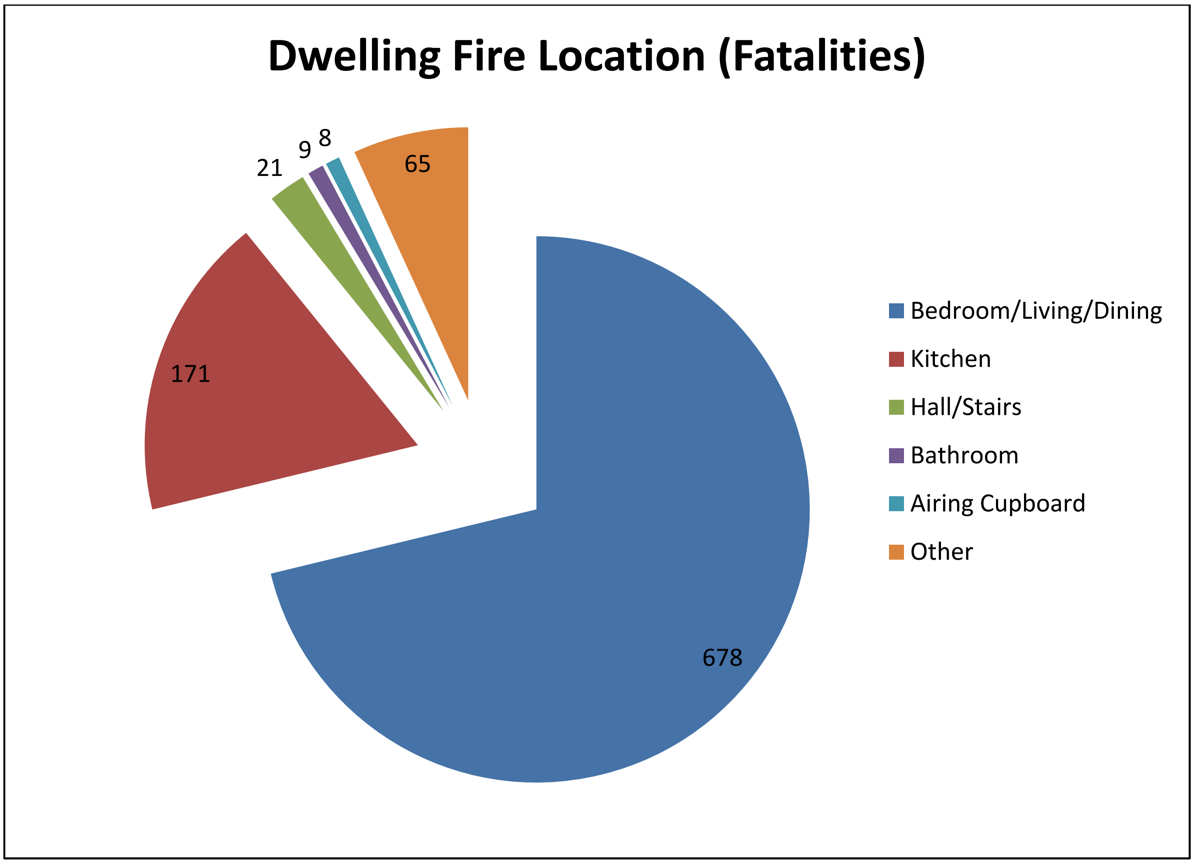


Figure 26 – Fatal casualties by fire location (Apr-09 to Mar-14)

ADF fatalities primarily occur as a result of fires in bedrooms, living and dining rooms, with these rooms accounting for 71% of fatalities. Some 18% of fatalities occur from fires in kitchens with the remaining 11% occurring from fires elsewhere within the house.

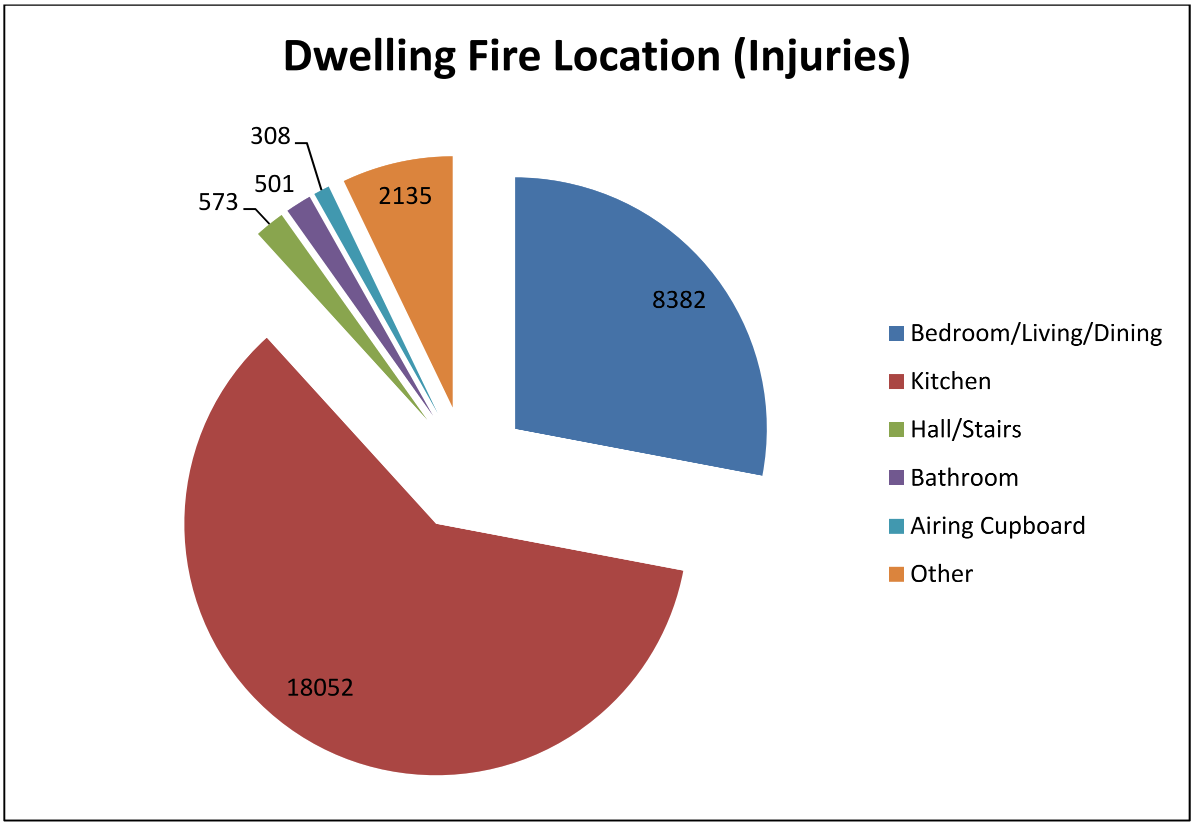


Figure 27 – Non-fatal casualties by fire location (Apr-09 to Mar-14)

Figure 27 shows that fire injuries are most likely to occur as a result of a fire in the kitchen with this room accounting for 60% of injuries. Fires in the bedroom, living and dining rooms are the cause of 28% of injuries with the remaining 12% of injuries occurring as a result of fires elsewhere within the home. Figure 28 looks at fire fatality rates.

Figure 28 – Fatality rates by fire location (Apr-09 to Mar-14)

Over the four year period, there were more than 90 thousand kitchen fires, which is approximately 3.4 times more than the almost 27 thousand occurring in bedroom, living and dining rooms combined. However, 678 fatalities occurred as a result of fires in bedroom, living and dining rooms which is approximately 4 times more than the 171 occurring as a result of fires in kitchens.

In summary, whilst there are significantly more fires starting in kitchens than in bedroom, living and dining rooms combined, the rate of fatalities for the latter is some 13.4 times greater per incidence of fire at 25.2 fatalities per 1,000 fires.

The rate of injuries by fire location are detailed in Figure 29. The number of fires is listed above however, 18,052 injuries occurred as a result of fires in the kitchen compared with 8,382 occurring from fires in bedroom, living and dining rooms. By stark contrast, the likelihood of being injured as a result of a fire in a bedroom, living or dining room is only 1.6 times greater than being injured as a result of a kitchen fire.

People receive injuries as a result of fires in bedroom, living and dining rooms at a rate of 312 injuries per 1,000 fires and at a rate of 199 injuries per 1,000 fires as a result of kitchen fires.

Figure 29 – Injury rates by fire location (Apr-09 to Mar-14)

2.2 Analysis of WMFS Raw Data

Having determined that fires in Bedroom, Living and Dining (BLD) rooms are 13.4 times more likely to cause a human fatality than a fire in a kitchen, further analysis is then required to establish the reason(s) behind this. The DCLG annual statistical reports do not provide this level of detail, so in order to look deeper into the statistical data, there is a requirement for access to raw data. Raw data has been accessed from WMFS and it will be analysed within this section of the thesis. National raw data has also been obtained from DCLG and will be considered in Section 2.3.

WMFS raw data covers a 6-year period from April 2009 to March 2015 inclusive, during this timeframe there were 131 fire fatalities and 3,714 fire injuries which are being considered. Of all the fire fatalities and injuries in the West Midlands over this period, only those which occurred as a result of an ADF, where the death/injury was fire related are being considered; this includes some 67 fatalities and 2,569 injuries. Whilst this data provides some insight into the factors contributing towards fire deaths and injuries, the size of the data set is relatively small in statistical terms, particularly with respect to fatalities.

The heat produced during combustion is not too dissimilar from one fire to the next within a typical dwelling, however the chemical constituency of the smoke can differ quite significantly where different fuels are involved. Remembering that up to 70% of fire deaths are contributed towards by smoke inhalation, the main objective within this part of the analysis is to identify what fuel was mainly responsible for the production of smoke. This data is specifically recorded by a fire officer following an incident and is requested by Question 8.7 of the IRS system as a Mandatory input [56].

2.2.1 Item Mainly Responsible (Fatalities)

An analysis of the raw data from within WMFS is given in Table 8 and shows that more than 70% of the 67 fatalities occurred as a result of a fire where the item mainly responsible for the spread of fire sits within either the "Furniture/Furnishings" or "Clothing/Textiles" groupings. These two groupings typically include those fuels which are synthetic based, such as foams, bedding, carpets and textiles, and typically have a chemical make-up which is capable of producing smoke containing a higher level of toxic chemical species.

With the frequency with which kitchen fires occur, the food grouping is the third highest in terms of WMFS fatalities over the period. Although, with the prevalence of kitchen fires, this fire type only contributes towards less than 10% of the fire fatalities.

Grouping	IRS Code	IRS Item	Number of fatalities	Total	%age	Cum. %age
Furniture/Furnishings	11	Bed/Mattress	12			
	12	Upholstered furniture	11			
	14	Floor coverings	2			
	37	Other/Unspecified furnishings	3	28	41.8%	41.8%
Clothing/Textiles	9	Bedding	5			
	10	Clothing	14			
	36	Other textiles	1	20	29.9%	71.6%
Food	6	Cooking oil or fat	5			
	7	Other	1	6	9.0%	80.6%
Rubbish/Waste/Recycling	30	Rubbish/Waste material	4	4	6.0%	86.6%
Structural/Fixtures/Fittings - Internal	34	Internal fittings	2			
	42	Wiring insulation	2	4	6.0%	92.5%
Other	99	Other	4	4	6.0%	98.5%
Explosives, gas, chemicals	24	Gases	1	1	1.5%	100.0%
		Total	67	67	100.0%	100.0%

Table 8 – Item mainly responsible in WMFS 09-15 (fatalities)

Having established that fires from the “Furniture/Furnishings” and “Clothing/Textiles” groupings are the cause of more than 70% of the fatalities, a final cross reference check is required to ensure that fires in the BLD rooms typically involve fuels from within these categories and that kitchen fires do not.

Table 9 is derived from a pivot table which checks this. In bedroom/bedsitting room fires, all 16 of the fatalities involved fuels contained within these two groupings. With living room fires, 25 of the 27 fatalities also involved these fuels and no fatalities were caused as a result of fires in dining rooms. So in total, 41 of the 43 fires in BLD rooms which caused a fatality were as a result of fuels packages fitting into these two groupings.

The two fuel types which caused the largest number of fatalities were Bed/Mattress and Upholstered Furniture.

Fire Room **Item Mainly Responsible for Fire Spread**	**Fatal Casualty**
Airing / Drying cupboard	**2**
Clothing	2
Bedroom	**15**
Any other furnishings or appliances	1
Bed / Mattress	11
Bedding	2
Floor coverings (incl. in vehicle) (carpet, mat, rug etc.)	1
Bedsitting room	**1**
Bedding	1
Corridor / Hall	**2**
Clothing	1
Rubbish/Waste material	1
Kitchen	**17**
Any other food	1
Clothing	3
Cooking oil or fat (incl. vapours)	5
Gases	1
Internal structures / fittings (incl. in vehicle)	2
Other	1
Rubbish/Waste material	3
Wiring insulation (e.g. electrical wire)	1
Living room	**27**
Any other furnishings or appliances	2
Bed / Mattress	1
Bedding	2
Clothing	7
Floor coverings (incl. in vehicle) (carpet, mat, rug etc.)	1
Other	2
Other textiles	1
Upholstered furniture (incl. vehicle seats)	11
Open plan area	**1**
Human Skin	1
Other - Inside building	**1**
Clothing	1
Utility room	**1**
Wiring insulation (e.g. electrical wire)	1
Grand Total	**67**

Table 9 – Fire room/item mainly responsible in WMFS 09-15 (fatalities)

For fires in kitchens, only 3 of the 17 fatalities were as a result of fuels fitting into the “Furniture/Furnishings” and “Clothing/Textiles” groupings. Only 6 of the 17 fatalities resulting from fires in kitchens involved fuels which sit within the “Food” grouping.

2.2.2 Item Mainly Responsible (Injuries)

Whilst Figure 27 suggests that as many as 60% of all fire injuries occur as a result of fires in kitchens, Table 10 shows that in the West Midlands, around 42% of all fire injuries occur as a result of fuels which sit in the “Food” grouping. Figure 27 also shows that 28% of all fire injuries occur as a result of fires in BLD rooms and Table 10 shows that in the West Midlands, around 27% of fire injuries occur as a result of fuels which sit in the “Furniture/Furnishings” and “Clothing/Textiles” groupings.

This analysis identifies a reasonable agreement between the numbers of injuries as a result of BLD room fires and the number of injuries as a result of fuels which sit in the “Furniture/Furnishings” and “Clothing/Textiles” groupings. It also suggests that a significant number of the fires which occur in kitchens do not involve fuels which are “Food” based; again a cross referencing analysis has been conducted and is presented in Table 11. In order to simplify this table, only the data for the BLD rooms and the kitchen are displayed, the data from all other rooms is omitted from the table.

Further analysis of Table 11 shows that, where fire injuries occurred, 68% of fires in BLD rooms involved fuels which sit in the “Furniture/Furnishings” and “Clothing/Textiles” groupings. Furthermore, where fire injuries occurred, 67% of fires in kitchens involved fuels which sit in the “Food” grouping.

Grouping	IRS Code	IRS Item	Number of injuries	Total	%age	Cum. %age
Food	6	Cooking oil or fat	686			
	7	Other	403	1,089	42.4%	42.4%
Furniture/Furnishings	11	Bed/Mattress	123			
	12	Upholstered furniture	86			
	13	Other furniture	56			
	14	Floor coverings	45			
	15	Window coverings	27			
	37	Other/Unspecified furnishings	58	395	15.4%	57.8%
Clothing/Textiles	9	Bedding	65			
	10	Clothing	134			
	36	Other textiles	97	296	11.5%	69.3%
Structural/Fixtures/Fittings - Internal	34	Internal fittings	130			
	38	Internal Other	10			
	42	Wiring insulation	168	308	12.0%	81.3%
Other	99	Other	191	191	7.4%	88.7%
Paper/Cardboard	43	Paper/Cardboard	71			
	44	Other	5	76	3.0%	91.7%
Foam, rubber, plastic	19	Foam - raw material only	4			
	20	Rubber - raw material only	1			
	21	Plastic - raw material only	64	69	2.7%	94.4%
Explosives, gas, chemicals	24	Gases	28			
	25	Petrol/Oil products	16			
	26	Paint, varnish, resins, creosote	1	45	1.8%	96.1%
Rubbish/Waste/Recycling	30	Rubbish/Waste material	29			
	31	Recycling - paper, cardboard	8	37	1.4%	97.5%
Wood	40	Other wooden	35	35	1.4%	98.9%
Structural/Fixtures/Fittings - External	17	Roof	8			
	18	External fittings	16	24	0.9%	99.8%
Not Known	0	Not known	4	4	0.2%	100.0%
		Total	2,569	2,569	100.0%	100.0%

Table 10 – Item mainly responsible in WMFS 09-15 (injuries)

Fire Room Item Mainly Responsible for Fire Spread	Non-fatal Casualty
Bedroom	**343**
Any other furnishings or appliances	8
Any other furniture	17
Bed / Mattress	111
Bedding	51
Clothing	33
Floor coverings (incl. in vehicle) (carpet, mat, rug etc.)	17
Foam - raw material only	2
Gases	2
Human Hair	1
Human Skin	1
Internal structures / fittings (incl. in vehicle)	7
Other	20
Other Paper/Cardboard	2
Other Structural / Fixtures / Fittings - Internal	2
Other textiles	18
Other wooden	2
Paper/Cardboard	18
Petrol / Oil products (incl. vapours)	1
Plastic - raw material only	4
Recycling - paper, cardboard	1
Rubbish/Waste material	1
Upholstered furniture (incl. vehicle seats)	1
Window coverings	10
Wiring insulation (e.g. electrical wire)	13
Bedsitting room	**29**
Any other food	4
Bed / Mattress	5
Bedding	2
Clothing	4
Cooking oil or fat (incl. vapours)	2
Floor coverings (incl. in vehicle) (carpet, mat, rug etc.)	1
Gases	1
Internal structures / fittings (incl. in vehicle)	1
Other wooden	1
Paper/Cardboard	2
Rubbish/Waste material	1
Upholstered furniture (incl. vehicle seats)	4
Wiring insulation (e.g. electrical wire)	1
Dining room	**12**
Clothing	2
Other textiles	1
Other wooden	3
Paper/Cardboard	1
Upholstered furniture (incl. vehicle seats)	1
Window coverings	1
Wiring insulation (e.g. electrical wire)	3
Kitchen	**1609**
Animal products	2
Any other food	396
Any other furnishings or appliances	32
Any other furniture	12

Bedding	5
Chemicals in raw state	2
Clothing	25
Cooking oil or fat (incl. vapours)	681
Floor coverings (incl. in vehicle) (carpet, mat, rug etc.)	2
Gases	21
Human Hair	1
Human Skin	7
Internal structures / fittings (incl. in vehicle)	76
Not known	1
Other	106
Other Paper/Cardboard	1
Other Structural / Fixtures / Fittings - Internal	6
Other textiles	53
Other wooden	9
Paper/Cardboard	29
Petrol / Oil products (incl. vapours)	5
Plastic - raw material only	42
Recycling - paper, cardboard	3
Rubber - raw material only	1
Rubbish/Waste material	11
Upholstered furniture (incl. vehicle seats)	1
Window coverings	4
Wiring insulation (e.g. electrical wire)	75
Living room	**302**
Any other furnishings or appliances	12
Any other furniture	22
Bed / Mattress	5
Bedding	5
Clothing	36
External structures / fittings (incl. vehicle)	2
Floor coverings (incl. in vehicle) (carpet, mat, rug etc.)	19
Foam - raw material only	2
Gases	4
Human Hair	1
Human Skin	4
Internal structures / fittings (incl. in vehicle)	16
Not known	3
Other	21
Other Paper/Cardboard	1
Other textiles	11
Other Vegetation	1
Other wooden	5
Paper/Cardboard	12
Petrol / Oil products (incl. vapours)	1
Plastic - raw material only	10
Recycling - paper, cardboard	1
Rubbish/Waste material	7
Upholstered furniture (incl. vehicle seats)	78
Window coverings	10
Wiring insulation (e.g. electrical wire)	13
Grand Total	**2569**

Table 11 – Fire room/item mainly responsible in WMFS 09-15 (injuries)

2.3 Analysis of DCLG Raw Data

In addition to obtaining raw data from WMFS, the author has also been able to gather raw data from the DCLG. This data is not generally available however, it can be made available to data analysts from the GB F&RSs on request. Not all of the raw data is available, for example, all data referring to attendance/intervention times at specific incidents is not provided.

Data from all GB F&RSs is provided although it is only available for three financial years (2009/10, 2010/11 and 2011/12). Filtering the data shows that over the 3-year period there were 566 fatalities and 17,642 injuries which occurred as a result of ADFs where the fatality/injury was fire related. This data set is much more statistically valid in terms of the number of fatalities/injuries, when compared with the WMFS data, particularly in respect to the number of fire fatalities.

On the basis of the raw data that is available, the following factors and trends have been analysed in greater depth: -

- The time at which the incident occurred
- The presence, location and failings of a fire alarm system
- How the fire started and spread, its location and size
- Any human factors which contributed towards ignition or failure to escape
- Victim details such as age, whether rescued and circumstances of fatality/injury

The detailed analysis is given in the following subsections and considers both fatalities and injuries for ADFs only and makes a comparison between the two.

Within Sections 2.3.1 to 2.3.5 the number of fatalities/injuries is considered in respect of a single factor, for example whether there was a smoke alarm present. However, it is widely recognised that serious events such as fire fatalities generally occur when a number of factors are all contributory.

In Section 2.3.6 a series of combined analyses are conducted to establish any typical combinations. For example, is the time of day significant to the location of the fire, i.e. do kitchen fires occur around meal times?

2.3.1 Time Analysis

The data provided by DCLG enables the author to establish the time of the incident and the month in which the incident occurred. The data shown in Figure 30 demonstrates that fire injuries and fatalities occur with a greater frequency throughout the winter months, probably as a result of the fact that people spend more time indoors both living and cooking during this period, and the fact that people are more likely to heat and light their homes during the winter.

There also seems to be a peak in both fatalities and injuries in the month of April however this is unexplained at this time. It may be that there is a link with this month traditionally being a holiday period.

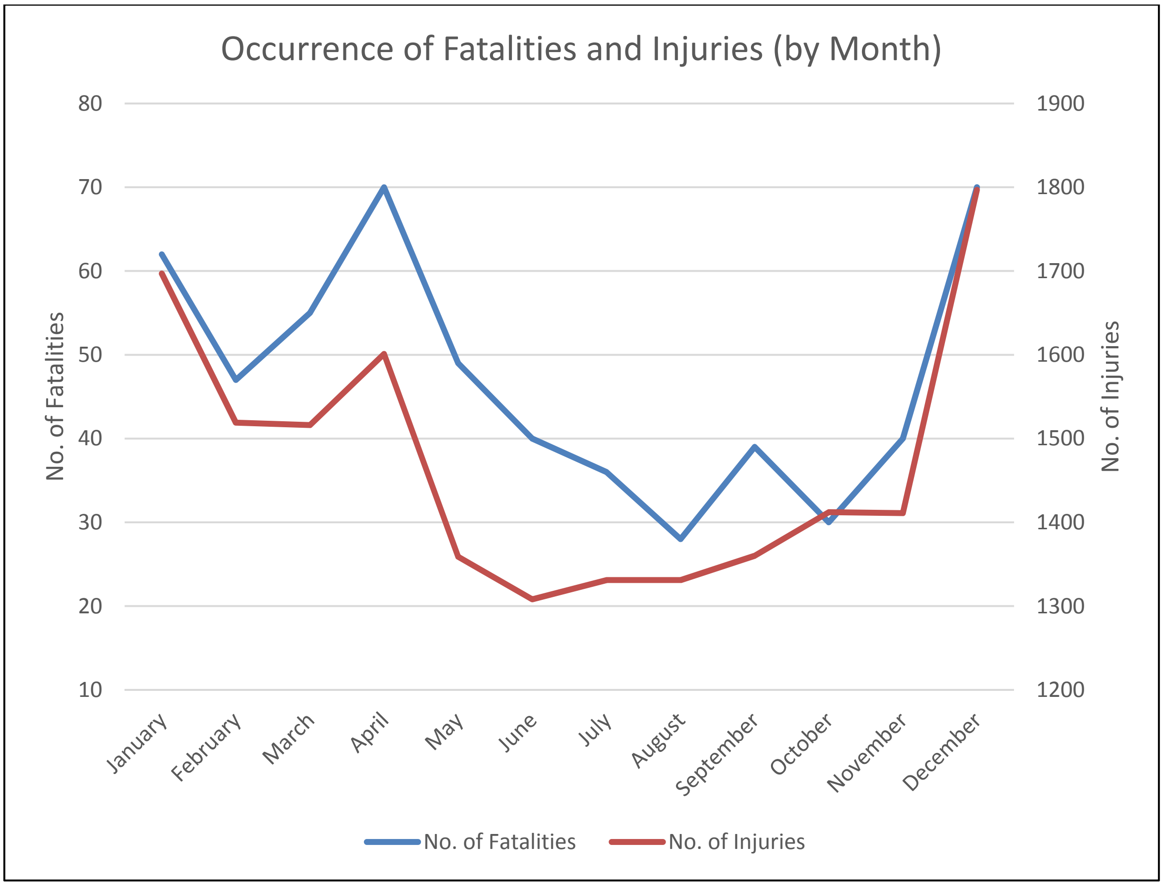


Figure 30 – Occurrence of fatalities and injuries DCLG 09-12 (by month)

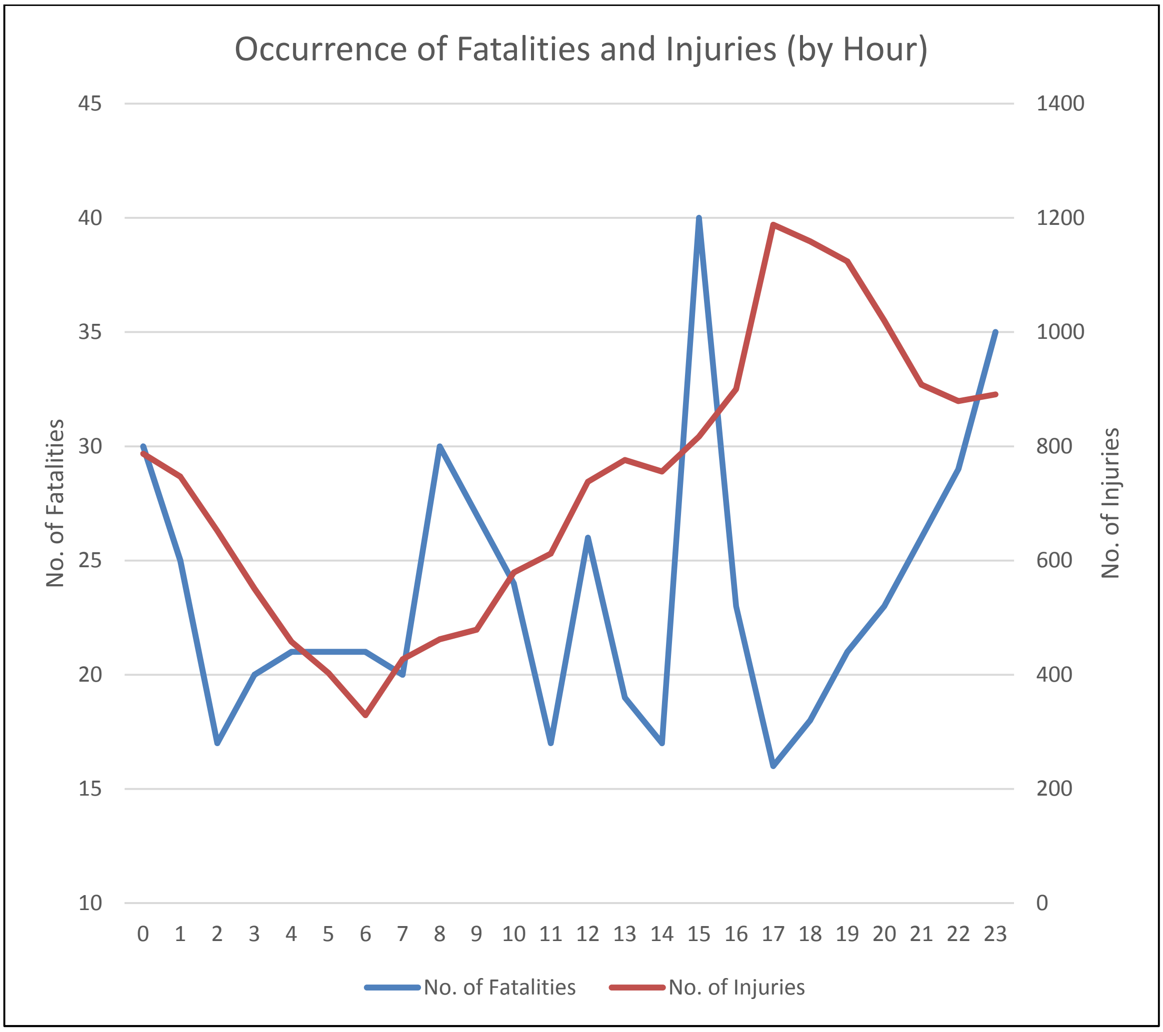


Figure 31 – Occurrence of fatalities and injuries DCLG 09-12 (by hour)

The time of day when people are injured or killed in ADFs is shown in Figure 31. The curve for fatalities does not show any particular trend other than a spike between 15-16pm. A slightly higher than average number of fire fatalities occur between 20pm and 2am. The curve for fire injuries in Figure 31 follows a more traditional shape with a trough between 1am and 11am and then an increased number of injuries from 12pm through to 00am the following day, with a peak at around 17-19pm.

2.3.2 Fire Alarm Analysis

This section considers the impact of having a fire alarm system within the property. It looks at the presence of fire alarms where fatalities and injuries have occurred, it establishes the location of the detector, whether the system operated and if it raised the alarm.

Table 12 shows the presence of a fire alarm system and it can be seen that 62% of fatalities and 73% of injuries occurred within a property with a smoke alarm. The presence of a smoke alarm is greater at those incidents where an injury occurred and it could be argued that the presence of the smoke alarm system is likely to have helped prevent a fatality at these incidents.

Alarm Present	Fatality		Injury	
	Count	Percentage	Count	Percentage
Yes	352	62.2%	12,946	73.4%
No	180	31.8%	4,481	25.4%
Don't Know	34	6.0%	215	1.2%
Grand Total	566	100.0%	17,642	100.0%

Table 12 – Presence of a fire alarm system DCLG 09-12

Table 13 shows the location of the fire alarm system where present. Traditionally fires are more likely to occur in habitable rooms and smoke detectors are located in rooms used for circulation such as hallways and landings. This leads to a low number of alarms being located in the room of fire origin, representing some 12-14% for injuries and fatalities.

Alarm Location	Fatality		Injury	
	Count	Percentage	Count	Percentage
Room of Origin	50	14.2%	1,537	11.9%
Same Floor as Fire	257	73.0%	10,080	77.9%
Different Floor from Fire	45	12.8%	1,329	10.3%
Grand Total	352	100.0%	12,946	100.0%

Table 13 – Alarm system location DCLG 09-12

Interestingly, a high number of alarms are located on the same floor as the fire as would be the recommendation of local F&RSs.

Of the 566 fatalities, there were 352 (62%) occasions where an alarm was present and only 228 (40%) times where the alarm actuated; of the 17,642 injuries, there were 12,946 (73%) occasions where an alarm was present and only 9,794 (56%) times where it actuated. For incidents where fatalities and injuries occurred the presence of a working smoke alarm was 40% and 56% respectively, with a greater coverage where injuries have occurred. Table 14 also identifies where the occupants are alerted and are not alerted when the alarm operates.

	Fatality		Injury	
Alarm Operated	Count	Percentage	Count	Percentage
Yes and raised alarm	135	38.4%	7,602	58.7%
Yes, but didn't raise alarm	93	26.4%	2,192	16.9%
No	124	35.2%	3,152	24.3%
Grand Total	352	100.0%	12,946	100.0%

Table 14 – Alarm system operated DCLG 09-12

Coverage then is much lower than the 88% of working smoke alarm ownership discussed in Section 1.7.5 [6]. This analysis suggests that, withstanding the fact that people are much more likely to own a smoke alarm now than they were 10-15 years ago, those groups within the community with a greater tendency to have a fire are less likely to have a working smoke alarm. In order to remedy this Fire Authorities continue to work to identify and target these more vulnerable groups within the community.

	Fatality		Injury	
Reason for Not Operating	Count	Percentage	Count	Percentage
Missing/Defective Battery	48	38.7%	1,004	31.9%
Fire Remote from Detector	16	12.9%	963	30.6%
Detector Removed	12	9.7%	220	7.0%
Fault with Alarm System	7	5.6%	411	13.0%
Other/Not Known	41	33.1%	554	17.6%
Grand Total	124	100.0%	3,152	100.0%

Table 15 – Reason that alarm system did not operate DCLG 09-12

Table 15 shows that the main reason for the alarm system not operating during these incidents was as a result of a missing or defective battery, for both fatalities and injuries. Completing a regular test of the smoke detectors would have identified these faults and some of the others in the list above.

	Fatality		Injury	
Reason for Not Raising the Alarm	Count	Percentage	Count	Percentage
Alarm raised before system operated	11	11.8%	1,283	58.5%
No Person in Earshot	11	11.8%	173	7.9%
Occupants did not Respond	36	38.7%	512	23.4%
Other/Not Known	35	37.6%	224	10.2%
Grand Total	93	100.0%	2,192	100.0%

Table 16 – Reason that the alarm system did not raise the alarm DCLG 09-12

For fire fatalities, Table 16 shows that the occupants do not respond to an actuating alarm 39% of the time. With fire injuries, it can be seen that the occupant becomes aware of the fire prior to the alarm actuating during 59% of incidents. This statistic is likely to have contributed towards the fact that these occupants were only injured during the incident and were not more seriously harmed.

2.3.3 Analysis of the Fire

When considering the fire itself, the raw data provides the opportunity for analysis of the source of ignition, the item mainly responsible for fire spread, the fire location and the fire size. This data is analysed to establish those factors which contribute towards having a detrimental impact upon those people exposed to the heat and smoke produced by the fire.

Source of Ignition	No. of Fatalities	No. of Injuries
Smoking Related	224	2,118
Cooking Appliance	70	9,213
Heating Equipment	54	1,009
Matches/Candles	50	1,291
Other Domestic Appliance	38	1,485
Naked Flame	26	274
Electricity Supply	21	996
Electric Lighting	5	269
Other/Not Known	78	987
Grand Total	566	17,642

Table 17 – Ignition source DCLG 09-12

The main source of ignition in fatal fires is related to the use of smoking materials and this is the cause of 40% of all ADF fatalities. In comparison, the main source of ignition for fire injuries is in relation to cooking appliances where these cause 52% of injuries. This data supports the analysis given in Section 2.1.3, where kitchen fires contribute towards 60% of dwelling fire injuries.

Table 18 shows the item mainly responsible for the spread of fire and it is therefore reasonable to assume that this is the item mainly responsible for the production of smoke in the early stages of fire development. In broad agreement with the analysis in Section 2.2, it shows that "Furniture/Furnishings" and "Clothing/Textiles" account for almost two thirds of fire fatalities, where as "Food" is the major contributor towards fire injuries.

Table 18 also contains the data for WMFS statistics from April 2009 to March 2015 (including 67 fatalities and 2,569 injuries resulting from ADFs) and there is reasonable agreement between the two sets of data.

Item Mainly Responsible	DCLG Data		WMFS Data	
	No. of Fatalities (%)	No. of Injuries (%)	No. of Fatalities (%)	No. of Injuries (%)
Furniture/Furnishings	41.7	15.5	41.8	15.4
Clothing/Textiles	21.9	12.6	29.8	11.5
Structure/Fittings - Internal	6.2	9.5	6.0	12.0
Food	3.7	34.3	8.9	42.4
Foam/Rubber/Plastic	3.0	5.8	0.0	2.7
Explosives/Gas/Chemicals	2.8	2.1	1.5	1.8
Rubbish/Waste/Recycling	2.1	2.2	6.0	1.4
Paper/Cardboard	1.4	2.8	0.0	3.0
Other/Not Known	17.1	15.2	6.0	9.8
Grand Total	100.0	100.0	100.0	100.0

Table 18 – Item mainly responsible for spread of fire DCLG 09-12/WMFS 09-15

Figure 32 shows that 71% of fatalities arise as a result of a fire in a bedroom/living/dining room (64% for WMFS) and 19% are from kitchen fires (25% for WMFS). They also show that 59% of injuries result from kitchen fires (63% for WMFS) and 29% result from a fire in a bedroom/living/dining room (27% for WMFS).

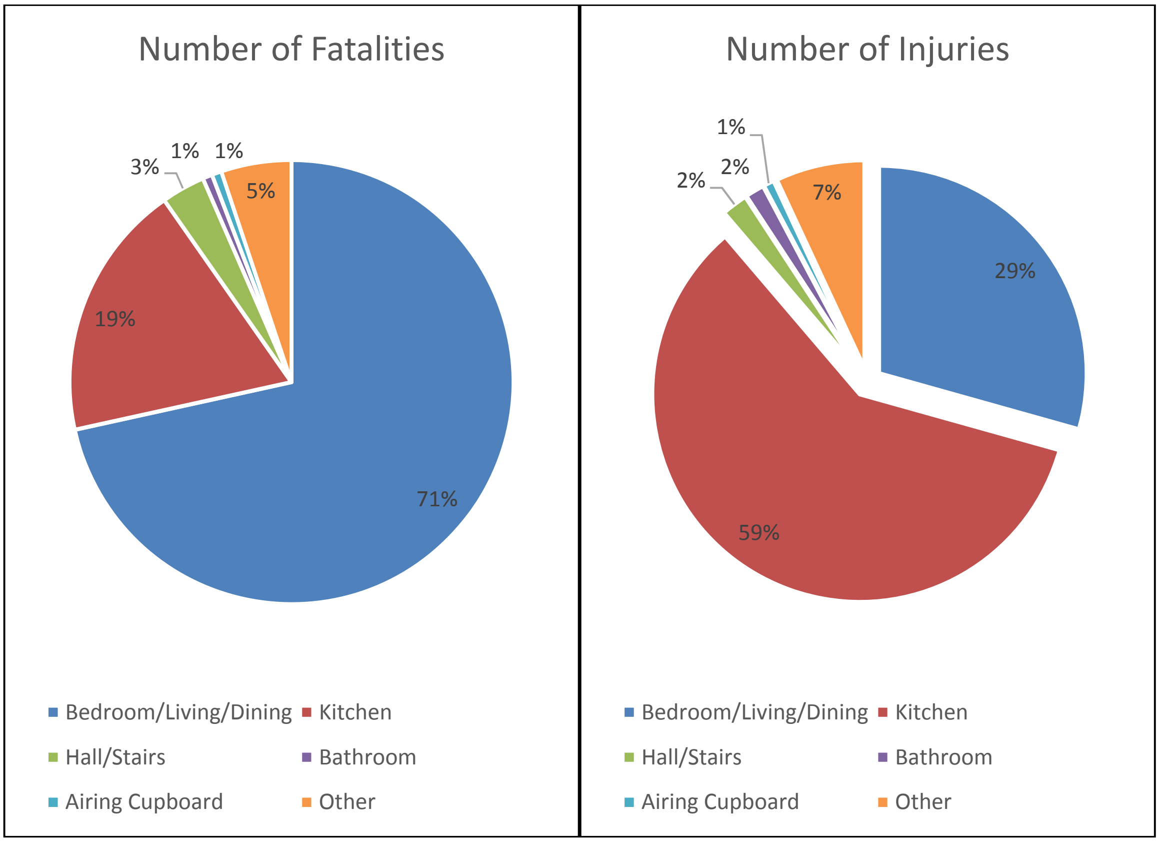


Figure 32 – Numbers of fatalities and injuries DCLG 09-12 (by fire location)

To some extent these data show the same trends as that in Section 2.1.3 and it is again in reasonable agreement with the figures from WMFS only. The West Midlands appears to have slightly greater numbers of fatalities and injuries from kitchen fires and slightly lower numbers from bedroom/living/dining room fires combined than the national average, but this may not be statistically significant.

It is also possible to analyse the number of fatalities and injuries against the size of the fire, or at least by the area of damage that it causes. Fire officers record two measurements, the first being the extent of damage caused by the fire and the second being the total extent of damage caused by fire, water, heat and smoke, based on floor area.

It would be reasonable to imagine that larger fires create a greater quantity of heat and smoke and therefore present an increased risk to the occupants of a building. This is borne out in Table 19, where it can be seen that 68% of all fatalities occur where fire damage is greater than $5m^2$ and that 72% of all fire injuries occur where fire damage is less than $5m^2$.

Fire Damage Area (m^2)	Fatalities		Injuries	
	Number	Cum. %age	Number	Cum. %age
None	22	3.9	2,540	14.4
Up to 5	160	32.2	10,128	71.8
6 - 10	108	51.2	2,030	83.3
11 - 20	102	69.3	1,377	91.1
21 - 50	89	85.0	1,030	97.0
51 - 100	49	93.6	371	99.1
101 - 200	21	97.3	101	99.6
201 - 500	8	98.8	38	99.8
501 - 1,000	6	99.8	21	100.0
1,001 - 2,000	0	99.8	3	100.0
2,001 - 5,000	1	100.0	3	100.0
Grand Total	566	100.0	17,642	100.0

Table 19 – Area of damage caused by fire DCLG 09-12

Figure 33 shows this information in graphical form with a propensity of red (injuries) below $5m^2$ and a propensity of blue (fatalities) where the fire damage is greater than $5m^2$.

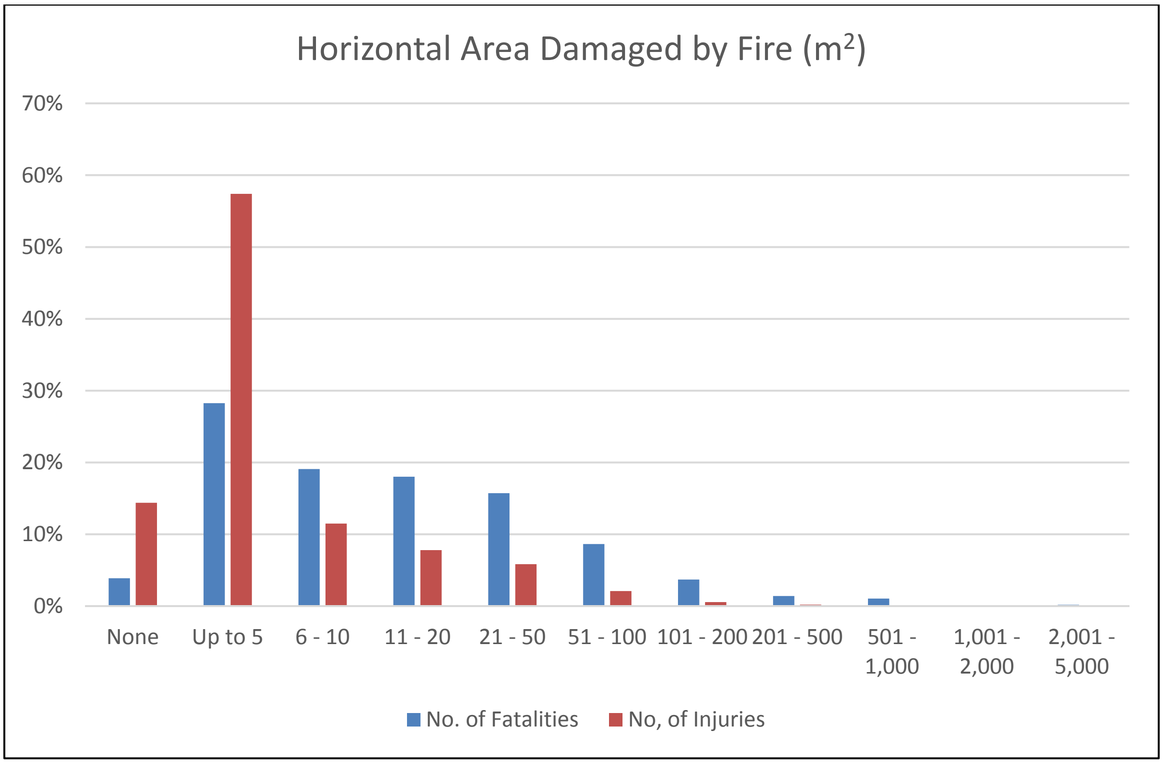


Figure 33 – Horizontal area damaged by fire DCLG 09-12

This is further reinforced by the total amount of damage during these fires as seen in Table 20, where it can be seen that 71% of all fatalities occur where the total damage is greater than 20m^2 and that 61% of all fire injuries occur where the total damage is less than 20m^2.

Total Damage Area (m^2)	Fatalities		Injuries	
	Number	Cum. (%)	Number	Cum. (%)
None	1	0.2	646	3.7
Up to 5	45	8.1	5,200	33.1
6 - 10	37	14.7	2,211	45.7
11 - 20	83	29.3	2,665	60.8
21 - 50	165	58.5	3,516	80.7
51 - 100	139	83.0	2,327	93.9
101 - 200	63	94.2	738	98.1
201 - 500	21	97.9	221	99.3
501 - 1,000	10	99.6	74	99.8
1,001 - 2,000	1	99.8	12	99.8
2,001 - 5,000	0	99.8	15	99.9
5,001 - 10,000	1	100.0	17	100.0
Grand Total	566	100.0	17,642	100.0

Table 20 – Total area of damage caused DCLG 09-12

Again, this is represented graphically in Figure 34 and again the red (injuries) are shifted to the left and the blue (fatalities) are shifted to the right. Whilst it is recognised that the size of the fire is an important factor when considering the likely outcome for those exposed in these situations, it is worth noting that fatalities do still occur where the fire size is relatively small and that people do survive large fire situations.

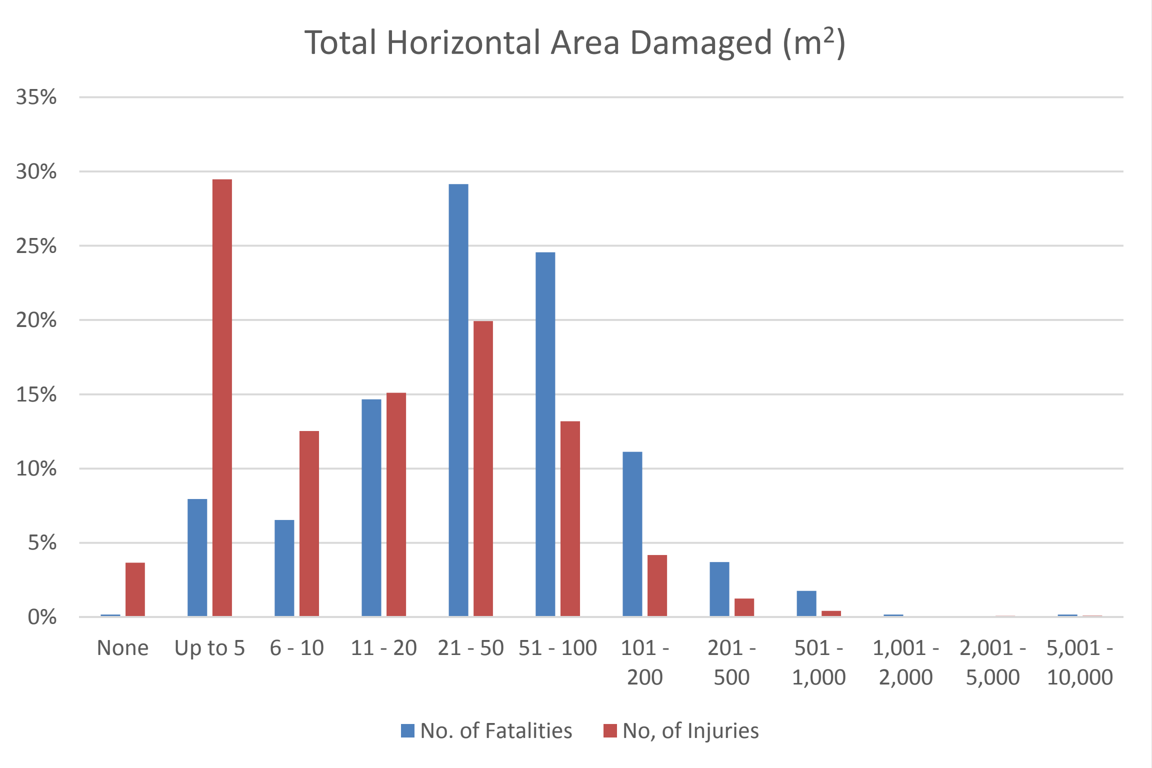


Figure 34 – Total horizontal area damaged DCLG 09-12

2.3.4 Analysis of the Human Factors

Raw data from DCLG allows for the analysis of those human factors which contribute towards a fire death or injury and also to establish if it was believed that drugs/alcohol played a part. According to Table 21 the top three human factors contributing towards fire fatalities are Falling Asleep (22%), Other Medical Condition (12%) and Disabled (8%) with the vast majority of cases having no human factors or that this information was not known.

The top three human factors contributing towards fire injuries are Distraction (21%), Falling Asleep (20%) and Other Medical Condition (6%) and again a significant number have no contributing factor or are unknown.

Human Factors	No. of Fatalities	No. of Injuries
Falling asleep/Asleep	122 (22%)	3,566 (20%)
Other medical condition/Illness	68 (12%)	1,036 (6%)
Disabled	45 (8%)	258 (1%)
Excessive and dangerous storage	13 (2%)	200 (1%)
Temporary lack of physical mobility	13 (2%)	106 (1%)
Distraction	12 (2%)	3,654 (21%)
None	92 (16%)	6,119 (35%)
Other/Not Known	201 (36%)	2,703 (15%)
Grand Total	566	17,642

Table 21 – Human factors contributing towards fatalities and injuries DCLG 09-12

Being under the influence of alcohol and/or drugs contributes towards 24% of fatalities and 19% of injuries, this information is also unknown in a significant number of circumstances.

Under Influence (Drugs or Alcohol)	No. of Fatalities	No. of Injuries
No	237	12,164
Yes	137	3,286
Don't know	192	2,192
Grand Total	566	17,642

Table 22 – The influence of drugs or alcohol DCLG 09-12

2.3.5 Victim Analysis

The IRS system gathers a significant amount of data about the people who are killed and injured in those incidents attended by the F&RS. Unfortunately, only a limited amount of this data has been provided by DCLG and that data is presented within this section of the thesis. It includes information about the age of the victim, the cause of the fatality and the extent of any injury.

Victim Age Bands	No. of Fatalities		No. of Injuries		
	Number	Percentage	Number	Percentage	Age of UK Population
0 to 15	42	7.4%	1,908	10.8%	19.0%
16 to 64	210	37.1%	11,109	63.0%	64.1%
65 plus	314	55.5%	4,625	26.2%	16.9%
Grand Total	566	100.0%	17,642	100.0%	100.0%

Table 23 – Age of victim DCLG 09-12

The actual age of each victim is recorded by the F&RS however the DCLG converts this information into age bands, presumably for data protection purposes. It is widely recognised that a disproportionate number of elderly people die each year in fires and this information is again borne out within this data [53]. Some 56% of all fire fatalities occur with people who are aged 65 or older, whereas the population of the UK who are this old is only 17% [80]. The number of injuries more closely represents the population of the UK, with a slight move towards the 65 and overs group being more susceptible to injury.

In the West Midlands (April 09 to March 15), there have been no fatalities in the age range 0 to 15, 48% of fatalities occurred in the band of 16 to 64 and 52% in the band 65 and over. WMFS statistics also identifies that males are more likely to become fatal casualties than females with 64% of fatalities being male.

The cause of fire fatalities is explored earlier in Section 1.7.9. Table 24 and Figure 35 give a further comparison of the DCLG raw data figures over the 3-year period and also the WMFS data over a 6-year period. All three data sets show reasonable agreement with smoke inhalation being responsible for around 45-50% of fatalities, a combination of burns and smoke giving around 20% and burns alone at around 15-20% with the remainder unknown.

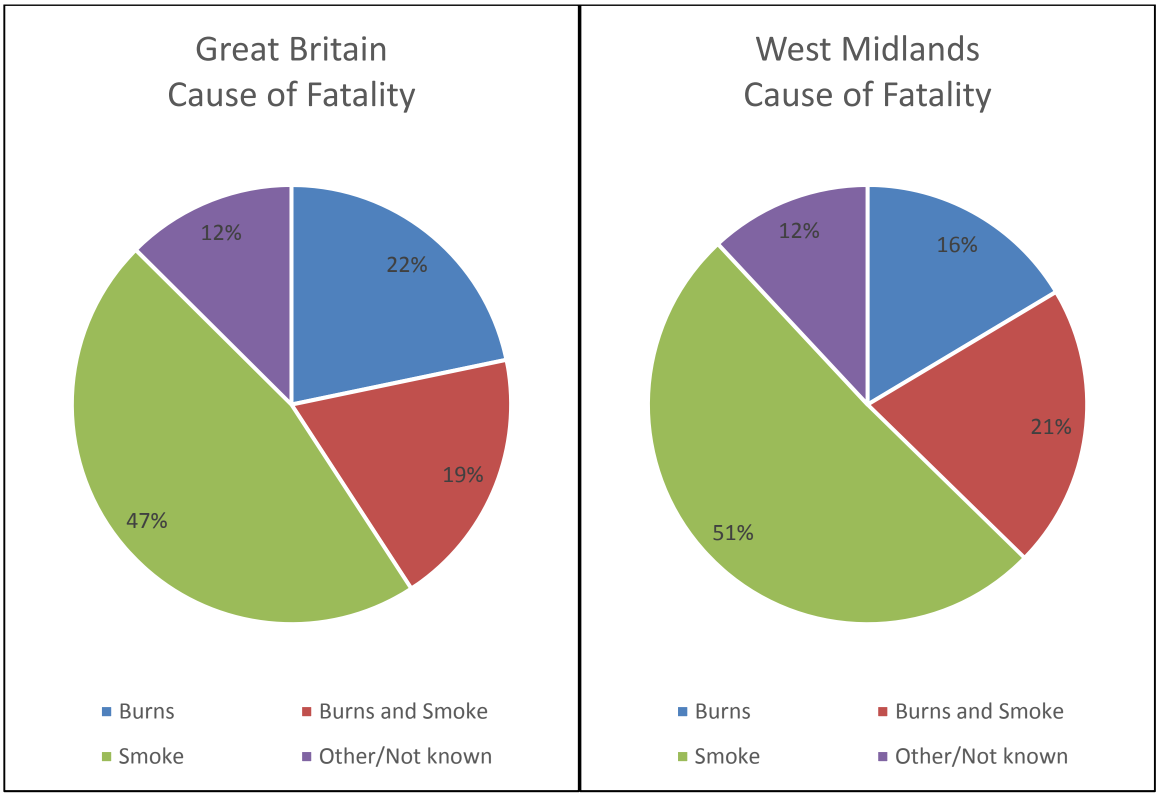


Figure 35 – Cause of fatality DCLG 09-12/WMFS 09-15

Cause of Fatality	DCLG raw data		WMFS raw data	
	Number	Percentage	Number	Percentage
Burns	123	21.7%	11	16.4%
Burns and Smoke	108	19.1%	14	20.9%
Smoke	264	46.6%	34	50.7%
Other/Not known	71	12.5%	8	11.9%
Grand Total	566	100.0%	67	100.0%

Table 24 – Cause of fatality DCLG 09-12/WMFS 09-15

Obviously this suggests that both the heat and smoke produced by fires can contribute towards human fatalities and that the mechanism by which each of these affect the occupants should be further explored.

Extent of Injury	No. of Injuries
Precautionary Check	3,653
First Aid given at Scene	6,241
Hospitalised (Injuries appear slight)	6,659
Hospitalised (Injuries appear serious)	1,089
Grand Total	17,642

Table 25 – Extent of Injury DCLG 09-12

The extent to which an occupant is injured is given in Table 25 and Figure 36, this data shows that the vast majority of all injuries require first aid to be given at the scene of the incident (often in the form of oxygen therapy) or require hospitalisation for injuries which appear to be slight. A significant number of casualties are given a precautionary check and only 6% of all injured casualties are hospitalised with what appears to be a serious injury.

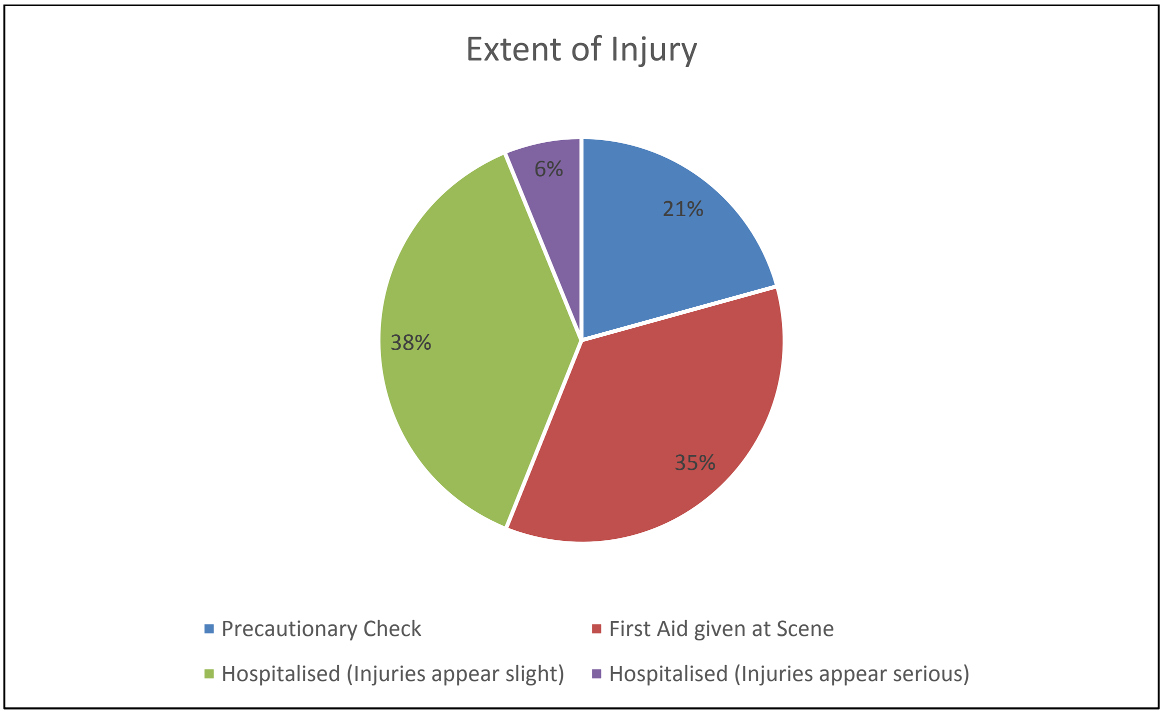


Figure 36 – Extent of injury DCLG 09-12

2.3.6 Combined Analysis (Time and Fire Location)

Of the 566 ADF fatalities, 481 occur as a result of a fire in either a bedroom, kitchen or living room, some 85%. A comparison of the fatal fires in these three locations is given in Figure 37 in conjunction with time of the fire. This graph shows that a moderate peak in kitchen fire fatalities occurs between 9-11am, bedroom fire fatalities peak between 15-17 pm and again between 21pm and midnight. There is a strong peak in living room fire fatalities between 15-16pm (also seen in Figure 31) and also a peak in the evening between 20pm and midnight.

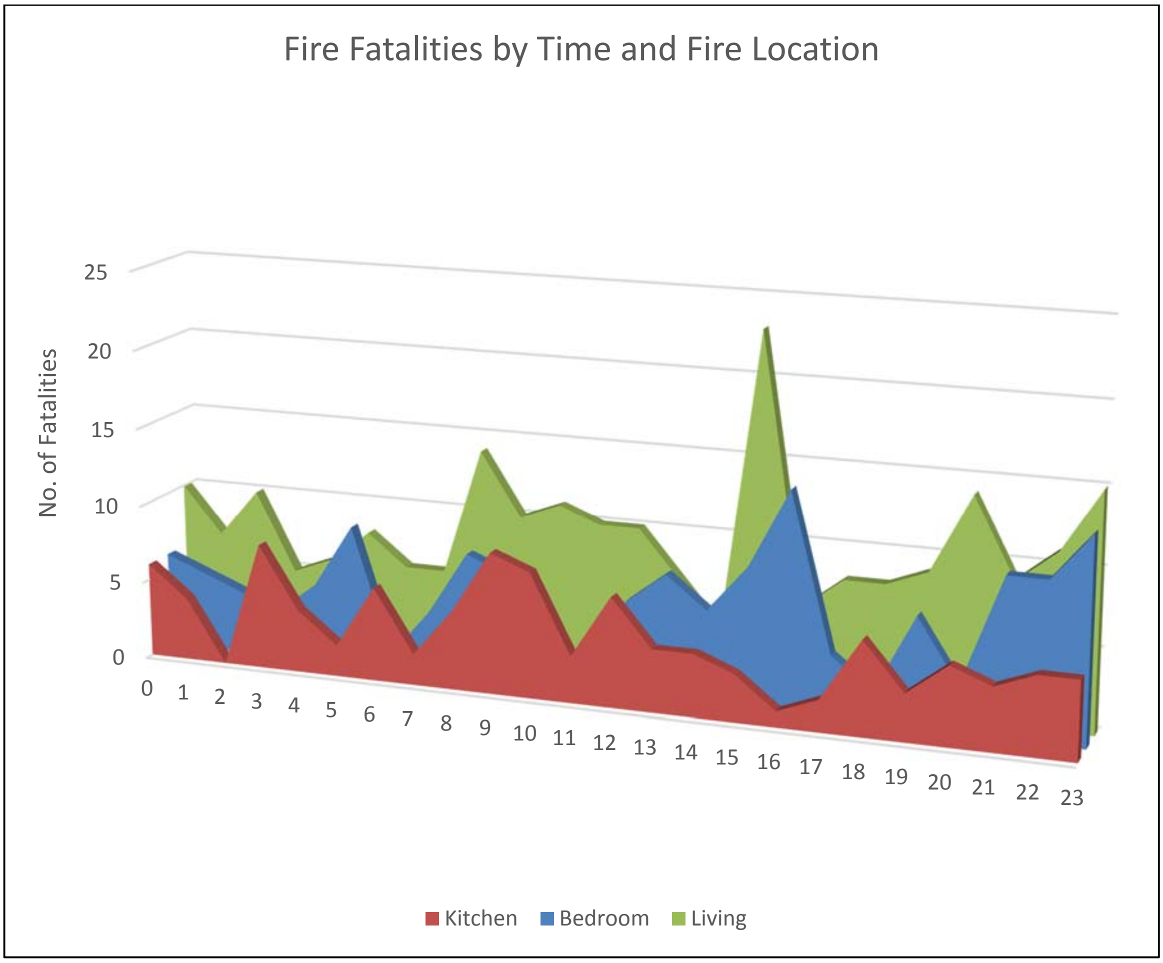


Figure 37 – Time and location of fire fatalities DCLG 09-12

Of the 17,642 ADF injuries 15,262 of them occur as a result of a fire in either a bedroom, kitchen or living room, some 87%. A comparison of those fires causing injuries, in these three locations, is given in Figure 38 in conjunction with the time of the fire. This graph shows that the vast majority of fire injuries occur as a result of kitchen fires and that living room fire injuries are above average from 17pm through to 5am the following day and below average for the remaining period. Similarly, bedroom fire fatalities are above average from 17pm through to 3am. For injuries resulting from kitchen fires, the peak appears to occur between 15pm and 21pm and this is a time where it is likely that people are cooking at home.

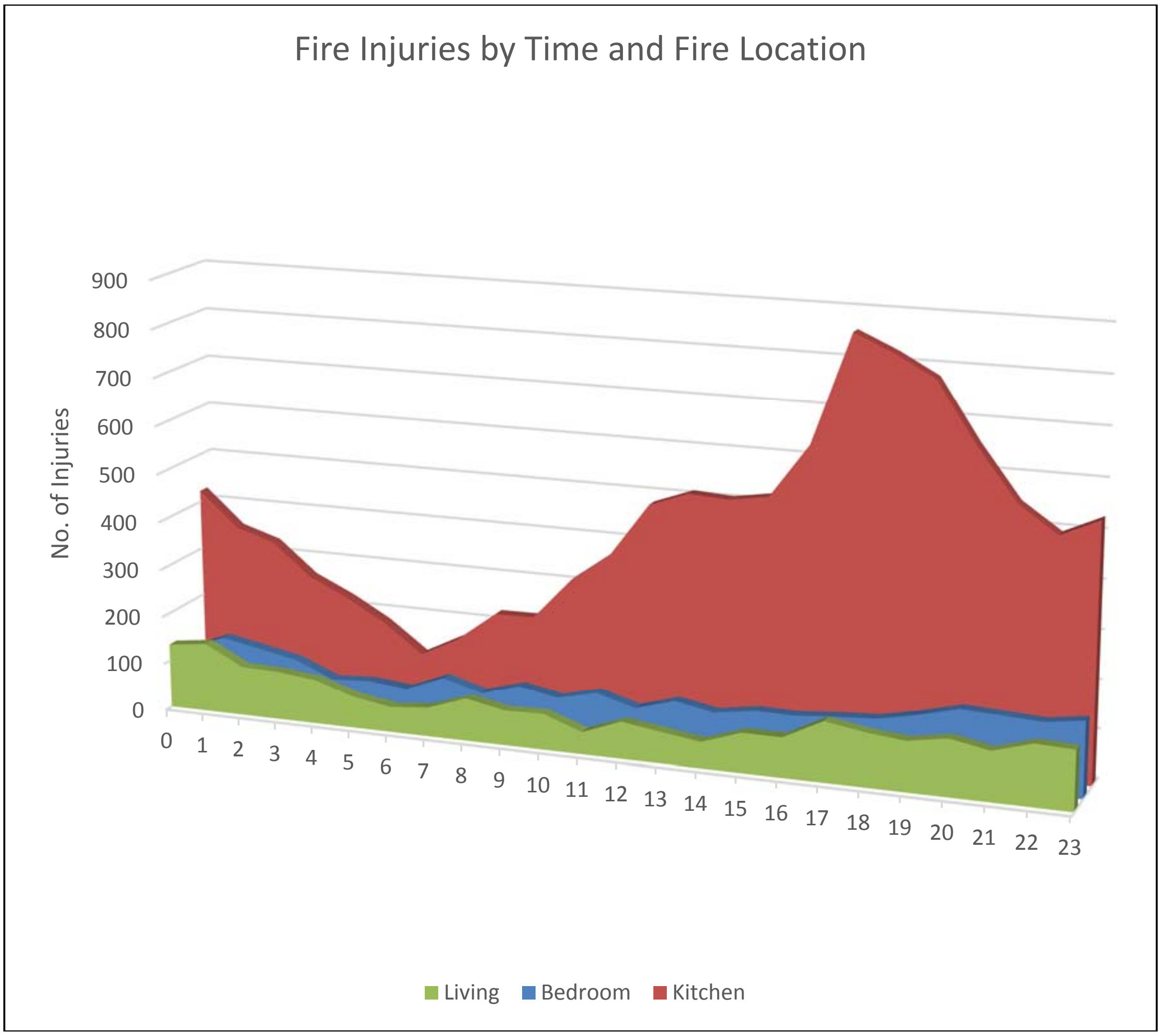


Figure 38 – Time and location of fire injuries DCLG 09-12

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2.4 Conclusions Drawn from the Statistical Analysis

The statistical analysis conducted within Section 1.7 and Chapter 2 has primarily been completed to understand the factors which lead towards fire injuries and fatalities in the UK. In addition, this data will help to identify those factors which should be considered and/or monitored within the experimental phase of this study. A summary of the conclusions drawn from these analyses are given below and will be used to determine the nature of the fire experimentation phase: -

- When considering the impact of human exposure to fire, this should be measured in respect of both heat exposure and smoke inhalation (Section 1.7.9)
- The vast majority of fire fatalities and injuries occur within dwelling fires where the motive was accidental (Section 1.7.11 and Section 2.1.2)
- The major rooms, within a dwelling, where fires occur that contribute towards human fatalities and injuries are the bedroom, living room and kitchen (Section 2.1.3)
- Living room and bedroom fires are more prominent for fire fatalities and kitchen fires lead to a greater number of fire injuries (Section 2.1.3)
- Some 70% of fire fatalities occur where the item mainly responsible for fire development is categorised as either “Furniture/Furnishings” or “Clothing/Textiles” and 95% of the fatalities occurring as a result of fires in BLD rooms involve this fuel type (Section 2.2.1)
- Some 42% of fire injuries occur where the item mainly responsible for fire development is categorised as a “Food” and 67% of the injuries occurring as a result of fires in kitchens involve this fuel type (Section 2.2.1)
- Working smoke alarms can improve the occupants chances of escaping safely although it is recognised that the people within our communities that are more likely to have a fire are less likely to own a working smoke alarm (Section 2.3.2)
- The main source of ignition in fire fatalities is “Smoking Related” with 40% and with fire injuries it is “Cooking Appliance” with 52% (Section 2.3.3)
- The size of the fire is critical with smaller fires more likely to lead to an injury and larger fires being more likely to lead to a fatality (Section 2.3.3)

Chapter 3 - Experimental Design

An understanding of the key factors leading to human casualties from fire has been established within Section 1.7 and Chapter 2. These factors and particularly those which are summarised in Section 2.4 have been used to design the experiments which have been carried out to gain further understanding of the hazards.

3.1 Project Aims

This section of the thesis aims to describe the design of the experiments which have been conducted to establish the timelines for human survivability. It will describe each individual scenario and will identify how the author will attempt to ensure that the data is of scientific value. It will also describe the methodologies for data gathering and will outline how comparisons between different experiments have been taken.

Each scenario is carefully designed to give a realistic fire and to present a hazard which is typical of those which are faced by members of the public in the UK. Overall the range of scenarios tested are believed to be representative of those of ADF.

It is critical that any large-scale fire testing should be representative of a realistic scenario and should also be reasonably reproducible such that good comparisons can be made between different tests. An assessment of the aforementioned studies by Su, Purser and Kerber have been considered alongside other sources of information on large-scale tests [81][82][83][84]. The purpose of this assessment has been to gain an increased understanding of large-scale experiments and fire chemistry, to inform the testing which has been conducted within this study.

3.2 Fire Scenarios Tested

A series of experiments have been designed with the aim of obtaining reproducible results for a number of realistic, domestic fire scenarios which have the potential to cause fire deaths and injuries, where the building is occupied. The objective of these experiments is to gather data indicating the point at which a given fire scenario is likely to render the occupants of a building incapacitated or dead. The following organisations have been working in collaboration to run these experiments and to gather the scientific data: -

- WMFS – project management, experimental design, risk assessment and safety marshal
- UCLAN (CFHS) – gas component, thermal and mass loss data analysis and expert advice
- SPRUE AEGIS – smoke detector actuation and smoke obscuration data analysis
- Birmingham City Council – provision of unoccupied buildings to enable experimentation

Details of the fire scenarios are summarised in Table 26. For all of the following scenarios gas component, thermal analysis and smoke detector actuation data have been gathered in various places throughout the property both within and outside of the fire compartment. Mass loss data has been gathered for Scenarios 2-7 and 9-11, which are located in the lounge. For scenarios 1 and 2, two experiments have been conducted to establish reproducibility.

Experiment No.	Scenario	Fire Location	Fuel	Fire Compartment Door	Ventilation	Open Vent Details
1	1	Kitchen	Cooking Oil	Open	2m^2	Front Door (full height 1m^2) Lounge Window (full height 1m^2)
2	1	Kitchen	Cooking Oil	Open	2m^2	Front Door (full height 1m^2) Lounge Window (full height 1m^2)
3	2	Lounge	Sofa	Open	2m^2	Front Door (full height 1m^2) Kitchen Window (full height 1m^2)
4	2	Lounge	Sofa	Open	2m^2	Front Door (full height 1m^2) Kitchen Window (full height 1m^2)
5	3	Lounge	Sofa	Closed	2m^2	Lounge Window (full height 2m^2)
6	3	Lounge	Sofa	Closed	2m^2	Lounge Window (full height 2m^2)
7	4	Lounge	Sofa	Open	0.5m^2	Lounge Window (upper 0.50m^2)
8	5	Lounge	Sofa	Open	0.5m^2	Lounge Window (upper 0.50m^2) Bedroom Window (full height 1m^2)
9	6	Lounge	Sofa	Closed	0.5m^2	Lounge Window (upper 0.50m^2)
10	7	Lounge	Sofa	Open	2m^2	Front Door (full height 1m^2) Bedroom Window (full height 1m^2)
11	8	Kitchen	Fully furnished	Open	2m^2	Front Door (full height 1m^2) Lounge Window (full height 1m^2)
12	9	Lounge	Fully furnished	Open	2m^2	Front Door (full height 1m^2) Kitchen Window (full height 1m^2)
13	10	Lounge	Fully furnished	Open	0.5m^2	Lounge Window (upper 0.50m^2)
14	11	Lounge	Fully furnished	Closed	2m^2	Lounge Window (full height 2m^2)

Table 26 – List of fire experiments

3.2.1 Scenario 1

Experiments 1 and 2 comprise a steady state fire simulating overheated cooking oil contained within a pan on a stove within the kitchen (i.e. the fire compartment and other rooms will otherwise contain no combustible materials). These experiments were well-ventilated and the fire compartment door was held open to allow the products of combustion to travel around the remainder of the property.

3.2.2 Scenario 2

Experiments 3 and 4 comprise a growing fire using a single sofa as the only fuel source (i.e. the fire compartment and other rooms otherwise contained no combustible materials). These experiments were well-ventilated and the fire compartment door was held open to allow the products of combustion to travel around the property.

3.2.3 Scenario 3

Experiments 5 and 6 comprise a growing fire using a single sofa as the only fuel source. These experiments were comparatively under-ventilated and the fire compartment door remained closed. This minimised the transfer of smoke within the property and the effectiveness of this basic passive fire protection measure has been established. The doors used within these experiments were traditional domestic doors, they were not fire doors and were not fitted with smoke seals.

It is reasonable to suggest that in a compartment where the doors and windows are all closed, the likelihood is that the fire will become starved of O_2 and will burn itself out. Ventilation direct to the fire compartment was therefore provided.

3.2.4 Scenario 4

Experiment 7 comprises a growing fire using a single sofa as the only fuel source. This experiment was under-ventilated (compared with Scenario 2) and the fire compartment door was held open to allow the products of combustion to travel around the remainder of the property.

3.2.5 Scenario 5

Experiment 8 comprises a growing fire using a single sofa as the only fuel source. This experiment was under-ventilated (compared with Scenario 2) and the fire compartment door was held open to allow the products of combustion to travel around the remainder of the property. A bedroom window was held open to consider the effects of first floor smoke ventilation.

3.2.6 Scenario 6

Experiment 9 comprises a growing fire using a single sofa as the only fuel source. This experiment was under-ventilated (compared with Scenario 3) with the window partially open and the fire compartment door closed. This minimised the transfer of smoke within the property and the effectiveness of this passive fire protection measure was established.

3.2.7 Scenario 7

Experiment 10 comprises a growing fire using a single sofa as the only fuel source. This experiment was well-ventilated and the fire compartment door was held open to allow the products of combustion to travel around the remainder of the property. A bedroom window was held open to consider the effects of first floor smoke ventilation.

3.2.8 Scenario 8

Experiment 11 initially comprises a steady state fire using cooking oil contained within a pan. Additional fire loading was contained within the kitchen only (i.e. floor and wall mounted kitchen units and other combustibles). This fire scenario therefore had the potential to grow into a fully involved compartment fire. This experiment was well ventilated and the fire compartment door was held open to allow the products of combustion to travel around the remainder of the property.

3.2.9 Scenario 9

Experiment 12 comprises a growing fire initially ignited on a single sofa. There was additional fire loading contained within the lounge only (i.e. additional furniture, carpet, curtains etc.). This fire scenario therefore had the potential to grow into a fully involved compartment fire. This experiment was well-ventilated and the fire compartment door was held open to allow the products of combustion to travel around the remainder of the property.

3.2.10 Scenario 10

Experiment 13 comprises a growing fire initially ignited on a single sofa. There was additional fire loading contained within the lounge only (i.e. additional furniture, carpet, curtains etc.). This fire scenario therefore had the potential to grow into a fully involved compartment fire. This experiment was under-ventilated and the fire compartment door was held open to allow the products of combustion to travel around the remainder of the property.

3.2.11 Scenario 11

Experiment 14 comprises a growing fire initially ignited on a single sofa. There was additional fire loading contained within the lounge only (i.e. additional furniture, carpet, curtains etc.). This fire scenario therefore had the potential to grow into a fully involved compartment fire. This experiment was well-ventilated and the fire compartment door remained closed. This minimised the transfer of smoke within the property and the effectiveness of this passive fire protection measure can be established.

3.3 Experimental Comparison

The scenarios have been designed such that the number of variables between different experiments is kept to a minimum. This is required in order to isolate the deliberate variations that have been made and to identify any effects that they have. The experimental design considers a number of variables as discussed in the following sections and was developed by the author, in consultation with managers from within WMFS, technical advisors from UCLAN and with Prof David Purser who has significant experience in undertaking large scale fire tests and quantifying the toxic gases produced [23].

3.3.1 Fuel Comparison

A comparison of the findings from Scenarios 1 and 2 yields information which identifies the specific hazards associated with cooking oil and upholstered furniture as different fuel types. The statistical analysis conducted within Chapter 2 identifies that fire fatalities typically arise as a result of fires involving furniture and furnishings. Conversely the statistics show that fire injuries typically occur as a result of fires involving foodstuffs, particularly cooking oil.

3.3.2 Passive Fire Protection Comparison

Passive fire protection, within these scenarios, is provided in the form of closed doors as recommended within WMFS's 'night time routine' campaign. This passive measure was evaluated for its ability to protect the occupants in all experiments. Gas concentrations were taken in two separate first floor bedrooms concurrently, one bedroom having a closed door and the other bedroom having an open door. Additionally, comparisons between Scenarios 2 and 3, Scenarios 4 and 6 and Scenarios 9 and 11 indicated the level of protection afforded when the fire compartment door was closed.

3.3.3 Comparison of Smoke Detector Actuation Times

A critical factor when considering survivability, within a domestic fire situation, is the occupant's recognition that they are faced with a hazardous situation as a result of early fire detection and alarm.

In all 11 scenarios, the point at which the fire is detected by the automatic heads was recorded by measuring the electrical response from the smoke detectors. This data informed the analysis in respect of the following parameters.

- The alarm actuation time was assessed to establish whether or not it was possible for the occupants to escape from within the property without the aid of the F&RS. Essentially, the tenability of the staircase was determined at a relevant point and deemed either passable or impassable, condition dependent.
- The alarm actuation time is a distinct point from which F&RS intervention times have been calculated, based on the assumption that once the occupants become aware that there is a fire, they call 999.

3.3.4 Comparison of Ventilation Levels

The degree of ventilation afforded to a compartment fire is also perceived to be critical when it comes to the rate of fire development and the rates of production of the various products of combustion. It is widely recognised that under-ventilated fires are more likely to produce increased levels of the asphyxiant gases CO and HCN [23] and other products of incomplete combustion. In order to determine the human effects of under-ventilated fires in comparison to well-ventilated fires, a comparison was made between Scenarios 2 and 4, Scenarios 3 and 6 and Scenarios 9 and 10. It is also recognised that a well-ventilated fire will potentially grow faster and an under-ventilated fire will potentially produce a higher yield of asphyxiant gases.

3.3.5 Comparison of Duplicate Tests

As part of the experimentation, a number of the tests are duplicated to try to assess the reproducibility of a specific test set up. It is was recognised that the phenomenon of fire is affected by many external factors and that it is not always possible to get reproducible results. Every effort was made to ensure that those external factors which are controllable are in fact controlled to help with reproducibility. Experiments 1 and 2, 3 and 4 and 5 and 6 are all identical and were used to establish reproducibility.

3.3.6 Comparison of Fire Loading

A comparison was made between experiments where a single item was involved in combustion and where the fire was allowed to spread to a fully furnished compartment. Scenario 1 has been compared with Scenario 8 to consider the fully furnished kitchen fire situation and Scenarios 2 and 9, Scenarios 4 and 10 and Scenarios 3 and 11 have been compared to consider a fully involved lounge fire.

3.4 Experimental Data Gathering

Working in conjunction with UCLAN (Rob Crewe/Richard Hull), SPRUE AEGIS (Stuart Hart/James King), ISG (Mark Smith) and WMFS (various) the fire experiments have been designed to locate the measurement equipment to best support this study. All organisations providing instrumentation to support the data gathering process have signed a data sharing agreement. Details of the various measurement processes are given below.

For the purposes of this study and in lieu of the fact that sensory irritancy and smoke obscuration are not likely to be significant factors, the focus will be towards assessing the hazards presented by the asphyxiant gases and heat.

During the experimentation and data gathering activities carried out within this project, temperature data has been gathered in a number of locations, however, no heat flux data has been collected. On this basis, the FED from the convective portion of heat only has been considered. It was expected that the convective portion will certainly be the main consideration outside of the fire compartment, where radiated heat doses are limited.

3.4.1 Gas Analysis

During the fire tests data was gathered to establish the gas concentrations for CO, CO_2, O_2 and HCN. The data for CO, CO_2 and O_2 was continuously monitored through the use of non-dispersive infrared (CO, CO_2) and electrochemical cells (O_2). This equipment takes 40 readings per minute such that the concentrations are updated every 1.5 seconds. HCN concentrations were determined by bubbling effluent through a sorbent solution (Sodium Hydroxide). Analysis of the solution allows the gas phase HCN concentrations to be calculated as an average over the time period of bubbler sampling. The HCN concentrations are less precisely known as a function of time, but are essential as they are expected to contribute significantly to the overall hazard to life.

Gas sampling was undertaken in two separate bedrooms on the first floor, one with its doorway open and one with its door closed. In addition, samples were taken on the first floor landing and within the fire compartment (remote from the fire), with all sample points being placed at a typical head height position of 1.6m above the floor. HCN data has only been gathered where nitrogen containing fuels are likely to be involved.

3.4.2 Mass Loss Data

In order to determine the rate at which the fuel is being consumed by the fire, a series of load cells were set up to calculate the mass loss of fuel. This data was utilised to establish the rates of smoke production, the yields of toxic products and typical fire growth rates. Comparisons were also be made to check the reproducibility of the live fire tests and this allows the results to be extrapolated to other fire scenarios. Mass loss data has only been collected for the sofa in the lounge fire scenarios.

3.4.3 Temperature Profiles

A series of thermocouple trees were located throughout the premises to gather data on the temperature profiles within various compartments. Thermocouples were attached to a vertical stanchion at 300 mm intervals to measure the temperature profile between floor and ceiling, with continuous data being recorded on a data logger. Thermocouple trees were located within the fire compartment (lounge or kitchen), on the first floor landing, and within the two bedrooms, for comparison and to look at dilution rates as the smoke is transported. Temperature profiles have been, analysed in conjunction with gas analysis to determine the quantity and concentration of smoke being produced by the fire.

3.4.4 Video Footage

Video footage was taken from within the building whilst the fire scenarios were being conducted. This evidence was used to interpret unexpected values in other streams of data. Video equipment using both visual and thermal imaging cameras was used to document fire growth and smoke transportation. Key locations for data gathering include the fire compartment, the hallway and the landing.

3.4.5 Smoke Detector Actuation Times

Domestic ionisation smoke detectors were fitted throughout the property and linked to data logging equipment. When each detector reaches its threshold it goes into alarm mode, producing an audible warning and a flashing light. During these experiments the audible warning had been disarmed for each detector to minimise noise interference and electrical responses from each detector were measured to determine the actuation time for that head. Different alarm heads, calibrated to have different actuation thresholds, were monitored either side of the standard threshold to obtain an accurate fire detection and alarm time.

Detectors were located within the typical locations of the property, namely in circulation spaces in the hallway on the ground floor and the landing on the first floor. Additional detection was also be placed within the fire compartment and within the bedrooms.

3.4.6 Visual Obscuration

A simple piece of apparatus was developed by Sprue to establish the visibility within a room at a given time. This apparatus can be seen in Plate 3 and is a controlled way of suspending a light source and a photoelectric cell, each 1m apart, at a height of 1.5 m above floor level. Data from this source can be converted to identify the reduction in visibility caused by the smoke and gives the distance to which the human eye can see.

It has been shown that smoke-logging to corridors or walkways will reduce the walking speed for an escaping person [85]. Where visibility along the escape route is reduced to less than 3 m it has been shown that the occupier is unlikely to travel through these conditions [42][86][87], it will be assumed that the occupants will turn and go back.

Plate 3 – Visual obscuration monitoring equipment

3.5 Calibration of Equipment

Efforts were made to ensure that all data gathering equipment is scientifically calibrated prior to use in a test; this will be achieved as follows: -

- $CO/CO_2/O_2$ – the equipment used for establishing the gas concentrations was regularly calibrated using standard calibration gas samples, these are shown in Appendix C
- HCN – samples for HCN concentrations were gathered and returned to UCLAN after each day of testing; their concentrations will be based on the mass of KCN used as a primary standard. Analysis was undertaken within 48 hours to avoid degradation of samples
- Temperature profiles – thermocouples tend to be fairly robust and reliable, each thermocouple was tested prior to the series of experiments
- Smoke detection – each head was individually calibrated by the manufacturer prior to use
- Mass loss – this equipment uses amplified electrical responses to quantify the load placed upon each cell; it is calibrated with a known mass before use
- Visual Obscuration – this equipment takes a fractional value which is compared to a baseline immediately prior to the test and can therefore establish obscuration without any calibration

3.6 Location for Fire Testing

Each of the fire tests was conducted within an unoccupied house in Birmingham. The property was offered to WMFS, for the purposes of running these tests, by Birmingham City Council. This property was carefully selected to enable the study to be completed in a real house so that the data would be relevant to a typical fire, rather than being completed in a custom-built test facility.

An external photograph of the premises is given in Plate 4 and shows that this is a semi-detached house. The fire tests were conducted in the property to the left of this photograph and much of the data logging equipment was stored in the property on the right with access holes being made in the interconnecting internal wall for pipework and cabling. All holes were then be sealed with fire resistant expanding foam to retain the building’s integrity. Security grills were removed as appropriate to allow for full control of the ventilation conditions.

Plate 4 – External picture of the property used for testing (left hand side)

The internal layout of the property can be seen in Figure 39 and Figure 40, which show the ground and first floor plans and show a ceiling height of 2.45 m throughout, not to scale.

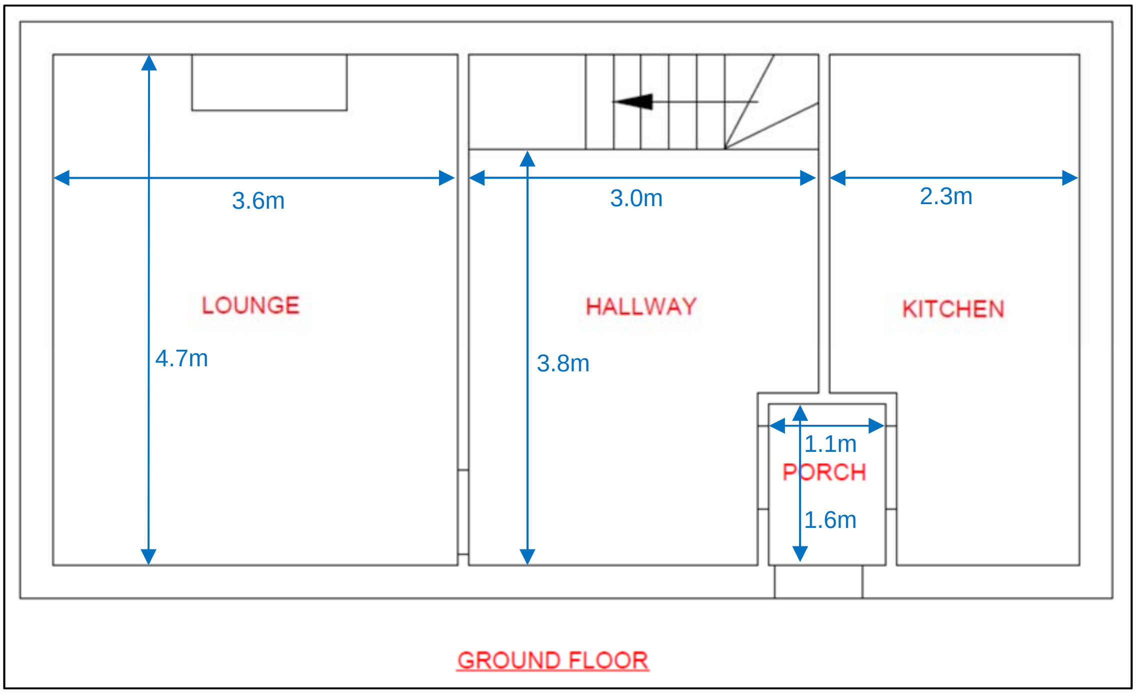

Figure 39 – Ground floor plan of property used for testing

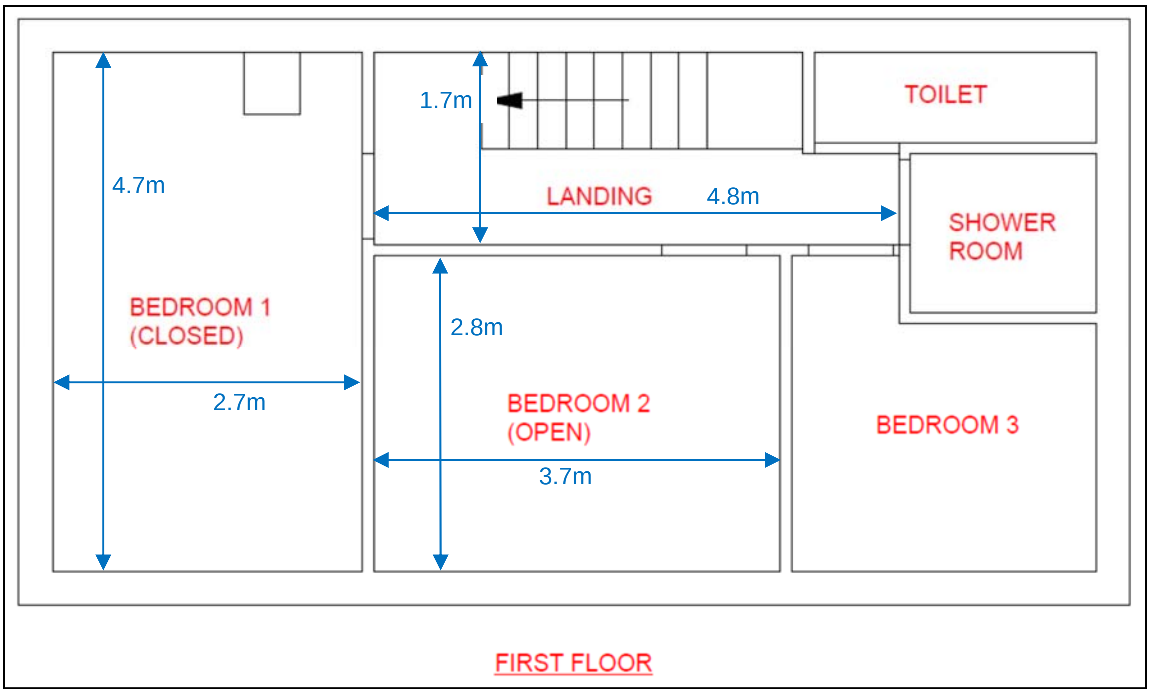

Figure 40 – First floor plan of property used for testing

3.7 Description of Fuel Sources

This section is used to describe the types of fuel which were used in each of the different fire scenarios and the method for ignition of these fuel packages.

3.7.1 Kitchen Fuel Source

On the basis of the conclusions drawn in Section 2.4, the kitchen fire scenarios involved the ignition of a quantity of cooking oil. A large pan was placed on top of a propane gas burner as seen in Plate 5. The pan was filled with 2.5 L of sunflower oil and the burner was ignited. The oil needed to be heated from its ambient temperature for some considerable time until it reached a point where piloted ignition could occur and flaming combustion could be sustained. The burner remained ignited for the duration of each of these experiments. Experiments 1 and 2 only involved the burning oil and Experiment 11 was allowed to spread from the oil to nearby combustible cupboards.

Plate 5 – Image of kitchen fire fuel source (post-ignition)

3.7.2 Lounge Fuel Source

The fuel in the lounge fire scenarios is an upholstered two-seat sofa. In order to achieve reproducibility between experiments, a total of eleven identical brand new sofas were purchased. The fuel for the lounge fires is much more complex in terms of its composition and these sofas conform to the current Furniture and Furnishings (Fire) (Safety) Regulations [60]. The furniture is delivered in 6 separate parts with a seat base, a seat back, a left arm, a right arm, four feet and a bag of fixings. The base, back and arms were all made from a timber frame with a mixture of polyurethane foam and non-woven polyester wadding used to provide cushioning.

The mass of each of the component parts of the sofa was accurately measured and the mass of each component is shown in Table 27 overleaf; the total mass of the sofa was just in excess of 63 kg. These masses are then grouped together in Table 28, which shows that 62% of the mass of the sofa comes from timber materials and 30% comes from manmade plastic materials either in an expanded foam or fibrous form. Non-combustible metal components make up 6% of the mass and the remaining 2% is made equally from cardboard and cotton.

In all experiments involving fires in the lounge, the sofa was placed in the same position against an external wall, as indicated in Figure 41, Section 3.8. The sofa was raised slightly onto a platform which was held up by the 4 load cells. This raised the sofa up slightly from the floor, by approximately 8 cm, but allowed the mass of the sofa to be recorded constantly throughout the experiment.

		Seat Base	Seat Back	Left Arm	Right Arm	Feet	Fixings	Total
Frame	Solid Pine	3.00	3.46	1.17	1.17	-	-	8.80
	Fibreboard	0.10	3.68	1.22	1.22	-	-	6.22
	Particleboard	2.60	1.04	6.20	6.20	-	-	16.04
	Plywood	1.52	2.76	0.62	0.62	-	-	5.52
	Cardboard	-	0.02	0.42	0.42	-	-	0.86
	Steel Support	0.60	-	-	-	-	-	0.60
Springs	Steel	2.30	-	-	-	-	-	2.30
Elastic Webbing	40% rubber 60% polypropylene	-	0.16	-	-	-	-	0.16
Covering Material	Non-woven Polypropylene	0.94	1.42	0.72	0.72	-	-	3.80
Cushioning	PU Foam (calf support - 20kg/m3)	0.04	-	0.04	0.04	-	-	0.12
	PU Foam (memory foam - 50kg/m3)	2.12	-	0.56	0.56	-	-	3.24
	PU Foam (standard - 25kg/m3)	0.20	0.02	-	-	-	-	0.22
	PU Foam (standard - 35kg/m3)	4.16	-	0.24	0.24	-	-	4.64
	Polyester Wadding (sheet form)	0.46	0.30	0.44	0.44	-	-	1.64
	Polyester Wadding loose form)	-	5.32	-	-	-	-	5.32
	Cotton Wadding bag	-	0.26	-	-	-	-	0.26
Leg	Solid Pine	-	-	-	-	2.52	-	2.52
Fire-retarding interliner	100% Cotton	0.22	0.10	0.04	0.04	-	-	0.40
Fixings	Metal Bolts	-	-	-	-	-	0.60	0.60
	Total	**18.26**	**18.54**	**11.67**	**11.67**	**2.52**	**0.60**	**63.26**

Grand Total	**63.26**	kgs

Table 27 – Material composition of the sofas used in lounge fires

Material	Mass (kg)	Percentage Mass
Timber	39.10	61.8
Polyurethane	8.22	13.0
Polyester	6.96	11.0
Polypropylene	3.96	6.3
Metal	3.50	5.5
Cardboard	0.86	1.4
Cotton	0.66	1.0
Total	63.26	100.0

Table 28 – Material groupings for the sofas used in lounge fires

Plate 6 – Image of lounge fire fuel source (pre-ignition)

In accordance with furniture and furnishings regulations compliance, the sofas would not readily ignite when exposed to a lit cigarette or match. Where house fires occur however, it is still commonplace for sofas which comply with these regulations to readily contribute towards the fire. This usually occurs as a result of a small fire being initiated and then spreading to the sofa. A typical example of this would be a newspaper or a material throw which is ignited first and creates enough heat to ignite the sofa.

In order to ensure that the sofa is ignited, the arm-rest and the vertical and horizontal cushion fabric was scored using a knife on each surface, in close proximity. This can be seen in Plate 7 where the material has a cut of approximately 12cm on the arm, the seat and the back. Two sheets of crumpled newspaper were placed into each of the three cuts. A photograph of the sofa shortly after ignition is given in Plate 8 to show the early stages of fire development.

Plate 7 – Method of ignition for the sofa

Plate 8 – Image of lounge fire fuel source (post-ignition)

In accordance with the findings of the statistical analysis, it might have been relevant to complete a number of tests involving fires in bedrooms. These additional experiments would have placed a burden on the experimental phase and may have meant that repeat experiments were not possible to establish reproducibility.

For the purposes of this study, it is reasonable to assume that a fire in a bedroom would present a risk to the occupants of the property, which is equivalent to that of a fire in the lounge.

3.8 Location of Sampling Points

Figure 41 and Figure 42 show the locations where measurements were taken.

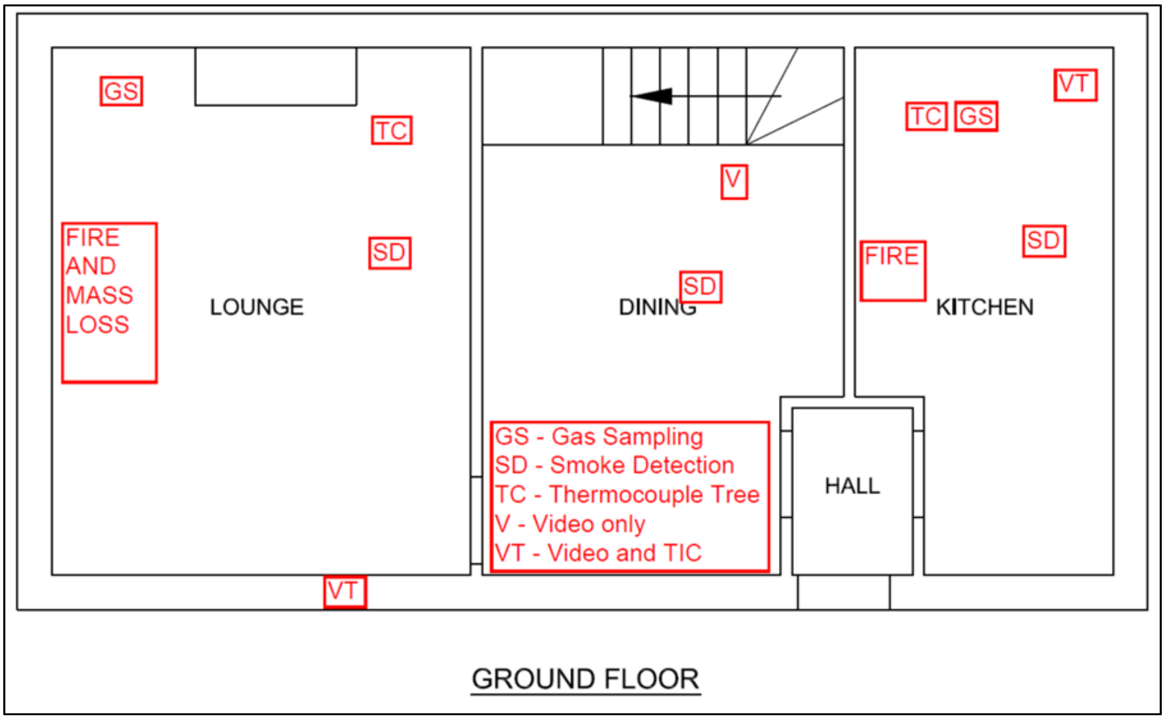

Figure 41 – Ground floor plan of property showing sampling points

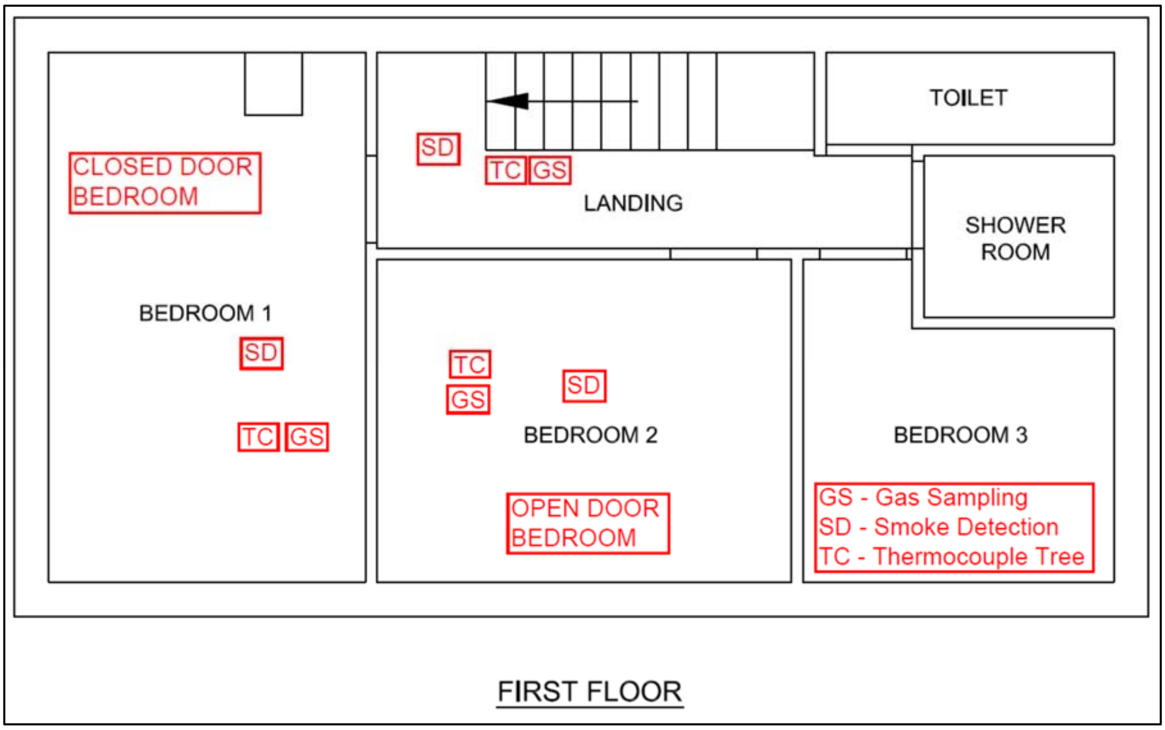

Figure 42 – First floor plan of property showing sampling points

On the ground floor, gas sampling and thermocouple readings were taken in the fire compartment only. During those scenarios where the fire is in the kitchen, there were no measurements from within the lounge and vice-versa and the corresponding door was closed.

All gas sampling points were taken at 160 cm from floor level to represent the height of the oronasal cavity for an average adult in the standing position [88]. All smoke detectors were ceiling mounted using manufacturer provided fittings. The thermocouple trees each had 8 temperature probes mounted upon them. Each of the 8 thermocouples was mounted 30 cm apart vertically and they measure the temperature at 30 cm, 60 cm, 90 cm, 120 cm, 150 cm, 180 cm, 210 cm and 240cm from floor level in a vertical plane. The uppermost thermocouple (240 cm from floor level) was 5 cm below the ceiling.

HD video camera footage was taken within the fire compartment and in the hallway for all experiments as was thermal imaging camera video footage. The cameras located inside the fire compartment were pointed in the direction of the fire source. The cameras located in the hallway were pointed towards the doorway to the fire compartment and slightly upwards to capture smoke and heat movement on the underside of the ceiling.

3.9 Scientific Validity of Data

One of the disadvantages of using an existing property for these tests was the limit to which variables can be controlled. The experimental design was such that a number of key variables were being tested. For example, if two tests are being conducted with the aim of establishing the difference between two different ventilation areas then it is important to ensure that these are kept constant throughout each experiment. The main concern here was that additional ventilation could be inadvertently created part way through an experiment through the failure of existing glazing having been exposed to heat. The following activities were undertaken prior to each experiment to ensure reproducibility and scientific validity of the data.

- All windows which are perceived to be at threat from heat were protected using plasterboard to prevent unwanted openings part way through an experiment
- Open windows were simulated using plasterboard to create an opening set to a predetermined size
- Any open doors were held in the open position at right angles to the doorway using timber door stops
- Composite boarding was applied to the walls and ceiling of the fire compartment to maintain the structural integrity of the building and to prevent smoke and heat travelling through the property through holes created during an earlier experiment
- A team of people worked between experiments to check for structural damage and to repair any areas where this may have occurred
- The property was cooled and aired between experiments to allow for temperatures to return to an ambient condition, positive pressure ventilation was used to assist
- Gas and temperature sampling points remained in position throughout all of the experiments

Chapter 4 - Analysis of Data Gathered

Of the 14 planned experiments, a total of 13 of these were conducted and a further planned experiment (Experiment 6) was not conducted at all due to time constraints. Experiment 6 was due to be one of two experiments which were a duplicate.

The ambient temperature over the period of the experiments was well above average with typical daytime temperatures between 28-32°C outside of the property. Wind speeds were moderately low and moving constantly in a South Westerly direction. The address of the property was 22 Tern Grove, Kings Norton, Birmingham.

Table 29 shows the matrix of data gathered during each experiment. Note that both low and high sensitivity smoke alarms are being used to record actuation times. Low and high sensitivity in respect of these experiments refers to the fact that the detectors are programmed to respond within the upper and lower sensitivity limits as prescribed by the British Standard [89].

The table shows that no useable data was gathered from the obscuration meter in the fire compartment with this being a result of the damage caused to it during some of the earlier experiments and it no longer being used.

The absence of mass loss data is as a result of this piece of equipment failing during testing. This is discussed further within Section 4.3.4.

		1	2	3	4	5	7	8	9	10	11	12	13	14
WMFS	Video (Fire Compartment)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Video (Hallway)	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	TIC (Fire Compartment)	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	TIC (Hallway)	🟥	🟩	🟥	🟩	🟥	🟩	🟥	🟥	🟥	🟩	🟥	🟥	🟥
SPRUE	Scatter Detector (Fire Comp./Low Sensit.)	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟥	🟥	🟥	🟩	🟩
	Scatter Detector (Fire Comp./High Sensit.)	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟥	🟥	🟥	🟩	🟩
	Obscuration Meter (Fire Compartment)	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	Scatter Detector (Hallway/Low Sensit.)	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟥	🟥	🟥	🟩	🟩
	Scatter Detector (Hallway/High Sensit.)	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟥	🟥	🟩	🟩
	Obscuration Meter (Hallway)	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	Scatter Detector (Landing/Low Sensit.)	🟥	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟥	🟩	🟥	🟩	🟩
	Scatter Detector (Landing/High Sensit.)	🟥	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟥	🟩	🟩
	Obscuration Meter (Landing)	🟥	🟩	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟥	🟥
	Scatter Detector (Open Bed./Low Sensit.)	🟥	🟩	🟥	🟩	🟩	🟥	🟥	🟩	🟥	🟩	🟥	🟥	🟥
	Scatter Detector (Open Bed./High Sensit.)	🟥	🟩	🟥	🟩	🟥	🟥	🟥	🟩	🟥	🟩	🟥	🟥	🟥
	Obscuration Meter (Open Bedroom)	🟥	🟩	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟥
	Scatter Detector (Closed Bed./Low Sensit.)	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥
	Scatter Detector (Closed Bed./High Sensit.)	🟥	🟩	🟥	🟩	🟩	🟩	🟥	🟩	🟥	🟩	🟩	🟥	🟥
	Obscuration Meter (Closed Bedroom)	🟥	🟩	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟥	🟥
UCLAN	Mass Loss Data	🟥	🟥	🟧	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	Gas Analysis $CO/CO_2/O_2$ (Fire Compart.)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥
	Gas Analysis HCN (Fire Compartment)	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩
	Temperature Profile (Fire Compartment)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Gas Analysis $CO/CO_2/O_2$ (Landing)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥
	Gas Analysis HCN (Landing)	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩
	Temperature Profile (Landing)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Gas Analysis $CO/CO_2/O_2$ (Open Bedroom)	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟥
	Gas Analysis HCN (Open Bedroom)	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩
	Temperature Profile (Open Bedroom)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Gas Analysis $CO/CO_2/O_2$ (Closed Bedroom)	🟩	🟩	🟥	🟩	🟥	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟥
	Gas Analysis HCN (Closed Bedroom)	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩
	Temperature Profile (Closed Bedroom)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥

Table 29 – Data gathered during experimentation

Key:

Red = no data was successfully gathered
Orange = data was gathered but its validity is in question
Green = useable data was gathered

4.1 Analysis of Individual Experiments – Group 1

The results from the 13 large-scale fire tests have been grouped together in order to present the data in an efficient way that will assist with making comparisons and will support the checking of reproducibility. The first group includes all three of the fires located in the kitchen; the second group includes all of the lounge fires where the lounge door was open and the third group covers all of the lounge fire scenarios where the lounge door was closed.

The first grouping covers Experiments 1, 2 and 11 and considers scenario 1 which involved just a pan of oil on fire and also scenario 8 which involves a pan of oil on fire which is subsequently allowed to spread to the nearby kitchen units.

4.1.1 Smoke Detector Analysis

In all three experiments smoke detectors which were located outside the kitchen actuated prior to piloted ignition of the cooking oil. Observation of these experiments showed that there was significant amounts of smoke and airborne particulate matter released during the pre-ignition phase. These clearly led to actuations of smoke detectors within the fire compartment and elsewhere within the property, all prior to ignition. The detector actuation times for the closed bedroom in Experiment 11 are short, compared to subsequent experiments, as the fire within this experiment has a higher fuel consumption rate and generates significantly more smoke.

Figure 43 shows the average actuation times and gives an indication of the rate at which smoke and airborne particulates are transported from one room to the next, within the property. Smoke detectors are not usually found in kitchens, although heat detectors are sometimes used, however it is reasonable to expect to see working smoke detectors located in the circulation spaces such as the hallway and landing.

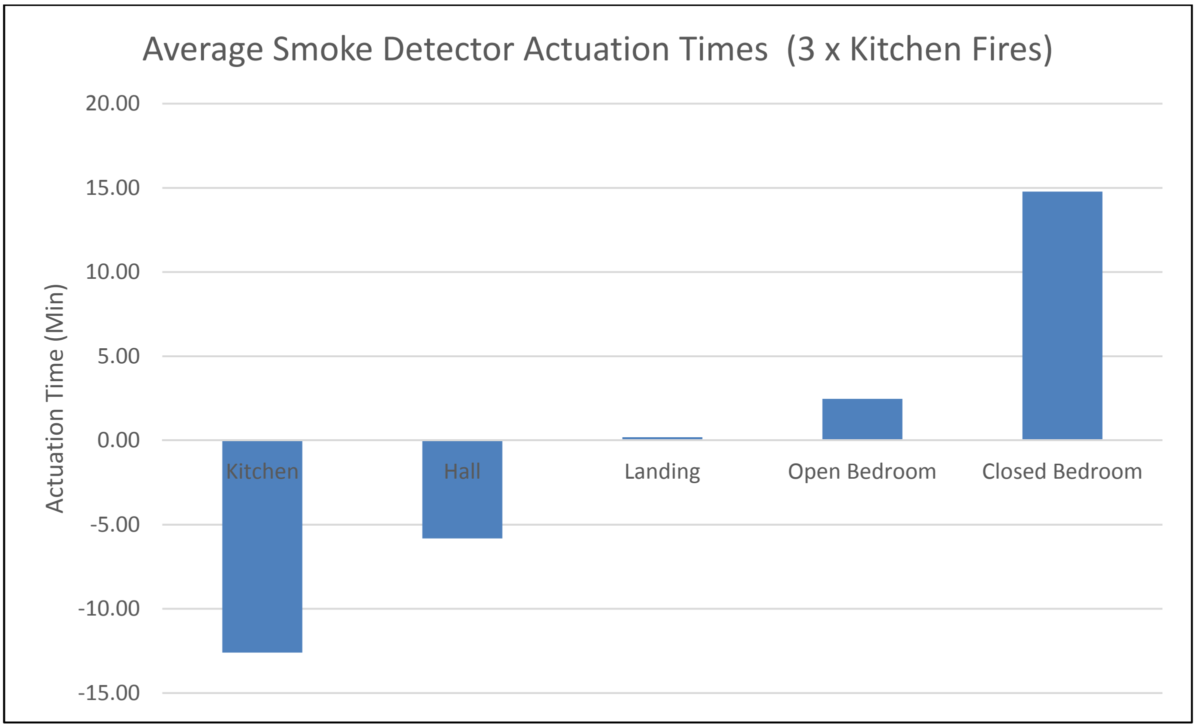

Figure 43 – Average smoke detector actuation times (kitchen fires)

4.1.2 Temperature Profiles

Figure 44 shows the temperature profiles for the three experiments where the fire was located within the kitchen. The figure shows temperature profiles within the kitchen only, at 150 cm above floor level. There appears to be good reproducibility between the duplicate Experiments 01 and 02 and temperatures increase significantly where the fire is allowed to spread to the other combustible items in Experiment 11.

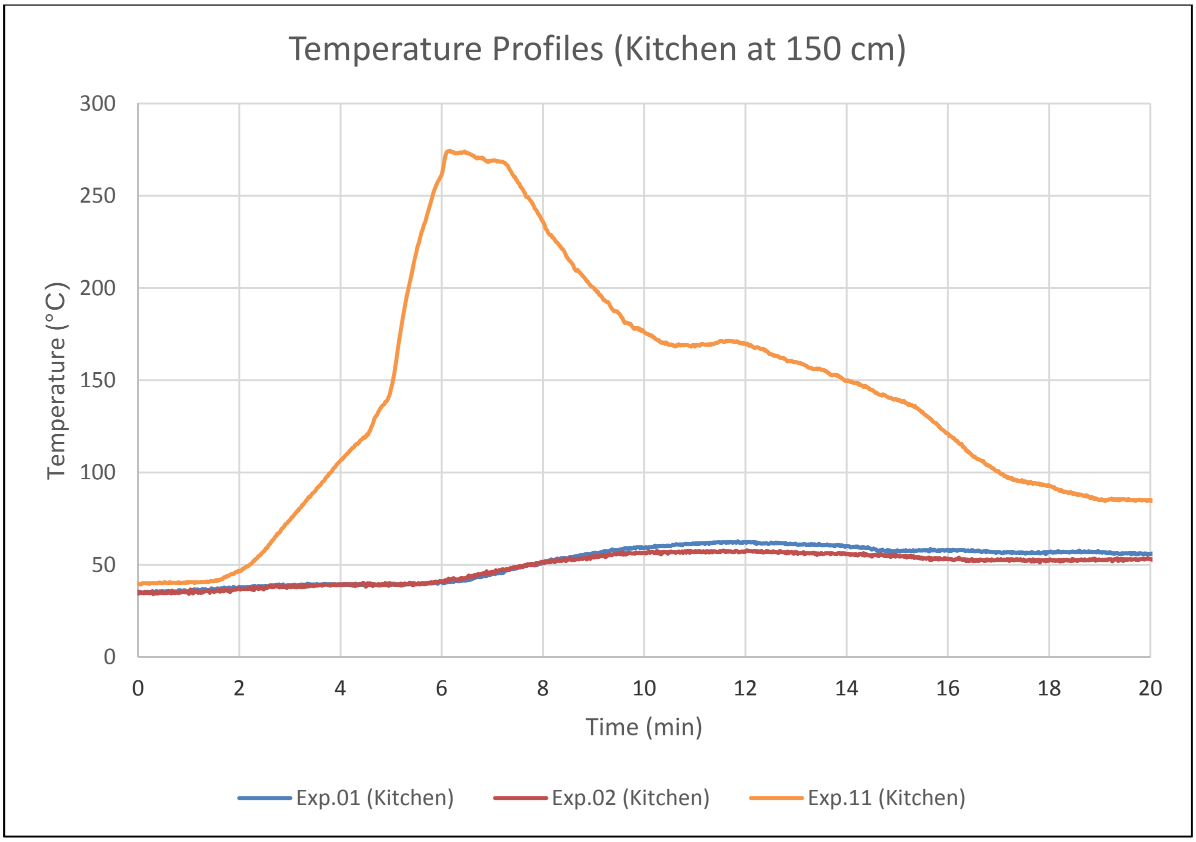

Figure 44 – Kitchen temperature profiles (at 150 cm)

The maximum temperatures, at head height within the kitchen, are around 60°C where only cooking oil is undergoing combustion, with temperatures increasing to a maximum of 275°C where the fire spreads to other combustibles.

Figure 45 shows the same profiles as Figure 44 except that they are taken on the landing. Again there is reproducibility between Experiments 01 and 02 where temperatures peak at just below 40°C and with Experiment 11 again the temperature profile is higher with a peak of around 70°C. Video evidence from Experiment 11 suggests that the fire reaches its maximum intensity at between 5 and 8 min after which there is no further fire spread and the fire subsides, corresponding to the temperature profiles observed.

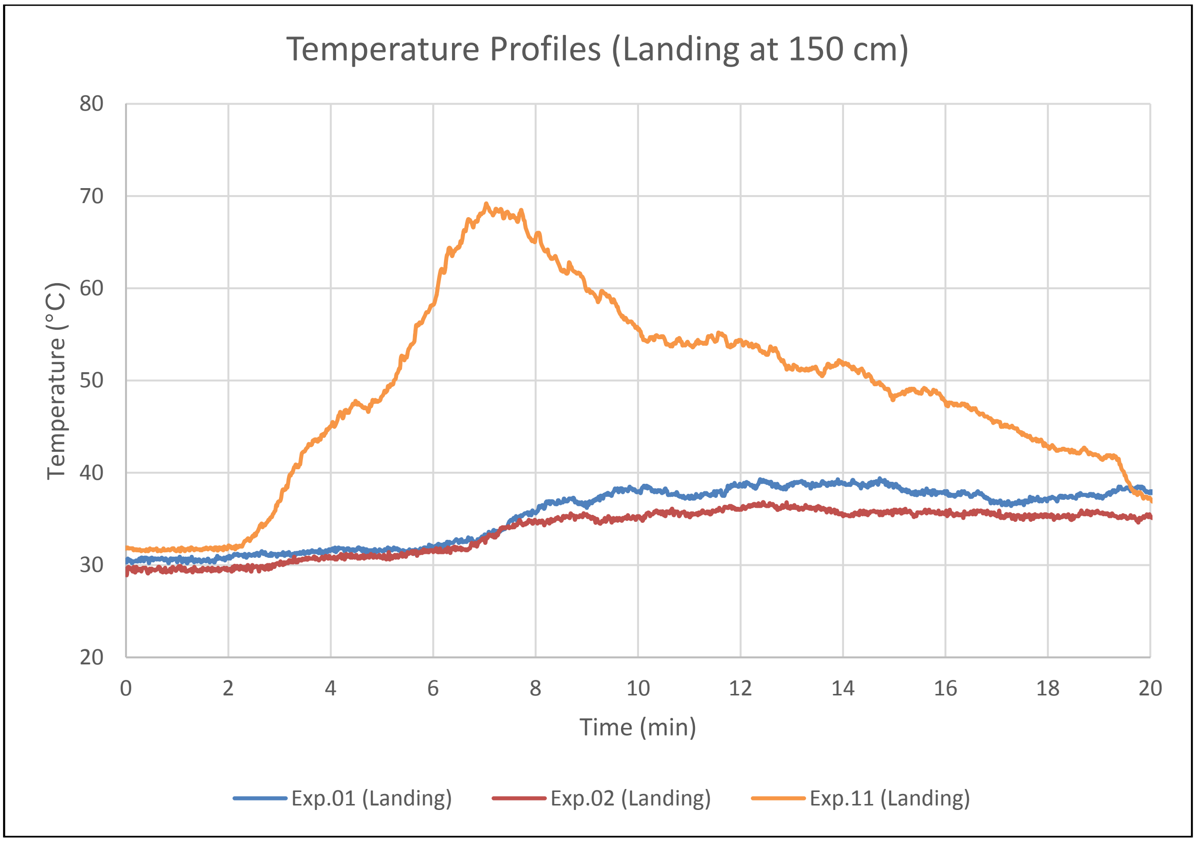

Figure 45 – Landing temperature profiles (at 150 cm)

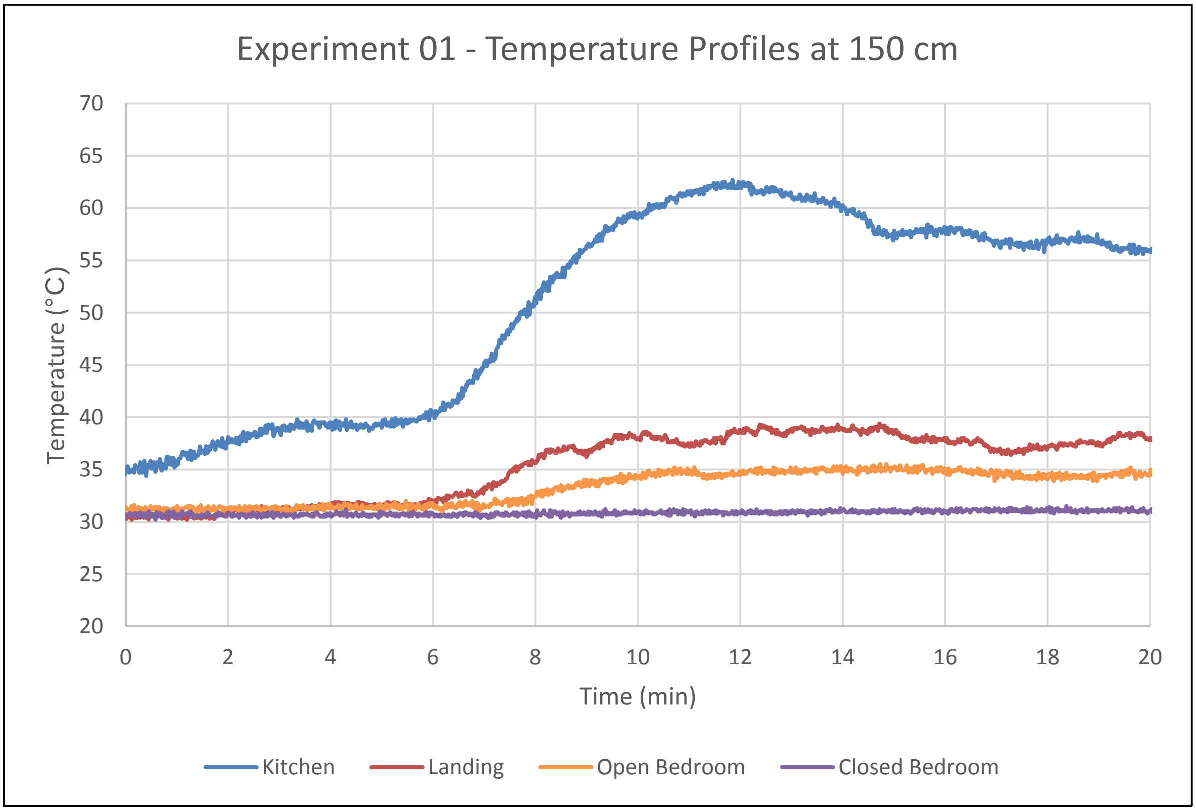

Figure 46 – Experiment 01 temperature profiles (at 150 cm)

Figure 46 shows the temperature profiles at each of the four sampling points within the kitchen, landing, open bedroom and closed bedroom, for Experiment 01 only. Temperatures are as expected, with the highest temperature in the fire compartment (kitchen) and temperatures reducing steadily as the smoke travels away from the fire. The reduction in temperature is due to two main causations: -

- Heat transfer from the smoke layer into the structure of the property
- Entrainment of ambient air due to turbulence having a diluting effect

This figure also demonstrates the time lag of smoke transfer from one compartment to the next, with temperatures in the kitchen beginning to rise at 6 min, on the landing the rise commences at around 7 min and in the open bedroom it begins at 8 min. This gives a reasonable indication of the rate at which the toxic effluent moves through the property.

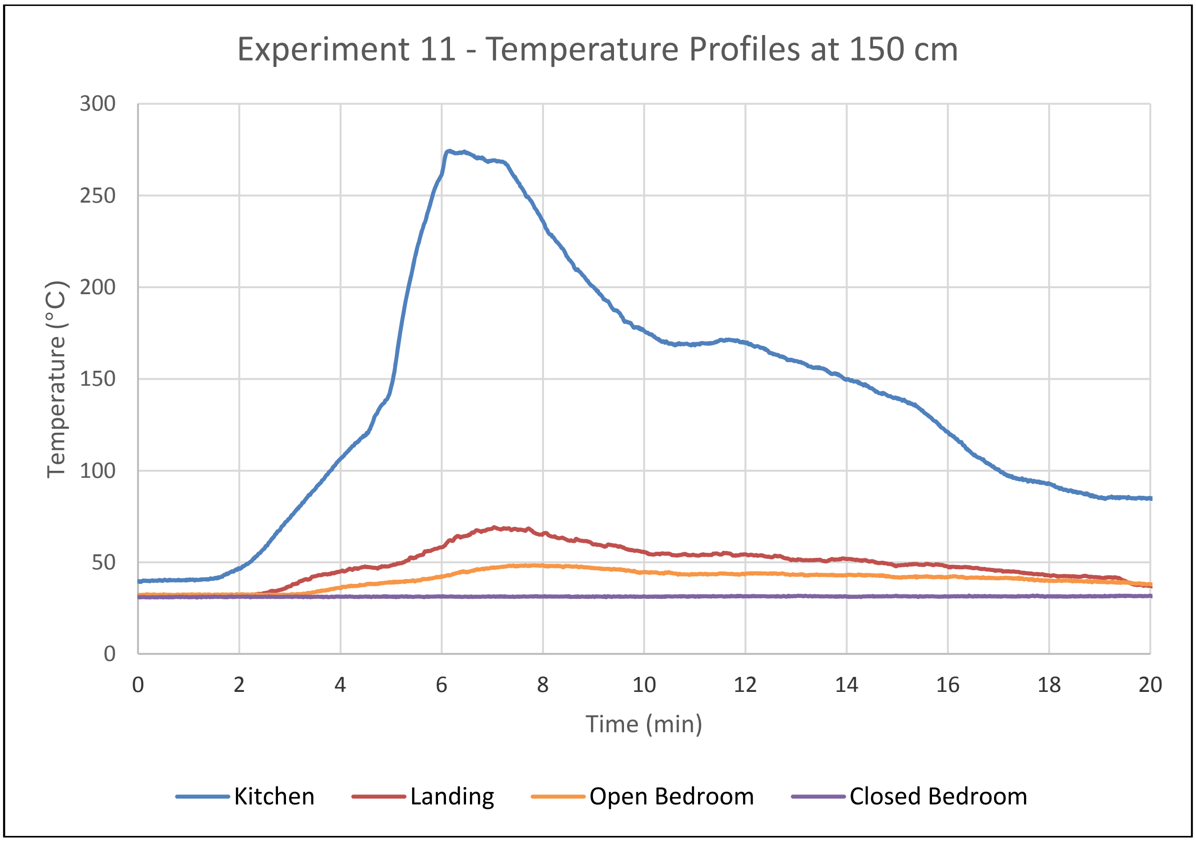

Figure 47 – Experiment 11 temperature profiles (at 150 cm)

Figure 47 shows the temperature profiles in the four rooms during Experiment 11. This graph clearly shows a lag in peak temperature with the peak at around 6 min in the kitchen, around 7 min on the landing and at 8 min within the open door bedroom. The one minute lag in smoke transfer between these three rooms is consistent with that seen in Figure 46, during Experiment 01.

It is also seen that there is little increase in temperature in the bedroom with the closed door. As these heat transfers are solely driven by convection, it is reasonable to suggest that only a small amount of smoke travels into this room. The closed door therefore performs a positive function in preventing smoke from freely travelling into the compartment it protects.

Figure 48 shows the temperature profiles within the kitchen during Experiment 11 at various heights. There were 8 thermocouples set 30 cm apart however the data gathered from the thermocouple at 210 cm from floor level was erroneous and is omitted from this figure.

The peak temperature of 537°C occurred just below the ceiling, whilst at 30 cm from the floor, the maximum temperature recorded was 119°C. Each of the thermocouples records gradually cooler temperatures from ceiling downwards as would be expected.

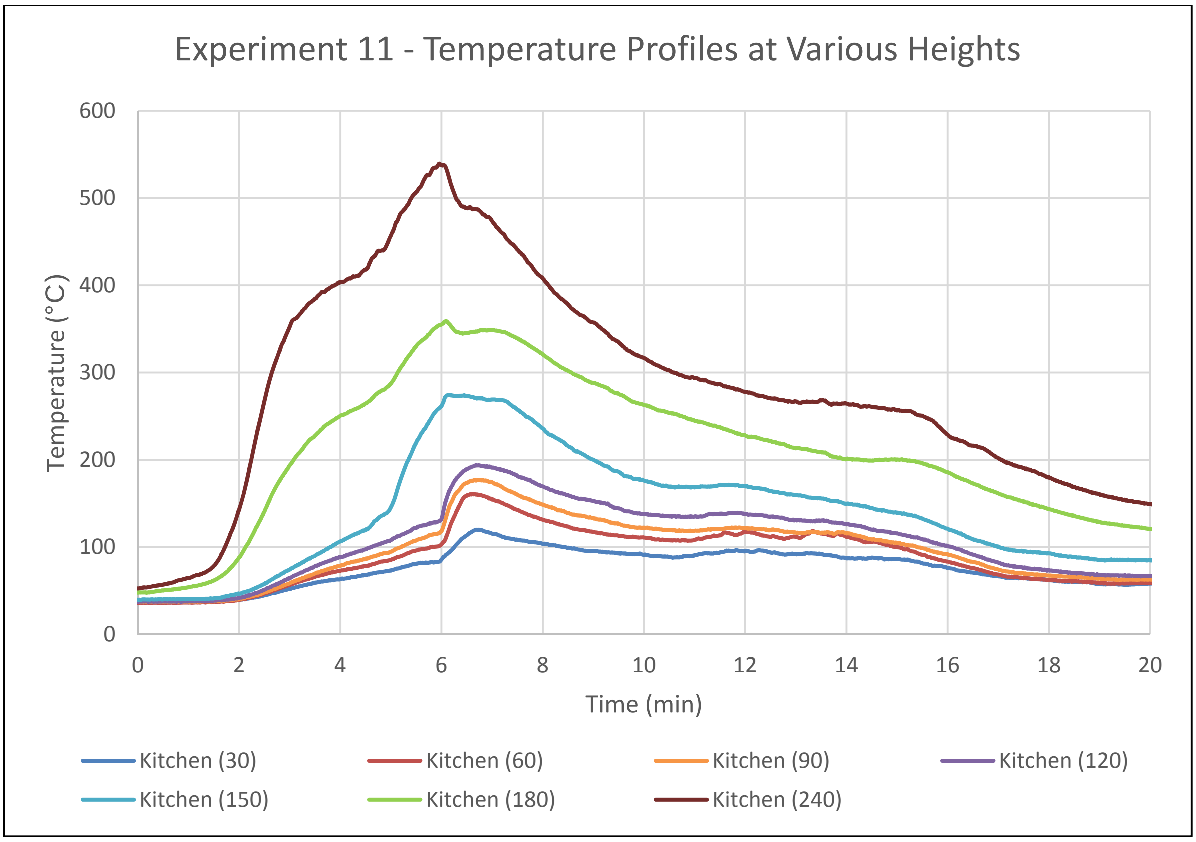

Figure 48 – Experiment 11 kitchen temperature profiles (at various heights)

4.1.3 Gas Concentrations

Table 30 shows the peak gas concentrations measured during Experiments 01, 02 and 11 for CO_2, CO and O_2. For CO_2 and CO this is an upper concentration peak and as oxygen depletion is being considered, for O_2 it is a lower concentration peak.

It shows that the concentrations of CO_2 and CO are relatively low during Experiments 01 and 02 and that the O_2 levels during these only drop a little below atmospheric conditions at 21%. The size of the fire was controlled to a relatively small amount of cooking oil during these experiments and therefore the gas concentrations seem appropriate.

Experiment Number	Room	CO_2 Peak (%)	Time (mm:ss)	CO Peak (%)	Time (mm:ss)	O_2 Peak (%)	Time (mm:ss)
Exp.01	Kitchen	0.21	19:17	0.03	11:17	20.75	19:12
	Landing	0.07	19:54	0.00	3:05	20.83	19:57
	Open (BR)	0.01	1:00	0.00	19:17	20.70	19:44
	Closed (BR)	0.00	-	0.01	13:30	21.00	-
Exp.02	Kitchen	0.89	7:03	0.06	19:43	19.78	7:01
	Landing	0.94	13:23	0.01	13:57	19.63	12:33
	Open (BR)	0.90	14:39	0.02	17:53	20.97	-
	Closed (BR)	0.90	14:41	0.01	14:41	21.00	-
Exp.11	Kitchen	13.44	6:26	2.70	6:06	1.87	6:22
	Landing	4.76	8:11	0.84	6:49	14.96	8:03
	Open (BR)	4.48	8:57	0.73	8:01	15.10	8:29
	Closed (BR)	0.52	18:28	0.08	18:28	20.30	18:12

Table 30 – Peak gas concentration times (kitchen scenarios)

In Experiment 11, where the fire was allowed to spread, it can be seen that the peak gas concentrations within the kitchen all appear at between 6:00 and 6:30, in line with the point at which the fire was at its peak, as seen through video evidence. A peak CO_2 of 13.4% was observed at 6:26, a peak CO of 2.7% occurred at 6:06 and a peak O_2 of 1.9% occurred at 6:22.

The data for each of the gas concentrations within the kitchen during Experiment 11 are given in Figure 49. These gas concentration curves are typical of this type of combustion experiment and show increases in CO_2 and CO at the same point where O_2 decreases.

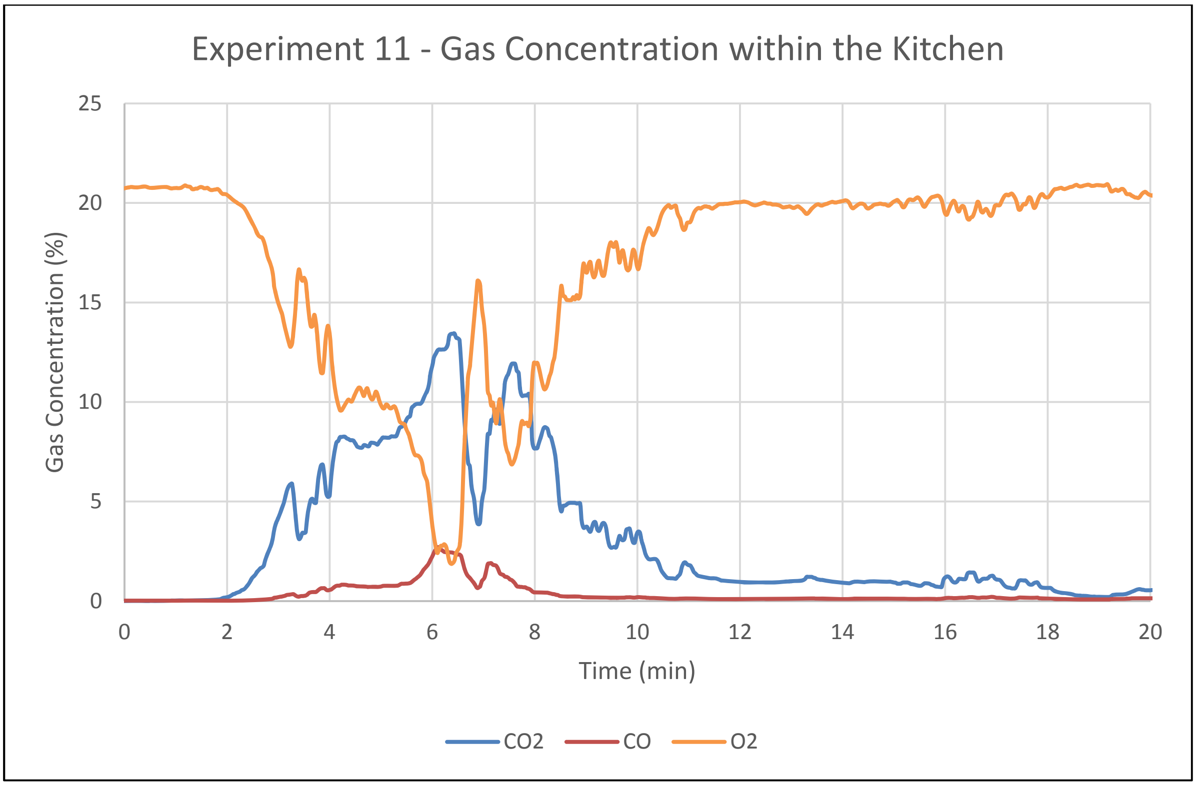

Figure 49 – Experiment 11 kitchen gas concentrations

It shows the fire in the growth phase up to around 5 min, the developed phase from 5 to 8 min before it starts to decay. This observation is consistent for the temperature profiles, the gas concentrations and the images seen in Plate 10.

Video evidence shows a minor explosion at floor level within the fire compartment at around 7 min, believed to be from a smoke detector which has fallen from the ceiling. This creates a significant shockwave which disturbs the flames on top of the kitchen units. It is possible that this shockwave causes turbulence in the upper smoke layer and momentarily introduces O_2 from the cool lower layer, thus creating a spike which is seen in Figure 49.

Figure 50 shows the ratio between the rates of production of CO and CO_2 within the kitchen. Experiment 11 was reasonably well-ventilated and the peak ratio occurs during the developed stage of the fire where CO is produced at a ratio of between 0.18 and 0.22 when compared with CO_2 production. As the O_2 concentration has fallen to below 10% it is reasonable to assume that the fire is ventilation-controlled.

In this figure all of the CO:CO_2 ratio data points prior to 2½ min are removed as the results are erroneous because of the extremely low levels of each gas being detected. The CO ratio is seen to increase sharply at the point where the fire transitions between the growth and developed phases. After 8 min the fire enters the decay phase and the CO ratio drops to 0.05 as the fuel starts to run out.

When comparing the CO production ratio with the O_2 concentration, it is observed that CO is produced much more prominently where the O_2 level drops below a 10% threshold.

Presumably as a result of the shockwave, the O_2 level near the fire is seen to increase momentarily at around 7 min. This peak is met with a dip in CO production before it rises again as the O_2 level drops back down. It can be said that, within certain constraints, these two curves represent the opposite of each other as would be expected during a vitiated combustion reaction.

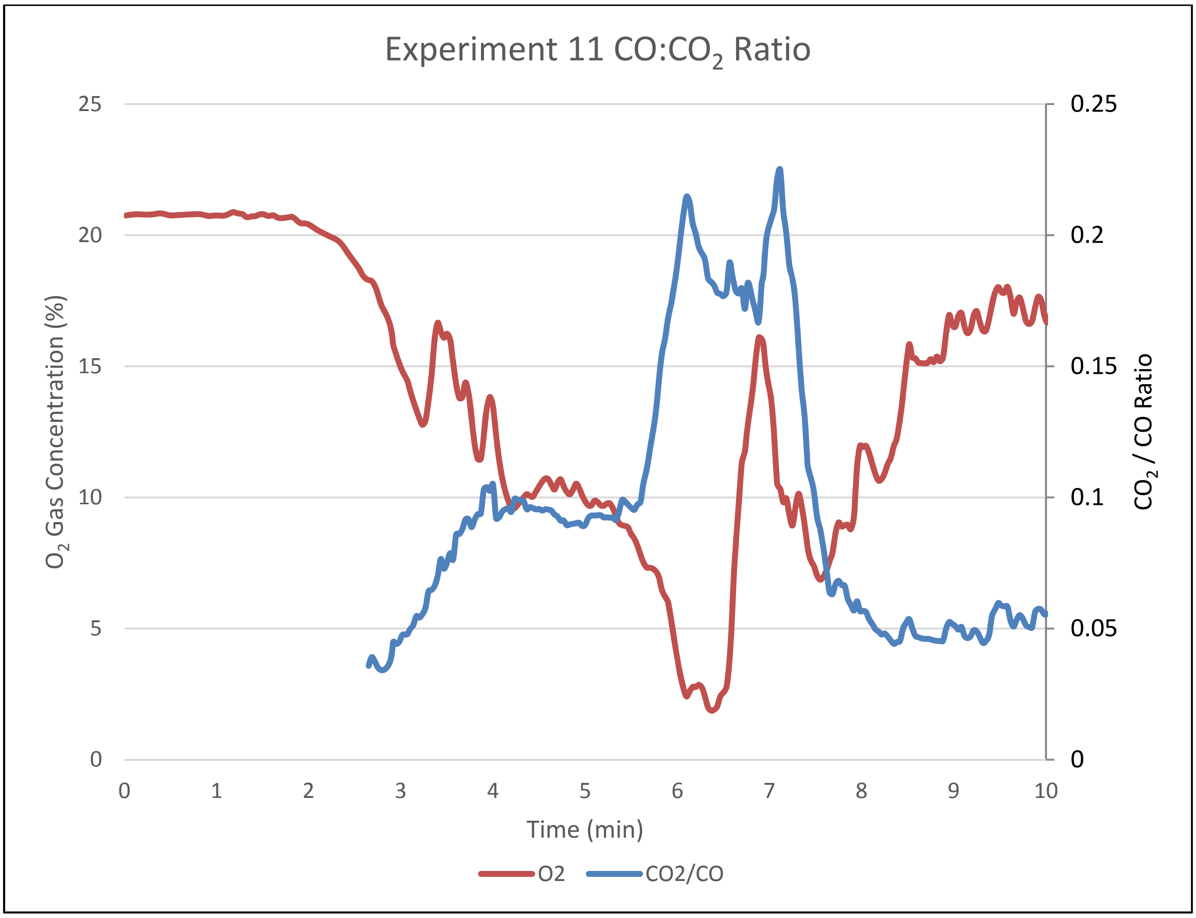

Figure 50 – Experiment 11 kitchen fire CO:CO$_2$ ratio (O$_2$ concentration)

4.1.4 Smoke Visibility

As discussed in Section 3.4.6, the hallway and landing are deemed impassable once the visibility drops below 3 m. The time at which this occurs is given in Table 31 for all three kitchen experiments, where available, and a visual representation of how visibility reduces in Experiment 02 can be seen in Figure 51.

Experiment Number	Location	Time to 3m visibility
Exp.01	Hallway	6:24
Exp.02	Hallway	4:20
	Landing	5:24
	Open Bedroom	7:40
	Closed Bedroom	>20:00
Exp.11	Landing	3:02
	Open Bedroom	3:44
	Closed Bedroom	9:35

Table 31 – Time for visibility of 3m (kitchen scenarios)

This data suggests that the visibility reduces fairly rapidly once the fire takes hold and that the hallway and landing, which are likely to be used to make an escape, become impassable somewhere between 4 and 6 min where the fire involves the oil only (Experiments 01 and 02). This figure is reduced to around 3 min where the fire is able to spread to other combustible materials within the fire compartment.

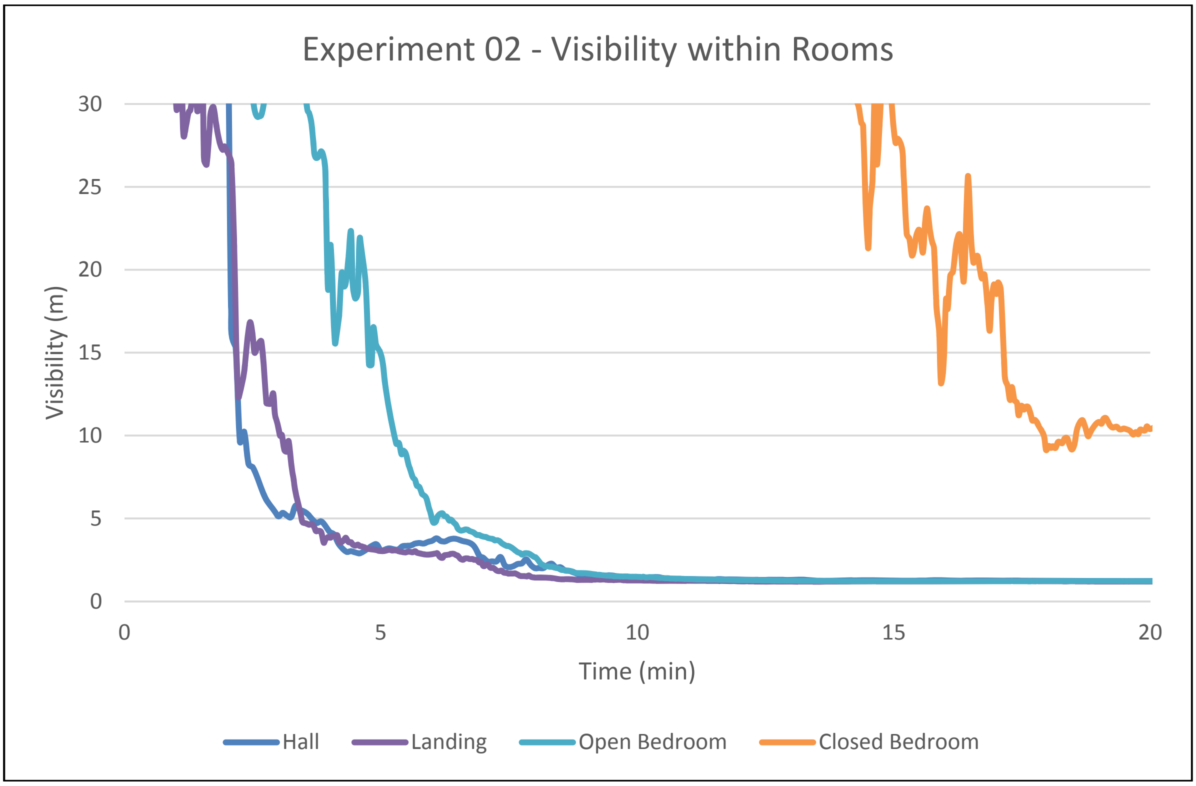

Figure 51 – Experiment 02 room visibility conditions

Figure 51 also shows the delay in smoke travelling from the kitchen, through the hallway and landing and towards the bedrooms. When it is considered that the two bedrooms are both open to the same landing area, the impact the door has on the closed bedroom to prevent smoke transfer is noticeable.

Visibility through smoke remains above the threshold of 3 m for the duration of Experiment 02, where a closed door provides protection.

4.1.5 Video Analysis

Video footage from within the fire compartment shows how the fire is developing throughout each of the experiments. The first image in Plate 9 shows the fire in Experiment 01 at 10s, 14 minutes and 20 minutes after ignition. Vertically attached to the tall kitchen unit is a white post with black markings every 20 cm from the ceiling down. Once the fire has developed it reaches a steady state, where it is observed that the smoke layer is consistently 80 cm thick, this is because the rate at which the fuel is consumed is controlled by the diameter of the pan. The level of smoke damage within the kitchen was consistent at the depth of 80 cm, as observed post-fire.

Plate 9 – Images from within the fire compartment for Experiment 01

In Plate 10, it can be seen that the fire spreads to other fuel packages within Experiment 11 and no such control to the depth of the smoke layer results. Also, the fire develops during the early images to a point at approximately 4 to 5 min where the additional fuel packages become fully involved in the fire. After the image taken at 8 min, it is noticeable that the fire is in the decay phase.

Plate 10 – Images from within the fire compartment for Experiment 11

4.1.6 Asphyxiant Gas FED Analysis

Equation 8, established in Section 1.6.1, has been used in the analysis of the gas concentration data to yield a time to human lethality in various rooms within the property. The time to lethality is established at two separate thresholds, for more vulnerable members of society at 1.0×FED and for the healthy adult population at 2.5×FED. Although a person can no longer act to help themselves once compromised tenability occurs, lethality is considered as the chosen threshold because a timely F&RS intervention can still prevent a fire death.

Table 32 shows the outcomes of this analysis and concludes that the conditions during Experiments 01 and 02 are such that the occupants of all of the rooms, including the fire compartment, are likely to survive the simulated fire scenario for over 20 min. This table also shows the actual dose received after 20 min in brackets, where FED is not reached within that period. For example, in Experiment 01 vulnerable persons located within the kitchen would have received a dose of 0.12×FED after 20 min exposure which is less than the threshold for lethality.

Experiment Number	Room	Time to 1.0xFED (vulnerable person)	Time to 2.5xFED (healthy adult)	Average time to 1.0xFED	Average time to 2.5xFED
Exp. 01	Kitchen	> 20 min (0.12)	> 20 min (0.12)	N/A	N/A
Exp. 02		> 20 min (0.22)	> 20 min (0.22)		
Exp. 11		4:38	5:44		
Exp. 01	Landing	> 20 min (0.00)	> 20 min (0.00)	N/A	N/A
Exp. 02		> 20 min (0.04)	> 20 min (0.04)		
Exp. 11		7:31	14:56		
Exp. 01	Open Bedroom	> 20 min (0.00)	> 20 min (0.00)	N/A	N/A
Exp. 02		> 20 min (0.00)	> 20 min (0.00)		
Exp. 11		8:27	15:32		
Exp. 01	Closed Bedroom	> 20 min (0.00)	> 20 min (0.00)	N/A	N/A
Exp. 02		> 20 min (0.00)	> 20 min (0.00)		
Exp. 11		> 20 min (0.06)	> 20 min (0.06)		

Table 32 – Asphyxiant gas FED time to lethality (kitchen scenarios)

In Experiment 11 it can be seen that a vulnerable person located within the kitchen would receive a fatal dose of toxic smoke at 4:38 whereas a healthy adult would survive until 5:44. There is good correlation between Experiments 01 and 02, however the results for Experiment 11 show somewhat more hazardous conditions as a result of the involvement of additional combustible materials.

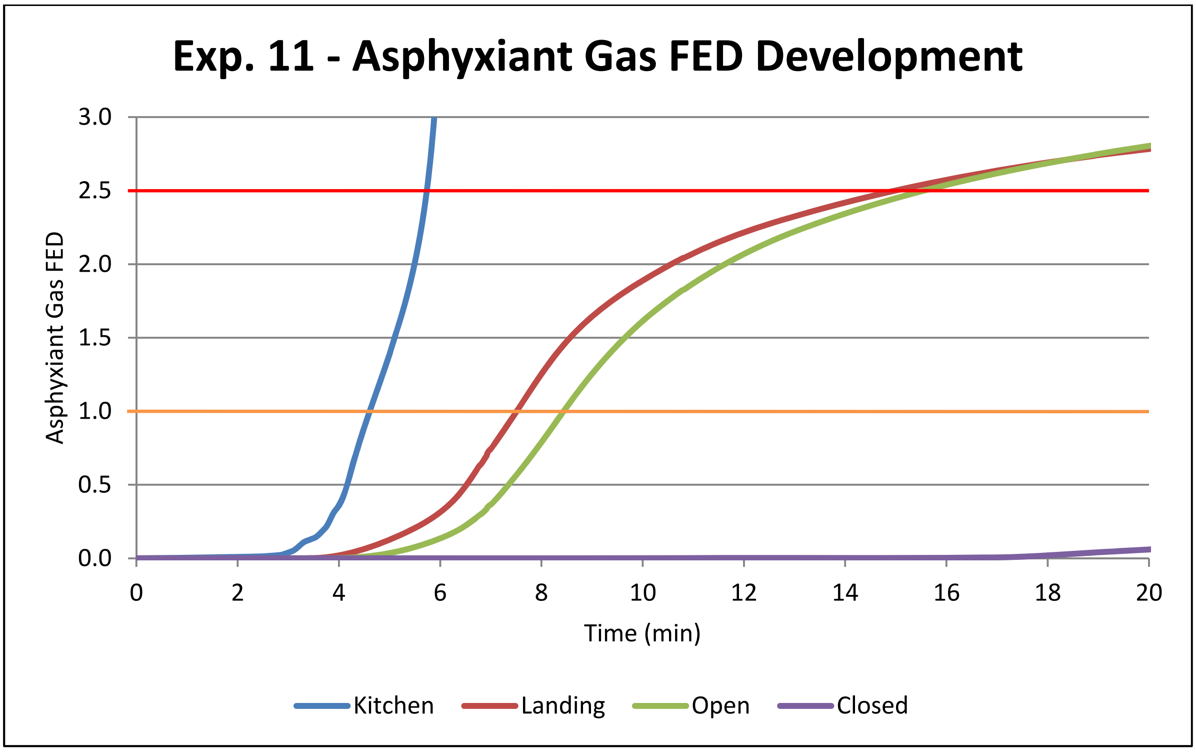

Figure 52 – Experiment 11 asphyxiant gas FED development

Figure 52 shows how the fractional effective dose develops as a factor of time during Experiment 11. It can be seen that conditions within the kitchen reach the thresholds of lethality (1.0 and 2.5) prior to the other rooms within the premises. As would be expected, the duration for human survivability increases within the individual compartments, the further they are from the fire source. Conditions within the closed door bedroom remain survivable throughout, as the closed door acts as a protective barrier.

4.1.7 Heat FED Analysis

Table 33 shows the time to lethality from exposure to heat and uses Equation 14 which was developed in Section 1.6.2. The data from thermocouple 5 within each of the locations was taken with this thermocouple being located at 1.5m above floor level.

It also shows that both vulnerable persons and healthy adults would survive the thermal conditions generated during Experiments 01 and 02, in all rooms including the fire compartment for in excess of 20 min. This table also shows the actual dose received after 20 min in brackets, where FED is not reached within that period. . During Experiment 11 fatal conditions are only seen within the kitchen and all conditions within all other rooms remain survivable, from the perspective of heat exposure.

Experiment Number	Room	Time to 1.0xFED (vulnerable person)	Time to 2.5xFED (healthy adult)	Average time to 1.0xFED	Average time to 2.5xFED
Exp. 01	Kitchen	> 20 min (0.29)	> 20 min (0.29)	N/A	N/A
Exp. 02		> 20 min (0.24)	> 20 min (0.24)		
Exp. 11		5:32	6:05		
Exp. 01	Landing	> 20 min (0.08)	> 20 min (0.08)	N/A	N/A
Exp. 02		> 20 min (0.06)	> 20 min (0.06)		
Exp. 11		> 20 min (0.26)	> 20 min (0.26)		
Exp. 01	Open Bedroom	> 20 min (0.06)	> 20 min (0.06)	N/A	N/A
Exp. 02		> 20 min (0.05)	> 20 min (0.05)		
Exp. 11		> 20 min (0.13)	> 20 min (0.13)		
Exp. 01	Closed Bedroom	> 20 min (0.05)	> 20 min (0.05)	N/A	N/A
Exp. 02		> 20 min (0.04)	> 20 min (0.04)		
Exp. 11		> 20 min (0.05)	> 20 min (0.05)		

Table 33 – Heat FED time to lethality (kitchen scenarios)

Lethality is likely to occur somewhere between 5:32 and 6:05 within the kitchen, during Experiment 11. Again, no average FED times are taken due to the variation between the fire scenarios. At 5:32, the temperature within the kitchen was recorded as 223°C and at 6:05, it was 273°C.

4.1.8 FED Conclusion

The data presented within this section demonstrates that Experiment 01 and Experiment 02 were comparable with respect to smoke detector actuation times, temperature profiles, gas concentrations and video analysis. In Experiments 01 and 02, it can be concluded that inadequate amounts of heat and toxic smoke are produced to cause serious concern to the occupants of the building, even if they are located within the fire compartment.

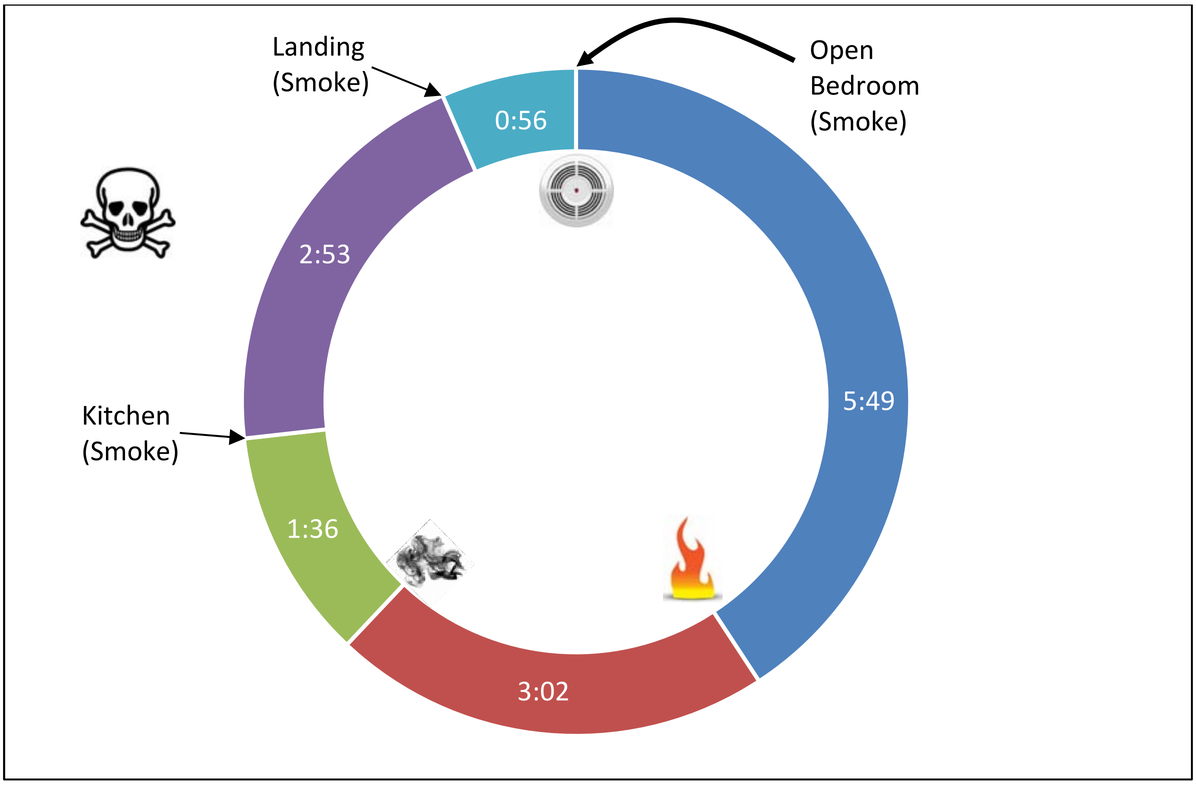

Figure 53 – Experiment 11 fire survival timeline

Conditions within Experiment 11 are considerably worse and therefore a more detailed analysis for the various times to reach lethal exposure can be made. Data indicate that smoke detectors located within the circulation areas are likely to provide an early warning at 5:49 prior to ignition. After ignition the escape route becomes impassable at 3:02 due to reduced visibility from smoke on the landing.

At 1:36, after the escape route becomes impassable, a fatality would occur within the kitchen; a further 2:53 and a fatality would occur on the landing; after a further 56 seconds a fatality would also occur within the open door bedroom and the closed door bedroom remains tenable for in excess of 20 min. All fatalities within Experiment 11 occur as a result of smoke inhalation and not as a result of heat exposure.

Event	Time
Alarm Actuation	-5:49
Ignition	0:00
Visibility Lost	3:02
Lethality (Fire Compartment)	4:38
Lethality (Landing)	7:31
Lethality (Open Bedroom)	8:27
Lethality (Closed Bedroom)	> 20:00

Table 34 – Lethality event / time analysis (kitchen scenarios)

Figure 53 and Table 34 summarise this analysis and show that, a person located outside of the fire compartment would have a minimum of approximately 9 min to make their escape before the escape route becomes impassable, assuming that the audible alarm is their first indication of fire. In addition, they would have at least a further 3 min before they could no longer survive the conditions on the landing. Where an occupant takes the decision not to escape but to protect themselves within a room with a closed door on the upper floor, they are likely to survive for in excess of 20 min after ignition.

The timeframes which allow for the occupants to make an escape or to protect themselves are relatively large and this may go some way to explain the comparatively high survival rates seen within kitchen fires, as indicated in Section 2.1.3.

4.2 Defining the HCN Concentrations

In order to establish the asphyxiant gas tenability limits for lounge fires it is necessary to monitor CO, CO_2, HCN and O_2, these are measured in real-time using sensors. They are recorded every 1.5 seconds throughout each test. Asphyxiant gas analysis also requires measurement of HCN, for which no suitable sensor is available. The most reliable method for fire effluent analysis involves trapping the gas in a sodium hydroxide solution in a bubbler, then using colourimetric reagents to quantify the HCN concentration. As the sofas are manufactured using polyurethane foam which is nitrogen-containing, it is therefore capable of producing HCN during combustion. However, the HCN is sampled for pre-set time periods and the average concentration over that period is determined.

Nitrogen containing fuels produce both CO and HCN and there is an equivalence between the rates of production of these two gases. The principle behind this approach is that HCN concentration has a linear dependency on CO concentration, both increasing as the fire becomes under-ventilated, Wang [90].

Initially a plot of all of the data points was made on one graph but it became apparent that the data suggests that the plume continues to be reactive as it moves away from the fire. Separate research suggests that the CO to CO_2 ratio in the plume will change, the further it travels from the fire source [76]. As the plume becomes diluted with clean air the O_2 concentration rises, and where the plume contains sufficient energy, the CO will oxidise to CO_2, thus reducing the ratio. Similarly, HCN may be oxidised to NO or NO_2 or form N_2, but almost certainly at a different rate and under different conditions to CO. This phenomenon might go towards explaining the reason for the changing ratio as HCN could be a more chemically stable constituent within the smoke layer.

Figure 54 to Figure 57 show the average CO and average HCN data points taken during these experiments at each of the sampling points and can be compared to establish an approximate correlation ratio. On each of these figures a line of best fit is determined for each set of data points with the assumption being made that the correlation ratio is linear and that it passes through the origin.

In the lounge there is a reasonable correlation ($R^2=0.57$) between the data points and that for a 1% concentration of CO in the smoke plume, 271 ppm of HCN would be expected. On the landing there is a good correlation ($R^2=0.70$) between the data points and that for a 1% concentration of CO in the smoke plume, 388 ppm of HCN would be expected. In the open bedroom there is a good correlation ($R^2=0.69$) between the data points and that for a 1% concentration of CO in the smoke plume, 418 ppm of HCN would be expected. In the closed bedroom there is a very good correlation ($R^2=0.81$) between the data points and that for a 1% concentration of CO in the smoke plume, 444 ppm of HCN would be expected.

The data points for the comparison of concentrations between both CO and HCN in the closed bedroom are all low as a result of the door being closed and preventing the free flow of smoke. The correlation ratios established within this section will be used within the analysis to determine the tenability times for asphyxiant gas exposure.

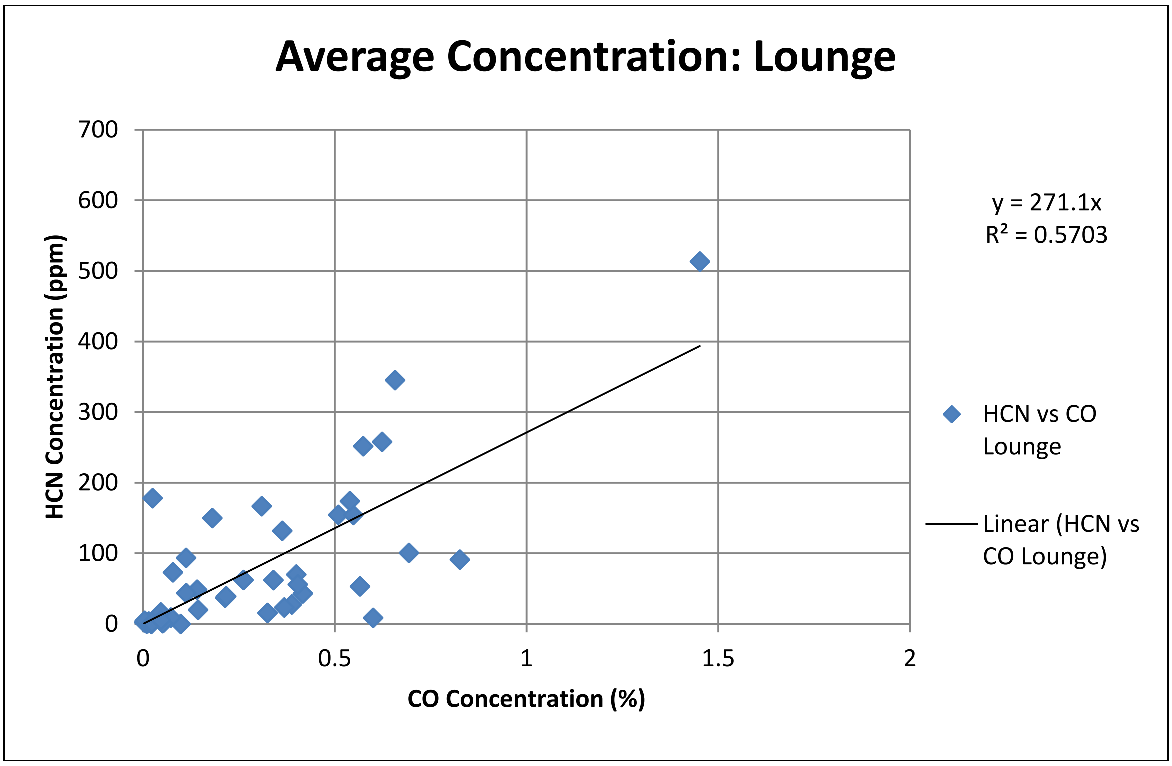

Figure 54 – CO to HCN equivalence ratio (lounge)

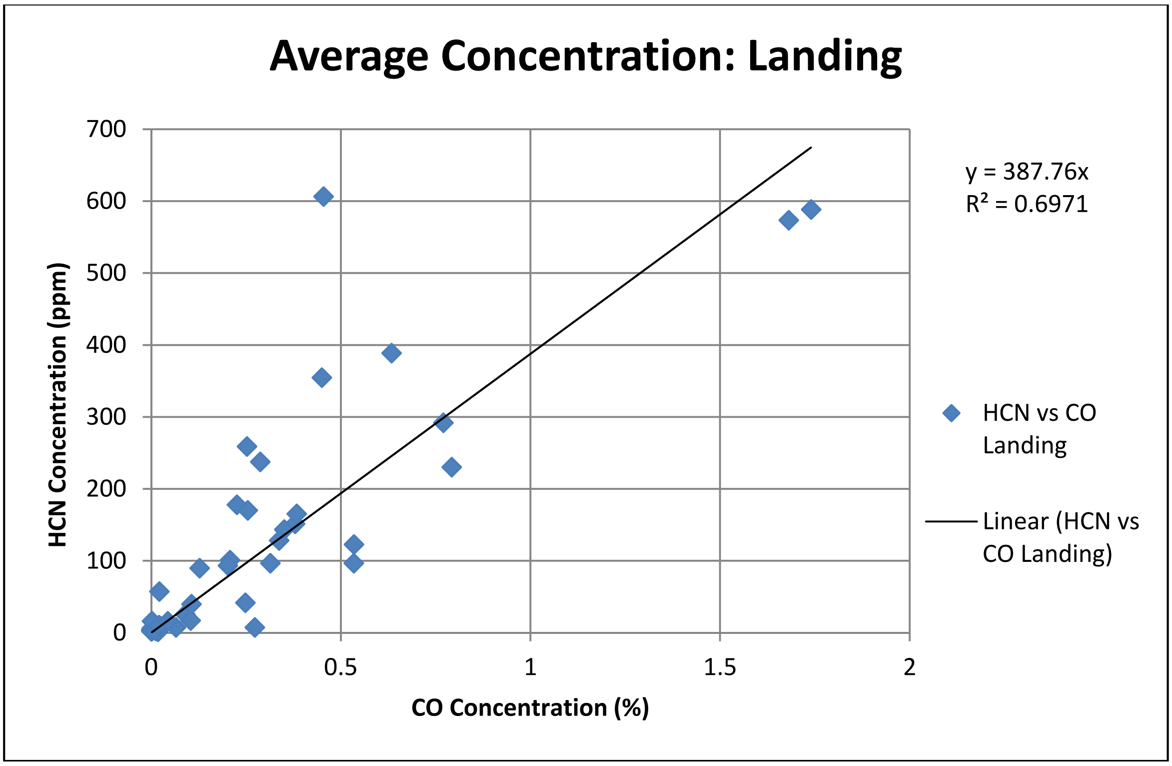

Figure 55 – CO to HCN equivalence ratio (landing)

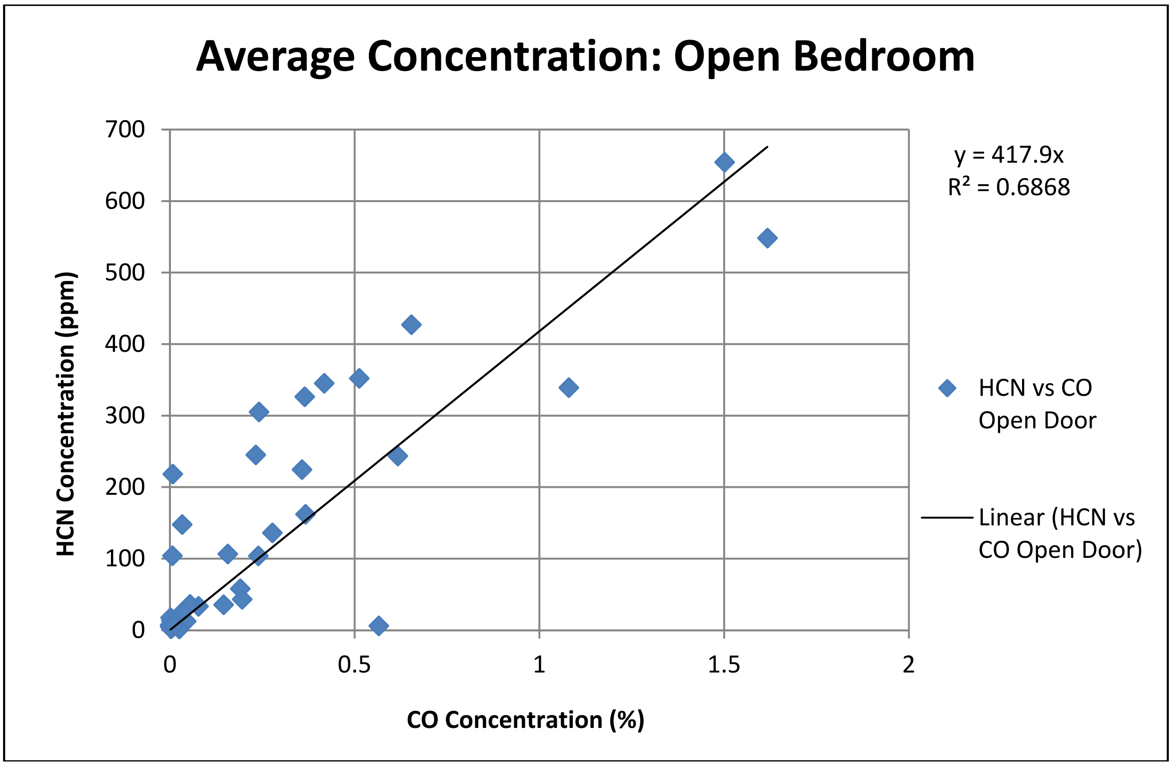

Figure 56 – CO to HCN equivalence ratio (open bedroom)

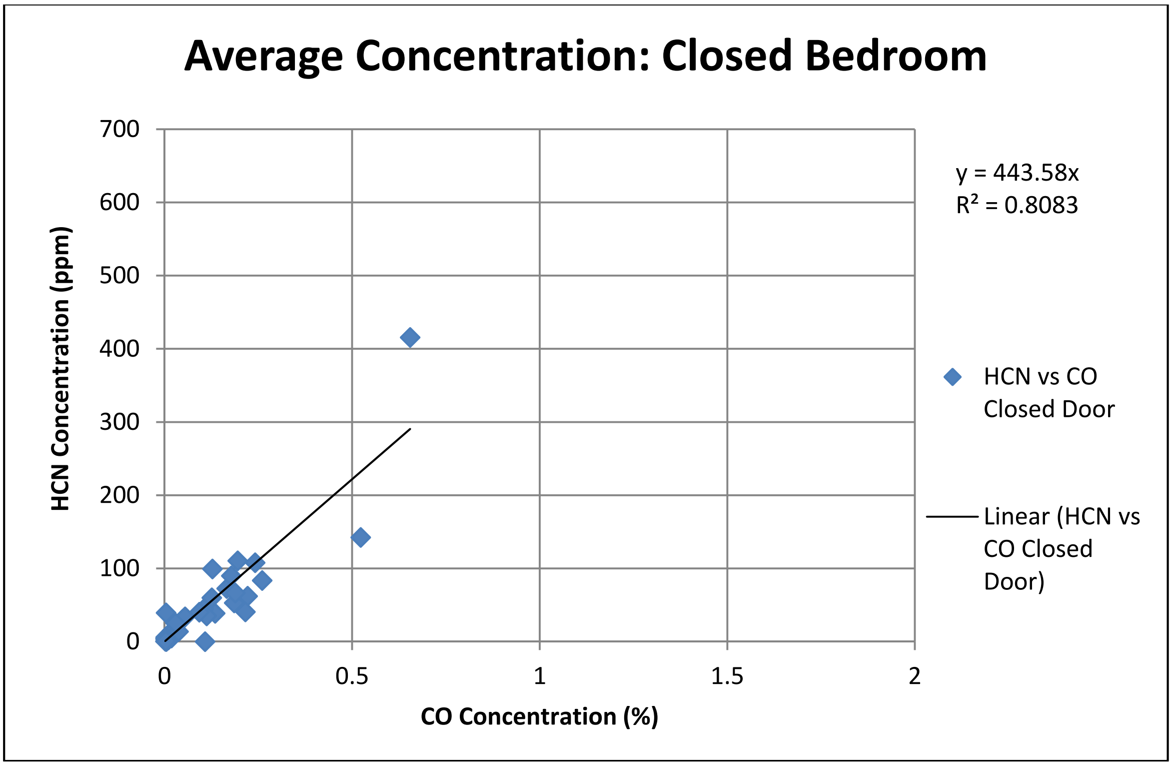

Figure 57 – CO to HCN equivalence ratio (open bedroom)

When considering this data, it is suggested that the $CO:CO_2$ ratio increases slightly as the smoke moves away from the fire. Table 35 shows the average $CO:CO_2$ ratios during the burning phase (typically between 6-15 min) for each of the experiments where the fire was in the lounge and the fire compartment door was open. It was not appropriate to include the data from the kitchen fires as this is a different fuel type and some of the gas data in the lounge fire compartment door closed experiments yielded erroneous results, as discussed in Section 4.4.1.

Experiment Number	Lounge	Landing	Open Bedroom
Exp.03	0.0518	0.0510	0.0535
Exp.04	0.0515	0.0901	0.0957
Exp.07	0.0391	0.0446	-
Exp.08	0.0369	0.0380	0.0471
Exp.10	0.0524	0.0512	0.0607
Exp.12	0.0564	0.0638	0.0639
Exp.13	0.0360	0.0363	0.0378
Average	0.0463	0.0536	0.0598

Table 35 – Average $CO:CO_2$ ratio in various compartments

This data shows that the average $CO:CO_2$ ratio within the fire compartment between these seven experiments, during the burning phase, was 0.0463 which is equivalent to a yield of 4.6% of CO per yield of CO_2 by mass. By comparison, over the same time period, the $CO:CO_2$ ratio on the landing was 0.0536 or 5.4% and in the open door bedroom was 0.0598 or 6.0%. Data for the closed bedroom door is not presented within this table because the concentrations were very low and therefore more susceptible to being inaccurate.

This data tends to suggest that oxidation of the CO is occurring particularly in and around the fire compartment, where it would be expected. It also suggests that further oxidisation between the landing and the open bedroom occurs.

Figure 58, shows the development of the CO:CO_2 ratio during the burning phase for Experiment 04. Prior to 6 min and after 18 min the data can become misleading as the concentrations are comparably quite low. This figure shows that there is an initial peak (up to 0.18) in the CO:CO_2 within the fire compartment during the growth phase of fire development and this then settles down to around 0.05 as the fire reaches steady state. By comparison, the CO:CO_2 ratio on the landing and in the open bedroom develop more slowly during the growth phase but then exceed that in the fire compartment at around 0.10 during the steady state phase.

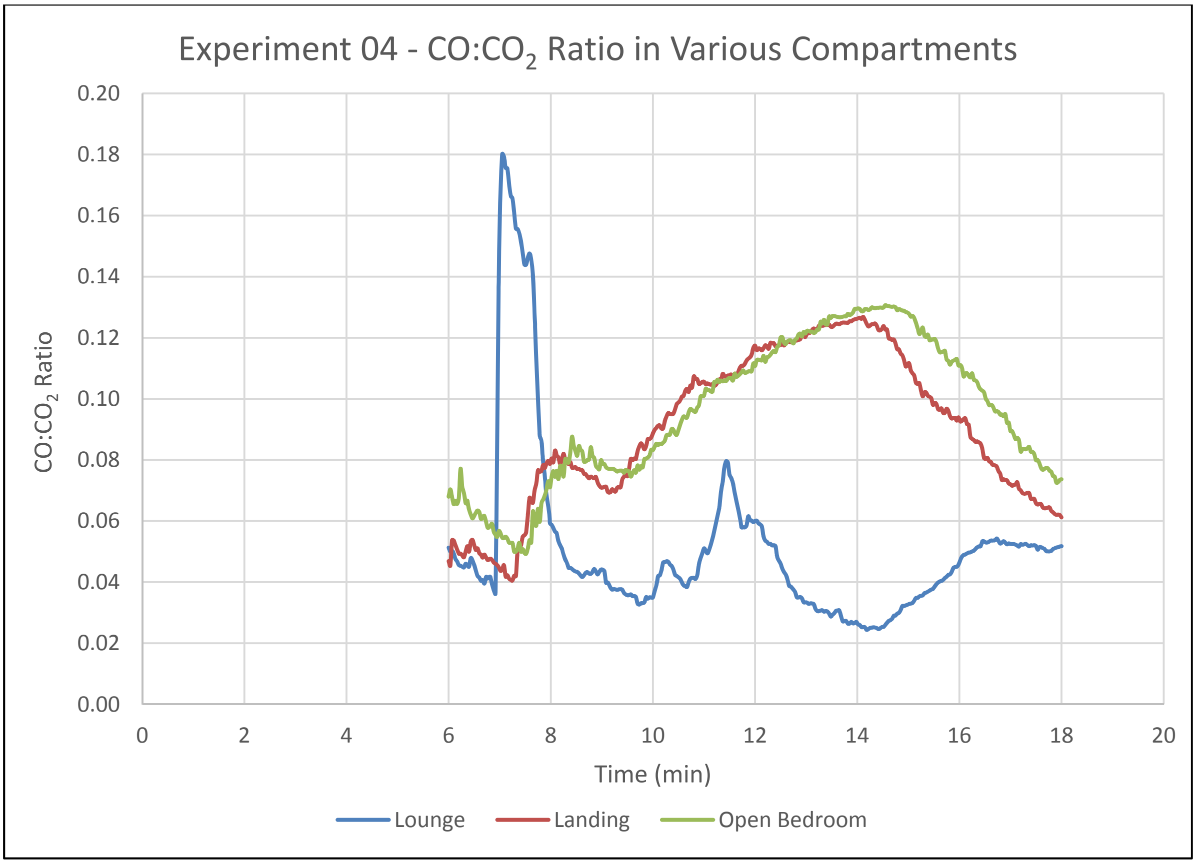

Figure 58 – Experiment 04 - CO:CO_2 ratio in various compartments

The data presented within this section of the thesis does suggest that it is reasonable to determine the HCN concentrations using these equivalence values, in order to conduct the asphyxiant gas analysis.

Figure 59 shows the individual HCN and CO data points taken during Experiment 08, in the lounge, and used in the production of Figure 54. The error bars show the timeframe over which the HCN concentration was gathered and the individual data points for both HCN and CO are an average taken over that timeframe.

This graph is representative of those found in the other experiments with the individual data for each experiment being given in Appendix E.

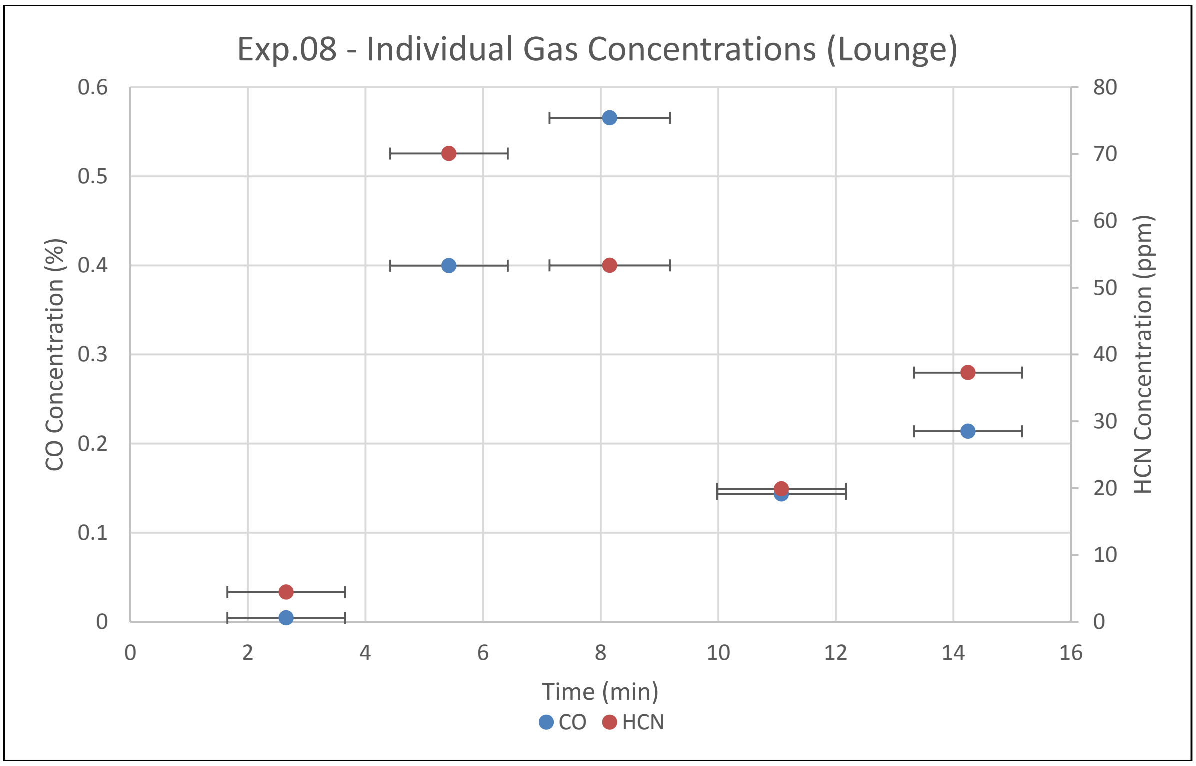

Figure 59 – Experiment 08 individual gas concentrations (lounge)

4.3 Analysis of Individual Experiments – Group 2

This section of the thesis gives a detailed analysis of those experiments which involve a fire in the lounge and where the lounge door is in the open position. The grouping covers Experiments 3, 4, 7, 8, 10, 12 and 13. The majority of these experiments involve the combustion of a sofa only, however with Experiments 12 and 13 there are additional fuel packages within the fire compartment, such as carpet, curtains and further pieces of furniture.

4.3.1 Smoke Detector Analysis

Smoke detection within the lounge occurs on average at around 1:37, however, it is not typical for smoke detectors to be located in the lounge. Smoke detectors are typically located within the hallway and landing and these actuated on average at 2:17 and 3:13, respectively. Unfortunately, it was not possible to obtain smoke detector actuation times in every room for every experiment due to time constraints and heat damage to the equipment and cabling and these points are averaged over, between 6 and 8 actuation times.

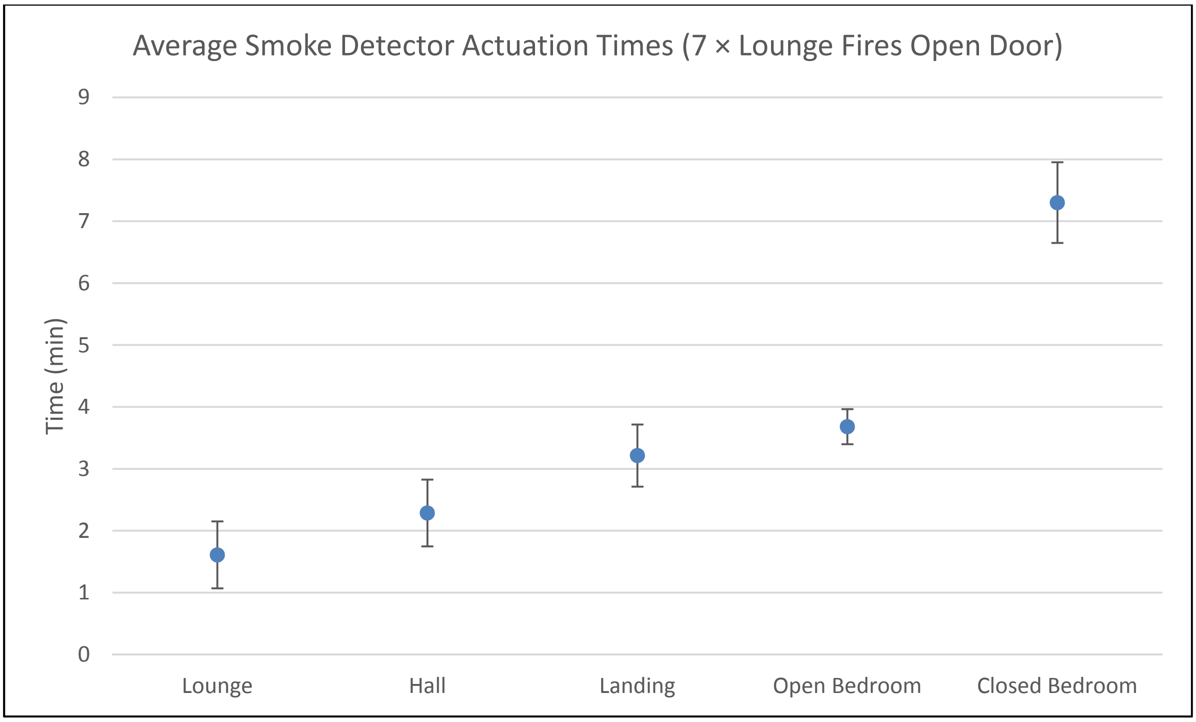

Figure 60 – Average smoke detector actuation times (lounge fires open door)

The focus was to get actuation times within the hallway and landing for use in the timeline assessments. A significant number of data points have been gathered in these locations and the results show reasonable reproducibility. Figure 60 shows the average response times and also gives an indication of the rate at which smoke is transported from one room to the next.

4.3.2 Temperature Profiles

Table 36 contains temperature profile data for each of the seven experiments in the lounge with the fire compartment door open. It shows reasonable agreement in the temperature development to 200°C and 400°C for six of the seven experiments with Experiment 03 showing considerably slower fire growth rates. For Experiments 04, 07, 08, 10, 12 and 13, the average time to reach 200°C is 6:32, however with Experiment 03 this took 11:22. Again, for Experiments 04, 07, 08, 10, 12 and 13, the average time to reach 400°C is 8:03, however with Experiment 03 this took 12:35 as a result of this slower fire development.

Experiment Number	Time to 200°C	Time to 400°C	Max.Temp. (°C)	Time to Max. Temp.
Exp.03	11:22	12:35	530	15:10
Exp.04	6:50	8:25	522	13:17
Exp.07	7:23	8:16	482	11:23
Exp.08	5:10	6:45	527	8:20
Exp.10	7:53	9:34	606	13:06
Exp.12	6:43	7:39	616	10:07
Exp.13	5:13	7:37	483	8:51

Table 36 – Temperature profiles (lounge open door scenarios)

With regards to the maximum temperatures during each experiment, the highest three temperatures, which averaged 584°C, all came from fires which had 2 m^2 ventilation, whereas the two lowest temperatures, which averaged 483°C, both came from fires which had 0.5 m^2 ventilation. This supports the understanding that the maximum burning rate in compartment fires is controlled by the amount of ventilation.

A comparison of the temperature profiles for each experiment is given in Figure 61 which confirms the fact that the fire development within Experiment 03 was somewhat slower than that of the other 6 experiments, within this grouping. The other 6 experiments do show a reasonably good correlation with the growth phase occurring between 5 and 8 min.

Of all seven of the experiments, two (Experiments 03 and 04) were duplicates. Clearly there is no significant agreement between the two temperature profile curves which does demonstrate the fact that there are many factors which can influence the rate at which a fire develops. It is observed that whist the fire development curves are all very similar, there can be some variation in duration of the incubation period.

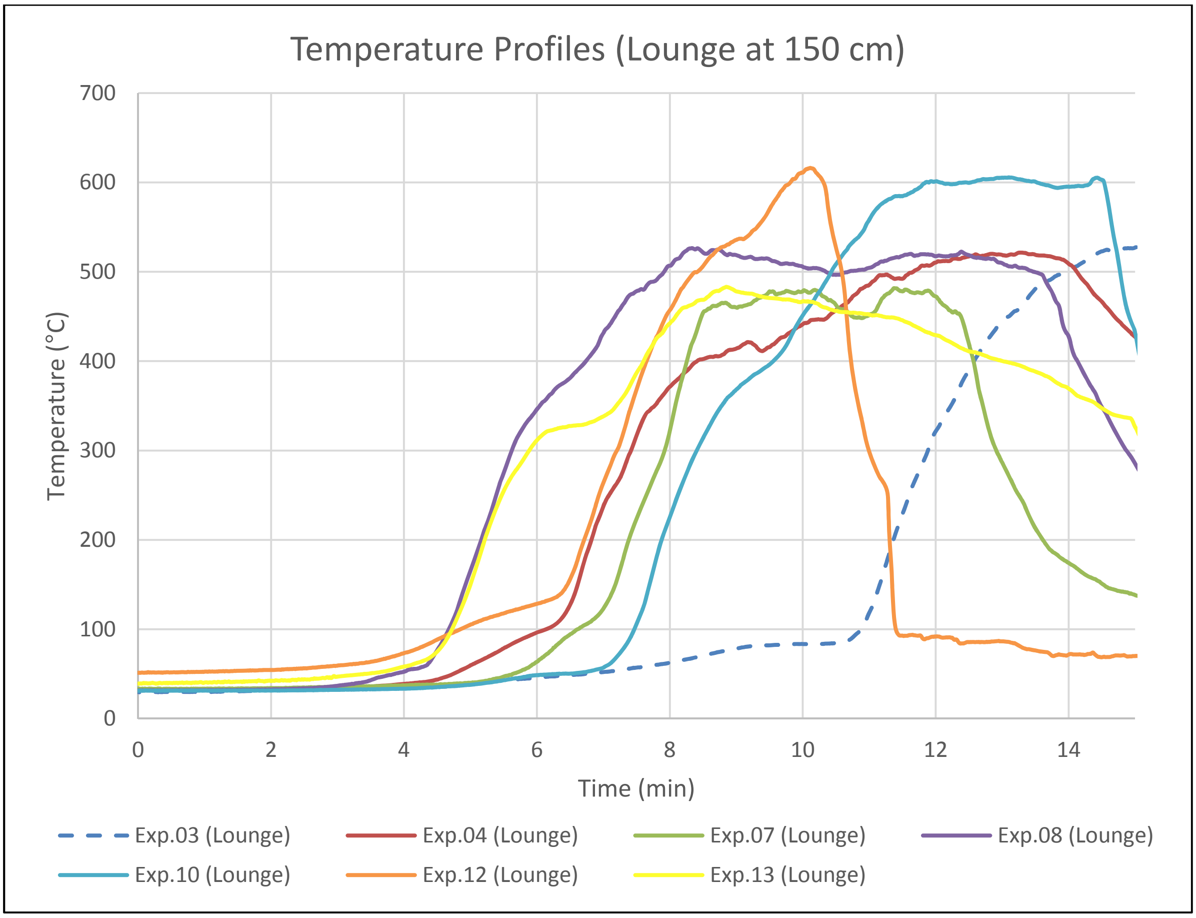

Figure 61 – Lounge open door temperature profiles (lounge at 150 cm)

It also shows that the decay phase of the fire development curve tends to start at around 13 to 15 min, at which point presumably, the majority of the available fuel has been consumed by the fire. Experiment 12 is seen to decay slightly earlier than some of the other experiments and this is probably as a result of it reaching higher temperatures early on which indicates that the fuel was consumed earlier by the fire.

Figure 62 shows the temperature profiles on the landing for each of the seven experiments and again the profiles follow a similar sequence to those in the lounge, with Experiment 03 being the obvious curve which is not comparable.

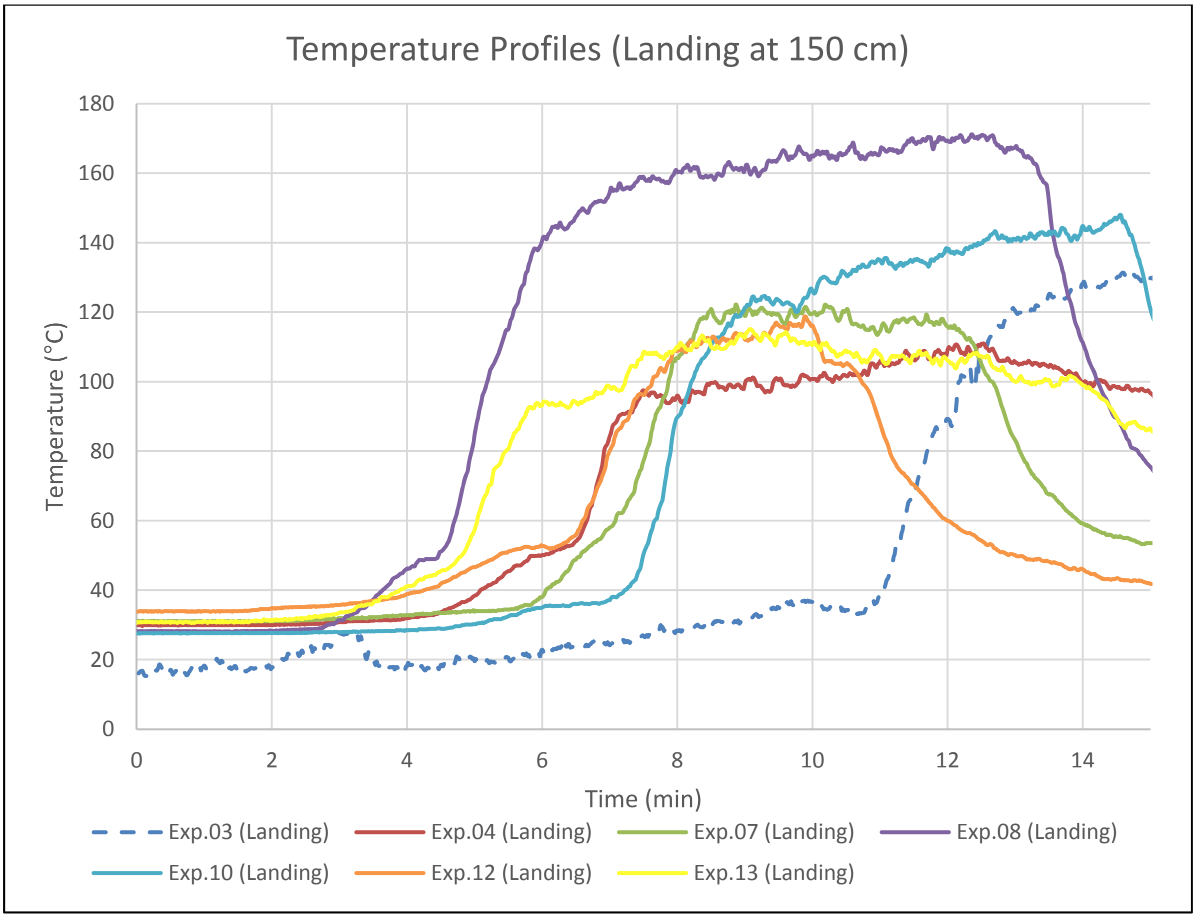

Figure 62 – Lounge open door temperature profiles (landing at 150 cm)

As with Figure 46, Figure 63 shows the temperature profiles at each of the four sampling points in the fire compartment, landing, open bedroom and closed bedroom, for Experiment 04 only. Temperatures are as would be expected with the highest temperature being recorded within the lounge and temperatures reducing steadily as the smoke travels away from the fire.

It is typical of the other experiments discussed within this section of the thesis with the maximum temperature in the fire compartment reaching 522°C, the maximum on the landing is 125°C, in the open bedroom it is 71°C and in the closed bedroom the maximum is 36°C. In the closed bedroom the temperature rises by only 6°C above the ambient temperature prior to the experiment in comparison with a rise of 41°C in the open bedroom. Again this is good evidence of the protection provided by the closed door.

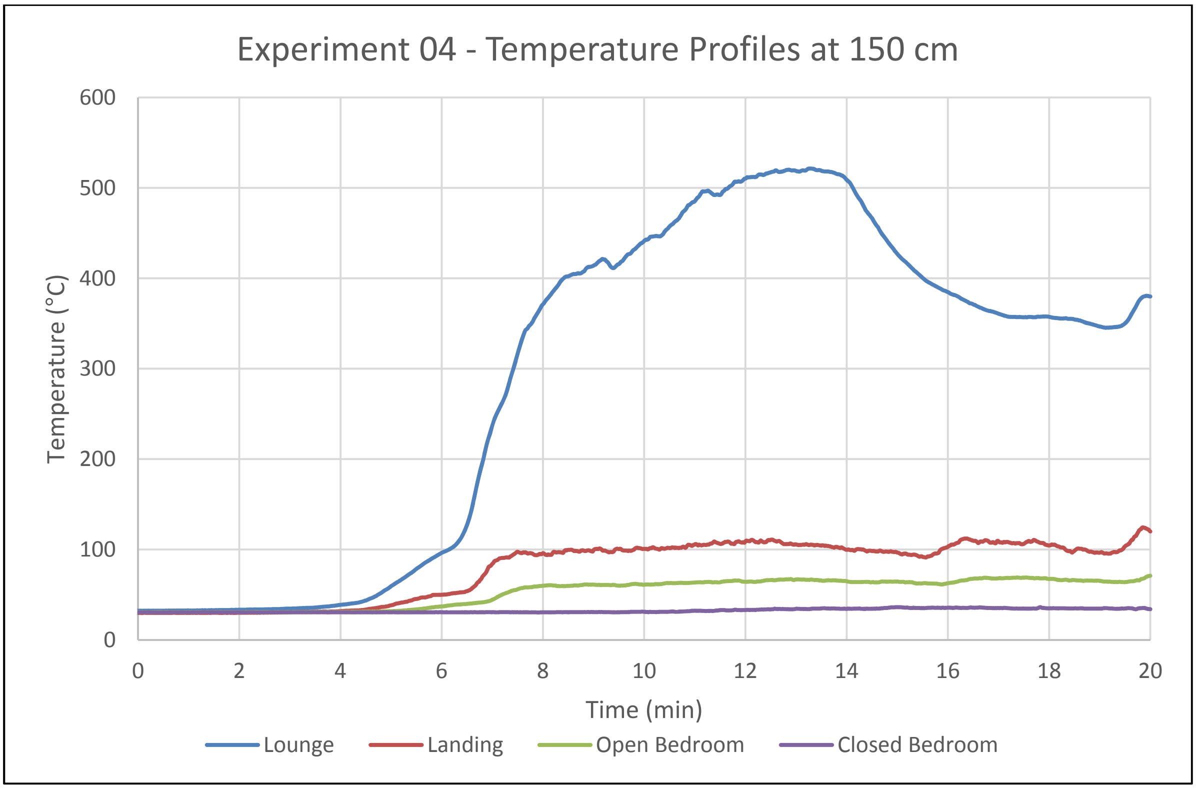

Figure 63 – Experiment 04 temperature profiles (at 150 cm)

Figure 64 shows the temperature profiles in the lounge at various heights during Experiment 04. Two of the thermocouples gave erroneous results, at 90 cm and at 30 cm. The temperature profile curves at 150 cm and above show a temperature variation of only 50°C within the smoke layer during the fully involved stage of the fire. It is interesting to see that the profile at 120 cm is significantly lower in temperature, some 150°C cooler during the same period. This indicates that the neutral plane, between the hot upper layer and the cooler lower layer, is likely to be located somewhere between 120 and 150 cm above floor level. The neutral plane seems to be consistently at this height whilst there is still a reasonable amount of fuel burning.

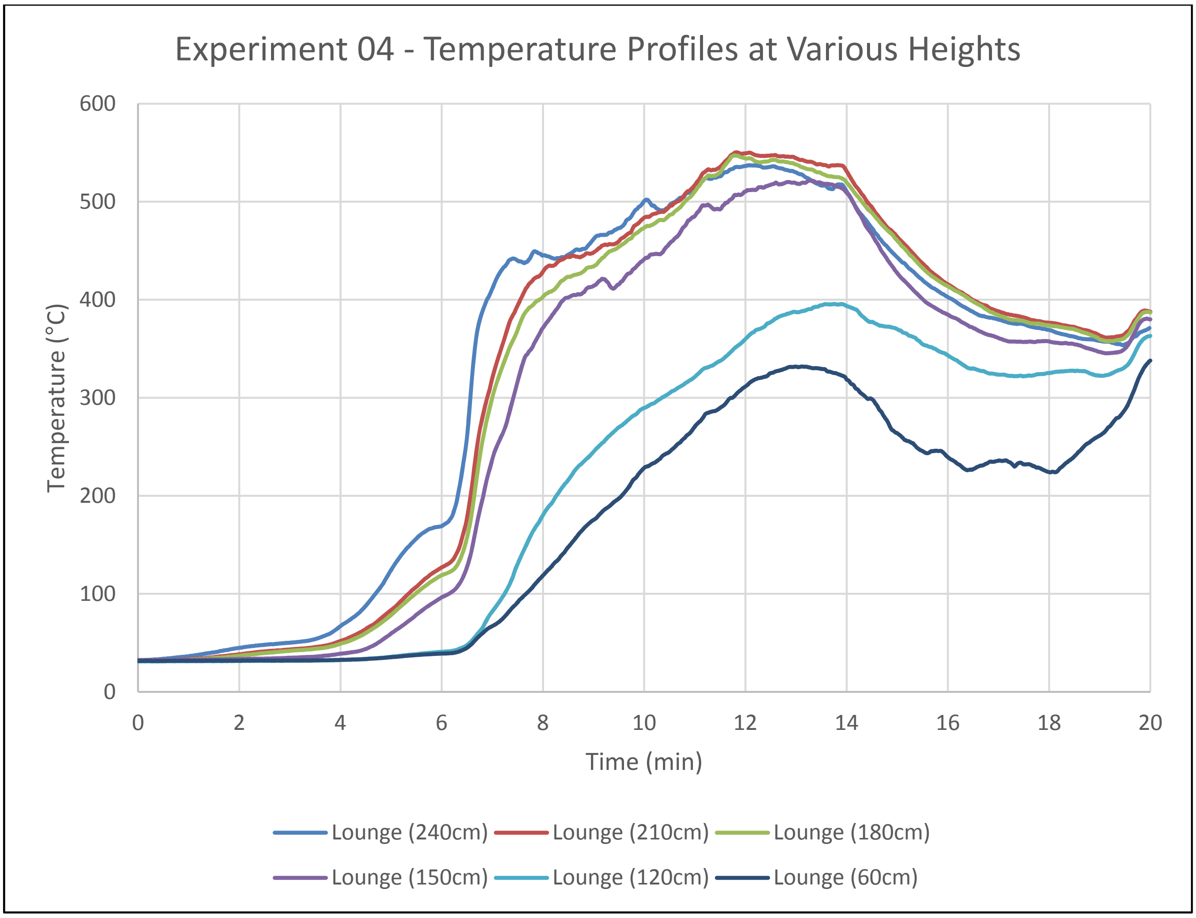

Figure 64 – Experiment 04 lounge temperature profiles (at various heights)

4.3.3 Gas Concentrations

Table 37 shows the peak gas concentrations measured during Experiments 03, 04, 07, 08, 10, 12 and 13 for CO_2, CO and O_2. For CO_2 and CO this is an upper concentration peak and, as O_2 depletion is being considered, for this compound it is a lower concentration peak. The data for HCN is derived from the CO concentration and is not therefore presented within this table.

Experiment Number	Room	CO_2 Peak (%)	Time	CO Peak (%)	Time	O_2 Peak (%)	Time
Exp.03	Lounge	12.43	13:03	0.81	13:53	6.81	13:47
	Landing	12.33	16:30	0.71	16:20	6.54	16:14
	Open (BR)	12.15	17:29	0.69	16:41	6.89	17:00
	Closed (BR)	12.13	17:35	0.69	17:08	7.06	17:06
Exp.04	Lounge	17.16	12:20	1.85	7:07	1.92	12:24
	Landing	15.23	13:39	1.91	13:57	3.91	12:29
	Open (BR)	14.63	14:13	1.89	14:17	4.33	14:01
	Closed (BR)	1.57	20:00	0.13	20:00	-	-
Exp.07	Lounge	14.18	11:33	0.69	12:45	4.83	11:33
	Landing	13.06	12:24	0.42	9:57	6.15	12:00
	Open (BR)	-	-	-	-	-	-
	Closed (BR)	4.19	18:45	0.18	18:42	15.81	18:39
Exp.08	Lounge	10.99	7:38	1.13	5:42	7.55	7:38
	Landing	8.55	9:07	0.51	9:07	10.54	9:08
	Open (BR)	7.55	12:36	0.42	11:48	11.11	12:17
	Closed (BR)	1.91	17:35	0.18	19:13	18.51	17:21
Exp.10	Lounge	13.43	11:00	0.64	11:18	5.51	11:00
	Landing	11.48	13:15	0.61	11:18	7.52	13:01
	Open (BR)	11.22	13:36	0.58	11:38	7.68	13:09
	Closed (BR)	5.04	19:21	0.31	20:00	15.11	18:20
Exp.12	Lounge	17.84	10:20	3.69	10:50	1.13	10:18
	Landing	13.45	10:28	2.42	11:10	4.78	10:53
	Open (BR)	12.42	11:20	2.10	11:50	5.49	11:25
	Closed (BR)	0.07	7:37	0.02	12:43	20.58	18:22
Exp.13	Lounge	12.26	8:50	0.63	8:44	6.87	8:44
	Landing	11.16	10:20	0.49	9:58	7.90	10:18
	Open (BR)	10.98	11:08	0.48	10:24	8.21	10:58
	Closed (BR)	4.93	20:00	0.22	20:00	15.86	20:00

Table 37 – Peak gas concentration times (lounge open door scenarios)

It shows that the average peak CO_2 level within the fire compartment, across all seven experiments, is 14%, with CO at 1.3% and O_2 at 5%. These peaks were typically recorded at between 7 and 13 min after ignition.

Figure 65 and Figure 66 show the gas concentration curves for two of the experiments where the fire was in the lounge and the lounge door was open. The first figure suggests that in Experiment 04, there was an incubation period of around 5 min; that the growth phase was between 5-7 min; that the fire was in the developed phase from 7-13 min before entering the decay phase. This experiment involved a larger ventilation area of 2.0 m^2 and the gas concentration curves are again typical of those seen within this type of combustion process.

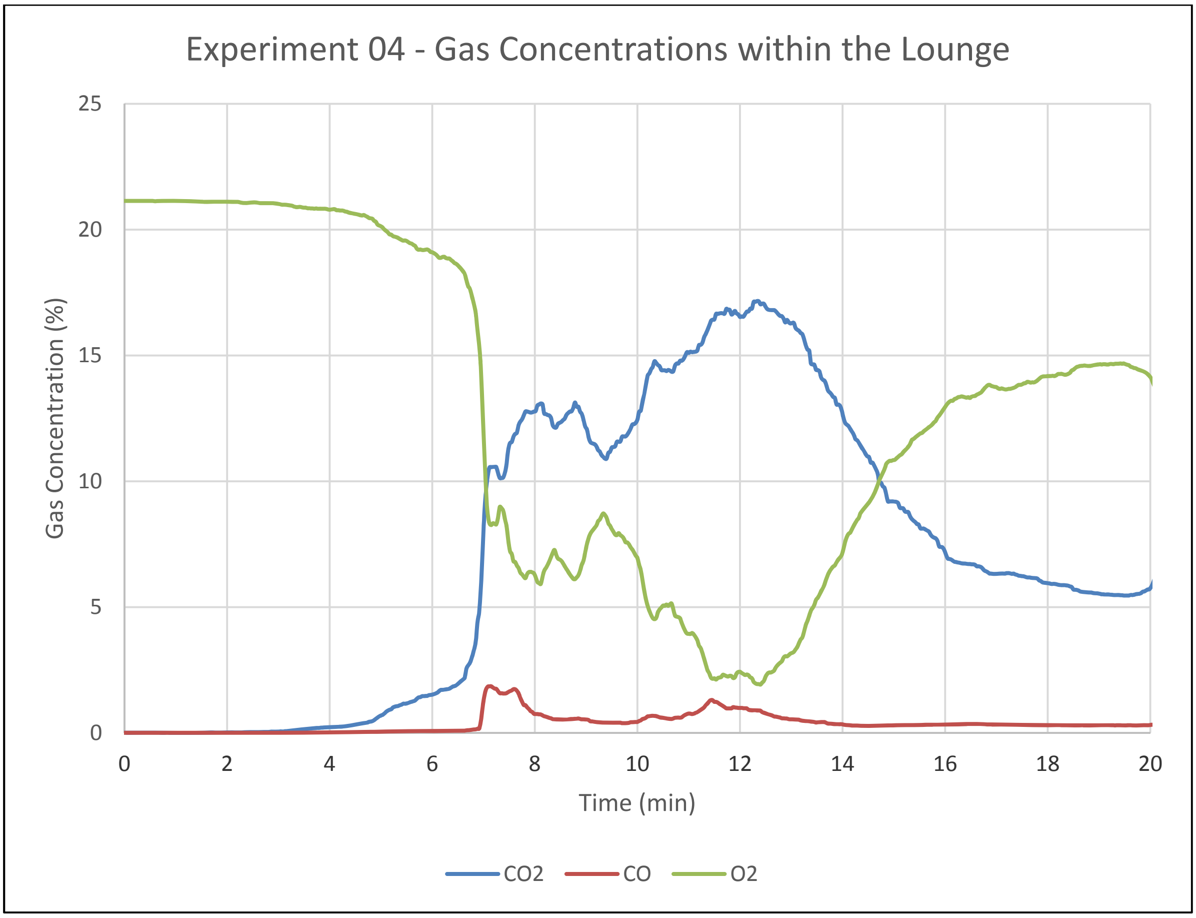

Figure 65 – Experiment 04 lounge gas concentrations

Figure 66 shows that in Experiment 08, there was an incubation period of around 4 min; that the growth phase was between 4-6 min; that the fire was in the developed phase from 6-13 min before entering the decay phase. This experiment involved a smaller ventilation area 0.5 m^2 and the gas concentration curves are again typical of those seen within this type of fire.

In comparison to Experiment 04, the peak gas concentrations in Experiment 08 are lower but the developed stage of the fire seems to last longer which would be typical of a more vitiated fire, where there is a greater degree of control due to reduced ventilation.

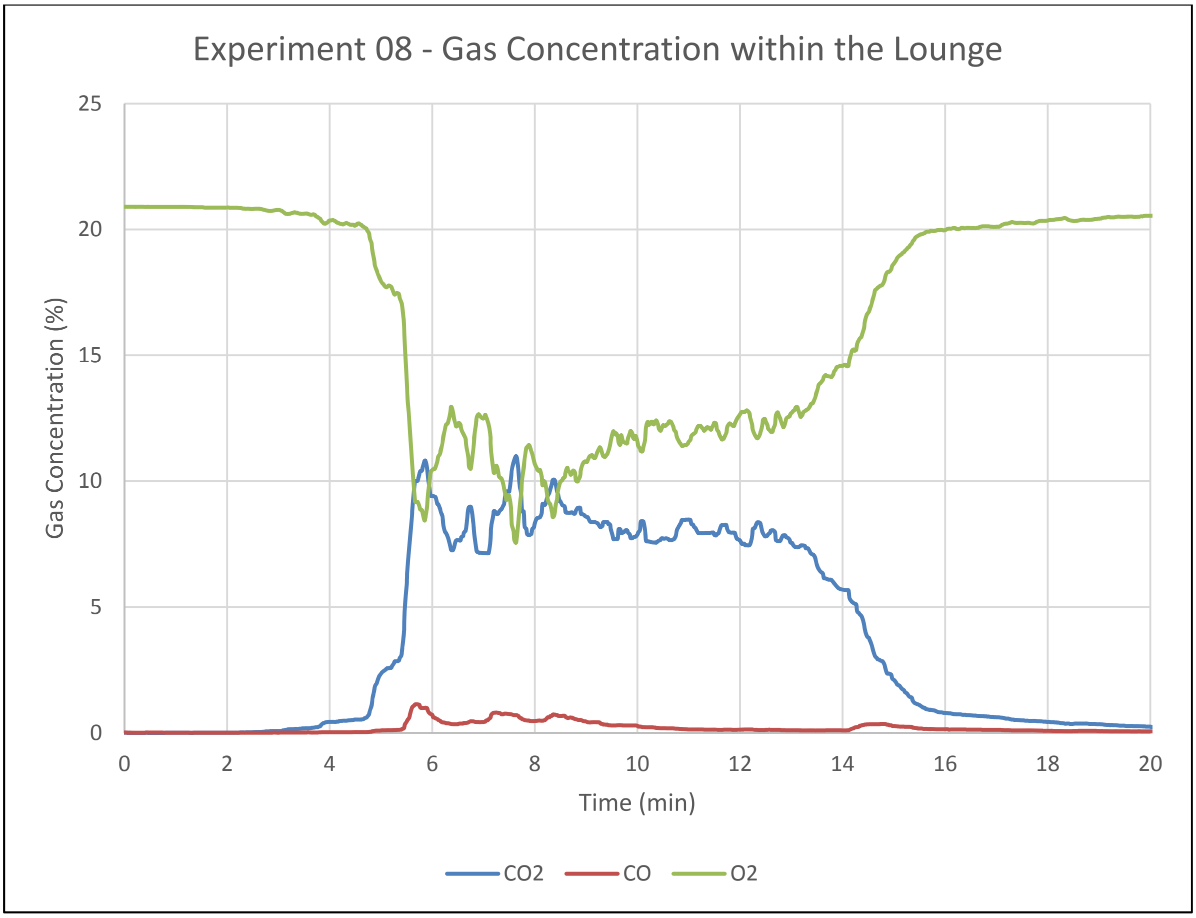

Figure 66 – Experiment 08 lounge gas concentrations

Figure 67 shows the CO:CO$_2$ ratios observed during the experiments where the ventilation levels were greater at 2.0 m^2.

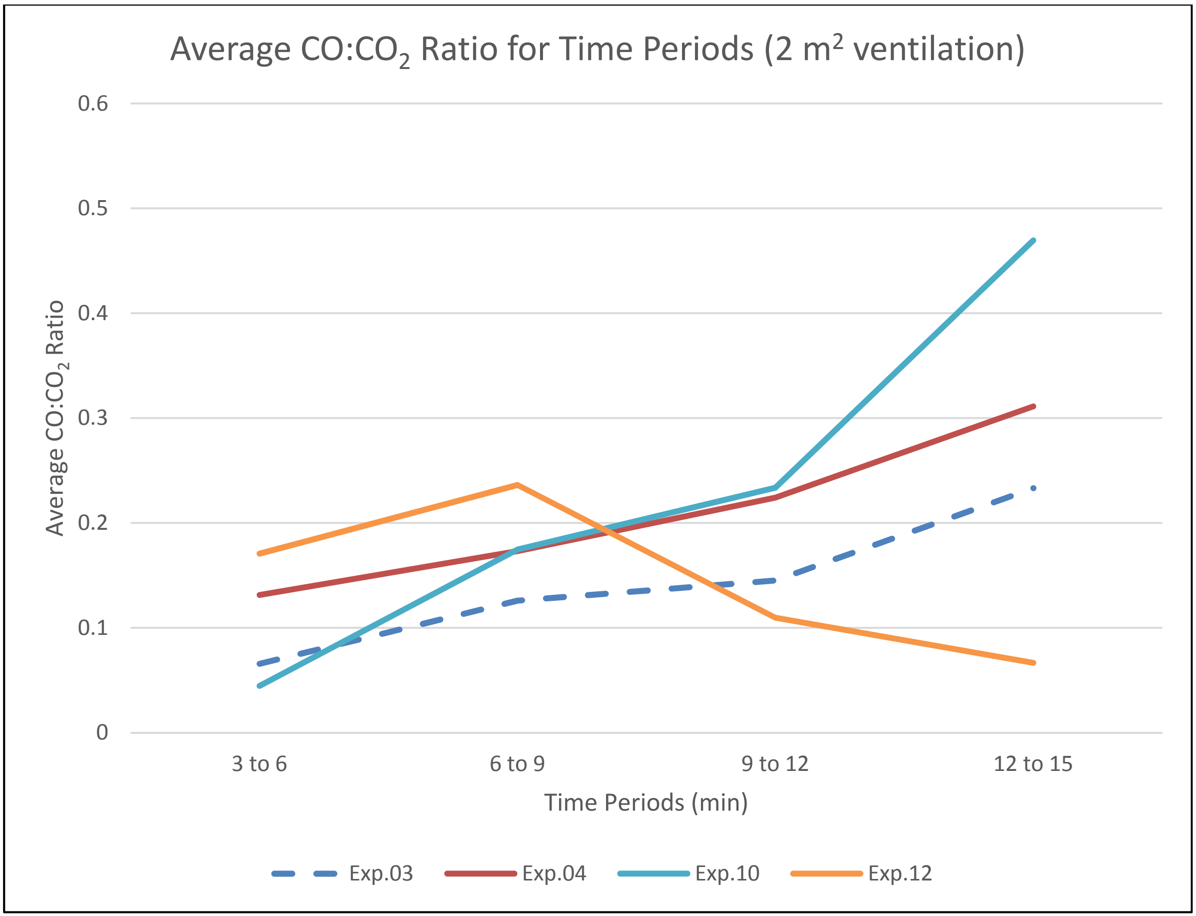

Figure 67 – Avg. CO:CO$_2$ for given time periods / fire compartment (2 m^2 vent)

The CO:CO$_2$ ratios are taken as averages over 4 times 3 minute periods. The data used to produce Figure 67 and Figure 68 is shown in Table 38 below for comparison.

Time Period	Vent 2.0 m^2	Vent 0.5 m^2
3-6 min	0.10	0.16
6-9 min	0.18	0.22
9-12 min	0.18	0.37
12-15 min	0.27	0.32
Average 3-15 min	0.18	0.27

Table 38 – CO:CO$_2$ ratios

For the higher ventilation rates, the data shows a reduced CO:CO$_2$ ratio which increases gradually with time. For the lower ventilation rates, the data shows an increase in the overall CO:CO$_2$ ratio, however, the ratio increases significantly between 3-12 min and then reduces slightly during the later phases when combustion becomes less ventilation-controlled as a result of a slower burning rate.

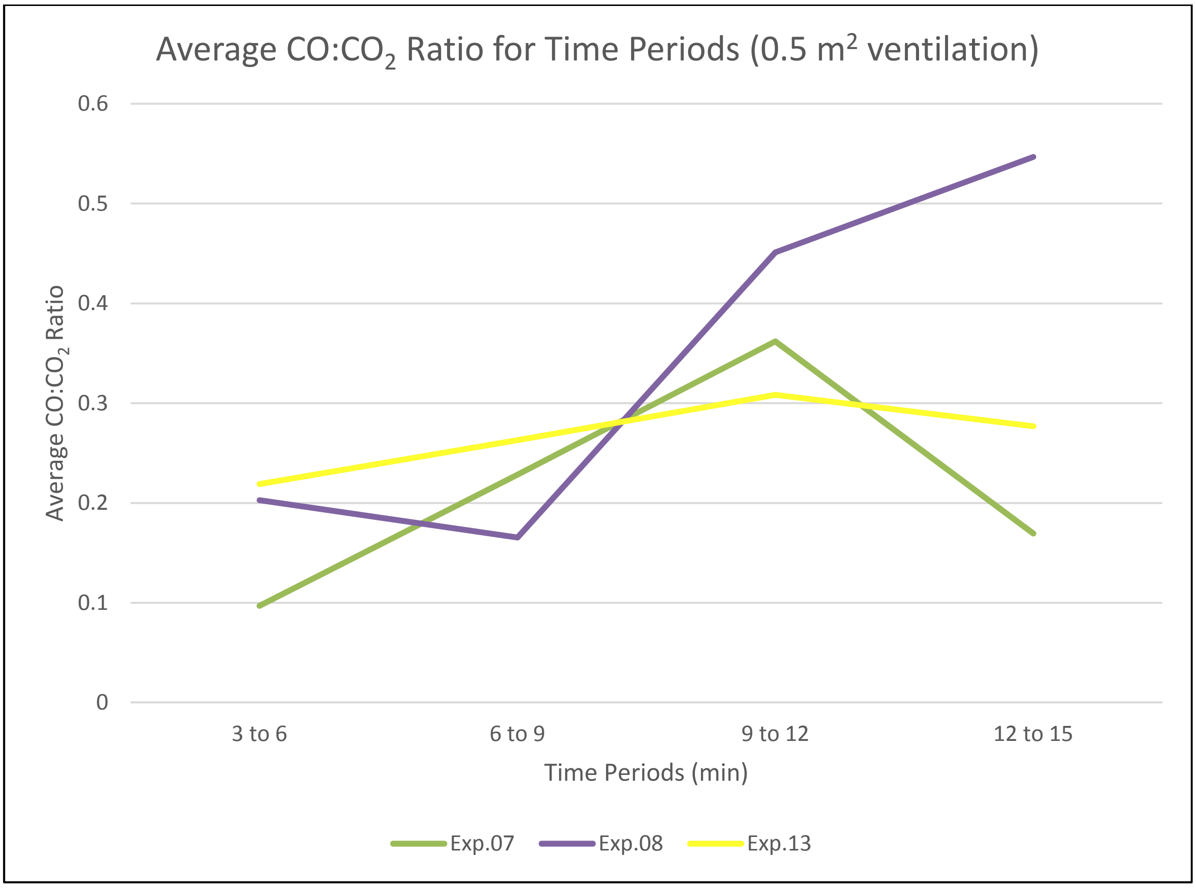

Figure 68 – Avg. CO:CO$_2$ for given time periods / fire compartment (0.5 m^2 vent)

The overall CO:CO$_2$ ratio average across the 4 well-ventilated experiments between 3 to 15 min is 0.18, whereas for the 3 less-ventilated experiments over the same period it is 0.27. In summary, the experiments where ventilation was 2.0 m^2 are able to burn more freely and produce larger volumes of smoke. However, whilst the experiments with a lower ventilation area (0.5 m^2) produce lower volumes of smoke as combustion is more tightly controlled, the smoke they produce has a higher ratio of the asphyxiant gas CO, compared to CO$_2$.

4.3.4 Mass Loss Analysis

Attempts were made to gather mass loss data for all 10 experiments conducted within the lounge. Figure 69 shows that the initial mass of the fuel source is 63.3 kg as established in Section 3.7.2. It also shows the mass loss during Experiment 03, indicating that during the first 11 min the fire consumed approximately 18 kgs of fuel, at this point the rate of fuel consumption increases and over the next 6 min (11 to 17) a further 31 kgs of fuel is consumed. Comparing the data with that in Figure 61, it can be seen that the temperature in the lounge rises sharply above 100°C after 11 min.

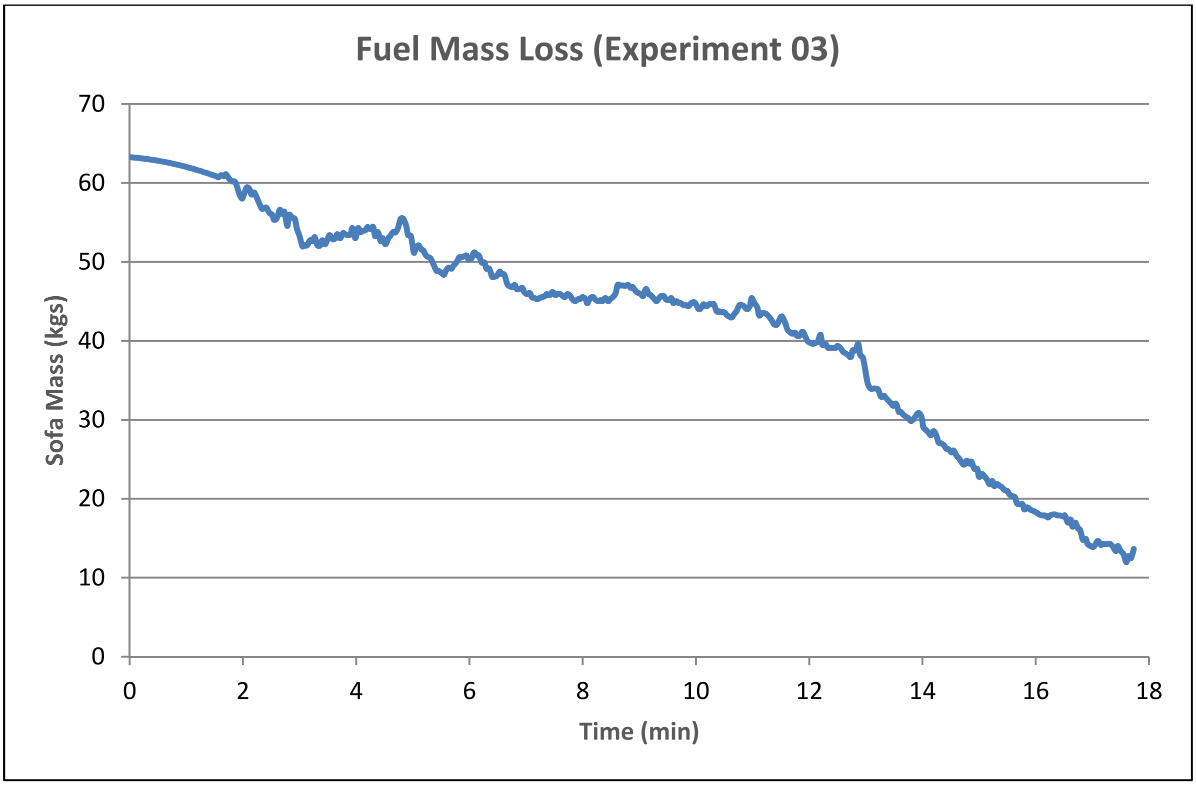

Figure 69 – Experiment 03 mass loss corrected readings

4.3.5 Smoke Visibility

During some of the experiments, the equipment used to gather smoke obscuration data was irreparably damaged and as a result, there is a limit to the amount of data that has been gathered. This data shows a reasonable degree of reproducibility and demonstrates that visibility reduces to less than the 3 m threshold within the hallway at approximately 4 min after ignition. At around 5 min, the same applies to the first floor landing; and the open bedroom achieves reduced visibility at around 8 min. The average time at which the escape route becomes impassable is 4:39.

Experiment Number	Location	Time to 3m visibility
Exp.04	Hallway	3:58
	Landing	5:05
	Open Bedroom	7:51
Exp.07	Open Bedroom	7:41
Exp.12	Landing	4:54
	Open Bedroom	7:51

Table 39 – Time for visibility of 3m (lounge door open scenarios)

With respect to a traditional means of escape (from a bedroom, down the stairs and out the front door) this suggests that, with the fire compartment door being open to the remainder of the property, the time available for a successful escape is approximately 2½ min from when the alarm sounds.

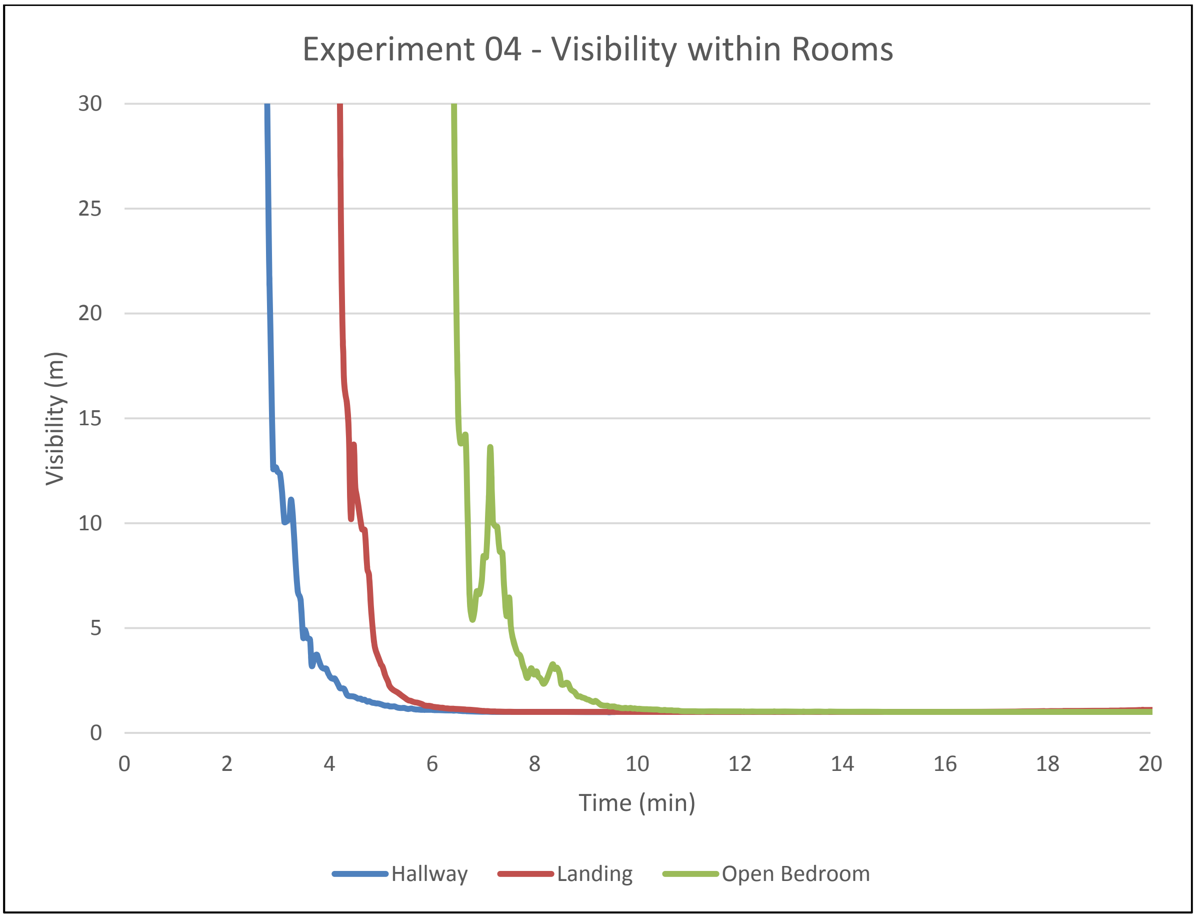

Figure 70 – Experiment 02 room visibility conditions

Figure 70 shows that once the fire takes hold the visibility within compartments which are open to the fire compartment reduces rapidly as smoke is transferred around the property.

Again there is a time lag between different compartments being affected by smoke with the lag being approximately 1.5 min from the hallway to the landing and then a further 2 min from the landing in to the open door bedroom. Unfortunately there is no data from within the closed door bedroom.

4.3.6 Video Analysis

The left hand image in Plate 11 shows a video still taken from within the hallway looking directly towards the lounge (fire compartment) door which is held open. The right hand image in the same plate is taken from a thermal imaging camera located in the same position as the video camera. The temperature of 22°C shown in the bottom corner of the image is taken between the cross hairs and represents the temperature of the wall/doorframe. Both of these images were taken at 10 seconds after ignition.

The dark colouration of the ceiling in the video image is not smoke but is a soot deposit from an earlier experiment. The light obscuration equipment can also be seen at the top of this image.

Plate 11 – Images from within the hallway for Experiment 04 (10s after ignition)

Plate 12 – Images from within the hallway for Experiment 04 (4 min after ignition)

In Plate 12 the same images are taken at 4 min after ignition and it can be seen that smoke is now being emitted from the fire compartment and that the temperature in the fire compartment doorway is unchanged at the level of the cross hairs. The temperature of the smoke being emitted at this point is less than 100°C. This is the time at which visibility is reduced to 3 m at head height. It can be seen that visibility at lower levels remains in excess of this distance as the camera position is located at approximately 70 cm from floor level near to the base of the staircase, as seen in Plate 13.

Plate 13 – Image showing the location of the video and TIC camera during Exp.04

Plate 14 shows that visibility within the hallway has almost completely been lost at 6 min after ignition, with the obscuration equipment recording a reading of 1 m. Large volumes of black smoke are being produced at this point.

Plate 14 – Image from within the hallway for Experiment 04 (6 min after ignition)

Plate 15 shows the thermal image taken at 7 min after ignition with the smoke layer emitting from the fire compartment at temperatures approaching 200°C. The cross hairs which appear at roughly two thirds of the way up the doorframe record a temperature of 83°C.

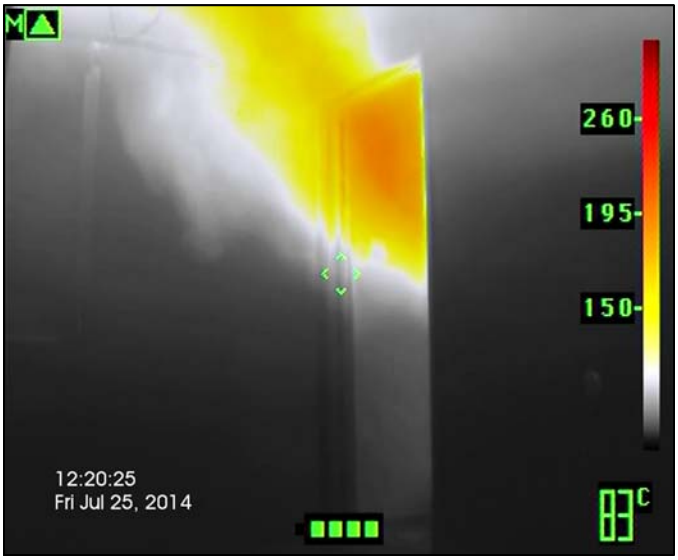

Plate 15 – Image from within the hallway for Experiment 04 (7 min after ignition)

Plates 16 to 19 show the rate of fire development as seen in Experiments 07 and 03. On the left hand side of each pair of images we see the fire developing during Exp.07 and on the right we see the fire during Exp.03, at 1 minute intervals. As discussed earlier within this section, the fire development during Exp.03 seemed significantly slower than in the other six experiments within the lounge with the compartment door open.

During the first 5 min of both experiments the fire develops at a relatively slow rate during the incubation period. The images after 6 and 7 min then show a significant growth in the fire size for Exp.07 but this does not occur until around 11 min within Exp.03. A comparison between each pair of images shows this disparity in fire growth and it is noted that the images for Exp.07 are typical for the remaining 5 experiments. These observations are also seen within the temperature development curve for these experiments, see Figure 71.

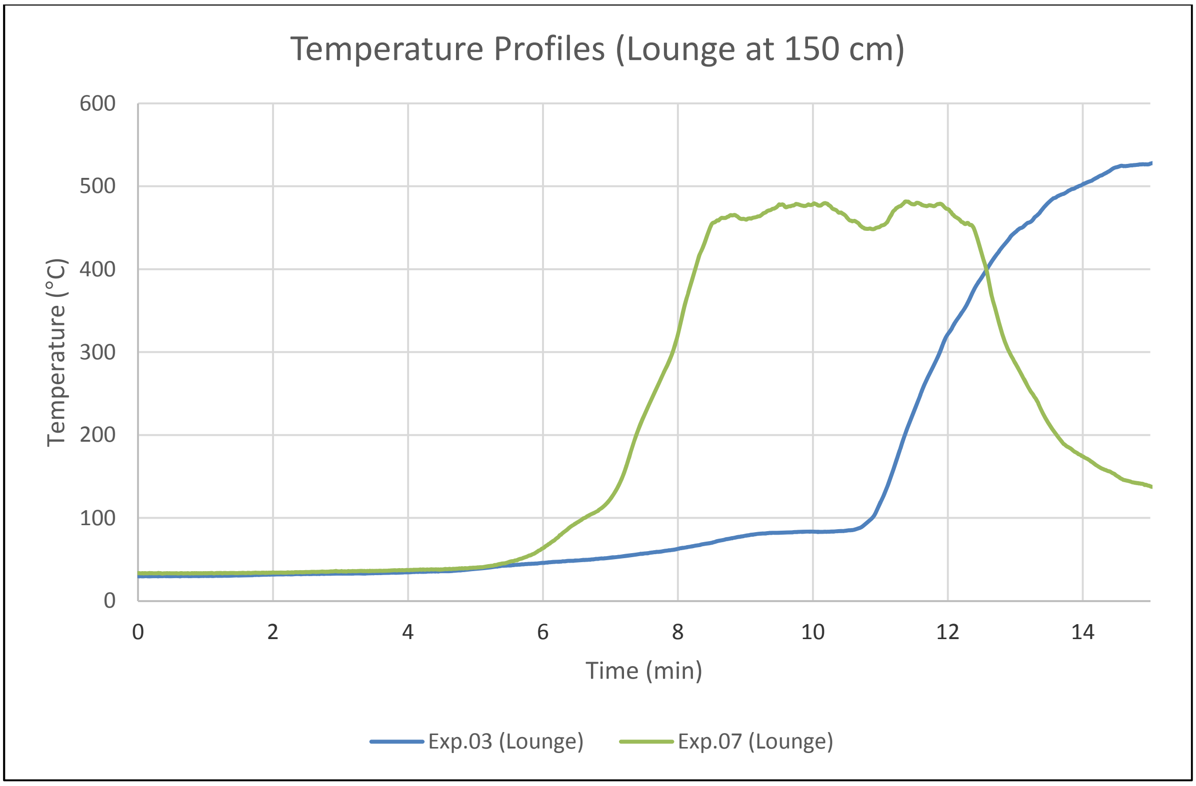

Figure 71 – Experiment 02 room visibility conditions

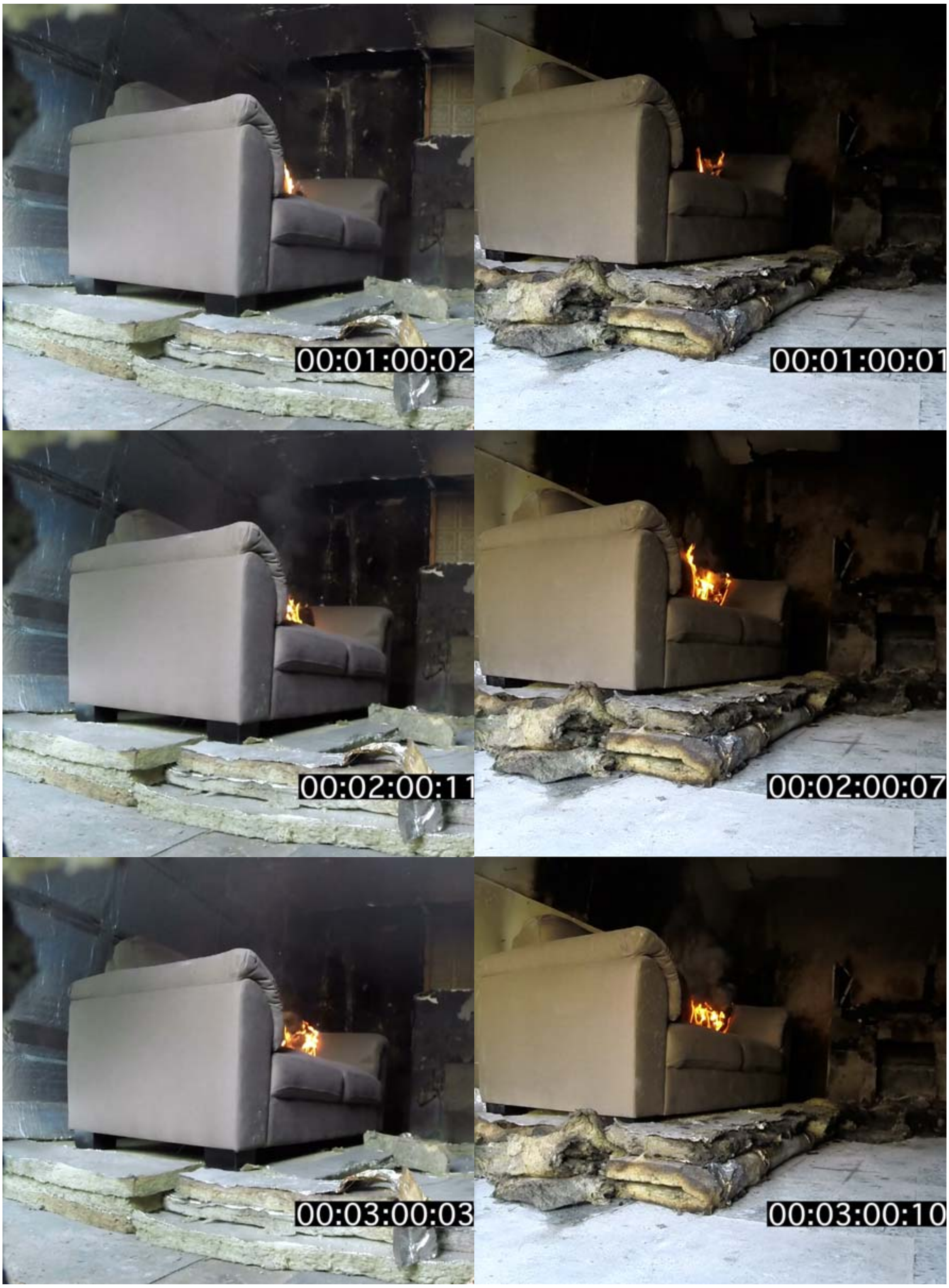

Plate 16 – Image of fire development Exp.07 and Exp.03 (1 to 3 min)

Plate 17 – Image of fire development Exp.07 and Exp.03 (4 to 6 min)

Plate 18 – Image of fire development Exp.07 and Exp.03 (7 to 9 min)

Plate 19 – Image of fire development Exp.07 and Exp.03 (10 to 12 min)

4.3.7 Asphyxiant Gas FED Analysis

Equation 8 will again be used in the analysis of the asphyxiant gas concentration data to yield a time to lethality in the various rooms within the property. The time to lethality is established for the more vulnerable members of the community at 1.0×FED and also for the healthy adult population at 2.5×FED.

Table 40 details the outcomes of this analysis and again shows that there is a significant discrepancy between Experiment 03 and the other 6 experiments which all show good reproducibility. Average figures are also shown within the table however these averages are based on the 6 experiments which showed good agreement and exclude the data from Exp.03. The standard deviation against these mean values is also given and does suggest that there is good agreement between the 6 experiments with standard deviations around 1 minute or less.

It shows that vulnerable people will receive a fatal dose of asphyxiant gases within the fire compartment at between 5:45-9:45 min with an average of 7:31; this figure increases to 8:08 when impacting upon a healthy adult. On the landing, survivability times for healthy adults are increased to 9-10 min in the open bedroom this increases further to 9¾-11 ¾ min and in the closed bedroom survival times are much increased to in excess of 20 min.

The relative contribution from both CO and HCN is considered for Experiment 04 in Section 4.4.4.

Experiment Number	Room	Time to 1.0xFED	Time to 2.5xFED	Average Time to 1.0xFED	Average Time to 2.5xFED
Exp. 03	Lounge	12:56	13:29	7:31 (SD – 1:22)	8:08 (SD – 1:43)
Exp. 04		7:05	7:11		
Exp. 07		8:20	9:28		
Exp. 08		5:43	6:01		
Exp. 10		9:42	10:44		
Exp. 12		7:03	7:13		
Exp. 13		7:09	8:10		
Exp. 03	Landing	13:55	14:32	8:44 (SD – 0:43)	9:34 (SD – 0:44)
Exp. 04		8:39	9:24		
Exp. 07		9:16	10:03		
Exp. 08		7:45	8:45		
Exp. 10		9:48	10:48		
Exp. 12		8:28	9:05		
Exp. 13		8:28	9:18		
Exp. 03	Open Bedroom	14:29	15:07	9:31 (SD – 0:33)	10:30 (SD – 0:56)
Exp. 04		9:18	9:58		
Exp. 07		-	-		
Exp. 08		9:43	11:48		
Exp. 10		10:23	11:12		
Exp. 12		9:13	9:45		
Exp. 13		8:58	9:48		
Exp. 03	Closed Bedroom	-	-	> 20 min	> 20 min
Exp. 04		> 20 min (0.05)	> 20 min (0.05)		
Exp. 07		> 20 min (0.87)	> 20 min (0.87)		
Exp. 08		> 20 min (0.77)	> 20 min (0.77)		
Exp. 10		18:09	> 20 min (1.84)		
Exp. 12		> 20 min (0.08)	> 20 min (0.08)		
Exp. 13		> 20 min (0.92)	> 20 min (0.92)		

Table 40 – Smoke FED time to lethality (lounge open door scenarios)

Figure 72 shows the data for Experiment 04, where the development of the asphyxiant gas FED curves can be seen. This graph shows that asphyxiant gases have a relatively minor impact upon human safety within the first 6 min, whilst the fire is in its incubation period. At around 7 min the build-up of the asphyxiant gases reaches fatal levels within the lounge (fire compartment) and the transition from 1.0×FED to 2.5×FED occurs almost instantaneously over a period of only 6 seconds.

Fatal levels of toxic smoke are seen on the landing at around 8½ min with another 40 seconds before survivability is threatened within the open door bedroom. Within the closed door bedroom there is little sign of toxic smoke levels until around 18 min with the FED reaching 0.05 at twenty min.

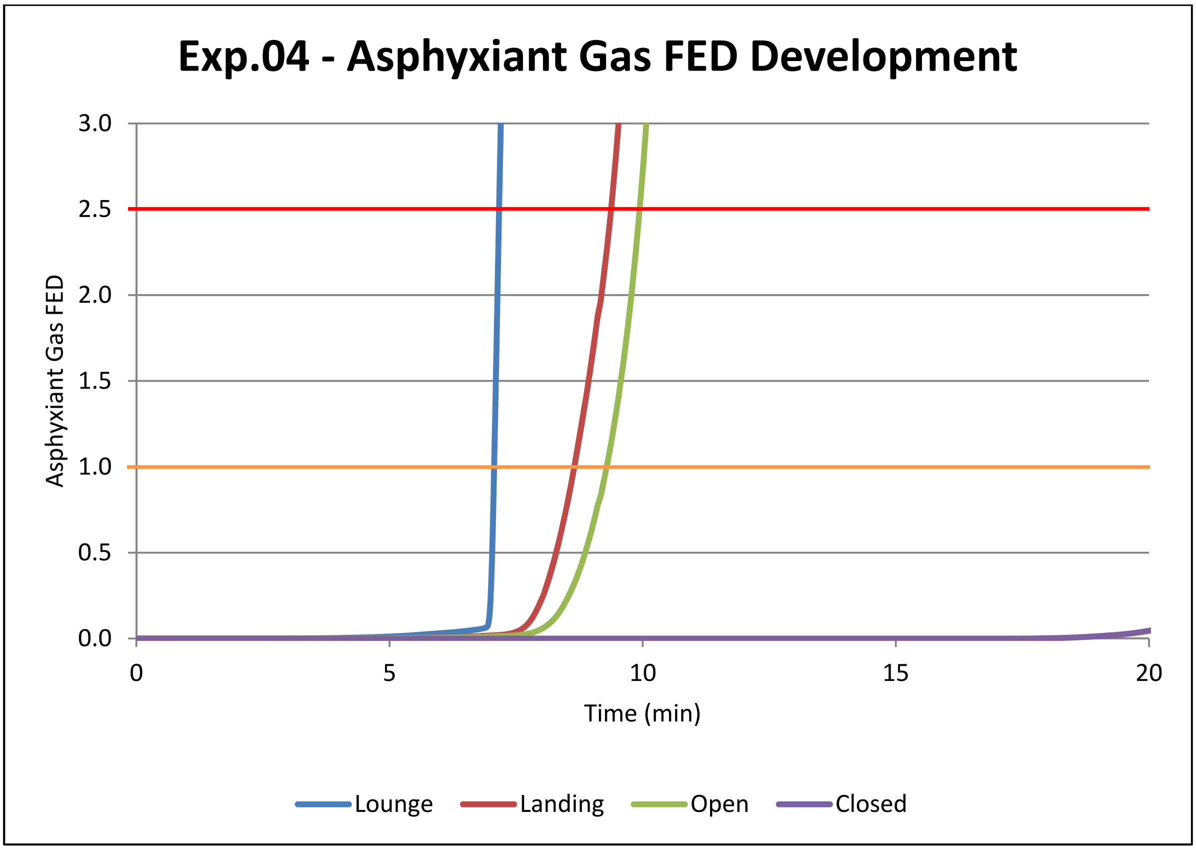

Figure 72 – Experiment 04 asphyxiant gas FED development

Figure 73 to Figure 76 show the FED development curves for all individual experiments within each of the rooms where FED data was gathered. Within Figure 75, the data for Exp.07 is omitted and within Figure 76 the data for Exp.03 is also omitted, both due to corrupted data from unrealistic gas concentrations.

These figures also show that there is good reproducibility in all experiments except for Exp.03, where the incubation period was inexplicably long. The asphyxiant gas concentrations in all 7 experiments are seen to be low during the early stages of fire growth and then the production of these gases and hence the FED curves increase exponentially after the early incubation period. It is observed that the transition from 1.0×FED to 2.5×FED is typically between 30-60 seconds in all rooms which are open to the fire compartment. In the bedroom with the closed door, it can be seen that this transition is significantly slower, with only one vulnerable person fatality being recorded.

As a result of the exponential growth of these fires, after their incubation period, there is only a small time difference between the survivability of the more vulnerable people and those who are healthy adults. Details of these differences are given in Table 41, where it can be seen that the average difference between 1.0×FED and 2.5×FED within the fire compartment is 37 seconds, this extends to 50 seconds on the landing and to 59 seconds in the open door bedroom. This increase within the closed door bedroom is significantly greater.

Room	Avg. Time from 1.0 to 2.5 FED
Lounge	0:37
Landing	0:50
Open Bedroom	0:59
Closed Bedroom	3-4 min

Table 41 – Time difference between 1.0 and 2.5 FED (lounge open door scenarios)

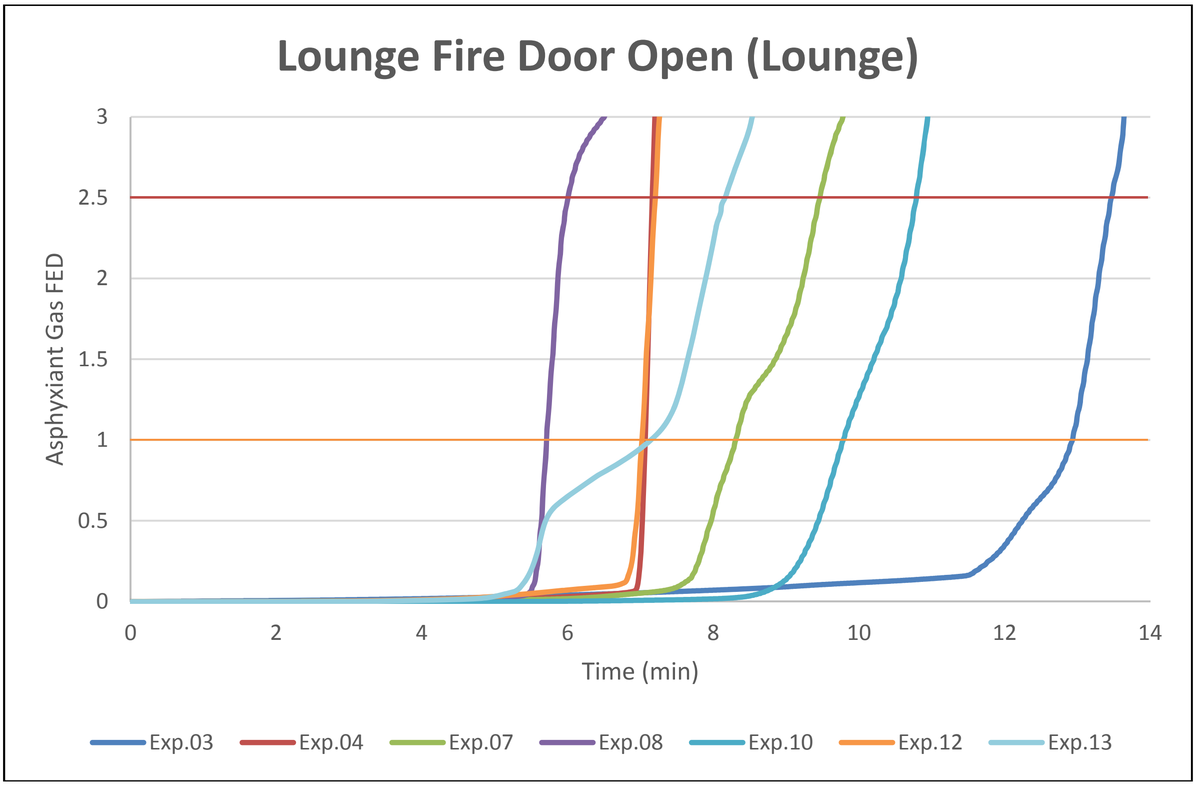

Figure 73 – Lounge fire door open asphyxiant gas FED development (lounge)

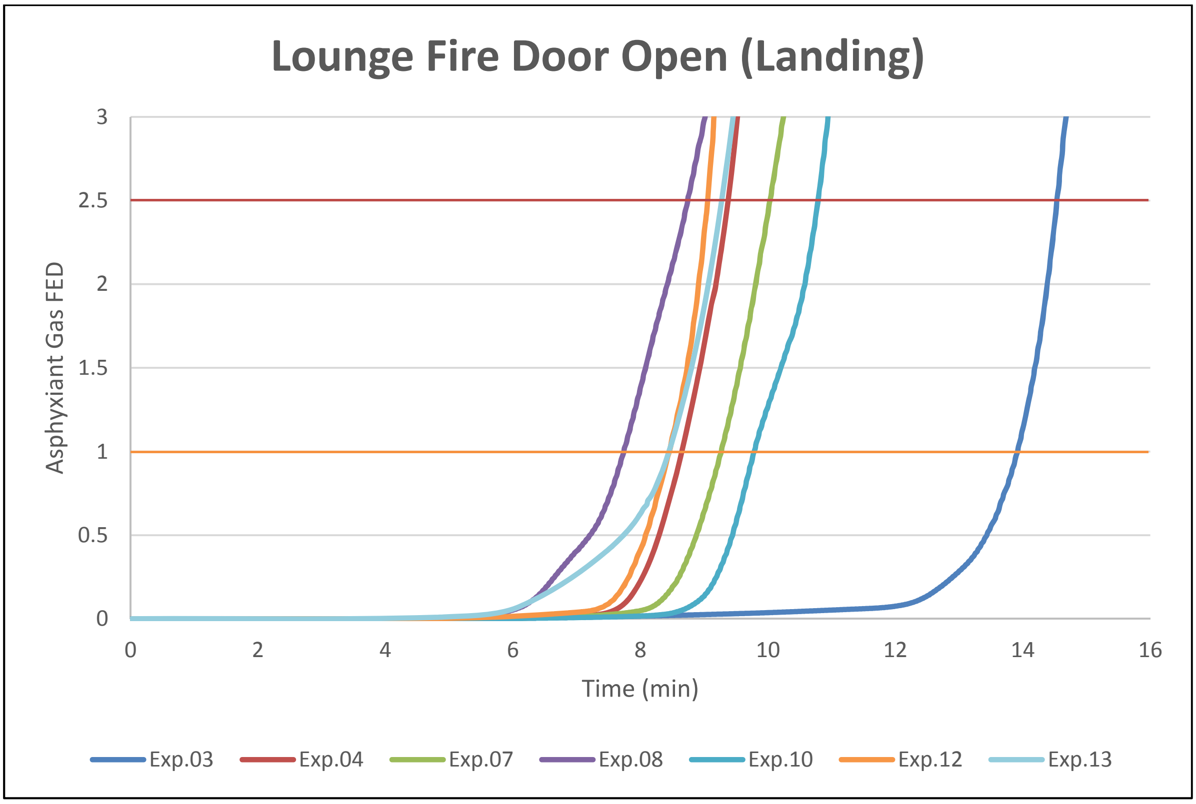

Figure 74 – Lounge fire door open asphyxiant gas FED development (landing)

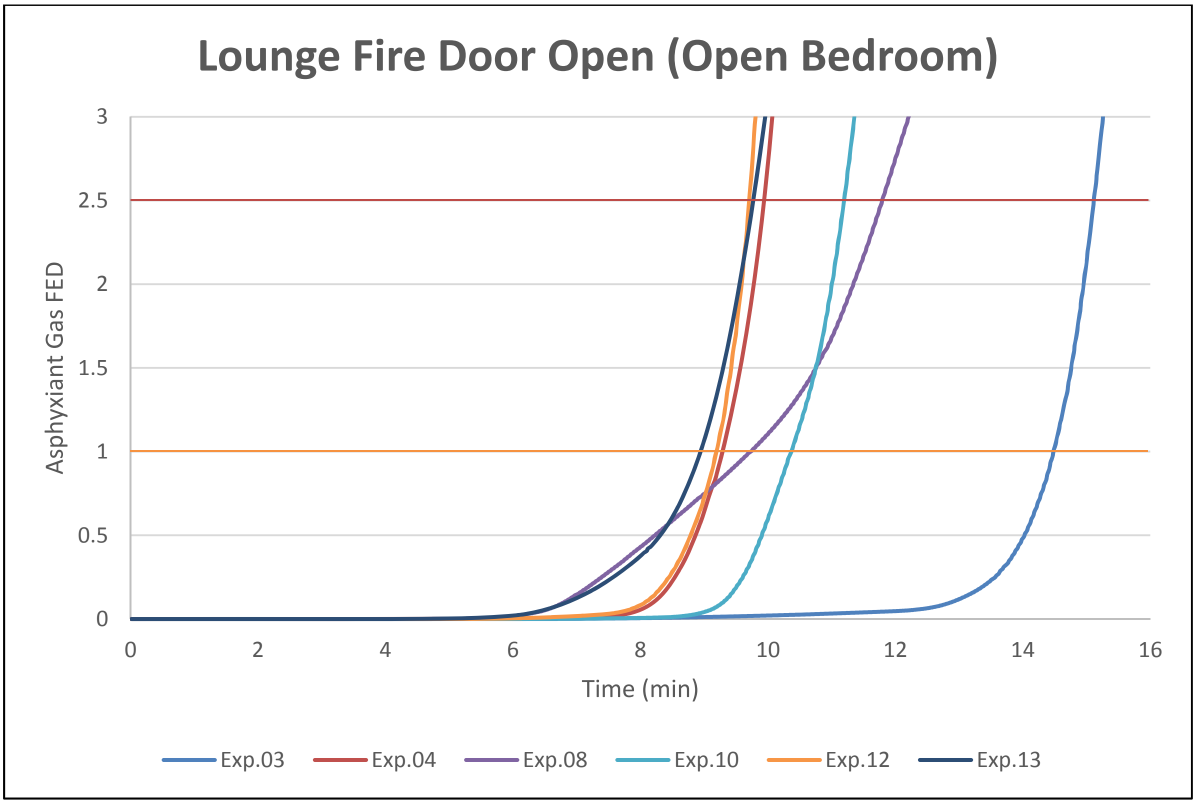

Figure 75 – Lounge fire door open asphyxiant gas FED development (open bed)

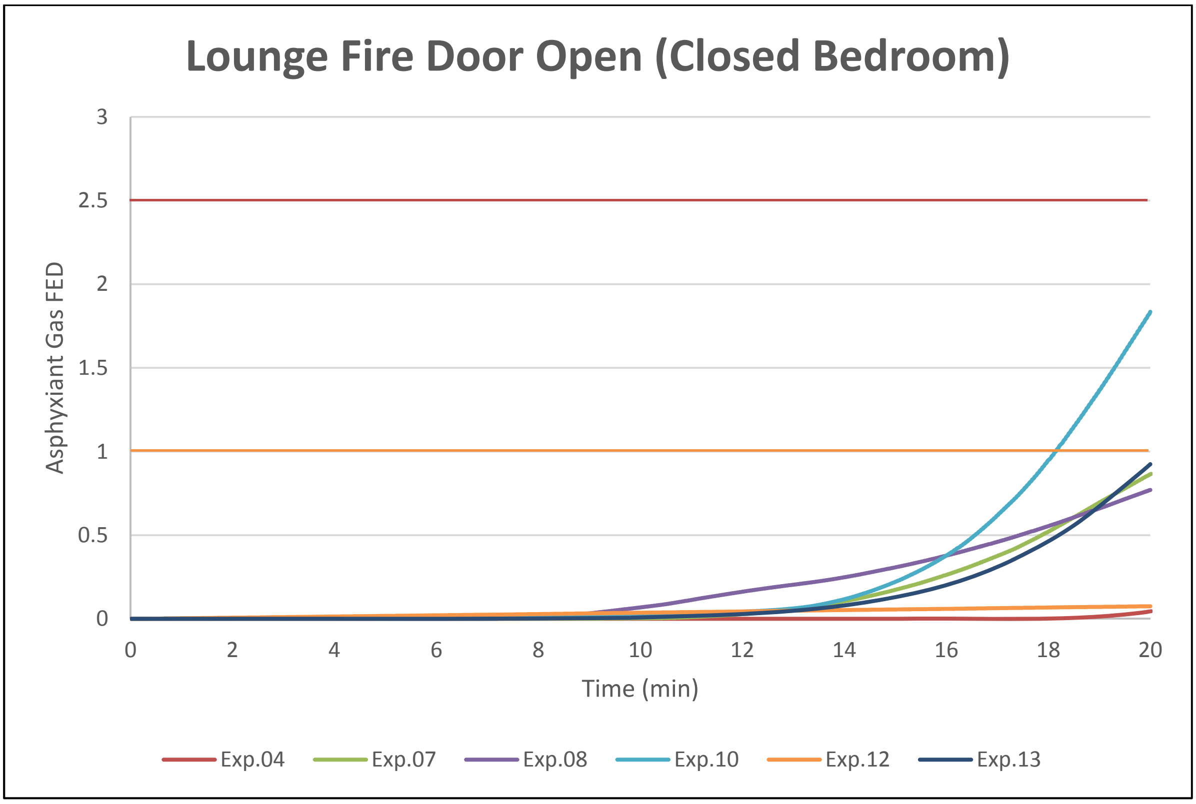

Figure 76 – Lounge fire door open asphyxiant gas FED development (closed bed)

Table 42 shows the average time difference for the two FED thresholds between one room and the next. For vulnerable persons, fatality within the landing occurs 1:13 later than the lounge, 47 seconds later in the open door bedroom and then the closed door bedroom remains largely tenable. Again this shows the value of a closed door between the fire and an occupant.

Rooms	Average Lag (1.0 × FED)	Average Lag (2.5 × FED)
Lounge to Landing	1:13	1:26
Landing to Open Bedroom	0:47	0:56

Table 42 – Average time lag between rooms (lounge open door scenarios)

4.3.8 Heat FED Analysis

As a result of the increased fuel loading within the lounge fire scenarios, significantly more heat is produced during combustion and increased temperatures within all rooms is observed, when compared with the kitchen fires. As a result, heat plays a more significant role with regards to the impact that the fire has on the occupants of the property. The time taken for heat to lead to the occupants of the building being fatally exposed are given in Table 43, with the average times given for both thresholds. The average times do not include the data obtained during Experiment 03 as a result of its significantly slower fire development.

This table shows that heat leads to fatal conditions within the lounge after around 7 min. Unlike the fires located within the kitchen, there is also enough heat generated to cause fatalities on the landing, with these occurring at in excess of 13 min on average. Conditions within the open door and closed door bedrooms are survivable for more than 20 min from the perspective of heat exposure.

The data for the 6 experiments where the fire developed similarly shows a reasonable agreement within the lounge as indicated by the standard deviations. The data gathered on the landing shows an increase in the spread of the data points. This is probably as a result of the differing sets of ventilation conditions, which may have a reduced impact within the fire compartment.

Experiment Number	Room	Time to 1.0xFED	Time to 2.5xFED	Average Time to 1.0xFED	Average Time to 2.5xFED
Exp. 03	Lounge	11:37	11:57	6:48 (SD – 1:07)	7:08 (SD – 1:07)
Exp. 04		7:06	7:28		
Exp. 07		7:40	8:00		
Exp. 08		5:28	5:45		
Exp. 10		8:11	8:30		
Exp. 12		6:51	7:14		
Exp. 13		5:31	5:53		
Exp. 03	Landing	15:42	> 20 min (2.05)	12:50 (SD – 4:07)	> 20 min
Exp. 04		14:02	> 20 min (1.84)		
Exp. 07		12:05	> 20 min (1.23)		
Exp. 08		7:28	9:49		
Exp. 10		11:37	16:06		
Exp. 12		> 20 min (0.80)	> 20 min (0.80)		
Exp. 13		11:46	> 20 min (1.53)		
Exp. 03	Open Bedroom	> 20 min (0.27)	> 20 min (0.27)	> 20 min	> 20 min
Exp. 04		> 20 min (0.38)	> 20 min (0.38)		
Exp. 07		> 20 min (0.28)	> 20 min (0.28)		
Exp. 08		> 20 min (0.95)	> 20 min (0.95)		
Exp. 10		> 20 min (0.47)	> 20 min (0.47)		
Exp. 12		> 20 min (0.19)	> 20 min (0.19)		
Exp. 13		> 20 min (0.31)	> 20 min (0.31)		
Exp. 03	Closed Bedroom	> 20 min (0.04)	> 20 min (0.04)	> 20 min	> 20 min
Exp. 04		> 20 min (0.06)	> 20 min (0.06)		
Exp. 07		> 20 min (0.06)	> 20 min (0.06)		
Exp. 08		> 20 min (0.05)	> 20 min (0.05)		
Exp. 10		> 20 min (0.05)	> 20 min (0.05)		
Exp. 12		> 20 min (0.06)	> 20 min (0.06)		
Exp. 13		> 20 min (0.05)	> 20 min (0.05)		

Table 43 – Heat FED time to lethality (lounge open door scenarios)

For Experiment 04, the data shown has been presented in a graphical form within Figure 77. This shows the development of the fractional effective dose as a function of time. Whilst the curve for heat within the fire compartment increases exponentially, the FED curves for rooms outside of the fire compartment are somewhat flatter when compared to those presented for asphyxiant gas FED in Figure 72.

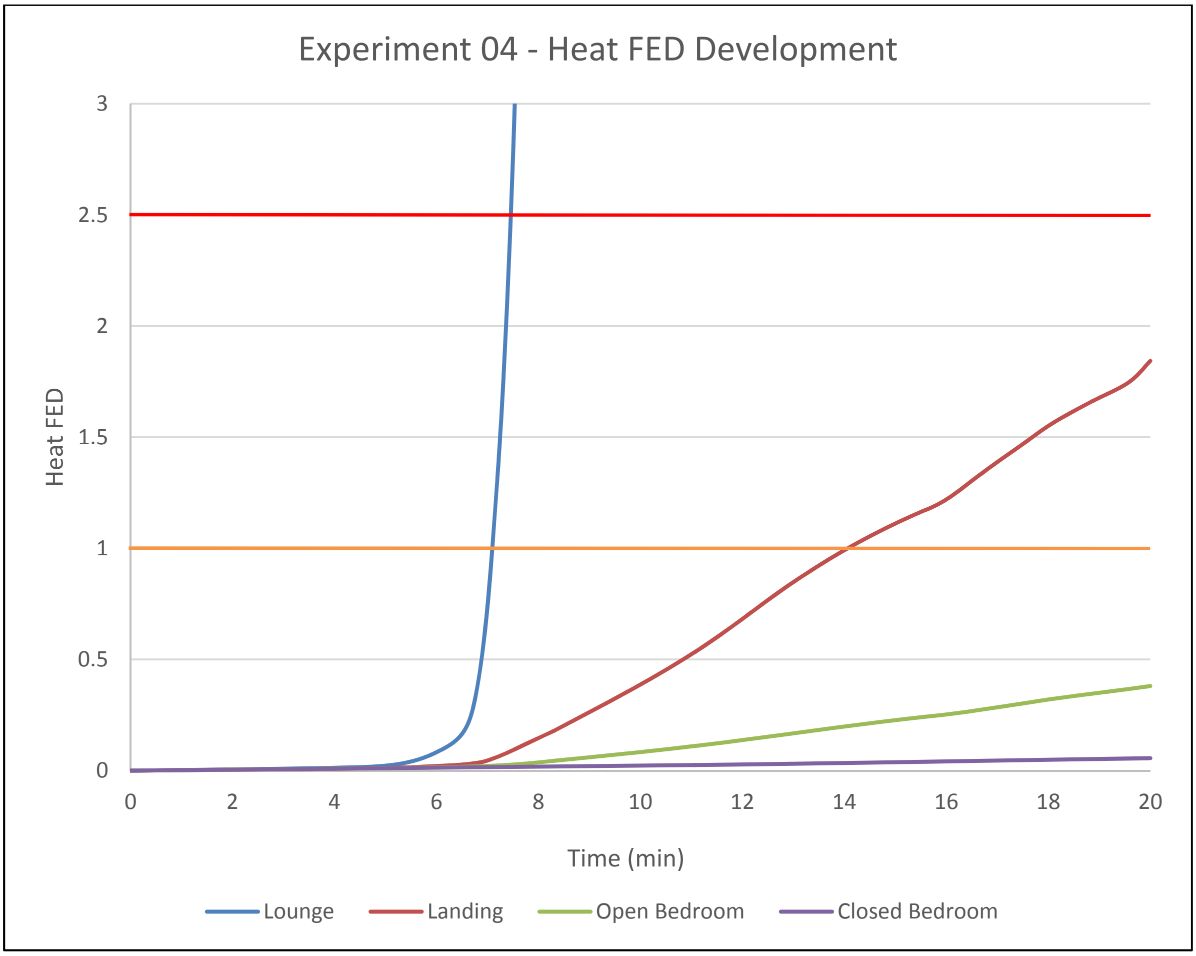

Figure 77 – Experiment 04 heat FED development

4.3.9 FED Conclusion

The data gathered during these experiments demonstrates that there are many factors which can influence fire development. Whilst every effort was made to accomplish reproducibility between experiments, this is not always achievable. Experiment 03 is clearly seen to develop at a significantly slower rate than the other 6 experiments, and shows experimental variation. Where it was appropriate to do so, the results from this experiment have been omitted.

The two different ventilation areas show some differences between experiments, however, where it was expected that differences would be observed, this is not always the case. To a greater extent, the difference between the ventilation areas was masked by the residual air contained within the remainder of the property, which the fire can access as a result of the fire compartment door being open. In the experiments where ventilation was 2.0 m^2 the quantities of heat and smoke produced were higher however, where the ventilation was 0.5 m^2, the $CO:CO_2$ ratio was higher, particularly when the fire was well-developed. The time taken to reach FED thresholds is relatively short in all rooms which are open to the fire compartment and as such, the area of ventilation was not significantly influential in determining the hazard.

In comparison with the kitchen fires, discussed in Section 4.1.1, these fires were able to consume a greater amount of fuel and therefore to produce more heat and smoke. The fuel also contains nitrogen and it was seen that HCN was produced during all 7 experiments. These larger fires and the fact that HCN was produced contributed significantly towards the rate at which a FED was attained. Table 44 shows the time taken for lethal conditions to be created within the four compartments, for each of the experiments. It shows lethal effects from heat in ‘orange’ and lethal effects resulting from asphyxiant gases in ‘grey’.

Experiment Number	Room	Time to 1.0 x FED	Time to 2.5 x FED
Exp. 03	Lounge	11:37	11:57
Exp. 04		7:05	7:11
Exp. 07		7:40	8:00
Exp. 08		5:28	5:45
Exp. 10		8:11	8:30
Exp. 12		6:51	7:13
Exp. 13		5:31	5:53
Exp. 03	Landing	13:55	14:32
Exp. 04		8:39	9:24
Exp. 07		9:16	10:03
Exp. 08		7:28	8:45
Exp. 10		9:48	10:48
Exp. 12		8:28	9:05
Exp. 13		8:28	9:18
Exp. 03	Open Bedroom	14:29	15:07
Exp. 04		9:18	9:58
Exp. 07		-	-
Exp. 08		9:43	11:48
Exp. 10		10:23	11:12
Exp. 12		9:13	9:45
Exp. 13		8:58	9:48
Exp. 03	Closed Bedroom	-	-
Exp. 04		> 20 min (0.05)	> 20 min (0.05)
Exp. 07		> 20 min (0.87)	> 20 min (0.87)
Exp. 08		> 20 min (0.77)	> 20 min (0.77)
Exp. 10		18:09	> 20 min (1.84)
Exp. 12		> 20 min (0.08)	> 20 min (0.08)
Exp. 13		> 20 min (0.92)	> 20 min (0.92)

Table 44 – Heat/asphyxiant gas FED time to lethality (lounge open door scenarios)

It can be seen that heat is slightly more hazardous than asphyxiant gases within the fire compartment, with lethality as a result of heat exposure being likely to occur approximately 1 minute before lethality due to asphyxiant gases. This outcome differs from the findings of D. Purser [23] although these experiments were conducted with a greater degree of ventilation to the fire compartment. As a result, the fire is able to develop at an increased rate, producing more heat.

Outside the fire compartment, the asphyxiant gases present a significantly greater hazard than exposure to heat as temperatures are much reduced.

Figure 78 and Table 45 show the timeline of events during these experiments with the average being taken from the 6 experiments which showed reproducible data, and omitting that from Experiment 03. This shows that smoke was detected in the hallway at 2:17 after ignition and that 2:43 later (5:00 after ignition) the internal escape route becomes impassable due to reduced visibility. When compared with the kitchen fire scenarios, the window for self-evacuation is much smaller at less than 3 min on average within these experiments, compared to 9 min.

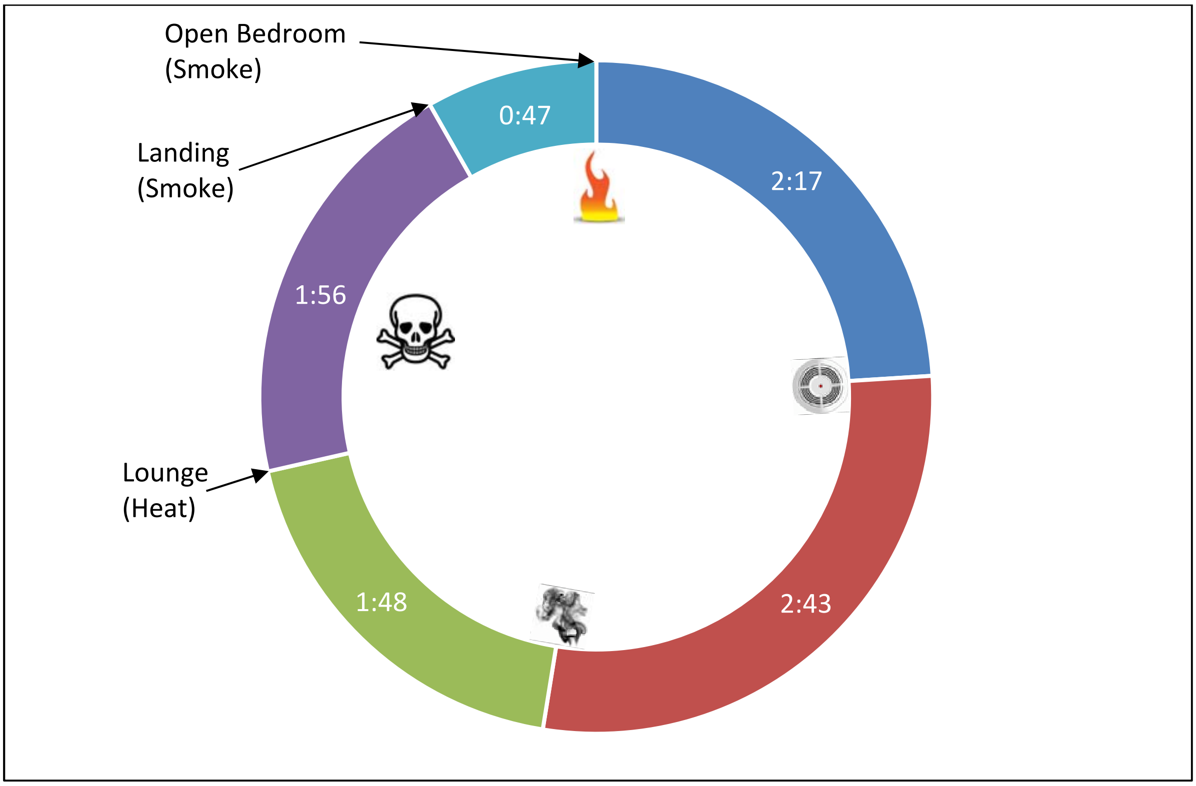

Figure 78 – Lounge fire door open fire survival timeline

Lethal conditions are then observed in the fire compartment at 6:48 as a result of heat; at 8:44 on the landing as a result of smoke and at 9:31 in the open door bedroom also as a result of smoke. Conditions within the closed door bedroom remain tenable for the duration of all experiments with respect to the healthy adult population and in only one of the experiments are lethal conditions observed with respect to the more vulnerable population.

Event	Time
Ignition	0:00
Alarm Actuation	2:17
Visibility Lost	5:00
Lethality (Fire Compartment)	6:48
Lethality (Landing)	8:44
Lethality (Open Bedroom)	9:31
Lethality (Closed Bedroom)	> 20:00

Table 45 – Lethality event / time analysis (lounge fire door open scenarios)

4.4 Detailed Analysis of Experiment 04

In analysing the data within these experiments, it becomes apparent that a significant amount of data has been captured within Experiment 04. As a result, it is possible to complete a more detailed analysis of this particular experiment in an attempt to establish any connections or correlations that may exist.

4.4.1 Fire Development

Figure 79 to Figure 84 shows a visual image of the fire as it develops and is complemented by a graph which shows the temperature and gas concentration curves at the point where the image was taken. Temperature data is recorded at 150 cm and gas concentration are at 160 cm above floor level. These figures clearly show the incubation period which covers the initial 5 min after which point there is a sharp increase in the rate at which the fire develops.

The most significant increase in fire development occurs between 6 and 7 min, where temperatures are seen to increase and there is a significant change in the gas concentrations. During the period between 7 and 8 min, it can be seen that the lack of ventilation seems to control the fire and it shifts into the steady state or ventilation-controlled phase.

Figure 79 – Experiment 04 – temperature/gas concentrations vs time (3 min)

Figure 80 – Experiment 04 – temperature/gas concentrations vs time (4 min)

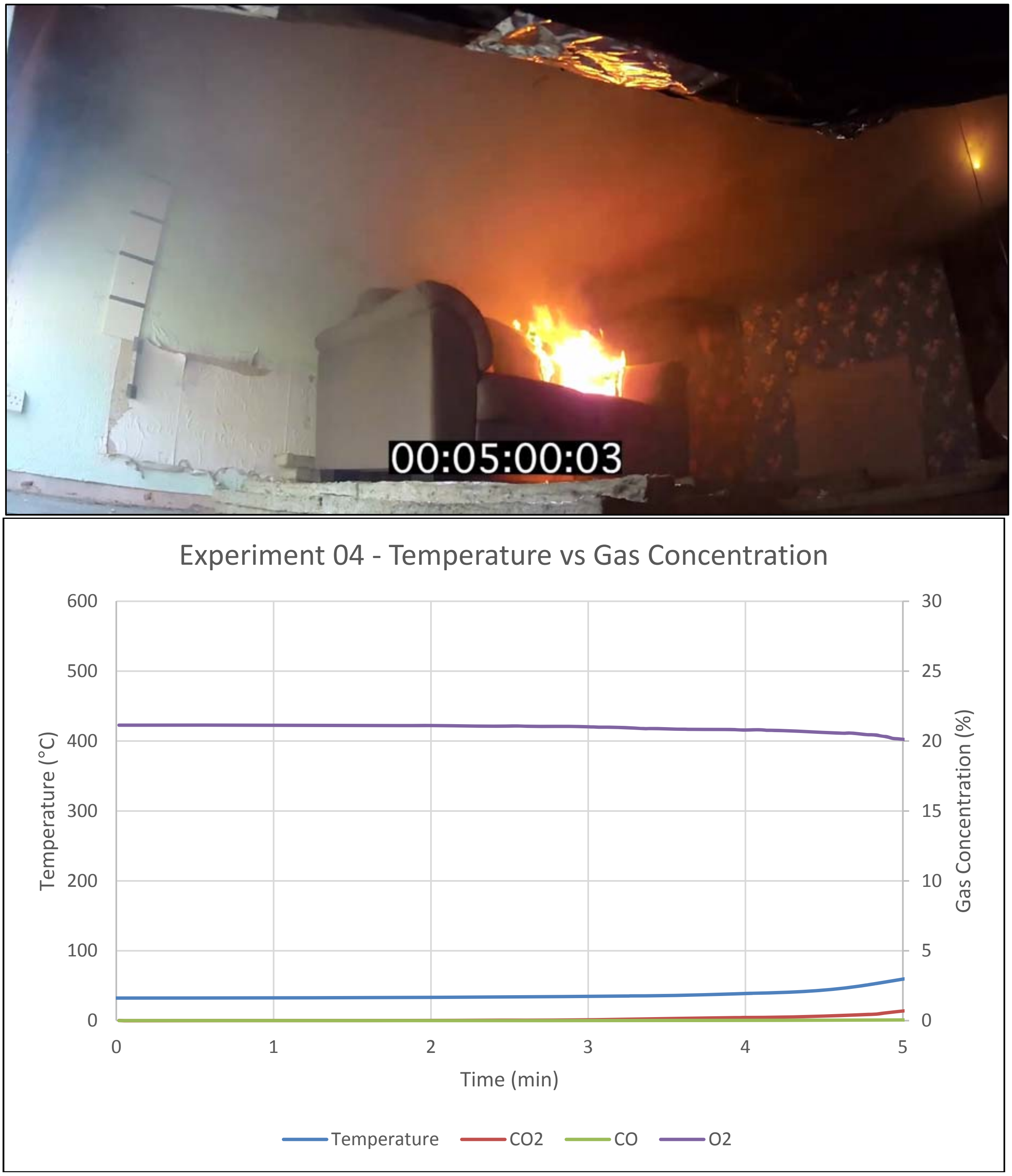

Figure 81 – Experiment 04 – temperature/gas concentrations vs time (5 min)

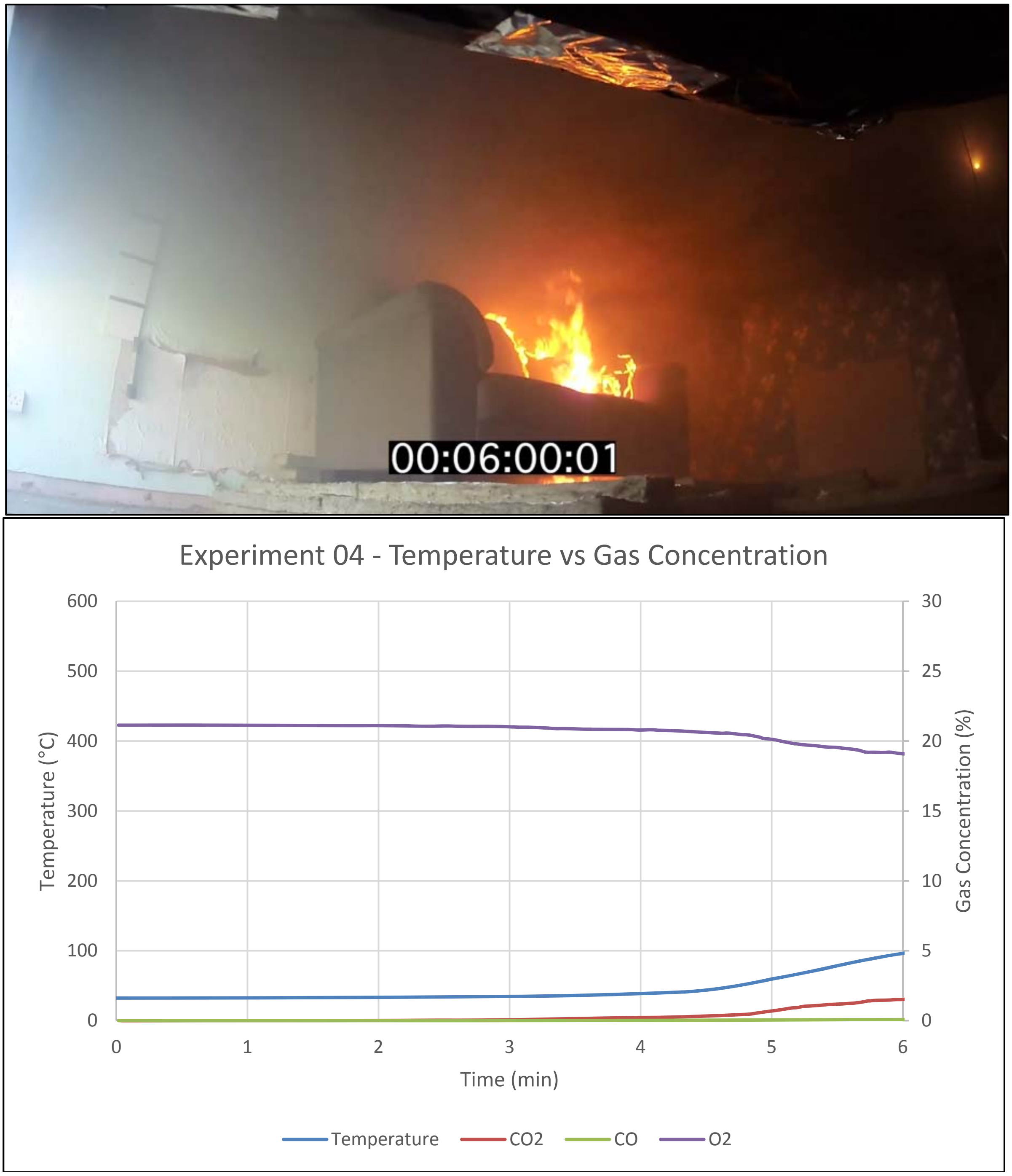

Figure 82 – Experiment 04 – temperature/gas concentrations vs time (6 min)

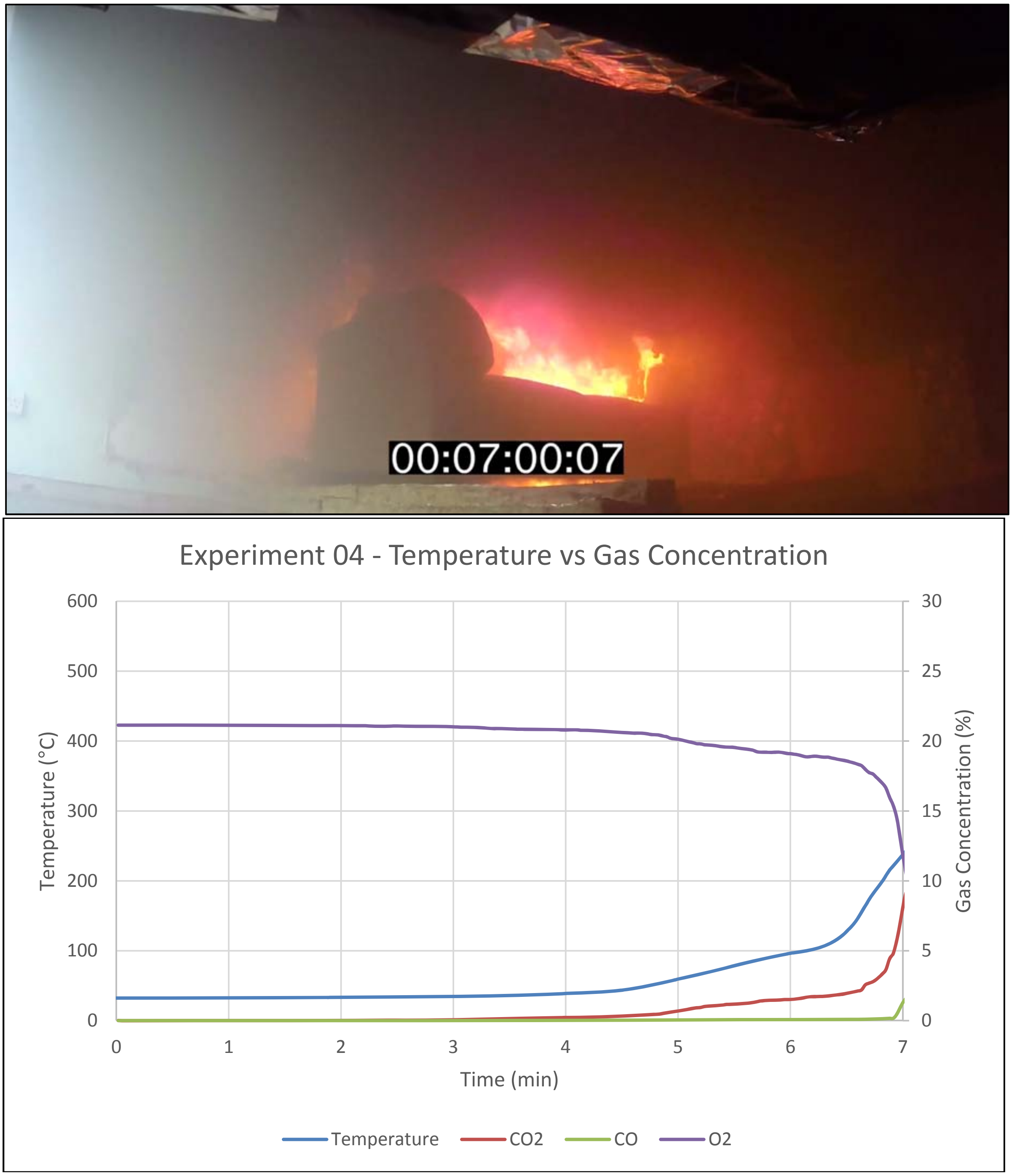

Figure 83 – Experiment 04 – temperature/gas concentrations vs time (7 min)

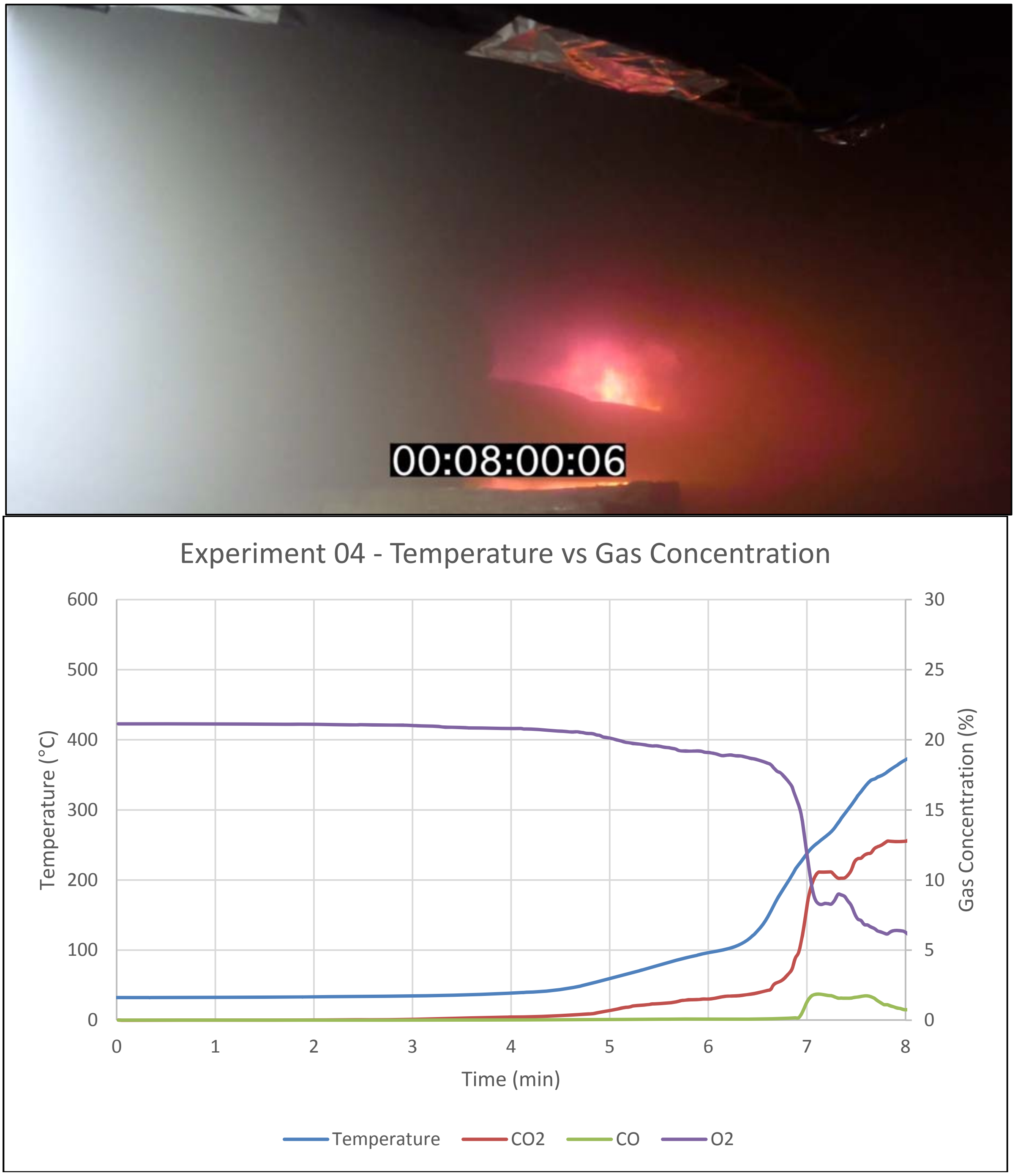

Figure 84 – Experiment 04 – temperature/gas concentrations vs time (8 min)

4.4.2 Smoke Detector Actuation Times

In order to establish if there is a correlation between the times at which smoke is detected by an automatic device and the temperature at ceiling level, this data is compared across the four compartments, where it is available. The results of this analysis are given in Table 46 and show that there is no apparent correlation between the two. In the fire compartment there is a rise in temperature of around 10°C at the point where the smoke detector actuates, but more remotely from the fire, the rise in temperature is considerably lower. This shows that the fire effluent cools significantly as it moves. Since the flow is convective, the loss of heat will slow the effluent movement.

This phenomenon is consistent with travel away from the fire to the point where there is only a 0.1°C temperature increase at the point of actuation in the most remote compartment. This demonstrates that although the fire plume is diluted to the point where temperatures are low, the devices remain sensitive enough to detect the smoke.

Room	Detector Actuation Time	Ceiling Temperature (°C)	Temperature above ambient (°C)
Lounge	01:04	41.9	9.7
Landing	02:53	31.1	1.4
Open Bedroom	03:41	30.8	0.4
Closed Bedroom	07:50	30.9	0.1

Table 46 – Exp. 04 – comparison of detector actuation times and ceiling temp.

4.4.3 Heat and Smoke FED Development

Data gathered, shows that lethal exposure to heat and to asphyxiant gas occurs at roughly the same time within the fire compartment, however, in more remote locations, this is not the case. Figure 85 shows all eight of the FED calculations made within Experiment 04 with both the heat and asphyxiant gas FEDs across the four different rooms. It shows that the FED from asphyxiant gases, within those compartments which are open to the fire, develop rapidly with a slight lag as the smoke layer travels around the property. In contrast, the FED from heat develops at a very different rate outside of the fire compartment and demonstrates that heat is much less hazardous to people where they are situated more remotely from the fire.

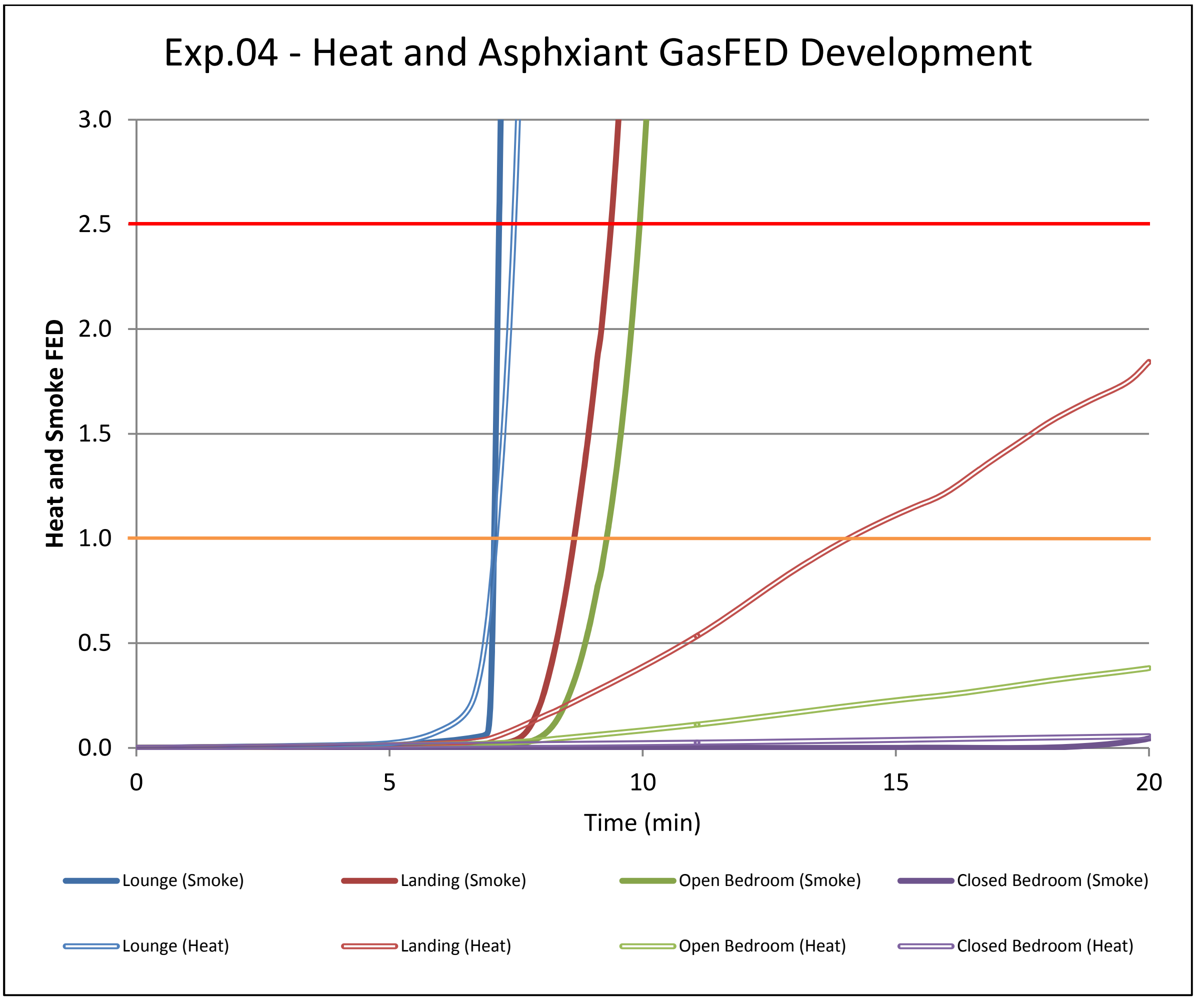

Figure 85 – Experiment 04 heat and smoke FED development

This data is explored further within Figure 86 to Figure 88, where the two FED curves are presented along with the temperature profile within the three compartments. The obvious difference between these three figures is the peak temperatures, being around 500°C in the fire compartment, 120°C on the landing and 70°C within the open bedroom. These temperature differences obviously occur as a result of the smoke plume being diluted as there are turbulent effects between the hot smoke layer and the cooler layer of residual air. Whilst this dilution has a significant impact on heat FED, the impact that it has on asphyxiant smoke FED is much less. This is as a result of the high concentrations of asphyxiant gases that are produced during combustion.

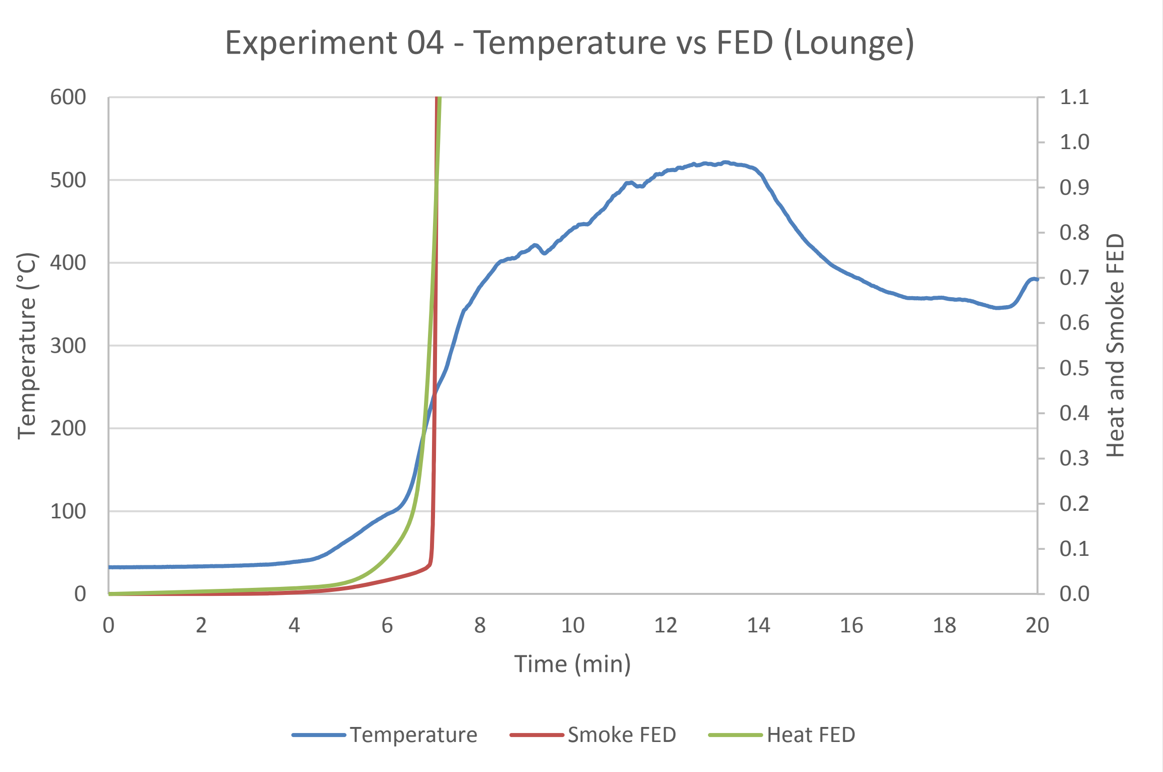

Figure 86 – Experiment 04 temperature vs FED (lounge)

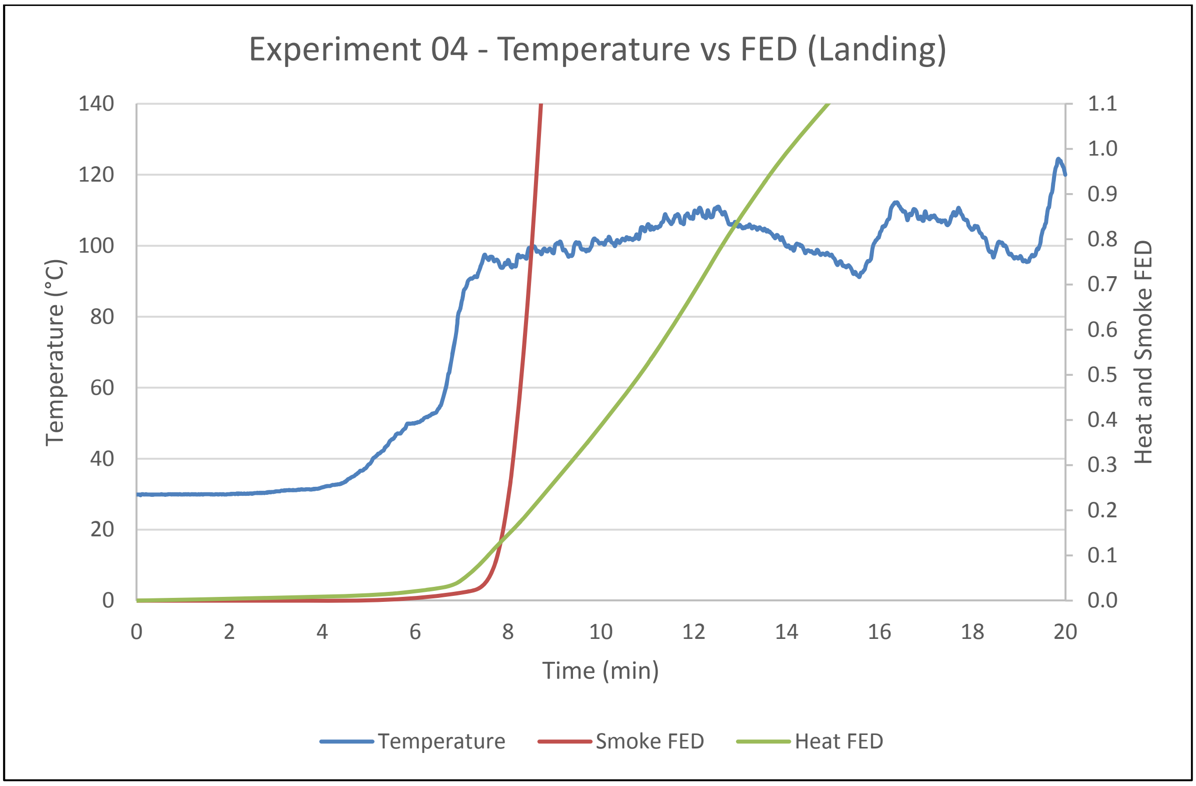

Figure 87 – Experiment 04 temperature vs FED (landing)

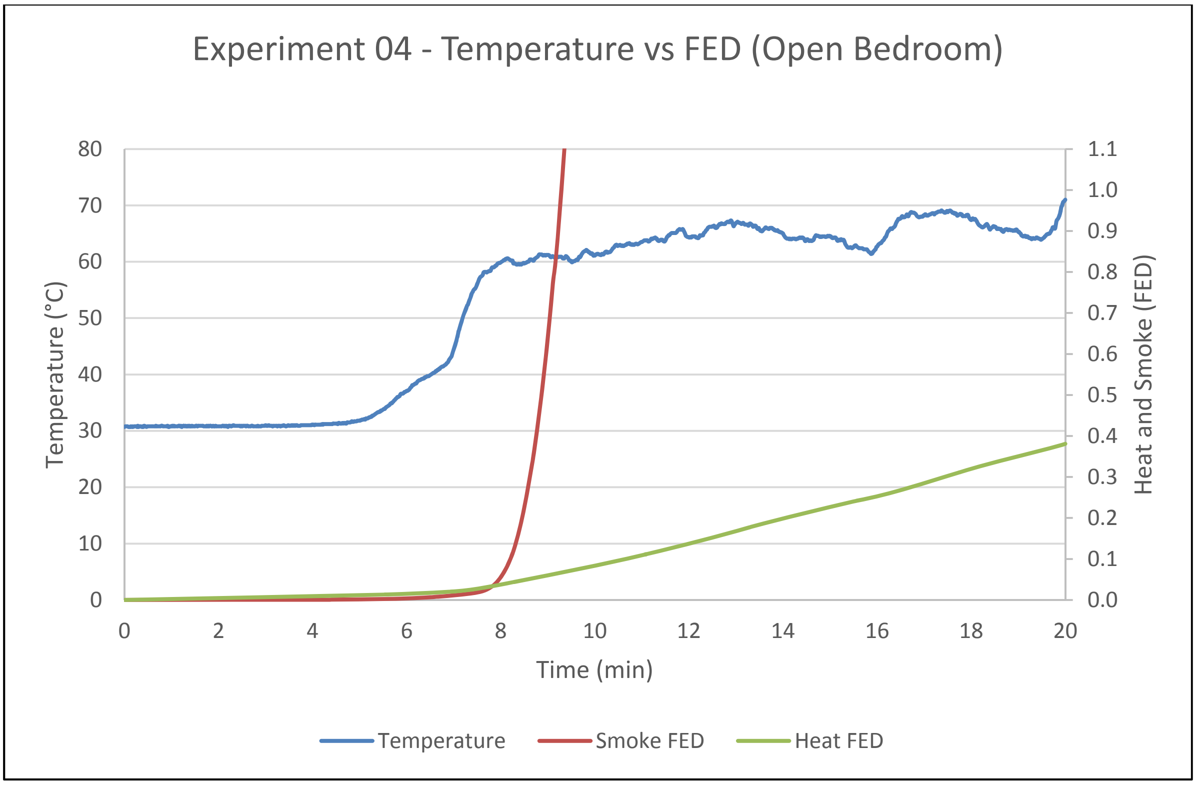

Figure 88 – Experiment 04 temperature vs FED (open bedroom)

4.4.4 Asphyxiant Smoke FED Development of Individual Gases

Figure 89 shows the individual FED development curves for CO (Red) and HCN (Green) as well as the additive curve for CO and HCN (Blue), within the fire compartment during Experiment 04. This chart only shows the curves between 6 and 8 min to better demonstrate how each of the two gases contribute towards the additive asphyxiant effect.

It shows that in the early stages of fire development (up to 7 min), where the concentrations of both asphyxiant gases are low, that the combined curve follows the CO curve well. After 7 min the fire starts to develop more rapidly and the concentrations of the two asphyxiant gases increases. Equation 8 includes an exponential factor for exposure to HCN and as a result the HCN curve starts to take over from the CO curve and contributes more towards the total asphyxiant exposure.

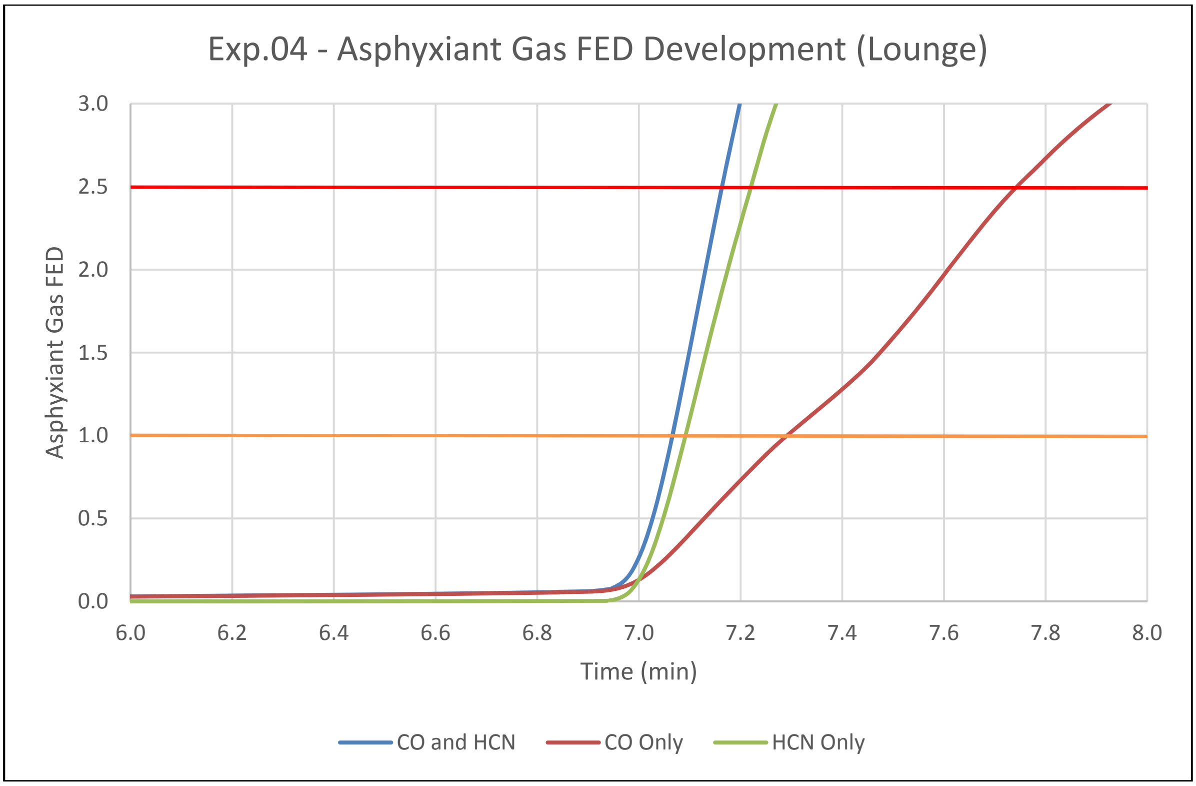

Figure 89 – Experiment 04 asphyxiant gas FED (lounge all gases)

From 7 min onwards, the green and blue curves track each other well and from this point onwards the greatest hazard to exposed people becomes HCN. On the basis of the FED calculations presented Section 4.3.8, it is seen that at 1.0×FED, 28.2% of the fractional effective dose comes as a result of exposure to CO and the remaining 71.8% comes as a result of exposure to HCN. Clearly HCN represents a significant portion of the hazard.

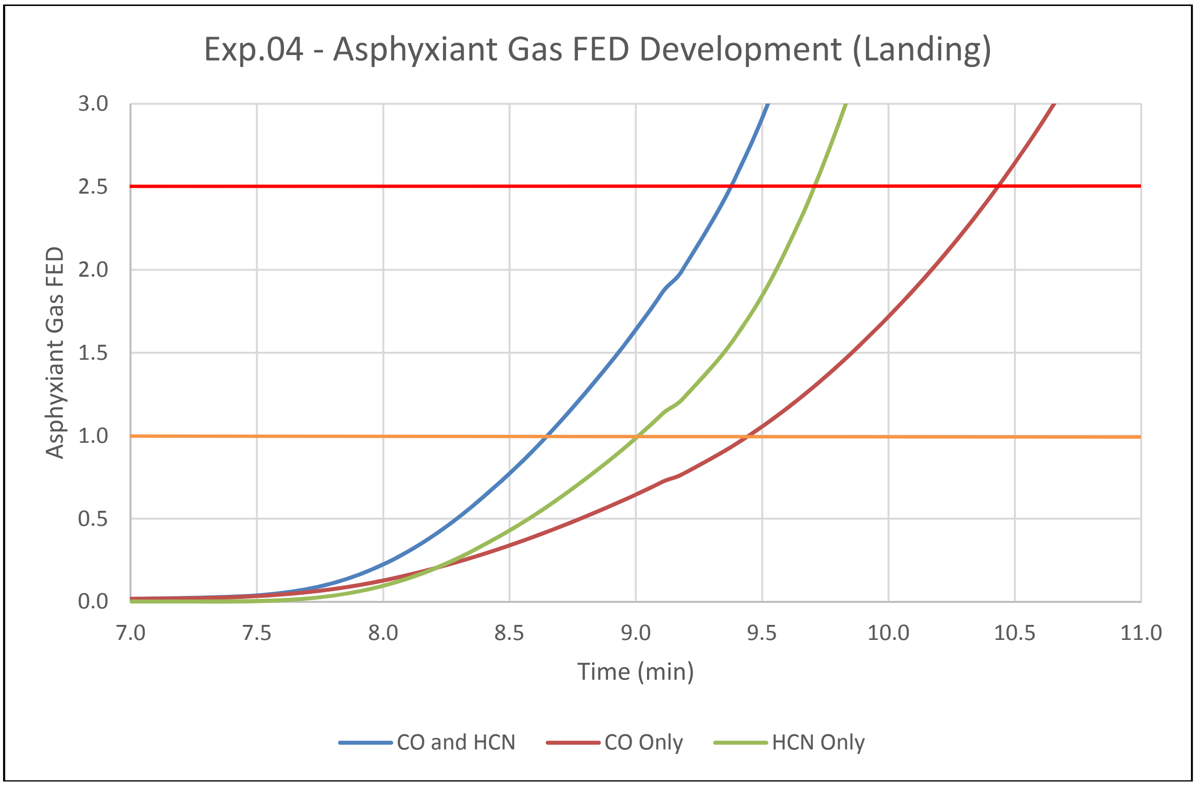

Figure 90 – Experiment 04 asphyxiant gas FED (landing all gases)

Figure 90 represents the FED development curves on the Landing, within the same experiment, between 7 and 11 min. During the early stages it is again seen that CO is the major contributor towards an asphyxiant effect but at around 8 min this switches to HCN. As a result of the generally lower concentrations of these two asphyxiant gases, more remote from the fire, it is seen that the impact of HCN (after 8 min) is not as significant as it is in the lounge. This is again observed as a result of the exponential factor.

This is also demonstrated in the percentage contribution of each of the asphyxiant gases, where it can be seen that at 1.0×FED, 42.4% of the fractional effective dose comes as a result of exposure to CO and the remaining 57.6% comes as a result of exposure to HCN. At lower concentrations of both gases the impact of CO increases.

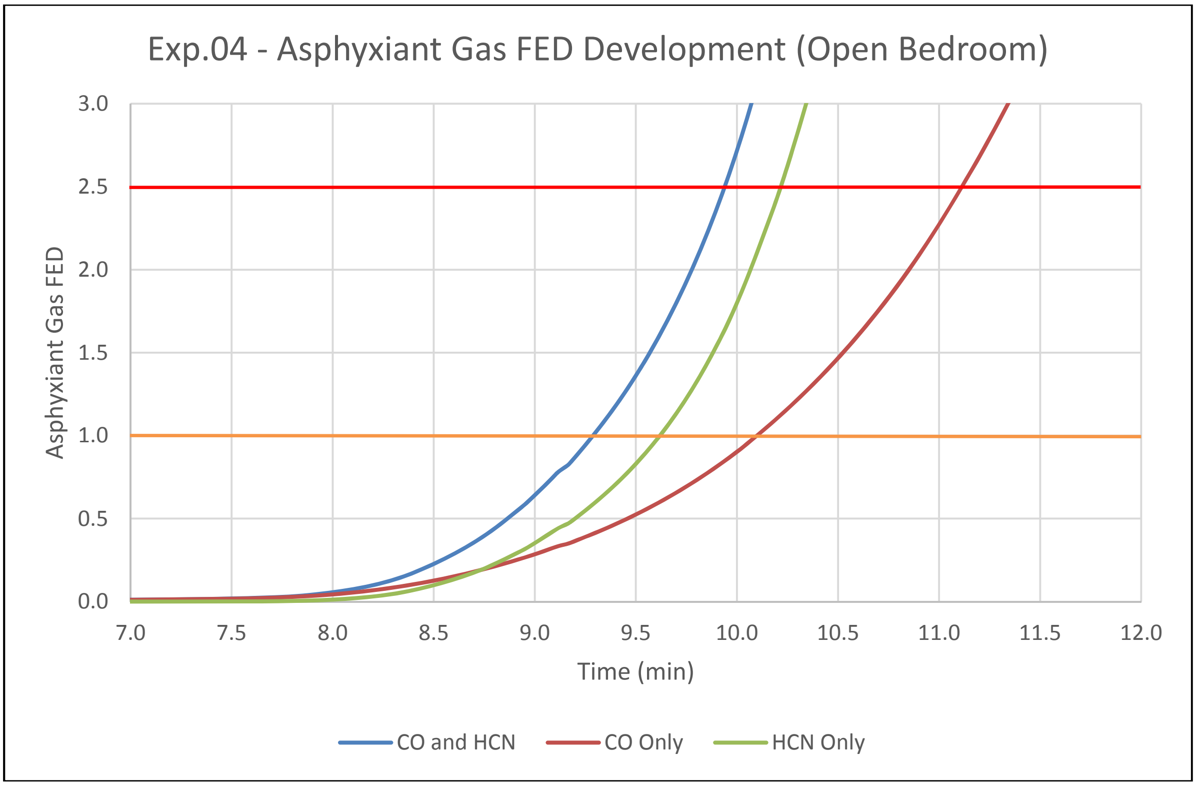

Figure 91 – Experiment 04 asphyxiant gas FED (open bedroom all gases)

Figure 91 shows the FED development curves for the individual gases and the combined effect, within the open bedroom. Essentially, the situation on the landing and in the open door bedroom are very similar, with a slight time delay. Again the percentage contribution of each of the asphyxiant gases are similar, where it is seen that at 1.0×FED, 40.9% of the fractional effective dose comes as a result of exposure to CO and the remaining 59.1% comes as a result of exposure to HCN. At lower concentrations of both gases the impact of CO increases to the detriment of HCN.

The percentage contribution of each of the two asphyxiant gases during Experiment 04, is presented in Table 47 at both 1.0×FED and 2.5×FED.

Room	1.0 x FED		2.5 x FED	
	Percentage CO contribution	Percentage HCN contribution	Percentage CO contribution	Percentage HCN contribution
Lounge	28.2%	71.8%	24.5%	75.5%
Landing	42.4%	57.6%	37.3%	62.7%
Open Bedroom	40.9%	59.1%	33.8%	66.2%

Table 47 – Experiment 04 – contribution from individual gases towards FED

The figures which are charted and tabulated within this section bare a similarity in both their shape and timing to graphs presented earlier in this thesis, taken from other experimental works. They bear similar results to those presented by Purser in Figure 21 and Figure 22, in Section 1.8.4.

4.5 Analysis of Individual Experiments – Group 3

This section of the thesis gives a detailed analysis of those experiments which involve a fire in the lounge and where the lounge door is in the closed position. These experiments have been conducted to investigate the effect that under-ventilation has on the asphyxiant gas concentrations and to make comparisons with Group 2 so that the value of a closed door can be assessed.

The grouping covers Experiments 05, 06, 09 and 14, with all but one of these experiments involving the combustion of a sofa only. Within Experiment 14 there are additional fuel packages inside the fire compartment, such as carpet, curtains and further pieces of furniture. Due to time constraints with the availability of the property and the large-scale testing, it was not possible to conduct Experiment 06.

In addition, whilst conducting Experiment 14 the compartment floor between the lounge and the closed door bedroom was breached, with evidence suggesting that this occurred at around 12 min after ignition. As a result there is an obvious discrepancy with respect to the gas concentrations and after 12 min, the gas concentrations in the closed bedroom reflect the ceiling failure, which, with normal building practices, would only be expected after a repeated series of fires. Therefore, the analysis within this section of the thesis will focus on Experiments 05 and 09 and on data observed from the early stages of Experiment 14.

4.5.1 Smoke Detector Analysis

Each individual actuation time and the averages for each of the alarm locations are given in Table 48. Smoke detection within the fire compartment occurs on average at around 2:08, however, it is not typical for smoke detectors to be located within this type of compartment. Smoke detectors are typically located within the hallway and landing and these actuated on average at 6:08 and 9:10, respectively. Unfortunately, it was not possible to obtain smoke detector actuation times in every room for every experiment due to time constraints and heat damage to equipment and cabling.

Room	Detector Type	Exp. 05	Exp. 09	Exp. 14	Avgerage mm:ss
Lounge	Low Sens.	3:00	2:01	2:05	2:08
	High Sens.	-	1:46	1:50	
Hallway	Low Sens.	6:50	6:26	6:37	6:08
	High Sens.	6:50	4:01	6:05	
Landing	Low Sens.	-	9:01	9:31	9:10
	High Sens.	-	8:42	9:26	
Open Bedroom	Low Sens.	15:53	11:23	-	12:34
	High Sens.	-	10:27	-	
Closed Bedroom	Low Sens.	-	-	-	-
	High Sens.	-	-	-	

Table 48 – Smoke detector actuation times (lounge closed door scenarios)

The focus was to get data for smoke detectors within the hallway and landing as these would be used in the assessment of the timelines. A significant number of data points have been gathered in these locations and the results show reasonable reproducibility. Figure 92 gives a visual representation of the average times given in the table and also gives an indication of the rate at which smoke is transported from one room to the next, within the property.

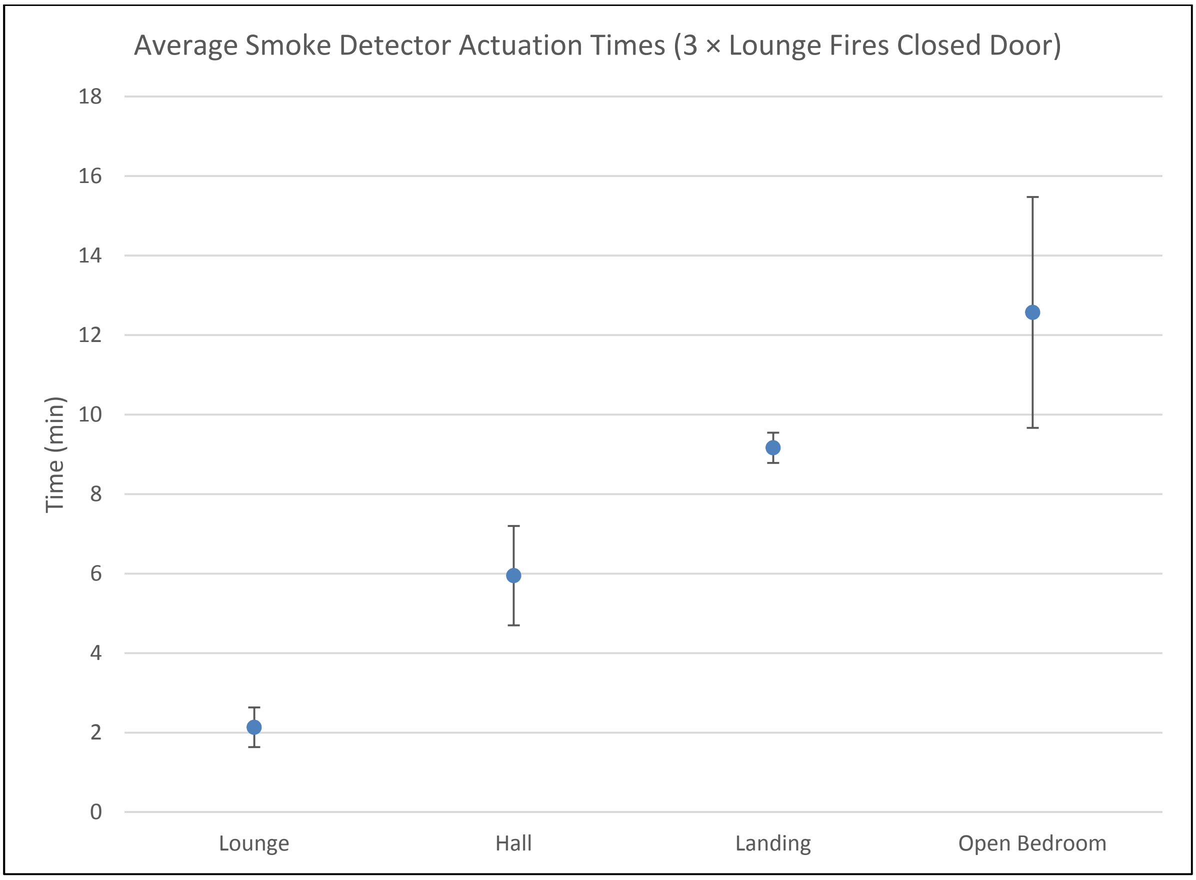

Figure 92 – Average smoke detector actuation times (lounge fires closed door)

4.5.2 Temperature Profiles

The temperature profiles observed within these three experiments do show a significant difference in respect of the fire growth between the experiments with the larger ventilation area (2.0 m^2) and the experiment with the smaller ventilation area (0.5 m^2).

Figure 93 shows the temperature profiles at 150 cm above floor level in the lounge for each of the three experiments. The temperature profiles for Experiments 05 and 14 (2.0 m^2 area of ventilation) seem to increase more freely from between 7 and 12 min. By comparison, the increase in temperature during Experiment 09 (0.5 m^2 area of ventilation) seems considerably more restricted. For Experiment 09 the increase in temperature develops much more steadily and over an extended period of time when compared with the other two experiments.

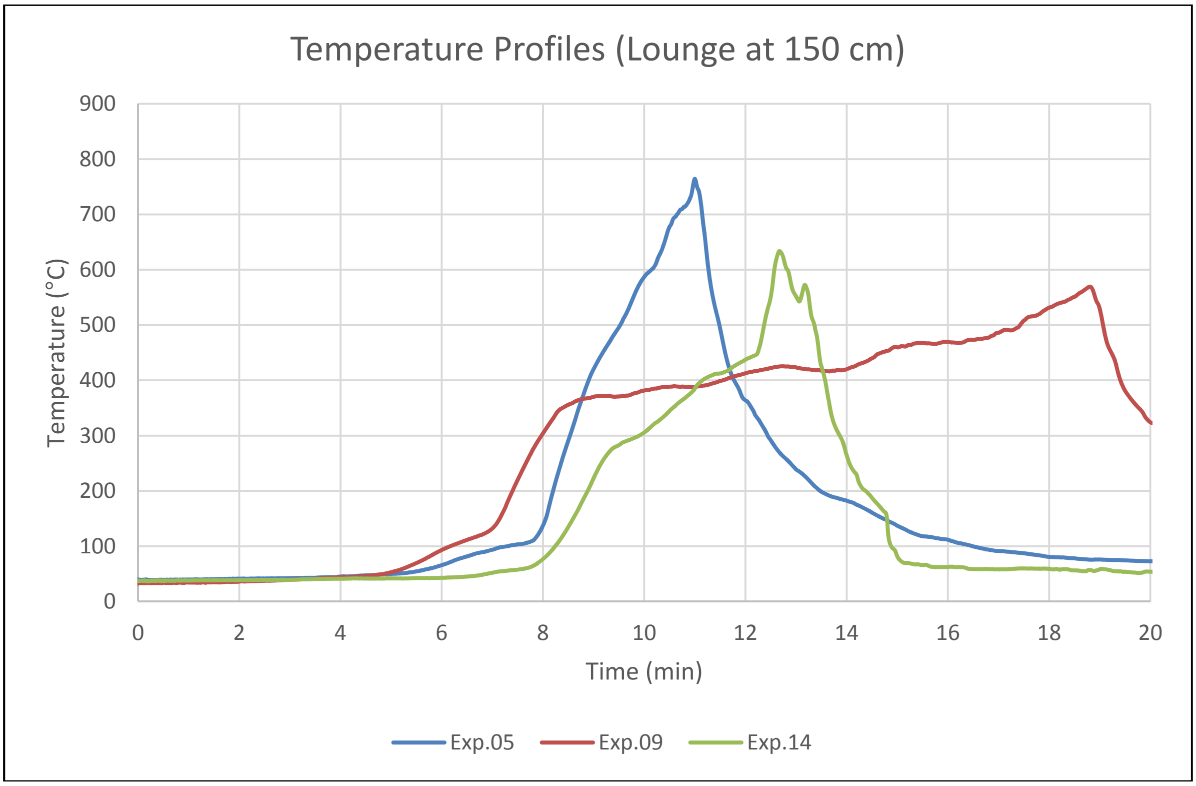

Figure 93 – Lounge closed door temperature profiles (lounge at 150 cm)

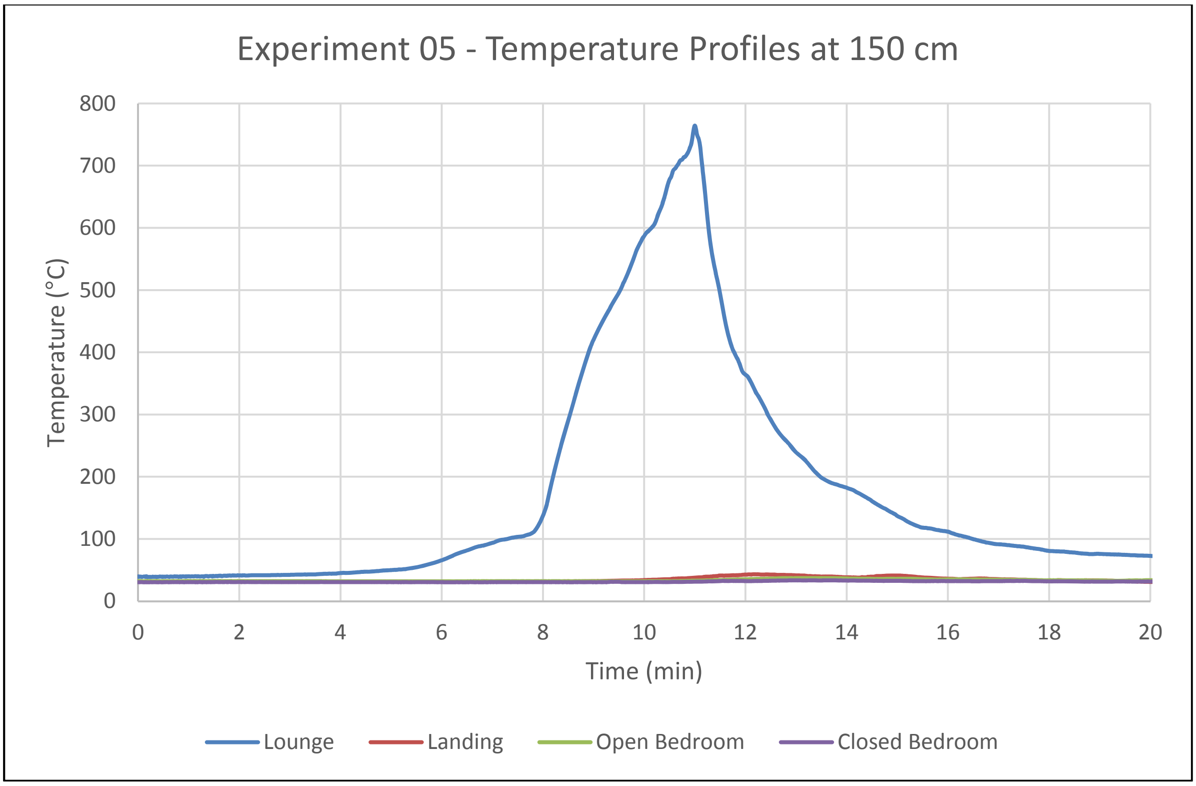

Figure 94 – Experiment 05 temperature profiles (at 150 cm)

Figure 94 shows the temperature profiles at each of the four sampling points at 150 cm above floor level for Exp.05. When compared with Figure 63, where the fire compartment door was open during Exp.04, significantly less heat was allowed to travel into the other rooms within the property as a result of the fire compartment door being closed.

It shows that the maximum temperature within the fire compartment was 764°C. Figure 95 shows the same temperature-time variation as Figure 94 but focuses on the lower temperature range. It shows that the maximum temperature on the landing was 43°C; in the open door bedroom it was 37°C and in the closed door bedroom it was 34°C. Ambient temperatures immediately prior to ignition were approximately 31°C and so the temperature rises outside of the fire compartment are minimal.

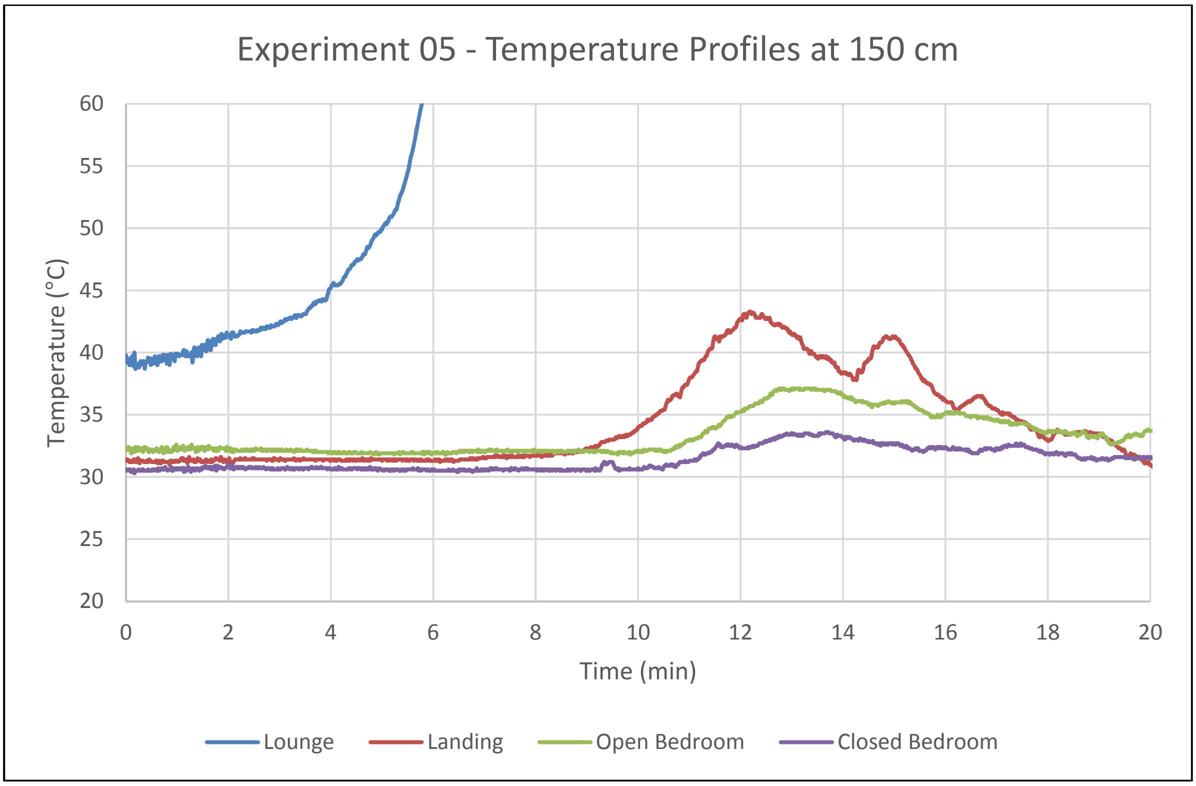

Figure 95 – Experiment 05 temperature profiles (at 150 cm)

The data shown in Figure 64 helped to identify the neutral plane between the hot upper layer and the cooler lower layer for Experiment 04, with this being estimated at 120-150 cm. A similar analysis is conducted for Experiment 14 using Figure 96, which shows that the four thermocouples in the upper part of the room (150-240 cm) show reasonable agreement, with slight degradation, in temperature. The lower three thermocouples (30-90 cm) also show a similar agreement. This suggests that the neutral plane between the hot upper layer and the cooler lower layer appears to occur at approximately 120 cm, in Experiment 14. The position of the neutral plane at 120 cm is particularly noticeable between 8 and 13 min.

The neutral plane is less clearly defined as the fire in this experiment moves to the ventilation-controlled phase at around 12 min.

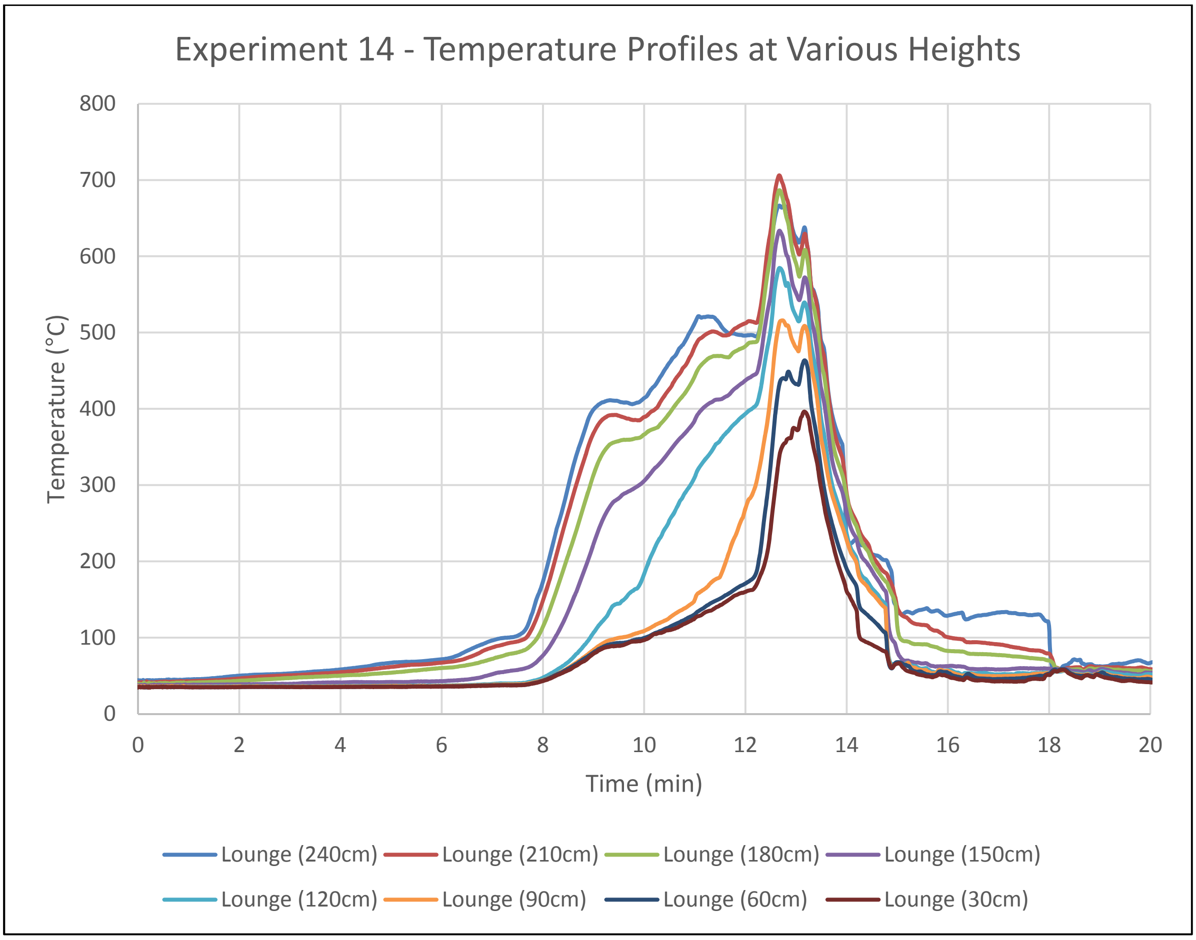

Figure 96 – Experiment 14 lounge temperature profiles (at various heights)

In contrast, the temperature profiles within Experiment 09 seem to be much more evenly spread out, which suggests that the separation between the upper and lower layers is less well defined. As a result of the relatively small opening within this room, allowing O_2 into the fire compartment, evidence suggests that fire development is heavily retarded and that the flow of air/smoke into and out of the fire compartment is somewhat reduced. As a result, the smoke layer appears to be cooler but it also appears to drop down to lower levels.

The temperature difference between the 240 cm and the 60 cm thermocouples, during the growth phase of the fire in Experiment 14 is approximately 375°C. The same thermocouples in Experiment 09 measure a temperature difference of around 200°C, which also suggests that the upper layer is thicker during Experiment 09, where the ventilation area was only 0.5 m^2. In Figure 97 the thermocouple readings at 30 cm are omitted due to erroneous results and again the neutral plane is less well defined where the fire is ventilation-controlled.

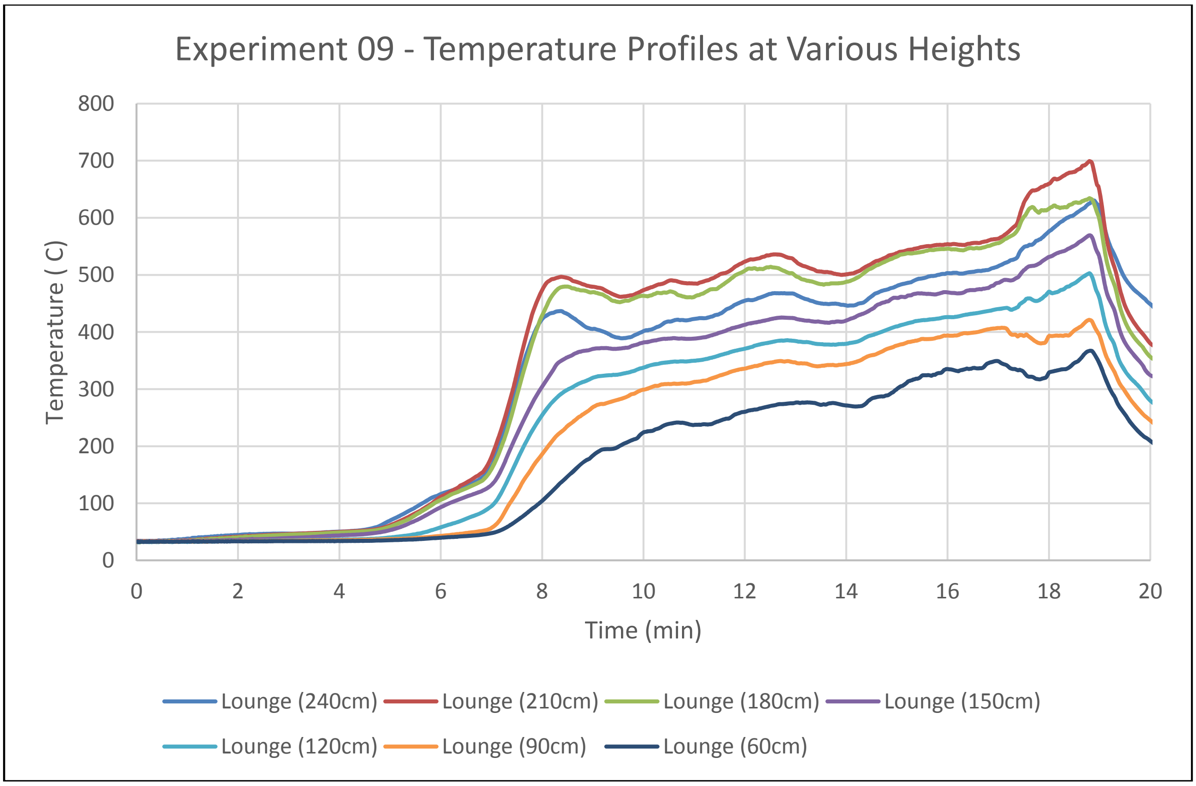

Figure 97 – Experiment 09 lounge temperature profiles (at various heights)

4.5.3 Gas Concentrations

Table 49 shows the peak gas concentrations measured during Experiments 05, 09 and 14 for CO_2, CO and O_2. For CO_2 and CO this is an upper concentration peak and, as oxygen depletion is being considered, for O_2 it is a lower concentration peak.

Experiment Number	Room	CO_2 Peak (%)	Time	CO Peak (%)	Time	O_2 Peak (%)	Time
Exp.05	Lounge	16.30	10:52	2.62	10:25	0.21	10:28
	Landing	1.16	12:01	0.12	12:14	19.46	11:44
	Open (BR)	0.96	13:09	0.10	13:03	19.69	13:06
	Closed (BR)	-	-	-	-	-	-
Exp.09	Lounge	16.03	12:54	1.01	12:50	2.67	12:54
	Landing	0.51	12:52	0.03	12:58	20.36	12:48
	Open (BR)	0.20	12:58	0.02	12:54	20.64	12:59
	Closed (BR)	-	-	-	-	-	-
Exp.14	Lounge	13.59	13:00	2.52	13:04	4.02	12:58
	Landing	-	-	-	-	-	-
	Open (BR)	-	-	-	-	-	-
	Closed (BR)	-	-	-	-	-	-

Table 49 – Peak gas concentration times (lounge closed door scenarios)

When graphs of the gas concentrations are produced for all three experiments, there is evidence to suggest that smoke has been transmitted directly from the fire compartment into the closed door bedroom located directly above it. The amount of leakage is minor within Experiments 05 and 09. Whilst this is a consistent outcome and is probably resultant of additional pressures in the fire compartment as a result of the lounge door being closed, it is believed that this situation is unrealistic. The damage to the compartment floor between these two rooms has only occurred as a result of repeat testing and is not expected to occur in a building where this was the first fire. As such these erroneous results have been omitted. The gas concentrations within the landing and the open door bedroom for Experiment 14 also yields erroneous results.

It shows that the average peak CO_2 level within the fire compartment, across all three experiments is 15%, with CO at 2.0% and O_2 at 2%. These peaks were typically recorded at between 11 and 13 min after ignition. When comparing this data with that of Table 37 for the open door scenarios, it can be seen that fire development is slower when the fire is restricted to obtaining O_2 via the external vent direct to the fire compartment. It also shows that whilst the peak CO_2 was slightly increased, the peak CO was notably increased which also suggests that the access to O_2 within this group of experiments was much reduced.

Figure 98 suggests that in Experiment 09, there was an incubation period of around 5 min; that the growth phase was between 5-8 min; that the fire was in the developed phase from 8-18 min before entering the decay phase. This experiment involved a smaller ventilation area 0.5 m^2 and the gas concentration curves are typical of those seen within this type of combustion process.

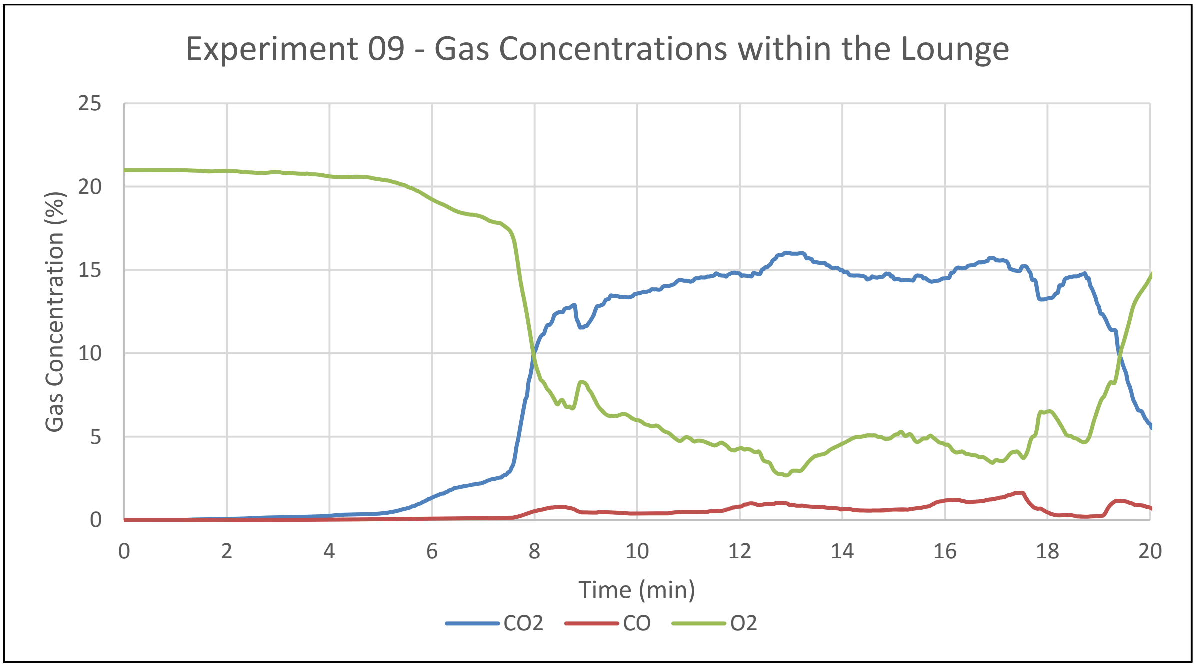

Figure 98 – Experiment 09 lounge gas concentrations

Figure 99 shows that in Experiment 14, there was an incubation period of around 6 min; that the growth phase was between 6-9 min; that the fire was in the developed phase from 9-13 min before entering the decay phase. This experiment involved a larger ventilation area 2.0 m^2 and the gas concentration curves are again typical of those seen within this type of combustion process.

In comparison Experiment 09, the developed phase in Experiment 14 lasts for a shorter period of only 4 min when compared with the 10 min developed phase in this experiment. This is again typical of a more vitiated fire, where there is a greater degree of control due to reduced ventilation in Experiment 09.

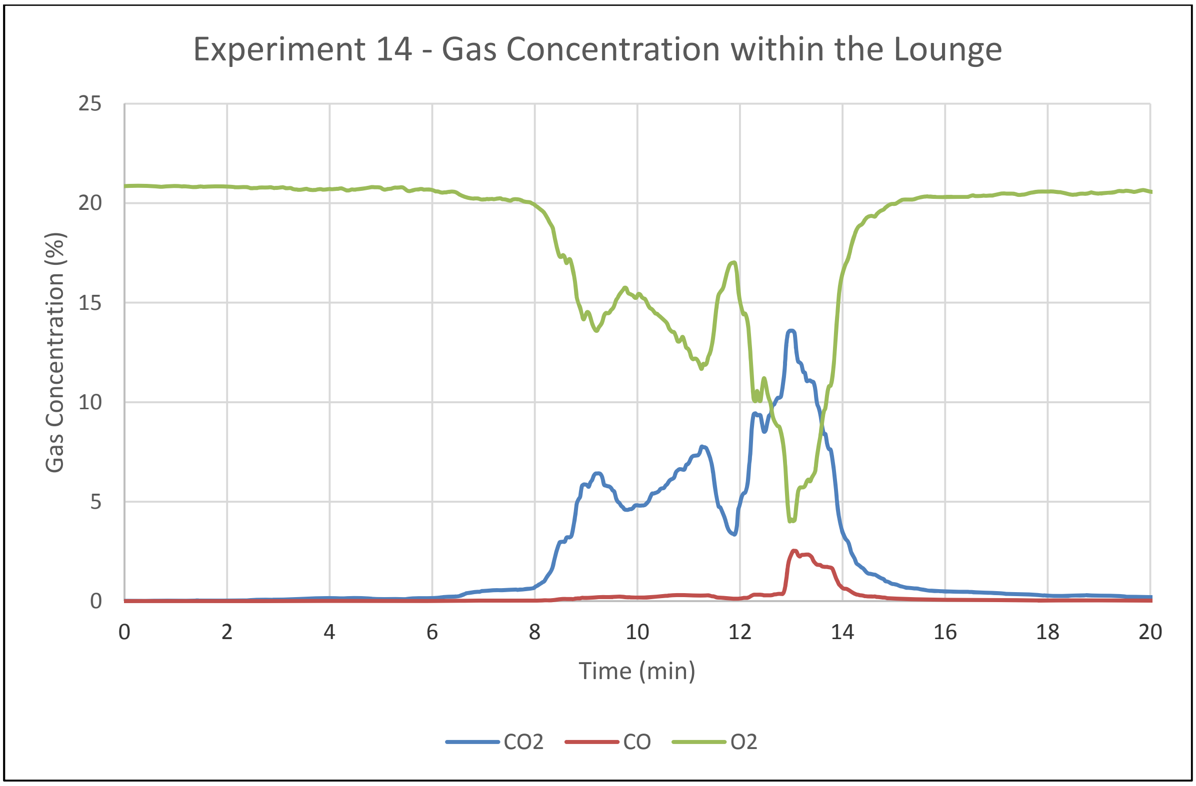

Figure 99 – Experiment 14 lounge gas concentrations

4.5.4 Smoke Visibility

During some of the experiments, the equipment used to gather smoke obscuration data was irreparably damaged and as a result, there is a limit to the amount of data that has been gathered. Only two reliable recordings of visual obscuration were made, both of which were on the landing, with the results presented in Table 50. The average time at which the escape route becomes impassable is 12:34.

Experiment Number	Location	Time to 3m visibility
Exp.05	Landing	13:22
Exp.09	Landing	11:46

Table 50 – Time for visibility of 3m (lounge door closed scenarios)

With respect to the opportunity for occupant self-evacuation, this suggests that with the fire compartment door being closed to the remainder of the property, the time available for a successful escape is approximately 6½ min from when the alarm sounds.

4.5.5 Video Analysis

The images presented in Plate 20 and Plate 21 show the fire development for Experiment 05 on the left, compared to Experiment 09 on the right. It can be seen that the smoke layer within Experiment 09 (right) drops down quickly and fire development is being severely retarded at 6-7 min as a result of the lack of O_2. At 9 min from ignition, the sofa within Experiment 05 is fully alight and burning freely as a result of sufficient air and oxygen. By comparison, the fire in Experiment 09 is somewhat smothered.

Plate 20 – Images from within the lounge for Exp.05 (left) and Exp.09 (right)

Plate 21 – Images from within the lounge for Exp.05 (left) and Exp.09 (right)

Plate 22 shows an image of a developed fire at 10 min after ignition, from Experiment 14, where there is additional fuel loading within the fire compartment. It can be seen that at this stage of the experiment it is only really the sofa that is contributing towards the fire, the remaining combustible materials are starting to pyrolyse at this point and a small amount of pyrolysed fuel can be seen leaving the armchair. Other fuel packages include a wooden table and chair and some carpet.

Plate 22 – Image from within the lounge for Experiment 14

Plate 23 shows three images also taken during Experiment 14 and these show the onset of flashover. In the first image (13:23) it can be seen that the carpet has shrunk due to heat exposure and that the carpet and armchair are pyrolysing heavily. The second image (13:24), taken 1 second later, shows an initial flame as the carpet reaches its auto-ignition temperature. The third image (13:28) shows that over a period of 5 seconds the fuel packages on the right hand side of the image have transformed from pyrolysis with no flaming, to being fully involved in fire. It is noteworthy that this has taken nearly 13½ min and that flashover is occurring a significant time after ignition.

Plate 23 – Images from within the lounge for Experiment 14

4.5.6 Asphyxiant Gas FED Analysis

Equation 8 will again be used in the analysis of the asphyxiant gas concentration data to yield a time to lethality in the various rooms within the property. The time to lethality is established for the more vulnerable members of the community at 1.0×FED and also for the healthy adult population at 2.5×FED.

Table 51 details the outcomes of this analysis. With the evidence of minor smoke leakage from the fire compartment into the closed door bedroom (during Experiments 05 and 09) and having considered all of the gas concentration data against what would be reasonable within these experiments, it has only been possible to produce an FED analysis within the fire compartment and on the landing. Average figures are also shown and this data does show quite clearly that there is a significant delay in the asphyxiant gases reaching the compartments outside of the lounge, as a result of the lounge door being closed.

Experiment Number	Room	Time to 1.0xFED	Time to 2.5xFED	Average Time to 1.0xFED	Average Time to 2.5xFED
Exp. 05	Lounge	9:11	10:04	8:42 (SD – 0:41)	9:18 (SD – 1:06)
Exp. 09		8:13	8:31		
Exp. 14		12:44	12:58		
Exp. 05	Landing	> 20 min (0.22)	> 20 min (0.22)	18:36	19:32
Exp. 09		18:36	19:32		
Exp. 14		-	-		
Exp. 05	Open Bedroom	-	-	19:16	N/A
Exp. 09		19:16	> 20 min (2.48)		
Exp. 14		-	-		
Exp. 05	Closed Bedroom	> 20 min (0.22)	> 20 min (0.22)	N/A	N/A
Exp. 09		-	-		
Exp. 14		-	-		

Table 51 – Smoke FED time to lethality (lounge closed door scenarios)

The data gathered during Experiment 14 also shows that significant amounts of smoke leaked from the fire compartment into the closed bedroom and it is reasonable to suggest that this has contributed towards the extended times to FED seen in this experiment. As such, all of the average and standard deviation data ignores the figures gathered during this experiment.

Ideally, more data points would have been collected from within this grouping. With regards to tenability on the landing, there are two data points for each FED threshold, as a result of a lack of a greater amount of data the lowest time is taken to give a margin of safety.

It shows that vulnerable people will receive a fatal dose of asphyxiant smoke within the fire compartment at between 8-9 min with an average of 8:42; this figure increases to 9:18 when impacting upon a healthy adult. On the landing, survivability times for more vulnerable people are increased to 18½ min; in the open bedroom this increases further to 19¼ min and in the closed bedroom survival times are much increased to well in excess of 20 min.

When compared with the data from Section 4.3.7, it is obvious that the landing and the open door bedroom are afforded a significantly greater degree of protection from having the fire compartment door closed. Tenability on the landing is extended for a period of approximately 10 min, when compared with the ‘lounge door open’ experiments.

Figure 100, shows the FED development curves for each of the three fires, within the lounge. Evidence suggests that the breach in the compartment floor during Experiment 14 occurred at around 12 min and the green curve would support this evidence although the line seems to flatten out at closer to 11:00. Otherwise, there seems to be a reasonable agreement between the other two experiments and the transition from a low FED through the two thresholds occurs over a relatively small timeframe.

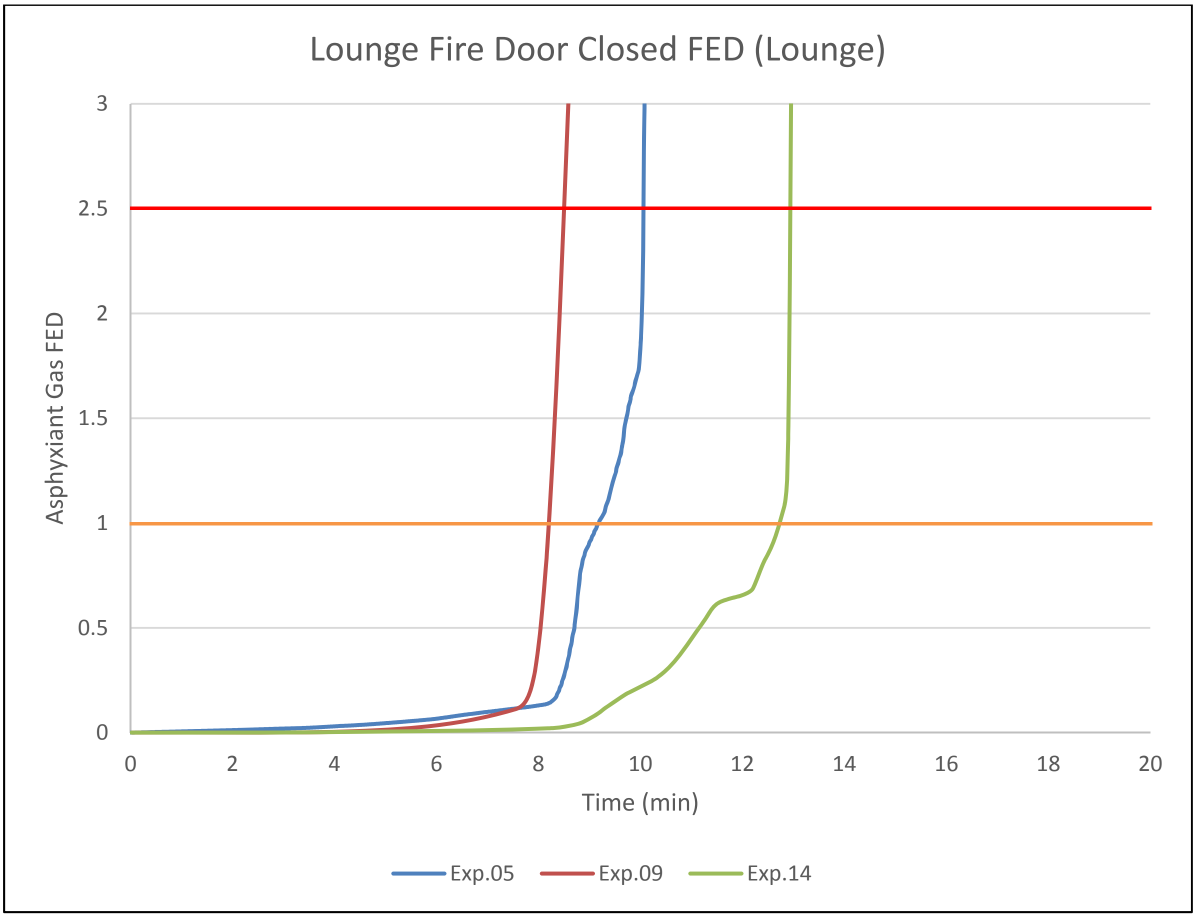

Figure 100 – Lounge fire door closed asphyxiant gas FED development (lounge)

Figure 101 shows the FED development curves for asphyxiant gases within the separate compartments during Experiment 09. When these curves are compared with those given in Figure 72 for Experiment 04 with the open lounge door, it is seen that the 3 curves are much closer together. For Experiment 04, the time difference between loss of tenability within the fire compartment and in the open bedroom is approximately 1:30, however, with Experiment 09, the difference in time is around 11 min.

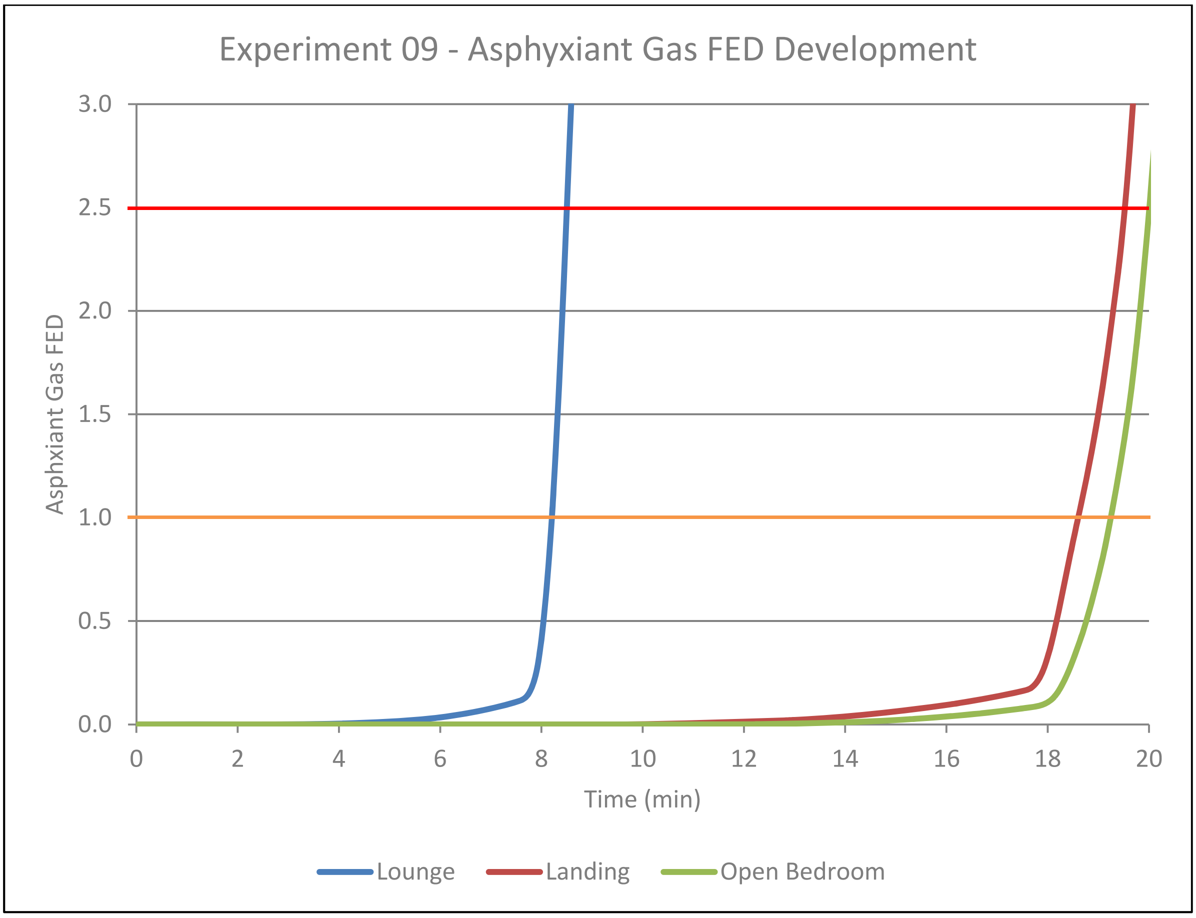

Figure 101 – Experiment 09 asphyxiant gas FED development

4.5.7 Heat FED Analysis

Again, with the increased fuel loading within the lounge fire scenarios, significantly more heat is produced during combustion and increased temperatures particularly within the fire compartment are observed. As a result, heat plays a more significant role with regards to the impact that the fire has on the occupants of the property. The time taken for heat to lead to the occupants of the building being fatally exposed are given in Table 52, with the average times given for both thresholds.

It shows that heat leads to fatal conditions within the lounge after around 8½ min. As a result of the protection afforded by the closed lounge door, heat is not expected to have an impact on the occupants of any of the rooms outside of the fire compartment, within the 20 minute timeframe of the experiments. The data for the 3 experiments shows a reasonable agreement within the lounge as indicated by the standard deviations. The closed bedroom FED data for Experiment 14 also confirms the direct transfer of smoke from the lounge.

Experiment Number	Room	Time to 1.0xFED	Time to 2.5xFED	Average Time to 1.0xFED	Average Time to 2.5xFED
Exp. 05	Lounge	8:26	8:41	8:24 (SD – 0:46)	8:44 (SD – 0.47)
Exp. 09		7:38	8:00		
Exp. 14		9:09	9:33		
Exp. 05	Landing	> 20 min (0.07)	> 20 min (0.07)	> 20 min	> 20 min
Exp. 09		> 20 min (0.58)	> 20 min (0.58)		
Exp. 14		> 20 min (0.10)	> 20 min (0.10)		
Exp. 05	Open Bedroom	> 20 min (0.06)	> 20 min (0.06)	> 20 min	> 20 min
Exp. 09		> 20 min (0.13)	> 20 min (0.13)		
Exp. 14		> 20 min (0.07)	> 20 min (0.07)		
Exp. 05	Closed Bedroom	> 20 min (0.05)	> 20 min (0.05)	> 20 min	> 20 min
Exp. 09		> 20 min (0.07)	> 20 min (0.07)		
Exp. 14		> 20 min (0.21)	> 20 min (0.21)		

Table 52 – Heat FED time to lethality (lounge closed door scenarios)

For Experiment 09, this data is given in Figure 102. This shows the development of the fractional effective doses as a function of time. Whilst the curve for heat within the fire compartment increases exponentially, the FED curves for rooms outside of the fire compartment only start to develop after 17 min and again these can be compared to the heat FED development curves shown in Figure 77 for Experiment 04. The closed lounge door significantly inhibits the flow of heat within the property to the rooms outside of the fire compartment.

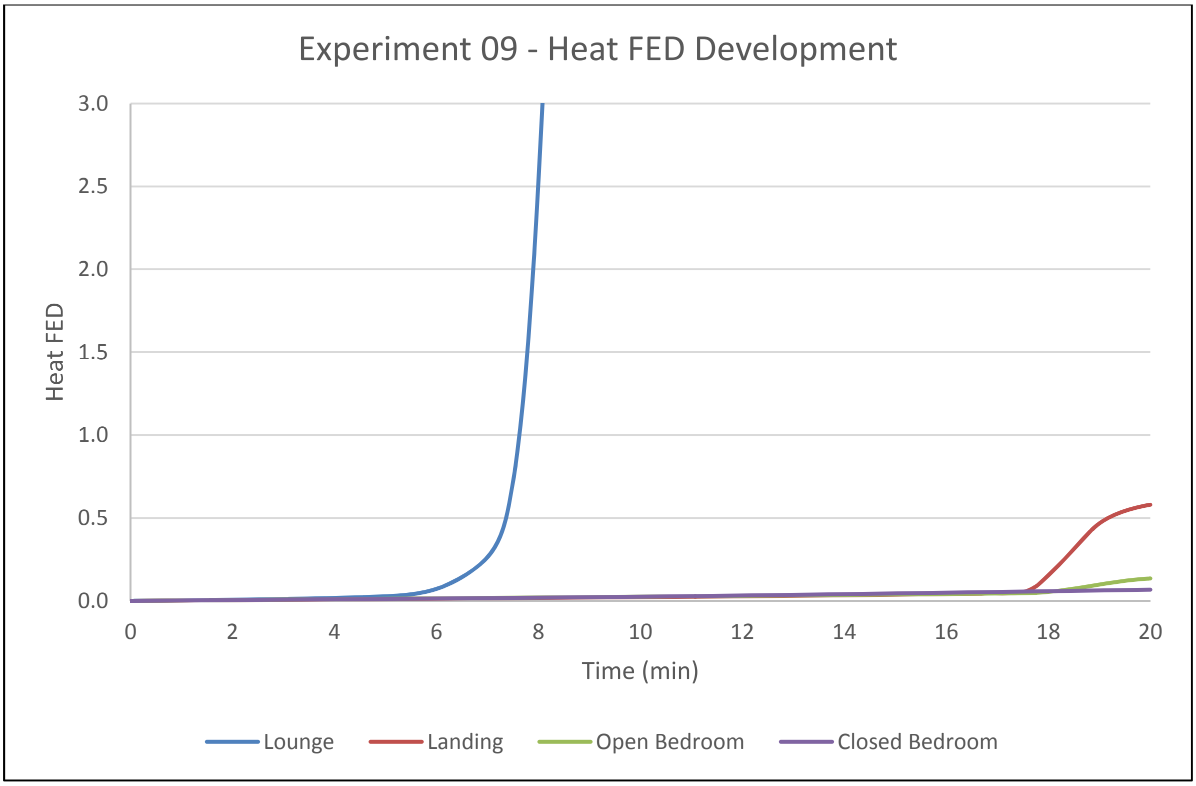

Figure 102 – Experiment 09 heat FED development

4.5.8 FED Conclusion

The data gathered during Experiments 05, 09 and 14 shows that fatal exposure to heat is likely to occur within the fire compartment at around 30 seconds before fatal exposure to the asphyxiant gases. Outside of the fire compartment the asphyxiant gases present a much greater hazard, when compared to heat with fatal exposure to these gases occurring in a significantly shorter time.

The closed door between the fire compartment and the remainder of the property does act to protect those occupants who are located elsewhere within the building. Whilst it is recognised that there is a delay of approximately 4 min for the smoke detectors to actuate (when compared with the lounge fires where the door was open) the escape route remains available for a further 8½ min after the fire starts. This results in a net gain of approximately 4½ min in the time available for self-evacuation.

It is also observed that the ventilation area is more critical within this group of experiments. These fires only have very limited access to the residual air within the remainder of the property as a result of the fire compartment door being closed and are almost totally reliant on air directly accessed via the external vents. As a result, the fire development profile where the ventilation area is 0.5 m^2, is very much ventilation-controlled and the consumption of the fuel is retarded by the lack of availability of O_2. The degree of ventilation-control placed upon these three experiments is much more noticeable than those discussed within Section 4.3, where the fire compartment door is held open.

Figure 103 and Table 53 show the timeline of events during these experiments with the average being taken from the 3 experiments, however the data from Experiment 14 is omitted after the point at which it becomes clear that the fire compartment ceiling has been breached. This shows that smoke was detected in the hallway at 6:08 after ignition. Within these experiments the sequence of events changes in respect of the fact that tenability within the fire compartment is lost prior to the escape route becoming impassable.

Tenability within the lounge is lost at 8:24 after ignition and only 2:16 after the alarm actuates. As discussed earlier, the escape route is protected by the closed fire compartment door and remains useable for a period of 6:26 after the alarm has actuated. Tenability on the landing is also extended as a result of the protection from the closed fire compartment door and is lost at 18:36 after ignition. Tenability within the open door bedroom occurs some 40 seconds later and the closed door bedroom remains tenable for the duration of the experiments.

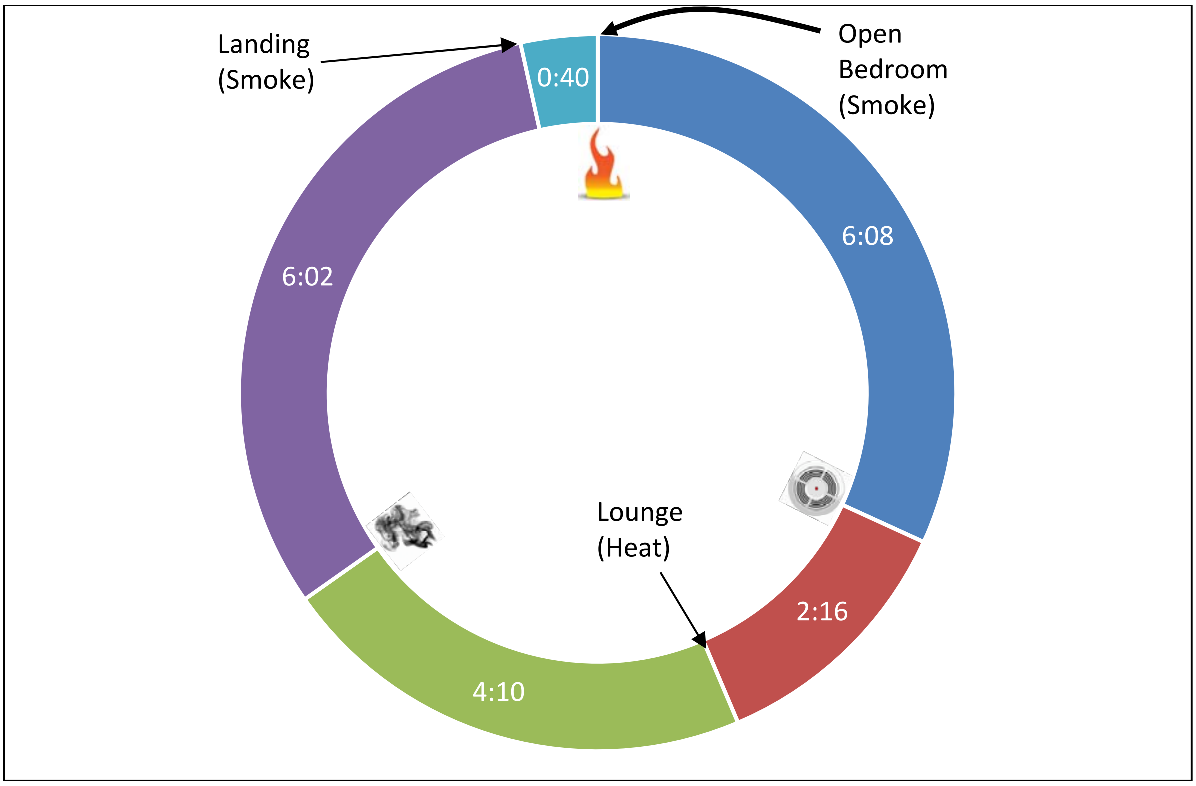

Figure 103 – Lounge fire door closed fire survival timeline

Event	Time
Ignition	0:00
Alarm Actuation	06:08
Visibility Lost	12:34
Lethality (Fire Compartment)	08:24
Lethality (Landing)	18:36
Lethality (Open Bedroom)	19:16
Lethality (Closed Bedroom)	> 20:00

Table 53 – Lethality event / time analysis (lounge fire door closed scenarios)

4.6 Comparison of Experimental Variables

This section establishes if the predetermined variables impacted experimental observations.

4.6.1 Fuel Comparison

A direct comparison of the two fuel types used in Scenarios 1 and 2 shows that the fires which involved upholstered furniture are nitrogen containing and produce HCN in contrast to the fires which consumed cooking oil, which do not contain nitrogen and do not produce HCN. The production of HCN presents a significantly greater threat to the occupants of a building, when involved in fire. The kitchen fires are also restricted by the availability of fuel where only 3 kg of oil is burned in Scenario 1 compared with 40-50 kg of timber and polyurethane in Scenario 2. The production of HCN, during Scenario 2 and the quantity of fuel consumed are the main factors in support of the fatality rates in bedroom/living/dining room fires being 13.4 times greater than in kitchen fires, as discussed in Section 2.1.3.

4.6.2 Passive Fire Protection Comparison

Data taken from each of the three experimental groupings is compared for the times to FED (in respect of the more relevant asphyxiant gas exposure rather than heat), between the open and closed door bedrooms. This data demonstrates that tenability within the closed door bedroom is extended for more than 10 min compared to the open bedroom as a result of the protection afforded by a closed door. This simple passive fire protection measure greatly increases a person's chances of surviving a domestic fire as it significantly increases the probability of a successful F&RS intervention. All F&RSs should continue to deliver this protection message, particularly when people are more vulnerable, whilst they are sleeping or have restricted mobility for example, or where intervention times are typically longer.

In addition, comparisons have been drawn for a number of scenarios to consider the impact of having the fire compartment door closed. The closed fire compartment door may have a detrimental effect on the time taken for an automatic detector to actuate, where fitted and working. This delay in raising the alarm is significant as current practice dictates that automatic detectors should be located in the hallway and landing areas. The delay in detection between scenarios where the fire compartment door was open and where it was closed is typically around 4 min.

However, closing the fire compartment door can also have a number of positive effects. It can help to reduce the rate of fire development and therefore heat and smoke production, particularly where there is a limited amount of ventilation to the fire compartment, as discussed throughout Section 4.5. The closed fire compartment door will also restrict the flow of heat and smoke into the other rooms within the house.

The joint impact of having a slower growing fire and a barrier to heat and smoke transfer, is that there is a net increase in the time that the escape route remains available of an extra 4½ min (after alarm actuation) where the fire compartment door is closed. In addition, the duration of tenability within the other compartments in the building is typically increased by approximately 10 min and therefore yields a net increase in survivability times of around 6 min from the fire alarm actuating.

4.6.3 Comparison of Smoke Detector Actuation Times

A comparison of the data presented within the different groupings shows that the time taken for smoke detectors to actuate is dependent on a number of factors. It is of significance that smoke detectors actuated at almost 6 min prior to ignition during the kitchen fire scenarios, as a result of the production of airborne particulate matter during early pyrolysis. This clearly gives the occupants more time to self-evacuate.

It is also of significance that the time to detection is affected by closed doors between the fire and the detector. Figure 104 shows the average time to detection taken from the fires in groups 2 and 3. It shows the delay caused by having a closed fire compartment door, however, the net gain as a result of this protection measure is also clearly demonstrated.

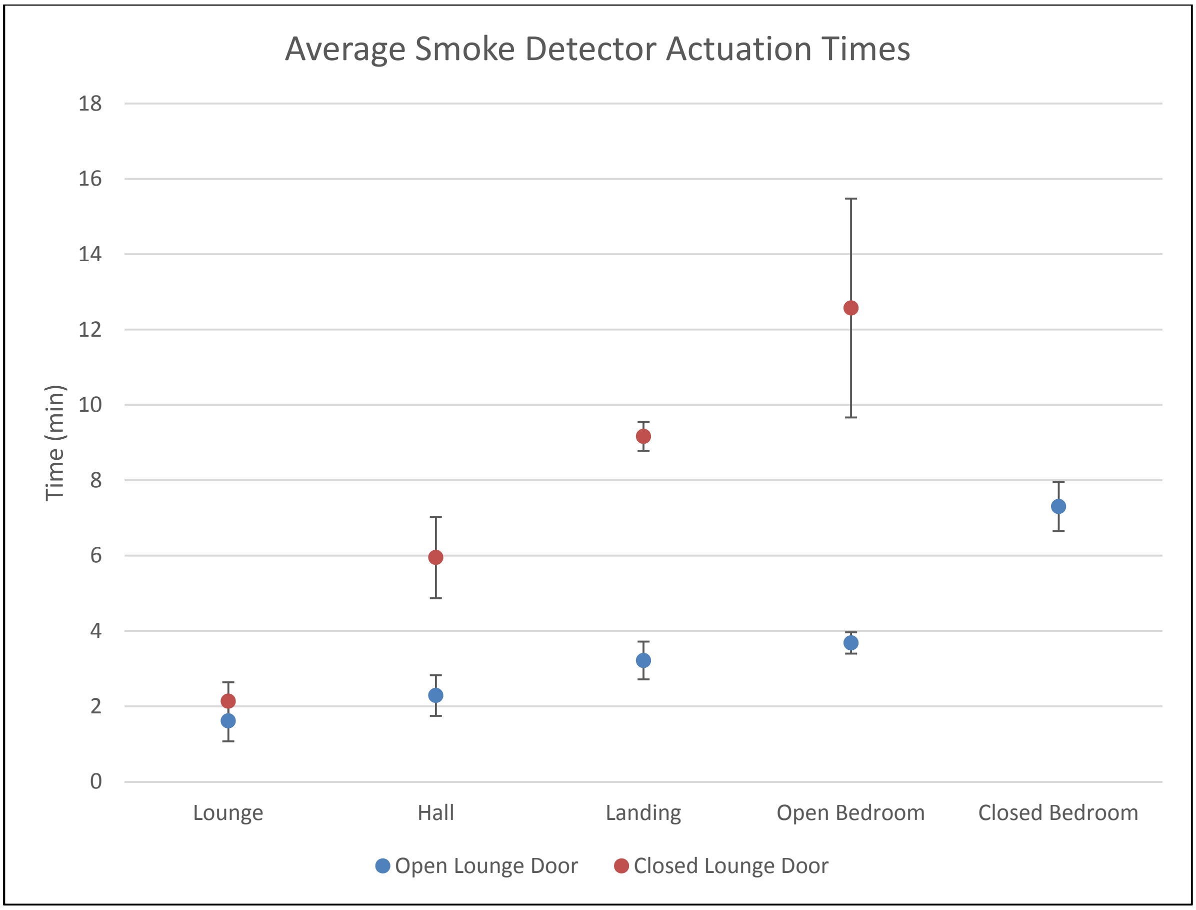

Figure 104 – Comparison of smoke detector actuation times

4.6.4 Comparison of Ventilation Levels

The impact that under-ventilated fires have on the rate of production of the asphyxiant gases CO and HCN, has been considered during the analysis of the experiments. The degree of ventilation was varied during experimental groupings 2 and 3 only, where the fire was located in the lounge.

In the group 2 experiments it was observed that there was a difference in the rates of production of these two gases between the well-ventilated and the under-ventilated experiments (see Figure 67 and Figure 68). The rate of fire development and the $CO:CO_2$ ratio within all experiments are linked to the amount of ventilation available to the fire. It was observed that the temperature profiles seen within the group 2 experiments did not differentiate between those experiments where the ventilation was 0.5 m^2 and those where it was 2.0 m^2 (see Figure 61). Any observed differences were well within the boundaries of experimental variability and it is not therefore appropriate to draw any conclusions. A major factor in respect of this appears to be that, with the fire compartment door being open, the fire has access to the air that is residual within the rest of the premises and that there is adequate oxygen already contained within the building to support combustion during the early stages.

By comparison, with the group 3 experiments there is a more noticeable variation. With the fire compartment door closed, the fire growth rate is much more dependent on the ventilation direct from outside into the fire compartment. Where this varies it can be seen that fire development is affected, this is shown in Figure 93 and discussed in Section 4.5.2. In these experiments the fire has no access to the air residual within the property because of the closed door.

The location of the ventilation openings can also have an impact upon fire development, specifically from a number of visual observations made during the experiments. During Experiment 08 it was seen that fire development appeared to be quicker in comparison to other similar experiments. Temperature profile data given in Figure 61 and Figure 62 support this observation and a hypothesis for this would be that with a ventilation opening being located on the first floor, the entire building acted like a chimney. The smaller vent on the ground floor appeared to act predominantly as an inlet vent with little smoke moving direct to the outside. This enabled the lower level vent to increase the influx of air and to support an increased fire growth rate.

4.6.5 Comparison of Duplicate Tests

The experimental design as detailed in Chapter 3, sets aside three separate scenarios as duplicates, to test the reproducibility of these scenarios. Experiments 01 and 02 were duplicate tests based on a pan of oil on fire within a kitchen with no further fuel sources being involved. These two experiments were very reproducible although this is not surprising for what is essentially a pool fire, where the availability of fuel is strictly controlled by the surface area of the pool.

Experiments 03 and 04 were also intended as duplicates. Figure 105 shows the temperature profiles of these two experiments. Experiment 03 has previously been identified to have a slower fire development where the incubation phase was extended by approximately 5 min. This provides a further demonstration that these tests can be impacted upon by a number of factors.

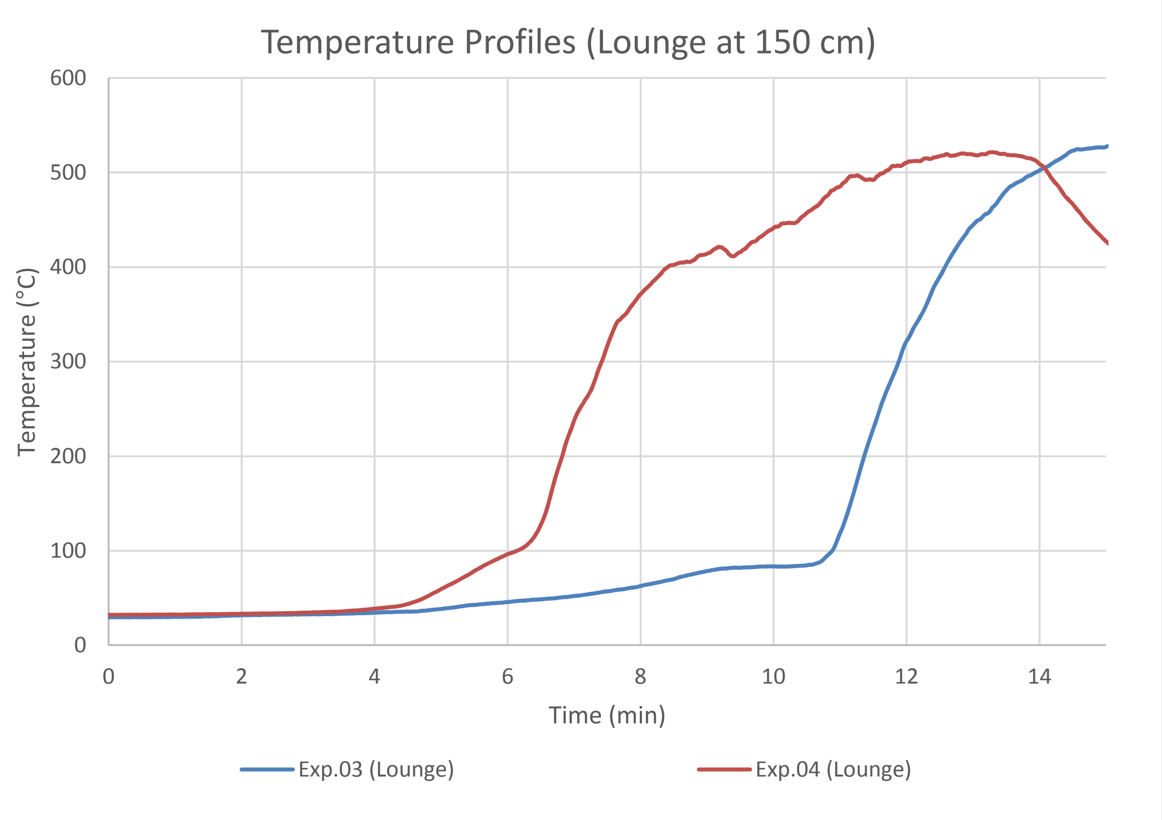

Figure 105 – Lounge open door temperature profiles (lounge at 150 cm)

Experiments 05 and 06 were also intended to be duplicates but Experiment 06 was never completed due to time constraints.

What has been observed is that within the three separate groupings, there was a reasonable amount of reproducibility. Within group 2 this is most apparent, probably as a result of this group having the highest number of individual experiments completed. Large-scale experiments such as these are both complex and expensive to complete and as a result it is not always feasible to conduct a significant enough number of tests to achieve a statistically valid data set. Within the constraints placed upon this project a reasonable agreement and averaged results is the most that can be achieved.

4.6.6 Comparison of Fire Loading

The fire loading within different experiments was increased to establish the impact upon the conditions within the property. With respect to the kitchen fires, when the fire was allowed to spread to the nearby kitchen units, this produced a much more hazardous situation. However, as a result of the production of airborne particles prior to ignition (and where smoke detection is fitted and working) both scenarios should be reasonably survivable as a result of the large timeframe for self-evacuation.

With respect to the scenarios involving lounge fires with upholstered furniture, there are two main considerations. The first is that tenability within those rooms which are open to the fire compartment (i.e. there is no closed door between the fire and that compartment) is usually lost within 10 min of ignition. It was observed that the onset of flashover could take more than 10 min. Therefore, tenability is lost within all open rooms before much of the additional fuel starts to contribute towards heat and smoke production.

The second consideration is that within those compartments which are closed to the fire compartment (i.e. protected by a closed door) tenability is extended as a result of the protection of the doors. The fact that additional heat and smoke are being produced as a result of the additional fuel loading becomes irrelevant because of the physical barrier which minimises the transfer of heat and smoke into these compartments.

As a result, it can be concluded that the additional fire loading in some of the experiments did not appear to significantly increase the hazard to the occupants.

4.7 Comparison of Tenability Timelines

Figure 106 shows how the timelines for compromised tenability (averaged across the three experimental groupings) compare to one another and helps to explain the hazards that arise as a result of the different scenarios.

It shows that the alarms actuated prior to ignition (-5:49) during the kitchen fires and that there was a 4 minute delay in detection as a result of the lounge door being closed in those experiments involving upholstered furniture. An earlier alarm would increase the likelihood of occupants surviving the incident as they will have more time to self-evacuate or wait for the F&RS.

It also shows that, whist early detection of the fire is achieved when the fire compartment door is open, tenability in terms of visibility through smoke on the escape route only extends for approximately 3 min after detection. By comparison, in those experiments where the fire compartment door is closed, tenability through visibility extends some 6½ min past detection.

The resulting net gain in visibility from the fire compartment door being closed would be of great assistance in situations where a working smoke alarm is fitted, the alarm is raised with the occupant and where the occupant is physically able to self-evacuate.

Figure 106 also shows that, in those experiments where the fire compartment door is closed, tenability within the fire compartment is lost before the visibility on the escape route is compromised. By comparison, where the fire compartment door is open, the visibility on the escape route is compromised before tenability within the fire compartment is lost.

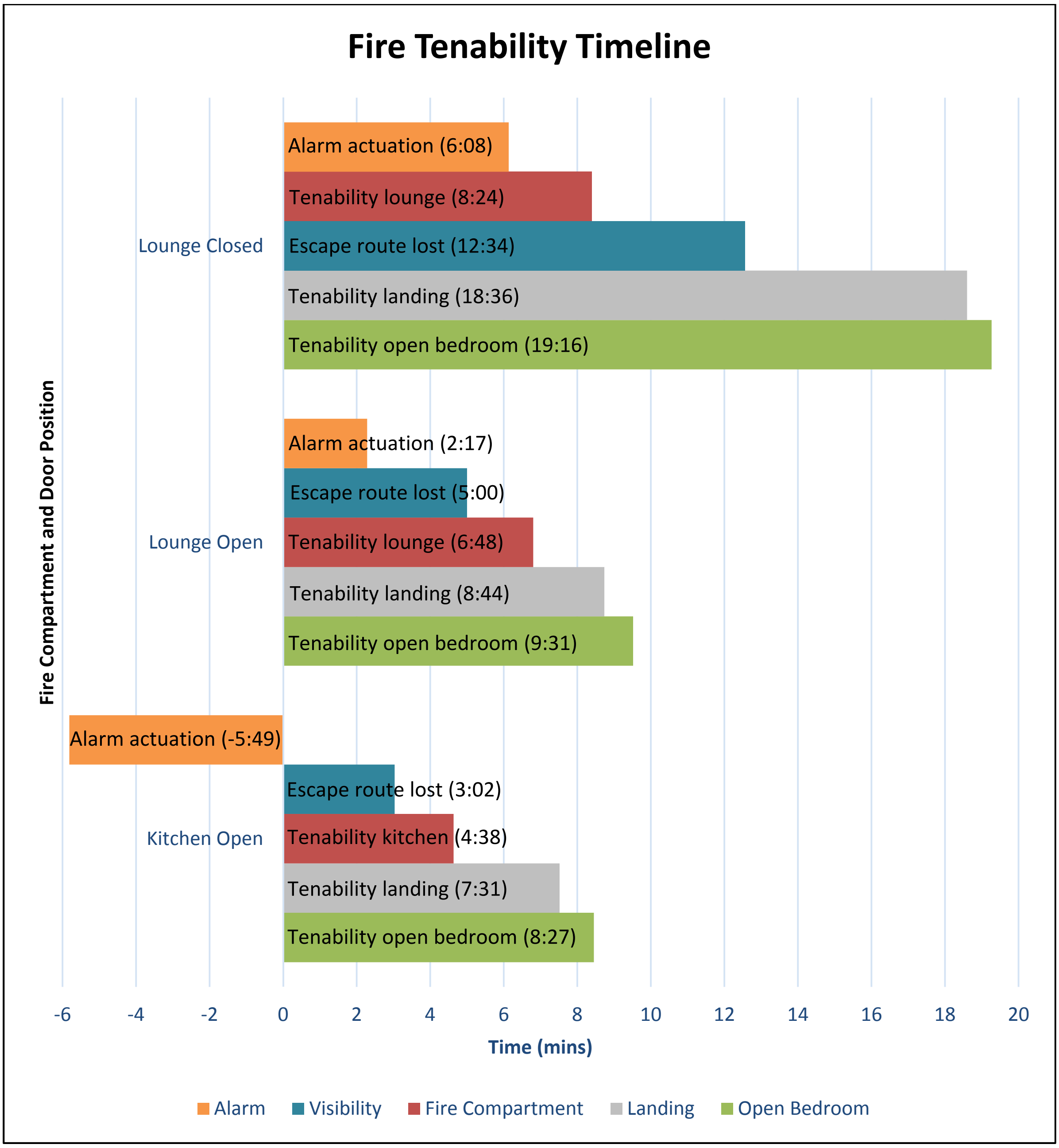

Figure 106 – Comparison of tenability timelines

When comparing the lounge fire scenarios, tenability within the fire compartment is lost, on average, at around 7 min when the compartment door is open and at around 8½ min when the fire compartment door is closed.

It shows that tenability on the landing is lost at around 7½ min after ignition during the kitchen fire scenarios; 9 min after ignition for the lounge fire door open scenarios and 18½ min after ignition for the lounge fire door closed scenarios.

It shows that there is roughly a 40-60 second delay in the loss of tenability from the landing to the open door bedroom. It should be remembered that tenability within the closed door bedroom remained above 20 min in all but one of the experiments.

Table 54 summarises the information within this section and shows the time duration between an alarm activation and another event occurring. For example, with the lounge fire door closed scenarios, tenability on the landing is 12:28 after the alarm actuates. So it is apparent that, where an occupant relies upon a fire alarm, the lounge fire scenarios where the compartment door is open present the most hazardous set of conditions.

Grouping	Tenability Lost			
	Visibility Lost	Fire Compartment	Landing	Open Bedroom
Kitchen (open)	8:51	10:27	13:20	14:16
Lounge (open)	2:43	4:31	6:27	7:14
Lounge (closed)	6:26	2:16	12:28	13:08

Table 54 – Tenability event / time analysis (lounge fire door closed scenarios)

4.8 Comparison of Results with Other Large-Scale Tests

These is a summary of the results from the 3 large-scale experiments discussed in Section 1.8.

1. **The effect of a closed door** – where two bedrooms are compared one with its door open and one with the door closed the difference can be considerable. Closing a door (typical domestic door not a fire door) can considerably reduce the amount of smoke transferred and this can increase the tenable duration from less than 7 min with an open door to more than 20 min when the door is closed. (*Supported by this study*).

2. **Delays in smoke detection with a closed door** – where the door of the fire compartment is closed, this can lead to an extended time to detection where the detector is located outside of that room. These experiments agree that whilst the time to detection is increased, the amount of time available for escape becomes significantly greater and therefore more than compensates for the delay in detector response. (*Supported by this study*).

3. **Tenability where heat is compared to asphyxiation from CO only** – where the occupant of a domestic building is located either within the fire compartment or close to it, there is a likelihood that incapacitation will result from exposure to either heat or to asphyxiant gas at around the same time. Where the occupant is located more remotely from the fire, the likelihood is that incapacitation from exposure to asphyxiant gases will occur however it is probable that temperatures will be sufficient to cause incapacitation. (*This study suggests that the effects of heat are likely to occur before the effect of CO close to the fire*).

4. **Tenability where heat is compared to asphyxiation from the combined effects of CO and HCN** – in experiments where both of the two main toxic gases are considered, a loss of consciousness due to smoke inhalation occurs prior to that from heat exposure both within the fire compartment and in other locations remote from it. (*This study suggests that the effects of heat and asphyxiant gases {combined CO/HCN} occur at approximately the same time*).

5. **Other effects occurring prior to incapacitation** – it is recognised that both visual obscuration and soreness to the eyes and respiratory tract will occur prior to incapacitation as a result of exposure to smoke. Both of these effects are unlikely to cause a loss of consciousness to an exposed occupant although it may impact upon their decision to evacuate the building or seek refuge. (*No data was gathered to support or dispute this conclusion*).

Chapter 5 - Comparison with F&RS Intervention Times

F&RSs within the UK perform 3 distinct roles. The Bain Report discusses these as a ‘modern approach to F&RS activities' [57], it states that the new emphasis must be on the ‘prevention’ of fire rather than the methods of dealing with it and that what is required is a new approach to ‘protecting’ people from the incidence of fire. It also states that a modern, flexible, risk-based approach to allocating intervention resources should be adopted.

1. Prevention – F&RSs utilise fire crews and other trained personnel to conduct prevention-based activities. This includes working with members of the public to raise awareness of the dangers of fire and providing advice on simple ways to minimise the risk of accidental fires.
2. Protection – this activity is two-fold, in the first instance F&RSs work to identify the common failings which result in fire deaths and injuries and they lobby to improve the national fire safety standards which protect people in both domestic and non-domestic buildings. Protection activities are also carried out whilst conducting prevention-based activities and will include the provision of smoke detectors and giving advice on what to do in the event of a fire.
3. Intervention – when fire prevention fails, fire crews are mobilised to incidents. They are required to extinguish fire and to make attempts to rescue any individuals who become trapped.

When there is a fire within a domestic property, the ideal outcome is that the occupants are able to self-evacuate prior to the attendance of the F&RS. Sometimes this is not possible either as a result of the occupants becoming trapped by the fire, or that they are unable to self-evacuate for some other reason. When this occurs, the F&RS will try to effect a rescue as part of an intervention, otherwise the occupants are likely to perish.

As fractional effective doses are time dependent then the 'time taken to effect a rescue' can be critical to the occupants. Within this section, appropriate F&RS intervention timelines are established and are compared to the tenability timelines presented in Section 4.7.

5.1 Stages of a F&RS Intervention

The stages of an F&RS intervention are rarely discussed when considering occupant survival. Sträng identified four distinct stages (dispatch, arrival, investigation and set-up times) [91][92]. Further development by the author identifies 8 stages, shown sequentially in Table 55 and described thereafter. This assessment is based on the assumption that the property contains a working smoke alarm. Standard deviations are presented (where available).

Time Step	Group 1 (mm:ss)	Group 2 (mm:ss)	Group 3 (mm:ss)
1. Time to alarm	-5:49 (2:25)	2:17 (0:32)	6:08 (1:05)
2. Occupier recognition		2:00 (-)	
3. Dial 999 through BT		0:30 (-)	
4. Call Handling		1:24 (0:44)	
5. Crew Reaction		1:16 (0:37)	
6. Travel		4:03 (2:00)	
7. Safe System		1:25 (-)	
8. Time to Rescue		3:02 (-)	
Lower Limit	2:05	12:04	15:22
Average	7:51	15:57	19:48
Upper Limit	13:37	19:50	24:14

Table 55 – F&RS intervention times

Table 55 shows the average intervention time for each group and also a lower and upper limit based on one standard deviation.

1. Time to alarm –the time between ignition and alarm actuation. This step is variable and is established for each of the experimental groupings. Standard deviations are provided.
2. Occupier recognition – time between alarm actuation and the point at which a call for help is made. The rationale for this time step is given in Section 5.2.
3. Dial 999 / BT exchange – time taken to dial 999, request the fire service at the BT exchange and then be put through to local authority fire control. A time of 30 seconds was established by conducting several test calls. The duration of these were consistently within a few seconds of each other and make no significant difference to the overall timeline, therefore standard deviations are not included.
4. Call handling – time taken from the call being passed to fire control to the point where a fire appliance is assigned to an incident. During this time step fire control will establish the nature and location of an incident and assign a suitable resource. The average time taken from 3,404 ADFs in the West Midlands is 1:24 over the period Apr 14 – Mar 16.
5. Crew reaction – time between a crew being assigned to an incident and a crew establishing that they are mobile to that incident. This includes the time taken for firefighters to gather at the fire appliance and get dressed in their fire kit and is based on the same 3,404 incidents.
6. Travel – time between a crew mobilising to and arriving at an incident, based on the same 3,404 ADF incidents.
7. Safe system – on arrival, the fire crew are required to put safe systems of work in place before they enter a building which is on fire. This figure was established based on a separate study which is discussed in Section 5.3.
8. Rescue – the final stage of an intervention is intended to have a positive effect on the occupants e.g. by extinguishing the fire, ventilating a building and rescuing casualties. This data was also established within the study discussed in Section 5.3.

5.2 Occupier Recognition Time

This time step is difficult to quantify as it is not directly recorded, it cannot be established from experimentation, the ignition time is not usually known and time frames gathered during conversation with the occupants after a real incident can be somewhat unreliable. Q.5.3 of the incident recording system does request that the fire officer estimate the time between discovery and first call, however this is only an estimation and is not generally established with any great accuracy. The time options for the reporting of this stage are also quite broad.

Fire officer estimations for the time between discovery and first call are gathered by WMFS. The data for ADFs (where a working smoke alarm and an occupant were both present) during the two year period from Apr 2014 to Mar 2016 are shown in Figure 107 which includes 2,199 incidents.

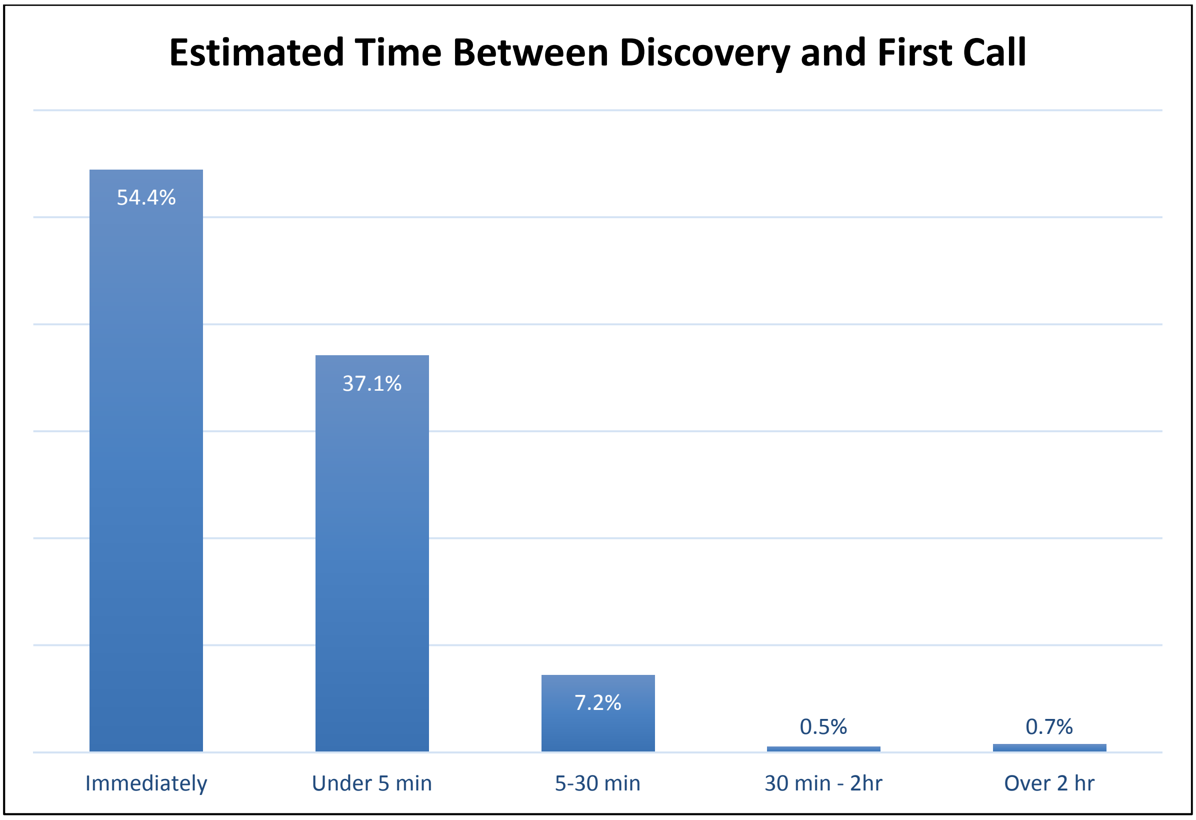

Figure 107 – Estimated time between discovery and first call

Assuming that ‘immediately’ is equivalent to 10 seconds and ‘under 5 min’ is equal to the midpoint (2.5 min), then for 91.5% of calls, the average time from discovery to first call is 1:07. Further assuming that ‘5–30 min’ is equal to the midpoint i.e. 17.5 min, then for 98.7% of calls, the average time between discovery and first call is 2:19. Based on this analysis it seems reasonable to use a figure of 2 min to estimate the time from discovery to first call. No standard deviation is given, as this figure is not developed from quantitative data.

5.3 Safe System and Rescue Time

In support of this project, it was necessary to establish how long it takes for firefighting crews to put safe systems of work in place before they enter a building fire and how long it takes to search for and rescue casualties.

Safe system activities will be completed both en route to and immediately upon arrival at an incident. These could include activities such as donning appropriate fire kit and breathing apparatus, obtaining an extinguishing media and completing a mandatory firefighter entry control procedure. Rescue activities may also take a while due to the conditions faced by firefighting crews and the need to search for casualties and firefight as they move through the building.

In order to achieve this, a colleague of the author gathered information from observing 20 WMFS training activities and achievable times for setting up safe systems of work were established [93]. The separate training activities involved crews from different stations across the West Midlands.

5.4 F&RS Intervention (Group 1)

A comparison of the group 1 tenability timeline from Figure 106 and the F&RS intervention timeline is given in Figure 108. The bar chart shows the times when fatal exposure within the various compartments occurs and the blue shaded area shows the intervention time window. The average intervention time is indicated by a green vertical line. The earliest feasible intervention is likely to take place at around 2 min after ignition with the latest time being around 13½ min and the average at 7:51.

5.5 F&RS Intervention (Group 2)

A comparison of the group 2 tenability timeline and the F&RS intervention timeline is given in Figure 109. The earliest feasible intervention is likely to take place at around 12 min after ignition with the latest time being around 20 min and the average at 15:57.

5.6 F&RS Intervention (Group 3)

A comparison of the tenability timeline and the F&RS intervention timeline is given in Figure 110. The earliest feasible intervention is likely to take place at around 15½ min after ignition with the latest time being around 24 min and the average at 19:50.

The window for a fire service intervention occurs at the same time that tenability is lost within the different rooms for experimental groupings 1 and 3 and therefore presents an opportunity for the F&RS to complete a successful rescue. However, tenability within group 2 is reached well before a fire service intervention and limits the opportunity for rescue, except where the occupants are protected by a closed door. This is analysed further in Section 5.8.

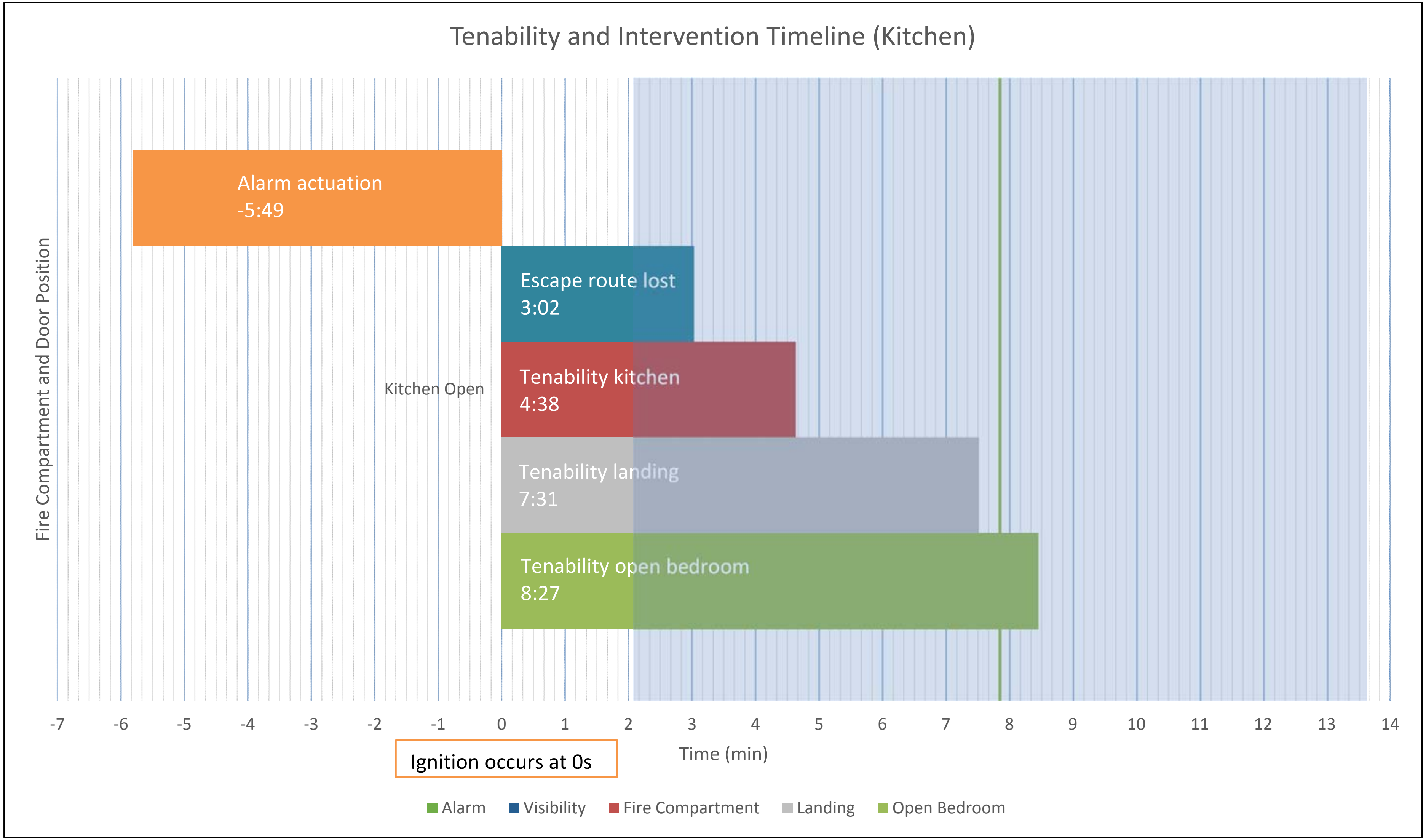

Figure 108 – Tenability and intervention timeline (group 1)

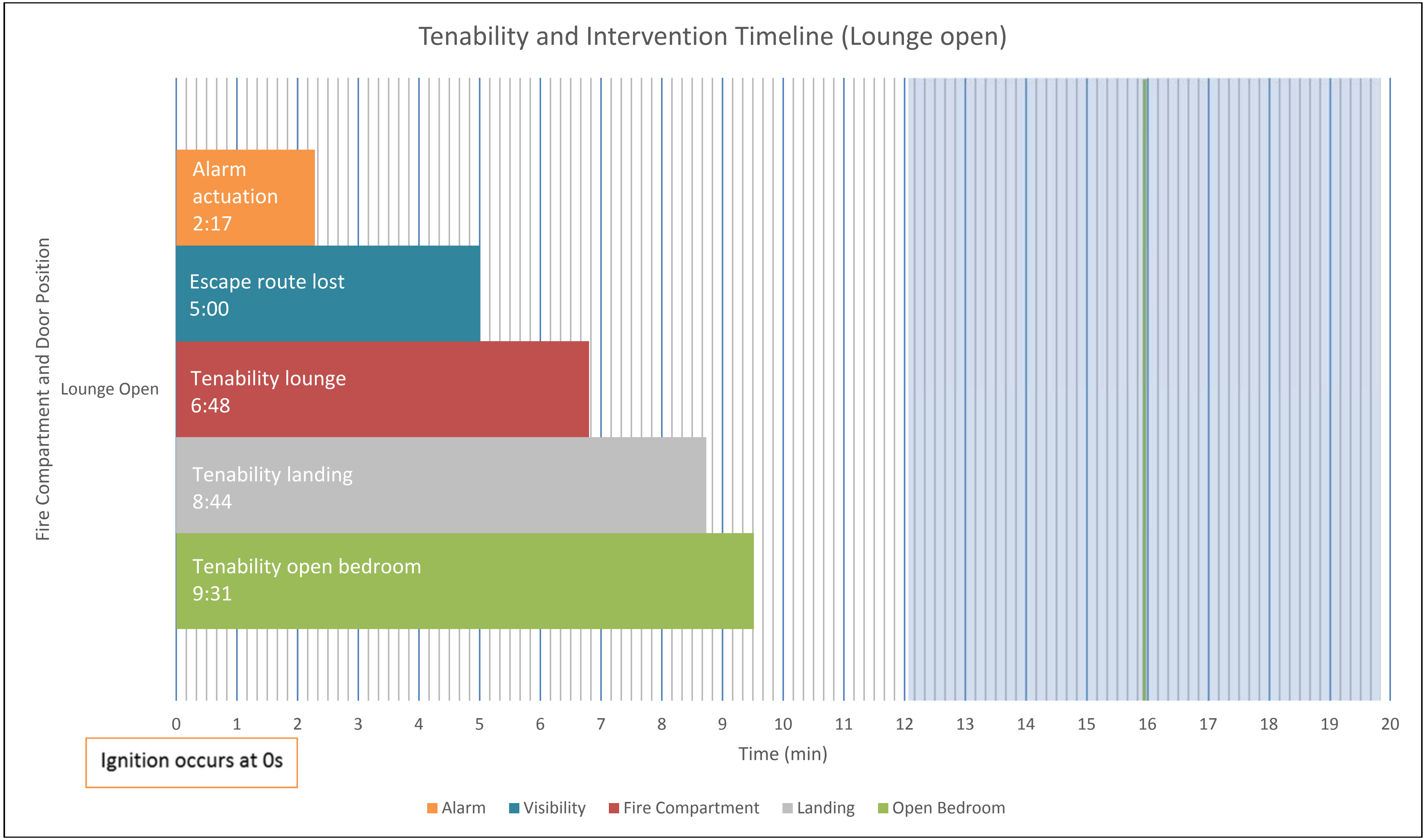

Figure 109 – Tenability and intervention timeline (group 2)

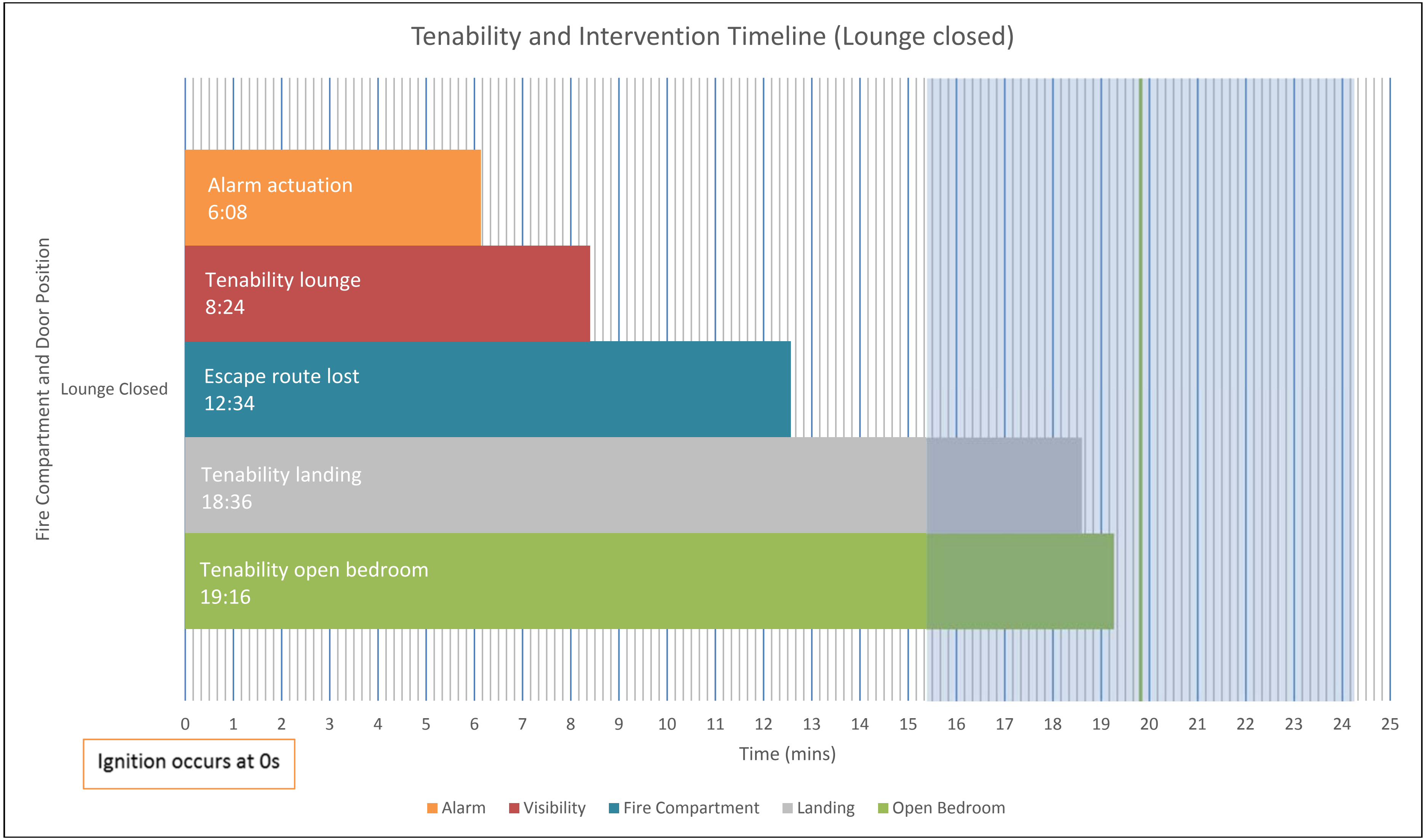

Figure 110 – Tenability and intervention timeline (group

5.7 Variations in Intervention Times

It is important to recognise that F&RS intervention times vary significantly across the UK, with shorter attendance times in large cities compared with those in more rural locations. Fire and rescue service provisions are based on risk, and there tends to be a greater degree of risk from fire in large urban areas. WMFS is one of 7 metropolitan fire brigades within England and this model could be used to assess the effectiveness of an F&RS response within any of these areas. The 7 metropolitan brigades are London, Greater Manchester, Merseyside, South Yorkshire, Tyne & Wear, West Midlands and West Yorkshire. In comparison, the F&RSs which operate in more rural areas are less likely to achieve the attendance standards discussed within this section, but equally the fire risk in those communities is generally lower.

5.8 Influencing Intervention Times for the Future

Each of the 8 time steps of an F&RS intervention are (to some extent) variable. Table 56 considers each time step individually and determines its criticality towards the overall time for an intervention, it also shows the percentage contribution of each time step to the total.

Time Step	Activity	Lounge (open)		Lounge (closed)	
1	Time to alarm	2:17	14.3%	6:08	31.0%
2	Occupier recognition	2:00	12.5%	2:00	10.1%
3	Dial 999 / BT Exchange	0:30	3.1%	0:30	2.5%
4	Call handling	1:24	8.8%	1:24	7.1%
5	Crew reaction	1:16	7.9%	1:16	6.4%
6	Travel	4:03	25.4%	4:03	20.5%
7	Safe system	1:25	8.9%	1:25	7.2%
8	Rescue	3:02	19.0%	3:02	15.3%
	Total	15:57	100.0%	19:48	100.0%
	Lower Limit (-1 S.D.)	12:04		15:22	
	Upper Limit (+1 S.D.)	19:50		24:14	

Table 56 – Influencing intervention times

The time steps in Table 56 have been colour coded in order of significance (see over).

Green coded time steps (low significance)

- 2. Occupier recognition – behavioural and very difficult to influence in the event of a fire.
- 3. Dial 999 / BT Exchange – relatively short and not under the control of the F&RS.

Amber coded time steps (some significance)

- 4. Call handling – contributing around 9% of the total time, opportunities to minimise this time step should be explored and could include continued staff training and software development.
- 5. Crew reaction – contributing around 7% of the total, opportunities to minimise should be explored with continued staff training and improved fire station design.
- 7. Safe system – contributing around 8% of the total, opportunities to minimise should be explored and could include continued staff training and other innovations.
- 8. Rescue – contributing around 17% of the total, opportunities to minimise should be explored and could include continued staff training, procedural development and other innovations.

Red coded time steps (critical significance)

- 1. Time to alarm – contributing 15-30% of the total, this is a critical factor in protecting domestic occupants. F&RSs undertake significant and targeted work to protect all properties with a working smoke alarm. This time step could be reduced significantly by more widespread use of interlinked smoke detection systems with further protection being afforded to high-risk rooms such as bedrooms and living rooms.
- 6. Travel – contributing between 20 and 25% of the total, this is also a critical factor. This time step is largely influenced by the number and type of fire engines and by the number and location of fire stations. Given recent reductions in the funding from central government, many F&RSs have taken the decision to reduce the number of fire engines and fire stations and this is likely to continue in the future. This is almost certain to increase the average travel time to an incident and therefore the total time taken for an intervention, as evidenced in a study undertaken by Lancaster University [3]. Consequently, there will be an increased risk when fire occurs and occupants become trapped or are otherwise unable to self-evacuate.

5.9 Dependence of Intervention Times on Life Safety

Based on analysis, it is possible to assess the likelihood that a person, in need of rescue, has of surviving in each scenario. Where the tenability limits are exceeded and this occurs prior to an F&RS intervention then the likelihood of survival is low; where tenability limits are reached during an intervention, the likelihood of survival is moderate and where an intervention occurs prior to tenability limits being reached, the likelihood of survival is high. The outcomes of this analysis are presented in Table 57.

Description	Group 1	Group 2	Group 3
Occupant Location	Kitchen Fire (Door Open)	Lounge Fire (Door Open)	Lounge Fire (Door Closed)
Fire Compartment	Moderate	Low	Low
Landing	Moderate	Low	Moderate
Open Bedroom	Moderate	Low	Moderate
Closed Bedroom	High	High	High

Table 57 – Likelihood of a successful F&RS intervention

It shows that the likelihood of survival is only low when the fire is located within the lounge and where the occupant is not protected by a closed door. In all other situations there is a possibility that the F&RS can successfully effect an occupant rescue.

Description	Group 1	Group 2	Group 3
Occupant Location	Kitchen Fire (Door Open)	Lounge Fire (Door Open)	Lounge Fire (Door Closed)
Fire Compartment	Moderate	Low	Low
Landing	Moderate	Low	Moderate
Open Bedroom	Moderate	Low	Moderate
Closed Bedroom	High	Moderate	High

Table 58 – Likelihood of a successful F&RS intervention (+2 min)

Table 58 shows the likely outcome where the average time of an intervention is increased by 2 min (a possible consequence of austerity measures). An increase of 2 min will not impact upon those situations where the likelihood of survival is low; however, where the likelihood of survival is moderate a 2 min increase could make a significant difference as the dose increases constantly. Notably, one of the scenarios is re-categorised from high to moderate.

The importance of a prompt F&RS intervention can be seen, when the FED curves (from Chapter 4) show the transition from 'suffering minor smoke inhalation' to having received a 'fatal dose' can occur in less than two minutes. Figure 111 shows this, with the asphyxiant gas FED curves observed during Experiment 09 (Figure 101) with the F&RS intervention time window overlaid for comparison (shaded blue).

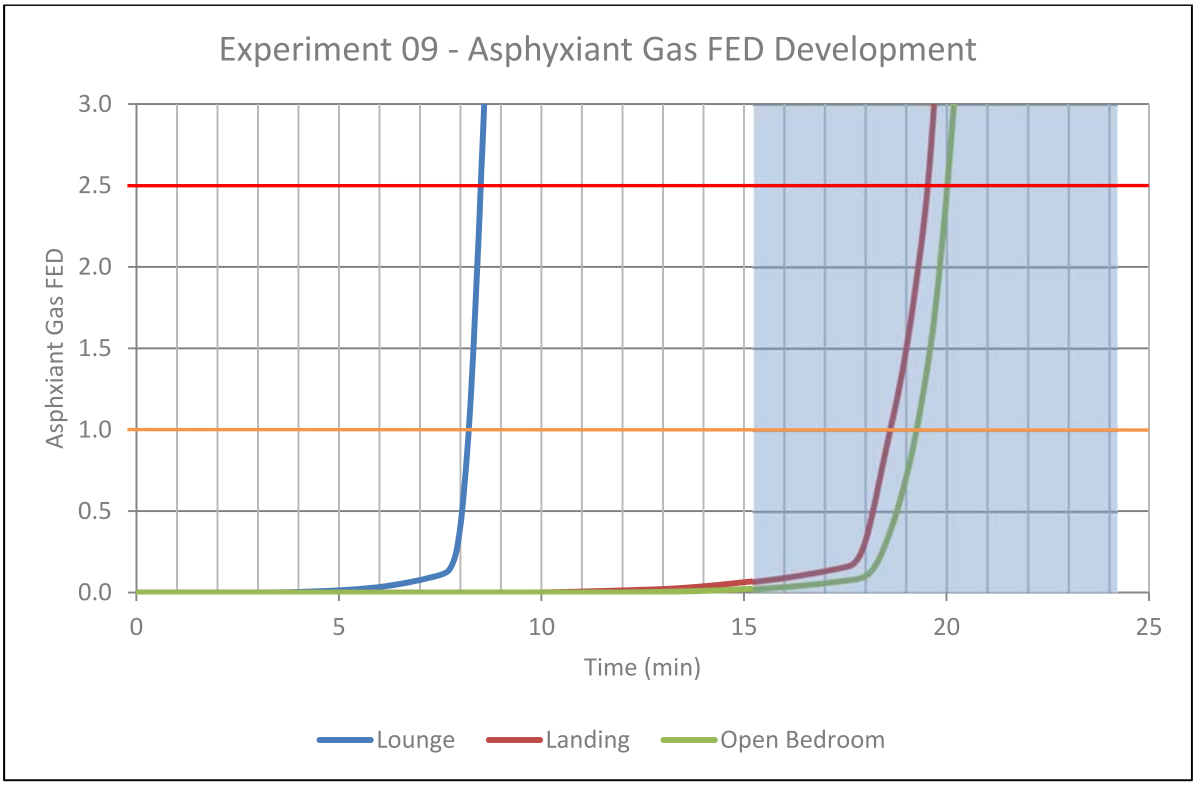

Figure 111 – Experiment 09 FED compared to intervention

Chapter 6 - Conclusions

6.1 Statistics Conclusions

An analysis of fire statistics has been undertaken to better understand the factors which might lead to fire deaths and injuries. In GB, over the three year period from April 2010 to March 2014, 77% of all fatalities and 80% of all injuries from fire occurred in dwellings, with 65% of fatalities and 70% of injuries from fire occurring as a result of 'accidental dwelling fires'. Over the same period 46% of fatalities occurred in ADFs where the fire started within the bedroom, living or dining rooms; and some 42% of fire injuries occurred in ADFs where the fire started within the kitchen.

Whilst it has been reported that 88% of all households in GB had a working smoke alarm in 2012/13 [6], in those fires where injuries occurred this figure drops to 43% and for fatalities it is only 24%. This demonstrates the additional risk to people where a fire occurs in the absence of a working smoke alarm and also suggests that those members of the community who are more likely to have a fire are less likely to have a working smoke alarm. It is recognised that those who act to mitigate the effects of fire present a different risk profile to those who are less active [94].

When fire occurs in a domestic property, the occupants are at risk from heat and asphyxiant gases. Asphyxiant gases present the greater hazard causing 50-70% of all ADF fatalities, whereas heat causes 30-50% of these. Some 70% of all fire fatalities occur where the item mainly responsible for fire development is furniture, furnishings, clothing or textiles; and 95% of fatalities result from the smoke from these fuels in bedrooms or living rooms fires.

When fire fatalities occur, the main source of ignition is ‘smoking related’ (40%) and for injuries it is ‘cooking appliances’ (52%). There is also a tendency for fire injuries to occur where the fire size is less than 5 m^2, with fatalities being likely where the fire is greater than this size.

The statistical analysis demonstrates that the most hazardous fire situation, with respect to the number of occupant fatalities, is a fire in a bedroom or living room which involves furniture, furnishings, clothing or textiles. Fires resulting in injuries are most likely to occur as a result of a kitchen fire involving foodstuffs. The statistical analysis has been used to inform the experimental activities and this constitutes a new approach in this field.

6.2 Experimental Conclusions

When a significant fire occurs within an occupied dwelling there are 3 realistic outcomes for the occupants: -

1. Self-Evacuation – The occupant becomes aware of the fire, has adequate time (and/or protection) to evacuate and is physically able to do so (*potential for non-fatal injury*).
2. Rescue – The occupant is unable to self-evacuate and is successfully rescued from the property (most likely by F&RS personnel) sustaining a non-fatal dose of heat or asphyxiant gases (*potential for non-fatal injury*).
3. Fatal Exposure – The occupant is not able to self-evacuate and receives a fatal dose of heat or asphyxiant gases prior to or whilst being rescued (*fatal injury occurs*).

A series of experiments have been conducted to establish the likely outcome for a number of scenarios which have been identified as ‘those most likely to cause injury or fatality for the occupants’. These experiments and the subsequent analysis lead to the following conclusions.

When a fire starts as a result of the ignition of overheated cooking oil in a kitchen and an alarm is fitted and working, there is a time window of more than 8¾ min to allow for self-evacuation before the escape route becomes impassable. During these fires a self-evacuation is likely to occur, where the occupants are physically able to do so and they are aware of the fire.

When occupants are unable to self-evacuate from a kitchen fire but the emergency services have been notified, it is highly likely that a rescue will occur prior to the occupant receiving a fatal dose of heat or asphyxiant gases. Injury from exposure to smoke is likely.

When a fire involves upholstered furniture in a living room the hazard to occupants is considerably greater. This results from an increased gas output (CO_2, CO and HCN) as a result of the higher mass burning rate of a sofa compared to cooking oil, the production of the additional asphyxiant gas HCN and also as a result of the reduced time between fire detection and the onset of compromised tenability. With this fire type, fatalities within the fire compartment are likely to result from exposure to heat; outside of the fire compartment fatalities are almost exclusively caused by exposure to the asphyxiant gases.

When the lounge door is open and a fire occurs within the lounge, the time window for self-evacuation is approximately 2¾ min before the escape route becomes impassable. The significant reduction in the time available for escape and the larger hazard created during lounge fires are key factors leading to the increased mortality rates that are discussed in Section 2.1.3. When the lounge door is closed, the time window for self-evacuation is much increased to around 6½ min before the escape route becomes impassable.

Experimental data show that the window for self-evacuation is much greater when the fire compartment door is closed (and the occupant resides outside the fire compartment). If a lounge is on fire and the lounge door is open the likelihood is that a fatal exposure to the asphyxiant gases will occur well before an F&RS intervention, unless there is an immediate self-evacuation. The only chances of preventing this outcome are prompt self-evacuation or for the occupant to protect themselves behind a closed door and wait to be rescued by the fire service.

When the lounge door is closed and the fire is contained, the time available for self-evacuation is more than doubled, a rescue is likely to take place prior to fatal exposure and those occupants who are protected by another closed door may survive for an extended period well after a typical F&RS intervention.

The experimental outcomes of this study compare well with similar studies which have previously been conducted. The value of the occupant being in a compartment with a closed door between them and the fire is clearly observed in this study as it is in others. Whilst these studies show that there is a delay in detection times where the fire compartment door is closed and the detector is located outside of the fire compartment, this delay is more than compensated for by the increase in the time available for self-evacuation. Several studies, including this one, also show that fatalities within the fire compartment can occur as a result of either heat or asphyxiant gases but in locations outside of the fire compartment, fatal exposure occurs almost exclusively from the inhalation of CO, HCN and CO_2.

Another conclusion of these experiments is that the residual air (in other rooms outside the fire compartment) offsets the effect of having an increased amount of ventilation, in fires where the fire compartment door is open and this air can be readily accessed by the fire. Where the fire compartment door is closed and the residual air is inaccessible, the amount of ventilation within the fire compartment becomes more critical. When ventilation is significantly reduced a fire will soon become vitiated and is likely to self-extinguish in a reduced O_2 atmosphere. The location of ventilation openings can also have a significant impact on fire growth and the production and circulation rates of heat and asphyxiant gases. The most hazardous example of this was when a vent (for outlet) was located on the first floor and a vent (for inlet) was located within the ground floor fire compartment.

In the sofa experiments, the two asphyxiant gases (CO and HCN) have an additive effect and contribute towards the occupants receiving a fatal dose. Based on the observed concentrations of these gases it was seen that HCN was the greatest contributor towards fatal exposure amounting to 60-75% compared with 25-40% coming from CO. It was observed that the ratio between the concentrations of asphyxiant gases CO and HCN seemed to change as the smoke plume moves away from the fire, possibly as a result of oxidation of CO to CO_2.

The approach taken to establish the HCN concentrations and to suggest that the CO:HCN ratio can change within the smoke plume also constitutes new work in this field. This is also the case for the comparison of the relative contribution of the individual asphyxiant gases to the total dose.

6.3 Conclusions on Intervention Dependence

In the event of an ADF, where the occupants are unable to self-evacuate, their only real chance of survival is for them to be rescued and the likelihood is that, during a severe fire, a rescue can only be performed by an attending fire crew.

FED and fatal exposure to heat or asphyxiant gases are dose (and therefore) time dependent. Consequently, unless fatal exposure occurs either well before or well after a typical F&RS intervention, then clearly intervention times will have a significant impact on the number of fire deaths and the seriousness of any fire injuries in the UK. Increases to intervention times will result in an increase in the number of fatalities and the seriousness of fire related injuries, if everything else remains equal.

A standard approach for assessing the effects of exposure to heat and asphyxiant gases has been established (ISO 13571) and has been used to develop a tenability timeline in a number of other studies. There is no evidence to suggest that a complete timeline for a fire service intervention has previously been established, nor is there any evidence that a comparison between occupant tenability and fire service intervention has been conducted.

This approach constitutes new work in the field and considers exposure in the context of assessing whether an occupant is likely to be alive at the point where they are rescued by the fire service. At this point, fire and/or ambulance crews will make attempts to overcome the effects of heat and asphyxiant gas exposure, with the aim of keeping the victim alive.

6.4 Further Work

In order to build upon this research study the author suggests that a number of activities should be undertaken.

Information gleaned from previous incidents helps to develop an understanding of the critical factors which lead to fatal and non-fatal injuries. Historical data can be used to develop strategies to reduce the number of casualties, however good data is not always readily available. A national database of information relating to fire deaths and injuries would support F&RSs when looking at intervention resourcing. Most importantly, this should be made available to appropriate persons within F&RSs to support decision making for risk-based intervention resourcing. At present, this type of analysis is conducted independently within F&RSs and as a result the statistical validity of the data is questionable. There would be value in establishing a national database, similar to the way in which the LIFEBID project is aimed at gathering data on human behaviour [95].

Experimental data provides a real insight to the hazards that are present during ADFs. Whilst it is costly and not always simple to conduct such experimental activities, more data gathering of this kind will support future understanding and the development of evidence-based decision making. In support of this there would be great value in developing continuous monitoring of HCN concentrations during experimentation.

A less expensive way of obtaining such data could be via the use of computational fluid dynamics (CFD) and efforts should be made to use any experimentally gathered data to calibrate such models to improve their realism.

This study also identifies the impact that ventilation conditions can have on fire development. Further understanding of this would support both the advice given to members of the public and could also inform firefighting tactics such that the positive impact of an intervention could potentially be achieved earlier.

Chapter 7 - Recommendations

On the basis of the conclusions made within this study, the following recommendations are made for limiting/reducing the number of fire deaths and injuries in the UK. This approach covers prevention, protection and intervention activities to achieve this objective.

This study shows that having a working smoke alarm within a dwelling is imperative for alerting occupants to the fire hazard and for giving them the greatest opportunity to act prior to the arrival of the F&RS. In addition, having a closed door between the occupant and the fire is likely to delay the onset of fatal exposure to asphyxiant gases by around 10 min. Having this benefit greatly increases the likelihood that the F&RS can successfully rescue trapped occupants and avert a fatal exposure.

Therefore, F&RS personnel should continue to lobby for a change to guidance, to extend the coverage of smoke detection/alarm into high risk rooms (living and bedrooms) and to ensure that detectors are interlinked. Protection activities should also be undertaken to continue to promote the benefits of closed doors. These measures are of particular importance to the more vulnerable members of our communities who are more likely to be affected by fire.

F&RSs should aim to maintain or even improve their intervention times, where possible, and should continue to give careful consideration towards resourcing their intervention provision and ensuring that training is given to firefighters and fire control operators who impact upon intervention times.

In light of the funding cuts within all public sector services, maintaining rapid intervention times is a real challenge for F&RSs and in many cases the current standards are being lowered as attendance times continue to increase.

Where increased intervention times are unavoidable, greater investment should be made in prevention and protection activities, which can offset the resultant risk. Managing budgets to successfully provide appropriate services is a very fine balance and one which should always be conducted on the basis of risk.

Section 5.8 discusses the options for ensuring that intervention times are minimised. There are opportunities to reduce the time taken to complete almost all of the 8 stages of an intervention, not all of which are costly and require additional resourcing. In general, reductions can be made through staff training, software development and improved operational procedures. These activities will deliver benefits but it is important to recognise that the two most effective ways of minimising intervention times and increasing the likelihood of survivability are to achieve early detection of fire and to ensure that crew travel times are minimised.

More widespread use of smoke detection and lobbying for national guidance to achieve this would help to reduce intervention times and also give people a greater chance of surviving an ADF. Measures should also be taken to reduce crew travel times by ensuring that the intervention function is properly resourced and by the use of local knowledge and a risk-based approach to provide the best coverage of this resource across each geographical area.

In the West Midlands, the average crew travel time to all ADF incidents (over the last two years) was 4 min and 3 seconds. The West Midlands is a largely urban area and like other conurbations, fire stations are reasonably well distributed and resourced. In more sparsely populated areas, fire stations are located with less frequency and can have a reduced resource, therefore the F&RSs operating in predominantly rural areas have significantly greater crew travel times.

However, the underlying risk of fire deaths in rural areas is generally much lower than in large towns and cities, resulting from a reduced frequency of fire, and therefore a risk-based approach is taken. In order to reduce the number of fire deaths and limit the extent of fire injuries, F&RSs should identify their 'at risk' areas and ensure that intervention times to these are minimised.

Chapter 8 - Limitations

In order to complete this study, it has been necessary to make a number of assumptions and the reader should also recognise that there are some limitations. These are both discussed in the context of the experimental data gathering and in establishing intervention timelines. All assumptions are made on the basis of information that has been gathered during the completion of this project and every effort has been made to ensure that they are as accurate and as appropriate as possible.

The following assumptions are made in respect of the experimental data gathering: -

- Exposure to heat and asphyxiant gases are considered for compromised tenability only, with sensory irritation and smoke obscuration being considered to have minor effects
- CO and HCN are the only asphyxiant gases considered with the production rate of HCN given on the basis of an equivalence to CO
- Equations used to calculate the FED end points have a level of uncertainty of up to 35%
- Exposure to heat and smoke occurs for an adult in a standing position
- People will choose not to escape through smoke which renders the visibility below 3 m
- There are wide variations in human tolerances to the effects of heat and smoke
- The item mainly responsible for the production of smoke in the early stages of fire development is the item first ignited
- Either an occupant of the property or a passer-by respond promptly to the fire alarm by contacting the fire service to report a fire
- A limited number of fire tests were completed and varaitaions were observed between identical experiments

The following assumptions are made in respect of establishing intervention timelines: -

- The property contains a working smoke alarm
- Occupier recognition times for fire alarms are established from fire statistics

Human susceptibility to the effects of the heat and smoke produced by a fire can be quite varied and it has been necessary to make some assumptions during data analysis. On this basis, it is recognised that it is a limitation of this project that it is not able to accurately determine the exact point at which any individual would succumb to their effects. Instead, this study gives a very good indication of the timeframe over which people can survive these effects and compares this to a realistic point at which a fire service intervention would take place.

Whilst it has been necessary to make a number of assumptions in order to conduct this study, the international standard ISO 13571 accepts that this is required to make calculations around the point at which compromised tenability occurs.

On the basis that these two timelines overlap, in many circumstances, it seems reasonable to suggest that human survivability can be effected by prompt firefighter activities.

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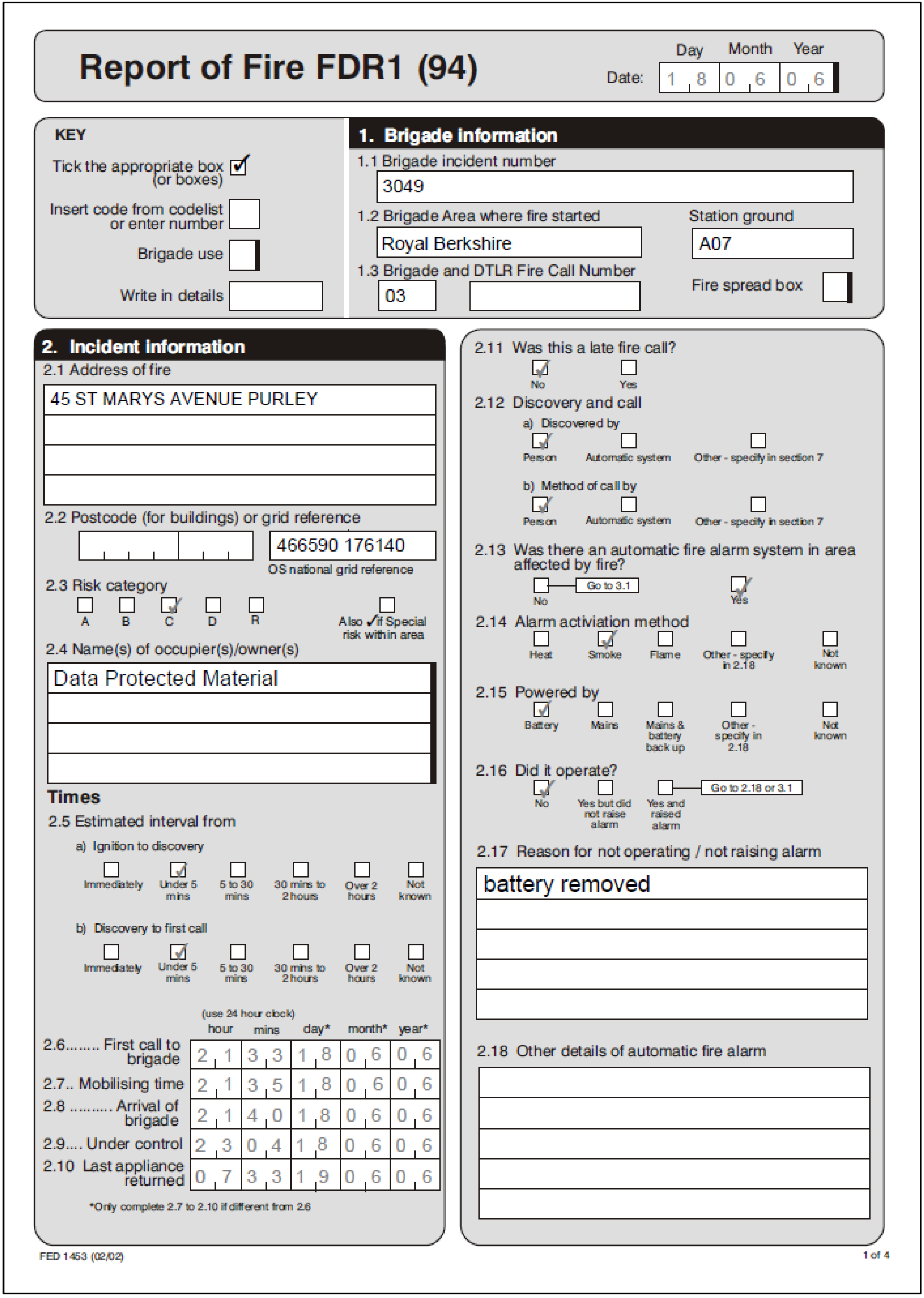
Appendices

Appendix A – Example of a Fire Data Report



Report of Fire FDR1 (94)

Date: Day 18 Month 06 Year 06

KEY

Tick the appropriate box (or boxes) ☑

Insert code from codelist or enter number ☐

Brigade use ☐

Write in details ☐

1. Brigade information

1.1 Brigade incident number: 3049

1.2 Brigade Area where fire started: Royal Berkshire

Station ground: A07

1.3 Brigade and DTLR Fire Call Number: 03

Fire spread box ☐

2. Incident information

2.1 Address of fire

45 ST MARYS AVENUE PURLEY

2.2 Postcode (for buildings) or grid reference

466590 176140

OS national grid reference

2.3 Risk category

☐ A ☐ B ☑ C ☐ D ☐ R

☐ Also ✓if Special risk within area

2.4 Name(s) of occupier(s)/owner(s)

Data Protected Material

Times

2.5 Estimated interval from

a) Ignition to discovery

☐ Immediately ☑ Under 5 mins ☐ 5 to 30 mins ☐ 30 mins to 2 hours ☐ Over 2 hours ☐ Not known

b) Discovery to first call

☐ Immediately ☑ Under 5 mins ☐ 5 to 30 mins ☐ 30 mins to 2 hours ☐ Over 2 hours ☐ Not known

(use 24 hour clock)

	hour	mins	day*	month*	year*
2.6........ First call to brigade	21	33	18	06	06
2.7.. Mobilising time	21	35	18	06	06
2.8 .... Arrival of brigade	21	40	18	06	06
2.9.... Under control	23	04	18	06	06
2.10 Last appliance returned	07	33	19	06	06

*Only complete 2.7 to 2.10 if different from 2.6

2.11 Was this a late fire call?

☑ No ☐ Yes

2.12 Discovery and call

a) Discovered by

☑ Person ☐ Automatic system ☐ Other - specify in section 7

b) Method of call by

☑ Person ☐ Automatic system ☐ Other - specify in section 7

2.13 Was there an automatic fire alarm system in area affected by fire?

☐ No — Go to 3.1 ☑ Yes

2.14 Alarm activiation method

☐ Heat ☑ Smoke ☐ Flame ☐ Other - specify in 2.18 ☐ Not known

2.15 Powered by

☑ Battery ☐ Mains ☐ Mains & battery back up ☐ Other - specify in 2.18 ☐ Not known

2.16 Did it operate?

☑ No ☐ Yes but did not raise alarm ☐ Yes and raised alarm — Go to 2.18 or 3.1

2.17 Reason for not operating / not raising alarm

battery removed

2.18 Other details of automatic fire alarm

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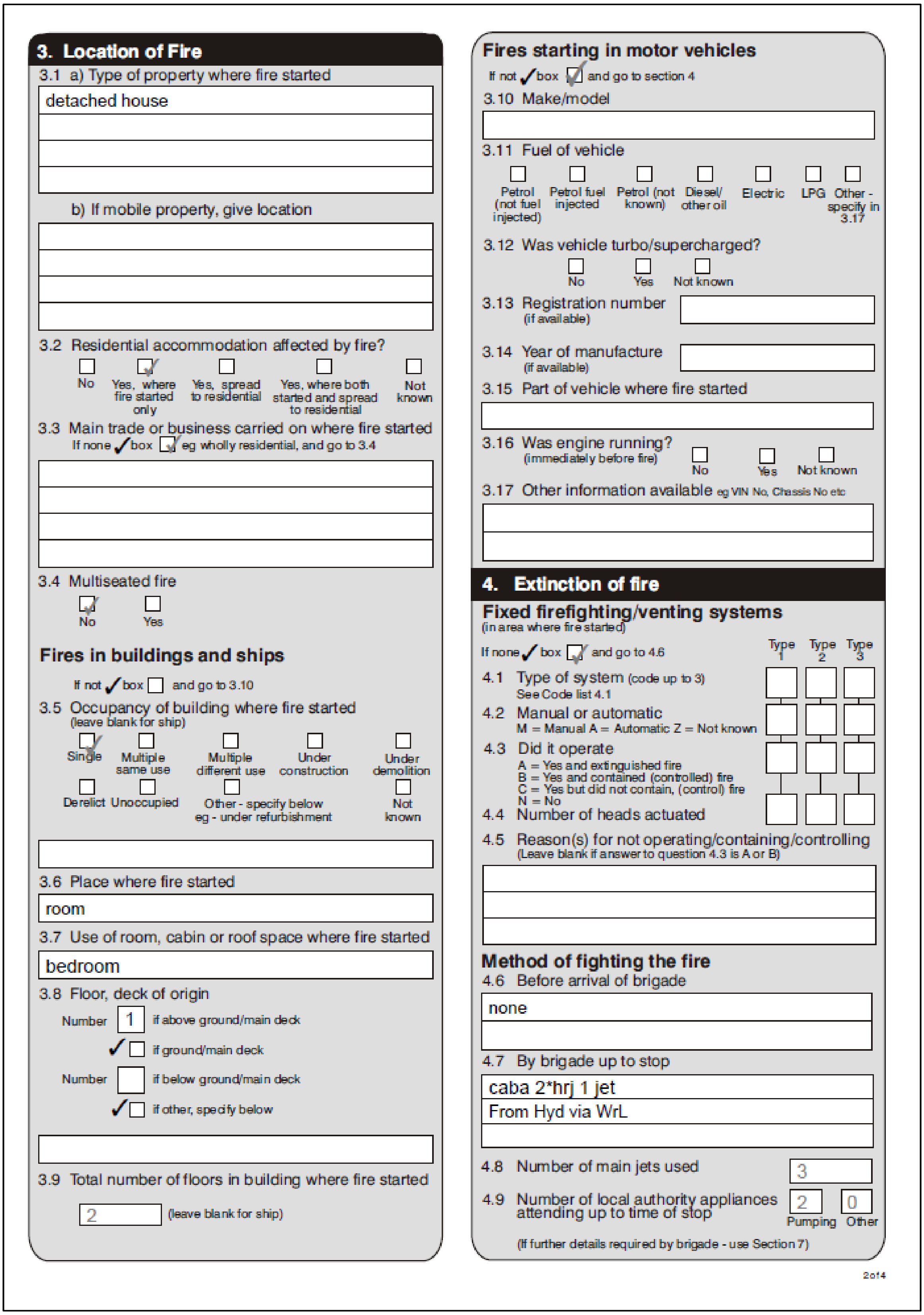


3. Location of Fire

3.1 a) Type of property where fire started

detached house

b) If mobile property, give location

3.2 Residential accommodation affected by fire?

☐ No ☑ Yes, where fire started only ☐ Yes, spread to residential ☐ Yes, where both started and spread to residential ☐ Not known

3.3 Main trade or business carried on where fire started

If none ✓ box ☑ eg wholly residential, and go to 3.4

3.4 Multiseated fire

☑ No ☐ Yes

Fires in buildings and ships

If not ✓ box ☐ and go to 3.10

3.5 Occupancy of building where fire started (leave blank for ship)

☑ Single ☐ Multiple same use ☐ Multiple different use ☐ Under construction ☐ Under demolition

☐ Derelict ☐ Unoccupied ☐ Other - specify below eg - under refurbishment ☐ Not known

3.6 Place where fire started

room

3.7 Use of room, cabin or roof space where fire started

bedroom

3.8 Floor, deck of origin

Number 1 if above ground/main deck

✓ ☐ if ground/main deck

Number ☐ if below ground/main deck

✓ ☐ if other, specify below

3.9 Total number of floors in building where fire started

2 (leave blank for ship)

Fires starting in motor vehicles

If not ✓ box ☑ and go to section 4

3.10 Make/model

3.11 Fuel of vehicle

☐ Petrol (not fuel injected) ☐ Petrol fuel injected ☐ Petrol (not known) ☐ Diesel/ other oil ☐ Electric ☐ LPG ☐ Other - specify in 3.17

3.12 Was vehicle turbo/supercharged?

☐ No ☐ Yes ☐ Not known

3.13 Registration number (if available)

3.14 Year of manufacture (if available)

3.15 Part of vehicle where fire started

3.16 Was engine running? (immediately before fire) ☐ No ☐ Yes ☐ Not known

3.17 Other information available eg VIN No, Chassis No etc

4. Extinction of fire

Fixed firefighting/venting systems

(in area where fire started)

If none ✓ box ☑ and go to 4.6

	Type 1	Type 2	Type 3
4.1 Type of system (code up to 3) See Code list 4.1			
4.2 Manual or automatic M = Manual A = Automatic Z = Not known			
4.3 Did it operate A = Yes and extinguished fire B = Yes and contained (controlled) fire C = Yes but did not contain, (control) fire N = No			
4.4 Number of heads actuated			

4.5 Reason(s) for not operating/containing/controlling (Leave blank if answer to question 4.3 is A or B)

Method of fighting the fire

4.6 Before arrival of brigade

none

4.7 By brigade up to stop

caba 2*hrj 1 jet

From Hyd via WrL

4.8 Number of main jets used 3

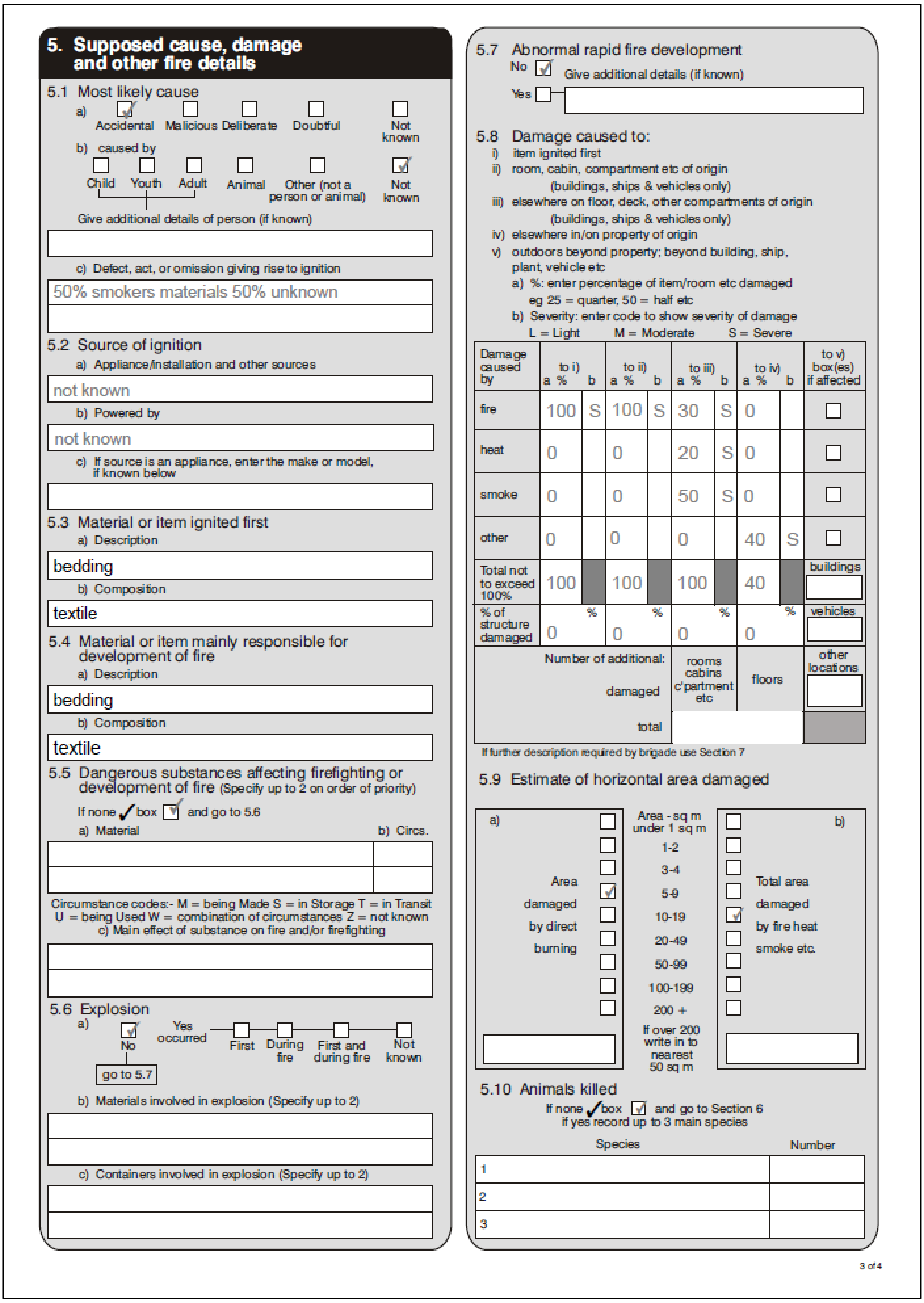
4.9 Number of local authority appliances attending up to time of stop

Pumping 2

Other 0

(If further details required by brigade - use Section 7)

2of4



5. Supposed cause, damage and other fire details

5.1 Most likely cause

a) ☑ Accidental ☐ Malicious ☐ Deliberate ☐ Doubtful ☐ Not known

b) caused by

☐ Child ☐ Youth ☐ Adult ☐ Animal ☐ Other (not a person or animal) ☑ Not known

Give additional details of person (if known)

c) Defect, act, or omission giving rise to ignition

50% smokers materials 50% unknown

5.2 Source of ignition

a) Appliance/installation and other sources

not known

b) Powered by

not known

c) If source is an appliance, enter the make or model, if known below

5.3 Material or item ignited first

a) Description

bedding

b) Composition

textile

5.4 Material or item mainly responsible for development of fire

a) Description

bedding

b) Composition

textile

5.5 Dangerous substances affecting firefighting or development of fire (Specify up to 2 on order of priority)

If none ✓ box ☑ and go to 5.6

a) Material	b) Circs.

Circumstance codes:- M = being Made S = in Storage T = in Transit U = being Used W = combination of circumstances Z = not known

c) Main effect of substance on fire and/or firefighting

5.6 Explosion

a) ☑ No — go to 5.7

Yes occurred ☐ First ☐ During fire ☐ First and during fire ☐ Not known

b) Materials involved in explosion (Specify up to 2)

c) Containers involved in explosion (Specify up to 2)

5.7 Abnormal rapid fire development

No ☑ Give additional details (if known)

Yes ☐

5.8 Damage caused to:

i) item ignited first
ii) room, cabin, compartment etc of origin (buildings, ships & vehicles only)
iii) elsewhere on floor, deck, other compartments of origin (buildings, ships & vehicles only)
iv) elsewhere in/on property of origin
v) outdoors beyond property; beyond building, ship, plant, vehicle etc
a) %: enter percentage of item/room etc damaged eg 25 = quarter, 50 = half etc
b) Severity: enter code to show severity of damage
L = Light M = Moderate S = Severe

Damage caused by	to i) a %	b	to ii) a %	b	to iii) a %	b	to iv) a %	b	to v) box(es) if affected
fire	100	S	100	S	30	S	0		☐
heat	0		0		20	S	0		☐
smoke	0		0		50	S	0		☐
other	0		0		0		40	S	☐
Total not to exceed 100%	100		100		100		40		buildings
% of structure damaged	0 %		0 %		0 %		0 %		vehicles

Number of additional:	rooms cabins c'partment etc	floors	other locations
damaged			
total			

If further description required by brigade use Section 7

5.9 Estimate of horizontal area damaged

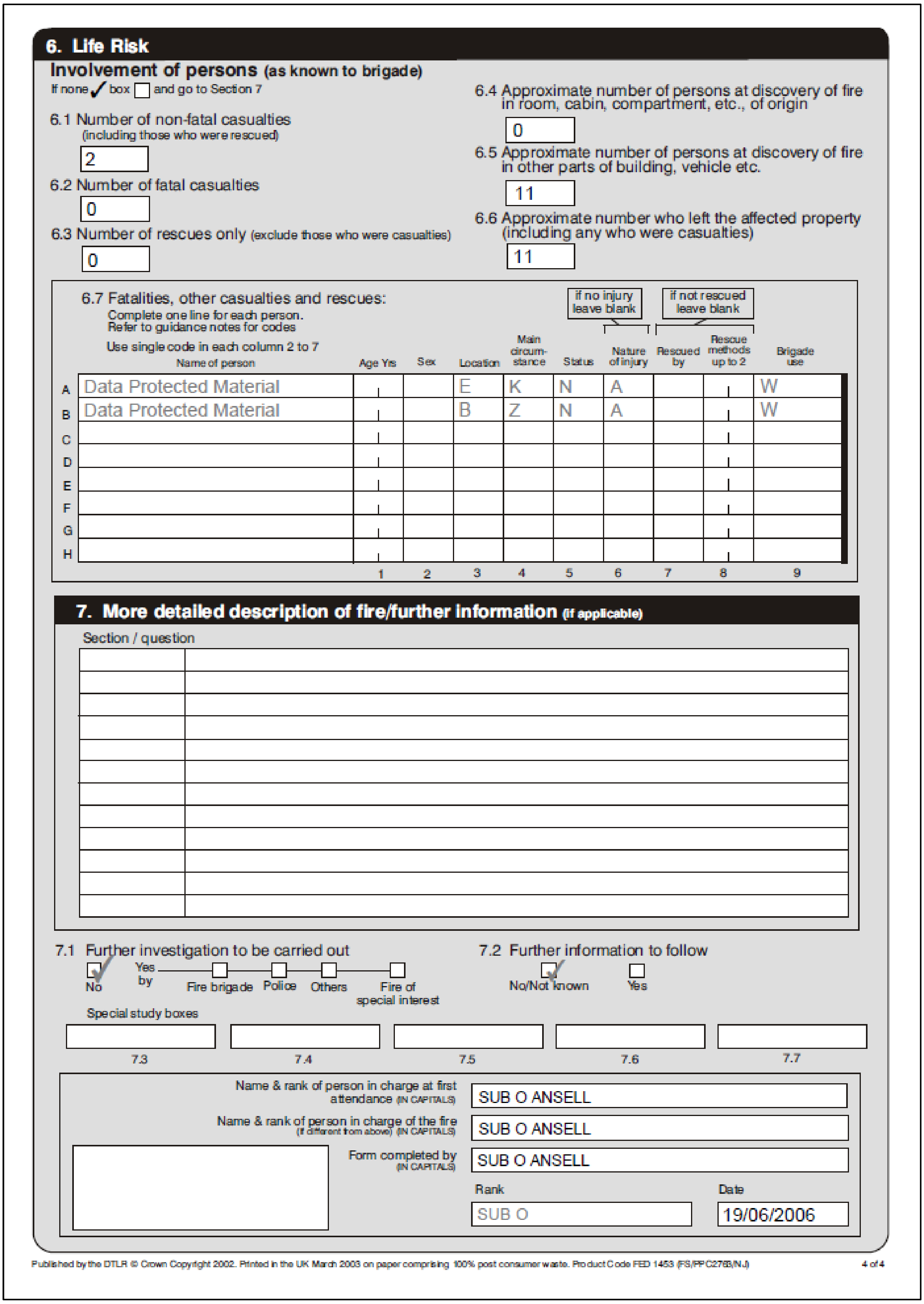
a) Area damaged by direct burning	Area - sq m	b) Total area damaged by fire heat smoke etc.
☐	under 1 sq m	☐
☐	1-2	☐
☐	3-4	☐
☑	5-9	☐
☐	10-19	☑
☐	20-49	☐
☐	50-99	☐
☐	100-199	☐
☐	200 +	☐
	If over 200 write in to nearest 50 sq m	

5.10 Animals killed

If none ✓ box ☑ and go to Section 6
if yes record up to 3 main species

	Species	Number
1		
2		
3		

3 of 4



6. Life Risk

Involvement of persons (as known to brigade)

If none ✓ box ☐ and go to Section 7

6.1 Number of non-fatal casualties (including those who were rescued)
2

6.2 Number of fatal casualties
0

6.3 Number of rescues only (exclude those who were casualties)
0

6.4 Approximate number of persons at discovery of fire in room, cabin, compartment, etc., of origin
0

6.5 Approximate number of persons at discovery of fire in other parts of building, vehicle etc.
11

6.6 Approximate number who left the affected property (including any who were casualties)
11

6.7 Fatalities, other casualties and rescues:
Complete one line for each person.
Refer to guidance notes for codes
Use single code in each column 2 to 7

if no injury leave blank

if not rescued leave blank

	Name of person	Age Yrs	Sex	Location	Main circumstance	Status	Nature of injury	Rescued by	Rescue methods up to 2	Brigade use
A	Data Protected Material			E	K	N	A			W
B	Data Protected Material			B	Z	N	A			W
C										
D										
E										
F										
G										
H										
		1	2	3	4	5	6	7	8	9

7. More detailed description of fire/further information (if applicable)

Section / question

7.1 Further investigation to be carried out
☑ No
Yes by ☐ Fire brigade ☐ Police ☐ Others ☐ Fire of special interest

7.2 Further information to follow
☑ No/Not known
☐ Yes

Special study boxes

7.3
7.4
7.5
7.6
7.7

Name & rank of person in charge at first attendance (IN CAPITALS) SUB O ANSELL

Name & rank of person in charge of the fire (if different from above) (IN CAPITALS) SUB O ANSELL

Form completed by (IN CAPITALS) SUB O ANSELL

Rank SUB O

Date 19/06/2006

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Appendix B – Large-scale Test House Storey Layout

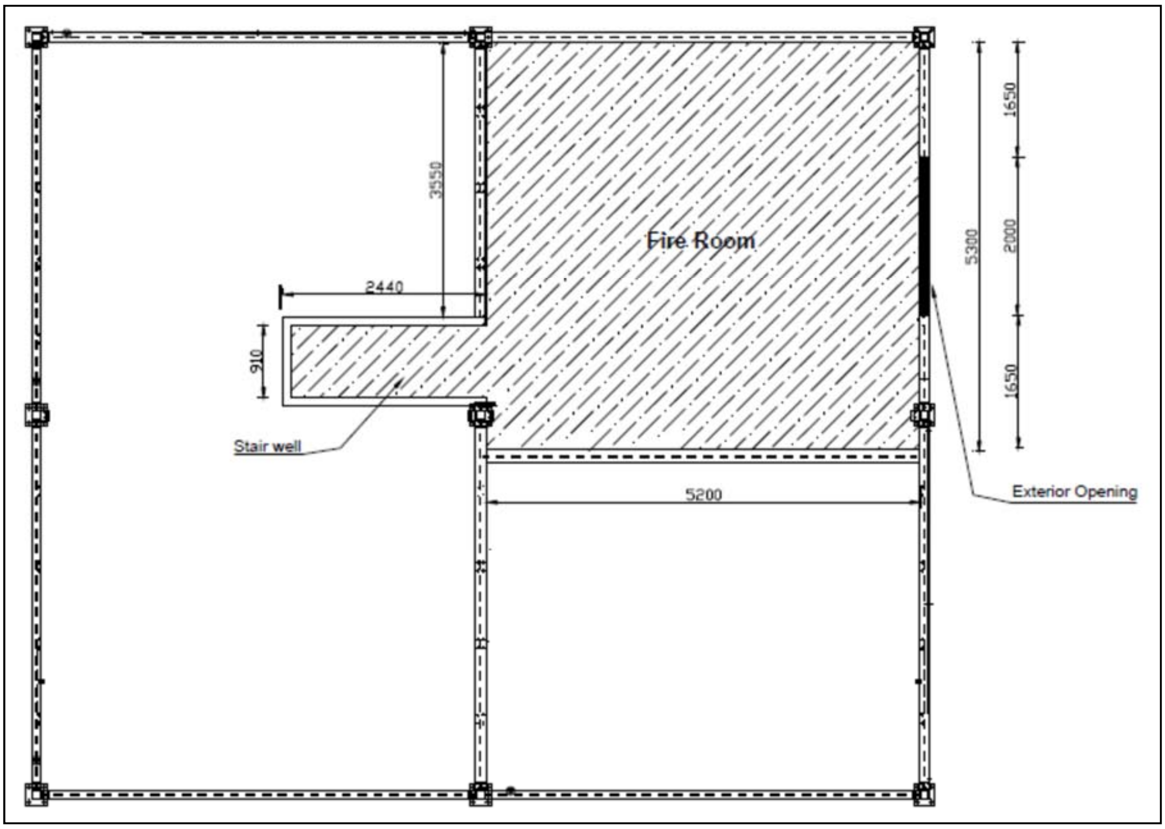


Figure A1 – NRC Canada study basement layout

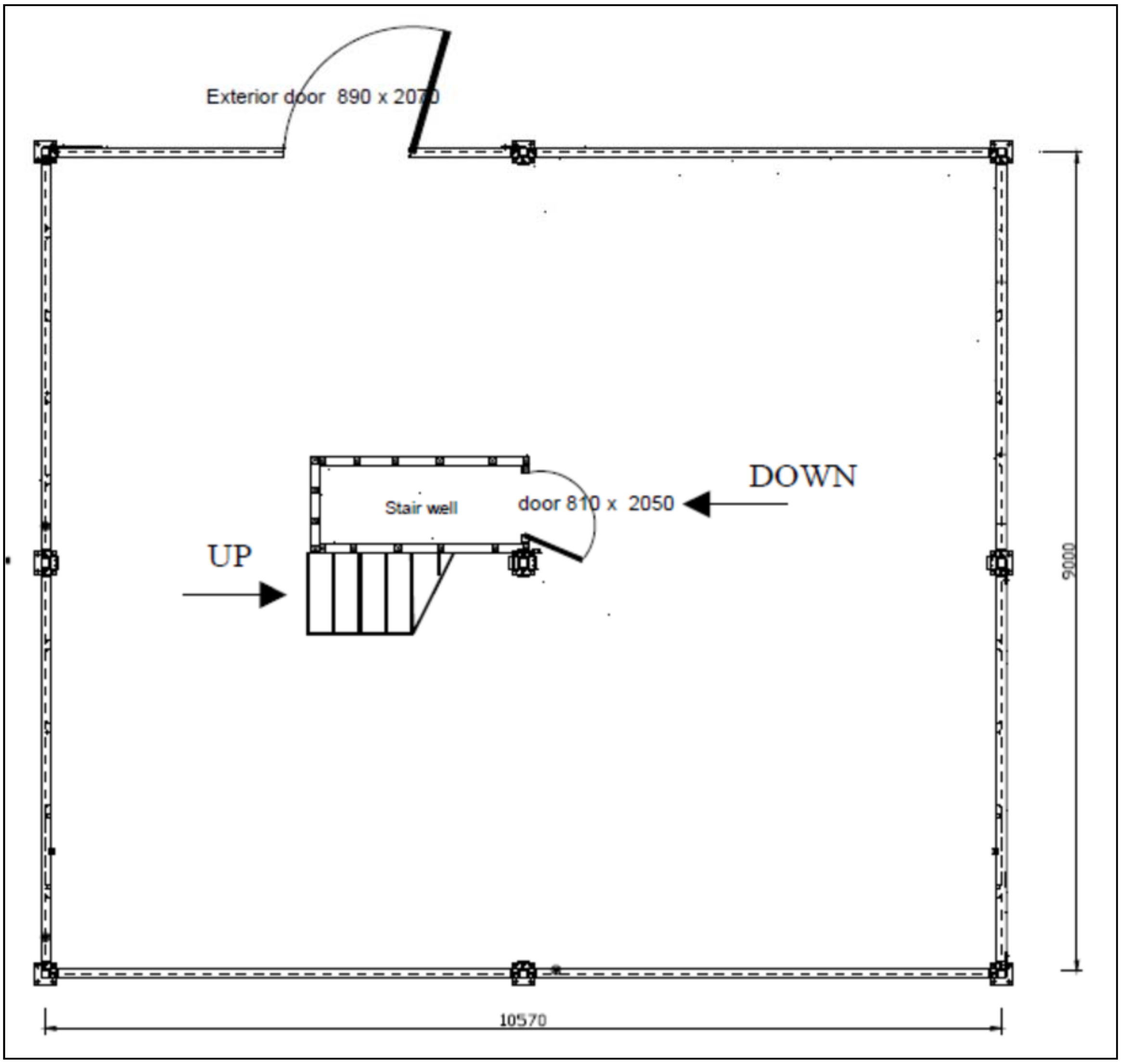


Figure A2 – NRC Canada study ground floor layout

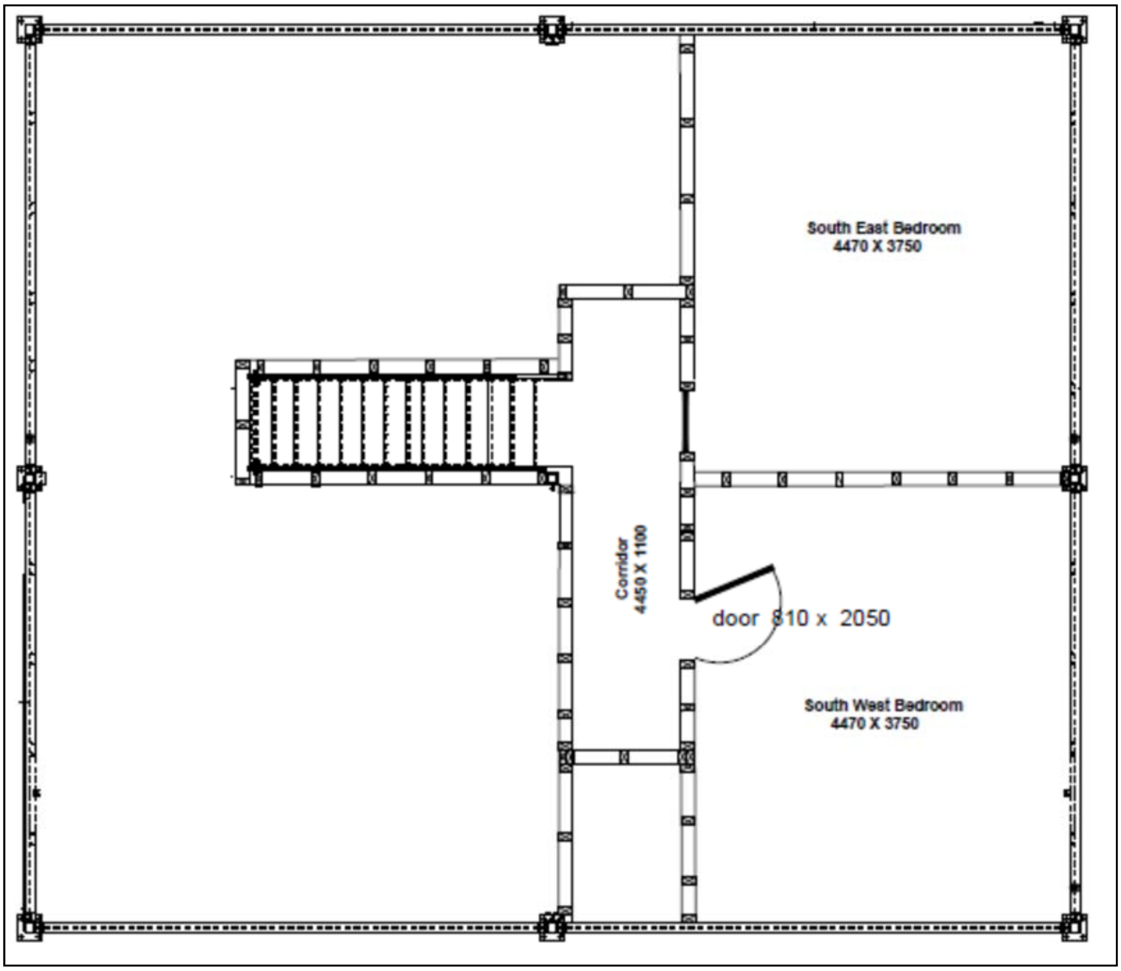
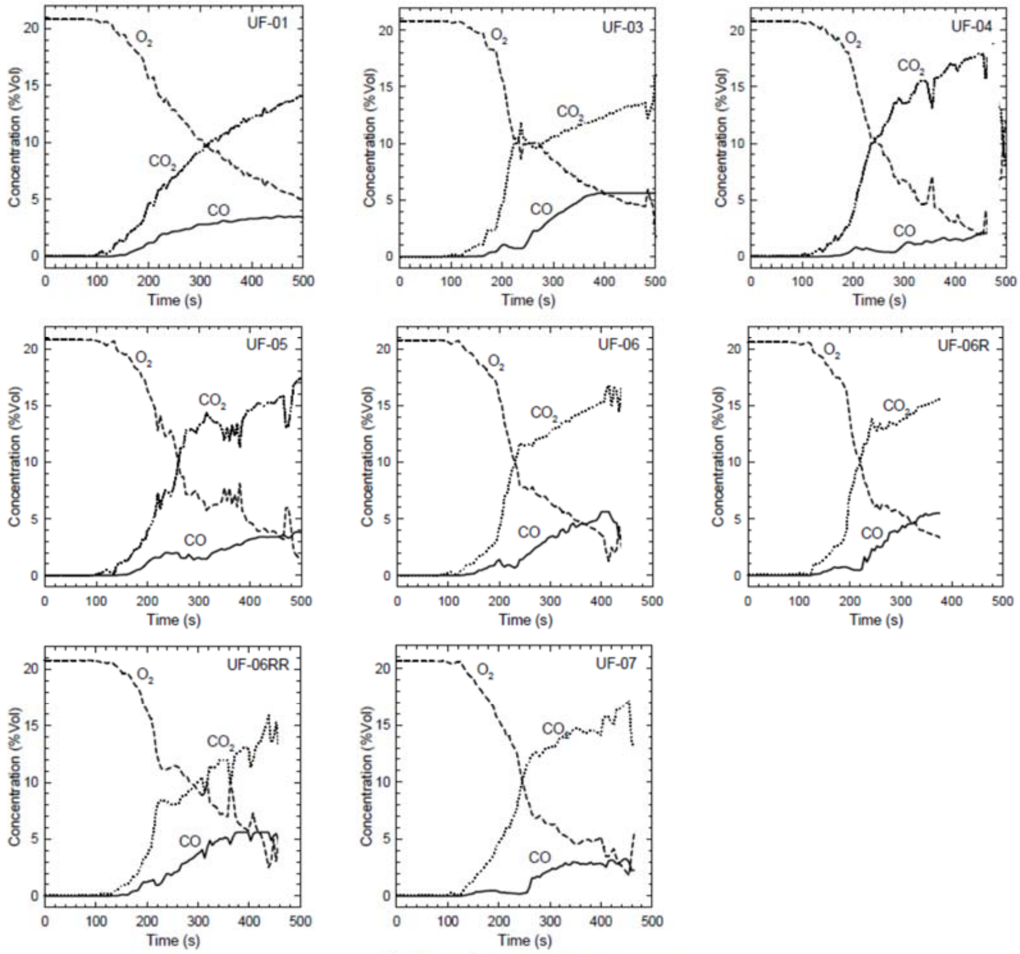
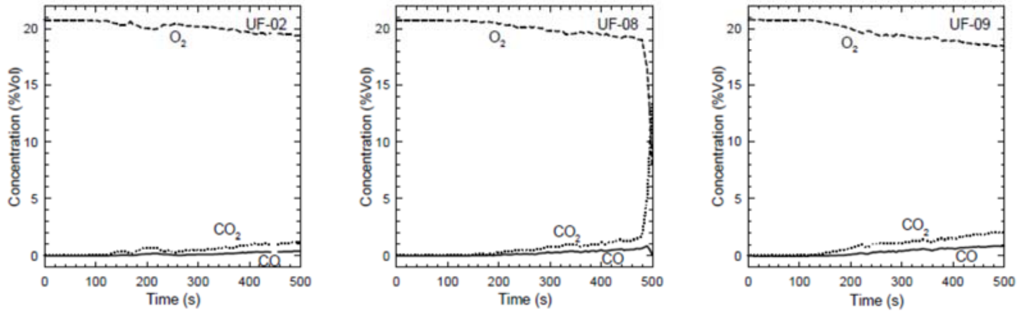


Figure A3 – NRC Canada study first floor layout

Appendix C – O_2, CO_2 and CO Conc. (NRC Canada)



a) Open basement doorway



b) Closed basement doorway

Figure 11. CO, CO_2 and O_2 concentrations measured at the southwest quarter point on the first storey at 1.5 m height

Figure A4 – Concentrations of O2, CO2 and CO in the NRC Canada study

Appendix D – Examples of Gas Calibration Curves

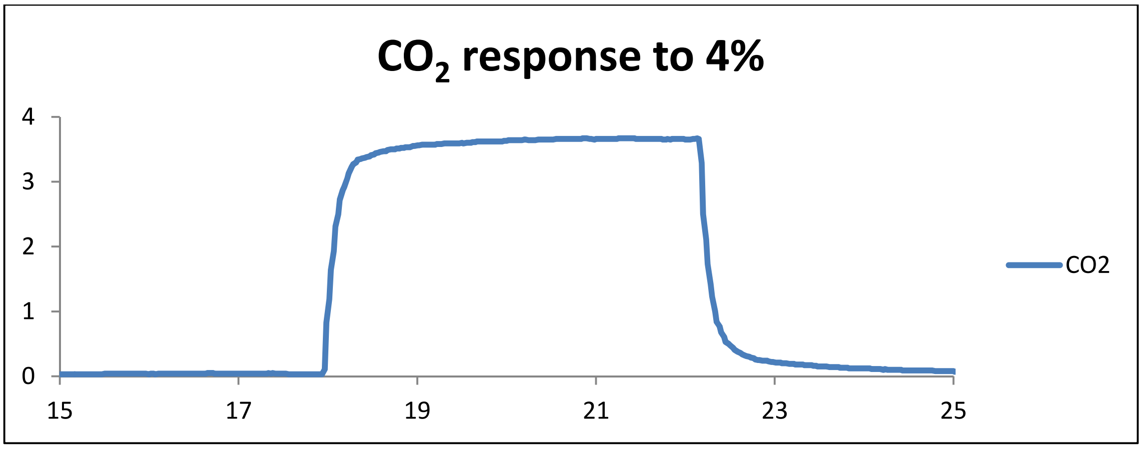


Figure A5 – CO2 calibration response to 4.0% carbon dioxide

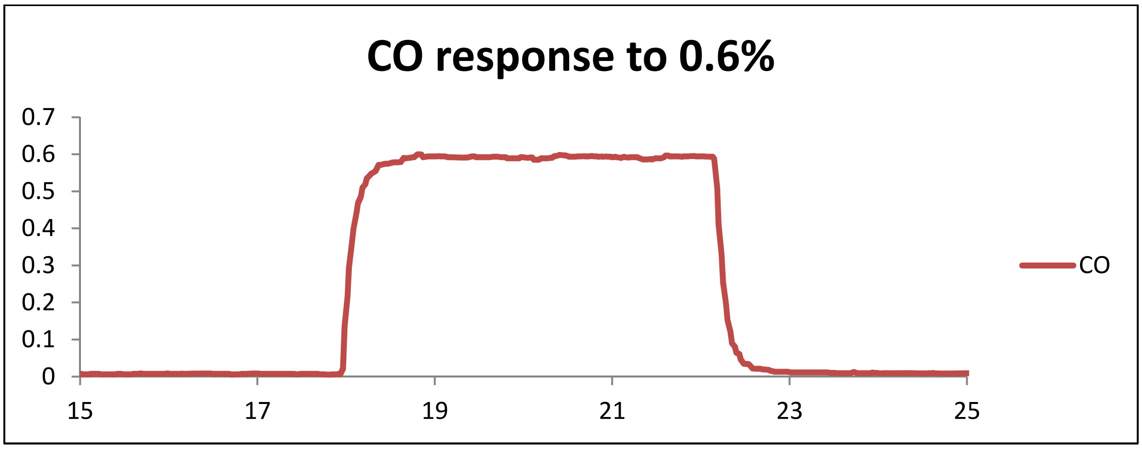


Figure A6 – CO calibration response to 0.6% carbon monoxide

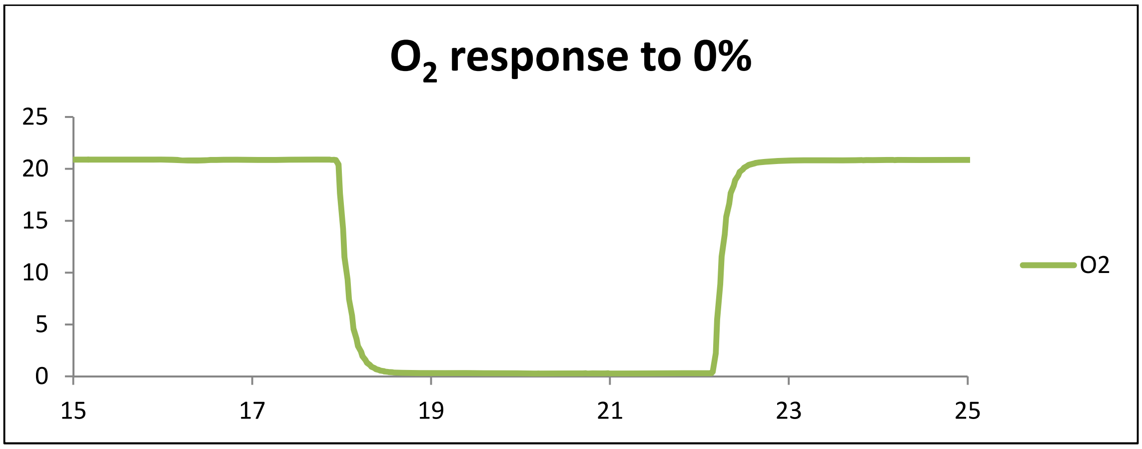


Figure A7 – O2 calibration response to 0.0% oxygen

Appendix E – Individual HCN & CO Gas Concentrations

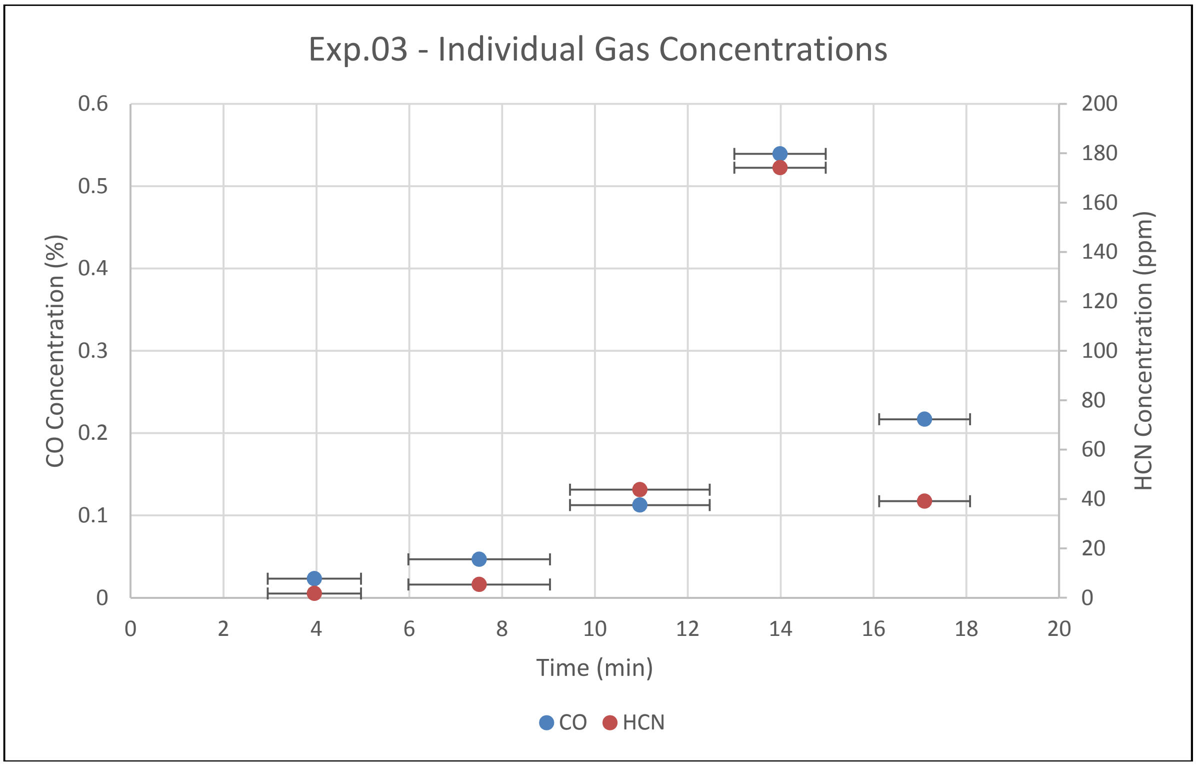


Figure A8 – Experiment 03 individual gas concentrations

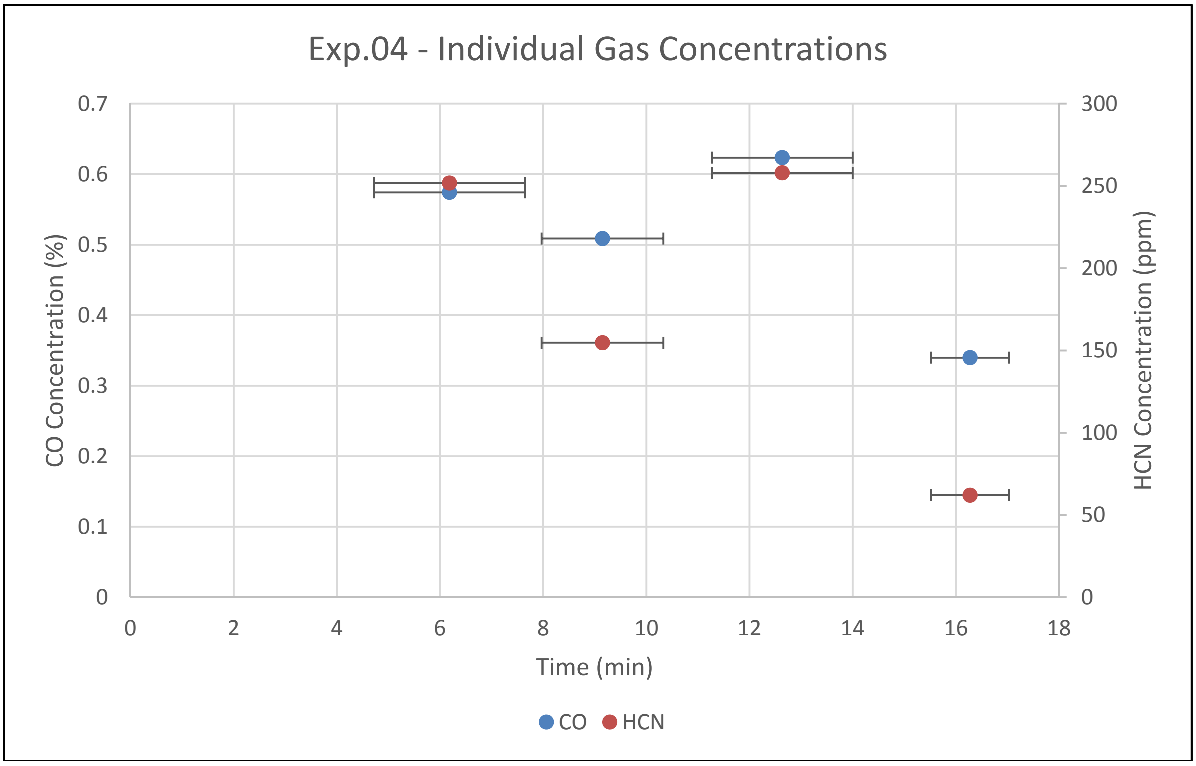


Figure A9 – Experiment 04 individual gas concentrations

Email: rgwalker@uclan.ac.uk

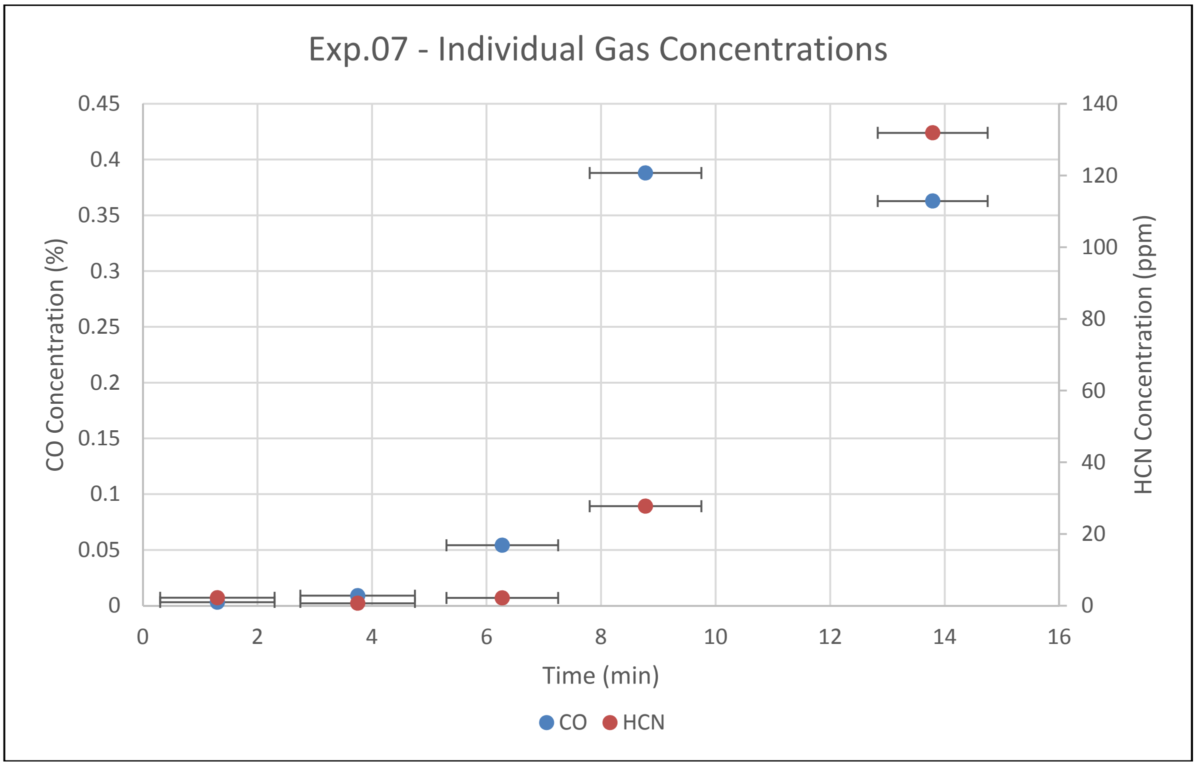


Figure A10 – Experiment 07 individual gas concentrations

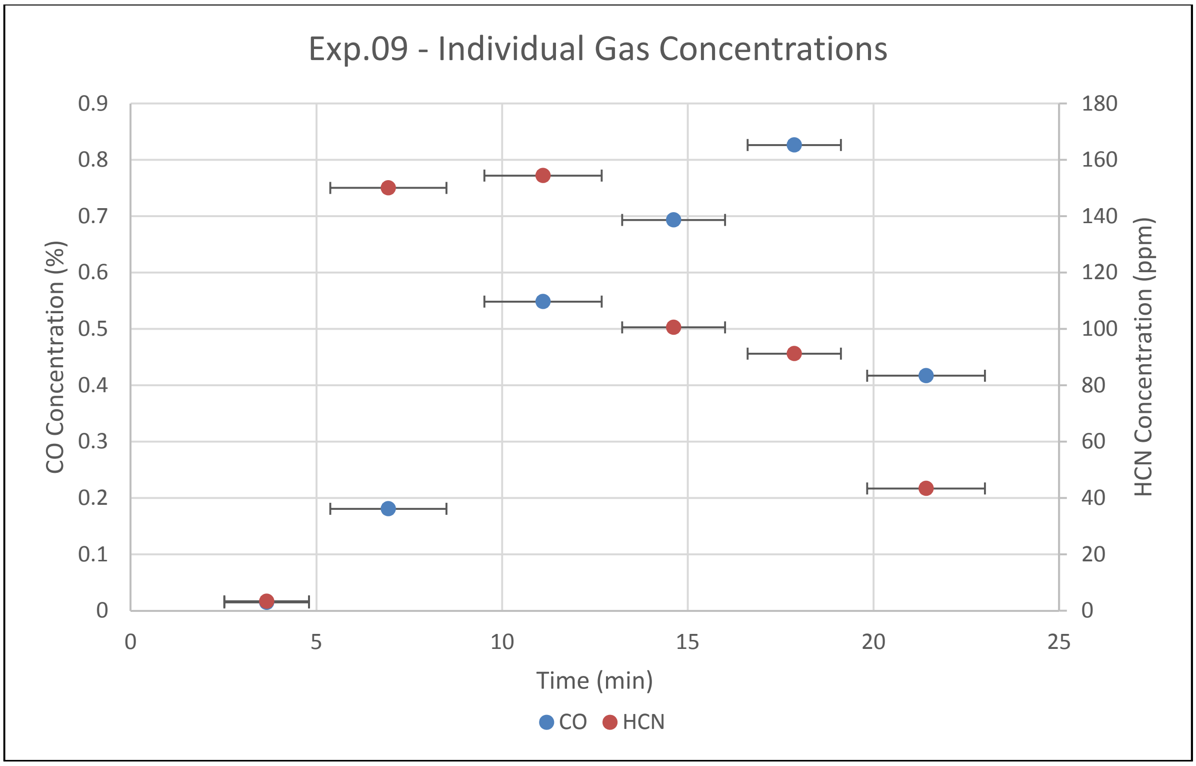


Figure A11 – Experiment 09 individual gas concentrations

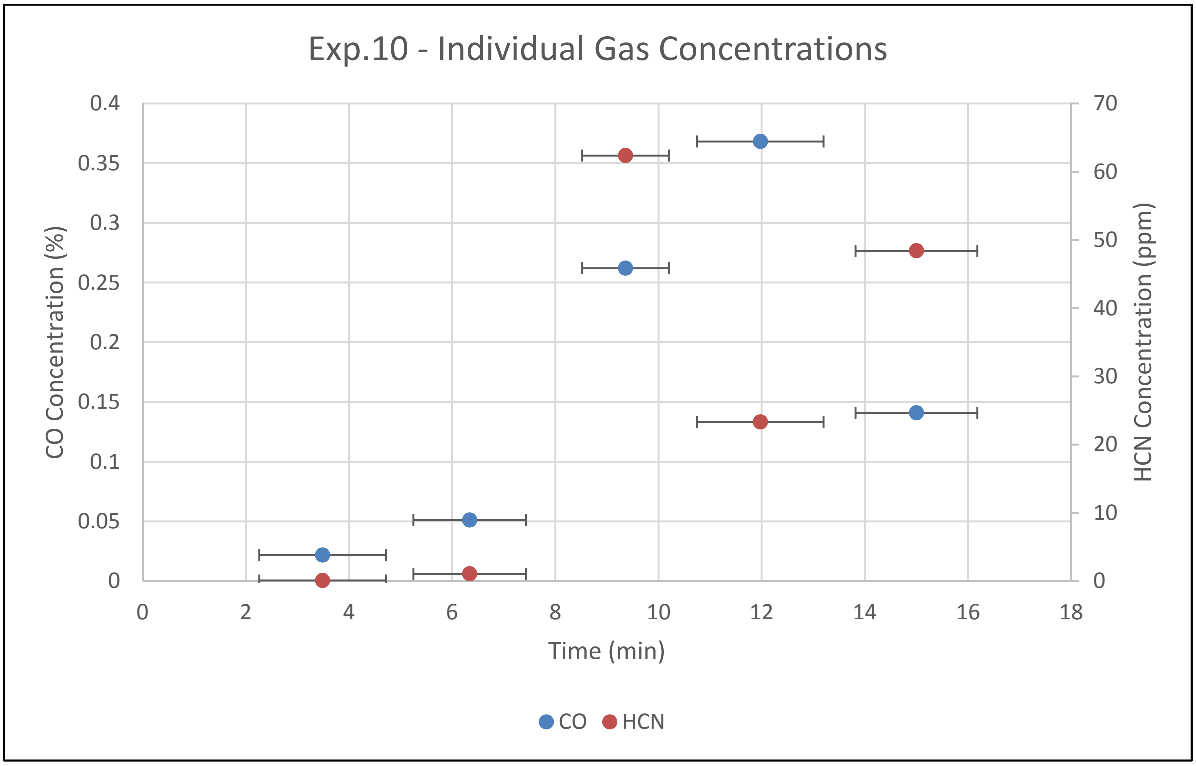


Figure A12 – Experiment 10 individual gas concentrations

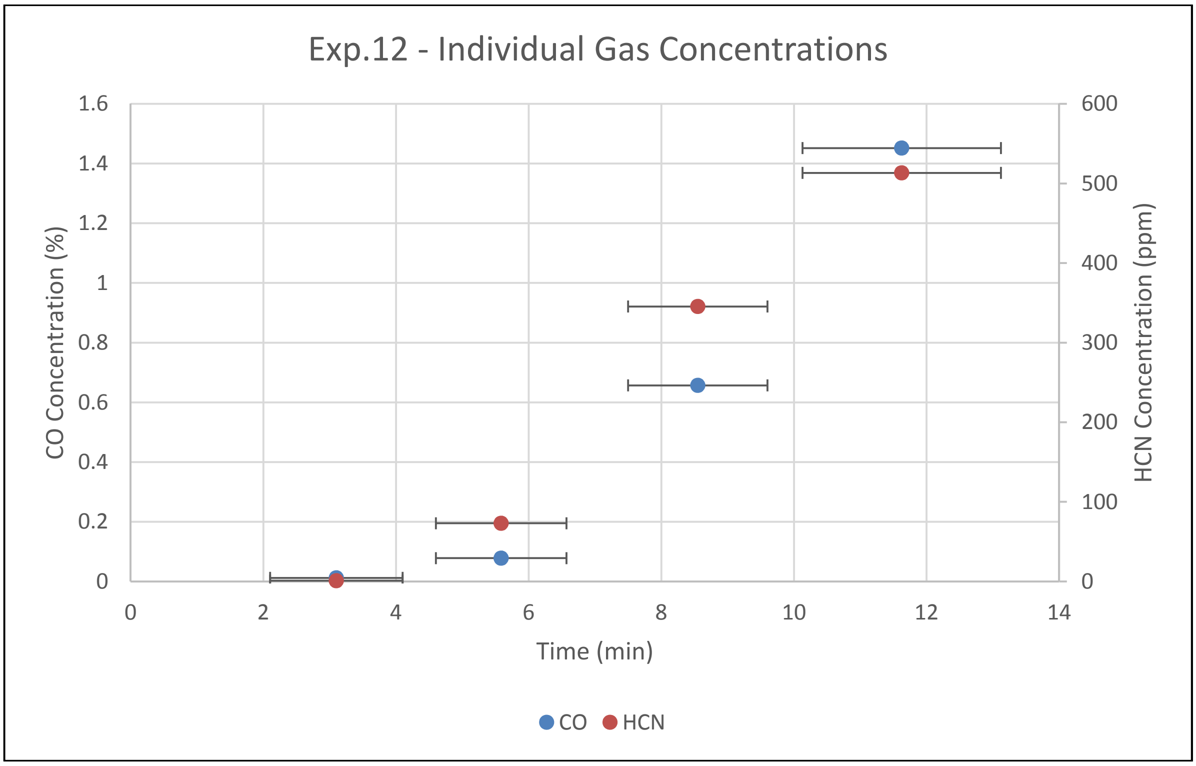


Figure A13 – Experiment 12 individual gas concentrations